HANDBOOK OF OPTICAL MATERIALS

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HANDBOOK OF OPTICAL MATERIALS

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Preface

The *Handbook of Optical Materials* is a compilation of the physical properties of optical materials used in optical systems and lasers. It contains extensive data tabulations but with a minimum of narration, in a style similar to that of the *CRC Handbook of Chemistry and Physics*. References to original or secondary sources of the data are included throughout. The objective of the handbook is to provide a convenient, reliable source of information on the properties of optical materials.

Data in a handbook of optical materials can be presented by material (e.g., SiO_2, CaF_2, Ge), by property (e.g., refractive index, thermal expansion, hardness), by wavelength region (e.g., infrared, visible, ultraviolet), or by application (e.g., transmitting optics, laser hosts, polarizers). In this handbook data are grouped by material properties. Thereby one can compare different materials with respect to their properties and suitability for a particular application.

The volume is divided into sections devoted to various forms of condensed matter (crystals, glasses, polymers, metals), liquids, and gases. Within each section physical properties, linear and nonlinear optical properties, and many special properties such as electrooptic, magnetoopic, and elastooptic properties of the materials are tabulated. The optical solids included are mainly inorganic materials; optical liquids are mainly organic substances.

If by an optical material one means a material that exhibits some optical property such as transmission, absorption, reflection, refraction, scattering, etc., the number of materials to be considered becomes unmanageable. Thus the inclusion of materials in this volume is selective rather than exhaustive. In the case of commercial optical glasses, for example, properties of representative types of glasses are given but not properties for all compositional variations. Glasses with special properties or for special applications are included, however.

Bulk materials rather than thin films and multilayer structures are considered. Although optical glasses epitomizes an engineered material, other engineered optical materials such as nanomaterials, quantum wells, or photonic crystals are also not included (although one of the last is listed in Appendix II).

Although today optics can encompass x-ray and millimeterwave optics, coverage is limited to materials for the spectral range from the vacuum ultraviolet (~100 nm) to the infrared (up to 100 μm) portion of the electromagnetic spectrum.

Among optical materials and properties not treated explicitly are photorefractive materials, liquid crystals, optical fibers, phase-change optical recording materials, luminescent materials (phosphors, scintillators), optical damage, and materials preparation and fabrication.

Much of the numerical data in this handbook is from Volumes III, IV, V, and Supplement 2 of the *CRC Handbook of Laser Science and Technology.* These volumes should be consulted for more detailed descriptions of properties and their measurement (the contents of the volumes and the contributors are given in the following pages). In many instances the data in these volumes have been reformatted and combined with additions and recent developments. Several new sections have been added. For example, gases can play various roles as

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an optical material—as transmitting media, active media for Faraday rotation, frequency conversion, filter, and phase conjugation. Physical and optical properties of a selected number of gases are therefore included in a final section.

The discovery of new optical materials has been accompanied by a somewhat bewildering and befuddling proliferation of abbreviations and acronyms. An appendix has been added to decode several hundred of these terms. Common or mineralogical names for optical materials are also included. Methods of preparing optical materials and thin films have developed their own terminology; many of these abbreviations are given in another appendix.

This volume has benefited from the efforts of many contributors to the *CRC Handbook of Laser Science and Technology* series. I am indebted to them for what in many cases have been very extensive compilations. In the course of preparing this volume I have also benefited from other input provided by Mark Davis, Alexander Marker, Lisa Moore, John Myers, and Charlene Smith; these are gratefully acknowledged. Finally, I appreciate the excellent help provided by Project Editors Samar Haddad and Joette Lynch, Production Supervisor Helena Redshaw, and the staff of the CRC Press in the process of preparing this handbook.

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The Author

Marvin John Weber received his education at the University of California, Berkeley, and was awarded the A.B., M.A., and Ph.D. degrees in physics. After graduation, Dr. Weber continued as a postdoctoral Research Associate and then joined the Research Division of the Raytheon Company where he was a Principal Scientist working in the areas of spectroscopy and quantum electronics. As Manager of Solid State Lasers, his group developed many new laser materials including rare-earth-doped yttrium orthoaluminate. While at Raytheon, he also discovered luminescence in bismuth germanate, a scintillator crystal widely used for the detection of high energy particles and radiation.

During 1966 to 1967, Dr. Weber was a Visiting Research Associate with Professor Arthur Schawlow's group in the Department of Physics, Stanford University.

In 1973, Dr. Weber joined the Laser Program at the Lawrence Livermore National Laboratory. As Head of Basic Materials Research and Assistant Program Leader, he was responsible for the physics and characterization of optical materials for high-power laser systems used in inertial confinement fusion research. From 1983 to 1985, he accepted a transfer assignment with the Office of Basic Energy Sciences of the U.S. Department of Energy in Washington, DC, where he was involved with planning for advanced synchrotron radiation facilities and for atomistic computer simulations of materials. Dr. Weber returned to the Chemistry and Materials Science Department at LLNL in 1986 and served as Associate Division Leader for condensed matter research and as spokesperson for the University of California/National Laboratories research facilities at the Stanford Synchrotron Radiation Laboratory. He retired from LLNL in 1993 and is at present a staff scientist in the Department of Nuclear Medicine and Functional Imaging of the Life Sciences Division at the Lawrence Berkeley National Laboratory.

Dr. Weber is Editor-in-Chief of the multi-volume *CRC Handbook Series of Laser Science and Technology*. He has also served as Regional Editor for the *Journal of Non-Crystalline Solids*, as Associate Editor for the *Journal of Luminescence* and the *Journal of Optical Materials*, and as a member of the International Editorial Advisory Boards of the Russian journals *Fizika i Khimiya Stekla* (Glass Physics and Chemistry) and *Kvantovaya Elektronika* (Quantum Electronics).

Among several honors he has received are an Industrial Research IR-100 Award for research and development of fluorophosphate laser glass, the George W. Morey Award of the American Ceramics Society for his basic studies of fluorescence, stimulated emission, and the atomic structure of glass, and the International Conference on Luminescence Prize for his research on the dynamic processes affecting luminescence efficiency and the application of this knowledge to laser and scintillator materials.

Dr. Weber is a Fellow of the American Physical Society, the Optical Society of America, and the American Ceramics Society and a member of the Materials Research Society.

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Section 1

CRYSTALLINE MATERIALS

1.1 Introduction*

Crystalline materials included in this section are insulators and semiconductors that have a transparent region within the range from the vacuum ultraviolet (from ~100 nm) to the infrared (up to 100 μm) portion of the electromagnetic spectrum. Crystals with wide band gaps are transparent from the ultraviolet through the visible region; crystals with a narrower band gap may appear opaque but are transparent in the infrared region. Using this broad transparency definition of optical crystals, virtually all known crystals can be included. Coverage, however, is limited to those crystals which either occur in nature or are produced in the laboratory for optical use or with potential for such use. For this reason hydrate or hydroxide crystals are generally excluded because they are thermally less stable and have limited tranmission range due to OH absorption. Highly hygroscopic materials are also excluded because of the obvious difficulty of handling, unless they have already been used, such as urea, KDP, CD*A, etc. Only pure compounds are considered. Compounds containing elements having intrinsic absorptions due to incompletely filled d or f shell electrons are also avoided.

Other critical issues for the use of optical crystals are solid-state phase transitions that occur as a function of both temperature and pressure and polymorphism. Compounds that have a very small stability field or serious phase transition problems have limited use as optical materials. Phase change and decomposition temperatures of crystals are noted in Section 1.5 on thermal properties. Generally only the thermodynamically stable structure at room temperature and pressure are listed in this section. Compounds that have naturally occurring polymorphic forms are included, however, e.g., $CaCO_3$, TiO_2, and aluminum silicate Al_2SiO_5. In other cases, only the stable phase is listed, e.g., quartz (α-SiO_2).

Many compounds were considered appropriate as entries of optical crystals in Sections 1.1–1.3 regardless of the amount of information available. As Chai* has noted, merely showing the existence of a compound with its chemical constituents can help to estimate the stability of its isomorphs and the structural tolerance of doping or other modifications. Most of the basic material properties such as optical transparency and refractive indices of an unstudied compound can be estimated with reasonable accuracy based on its better studied isomorphs that have measured properties listed in the tables.

Optical crystals in Sections 1.1–1.3 are classified into three categories:

Isotropic crystals include materials through which monochromatic light travels with the same speed, regardless of the direction of vibration, and the vibration direction of a light ray is always perpendicular to the ray path. Whereas amorphous materials such as glasses and plastics are isotropic, only those crystals with cubic symmetry are isotropic.

* This section was adapted from "Optical crystals" by B. H. T. Chai, *Handbook of Laser Science and Technology, Suppl. 2, Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 3 ff (with additions).

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Anisotropic crystals include materials through which a light ray may travel with different speeds for different directions of vibration and in which the angle between the vibration directions and ray path may not always be 90°. The index of refraction of such crystals varies according to the vibration direction of the light; the optical indicatrix is no longer a sphere but an ellipsoid. Depending on the geometry of the ellipsoid, it is necessary to divide the class of the anisotropic materials further into two subgroups. Crystals with tetragonal, hexagonal, and trigonal (or rhombohedral) symmetry exhibit a unique index of refraction (symbolized as e or ε) when light vibrates parallel to the *c*-axis (the extraordinary ray). For light vibrating at 90° to the *c*-axis (the ordinary ray), the refractive indices are the same (symbolized as o or ω) in all 360° directions. Crystals with these types of optical properties are called *uniaxial crystals*. Crystals with orthorhombic, monoclinic, and triclinic symmetry possess three significant indices of refraction, commonly symbolized as x, y, and z or α, β, and γ in the order from smallest to largest. The shape of the indicatrix is a three-dimensional ellipsoid with all central sections being ellipses, except for two. These two are circular sections with a radius of β. The normal of the two circular sections are called the optical axes. Crystals with these types of optical properties are called *biaxial crystals*. In Sections 1.2 and 1.3 crystals are grouped as isotropic, uniaxial, and biaxial.

Crystal symmetry plays a critical role in the selection of material for optical applications. Optically isotropic crystals are used most frequently for windows and lenses although a uniaxial single crystal (such as sapphire) precisely oriented along the optical axis can be used as a window material. Faraday rotator crystals for optical isolators based must be cubic or uniaxial, not biaxial. Anisotropic single crystals are widely used for other specific optical applications such as the polarizers, optical wave plates, and wedges. In nonlinear frequency conversion, all the optical materials used at present must not only be crystalline but also highly anisotropic and noncentrosymmetric.

For simplicity of crystal orientation and fabrication, materials with highest symmetry are preferred. It is easy to orient crystals with cubic (isometric), tetragonal, and hexagonal (uniaxial) symmetries. For the biaxial crystals, orthorhombic symmetry is still relatively easy to orient because all the crystallographic axes are still orthogonal and in alignment with the optical indicatrix axes. In monoclinic crystals, the crystallographic *a*- and *c*-axes are no longer orthogonal. With the exception of the *b*-axis, two of the optical indicatrix axes are no longer aligned with the crystallographic ones. With a few exceptions, crystals with triclinic symmetry are not listed because they are difficult to orient and have too many parameters to define (no degeneracy at all).

The preceding symmetry properties of a crystal structure refer to space group operations. For measured macroscopic properties the point group (the group of operations under which the property remains unchanged) is of interest. Eleven of the 32 point groups are centrosymmetric. Except for cubic 432, the remaining groups exhibit polarization when the crystal is subject to an applied stress (piezoelectric). Ten of these latter groups possess a unique polar axis and are pyroelectric, i.e., spontaneous polarize in the absence of stress. Crystallographic point groups and related properties are listed in the following table.

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Crystallographic Point Groups and Properties

Crystal system	International symbol	Schoenflies symbol	Centro-symmetric	Piezo-electric	Pyro-electric
Cubic	m3m	O_h	■		
	–43m	T_d		■	
	432	O			
	m3	T_h	■		
	23	T		■	
Hexagonal	6/mmm	D_{6h}	■		
	–6m2	D_{3h}		■	
	6mm	C_{6v}		■	■
	622	D_6		■	
	6/m	C_{6h}	■		
	–6	C_{3h}		■	
	6	C_6		■	■
Tetragonal	4/mmm	D_{4h}	■		
	–42m	D_{2d}		■	
	4mm	C_{4v}		■	■
	422	D_4		■	
	4/m	C_{4h}	■		
	–4	S_4		■	
	4	C_4		■	■
Trigonal	–3m	D_{3d}	■		
	3m	C_{3v}		■	■
	32	D_3		■	
	–3	S_6	■		
	3	C_3		■	■
Orthorhombic	mmm	D_{2h}	■		
	mm2	C_{2v}		■	■
	222	D_2		■	
Monoclinic	2/m	C_{2h}	■		
	m	C_s		■	■
	2	C_2		■	■
Triclinic	–1	C_i	■		
	1	C_1		■	■

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Crystals in the following table are listed alphabetically by chemical name (with mineral name* and acronym in parentheses) and include the chemical formula, crystal system, and space group. In the space group notation, a negative number indicates inversion symmetry.

* A mineralogy database containing names, physical properties, and an audio pronunciation guide for a very large number of materials is available at www.webmineral.com.

Name, Formula, Crystal System, and Space Group for Optical Crystals

Name	Formula	Crystal system (Space group)
Aluminum antimonide	AlSb	Cubic (F–43m)
Aluminum arsenate	$AlAsO_4$	Trigonal ($P3_12$)
Aluminum arsenide	AlAs	Cubic (F–43m)
Aluminum borate	$AlBO_3$	Trigonal (R–3c)
Aluminum borate	$Al_4B_2O_9$	Orthorhombic (Pbam)
Aluminum fluoride	AlF_3	Rhombohedral (R32)
Aluminum fluorosilicate (topaz)	$Al_2SiO_4F_2$	Orthorhombic (Pbnm)
Aluminum gallate	$AlGaO_3$	Hexagonal ($P6_3mmc$)
Aluminum germanate	$Al_2Ge_2O_7$	Monoclinic (C2/c)
Aluminum germanate	$Al_6Ge_2O_{13}$	Orthorhombic (Pbnm)
Aluminum germanate	$Al_6Ge_2O_{13}$	Orthorhombic (Pbnm)
Aluminum hafnium tantalate	$AlHfTaO_6$	Orthorhombic (Pbcn)
Aluminum molybdate	$Al_2(MoO_4)_3$	Monoclinic ($P2_1/a$)
Aluminum niobate	$AlNbO_4$	Monoclinic (C2/m)
Aluminum nitride	AlN	Hexagonal (6_3mc)
Aluminum oxide (corundum, sapphire, alumina)	Al_2O_3	Trigonal (R–3c)
Aluminum oxynitrate (ALON)	$Al_{23}O_{27}N_5$	Cubic (Fd3m)
Aluminum phosphate (berlinite)	$AlPO_4$	Trigonal ($P3_12$)
Aluminum phosphide	AlP	Hexagonal (6_3mc)
Aluminum silicate (andalusite)	Al_2SiO_5	Orthorhombic (Pmam)
Aluminum silicate (kyanite)	Al_2SiO_5	Triclinic (P–1)
Aluminum silicate (mullite)	$Al_6Si_2O_{13}$	Orthorhombic (Pbnm)
Aluminum silicate (sillimanite)	Al_2SiO_5	Orthorhombic (Pbnm)
Aluminum tantalate (alumotantite)	$AlTaO_4$	Orthorhombic ($Pc2_1n$)
Aluminum titanium tantalate	$AlTiTaO_6$	Tetragonal ($P4_2/mmm$)
Aluminum tungstate	$Al_2(WO_4)_3$	Orthorhombic (Pcna)
Amino carbonyl (urea)	$(NH_2)_2CO$	Tetragonal (I–42m)
Ammonium aluminum selenate	$NH_4Al(SeO_4)_2$	Trigonal (P321)
Ammonium aluminum sulfate	$NH_4Al(SO_4)_2$	Trigonal (P321)
Ammonium dihydrogen phosphate (ADP)	$NH_4H_2PO_4$	Tetragonal (I–42m)
Ammonium gallium selenate	$NH_4Ga(SeO_4)_2$	Trigonal (P321)
Ammonium gallium sulfate	$NH_4Ga(SO_4)_2$	Trigonal (P321)
Ammonium pentaborate	$NH_4B_5O_8•4H_2O$	Orthorhombic (Aba2)
Antimony niobate (stibiocolumbite)	$SbNbO_4$	Orthorhombic ($Pna2_1$)
Antimony oxide (senarmontite)	Sb_2O_3	Cubic (Fd3m)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Antimony oxide (valentinite)	Sb_2O_3	Orthorhombic (Pccn)
Antimony tantalate (stibiotantalite)	$SbTaO_4$	Orthorhombic ($Pc2_1n$)
Arsenic antimony sulfide (getchellite)	$AsSbS_3$	Monoclinic (P21/a)
Arsenic oxide (arsenolite)	As_2O_3	Cubic (Fd3m)
Arsenic sulfide (orpiment)	As_2S_3	Monoclinic (P21n)
Arsenic sulfide (realgar)	AsS	Monoclinic (P21n)
Barium aluminate	$BaAl_2O_4$	Hexagonal ($P6_322$)
Barium aluminate	$Ba_3Al_2O_6$	Cubic (Pa3)
Barium aluminum borate	$BaAl_2B_2O_7$	Monoclinic (P2/c)
Barium aluminum fluoride	$Ba_3Al_2F_{12}$	Orthorhombic (Pnnm)
Barium aluminum germanate	$BaAl_2Ge_2O_8$	Monoclinic ($P2_1/a$)
Barium aluminum silicate (celsian)	$BaAl_2Si_2O_8$	Monoclinic (I2/a)
Barium antimonate	$BaSb_2O_6$	Triclinic ($P\bar{3}1m$)
Barium beryllium fluorophosphate (babefphite)	$BaBe(PO_4)F$	Hexagonal($P\bar{6}c2$)
Barium beryllium silicate (barylite)	$BaBe_2Si_2O_7$	Orthorhombic (Pnma)
Barium tetraborate	BaB_4O_7	Monoclinic (P21/c)
Barium borate	ß-BaB_2O_4	Trigonal (R3c)
Barium cadmium aluminum fluoride	$BaCdAlF_7$	Monoclinic (C2/c)
Barium cadmium gallium fluoride	$BaCdGaF_7$	Monoclinic (C2/c)
Barium cadmium magnesium aluminum fluoride	$Ba_2CdMgAl_2F_{14}$	Monoclinic (C2/c)
Barium calcium magnesium aluminum fluoride	$Ba_2CaMgAl_2F_{14}$	Monoclinic (C2/c)
Barium calcium magnesium silicate	$BaCa_2Mg(SiO_4)_2$	Orthorhombic
Barium calcium silicate (walstromite)	$BaCa_2Si_3O_9$	Triclinic(P−1)
Barium carbonate (witherite)	$BaCO_3$	Orthorhombic (Pnam)
Barium chloroarsenate (movelandite)	$Ba_5(AsO_4)_3Cl$	Hexagonal($P6_3/m$)
Barium chloroborate	$Ba_2B_5O_9Cl$	Tetragonal ($P4_22_1\bar{2}$)
Barium chlorophosphate (alforsite)	$Ba_5(PO_4)_3Cl$	Hexagonal($P6_3/m$)
Barium chlorovanadate	$Ba_5(VO_4)_3Cl$	Hexagonal($P6_3/m$)
Barium fluoride-calcium fluoride (T-12)	BaF_2-CaF_2	Cubic (Fm3m)
Barium fluoride (frankdicksonite)	BaF_2	Cubic (Fm3m)
Barium fluoroarsenate	$Ba_5(AsO_4)_3F$	Hexagonal($P6_3/m$)
Barium fluorophosphate	$Ba_5(PO_4)_3F$	Hexagonal($P6_3/m$)
Barium fluorovanadate	$Ba_5(VO_4)_3F$	Hexagonal($P6_3/m$)
Barium gallium fluoride	$BaGaF_5$	Orthorhombic ($P2_12_12_1$)
Barium germanate	$BaGeO_3$	Orthorhombic
Barium germanate	$BaGe_2O_5$	Monoclinic ($P2_1/a$)
Barium germanate	$BaGe_4O_9$	Hexagonal($P\bar{6}c2$)
Barium germanium aluminate	$BaGeAl_6O_{12}$	Orthorhombic (Pnnm)
Barium germanium gallate	$BaGeGa_6O_{12}$	Othorhombic (Pnnm)
Barium hexa-aluminate	$BaAl_{12}O_{19}$	Hexagonal ($P6_3/mmc$)
Barium lithium niobate	$Ba_2LiNb_5O_{15}$	Orthorhombic (Im2a)
Barium lutetium borate	$Ba_3Lu(BO_3)_3$	Hexagonal($P6_3cm$)
Barium magnesium aluminum fluoride	Ba_2MgAlF_9	Tetragonal (P4)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Barium magnesium fluoride	$BaMgF_4$	Orthorhombic ($A2_1am$)
Barium magnesium fluoride	Ba_2MgF_6	Tetragonal (I422)
Barium magnesium germanate	$Ba_2MgGe_2O_7$	Tetragonal ($P42_1m$)
Barium magnesium silicate	$Ba_2MgSi_2O_7$	Tetragonal ($P42_1m$)
Barium magnesium tantalate	$Ba_3MgTa_2O_9$	Cubic (Fm3m)
Barium magnesium vanadate	$BaMg_2(VO_4)_2$	Tetragonal ($I4_1/acd$)
Barium molybdate	$BaMoO_4$	Tetragonal ($I4_1/a$)
Barium niobate	$BaNb_2O_6$	Orthorhombic (Pcan)
Barium nitrate (nitrobarite)	$Ba(NO_3)_2$	Cubic ($P2_13$)
Barium scandate	$Ba_2Sc_4O_9$	Trigonal(R–3)
Barium scandate	$BaSc_2O_4$	Monoclinic (C2/c)
Barium scandate	$Ba_6Sc_6O_{15}$	Tetragonal
Barium silicate (sabbornite)	β-$BaSi_2O_5$	Orthorhombic (Pmnb)
Barium sodium niobate	$Ba_2NaNb_5O_{15}$	Orthorhombic (Im2a)
Barium sodium phosphate	$Ba_2Na(PO_5)_5$	Orthorhombic (P212121))
Barium strontium niobate	$Ba_3SrNb_2O_9$	Hexagonal (P63/mmc)
Barium strontium tantalate	$Ba_3SrTa_2O_9$	Hexagonal (P63/mmc)
Barium sulfate (barite)	$BaSO_4$	Orthorhombic (Pbnm)
Barium tantalate	$BaTa_2O_6$	Orthorhombic (Pcan)
Barium tantalate	$BaTa_2O_6$	Orthorhombic (Pcan)
Barium tin borate	$BaSnB_2O_6$	Trigonal(R–3)
Barium tin silicate (pabstite)	$BaSnSi_3O_9$	Hexagonal (P–6c2)
Barium titanate	$BaTiO_3$	Cubic (Fm3m)
Barium titanate	$BaTiO_3$	Tetragonal (Pm3m)
Barium titanium aluminate	$BaTiAl_6O_{12}$	Orthorhombic (Pnnm)
Barium titanium aluminate	$Ba_3TiAl_{10}O_{20}$	Monoclinic (C2/m)
Barium titanium borate	$BaTiB_2O_6$	Trigonal(R–3)
Barium titanium gallate	$BaTiGa_6O_{12}$	Orthorhombic (Pnnm)
Barium titanium oxide	$BaTi_4O_9$	Orthorhombic (Pnmm)
Barium titanium silicate (benitoite)	$BaTiSi_3O_9$	Hexagonal (P–6c2)
Barium titanium silicate (fresnoite)	$Ba_2TiSi_2O_8$	Tetragonal (P4bm)
Barium tungstate	$BaWO_4$	Tetragonal ($I4_1/a$)
Barium vanadate	$Ba_3(VO_4)_2$	Rhombohedral (R–3m)
Barium yttrium borate	$Ba_3Lu(BO_3)_3$	Hexagonal($P6_3cm$)
Barium yttrium fluoride	BaY_2F_8	Monoclinic (C2/m)
Barium yttrium oxide	BaY_2O_4	Orthorhombic (Pnab)
Barium zinc aluminum fluoride	Ba_2ZnAlF_9	Orthorhombic (Pnma)
Barium zinc fluoride	$BaZnF_4$	Othorhombic (C222)
Barium zinc fluoride	$Ba_2Zn_3F_{10}$	Monoclinic (C2/m)
Barium zinc fluoride	Ba_2ZnF_6	Tetragonal (I422)
Barium zinc gallium fluoride	Ba_2ZnGaF_9	Monoclinic ($P2_{1/n}$)
Barium zinc germanate	$BaZnGeO_4$	Hexagonal ($P6_3$)
Barium zinc germanate	$Ba_2ZnGe_2O_7$	Tetragonal ($P42_1m$)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Barium zinc silicate	$Ba_2ZnSi_2O_7$	Tetragonal ($P42_1m$)
Barium zinc silicate	$BaZnSiO_4$	Hexagonal ($P6_3$)
Barium zirconium silicate	$Ba_2ZrSi_2O_8$	Tetragonal (P4bm)
Barium zirconium silicate	$Ba_2Zr_2Si_3O_{12}$	Cubic ($P2_13$)
Barium zirconium silicate (bazirite)	$BaZrSi_3O_9$	Hexagonal ($P6_322$)
Beryllium aluminate	$BeAl_6O_{10}$	Orthorhombic (Pca2)
Beryllium aluminate (chrysoberyl)	$BeAl_2O_4$	Orthorhombic (Pnma)
Beryllium aluminum silicate (beryl)	$Be_3Al_2Si_6O_{18}$	Hexagonal (P6/mcc)
Beryllium fluoroborate (hambergite)	Be_2BO_3F	Monoclinic (C21)
Beryllium germanate	Be_2GeO_4	Trigonal(R–3)
Beryllium magnesium aluminate (taaffeite)	$BeMg_3Al_8O_{16}$	Hexagonal
Beryllium oxide (bormellite)	BeO	Hexagonal ($P6_3/mc$)
Beryllium scandium silicate (bazzite)	$Be_3Sc_2Si_6O_{18}$	Hexagonal (P6/mcc)
Beryllium silicate (phenakite)	Be_2SiO_4	Trigonal(R–3)
Bismuth aluminate	$Bi_2Al_4O_9$	Orthorhombic (Pbam)
Bismuth antimonate	$BiSbO_4$	Monoclinic ($P2_1/c$)
Bismuth borate	$Bi_4B_2O_9$	Monoclinic ($P2_1/c$)
Bismuth germanate	$Bi_2Ge_3O_9$	Hexagonal ($P6_3/m$)
Bismuth germanate	Bi_2GeO_5	Orthorhombic ($Cmc2_1$)
Bismuth germanate	$Bi_{12}GeO_{20}$	Cubic (I23)
Bismuth germanate (BGO)	$Bi_4Ge_3O_{12}$	Cubic (I43d)
Bismuth metaborate	BiB_3O_6	Monoclinic (2/m)
Bismuth molybdate	$Bi_2Mo_2O_9$	Monoclinic ($P2_1/m$)
Bismuth molybdate	$Bi_2Mo_3O_{12}$	Monoclinic ($P2_1/m$)
Bismuth niobate	$BiNbO_4$	Orthorhombic (Pann)
Bismuth oxide (bismite)	Bi_2O_3	Monoclinic ($P2_1/c$)
Bismuth oxymolybdate (koechlinite)	γ-Bi_2MoO_6	Orthorhombic (Pba2)
Bismuth oxytungstate (rusellite)	Bi_2WO_6	Orthorhombic (Pba2)
Bismuth silicate	Bi_2SiO_5	Orthorhombic ($Cmc2_1$)
Bismuth silicate (eulytite)	$Bi_4Si_3O_{12}$	Cubic (I43d)
Bismuth silicate (sillenite, BSO)	$Bi_{12}SiO_{20}$	Cubic (I23)
Bismuth tantalate	$BiTaO_4$	Orthorhombic (Pnna)
Bismuth tin oxide	$Bi_2Sn_2O_7$	Hexagonal ($P6_3/m$)
Bismuth titanate	$Bi_4Ti_3O_{12}$	Orthorhombic (B2cb)
Bismuth titanium niobate	Bi_3TiNbO_9	Orthorhombic ($A2_1am$)
Bismuth titanium oxide	$Bi_{12}TiO_{20}$	Cubic (I23)
Bismuth vanadate (clinobisvanite)	$BiVO_4$	Monoclinic (I2/a)
Bismuth vanadate (dreyerite)	$BiVO_4$	Tetragonal ($I4_1/amd$)
Bismuth vanadate (pucherite)	$BiVO_4$	Orthorhombic (Pnca)
Boron nitride	BN	Cubic (F–43m)
Boron phosphide	BP	Cubic (F–43m)
Cadmium antimonade	$Cd_2Sb_2O_7$	Cubic (Fd3m)
Cadmium borate	CdB_4O_7	Orthorhombic (Pbca)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Cadmium borate	$Cd_2B_2O_5$	Triclinic (P1)
Cadmium borate	$Cd_2B_6O_{11}$	Monoclinic ($P2_1/b$)
Cadmium borate	CdB_2O_4	Cubic (P–43m)
Cadmium carbonate (otavite)	$CdCO_3$	Rhombohedral (R−3c)
Cadmium chloride	$CdCl_2$	Rhombohedral (R–3m)
Cadmium chloroarsenate	$Cd_5(AsO_4)_3Cl$	Hexagonal ($P6_3/m$)
Cadmium chlorophosphate	$Cd_5(PO_4)_3Cl$	Hexagonal($P6_3/m$)
Cadmium chlorovanadate	$Cd_5(VO_4)_3Cl$	Hexagonal ($P6_3/m$)
Cadmium fluoride	CdF_2	Cubic (Fm3m)
Cadmium fluorophosphate	$Cd_5(PO_4)_3F$	Hexagonal ($P6_3/m$)
Cadmium gallate	$CdGa_2O_4$	Cubic (Fd3m)
Cadmium germanate	Cd_2GeO_4	Orthorhombic (Pbnm)
Cadmium germanium arsenide	$CdGeAs_2$	Tetragonal (I–42d)
Cadmium germanium phosphide	$CdGeP_2$	Tetragonal (I–42d)
Cadmium indium oxide spinel	$CdIn_2O_4$	Cubic (Fd3m)
Cadmium iodide	CdI_2	Hexagonal ($P6_3mc$)
Cadmium niobate	$Cd_2Nb_2O_7$	Cubic (Fd3m)
Cadmium oxide (monteponite)	CdO	Cubic (Fm3m)
Cadmium scandium germanate	$Cd_3Sc_2Ge_3O_{12}$	Cubic (Ia3d)
Cadmium selenide (cadmoselite)	CdSe	Hexagonal (P6mm)
Cadmium silicon arsenide	$CdSiAs_2$	Tetragonal (I–42d)
Cadmium silicon phosphide	$CdSiP_2$	Tetragonal (I–42d)
Cadmium sulfide (greenockite)	CdS	Hexagonal (6mm)
Cadmium tellurite (Irtran 6)	CdTe	Cubic (Fm3m)
Cadmium tin arsenide	$CdSnAs_2$	Tetragonal (I–42d)
Cadmium tin borate	$CdSnB_2O_6$	Rhombohedral (R–3c)
Cadmium tin phosphide	$CdSnP_2$	Tetragonal (I–42d)
Cadmium titanate	$CdTiO_3$	Rhombohedral(R–3)
Cadmium tungstate	$CdWO_4$	Monoclinic (P2/c)
Cadmium vanadate	CdV_2O_6	Monoclinic (C2/m)
Cadmium vanadate	$Cd_2V_2O_7$	Monoclinic (C2/m)
Calcium aluminate	$CaAl_2O_4$	Monoclinic ($P2_1/n$)
Calcium aluminate	$Ca_3Al_2O_6$	Cubic (Pa–3)
Calcium aluminate	$CaAl_4O_7$	Monoclinic (C2/c)
Calcium aluminate	$Ca_5Al_6O_{14}$	Orthorhombic (C222)
Calcium aluminate (brownmillerite)	$Ca_2Al_2O_5$	Orthorhombic
Calcium aluminate (mayenite)	$Ca_{12}Al_{14}O_{33}$	Cubic (I43d)
Calcium aluminum borate	$CaAlBO_4$	Otthorhombic (Pnam)
Calcium aluminum borate	$CaAl_2B_2O_7$	Hexagonal ($P6_322$)
Calcium aluminum borate (johachidolite)	$CaAlB_3O_7$	Orthorhombic (Cmma)
Calcium aluminum fluoride	$CaAlF_5$	Monoclinic (C2/c)
Calcium aluminum fluoride	Ca_2AlF_7	Orthorhombic (Pnma)
Calcium aluminum fluoride (prosopite)	$CaAl_2F_8$	Monoclinic

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Calcium aluminum germanate	$Ca_2Al_2GeO_7$	Tetragonal ($P42_1m$)
Calcium aluminum germanate	$Ca_3Al_2Ge_3O_{12}$	Cubic (Ia3d)
Calcium aluminum oxyfluoride	$Ca_2Al_3O_6F$	Hexagonal
Calcium aluminum silicate (anorthite)	$CaAl_2Si_2O_8$	Triclinic(P–1)
Calcium aluminum silicate (gehlenite, CAS)	$Ca_2Al_2SiO_7$	Tetragonal ($P42_1m$)
Calcium aluminum silicate (grossularite)	$Ca_3Al_2Si_3O_{12}$	Cubic (Ia3d)
Calcium antimonate	$Ca_2Sb_2O_7$	Orthorhombic (Imm2)
Calcium antimonate	$Ca_2Sb_2O_7$	Cubic (Fd3m)
Calcium barium carbonate (alstonite)	$CaBa(CO_3)_2$	Orthorhombic (Pnam)
Calcium beryllium fluorophosphate (herderite)	$CaBe(PO_4)F$	Monoclinic
Calcium beryllium phosphate (hurlbutite)	$CaBe_2(PO_4)_2$	Monoclinic ($P2_1/a$)
Calcium beryllium silicate (gugiaite)	$Ca_2BeSi_2O_7$	Tetragonal ($P42_1m$)
Calcium borate	$Ca_2B_2O_5$	Monoclinic ($P2_1/a$)
Calcium borate	$Ca_2B_6O_{11}$	Monoclinic ($P2_1/b$)
Calcium borate	CaB_4O_7	Monoclinic ($P2_1/c$)
Calcium borate	$Ca_3B_2O_6$	Rhombohedral (R–3c)
Calcium borate (calciborite)	CaB_2O_4	Orthorhombic (Pnca)
Calcium boron silicate (danburite)	$CaB_2Si_2O_8$	Orthorhombic (Pmam)
Calcium carbonate (aragonite)	$CaCO_3$	Orthorhombic (Pnam)
Calcium carbonate (calcite)	$CaCO_3$	Rhombohedral (R–3c))
Calcium carbonate (vaterite)	$CaCO_3$	Hexagonal ($P6_3/mmc$)
Calcium chloroarsenate	Ca_2AsO_4Cl	Orthorhombic (Pbcm)
Calcium chloroarsenate	$Ca_5(AsO_4)_3Cl$	Hexagonal($P6_3/m$)
Calcium chloroborate	Ca_2BO_3Cl	Monoclinic ($P2_1/c$)
Calcium chloroborate	$Ca_2B_5O_9Cl$	Tetragonal ($P4_22_12$)
Calcium chlorophosphate	Ca_2PO_4Cl	Orthorhombic (Pbcm)
Calcium chlorophosphate (chlorapatite)	$Ca_5(PO_4)_3Cl$	Hexagonal($P6_3/m$)
Calcium chlorovanadate	Ca_2VO_4Cl	Orthorhombic (Pbcm)
Calcium chlorovanadate	$Ca_5(VO_4)_3Cl$	Hexagonal($P6_3/m$)
Calcium fluoride (fluorite, fluorspar, Irtran 3)	CaF_2	Cubic (Fm3m)
Calcium fluoroarsenate (svabite, CAAP)	$Ca_5(AsO_4)_3F$	Hexagonal($P6_3/m$)
Calcium fluoroborate (fabianite)	CaB_3O_5F	Orthorhombic ($Pbn2_1$)
Calcium fluorophosphate (apatite, FAP)	$Ca_5(PO_4)_3F$	Hexagonal($P6_3/m$)
Calcium fluorophosphate (spodiosite)	$Ca_2(PO_4)F$	Orthorhombic (Pbcm)
Calcium fluorovanadate (VAP)	$Ca_5(VO_4)_3F$	Hexagonal($P6_3/m$)
Calcium gadolinium aluminate	$CaGaAlO_4$	Hexagonal ($P6_3/m$)
Calcium gadolinium double borate	$Ca_3Gd_2(BO_3)_4$	Orthorhombic ($Pc2_1n$)
Calcium gadolinium oxysilicate	$CaGd_4(SiO_4)_3O$	Tetragonal (I4/mmm)
Calcium gadolinium phosphate	$Ca_3Gd(PO_4)_3$	Cubic (I–43d)
Calcium gallate	$CaGa_2O_4$	Monoclinic ($P2_1/c$)
Calcium gallate	$Ca_3Ga_4O_9$	Orthorhombic (Cmm2)
Calcium gallate	$Ca_5Ga_6O_{14}$	Orthorhombic ($Cmc2_1$)
Calcium gallium germanate	$Ca_2Ga_2GeO_7$	Tetragonal ($P42_1m$)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Calcium gallium germanate	$Ca_3Ga_2Ge_4O_{14}$	Trigonal ($P32_1$)
Calcium gallium germanium garnet	$Ca_3Ga_2Ge_3O_{12}$	Cubic (Ia3d)
Calcium gallium silicate (CGS)	$Ca_2Ga_2SiO_7$	Tetragonal ($P42_1m$)
Calcium germanate	$CaGe_2O_5$	Monoclinic ($P2_1/a$)
Calcium germanate	$CaGe_4O_9$	Hexagonal (P–6c2)
Calcium hexa-aluminate	$CaAl_{12}O_{19}$	Hexagonal (P63/mmc)
Calcium indate	$CaIn_2O_4$	Orthorhombic (Pbcm)
Calcium indium germanate	$Ca_3In_2Ge_3O_{12}$	Cubic (Ia3d)
Calcium indium oxide	$Ca_3In_2O_6$	Orthorhombic (Pbam)
Calcium iodate (lautarite)	$Ca(IO_3)_2$	Monoclinic
Calcium lanthanum aluminate	$CaLaAlO_4$	Tetragonal (I4/mmm)
Calcium lanthanum borate	$CaLaBO_4$	Hexagonal ($P6_322$)
Calcium lanthanum oxyphosphate	$Ca_4La(PO_4)_3O$	Hexagonal ($P6_3/m$)
Calcium lanthanum oxysilicate	$CaLa_4(SiO_4)_3O$	Hexagonal ($P6_3/m$)
Calcium lanthanum phosphate	$Ca_3La(PO_4)_3$	Cubic (I–43d)
Calcium lanthanum sulfide	$CaLa_2S_4$	Cubic (I–43d)
Calcium lithium magnesium vanadate	$Ca_2LiMg_2V_3O_{12}$	Cubic (Ia3d)
Calcium lithium magnesium vanadate	$Ca_3LiMgV_3O_{12}$	Cubic (Ia3d)
Calcium lithium zinc vanadate	$Ca_2LiZn_2V_3O_{12}$	Cubic (Ia3d)
Calcium lithium zinc vanadate	$Ca_3LiZnV_3O_{12}$	Cubic (Ia3d)
Calcium lutetium germanate	$Ca_3Lu_2Ge_3O_{12}$	Cubic (Ia3d)
Calcium magnesium borate (kurchatovite)	$CaMgB_2O_5$	Orthorhombic
Calcium magnesium carbonate (dolomite)	$CaMg(CO_3)_2$	Rhombohedral (R–3c)
Calcium magnesium carbonate (huntite)	$CaMg_3(CO_3)_4$	Rhombohedral (R32)
Calcium magnesium fluoroarsenate (tilasite)	$CaMgAsO_4F$	Orthorhombic
Calcium magnesium fluorophosphate (isokite)	$CaMgPO_4F$	Monoclinic (C2/c)
Calcium magnesium germanate	$CaMgGe_2O_6$	Monoclinic (C2/c)
Calcium magnesium silicate (akermanite)	$Ca_2MgSi_2O_7$	Tetragonal ($P42_1m$)
Calcium magnesium silicate (diopside)	$CaMgSi_2O_6$	Monoclinic (C2/c)
Calcium magnesium silicate (merwinite)	$Ca_3MgSi_2O_8$	Monoclinic ($P2_1/a$)
Calcium magnesium silicate (monticellite)	$CaMgSiO_4$	Orthorhombic (Pmnb)
Calcium magnesium vanadate	$CaMg_2(VO_4)_2$	Tetragonal ($I4_1/acd$)
Calcium molybdate	$CaMoO_4$	Tetragonal ($I4_1/a$)
Calcium niobate	$Ca_2Nb_2O_7$	Orthorhombic ($Pn2_1a$)
Calcium niobate (rynersonite)	$CaNb_2O_6$	Orthorhombic (Pcan)
Calcium niobium gallium garnet	$Ca_3(Nb,Ga)_2Ga_3O_{12}$	Cubic (Ia3d)
Calcium oxide (lime)	CaO	Cubic (Fm3m)
Calcium phosphate	β-CaP_2O_7	Hexagonal (P–6c2)
Calcium phosphate	β-CaP_2O_7	Tetragonal ($P4_1$)
Calcium scandate	$CaSc_2O_4$	Orthorhombic (Pnam)
Calcium scandium germanate	$Ca_3Sc_2Ge_3O_{12}$	Cubic (Ia3d)
Calcium scandium silicate	$Ca_3Sc_2Si_3O_{12}$	Cubic (Ia3d)
Calcium silicate (larnite)	b-Ca_2SiO_4	Monoclionic ($P2_1/n$)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Calcium silicate (rankinite)	$Ca_3Si_2O_7$	Monoclinic
Calcium silicate (wollastonite)	$CaSiO_3$	Triclinic(P–1)
Calcium sodium magnesium vanadate	$Ca_2NaMg_2V_3O_{12}$	Cubic (Ia3d)
Calcium sodium zinc vanadate	$Ca_2NaZn_2V_3O_{12}$	Cubic (Ia3d)
Calcium sulfate (anhydrite)	$CaSO_4$	Orthorhombic (Bbmm)
Calcium tantalate	$CaTa_2O_6$	Orthorhombic (Pcan)
Calcium tellurate (denningite)	$Ca_2Te_2O_5$	Tetragonal
Calcium tin borate (nordenskiöldine)	$CaSnB_2O_6$	Trigonal (R–3m)
Calcium tin oxide	$CaSnO_3$	Orthorhombic ($P2_12_12_1$)
Calcium tin silicate (malayaite)	$CaSnSiO_5$	Monoclinic ($P2_1/a$)
Calcium titanate (perovskite)	$CaTiO_3$	Cubic (Pm3m)
Calcium titanium germanate	$CaTiGeO_4$	Monoclinic ($P2_1/a$)
Calcium titanium silicate (sphene)	$CaTiSiO_5$	Monoclinic ($P2_1/a$)
Calcium tungstate (scheelite)	$CaWO_4$	Tetragonal ($I4_1/a$)
Calcium vanadate	CaV_2O_6	Monoclinic (C2/m)
Calcium vanadate	$Ca_2V_2O_7$	Monoclinic (C2/m)
Calcium vanadate	$Ca_3(VO_4)_2$	Trigonal (R3c)
Calcium yttrium aluminate	$CaYAlO_4$	Tetragonal (I4/mmm)
Calcium yttrium borate	$CaYBO_4$	Orthorhombic (Pnam)
Calcium gadolinium double borate	$Ca_3Y_2(BO_3)_4$	Orthorhombic ($Pc2_1n$)
Calcium yttrium magnesium germanium garnet	$CaY_2Mg_2Ge_3O_{12}$	Cubic (Ia3d)
Calcium yttrium oxysilicate	$Ca_4Y_6(SiO_4)_6$	Hexagonal ($P6_3/m$)
Calcium yttrium oxysilicate (SOAP)	$CaY_4(SiO_4)_3O$	Hexagonal ($P6_3/m$)
Calcium zinc fluoride	$CaZnF_4$	Tetragonal ($I4_1/a$)
Calcium zinc germanate	$CaZnGe_2O_6$	Monoclinic (C2/c)
Calcium zinc silicate (esperite)	$CaZnSiO_4$	Tetragonal ($P–42_1m$)
Calcium zinc silicate (hardystonite)	$Ca_2ZnSi_2O_7$	Tetragonal ($P–42_1m$)
Calcium zirconium boron aluminate (painite)	$CaZrBAl_9O_{18}$	Hexagonal ($P6_3$)
Calcium zirconium silicate (gittinsite)	$CaZrSi_2O_7$	Monoclinic (C2/m)
Calcium zirconium titanate (zirkelite)	$CaZrTi_2O_7$	Monoclinic (C2/m)
Calcium zirconium titanium silicate	$Ca_3(Zr,Ti)Si_2O_9$	Monoclinic
Carbon (diamond)	C	Cubic (F–43m)
Cesium aluminum sulfate	$CsAl(SO_4)_2$	Trigonal (P321)
Cesium beryllium fluoride	Cs_2BeF_4	Orthorhombic ($Pna2_1$)
Cesium borate (CBO)	CsB_3O_5	Orthorhombic ($P2_12_12_1$)
Cesium bromide	CsBr	Cubic (Fm3m)
Cesium cadmium bromide	Cs_2CdBr_4	Orthorhombic (Pnma)
Cesium cadmium bromide	$CsCdBr_3$	Cubic (Pm3m)
Cesium cadmium chloride	Cs_2CdCl_4	Tetragonal (I4/mmm)
Cesium cadmium fluoride	$CsCdF_3$	Cubic (Pm3m)
Cesium cadmium zinc fluoride	Cs_2CdZnF_6	Rhombohedral (R–3m)
Cesium calcium fluoride	$CsCaF_3$	Cubic (Pm3m)
Cesium chloride	CsCl	Cubic (Fm3m)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Cesium dideuterium arsenate	CsD_2AsO_4	Tetragonal (I–42m)
Cesium dideuterium phosphate	CsD_2PO_4	Tetragonal (I–42m)
Cesium dihydrogen arsenate	CsH_2AsO_4	Tetragonal (I–42m)
Cesium dihydrogen phosphate	CsH_2PO_4	Tetragonal (I–42m)
Cesium fluoride	CsF	Cubic (Fm3m)
Cesium gadolinium molybdate	$CsGd(MoO_4)_2$	Orthorhombic (Pnma)
Cesium gallium sulfate	$CsGa(SO_4)_2$	Trigonal (P321)
Cesium germanate	Ga_2GeO_5	Orthorhombic (Pnnm)
Cesium iodide	CsI	Cubic (Fm3m)
Cesium lanthanum tungstate	$CsLa(WO_4)_2$	Tetragonal ($P4_2/nmc$)
Cesium lithium aluminum fluoride	$Cs_2LiAl_3F_{12}$	Rhombohedral (R–3m)
Cesium lithium aluminum fluoride	Cs_2LiAlF_6	Hexagonal ($P6_3/mmc$)
Cesium lithium beryllium fluoride	$CsLiBeF_4$	Monoclinic ($P2_1/n$)
Cesium lithium borate (CLBO)	$CsLiB_6O_{10}$	Tetragonal (I–42d)
Cesium lithium gallium fluoride	$Cs_2LiGa_3F_{12}$	Rhombohedral (R–3m)
Cesium lithium gallium fluoride	Cs_2LiGaF_6	Hexagonal ($P6_3/mmc$)
Cesium lithium sulfate	$CsLiSO_4$	Orthorhombic (Pc2)
Cesium magnesium chloride	Cs_2MgCl_4	Orthorhombic (Pnma)
Cesium mercury iodide	Cs_2HgI_4	Monoclinic ($P2_1$)
Cesium niobium borate (CNB)	$CsNbB_2O_6$	Orthorhombic ($Pn2_1m$)
Cesium niobium sulfate	$CsNbO(SO_4)_2$	Orthorhombic
Cesium potassium aluminum fluoride	$Cs_2KAl_3F_{12}$	Rhombohedral (R–3m)
Cesium potassium lanthanum fluoride	Cs_2KLaF_6	Cubic (Fm3m)
Cesium scandium molybdate	$CsSc(MoO_4)_2$	Trigonal (P–3m1)
Cesium scandium tungstate	$CsSc(WO_4)_2$	Trigonal (P–3m1)
Cesium silver fluoride	Cs_2AgF_4	Tetragonal (I4/mmm)
Cesium sodium aluminum fluoride	$Cs_2NaAl_3F_{12}$	Rhombohedral (R–3m)
Cesium sodium aluminum fluoride	Cs_2NaAlF_6	Rhombohedral (R–3m)
Cesium sodium gallium fluoride	Cs_2NaGaF_6	Rhombohedral ($R\bar{3}m$)
Cesium sodium yttrium fluoride	Cs_2NaYF_6	Cubic (Fm3m)
Cesium strontium fluoride	$CsSrF_3$	Cubic (Pm3m)
Cesium tin germanate	$Cs_2SnGe_3O_9$	Hexagonal ($P6_3/m$)
Cesium titanium germanate	$Cs_2TiGe_3O_9$	Hexagonal ($P6_3/m$)
Cesium titano arsenate (CTA)	$CsTiOAsO_4$	Orthorhombic ($P2_1nb$)
Cesium zinc aluminum fluoride	$CsZnAlF_6$	Orthorhombic
Cesium zinc bromide	Cs_2ZnBr_4	Orthorhombic (Pnma)
Cesium zinc chloride	Cs_2ZnCl_4	Orthorhombic (Pnma)
Copper bromide (cuprous)	CuBr	Cubic (Fm3m)
Copper chloride (cuprous, nantokite)	CuCl	Cubic (Fm3m)
Copper iodide (cuprous, marshite)	CuI	Cubic (Fm3m)
Cuprous oxide (cuprite)	Cu_2O	Cubic (Pm3m)
Gadolinium aluminate	$Gd_4Al_2O_9$	Monoclinic ($P2_1/a$)
Gadolinium aluminate	$GdAlO_3$	Orthorhombic (Pbnm)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Gadolinium aluminum borate	$GdAl_3(BO_3)_4$	Trigonal (R32)
Gadolinium aluminum germanate	$GdAlGe_2O_7$	Monoclinic ($P2_1/c$)
Gadolinium borate	$Gd(BO_2)_3$	Monoclinic (I2/a)
Gadolinium borate	$GdBO_3$	Hexagonal ($P6_3/mmc$)
Gadolinium calcium oxyborate	$GdCa_4O(BO_3)_3$	Monoclinic (Cm)
Gadolinium gallium borate	$GdGa_3(BO_3)_4$	Trigonal (R32)
Gadolinium gallium garnet (GGG)	$Gd_3Ga_5O_{12}$	Cubic (Ia3d)
Gadolinium gallium germanate	$GdGaGe_2O_7$	Monoclinic ($P2_1/c$)
Gadolinium germanate	Gd_2GeO_5	Monoclinic ($P2_1/c$)
Gadolinium germanium beryllate	$Gd_2GeBe_2O_7$	Tetragonal ($P42_1m$)
Gadolinium indate	$GdInO_3$	Hexagonal ($P6_3cm$)
Gadolinium magnesium borate	$GdMgB_5O_{10}$	Monoclinic ($P2_1/c$)
Gadolinium molybdate	$Gd_2(MoO_4)_3$	Orthorhombic (Pba2)
Gadolinium niobate	$GdNbO_4$	Monoclinic (I2/a)
Gadolinium niobate	Gd_3NbO_7	Orthorhombic ($C222_1$)
Gadolinium orthosilicate	Gd_2SiO_5	Monoclinic ($P2_1/c$)
Gadolinium oxide	Gd_2O_3	Monoclinic (C2/m)
Gadolinium oxymolybdate	Gd_2MoO_6	Monoclinic (I2/c)
Gadolinium oxysulfate	$Gd_2O_2SO_4$	Orthorhombic
Gadolinium oxytungstate	Gd_2WO_6	Monoclinic (I2/c)
Gadolinium pentaphosphate	GdP_5O_{14}	Monoclinic ($P2_{1/c}$)
Gadolinium phosphate	$GdPO_4$	Monoclinic ($P2_1/n$)
Gadolinium scandate	$GdScO_3$	Orthorhombic (Pbnm)
Gadolinium scandium aluminum garnet (GSAG)	$Gd_3Sc_2Al_3O_{12}$	Cubic (Ia3d)
Gadolinium scandium gallium garnet (GSGG)	$Gd_3Sc_2Ga_3O_{12}$	Cubic (Ia3d)
Gadolinium strontium borate	$Gd_2Sr_3(BO_3)_4$	Orthorhombic ($P2_1cn$)
Gadolinium tantalate	Gd_3TaO_7	Orthorhombic ($C222_1$)
Gadolinium titanate	$Gd_2Ti_2O_7$	Cubic (Fd3m)
Gadolinium tungstate	$Gd_2(WO_4)_3$	Monoclinic (C2/c)
Gadolinium vanadate	$GdVO_4$	Tetragonal ($I4_1/amd$)
Gallium antimonide	GaSb	Cubic (F–43m)
Gallium arsenide	GaAs	Cubic (F–43m)
Gallium germanate	α-Ga_4GeO_8	Monoclinic (C2/m)
Gallium molybdate	$Ga_2(MoO_4)_3$	Monoclinic ($P2_1/a$)
Gallium niobate	$GaNbO_4$	Monoclinic (C2)
Gallium nitride - wurtzite	α-GaN	Hexagonal($P6_3mc$)
Gallium nitride - zincblende	β-GaN	Cubic (F–43m)
Gallium oxide	β-Ga_2O_3	Monoclinic (A2/m)
Gallium phosphate	$GaPO_4$	Trigonal ($P3_12$)
Gallium phosphide	GaP	Cubic (F–43m)
Gallium selenide	GaSe	Hexagonal(P–62m)
Gallium sulfide	GaS	Hexagonal(P–62m)
Gallium tungstate	$Ga_2(WO_4)_3$	Orthorhombic (Pcna)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Germanium	Ge	Cubic (F–43m)
Germanium oxide (argutite)	GeO_2	Tetragonal ($P4_2/mnm$)
Hafnium oxide	HfO_2	Monoclinic ($P2_1/c$)
Hafnium silicate (hafnon)	$HfSiO_4$	Tetragonal ($I4_1/amd$)
Indium antimonide	InSb	Cubic (F–43m)
Indium arsenide	InAs	Cubic (F–43m)
Indium borate	$InBO_3$	Rhombohedral (R–3c)
Indium cadmium borate	$InCdBO_4$	Orthorhombic (Pnam)
Indium calcium borate	$InCaBO_4$	Orthorhombic (Pnam)
Indium gallate	$InGaO_3$	Monoclinic (C2/m)
Indium molybdate	$In_2(MoO_4)_3$	Monoclinic ($P2_1/a$)
Indium niobate	$InNbO_4$	Monoclinic (P2/c)
Indium nitride	InN	Hexagonal($P6_3mc$)
Indium oxide	In_2O_3	Rhombohedral (R3c)
Indium phosphate	$InPO_4$	Orthorhombic (Cmcm)
Indium phosphide	InP	Cubic (F–43m)
Indium tantalate	$InTaO_4$	Monoclinic (P2/c)
Indium tungstate	$In_2(WO_4)_3$	Orthorhombic (Pcna)
Indium vanadate	$InVO_4$	Monoclinic (C2/m)
Iodic acid	HIO_3	Orthorhombic ($P2_12_12_1$)
Lanthanum aluminate	$LaAlO_3$	Trigonal (R–3m)
Lanthanum aluminum germanate	$LaAlGe_2O_7$	Monoclinic ($P2_1/c$)
Lanthanum aluminum germanate	$LaAlGe_2O_7$	Monoclinic ($P2_1/c$)
Lanthanum antimonade	$LaSbO_4$	Monoclinic ($P2_1/c$)
Lanthanum antimonade	La_3SbO_7	Orthorhombic (Cmcm)
Lanthanum barium borate	$La_2Ba_3(BO_3)_4$	Orthorhombic ($P2_1cn$)
Lanthanum barium gallate	$BaLaGa_3O_7$	Tetragonal ($P42_1m$)
Lanthanum barium germanate	$LaBaGa_3O_7$	Tetragonal ($P42_1m$)
Lanthanum beryllate (BEL)	$La_2Be_2O_5$	Monoclinic (C2/c)
Lanthanum borate	$LaBO_3$	Orthorhombic (Pnam)
Lanthanum boron germanate	$LaBGeO_5$	Trigonal (C3m)
Lanthanum boron molybdate	$LaBMoO_6$	Monoclinic ($P2_1$)
Lanthanum boron silicate (stillwellite)	$LaBSiO_5$	Trigonal (C3m)
Lanthanum boron tungstate	$LaBWO_6$	Monoclinic ($P2_1$)
Lanthanum calcium aluminate	$LaCaAl_3O_7$	Tetragonal ($P42_1m$)
Lanthanum calcium borate	$La_2Ca_3(BO_3)_4$	Orthorhombic ($P2_1cn$)
Lanthanum calcium gallate	$LaCaGa_3O_7$	Tetragonal ($P42_1m$)
Lanthanum chloride	$LaCl_3$	Hexagonal ($P6_3/m$)
Lanthanum fluoride (tysonite)	LaF_3	Trigonal (P–3c1)
Lanthanum gallate	$LaGaO_3$	Orthorhombic (Pbnm)
Lanthanum gallium germanate	$LaGaGe_2O_7$	Monoclinic ($P2_1/c$)
Lanthanum gallium germanate	$La_3Ga_5GeO_{14}$	Trigonal ($P32_1$)
Lanthanum gallium silicate	$La_3Ga_5SiO_{14}$	Trigonal ($P32_1$)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Lanthanum germanium beryllate	$La_2GeBe_2O_7$	Tetragonal ($P42_1m$)
Lanthanum indate	$LaInO_3$	Orthorhombic (Pbnm)
Lanthanum lutetium gallium garnet (LLGG)	$La_3Lu_2Ga_3O_{12}$	Cubic (Ia3d)
Lanthanum magnesium borate	$LaMgB_5O_{10}$	Monoclinic ($P2_1/c$)
Lanthanum magnesium hexa-aluminate (LMA)	$LaMgAl_{11}O_{19}$	Hexagonal ($P6_3/mmc$)
Lanthanum metaborate	LaB_3O_6	Monoclinic (I2/a)
Lanthanum molbydate	$La_2(MoO_4)_3$	Monoclinic (C2/c)
Lanthanum molybdate	$La_2(MoO_4)_3$	Tetragonal (I–42m)
Lanthanum niobate	$LaNbO_4$	Monoclinic (I2/a)
Lanthanum niobate	$LaNb_5O_{14}$	Orthorhombic (Pnam)
Lanthanum niobate	La_3NbO_7	Othorhombic (Cmcm)
Lanthanum niobogallate	$La_3Nb_{0.5}Ga_{5.5}O_{14}$	Trigonal ($P32_1$)
Lanthanum oxide	La_2O_3	Trigonal (P–3m1)
Lanthanum oxybromide	LaOBr	Tetragonal (P4/nmm)
Lanthanum oxymolybdate	La_2MoO_6	Tetragonal (I–42m)
Lanthanum oxysulfate	$La_2O_2SO_4$	Orthorhombic
Lanthanum oxysulfide	La_2O_2S	Trigonal (P–3m)
Lanthanum oxytungstate	La_2WO_6	Hexagonal ($P6_3/mmc$)
Lanthanum pentaphosphate	LaP_5O_{14}	Orthorhombic (Pcmn)
Lanthanum phosphate (monazite)	$LaPO_4$	Monoclinic ($P2_1/n$)
Lanthanum scandate	$LaScO_3$	Orthorhombic (Pbnm)
Lanthanum scandium borate	$LaSc_3(BO_3)_4$	Monoclinic
Lanthanum silicate	La_2SiO_5	Monoclinic
Lanthanum strontium borate	$La_2Sr_3(BO_3)_4$	Orthorhombic ($P2_1cn$)
Lanthanum strontium gallate	$LaSrGa_3O_7$	Tetragonal ($P42_1m$)
Lanthanum tantalate	La_3TaO_7	Orthorhombic (Cmcm)
Lanthanum tantalogallate	$La_3Ta_{0.5}Ga_{5.5}O_{14}$	Trigonal ($P32_1$)
Lanthanum titanate	La_2TiO_5	Orthorhombic (Pnam)
Lanthanum titanate	$La_2Ti_2O_7$	Monoclinic ($P2_1/c$)
Lanthanum tungstate	$La_2(WO_4)_3$	Monoclinic (C2/c)
Lanthanum yttrium tungstate	$LaY(WO_4)_3$	Monoclinic (C2/c)
Lathanium vanadate	$LaVO_4$	Monoclinic ($P2_1/c$)
Lead antimonade	$Pb_2Sb_2O_7$	Cubic (Fd3m)
Lead bismuth niobate	$PbBi_2Nb_2O_9$	Othorhombic (Fmm2)
Lead bromide	$PbBr_2$	Othorhombic (Pnma)
Lead cadmium niobate	$Pb_3CdNb_2O_9$	Orthorhombic
Lead calcium chloroarsenate (hedyphane)	$Pb_3Ca_2(AsO_4)_3Cl$	Hexagonal ($P6_3/m$)
Lead carbonate (cerussite)	$PbCO_3$	Orthorhombic (Pnam)
Lead chloride (cotunnite)	$PbCl_2$	Orthorhombic (Pnam)
Lead chloroarsenate (mimetite)	$Pb_5(AsO_4)_3Cl$	Hexagonal ($P6_3/m$)
Lead chlorophosphate (pyromorphite)	$Pb_5(PO_4)_3Cl$	Hexagonal ($P6_3/m$)
Lead chlorovanadate (vanadinite)	$Pb_5(VO_4)_3Cl$	Hexagonal ($P6_3/m$)
Lead fluoride	PbF_2	Cubic (Fm3m)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Lead fluoroarsenate	$Pb_5(AsO_4)_3F$	Hexagonal ($P6_3/m$)
Lead fluorophosphate	$Pb_5(PO_4)_3F$	Hexagonal ($P6_3/m$)
Lead fluorovanadate	$Pb_5(VO_4)_3F$	Hexagonal ($P6_3/m$)
Lead germanate	$PbGeO_3$	Monoclinic ($P2_1/a$)
Lead germanate	Pb_3GeO_5	Monoclinic (P12)
Lead germanate	$Pb_3Ge_3O_{11}$	Trigonal (P3)
Lead germanate	$Pb_5Ge_2O_7$	Hexagonal
Lead hafnate	$PbHfO_3$	Orthorhombic (Pbam)
Lead hexa-aluminate (magnetoplumbite)	$PbAl_{12}O_{19}$	Hexagonal ($P6_3/mmc$)
Lead indium niobate	Pb_2InNbO_6	Rhombohedral
Lead iodide	*2H*-PbI_2	Trigonal (P3m1)
Lead magnesium niobate	$Pb_3MgNb_2O_9$	Orthorhombic
Lead molybdate (wulfenite)	$PbMoO_4$	Tetragonal ($I4_1/a$)
Lead niobate (changbaiite)	$PbNb_2O_6$	Orthorhombic (Cm2m)
Lead nitrate	$Pb(NO_3)_2$	Cubic (Pa3)
Lead oxide (litharge)	PbO	Tetragonal (P4/nmm)
Lead oxide (massicot)	PbO	Orthorhombic (Pbcm)
Lead phosphate	$Pb_3(PO_4)_2$	Monoclinic (PC2/c)
Lead potassium niobate	$Pb_2KNb_5O_{15}$	Orthorhombic (Im2m)
Lead scandium niobate	Pb_2ScNbO_6	Rhombohedral
Lead selenate (kerstenite)	$PbSeO_4$	Orthorhombic (Pnma)
Lead selenide (clausthalite)	PbSe	Cubic (Fm3m)
Lead selenite (molybdomenite)	$PbSeO_3$	Monoclinic
Lead silicate (alamosite)	$PbSiO_3$	Monoclinic (Pn)
Lead sodium niobate	$PbNaNb_5O_{15}$	Orthorhombic (Im2a)
Lead sulfate (anglesite)	$PbSO_4$	Orthorhombic (Pnma)
Lead sulfide (galena)	PbS	Cubic (Fm3m)
Lead tantalate	$PbTa_2O_6$	Orthorhombic (Cm2m)
Lead telluride (altaite)	PbTe	Cubic (Fm3m)
Lead titanate (macedonite)	$PbTiO_3$	Tetragonal (P4mm)
Lead titanium phosphate	$PbTiP_2O_8$	Orthorhombic
Lead tungstate (stolzite)	$PbWO_4$	Tetragonal ($I4_1/a$)
Lead vanadate	$Pb_3(VO_4)_2$	Monoclinic (P2/c)
Lead vanadate (chervetite)	$Pb_2V_2O_7$	Monoclinic (P21/a)
Lead $_{zi}$nc niobate	Pb3ZnNb2O$_9$	Orthorhombic
Lead zinc silic$_a$te	Pb2ZnSi2O7	Tetragonal (P421m)
Lead zinc silicate (larsenite)	PbZnSiO4	Orthorhombic (Pnam)
Lithium aluminate	Li5AlO4	Orthorhombic (Pbca)
Lithium aluminate	γ-$LiAlO_2$	Tetragonal ($P4_12_12$)
Lithium aluminate spinel	$LiAl_5O_8$	Cubic ($P4_132$)
Lithium aluminum borate	$Li_6Al_2(BO_3)_4$	Triclinic(P−1)
Lithium aluminum fluorophosphate (amblygonite)	$LiAl(PO_4)F$	Triclinic(P−1)
Lithium aluminum germanate	$LiAlGe_2O_6$	Monoclinic (P21/n)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Lithium aluminum germanate	$LiAlGeO_4$	Trigonal(R–3)
Lithium aluminum molybdate	$LiAl(MoO_4)_2$	Triclinic(P–1)
Lithium aluminum silicate	$LiAlSi_2O_6$	Monoclinic (C2/c)
Lithium aluminum silicate	$LiAlSi_4O_{10}$	Monoclinic ($P2_1/n$)
Lithium aluminum silicate (eucryptite)	$LiAlSiO_4$	Rhombohedral(R–3)
Lithium aluminum silicate (petalite)	$LiAlSi_4O_{10}$	Monoclinic ($P2_1/n$)
Lithium aluminum silicate (spodumene)	$LiAlSi_2O_6$	Rhombohedral(R–3)
Lithium barium aluminum fluoride (LiBAF)	$LiBaAlF_6$	Monoclinic ($P2_1/a$)
Lithium barium fluoride	$LiBaF_3$	Cubic (Pm3m)
Lithium barium gallium fluoride	$LiBaGaF_6$	Monoclinic ($P2_1/a$)
Lithium beryllium fluoride	Li_2BeF_4	Cubic (Fd3m)
Lithium beryllium silicate (liberite)	Li_2BeSiO_4	Monoclinic (Pn)
Lithium borate	$LiBO_2$	Monoclinic ($P2_1/c$)
Lithium borate	LiB_3O_5	Orthorhombic ($Pna2_1$)
Lithium bromide	LiBr	Cubic (Fm3m)
Lithium cadmium borate	$LiCdBO_3$	Hexagonal (P–6)
Lithium cadmium chloride	Li_2CdCl_4	Cubic (Fd3m)
Lithium cadmium indium fluoride	$LiCdInF_6$	Trigonal (P321)
Lithium calcium aluminum fluoride (LiCAF)	$LiCaAlF_6$	Trigonal(P–31c)
Lithium calcium gallium fluoride (LiCGaF)	$LiCaGaF_6$	Trigonal(P–31c)
Lithium calcium germanate	Li_2CaGeO_4	Tetragonal (I–42m)
Lithium calcium indium fluoride	$LiCaInF_6$	Trigonal (P321)
Lithium calcium silicate	Li_2CaSiO_4	Tetragonal (I–42m)
Lithium carbonate (zabuyelite)	Li_2CO_3	Monoclinic (C2/c)
Lithium chloride	LiCl	Cubic (Fm3m)
Lithium fluoride (griceite)	LiF	Cubic (Fm3m)
Lithium gadolinium borate	$Li_3Gd_2(BO_3)_3$	Monoclinic ($P2_1/n$)
Lithium gadolinium borate	$Li_6Gd(BO_3)_3$	Monoclinic ($P2_1/b$)
Lithium gadolinium molybdate	$LiGd(MoO_4)_2$	Tetragonal ($I4_1/a$)
Lithium gadolinium molybdate	$LiGd(MoO_4)_2$	Tetragonal ($I4_1/a$)
Lithium gadolinium oxide	$LiGdO_2$	Orthorhombic (Pnma)
Lithium gadolinium tetrafluoride (GLF)	$LiGdF_4$	Tetragonal ($I4_1/a$)
Lithium gadolinium tetraphosphate	$LiGdP_4O_{12}$	Monoclinic (I2/c)
Lithium gadolinium tungstate	$LiGd(WO_4)_2$	Tetragonal ($I4_1/a$)
Lithium gallate	$LiGaO_2$	Orthorhombic ($Pna2_1$)
Lithium gallate	Li_5GaO_4	Orthorhombic (Pnam)
Lithium gallate spinel	$LiGa_5O_8$	Cubic ($P4_132$)
Lithium gallium germanate	$LiGaGe_2O_6$	Monoclinic ($P2_1/c$)
Lithium gallium germanate	$LiGaGe_2O_6$	Monoclinic ($P2_1/c$)
Lithium gallium germanate	$LiGaGeO_4$	Trigonal(R–3)
Lithium gallium silicate	$LiGaSi_2O_6$	Monoclinic (C2/c)
Lithium gallium silicate	$LiGaSiO_4$	Rhombohedral(R–3)
Lithium gallium tungstate	$LiGa(WO_4)_2$	Monoclinic (P2/c)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Lithium germanate	Li_2GeO_3	Orthorhombic ($Cmc2_1$)
Lithium indium germanate	$LiInGe_2O_6$	Orhtorhimbic (Pbca)
Lithium indium molybdate	$LiIn(MoO_4)_2$	Monoclinic ($P2_1/c$)
Lithium indium oxide	Li_3InO_3	Trigonal (P–3c1)
Lithium indium oxide	$LiInO_2$	Tetragonal($I4_1/amd$)
Lithium indium silicate	$LiInSiO_4$	Orthorhombic (Pnma)
Lithium indium silicate	$LiInSi_2O_6$	Monoclinic (C2/c)
Lithium indium tungstate	$LiIn(WO_4)_2$	Monoclinic (P2/c)
Lithium iodate	α-$LiIO_3$	Hexagonal ($P6_3$)
Lithium iodide	LiI	Cubic (Fm3m)
Lithium lanthanum borate	$Li_3La_2(BO_3)_3$	Monoclinic ($P2_1/n$)
Lithium lanthanum molybdate	$LiLa(MoO_4)_2$	Orthorhombic (Pbca)
Lithium lanthanum oxide	$LiLaO_2$	Orthorhombic (Pbmm)
Lithium lanthanum tetraphosphate	$LiLaP_4O_{12}$	Monoclinic (I2/c)
Lithium lanthanum tungstate	$LiLa(WO_4)_2$	Tetragonal ($I4_1/a$)
Lithium lutetium borate	$Li_6Lu(BO_3)_3$	Monoclinic ($P2_1/b$)
Lithium lutetium fluoride	$LiLuF_4$	Tetragonal ($I4_1/a$)
Lithium lutetium germanate	$LiLuGeO_4$	Orthorhombic (Pbcn)
Lithium lutetium oxide	$LiLuO_2$	Tetragonal ($I4_1/amd$)
Lithium lutetium silicate	$LiLuSiO_4$	Orthorhombic (Pbcn)
Lithium lutetium tetraphosphate	$LiLuP_4O_{12}$	Monoclinic (I2/c)
Lithium lutetium tungstate	$LiLu(WO_4)_2$	Monoclinic (P2/c)
Lithium magnesium aluminum fluoride	$LiMgAlF_6$	Trigonal (P321)
Lithium magnesium borate	$LiMgBO_3$	Monoclinic (C2/c)
Lithium magnesium borate	$Li_2MgB_2O_5$	Monoclinic
Lithium magnesium chloride	Li_2MgCl_4	Cubic (Fd3m)
Lithium magnesium gallium fluoride	$LiMgGaF_6$	Tetragonal ($P4_2/mmm$)
Lithium magnesium germanate	Li_2MgGeO_4	Orthorhombic ($Pmn2_1$)
Lithium magnesium indium fluoride	$LiMgInF_6$	Trigonal (P321)
Lithium niobate	$LiNbO_3$	Trigonal (R3c)
Lithium phosphate (lithiophosphate)	Li_3PO_4	Orthorhombic
Lithium scandate	$LiScO_2$	Tetragonal($I4_1/amd$)
Lithium scandium germanate	$LiScGeO_4$	Orthorhombic (Pbnm)
Lithium scandium germanate	$LiScGe_2O_6$	Orthorhombic (Pbca)
Lithium scandium silicate	$LiScSiO_4$	Orthorhombic (Pbnm)
Lithium scandium silicate	$LiScSi_2O_6$	Monoclinic (C2/c)
Lithium scandium tungstate	$LiSc(WO_4)_2$	Monoclinic (P2/c)
Lithium silicate	Li_2SiO_3	Orthorhombic ($Ccm2_1$)
Lithium strontium aluminum fluoride (LiSAF)	$LiSrAlF_6$	Trigonal(P–31c)
Lithium strontium gallium fluoride (LiSGF)	$LiSrGaF_6$	Trigonal(P–31c)
Lithium tantalate (LT)	$LiTaO_3$	Trigonal (R3c)
Lithium tetraborate (diomignite)	$Li_2B_4O_7$	Tetragonal ($I4_1cd$)
Lithium triborate (LBO)	LiB_3O_5	Orthorhombic ($Pn2_1a$)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Lithium vanadate	$LiVO_3$	Monoclinic (C2/c)
Lithium vanadate	Li_3VO_4	Orthorhombic ($Pmn2_1$)
Lithium yttrium borate	$Li_3Y_2(BO_3)_3$	Monoclinic ($P2_1/n$)
Lithium yttrium borate	$Li_6Y(BO_3)_3$	Monoclinic ($P2_1/b$)
Lithium yttrium fluoride (YLF)	$LiYF_4$	Tetragonal ($I4_1/a$)
Lithium yttrium germanate	$LiYGeO_4$	Orthorhombic (Pbcn)
Lithium yttrium oxide	$LiYO_2$	Monoclinic ($P2_1/c$)
Lithium yttrium silicate	$LiYSiO_4$	Orthorhombic (Pbcn)
Lithium yttrium tungstate	$LiY(WO_4)_2$	Monoclinic (P2/c)
Lithium zinc borate	$LiZnBO_3$	Monoclinic (C2/c)
Lithium zinc indium fluoride	$LiZnInF_6$	Trigonal (P321)
Lithium zinc niobate	$LiZnNbO_4$	Tetragonal ($P4_122$)
Lutetium aluminum borate	$LuAl_3(BO_3)_3$	Trigonal (R32)
Lutetium aluminum garnet	$Lu_3Al_5O_{12}$	Cubic (Ia3d)
Lutetium borate	$LuBO_3$	Rhombohedral (R−3c)
Lutetium calcium borate	$LuCaBO_4$	Orthorhombic (Pnam)
Lutetium gallium garnet	$Lu_3Ga_5O_{12}$	Cubic (Ia3d)
Lutetium molybdate	$Lu_2(MoO_4)_3$	Orthorhombic (Pbcn)
Lutetium orthosilicate	Lu_2SiO_5	Monoclinic (C2/c)
Lutetium oxide	Lu_2O_3	Cubic (Ia3)
Lutetium oxymolybdate	Lu_2MO_6	Monoclinic (I2/c)
Lutetium oxysulfate	$Lu_2O_2SO_4$	Orthorhombic
Lutetium oxytungstate	Lu_2WO_6	Monoclinic (P2/c)
Lutetium pentaphosphate	LuP_5O_{14}	Monoclinic (C2/c)
Lutetium phosphate	$LuPO_4$	Tetragonal ($I4_1/amd$)
Lutetium scandate	$LuScO_3$	Cubic (Ia3)
Lutetium scandium aluminum garnet (LSAG)	$Lu_3Sc_2Al_3O_{12}$	Cubic (Ia3d)
Lutetium tantalate	$LuTaO_4$	Monoclinic (P2/a)
Lutetium titanate	$Lu_2Ti_2O_3$	Cubic (Fd3m)
Lutetium tungstate	$Lu_2(WO_4)_3$	Orthorhombic (Pcna)
Lutetium vanadate	$LuVO_4$	Tetragonal ($I4_1/amd$)
Magnesium aluminate (spinel)	$MgAl_2O_4$	Cubic (Fd3m)
Magnesium aluminum borate (sinhalite)	$MgAlBO_4$	Orthorhombic (Pnma)
Magnesium aluminum borosilicate (grandidierite)	$MgAl_3BSiO_9$	Orthorhombic
Magnesium aluminum silicate (cordierite)	$Mg_2Al_3(Si_5Al)O_{18}$	Hexagonal (P6/mcc)
Magnesium aluminum silicate (sapphirine)	$Mg_4Al_8Si_2O_{20}$	Monoclinic ($P2_1/a$)
Magnesium aluminum silicate garnet (pyrope)	$Mg_3Al_2Si_3O_{12}$	Cubic (Ia3d)
Magnesium borate (kotoite)	$Mg_3B_2O_6$	Orthorhombic (Pnma)
Magnesium borate (suanite)	$Mg_2B_2O_5$	Monoclinic
Magnesium carbonate (magnesite)	$MgCO_3$	Rhombohedral (R−3c)
Magnesium chloroborate (boracite)	$Mg_3B_7O_{13}Cl$	Orthorhombic
Magnesium fluoride (sellaite, Irtran 1)	MgF_2	Tetragonal ($P4_2/mnm$)
Magnesium fluoroborate	Mg_2BO_3F	Orthorhombic

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Magnesium fluoroborate	$Mg_5(BO_3)_3F$	Orthorhombic (P*nb)
Magnesium fluorophosphate (wagnerite)	Mg_2PO_4F	Monoclinic (P21/a)
Magnesium gallate spinel	$MgGa_2O_4$	Cubic (Fd3m)
Magnesium gallium borate	$MgGaBO_4$	Orthorhombic (Pnam)
Magnesium gallium germanate	$Mg_4Ga_8Ge_2O_{20}$	Monoclinic ($P2_1/a$)
Magnesium germanate	$MgGeO_3$	Orthorhombic (Pbca)
Magnesium germanate	Mg_2GeO_4	Orthorhombic (Pnma)
Magnesium molybdate	$MgMoO_4$	Monoclinic (C2/m)
Magnesium oxide (periclase, Irtran 5)	MgO	Cubic (Fm3m)
Magnesium phosphate (farringtonite)	$Mg_3(PO_4)_2$	Monoclinic
Magnesium pyroarsenate	$Mg_2As_2O_7$	Monoclinic (C2/m)
Magnesium silicate (enstatite)	$MgSiO_3$	Monoclinic ($P2_1/c$)
Magnesium silicate (forsterite)	Mg_2SiO_4	Orthorhombic (Pbcn)
Magnesium titanate	$MgTi_2O_5$	Orthorhombic (Bbmm)
Magnesium titanate	Mg_2TiO_4	Cubic (Fd3m)
Magnesium titanate (geikielite)	$MgTiO_3$	Trigonal(R–3)
Magnesium titanium sulfate	$MgTi(SO_4)_2$	Monoclinic ($P2_1/n$)
Magnesium titanum borate (warwickite)	$Mg_3TiB_2O_8$	Orthorhombic
Magnesium tungstate	$MgWO_4$	Monoclinic (P2/c)
Magnesium vanadate	MgV_2O_6	Orthorhombic (Pbcn)
Magnesium vanadate	$MgVO_3$	Monoclinic ($Cmc2_1$)
Magnesium vanadate	$Mg_2V_2O_7$	Monoclinic (C2/m)
Magnesium vanadate	$Mg_3(VO_4)_2$	Orthorhombic (Cmca)
Manganese fluoride	MnF_2	Tetragonal ($P4_2/mnm$)
Manganese oxide (manganosite)	MnO	Cubic (Fm3m)
Mercurous bromide (kuzminite)	Hg_2Br_2	Tetragonal (I4/mmm)
Mercurous chloride (calomel)	Hg_2Cl_2	Tetragonal (I4/mmm)
Mercurous iodide (moschelite)	Hg_2I_2	Tetragonal (I4/mmm)
Mercury antimonade	$Hg_2Sb_2O_7$	Cubic (Fd3m)
Mercury chloride	$HgCl_2$	Orthorhombic (Pmnb)
Mercury iodide	HgI_2	Tetragonal ($P4_2/mmc$)
Mercury oxide	HgO	Orthorhombic (Pmna)
Mercury peroxide	Hg_2O_2	Monoclinic (C2/m)
Mercury selenide (tiemannite)	HgSe	Cubic (F43m)
Mercury sulfide (cinnabar)	HgS	Trigonal (R32)
Mercury tellurite (coloradoite)	HgTe	Cubic (F43m)
Neodymium calcium aluminum oxide	$NdCaAlO_4$	Tetragonal (I4/mmm)
Neodymium gallate	$NbGaO_3$	Orthorhombic (Pbnm)
Neodymium yttrium aluminum borate	$Nd_xY_{1-x}Al_3(BO_3)_4$	Trigonal (R32)
Niobium phosphate	$NbOPO_4$	Tetragonal (P4/n)
Potassium aluminum borate	$K_2A_2lB_2O_7$	Trigonal (P321)
Potassium aluminum fluoride	K_3AlF_6	Cubic (Pm3m)
Potassium aluminum germanate	$KAlGeO_4$	Hexagonal ($P6_3$)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Potassium aluminum molybdate	$KAl(MoO_4)_2$	Trigonal (P–3m1)
Potassium aluminum silicate (kaliophilite)	$KAlSiO_4$	Hexagonal ($P6_3$)
Potassium aluminum silicate (leucite)	$KAlSi_2O_6$	Tetragonal ($I4_1/a$)
Potassium aluminum silicate (orthoclase)	$KAlSi_3O_8$	Monoclinic (C2/m)
Potassium aluminum silicate hydroxide (mica)	$KAl_3Si_3O_{10}•(OH)_2$	Monoclinic
Potassium aluminum sulfate	$KAl(SO_4)_2$	Trigonal (P321)
Potassium aluminum tetrafluoride	$KAlF_4$	Tetragonal (P4/mbm)
Potassium beryllium fluoride	K_2BeF_4	Orthorhombic ($Pna2_1$)
Potassium beryllium fluoroborate (KBBF)	$KBe_2BO_3F_2$	Trigonal (R32)
Potassium bismuth niobate	$KBiNb_5O_{15}$	Tetragonal
Potassium boron fluoride (avogadvite)	KBF_4	Orthorhombic (Cmcm)
Potassium bromide	KBr	Cubic (Fm3m)
Potassium cadmium fluoride	$KCdF_3$	Cubic (Pm3m)
Potassium calcium fluoride	$KCaF_3$	Cubic (Pm3M)
Potassium calcium silicate	K_2CaSiO_4	Orthorhombic (Pnmm)
Potassium calcium zirconium silicate (wadeite)	$K_2CaZr(SiO_3)_4$	Hexagonal ($P6_3m$)
Potassium chloride (sylvite)	KCl	Cubic (Fm3m)
Potassium dideuterium phosphate (KDP)	KD_2PO_4	Hexagonal ($P6_3$)
Potassium dihydrogen phosphate (KDP)	KH_2PO_4	Tetragonal (I–42m)
Potassium fluoride (carobbiite)	KF	Cubic (Fm3m)
Potassium gadolinium niobate	$K_2GdNb_5O_{15}$	Tetragonal
Potassium gadolinium tungstate	$KGd(WO_4)_2$	Monoclinic (C2/c)
Potassium gadolinium vanadate	$K_3Gd(VO_4)_2$	Monoclinic ($P2_1/m$)
Potassium gallium germanate	$KGaGeO_4$	Hexagonal ($P6_3$)
Potassium gallium silicate	$KGaSi_3O_8$	Monoclinic (C2/m)
Potassium gallium silicate	$KGaSiO_4$	Hexagonal ($P6_3$)
Potassium indium molybdate	$KIn(MoO_4)_2$	Orthorhombic (Pnam)
Potassium indium tungstate	$KIn(WO_4)_2$	Trigonal (P–3m1)
Potassium iodide	KI	Cubic (Fm3m)
Potassium iodide	KIO_3	Monoclinic (P1)
Potassium lanthanum molybdate	$KLa(MoO_4)_4$	Tetragonal ($I4_1/a$)
Potassium lanthanum niobate	$K_2LaNb_5O_{15}$	Tetragonal
Potassium lanthanum phosphate	$K_3La(PO_4)_2$	Monoclinic ($P2_1/m$)
Potassium lanthanum tetraphosphate	$KLaP_4O_{12}$	Monoclinic ($P2_1$)
Potassium lanthanum tungstate	$KLa(WO_4)_2$	Monoclinic (C2/m)
Potassium lead chloride	KPb_2Cl_5	Monoclinic ($P2_1/c$)
Potassium lithium beryllium fluoride	$KLiBeF_4$	Hexagonal (P–3m1)
Potassium lithium gadolinium fluoride (KLGF)	$KLiGdF_5$	Monoclinic ($P2_1/c$)
Potassium lithium niobate (KLN)	$K_3Li_2Nb_5O_{15}$	Tetragonal (P4bm)
Potassium lithium yttrium fluoride (KLYF)	$KLiYF_5$	Monoclinic (P21/c)
Potassium lutetium tungstate	$KLu(WO_4)_4$	Monoclinic (C2/c)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Potassium lutetium vanadate	$K_3Lu(VO_4)_4$	Monoclinic (P21/m)
Potassium magnesium chloride	K_2MgCl_4	Tetragonal (I4/mmm)
Potassium magnesium fluoride	K_2MgF_4	Tetragonal (I4/mmm)
Potassium magnesium fluoride	$KMgF_3$	Cubic (Pm3m)
Potassium magnesium sulfate (langbeinite)	$K_2Mg_2(SO_4)_3$	Cubic ($P2_13$)
Potassium niobate (KN)	$KNbO_3$	Orthorhombic (Amm2)
Potassium niobium borate	$KNbB_2O_6$	Orthorhombic ($Pn2_1m$)
Potassium nitrate (nitre)	KNO_3	Orthorhombic (Pmcn)
Potassium pentaborate	$KB_5O_8{\bullet}4H_2O$	Orthorhombic (Aba2)
Potassium scandium molybdate	$KSc(MoO_4)_2$	Tetragonal (P–3m1)
Potassium scandium tungstate	$KSc(WO_4)_2$	Trigonal (P–3m1)
Potassium scandium vanadate	$KSc(VO_4)_2$	Trigonal
Potassium sodium aluminum fluoride (elpasolite)	K_2NaAlF_6	Cubic (Fm3m)
Potassium sodium gallium fluoride	K_2NaGaF_6	Cubic (Fm3m)
Potassium sodium lithium niobate	$KNaLi_2Nb_5O_{15}$	Trigonal
Potassium sodium lithum niobate	$K_2NaLi_2Nb_5O_{15}$	Tetragonal (P4bm)
Potassium strontium sulfate (kalistrontite)	$K_2Sr(SO_4)_2$	Trigonal
Potassium tantalate	$KTaO_3$	Cubic (Pm–3m)
Potassium tantalum borate	$KTaB_2O_6$	Orthorhombic (Pmm)
Potassium tin germanate	$K_2SnGe_3O_9$	Trigonal (P–3c1)
Potassium tin silicate	$K_2SnSi_3O_9$	Hexagonal ($P6_3/m$)
Potassium titanium germanate	$K_2TiGe_3O_9$	Trigonal (P–3c1)
Potassium titanium niobate	$KTiNbO_5$	Orthorhombic (Pnma)
Potassium titanium niobate	KTi_3NbO_9	Orthorhombic (Pnmm)
Potassium titanoarsenate (KTA)	$KTiOAsO_4$	Orthorhombic ($P2_1nb$)
Potassium titanophosphate (KTP)	$KTiOPO_4$	Orthorhombic ($P2_1nb$)
Potassium titanum silicate	$K_2TiSi_3O_9$	Hexagonal ($P6_3/m$)
Potassium vanadate	KVO_3	Orthorhombic (Pmab)
Potassium yttrium fluoride	KY_3F_{10}	Cubic (Fm3m)
Potassium yttrium molybdate	$KY(MoO_4)_2$	Orthorhombic (Pbna)
Potassium yttrium niobate	$K_2YNb_5O_{15}$	Tetragonal
Potassium yttrium tetrafluoride (KYF)	KYF_4	Trigonal ($P3_1$)
Potassium yttrium tungstate	$KY(WO_4)_2$	Monoclinic (C2/c)
Potassium yttrium vanadate	$K_3Y(VO_4)_2$	Monoclinic
Potassium zinc fluoride	K_2ZnF_4	Tetragonal (I4/mmm)
Potassium zinc fluoride	$KZnF_3$	Tetragonal
Rubidium aluminum selenate	$RbAl(SeO_4)_2$	Trigonal (P321)
Rubidium aluminum silicate	$RbAlSiO_4$	Orthorhombic (Pcmn)
Rubidium aluminum silicate	$RbAlSi_2O_6$	Tetragonal ($I4_1/a$)
Rubidium aluminum sulfate	$RbAl(SO_4)_2$	Trigonal (P321)
Rubidium aluminum tetrafluoride	$RbAlF_4$	Tetragonal (P4/mmm)
Rubidium beryllium fluoride	Rb_2BeF_4	Orthorhombic ($Pna2_1$)
Rubidium bismuth molybdate	$RbBi(MoO_4)_2$	Monoclinic ($P2_1/c$)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Rubidium bromide	RbBr	Cubic (Fm3m)
Rubidium cadmium fluoride	$RbCdF_3$	Cubic (Pm3m)
Rubidium calcium fluoride	$RbCaF_3$	Cubic (Pm3m)
Rubidium chloride	RbCl	Cubic (Fm3m)
Rubidium dihydrogen arsenate (RDA)	RbH_2AsO_4	Tetragonal ($I4_1/a$)
Rubidium dihydrogen phosphate (RDP)	RbH_2PO_4	Tetragonal ((I–42m)
Rubidium fluoride	RbF	Cubic (Fm3m)
Rubidium gadolinium bromide	$RbGd_2Br_7$	Orthorhombic (Pnma)
Rubidium gadolinium vanadate	$Rb_3Gd(VO_4)_2$	Trigonal
Rubidium gadolinium vanadate	$RbGd(VO_4)_2$	Tetragonal (P4/mmm)
Rubidium gallium selenate	$RbGa(SeO_4)_2$	Trigonal (P321)
Rubidium gallium sulfate	$RbGa(SO_4)_2$	Trigonal (P321)
Rubidium indium molybdate	$RbIn(MoO_4)_2$	Trigonal (P321)
Rubidium indium tungstate	$RbIn(WO_4)_2$	Trigonal (P321)
Rubidium iodide	RbI	Cubic (Fm3m)
Rubidium lanthanum niobate	$Rb_2LaNb_5O_{15}$	Tetragonal
Rubidium lanthanum tungstate	$RbLa(WO_4)_2$	Monoclinic (C2/c)
Rubidium lithium aluminum fluoride	Rb_2LiAlF_6	Rhombohedral (R–3m)
Rubidium lithium gallium fluoride	Rb_2LiGaF_6	Rhombohedral (R–3m)
Rubidium lutetium vanadate	$Rb_3Lu(VO_4)_2$	Trigonal
Rubidium lutetium vanadate	$RbLu(VO_4)_2$	Trigonal
Rubidium magnesium chloride	Rb_2MgCl_4	Tetragonal (I4/mmm)
Rubidium magnesium fluoride	Rb_2MgF_4	Tetragonal (I4/mmm)
Rubidium niobium borate	$RbNbB_2O_6$	Orthorhombic ($Pn2_1m$)
Rubidium pentaborate	$RbB_5O_8{\cdot}4H_2O$	Orthorhombic (Aba2)
Rubidium potassium gallium fluoride	Rb_2KGaF_6	Cubic (Fm3m)
Rubidium scandium molybdate	$RbSc(MoO_4)_2$	Trigonal (P–3m1)
Rubidium scandium tungstate	$RbSc(WO_4)_2$	Trigonal (P–3m1)
Rubidium scandium vanadate	$Rb_3Sc(VO_4)_2$	Trigonal
Rubidium scandium vanadate	$RbSc(VO_4)_2$	Trigonal
Rubidium sodium beryllium fluoride	Rb_3NaBeF_8	Hexagonal ($P6_3$)
Rubidium sodium indium fluoride	Rb_2NaInF_6	Cubic (Fm3m)
Rubidium tantalum borate	$RbTaB_2O_6$	Orthorhombic ($Pn2_1m$)
Rubidium tin germanate	$Rb_2SnGe_3O_9$	Trigonal (P–3c1)
Rubidium tin silicate	$Rb_2SnSi_3O_9$	Hexagonal ($P6_3/m$)
Rubidium titanium germanate	$Rb_2TiGe_3O_9$	Trigonal (P–3c1)
Rubidium titanium silicate	$Rb_2TiSi_3O_9$	Hexagonal ($P6_3/m$)
Rubidium titano arsenate (RTA)	$RbTiOAsO_4$	Orthorhombic ($P2_1nb$)
Rubidium titano phosphate (RTP)	$RbTiOPO_4$	Orthorhombic ($P2_1nb$)
Rubidium yttrium vanadate	$Rb_3Y(VO_4)_2$	Trigonal
Rubidium yttrium vanadate	$RbY(VO_4)_2$	Trigonal
Rubidium zinc bromide	Rb_2ZnBr_4	Orthorhombic (Pnma)
Rubidium zinc chloride	Rb_2ZnCl_4	Orthorhombic (Pnma)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Rubidium zinc fluoride	Rb_2ZnF_4	Tetragonal (I4/mmm)
Rubidium zinc fluoride	$RbZnF_3$	Cubic (Pm3m)
Scandium aluminum beryllate (SCAB)	$ScAlBeO_4$	Orthorhombic (Pmcn)
Scandium borate	$ScBO_3$	Rhombohedral (R–31)
Scandium calcium borate	$ScCaBO_4$	Orthorhombic (Pnam)
Scandium gallate	$ScGaO_3$	Monoclinic (A2/m)
Scandium germanate	Sc_2GeO_5	Monoclinic (B2/b)
Scandium magnesium borate	$ScMgBO_4$	Orthorhombic (Pnam)
Scandium metaphosphate	$Sc(PO_3)_3$	Monoclinic (Cc)
Scandium molybdate	$Sc_2(MoO_4)_3$	Orthorhombic (Pbcn)
Scandium niobate	$ScNbO_4$	Monoclinic (P2/c)
Scandium orthosilicate	Sc_2SiO_5	Monoclinic (I2/a)
Scandium oxide	Sc_2O_3	Cubic (I213)
Scandium phosphate	$ScPO_4$	Tetragonal ($I4_1$/amd)
Scandium silicate	$Sc_2Si_2O_7$	Monoclinic (C2/m)
Scandium tantalate	$ScTaO_4$	Monoclinic (P2/c)
Scandium titanate	Sc_2TiO_5	Orthorhombic (Bbmm)
Scandium tungstate	$Sc_2(WO_4)_3$	Orthorhombic (Pcna)
Scandium vanadate	$ScVO_4$	Tetragonal ($I4_1$/amd)
Scandium yttrium silicate (thortveitite)	$(Sc,Y)_2Si_2O_7$	Monoclinic (C2/m)
Selenium	Se	Trigonal (32)
Selenium dioxide (downeyite)	SeO_2	Tetragonal ($P4_2$/nbc)
Silicon	Si	Cubic (F–43m)
Silicon carbide (carborundum, moissanite)	α-SiC (2H)	Hexagonal ($P6_3$/m)
Silicon carbide	β-SiC (3C)	Cubic (Fd3m)
Silicon dioxide (α-quartz)	SiO_2	Trigonal ($P3_12$)
Silicon nitride	Si_3N_4	Hexagonal ($P6_3$/m)
Silver antimony sulfide (pyrargyrite)	Ag_3SbS_3	Trigonal (R3c)
Silver arsenic selenide	Ag_3AsSe_3	Trigonal (R3c)
Silver arsenic sulfide (proustite)	Ag_3AsS_3	Trigonal (R3c)
Silver arsenic sulfide (trechmannite)	$AgAsS_2$	Tetragonal (I–42d)
Silver bromide (bromyrite)	AgBr	Cubic (Fm3m)
Silver chloride (cerargyrite)	AgCl	Cubic (Fm3m)
Silver gallium selenide	$AgGaSe_2$	Tetragonal (I–42d)
Silver gallium sulfide	$AgGaS_2$	Tetragonal (I–42d)
Silver iodide (iodargyrite)	AgI	Hexagonal ($P6_3$mc)
Silver mercury iodide	Ag_2HgI_4	Tetragonal (I–4)
Sodium aluminum borate	$Na_2Al_2B_2O_7$	Tetragonal (I–42d)
Sodium aluminum chlorosilicate (sodalite)	$Na_8Al_6Si_6O_{24}Cl_2$	Cubic
Sodium aluminum fluoride (chiolite)	$Na_5Al_3F_{14}$	Tetragonal (P4/mnc)
Sodium aluminum fluoride (cryolite)	Na_3AlF_6	Monoclinic ($P2_1$/n)
Sodium aluminum fluoroarsenate (durangite)	$NaAl(AsO_4)F$	Monoclinic (C2/c)
Sodium aluminum fluorophosphate (lacroixite)	$NaAl(PO_4)F$	Monoclinic

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Sodium aluminum germanate	$NaAlGeO_4$	Monoclinic ($P2_1/n$)
Sodium aluminum silicate (albite)	$NaAlSi_3O_8$	Triclinic (P–1)
Sodium aluminum silicate (nepheline)	$NaAlSiO_4$	Hexagonal ($P6_3$)
Sodium antimony beryllate (swedenburgite)	$NaSbBe_4O_7$	Hexagonal ($P6_3mc$)
Sodium barium phosphate	$NaBaPO_4$	Hexagonal ($P\bar{3}m1$)
Sodium barium titanium silicate (batisite)	$Na_2BaTi_2Si_4O_{14}$	Orthorhombic
Sodium beryllium fluoride	Na_2BeF_4	Monoclinic ($P2_1/n$)
Sodium beryllium fluoroborate	$NaBe_2BO_3F_2$	Trigonal (R32)
Sodium beryllium phosphate (beryllonite)	$NaBePO_4$	Monoclinic ($P2_1/n$)
Sodium beryllium silicate (chkalovite)	$Na_2BeSi_2O_6$	Orthorhombic (Fddd)
Sodium beryllium silicate	Na_2BeSiO_4	Orthorhombic ($Pca2_1$)
Sodium bismuth magnesium vanadate	$Na_2BiMg_2V_3O_{12}$	Cubic (Ia3d)
Sodium bismuth zinc vanadate	$Na_2BiZn_2V_3O_{12}$	Cubic (Ia3d)
Sodium boron fluoride (ferruccite)	$NaBF_4$	Orthorhombic (Cmcm)
Sodium bromide	NaBr	Cubic (Fm3m)
Sodium cadmium magnesium fluoride	$NaCdMg_2F_7$	Cubic (Fd3m)
Sodium cadmium phosphate	$NaCdPO_4$	Orthorhombic (Pnma)
Sodium cadmium zinc fluoride	$NaCdZn_2F_7$	Cubic (Fd3m)
Sodium calcium fluorophosphate (arctite)	$Na_2Ca_4(PO_4)_3F$	Trigonal
Sodium calcium fluorophosphate (nacaphite)	Na_2CaPO_4F	Orthorhombic
Sodium calcium magnesium phosphate (brianite)	$Na_2CaMg(PO_4)_2$	Orthorhombic
Sodium calcium phosphate (bushwaldite)	$NaCaPO_4$	Orthorhombic (Pnam)
Sodium calcium silicate	Na_2CaSiO_4	Cubic (Fm3m)
Sodium calcium silicate (combeite)	$Na_2Ca_2Si_3O_9$	Trigonal ($P3_122_1$)
Sodium calcium yttrium fluoride (α-gagarinite)	α-$NaCaYF_6$	Hexagonal
Sodium carbonate (natrite	Na_2CO_3	Hexagonal ($P6_3mc$)
Sodium chloride (halite)	NaCl	Cubic (Fm3m)
Sodium fluoride (villiaumite)	NaF	Cubic (Fm3m)
Sodium gadolinium arsenate	$Na_3Gd(AsO_4)_2$	Monoclinic (Cc)
Sodium gadolinium germanate	$NaGdGeO_4$	Orthorhombic ($Pbn2_1$)
Sodium gadolinium germanate	$Na_5GdGe_4O_{12}$	Trigonal (R32)
Sodium gadolinium magnesium vanadate	$Na_2GdMg_2V_3O_{12}$	Cubic (Ia3d)
Sodium gadolinium molybdate	$NaGd(MoO_4)_2$	Tetragonal ($I4_1/a$)
Sodium gadolinium oxide	$NaGdO_2$	Tetragonal ($I4_1/amd$)
Sodium gadolinium phosphate	$Na_3Gd(PO_4)_2$	Monoclinic
Sodium gadolinium pyrophosphate	$NaGdP_2O_7$	Monoclinic
Sodium gadolinium silicate	$NaGdSiO_4$	Orthorhombic ($Pbn2_1$)
Sodium gadolinium silicate	$Na_3GdSi_3O_9$	Orthorhombic ($P2_12_12_1$)
Sodium gadolinium silicate	$Na_5GdSi_4O_{12}$	Trigonal (R32)
Sodium gadolinium tetraphosphate	$NaGdP_4O_{12}$	Monoclinic ($P2_1/n$)
Sodium gadolinium tungstate	$NaGd(WO_4)_2$	Tetragonal ($I4_1/a$)
Sodium gadolinium vanadate	$Na_3Gd(VO_4)_2$	Monoclinic (Cc)
Sodium gallium borate	$Na_2Ga_2B_2O_7$	Tetragonal

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Sodium gallium germanate	$NaGaGeO_4$	Monoclinic ($P2_1/n$)
Sodium gallium germanate	$NaGaGe_2O_6$	Monoclinic (C2/c)
Sodium gallium silicate	$NaGaSiO_4$	Monoclinic ($P2_1/n$)
Sodium germanate	Na_2GeO_3	Orthorhombic ($Cmc2_1$)
Sodium indate	$NaInO_2$	Rhombohedral (R3/m)
Sodium indium germanate	$Na_5InGe_4O_{12}$	Trigonal (R32)
Sodium indium molybdate	$NaIn(MoO_4)_2$	Triclinic (P–1)
Sodium indium silicate	$Na_5InSi_4O_{12}$	Trigonal (R32)
Sodium iodide	NaI	Cubic (Fm3m)
Sodium lanthanum arsenate	$Na_3La(AsO_4)_2$	Orthorhombic ($Pbc2_1$)
Sodium lanthanum borate	$Na_3La(BO_3)_2$	Monoclinic ($P2_1/c$)
Sodium lanthanum borate	$Na_3La_2(BO_3)_3$	Orthorhombic (Amm2)
Sodium lanthanum borate	$Na_{18}La(BO_3)_7$	Monoclinic
Sodium lanthanum molybdate	$NaLa(MoO_4)_2$	Tetragonal ($I4_1/a$)
Sodium lanthanum oxide	$NaLaO_2$	Tetragonal ($I4_1/amd$)
Sodium lanthanum phosphate	$Na_3La(PO_4)_2$	Orthorhombic ($Pbc2_1$)
Sodium lanthanum pyrophosphate	$NaLaP_2O_7$	Orthorhombic
Sodium lanthanum tetraphosphate	$NaLaP_4O_{12}$	Monoclinic ($P2_1/n$)
Sodium lanthanum tungstate	$NaLa(WO_4)_2$	Tetragonal ($I4_1/a$)
Sodium lanthanum vanadate	$Na_3La(VO_4)_2$	Orthorhombic ($Pbc2_1$)
Sodium lithium aluminum borosilicate (elbaite)	$Na(Li,Al)_3Al_6(BO_3)_3$-$Si_6O_{18}(OH)$	Trigonal (R3m)
Sodium lithium aluminum fluoride	Na_2LiAlF_6	Monoclinic ($P2_1/n$)
Sodium lithium aluminum fluorogarnet	$Na_3Li_3Al_2F_{12}$	Cubic (Ia3d)
Sodium lithium gallium fluorogarnet (GFG)	$Na_3Li_3Ga_2F_{12}$	Cubic (Ia3d)
Sodium lithium indium fluorogarnet	$Na_3Li_3In_2F_{12}$	Cubic (Ia3d)
Sodium lithium niobate	$Na_3Li_2Nb_5O_{15}$	Tetragonal (P4bm)
Sodium lithium scandium fluorogarnet	$Na_3Li_3Sc_2F_{12}$	Cubic (Ia3d)
Sodium lithium vanadate	$NaLiV_2O_6$	Monoclinic (C2/c)
Sodium lithium yttrium silicate	$Na_2LiYSi_6O_{15}$	Orthorhombic (Cmca)
Sodium lithium zirconium silicate (Zektzerite)	$Na_2LiZrSi_6O_{15}$	Orthorhombic (Cmca)
Sodium lutetium arsenate	$Na_3Lu(AsO_4)_2$	Monoclinic (Cc)
Sodium lutetium germanate	$NaLuGeO_4$	Orthorhombic ($Pbn2_1$)
Sodium lutetium germanate	$Na_5LuGe_4O_{12}$	Trigonal (R32)
Sodium lutetium magnesium vanadate	$Na_2LuMg_2V_3O_{12}$	Cubic (Ia3d)
Sodium lutetium oxide	$NaLuO_2$	Tetragonal($I4_1/amd$)
Sodium lutetium phosphate	$Na_3Lu(PO_4)_2$	Monoclinic
Sodium lutetium pyrophosphate	$NaLuP_2O_7$	Monoclinic
Sodium lutetium silicate	$NaLuSiO_4$	Orthorhombic (Pbcn)
Sodium lutetium silicate	$Na_5LuSi_4O_{12}$	Trigonal (R32)
Sodium lutetium vanadate	$Na_3Lu(VO_4)_2$	Monoclinic ($P2_1/n$)
Sodium magnesium aluminum fluoride (weberite)	$NaMgAlF_7$	Orthorhombic (Imm2)
Sodium magnesium carbonate (eitelite)	$Na_2Mg(CO_3)_2$	Trigonal (R–3)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Sodium magnesium fluoride (neighborite)	$NaMgF_3$	Orthorhombic (Pcmm)
Sodium magnesium gallium fluoride	$NaMgGaF_7$	Orthorhombic (Imm2)
Sodium magnesium indium fluoride	$NaMgInF_7$	Orthorhombic (Imm2)
Sodium magnesium scandium fluoride	$NaMgScF_7$	Orthorhombic (Imm2)
Sodium magnesium silicate	Na_2MgSiO_4	Monoclinic
Sodium niobate (natroniobite)	$NaNbO_3$	Orthorhombic (Pbma)
Sodium nitrate (soda-nitre)	$NaNO_3$	Trigonal (R–3c)
Sodium potassium titanoniobosilicate	$Na_2KTiNbSi_4O_{14}$	Orthorhombic
Sodium scandium germanate	$NaScGeO_4$	Orthorhombic (Pbnm)
Sodium scandium germanate	$NaScGe_2O_6$	Monoclinic (C2/m)
Sodium scandium germanate	$Na_5ScGe_4O_{12}$	Trigonal (R32)
Sodium scandium indium vanadate	$Na_3Sc_{1.5}In_{0.5}V_3O_{12}$	Cubic (Ia3d)
Sodium scandium oxide	$NaScO_2$	Rhombohedral (R3/m)
Sodium scandium silicate	$Na_3ScSi_2O_7$	Orthorhombic (Pbcn)
Sodium scandium silicate	$Na_5ScSi_4O_{12}$	Trigonal (R32)
Sodium scandium silicate (jervisite)	$NaScSi_2O_6$	Monoclinic (C2/c)
Sodium scandium vanadate	$Na_3Sc_2V_3O_{12}$	Cubic (Ia3d)
Sodium silicate	Na_2SiO_3	Orthorhombic ($Cmc2_1$)
Sodium silicate (natrosilite)	$Na_2Si_2O_5$	Monoclinic(P21/a)
Sodium strontium aluminum fluoride	$NaSrAlF_6$	Orthorhombic ($Pna2_1$)
Sodium strontium aluminum fluoride (jarlite)	$NaSr_3Al_3F_{16}$	Monoclinic
Sodium strontium phosphate	$Na_2Sr(PO_2)_4$	Tetragonal (P4/nbm)
Sodium tantalate	$NaTaO_3$	Orthorhombic (Pbma)
Sodium titanium silicate (lorenzenite)	$Na_2Ti_2Si_2O_9$	Orthorhombic (Pnca)
Sodium titanium silicate (natisite)	$Na_2TiOSiO_4$	Tetragonal (P4/nmm)
Sodium vanadate	$NaVO_3$	Monoclinic (C2/c)
Sodium yttrium fluoride	$5NaF–9YF_3$	Cubic (Ia3d)
Sodium yttrium fluorosilicate	$Na_5Y_4(SiO_4)_4F$	Rhombohedral (R–3)
Sodium yttrium germanate	$NaYGeO_4$	Orthorhombic ($Pbn2_1$)
Sodium yttrium germanate	$Na_5YGe_4O_{12}$	Trigonal (R32)
Sodium yttrium magnesium vanadate	$Na_2YMg_2V_3O_{12}$	Cubic (Ia3d)
Sodium yttrium molybdate	$NaY(MoO_4)_2$	Tetragonal ($I4_1/a$)
Sodium yttrium oxide	$NaYO_2$	Monoclinic ($P2_1/c$)
Sodium yttrium silicate	$NaYSiO_4$	Orthorhombic (Pbcn)
Sodium yttrium silicate	$Na_3YSi_3O_9$	Orthorhombic ($P2_12_12_1$)
Sodium yttrium silicate	$Na_3YSi_2O_7$	Hexagonal ($P6_3/m$)
Sodium yttrium silicate	$Na_5YSi_4O_{12}$	Trigonal (R32)
Sodium yttrium tetrafluoride	$NaYF_4$	Trigonal ($P3_1$)
Sodium zinc chloride	$NaZnF_3$	Orthorhombic (Pnmc)
Sodium zinc fluoride	Na_2ZnCl_4	Orthorhombic (Pnma)
Strontium aluminate	$SrAl_2O_4$	Monoclinic ($P2_1/n$)
Strontium aluminate	$SrAl_4O_7$	Monoclinic (C2/c)
Strontium aluminate	$Sr_3Al_2O_6$	Cubic (Pa3)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Strontium aluminum fluoride	$SrAlF_5$	Tetragonal (P4)
Strontium aluminum germanate	$SrAl_2Ge_2O_8$	Monoclinic ($P2_1/a$)
Strontium aluminum silicate	$SrAl_2Si_2O_8$	Monoclinic ($P2_1/a$)
Strontium aluminum silicate	$Sr_2Al_2SiO_7$	Tetragonal ($P42_1m$)
Strontium barium niobate (SBN)	$Sr_{0.6}Ba_{0.4}Nb_2O_6$	Tetragonal
Strontium borate	SrB_2O_4	Orthorhombic (Pnca)
Strontium borate	SrB_4O_7	Orthorhombic (Pbca)
Strontium borate	$Sr_3B_2O_6$	Rhombohedral (R–3c)
Strontium bromovanadate	Sr_2VO_4Br	Orthorhombic (Pbcm)
Strontium carbonate (strontianite)	$SrCO_3$	Orthorhombic (Pnam)
Strontium chloroarsenate	Sr_2AsO_4Cl	Orthorhombic (Pbcm)
Strontium chloroarsenate	$Sr_5(AsO_4)_3Cl$	Hexagonal($P6_3/m$)
Strontium chloroborate	$Sr_2B_5O_9Cl$	Tetragonal ($P4_22_12$)
Strontium chlorophosphate	$Sr_5(PO_4)_3Cl$	Hexagonal($P6_3/m$)
Strontium chlorovanadate	Sr_2VO_4Cl	Orthorhombic (Pbcm)
Strontium chlorovanadate	$Sr_5(VO_4)_3Cl$	Hexagonal($P6_3/m$)
Strontium fluoride	SrF_2	Cubic (Fm3m)
Strontium fluoroarsenate	$Sr_5(AsO_4)_3F$	Hexagonal($P6_3/m$)
Strontium fluorophosphate (SFAP)	$Sr_5(PO_4)_3F$	Hexagonal($P6_3/m$)
Strontium fluorovanadate (SVAP)	$Sr_5(VO_4)_3F$	Hexagonal($P6_3/m$)
Strontium gadolinium aluminate	$SrGdAlO_4$	Tetragonal (I4/mmm)
Strontium gadolinium gallate (SGGM)	$SrGdGa_3O_7$	Tetragonal ($P42_1m$)
Strontium gadolinium phosphate	$Sr_3Gd(PO_4)_3$	Cubic (I–43d)
Strontium gadolinum oxide	$SrGd_2O_4$	Orthorhombic (Pnma)
Strontium gallate	$SrGa_2O_4$	Monoclinic ($P2_1/n$)
Strontium gallium fluoride	$SrGaF_5$	Tetragonal (P4)
Strontium gallium germanate	$Sr_3Ga_2Ge_4O_{14}$	Trigonal ($P32_1$)
Strontium gallium silicate	$SrGa_2Si_2O_8$	Monoclinic ($P2_1/a$)
Strontium gallium silicate	$Sr_2Ga_2SiO_7$	Tetragonal ($P42_1m$)
Strontium hexa-aluminate	$SrAl_{12}O_{19}$	Hexagonal ($P6_3/mmc$)
Strontium indium germanium garnet	$Sr_3In_2Ge_3O_{12}$	Cubic (Ia3d)
Strontium indium oxide	$SrIn_2O_4$	Orthorhombic (Pnma)
Strontium lanthanum aluminate	$SrLaAlO_4$	Tetragonal (I4/mmm)
Strontium lanthanum borate	$SrLaBO_4$	Hexagonal ($P6_322$)
Strontium lanthanum gallate	$SrLaGaO_4$	Tetragonal (I4/mmm)
Strontium lanthanum oxysilicate	$SrLa_4(SiO_4)_3O$	Hexagonal ($P6_3/m$)
Strontium lanthanum phosphate	$Sr_3La(PO_4)_3$	Cubic (I–43d)
Strontium lutetium oxide	$SrLu_2O_4$	Orthorhombic (Pnma)
Strontium magnesium germanate	$Sr_2MgGe_2O_7$	Tetragonal ($P42_1m$)
Strontium magnesium silicate	$Sr_2MgSi_2O_7$	Tetragonal ($P42_1m$)
Strontium magnesium vanadate	$SrMg_2(VO_4)_2$	Tetragonal ($I4_1/acd$)
Strontium molybdate	$SrMoO_4$	Tetragonal ($I4_1/a$)
Strontium niobate	$SrNb_2O_6$	Orthorhombic (Pcan)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Strontium niobate	$Sr_2Nb_2O_7$	Orthorhombic ($Cmc2_1$)
Strontium niobate	$Sr_5Nb_4O_{15}$	Monoclinic ($P2_1/m$)
Strontium niobate	$SrNb_2O_6$	Monoclinic ($P2_1/c$)
Strontium potassium niobate	$Sr_2KNb_5O_{15}$	Orthorhombic (Im2a)
Strontium potassium tantalate	$Sr_2KTa_5O_{15}$	Orthorhombic (Im2a)
Strontium scandate	$SrSc_2O_4$	Orthorhombic (Pnam)
Strontium scandium germanium garnet	$Sr_3Sc_2Ge_3O_{12}$	Cubic (Ia3d)
Strontium silicate	$SrSiO_3$	Monoclinic (C2)
Strontium sodium niobate	$Sr_2NaNb_5O_{15}$	Orthorhombic (Im2a)
Strontium sulfate (celestite)	$SrSO_4$	Orthorhombic (Pmma)
Strontium tantalate	$Sr_2Ta_2O_7$	Orthorhombic (Pnma)
Strontium tin borate	$SrSnB_2O_6$	Trigonal (R–3)
Strontium tin oxide	$SrSnO_3$	Cubic ($P2_13$)
Strontium titanate	$Sr_3Ti_2O_7$	Tetragonal (I4/mmm)
Strontium titanate (tausonite)	$SrTiO_3$	Cubic (Pm3m)
Strontium titanium borate	$SrTiB_2O_6$	Trigonal (R–3)
Strontium tungstate	$SrWO_4$	Tetragonal ($I4_1/a$)
Strontium vanadate	SrV_2O_6	Monoclinic (C2/m)
Strontium vanadate	β-$Sr_2V_2O_7$	Tetragonal ($I4_1/amd$)
Strontium vanadate	$Sr_3(VO_4)_2$	Rhombohedral ($R\bar{3}m$)
Strontium vanadate	β-$Sr_2V_2O_7$	Tetragonal ($P4_1$)
Strontium vanadate	$SrVO_3$	Cubic (Pm3m)
Strontium yttrium borate	$Sr_3Y(BO_3)_3$	Trigonal (R–3)
Strontium yttrium oxide	SrY_2O_4	Orthorhombic (Pnma)
Strontium yttrium oxysilicate	$SrY_4(SiO_4)_3O$	Hexagonal ($P6_3/m$)
Strontium zinc fluoride	$SrZnF_4$	Tetragonal ($I4_1/a$)
Strontium zinc germanate	$SrZnGe_2O_6$	Monoclinic (C2/c)
Strontium zinc germanate	$Sr_2ZnGe_2O_7$	Tetragonal ($P42_1m$)
Strontium zinc silicate	$Sr_2ZnSi_2O_7$	Tetragonal ($P42_1m$)
Strontium zirconate	$SrZrO_3$	Orthorhombic (Pnma)
Strontium zirconium borate	$SrZrB_2O_6$	Trigonal (R–3)
Strontiun tantalate	$SrTa_2O_6$	Orthorhombic (Pcan)
Strontiun tantalate	$Sr_2Ta_2O_7$	Orthorhombic (Cmcm)
Strontiun tantalate	$Sr_5Ta_4O_{15}$	Hexagonal
Strontiun tantalate	$Sr_6Ta_2O_{11}$	Cubic
Tantalum borate (behierite)	$TaBO_4$	Tetragonal ($I4_1/amd$)
Tantalum oxide (tantite)	Ta_2O_5	Orthorhombic (P2mm)
Tantalum oxyphosphate	$TaOPO_4$	Tetragonal (P4/n)
Tellurium	Te	Trigonal (32)
Tellurium oxide (tellurite)	TeO_2	Orthorhombic (Pbca)
Thallium aluminum selenate	$TlAl(SeO_4)_2$	Trigonal (P321)
Thallium aluminum sulfate	$TlAl(SO_4)_2$	Trigonal (P321)
Thallium aluminum tetrafluoride	$TlAlF_4$	Tetragonal (P4/mmm)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Thallium arsenic selenide	Tl_3AsSe_3	Trigonal (R3c)
Thallium arsenic sulfide (ellisite)	Tl_3AsS_3	Trigonal (R3c)
Thallium bromide	TlBr	Cubic (Fm3m)
Thallium bromoiodide (KRS-5)	Tl(Br,I)	Cubic (Fm3m)
Thallium chloride	TlCl	Cubic (Fm3m)
Thallium chlorobromide (KRS-6)	Tl(Cl,Br)	Cubic (Fm3m)
Thallium gallium selenate	$TlGa(SeO_4)_2$	Trigonal (P321)
Thallium gallium sulfate	$TlGa(SO_4)_2$	Trigonal (P321)
Thallium niobium borate	$TlNbB_2O_6$	Orthorhombic ($Pn2_1m$)
Thallium oxide (avicennite)	Tl_2O_3	Cubic (Ia3d)
Thallium tantalium borate	$TlTaB_2O_6$	Orthorhombic ($Pn2_1m$)
Thallium tin germanate	$Tl_2SnGe_3O_9$	Trigonal (P–3c1)
Thallium titanium germanate	$Tl_2TiGe_3O_9$	Hexagonal ($P6_3/m$)
Thorium oxide (thorianite)	ThO_2	Cubic (Fm3m)
Thorium silicate (thorite)	$ThSiO_4$	Tetragonal ($I4_1/amd$)
Tin dioxide (cassiterite)	SnO_2	Tetragonal ($P4_2/mnm$)
Titanium dioxide (rutile)	TiO_2	Tetragonal ($P4_2/mnm$)
Tourmaline (elbaite)	$Na(Li,Al)_3Al_6(BO_3)_3$-$Si_6O_{18}(OH)$	Trigonal (R3m)
Urea	$(NH_2)_2CO$	Tetragonal (I–42m)
Vanadium oxide (shcherbinaite)	V_2O_5	Orthorhombic (Pmmm)
Yttrium aluminate	$Y_4Al_2O_9$	Monoclinic ($P2_1/a$)
Yttrium aluminate (YAP, YALO)	$YAlO_3$	Orthorhombic (Pnma)
Yttrium aluminum borate (YAB)	$YAl_3(BO_3)_4$	Trigonal (R32)
Yttrium aluminum garnet (YAG)	$Y_3Al_5O_{12}$	Cubic (Ia3d)
Yttrium antimonade	Y_3SbO_7	Orthorhombic ($C222_1$)
Yttrium arsenate (chernovite)	$YAsO_4$	Tetragonal ($I4_1/amd$)
Yttrium beryllate	$YBeBO_4$	Monoclinic (C2/c)
Yttrium beryllium aluminate	$Y_2BeAl_2O_7$	Tetragonal ($P42_1m$)
Yttrium borate	YBO_3	Hexagonal ($P6_3/mmc$)
Yttrium calcium aluminate	$YCaAl_3O_7$	Tetragonal ($P42_1m$)
Yttrium calcium gallium beryllium silicate	$YCaGaBe_2Si_2O_{10}$	Monoclinic ($P2_1/c$)
Yttrium calcium oxyborate	$YCa_4O(BO_3)_3$	Monoclinic (Cm)
Yttrium chlorosilicate	$Y_3(SiO_4)_2Cl$	Orthorhombic (Pnma)
Yttrium fluoride	YF_3	Orthorhombic (Pnma)
Yttrium gadolinium antimonade	Y_2GdSbO_7	Orthorhombic ($C222_1$)
Yttrium gadolinium niobate	YGd_2NbO_7	Orthorhombic ($C222_1$)
Yttrium gadolinium tantalate	Y_2GdTaO_7	Orthorhombic ($C222_1$)
Yttrium gallium borate	$YGa_3(BO_3)_4$	Trigonal (R32)
Yttrium gallium garnet (YGG)	$Y_3Ga_5O_{12}$	Cubic (Ia3d)
Yttrium germanate	Y_2GeO_5	Monoclinic ($P2_1/c$)
Yttrium germanium beryllate	$Y_2GeBe_2O_7$	Tetragonal ($P42_1m$)
Yttrium hafnium tantalate	$YHfTaO_6$	Orthorhombic

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Yttrium indate	$YInO_3$	Hexagonal ($P6_3cm$)
Yttrium indium gallium garnet	$Y_3In_2Ga_3O_{12}$	Cubic (Ia3d)
Yttrium iron garnet (YAG)	$Y_3Fe_5O_{12}$	Cubic (Ia3d)
yttrium lithium fluoride (YLF)	$LiYF_4$	Tetragonal ($I4_1/a$)
Yttrium magnesium beryllium silicate (gadolinite)	$Y_2MgBe_2Si_2O_{10}$	Monoclinic ($P2_1/c$)
Yttrium molybdate	$Y_2(MoO_4)_3$	Orthorhombic (Pbcn)
Yttrium niobate (fergusonite)	$YNbO_4$	Monoclinic (C2/c)
Yttrium orthosilicate (YOS, YSO)	Y_2SiO_5	Monoclinic (C2/c)
Yttrium oxide (yttria)	Y_2O_3	Cubic (Ia3)
Yttrium oxychloride	YOCl	Rhombohedral (R–3m)
Yttrium molybdate	$Y_2Mo_2O_7$	Cubic (Fd3m)
Yttrium oxymolybdate	Y_2MoO_6	Monoclinic (I2/c)
Yttrium oxysulfate	Y_2OS_2	Monoclinic ($P2_1/c$)
Yttrium oxytungstate	Y_2WO_6	Monoclinic (P2/c)
Yttrium pentaphosphate	YP_5O_{14}	Orthorhombic (Pcmn)
Yttrium phosphate (xenotime)	YPO_4	Tetragonal ($I4_1/amd$)
Yttrium scandate	$YScO_3$	Orthorhombic (Pbnm)
Yttrium scandium aluminum garnet (YSAG)	$Y_3Sc_2Al_3O_{12}$	Cubic (Ia3d)
Yttrium scandium gallium garnet (YSGG)	$Y_3Sc_2Ga_3O_{12}$	Cubic (Ia3d)
Yttrium silicate (keiviite)	$Y_2Si_2O_7$	Monoclinic (C2/m)
Yttrium silicon beryllate	$Y_2SiBe_2O_7$	Tetragonal ($P42_1m$)
Yttrium tantalate	Y_3TaO_7	Orthorhombic ($C222_1$)
Yttrium tantalate (formanite)	$YTaO_4$	Monoclinic (P2/a)
Yttrium titanate	$Y_2Ti_2O_7$	Cubic (Fd3m)
Yttrium titanium silicate (trimounsite)	$Y_2Ti_2SiO_9$	Monoclinic
Yttrium titanium tantalate	$YTiTaO_6$	Orthorhombic (Pbcn)
Yttrium tungstate	$Y_2(WO_4)_3$	Orthorhombic (Pcna)
Yttrium vanadate (wakefieldite)	YVO_4	Tetragonal ($I4_1/amd$)
Yttrium zinc beryllium silicate	$Y_2ZnBe_2Si_2O_{10}$	Monoclinic ($P2_1/c$)
Zinc aluminate (gahnite)	$ZnAl_2O_4$	Cubic (Fd3m)
Zinc antimonate (ordonezite)	$ZnSb_2O_6$	Tetragonal ($P4_2/mnm$
Zinc arsenate	$ZnAsO_4$	Monoclinic ($P2_1/c$)
Zinc arsenide (reinerite)	$Zn_3(AsO_3)_2$	Orthorhombic (Pbam)
Zinc borate	$Zn_3(BO_3)_2$	Monoclinic (P2/c)
Zinc borate	ZnB_4O_7	Othorhombic (Pbca)
Zinc borate	$Zn_4B_6O_{13}$	Cubic (I–43m)
Zinc carbonate (smithsonite)	$ZnCO_3$	Rhombohedral ($R\bar{3}c$)
Zinc chloride	$ZnCl_2$	Tetragonal ($P4_2/mnm$)
Zinc fluoride	ZnF_2	Tetragonal ($P4_2/mnm$)
Zinc gallate	$ZnGa_2O_4$	Cubic (Fd3m)
Zinc germanate	Zn_2GeO_4	Tetragonal ($I4_122$)
Zinc germanium arsenide	$ZnGeAs_2$	Tetragonal (I–42d)
Zinc germanium phosphide	$ZnGeP_2$	Tetragonal (I–42d)

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Name, Formula, Crystal System, and Space Group for Optical Crystals—*continued*

Name	Formula	Crystal system (Space group)
Zinc oxide (zincite)	ZnO	Hexagonal (6mm)
Zinc pyroarsenade	$Zn_2As_2O_7$	Monoclinic (C2/m)
Zinc selenide (stilleite, Irtran 4)	ZnSe	Cubic (Fm3m)
Zinc silicate (willemite)	Zn_2SiO_4	Trigonal (R–3)
Zinc silicon arsenide	$ZnSiAs_2$	Tetragonal (I–42d)
Zinc silicon phosphide	$ZnSiP_2$	Tetragonal (I–42d)
Zinc sulfide (sphalerite, Irtran 2, zincblende)	β-ZnS	Cubic (Fm3m)
Zinc sulfide (wurtzite)	α-ZnS	Hexagonal (P6mm)
Zinc telluride	ZnTe	Cubic (Fm3m)
Zinc tin antimonide	$ZnSnSb_2$	Tetragonal (I–42d)
Zinc tin arsenide	$ZnSnAs_2$	Tetragonal (I–42d)
Zinc tin phosphide	$ZnSnP_2$	Tetragonal (I–42d)
Zinc tungstate	$ZnWO_4$	Monoclinic (P2/c)
Zinc vanadate	ZnV_2O_6	Monoclinic (C2)
Zirc silicon arsenate	$ZnSiAs_2$	Cubic (F–43m)
Zirconium oxide	ZrO_2	Tetragonal ($P4_2$/nmc)
Zirconium oxide (cubic zirconia, CZ)	ZrO_2:0.12Y_2O_3	Cubic (Fm3m)
Zirconium silicate (zircon)	$ZrSiO_4$	Tetragonal ($I4_1$/amd)

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1.2 Physical Properties*

Physical properties of optical crystals in this section are grouped into three tables: isotropic crystals, uniaxial crystals, and biaxial crystals. Materials are listed alphabetically in order of the chemical formulas. The following properties are included:

Density: Data are for room temperature.

Hardness: This is an empirical and relative measure of a material's resistance to wear. Average Knoop (indentation test) hardness numbers or range of values at room temperature are given when available. In many cases only Vicker (V) or Mohs hardness are known. This is indicated parentheses after the value. The hardness of a crystal varies with orientation even for cubic symmetry crystals.

Cleavage: The ease of cleavage varies greatly depending on the crystal quality and the nature and direction of stress applied. In many crystals there can be more than one set of cleavage planes. Miller indices are used to denote the cleavage planes. The actual number of cleavage planes depends on the plane orientation relative to the symmetry of the crystal. Only the easiest cleavage plane for each crystal is listed. They are ranked qualitatively as perfect (p) or imperfect (i). A crystal listed with a perfect cleavage plane can crack along that direction with a smooth surface if a stress is applied. The imperfect cleavage plane means that the crack does not easily move along the plane, although a small area of oriented flat surfaces may form along the cracking surface when the crystal is fractured.

Solubility: Solubility is defined as the weight loss in grams per 100 grams of water. The dissolution temperature in °C is included in parentheses, if given. If the solubility is less than 10^{-3} g/100 g, the material is generally considered to be insoluble. If a crystal is listed as insoluble, it means that, when submerged in water with a reasonable amount of time (a day or so), no noticeable loss of weight nor visible surface erosion of the crystal is observed.

* This section was adapted from "Optical Crystals" by B. H. T. Chai, *Handbook of Laser Science and Technology, Suppl. 2, Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 30 ff (with additions).

1.2.1 Isotropic Crystals

Physical Properties of Isotropic Crystalline Materials

Cubic material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
AgBr	6.473	7	None	1.2×10^{-5} (20)
AgCl	5.56	9.5	None	1.5×10^{-4} (20)
AlAs	3.729	–	(111)-p	Insoluble
$Al_{23}O_{27}N_5$ (ALON)	3.713	1850	–	Insoluble
AlP	2.40	–	–	Slightly soluble
AlSb	4.26	–	–	
As_2O_3	3.87	1.5 (Mohs)	(111)	Soluble
$Ba(NO_3)_2$	3.24	–	None	Soluble
$Ba_2Zr_2Si_3O_{12}$	–	–	–	Insoluble
$Ba_3Al_2O_6$	5.008	–	–	–

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Physical Properties of Isotropic Crystalline Materials—*continued*

Cubic material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
$Ba_3MgTa_2O_9$	6.435	–	–	Insoluble
BaF_2	4.83	82(500)	(111)-p	0.12
BaF_2-CaF_2	4.89	–	(111)-p	0.16
$Bi_{12}GeO_{20}$	9.22	4.5(Mohs)	None	Insoluble
$Bi_{12}SiO_{20}$	9.20	–	None	Insoluble
$Bi_{12}TiO_{20}$	9.069	–	None	Insoluble
$Bi_4Ge_3O_{12}$	7.13	5.0 (Mohs)	None	Insoluble
$Bi_4Si_3O_{12}$	6.60	4.5 (Mohs)	(110)-i	Insoluble
BN	3.48	4600	(111)	Insoluble
BP	2.97	3600	–	Insoluble
C (diamond)	3.51	5700–10400	(111)	Insoluble
$Ca_{12}Al_{14}O_{33}$	2.68	–	None	Insoluble
$Ca_2LiMg_2V_3O_{12}$	3.447	–	–	–
$Ca_2LiZn_2V_3O_{12}$	3.726	–	–	–
$Ca_2NaMg_2V_3O_{12}$	3.414	–	–	–
$Ca_2NaZn_2V_3O_{12}$	3.976	–	–	–
$Ca_2Sb_2O_7$	–	–	None	Insoluble
$Ca_3Al_2Ge_3O_{12}$	4.357	–	None	Insoluble
$Ca_3Al_2Si_3O_{12}$	3.60	7 (Mohs)	None	Insoluble
$Ca_3Ga_2Ge_3O_{12}$	4.837	–	None	Insoluble
$Ca_3Gd(PO_4)_3$	3.900	–	–	Insoluble
$Ca_3In_2Ge_3O_{12}$	5.063	–	None	Insoluble
$Ca_3La(PO_4)_3$	3.678	–	–	Insoluble
$Ca_3Lu_2Ge_3O_{12}$	5.668	–	None	Insoluble
$Ca_3Sc_2Ge_3O_{12}$	4.203	–	None	Insoluble
$Ca_3Sc_2Si_3O_{12}$	3.514	–	None	Insoluble
CaF_2	3.180	158	(111)-p	1.6×10^{-3} (18)
$CaLa_2S_4$	4.524	570	–	–
CaO	3.3	3.5	(100)-p	0.13(10)
$CaTiO_3$	3.98	–	–	Insoluble
$CaY_2Mg_3Ge_3O_{12}$	–	–	None	Insoluble
$Cd_2Nb_2O_7$	6.216	–	None	Insoluble
$Cd_2Sb_2O_7$	–	–	None	Insoluble
$Cd_3Sc_2Ge_3O_{12}$	5.749	–	None	Insoluble
CdB_2O_4	4.58	–	–	–
CdF_2	6.64	–	(111)-p	4.4 (20)
$CdGa_2O_4$	–	–	None	Insoluble
$CdIn_2O_4$	7.00	–	None	–
CdO	8.24	3 (Mohs)	(111)	–
CdTe	6.20	56	(110)-p	Very slightly soluble
Cs_2KLaF_6	3.95	–	None	Slightly soluble
Cs_2NaYF_6	4.397	–	None	Slightly soluble
CsBr	4.44	19.5	None	124 (25)

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Physical Properties of Isotropic Crystalline Materials—*continued*

Cubic material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
$CsCaF_3$	4.123	–	–	Slightly soluble
$CsCdF_3$	5.62	–	–	–
CsCl	3.9	–	None	186 (20)
CsF	4.638	–	(100)-p	367 (18)
CsI	4.510	1–2 (Mohs)	None	44 (0)
$CsSrF_3$	4.299	–	–	–
Cu_2O	6.11	3.5 (Mohs)	(111)-i	Insoluble
CuBr	4.77	21	–	Very slightly soluble
CuCl	4.14	2.5 (Mohs)	(110)-p	6.1×10^{-3}
CuI	5.68	2.5 (Mohs)	(110)-p	–
GaAs	5.316	721	(111)-p	$<5 \times 10^{-3}$ (25)
GaP	4.13	–	(111)-p	Insoluble
GaSb	5.619	–	(111)-p	Insoluble
$Gd_2Ti_2O_7$	6.52	1114	None	Insoluble
$Gd_3Ga_5O_{12}$	7.02	6.5–7(Mohs)	None	Insoluble
$Gd_3Sc_2Al_3O_{12}$	5.82	7.5 (Mohs)	None	Insoluble
$Gd_3Sc_2Ga_3O_{12}$	–	7.0 (Mohs)	None	Insoluble
Ge	5.35	800	(111)	Insoluble
$Hg_2Sb_2O_7$	–	–	None	Insoluble
HgSe	8.266	–	–	Insoluble
HgTe	–	–	–	–
InAs	5.66	330	(111)-p	Insoluble
InP	4.8	430	(111)-p	Insoluble
InSb	5.78	225	(111)-p	Insoluble
$K_2Mg_2(SO_4)_3$	2.83	3.5 (Mohs)	None	Slightly soluble
K_2NaAlF_6	2.99	2.5 (Mohs)	None	Slightly soluble
K_2NaGaF_6	3.34	–	None	Slightly soluble
K_3AlF_6	–	–	None	Soluble
KBr	2.75	7.0(200)	(100)-p	65.2 (20)
$KCaF_3$	2.709	–	–	–
$KCdF_3$	4.264	–	–	–
KCl	1.984	9.3(200)	(100)-p	34.7 (20)
KF	2.48	2 (Mohs)	(100)-p	92.3 (18)
KI	3.12	5	(100)-p	144 (20)
$KMgF_3$	3.15	2.5 (Mohs)	None	Insoluble
$KTaO_3$	7.015	–	–	Insoluble
KY_3F_{10}	4.312	4.5 (Mohs)	None	Insoluble
$La_3Lu_2Ga_3O_{12}$	–	7.0 (Mohs)	None	Insoluble
Li_2BeF_4	2.289	–	–	–
Li_2CdCl_4	2.956	–	–	–
Li_2MgCl_4	2.119	–	–	–
$LiAl_5O_8$	3.625	–	None	Insoluble
$LiBaF_3$	5.242	–	–	–

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Physical Properties of Isotropic Crystalline Materials—*continued*

Cubic material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
LiBr	3.464	–	(100)-p	145 (4)
LiCl	2.068	–	(100)-p	63.7 (0)
LiF	2.635	110 (600)	(100)-p	0.27 (18)
$LiGa_5O_8$	5.819	–	None	Insoluble
LiI	4.076	–	(100)-p	168 (20)
Lu_2O_3	9.426	–	–	–
$Lu_2Ti_2O_7$	7.31	1264	None	Insoluble
$Lu_3Al_5O_{12}$	6.695	7.5 (Mohs)	None	Insoluble
$Lu_3Ga_5O_{12}$	7.828	7.0 (Mohs)	None	Insoluble
$Lu_3Sc_2Ga_3O_{12}$	–	7.0 (Mohs)	None	Insoluble
$LuScO_3$	–	–	–	Insoluble
Mg_2TiO_4	3.546	–	–	Insoluble
$Mg_3Al_2Si_3O_{12}$	3.58	7.5 (Mohs)	None	Insoluble
$MgAl_2O_4$	3.58	1140 (1000)	None	Insoluble
$MgGa_2O_4$	5.37	7.0 (Mohs)	None	Insoluble
MgO	3.58	690 (600)	(100)-p	6.2×10^{-4}
MnO	5.44	5.5 (Mohs)	(100)-p	Insoluble
$Na_2BiMg_2V_3O_{12}$	4.388	–	–	–
$Na_2BiZn_2V_3O_{12}$	4.919	–	–	–
Na_2CaSiO_4	2.821	–	–	Insoluble
$Na_2GdMg_2V_3O_{12}$	4.115	–	–	–
$Na_2LuMg_2V_3O_{12}$	4.332	–	–	–
$Na_2YMg_2V_3O_{12}$	3.668	–	–	–
$Na_3Li_3Al_2F_{12}$	2.77	2 (Mohs)	(011)-i	–
$Na_3Li_3Ga_2F_{12}$	3.20	2 (Mohs)	None	–
$Na_3Li_3In_2F_{12}$	3.54	2 (Mohs)	None	–
$Na_3Li_3Sc_2F_{12}$	2.66	2 (Mohs)	None	–
$Na_3Sc_2V_3O_{12}$	3.342	–	–	–
$Na_8Al_6Si_6O_{24}Cl_2$	2.27	5.5 (Mohs)	(110)-i	Insoluble
NaBr	3.203	–	(100)-p	91 (20)
$NaCdMg_2F_7$	3.968	–	–	–
$NaCdZn_2F_7$	4.838	–	–	–
NaCl	2.165	18 (200)	(100)-p	39.8 (0)
NaF	2.588	60	(100)-p	4.2 (18)
$5NaF\text{-}9YF_3$	4.22	2 (Mohs)	None	Insoluble
NaI	3.667	–	(100)-p	179 (20)
$Pb(NO_3)_2$	4.530	–	–	–
$Pb_2Sb_2O_7$	–	–	None	Insoluble
PbF_2	8.24	200	(111)-p	0.064 (20)
PbS	7.5	2.5–2.75 (Mohs)	(100)-p	6.6×10^{-5}
PbSe	8.10	–	(100)-p	Insoluble
PbTe	8.164	–	(100)-p	Insoluble
Rb_2KGaF_6	3.751	–	None	–

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Physical Properties of Isotropic Crystalline Materials—*continued*

Cubic material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
Rb_2NaInF_6	4.302	–	None	–
RbBr	3.35	–	(100)-p	98 (5)
$RbCaF_3$	3.632	–	–	–
RbCl	2.80	–	(100)-p	77 (0)
RbF	–	–	(100)-p	367 (18)
RbI	3.55	1.0 (Mohs)	(100)-p	152 (17)
$RbZnF_3$	5.007	–	–	–
Sb_2O_3	5.50	2–2.5 (Mohs)	(111)-i	Insoluble
Sc_2O_3	3.840	–	–	Insoluble
Si	2.33	1150	(111)	Insoluble
β-SiC	3.214	2880	–	Insoluble
β-SiC (CVD)	3.21	2540	–	Insoluble
$Sr_3Al_2O_6$	4.136	–	–	–
$Sr_3Gd(PO_4)_3$	–	–	–	Insoluble
$Sr_3In_2Ge_3O_{12}$	5.632	–	None	Insoluble
$Sr_3La(PO_4)_3$	–	–	–	Insoluble
$Sr_3Sc_2Ge_3O_{12}$	4.838	–	None	Insoluble
$Sr_6Nb_2O_{11}$	5.0	–	–	Insoluble
$Sr_6Ta_2O_{11}$	6.088	–	–	Insoluble
SrF_2	4.24	130	(111)-p	0.012 (20)
$SrSnO_3$	6.432	–	–	Insoluble
$SrTiO_3$	5.122	595	None	Insoluble
$SrVO_3$	5.46	–	–	–
ThO_2	9.86	600	None	Insoluble
Tl(Br,I)	7.371	40 (500)	None	–
Tl(Cl,Br)	7.192	39 (500)	None	<0.32 (20)
Tl_2O_3	10.35	–	–	Insoluble
TlBr	7.557	12 (500)	None	0.05 (25)
TlCl	7.604	13 (500)	None	0.32 (20)
Y_2O_3	5.01	875	–	1.8×10^{-5} (20)
$Y_2Ti_2O_7$	4.987	1099	None	Insoluble
$Y_3Al_5O_{12}$	4.56	135 (200)	None	Insoluble
$Y_3Ga_5O_{12}$	5.79	7.0 (Moh)	None	Insoluble
$Y_3In_2Ga_3O_{12}$	6.03	–	None	Insoluble
$Y_3Sc_2Al_3O_{12}$	4.55	–	None	Insoluble
$Y_3Sc_2Ga_3O_{12}$	5.184	7.0 (Moh)	None	Insoluble
$Zn_4B_6O_{13}$	4.19	–	–	–
$ZnAl_2O_4$	4.62	7.5 (Moh)	None	Insoluble
$ZnGa_2O_4$	6.089	7.0 (Moh)	None	Insoluble
β-ZnS	4.09	178	(110)-p	6.9×10^{-4} (18)
β-ZnS (CVD)	4.04	178	–	–
ZnSe	5.42	137	(110)-p	0.001(25)
$ZnSiAs_2$	4.747	–	–	Insoluble

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Physical Properties of Isotropic Crystalline Materials—*continued*

Cubic material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
ZnTe	6.34	82	(110)-p	Insoluble
ZrO_2	5.64	990	None	Insoluble

1.2.2 Uniaxial Crystals

Physical Properties of Uniaxial Crystalline Materials

Uniaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
Ag_2HgI_4	6.091	–	–	–
Ag_3AsS_3	5.49	2–2.5 (Mohs)	(10$\underline{1}$1)	Insoluble
Ag_3AsSe_3	6.521	–	–	Insoluble
Ag_3SbS_3	5.82	2.5 (Mohs)	(10$\underline{1}$1)-i	Insoluble
$AgAsS_2$	–	–	–	Insoluble
$AgGaS_2$	4.702	–	(112)-p	Insoluble
$AgGaSe_2$	5.70	–	(112)-p	Insoluble
AgI	5.7	1.5 (Mohs)	(0001)-p	Insoluble
Al_2O_3	3.98	1370 (1000)	None	9.8×10^{-5}
$AlAsO_4$	3.359	–	–	Insoluble
AlF_3	3.192	–	–	–
$AlGaO_3$	4.78	–	(0001)-p	Insoluble
AlN	3.261	–	–	Insoluble
$AlPO_4$	2.566	5 (Mohs)	None	Insoluble
$AlTiTaO_6$	6.26	–	–	Insoluble
$Ba_2B_5O_9Cl$	3.762	–	–	Insoluble
Ba_2MgAlF_9	4.157	–	–	–
Ba_2MgF_6	5.08	–	–	Insoluble
$Ba_2MgGe_2O_7$	4.79	–	(001)	Insoluble
$Ba_2MgSi_2O_7$	4.265	–	(001)	Insoluble
$Ba_2Sc_4O_9$	5.372	–	–	Insoluble
$Ba_2TiSi_2O_8$	4.43	3.80	(001)-i	Insoluble
Ba_2ZnF_6	5.514	–	–	Insoluble
$Ba_2ZnGe2O_7$	–	–	(001)	Insoluble
$Ba_2ZnSi_2O_7$	–	–	(001)	Insoluble
$Ba_2ZrSi_2O_8$	–	–	–	Insoluble
$Ba_3(VO_4)_2$	5.176	–	–	–
$Ba_3Sc_4O_9$	5.318	–	–	Insoluble
$Ba_3SrNb_2O_9$	–	–	–	Insoluble
$Ba_3SrTa_2O_9$	–	–	–	Insoluble
$Ba_5(AsO_4)_3F$	5.073	–	(10$\underline{1}$1)-i	Insoluble

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Physical Properties of Uniaxial Crystalline Materials—*continued*

Uniaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
$Ba_5(AsO_4)_3Cl$	5.086	4.5 (Mohs)	(0001)-i	Insoluble
$Ba_5(PO_4)_3Cl$	4.802	–	–	Insoluble
$Ba_5(PO_4)_3F$	4.81	–	$(10\underline{1}1)$-i	Insoluble
$Ba_5(VO_4)_3Cl$	4.728	–	$(10\underline{1}1)$-i	Insoluble
$Ba_5(VO_4)_3F$	4.766	–	$(10\underline{1}1)$-i	Insoluble
$Ba_6Sc_6O_{15}$	5.115	–	–	Insoluble
$BaAl_{12}O_{19}$	4.075	–	–	Insoluble
$BaAl_2O_4$	4.080	–	–	Insoluble
β-BaB_2O_4	3.85	4 (Mohs)	(0001)-i	Slightly soluble
$BaBe(PO_4)F$	4.31	–	None	Insoluble
$BaGe_4O_9$	–	–	None	Insoluble
$BaMg_2(VO_4)_2$	4.226	–	–	–
$BaMoO_4$	4.946	–	–	–
$BaSb_2O_6$	–	–	–	–
$BaSnB_2O_6$	4.848	–	–	Insoluble
$BaSnSi_3O_9$	4.03	6 (Mohs)	None	Insoluble
$BaTiB_2O_6$	4.211	–	–	Insoluble
$BaTiO_3$	6.02	5 (Mohs)	–	Insoluble
$BaTiSi_3O_9$	3.64	6 (Mohs)	None	Insoluble
$BaWO_4$	6.383	–	–	Insoluble
$BaZnGeO_4$	5.12	–	–	Insoluble
$BaZnSiO_4$	4.706	–	–	Insoluble
$BaZrSi_3O_9$	3.85	–	None	Insoluble
Be_2GeO_4	3.893	–	None	Insoluble
Be_2SiO_4	2.96	1100	$(10\underline{1}0)$	Insoluble
$Be_3Al_2Si_6O_{18}$	2.66	7.5–8 (Mohs)	None	Insoluble
$Be_3Sc_2Si_6O_{18}$	2.77	6.5 (Mohs)	None	Insoluble
$BeMg_3Al_8O_{16}$	3.60	8.5 (Mohs)	–	Insoluble
BeO(dreyerite)	3.01	1250	$(10\underline{1}0)$-i	2×10^{-5} (20)
$Bi_2Ge_3O_9$	6.20	5.5 GPa	(0001)-p	Insoluble
$BiVO_4$ (dreyerite)	6.25	–	(110)-p	Insoluble
$Ca_2Al_2GeO_7$	3.421	–	(001)	Insoluble
$Ca_2Al_2SiO_7$	3.04	5.5 (Mohs)	(001)	Insoluble
$Ca_2Al_3O_6F$	2.95	–	$(10\underline{1}1)$-i	Insoluble
$Ca_2B_5O_9Cl$	2.639	–	–	Insoluble
$Ca_2BeSi_2O_7$	–	–	–	Insoluble
$Ca_2Ga_2GeO_7$	4.14	–	(001)	Insoluble
$Ca_2Ga_2SiO_7$	4.07	–	(001)	Insoluble
$Ca_2MgSi_2O_7$	2.94	5.5 (Mohs)	(001)-i	Insoluble
$Ca_2Te_2O_5$	5.05	4 (Mohs)	(001)-p	Insoluble
$Ca_2ZnSi_2O_7$	3.39	3.5 (Mohs)	(001)	Insoluble
$Ca_3B_2O_6$	3.09	–	–	Insoluble

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Physical Properties of Uniaxial Crystalline Materials—*continued*

Uniaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
$Ca_3Ga_2Ge_4O_{14}$	4.590	–	None	Insoluble
$Ca_4La(PO_4)_3O$	–	–	–	Insoluble
$Ca_4Y_6(SiO_4)_6O$	–	–	None	Insoluble
$Ca_5(AsO_4)_3Cl$	3.635	–	–	Insoluble
$Ca_5(AsO_4)_3F$	3.5	4.5 (Mohs)	(10$\underline{1}$1)-i	Insoluble
$Ca_5(PO_4)_3Cl$	2.90	5 (Mohs)	(0001)-i	Insoluble
$Ca_5(PO_4)_3F$	3.20	540	(0001)-i	Insoluble
$Ca_5(VO_4)_3F$	–	–	(10$\underline{1}$1)-i	Insoluble
$Ca_5(VO_4)_3Cl$	3.174	–	(10$\underline{1}$1)-i	Insoluble
$CaAl_{12}O_{19}$	3.78	–	–	Insoluble
$CaAl_2B_2O_7$	2.44	–	–	–
$CaCO_3$–calcite	2.715	75–135	(10$\underline{1}$1)-p	1.4×10^{-3} (25)
$CaCO_3$–vaterite	2.68	3 (Mohs)	–	Insoluble
$CaGd_4(SiO_4)_3O$	6.030	–	None	Insoluble
$CaGdAlO_4$	5.97	716	(001)	Insoluble
$CaGe_4O_9$	–	–	None	Insoluble
$CaLa_4(SiO_4)_3O$	5.112	–	None	Insoluble
$CaLaAlO_4$	–	–	(001)	Insoluble
$CaLaBO_4$	4.136	–	–	Insoluble
$CaMg(CO_3)_2$	2.86	3.5 (Mohs)	(10$\underline{1}$1)-p	Insoluble
$CaMg_3(CO_3)_4$	3.71	335	(10$\underline{1}$1)-p	Insoluble
$CaMoO_4$	4.25	4.0 (Mohs)	(112)(110)	–
$CaSnB_2O_6$	4.22	5.5 (Mohs)	(0001)-p	Insoluble
$CaWO_4$	6.062	4.5–5 (Mohs)	(101)-i	6.4×10^{-4} (15)
$CaY_4(SiO_4)_3O$	4.47	702	None	Insoluble
$CaYAlO_4$	–	–	–	Insoluble
$CaZrBAl_9O_{18}$	4.01	8 (Mohs)	None	Insoluble
$Cd_5(AsO_4)_3Cl$	5.917	–	(10$\underline{1}$1)-i	Insoluble
$Cd_5(PO_4)_3Cl$	5.600	–	(10$\underline{1}$1)-i	Insoluble
$Cd_5(PO_4)_3F$	5.784	–	(10$\underline{1}$1)-i	Insoluble
$Cd_5(VO_4)_3Cl$	5.375	–	(10$\underline{1}$1)-i	Insoluble
$CdCl_2$	4.047	–	–	140 (25)
$CdCO_3$	5.02	–	(10$\underline{1}$1)-p	Insoluble
CdI_2	5.670	–	–	86 (25)
CdS	4.82	122 (25)	(11$\underline{2}$2)-i	1.3×10^{-4} (18)
CdSe	5.81	44–90	–	Insoluble
$CdSnB_2O_6$	5.479	–	–	Insoluble
$CdTiO_3$	5.881	–	–	Insoluble
Cs_2AgF_4	5.02	–	–	–
Cs_2CdCl_4	3.697	–	–	–
Cs_2CdZnF_6	5.342	–	–	–
$Cs_2KAl_3F_{12}$	3.76	–	–	–
$Cs_2LiAl_3F_{12}$	3.949	–	–	–

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Physical Properties of Uniaxial Crystalline Materials—*continued*

Uniaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
Cs_2LiAlF_6	4.38	–	–	–
$Cs_2LiGa_3F_{12}$	4.43	–	–	–
Cs_2LiGaF_6	4.406	–	–	–
$Cs_2NaAl_3F_{12}$	3.817	–	–	–
Cs_2NaAlF_6	4.346	–	–	–
Cs_2NaGaF_6	4.654	–	–	–
$Cs_2SnGe_3O_9$	5.145	–	–	Insoluble
$Cs_2TiGe_3O_9$	4.835	–	–	Insoluble
$CsAl(SO_4)_2$	3.382	–	–	–
CsH_2AsO_4	3.747	1.5 (Mohs)	(101)-p	Very soluble
CsH_2PO_4	3.253	1.5 (Mohs)	(101)-p	Very soluble
$CsSc(MoO_4)_2$	3.54	–	$(10\underline{1}1)$-p	–
$CsSc(WO_4)_2$	4.74	–	$(10\underline{1}1)$-p	–
α-GaN	6.109	750	—	Insoluble
$GaPO_4$	2.995	4 (Mohs)	None	Insoluble
GaS	3.86	–	–	–
GaSe	5.03	–	–	–
$GdAl_3(BO_3)_4$	4.335	7 (Mohs)	$(10\underline{1}1)$	Insoluble
$GdBO_3$	6.357	–	–	Insoluble
$GdGa_3(BO_3)_4$	5.257	–	$(10\underline{1}1)$	Insoluble
$GdInO_3$	7.41	–	–	–
$GdVO_4$	5.474	–	(110)-p	Insoluble
GeO_2	6.239	–	None	Insoluble
$HfSiO_4$	6.97	–	(110)-i	Insoluble
Hg_2Br_2	7.68	1.5 (Mohs)	(110)	Insoluble
Hg_2Cl_2	7.15	1.5 (Mohs)	(110)-i	3×10^{-4}
Hg_2I_2	7.68	–	–	Insoluble
HgI_2	6.28	–	–	0.0055 (35)
HgS	8.10	2–2.5 (Mohs)	(1010)-p	1×10^{-6} (18)
In_2O_3	7.31	–	–	–
$InBO_3$	5.555	–	$(10\underline{1}1)$-p	Insoluble
$K_2BiNb_5O_{15}$	5.29	–	–	–
$K_2CaZr(SiO_3)_4$	3.10	5.5 (Mohs)	None	Insoluble
$K_2GdNb_5O_{15}$	5.147	–	–	Insoluble
$K_2LaNb_5O_{15}$	4.921	–	–	Insoluble
K_2MgCl_4	2.13	–	–	–
K_2MgF_4	2.839	–	(001)-p	–
$K_2NaLi_2Nb_5O_{15}$	–	–	(001)-p	Insoluble
$K_2SnGe_3O_9$	4.324	–	–	Insoluble
$K_2SnSi_3O_9$	3.46	–	–	Insoluble
$K_2Sr(SO_4)_2$	3.20	2 (Mohs)	(0001)-p	Slightly soluble
$K_2TiGe_3O_9$	3.945	–	–	Insoluble
$K_2TiSi_3O_9$	3.239	–	–	Insoluble

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Physical Properties of Uniaxial Crystalline Materials—*continued*

Uniaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
$K_2YNb_5O_{15}$	4.807	–	–	Insoluble
K_2ZnF_4	3.378	–	(001)-p	–
$K_3LiNb_5O_{15}$	4.376	–	(001)-p	Insoluble
$K_3Sc(VO_4)_2$	3.02	–	–	Slightly soluble
$KAl(MoO_4)_2$	3.42	–	(10$\underline{1}$1)-p	–
$KAl(SO_4)_2$	2.481	–	–	–
$KAlF_4$	3.009	–	–	–
$KAlGeO_4$	3.617	–	–	Insoluble
KAlSi2O$_6$	2.47	5.5 (Mohs)	None	Insoluble
$KAlSiO_4$	2.59	6 (Mohs)	None	Insoluble
KD_2PO_4	–	1.5 (Mohs)	(101)-p	Very soluble
$KGaGeO_4$	4.261	–	–	Insoluble
$KGaSiO_4$	3.691	–	–	Insoluble
KH_2PO_4	2.338	1.5 (Mohs)	(101)-p	33 (25)
$KIn(WO_4)_2$	5.13	–	(10$\underline{1}$1)-p	–
$KLa(MoO_4)_2$	4.61	–	–	–
$KLiBeF_4$	2.284	–	–	–
$KSc(MoO_4)_2$	3.23	–	(10$\underline{1}$1)-p	–
$KSc(WO_4)_2$	4.64	–	(10$\underline{1}$1)-p	–
KYF_4	3.49	3 (Mohs)	None	Insoluble
$KZnF_3$	4.018	2.5 (Mohs)	None	Insoluble
$La_2GeBe_2O_7$	5.424	–	(001)	Insoluble
La_2MoO_6	5.834	–	(100)-p	–
La_2O_2S	5.75	350–450	–	–
La_2O_3	6.574	–	–	–
La_2WO_6	7.44	–	–	–
$La_3Ga_5GeO_{14}$	–	–	None	Insoluble
$La_3Ga_5SiO_{14}$	5.754	–	None	Insoluble
$La_3Nb_{0.5}Ga_{5.5}O_{14}$	5.934	–	None	Insoluble
$La_3Ta_{0.5}Ga_{5.5}O_{14}$	6.164	–	None	Insoluble
$LaAlO_3$	–	–	–	Insoluble
$LaBaGa_3O_7$	5.60	–	(001)	Insoluble
$LaBGeO_5$	5.04	–	–	Insoluble
$LaBSiO_5$	4.58	–	–	Insoluble
$LaCaAl_3O_7$	–	–	(001)	Insoluble
$LaCaGa_3O_7$	–	–	(001)	Insoluble
$LaCl_3$	3.85	–	–	–
LaF_3	5.94	450	(0001)	Insoluble
$LaMgAl_{11}O_{19}$	4.285	–	–	Insoluble
$LaSrGa_3O_7$	5.64	–	(001)-i	Insoluble
$Li_2B_4O_7$	2.44	–	None	Slightly soluble
Li_2CaGeO_4	3.63	–	–	Insoluble
Li_2CaSiO_4	2.935	–	–	Insoluble

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Physical Properties of Uniaxial Crystalline Materials—*continued*

Uniaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
Li_3InO_3	4.394	–	–	–
$LiAlGeO_4$	3.338	–	None	Insoluble
γ-$LiAlO_2$	2.615	–	–	Insoluble
$LiAlSiO_4$	2.66	6.5 (Mohs)	(10$\underline{1}$1)	Insoluble
$LiCaAlF_6$	2.983	3.5 (Mohs)	None	0.005
$LiCaGaF_6$	3.517	–	None	Very slightly soluble
$LiCaInF_6$	–	–	None	Very slightly soluble
$LiCdBO_3$	4.53	–	–	–
$LiCdInF_6$	–	–	None	Very slightly soluble
$LiGaGeO_4$	4.077	–	None	Insoluble
$LiGaSiO_4$	3.445	–	–	Insoluble
$LiGd(MoO_4)_2$	5.273	–	–	–
$LiGd(WO_4)_2$	7.19	–	–	–
$LiGdF_4$	5.343	3.5 (Mohs)	None	Insoluble
$LiIO_3$	4.487	3.5 (Mohs)	–	80 (18)
$LiLa(WO_4)_2$	6.57	–	–	–
$LiLuF_4$	6.186	3.5 (Mohs)	None	Insoluble
$LiMgAlF_6$	3.14	–	–	Insoluble
$LiMgGaF_6$	3.772	–	–	Insoluble
$LiMgInF_6$	4.267	–	–	–
$LiNbO_3$	4.644	5 (Mohs)	(10$\underline{1}$1)-p	Insoluble
$LiSrAlF_6$	3.45	3.0 (Mohs)	None	0.05
$LiSrGaF_6$	3.600	2.5 (Mohs)	None	0.10
$LiTaO_3$	7.43	6 (Mohs)	(10$\underline{1}$1)	Insoluble
$LiYF_4$	3.99	260–325	None	Insoluble
$LiZnInF_6$	–	–	None	Very slightly soluble
$LiZnNbO_4$	4.504	–	–	–
$LuAl_3(BO_3)_4$	4.569	7 (Mohs)	(10$\underline{1}$1)	Insoluble
$LuBO_3$	6.871	–	–	Insoluble
$LuPO_4$	–	–	–	Insoluble
$LuVO_4$	6.263	–	(110)-p	Insoluble
$Mg_2Al_3(Si_5Al)O_{18}$	2.53	7 (Mohs)	(10$\underline{1}$0)-i	Insoluble
$MgCO_3$	3.00	4 (Mohs)	(10$\underline{1}$1)-p	Insoluble
MgF_2	3.18	415	(010),(110)	$< 2 \times 10^{-4}$
$MgTiO_3$	4.03	5.5 (Mohs)	(10$\underline{1}$1)-i	Insoluble
MnF_2	4.478	–	–	0.66 (40)
$Na_2Al_2B_2O_7$	2.62	–	–	–
$Na_2Ca_2Si_3O_9$	2.840	–	–	Insoluble
Na_2CO_3	2.27	–	–	Very soluble
$Na_2Mg(CO_3)_2$	2.74	3.5 (Mohs)	(0001)-i	–
$Na_2TiOSiO_4$	–	3.5 (Mohs)	(001)-p	Insoluble
$Na_3Li_2Nb_5O_{15}$	–	–	(001)-p	Insoluble
$Na_3YSi_2O_7$	3.063	–	–	Insoluble

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Physical Properties of Uniaxial Crystalline Materials—*continued*

Uniaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
$Na_5Al_3F1_4$	3.00	3.5 (Mohs)	(001)-p	–
$Na_5GdGe_4O_{12}$	3.861	–	–	Insoluble
$Na_5GdSi_4O_{12}$	3.213	–	–	Insoluble
$Na_5InGe_4O_{12}$	3.831	–	–	Insoluble
$Na_5InSi_4O_{12}$	3.134	–	–	Insoluble
$Na_5LuGe_4O_{12}$	4.051	–	–	Insoluble
$Na_5LuSi_4O_{12}$	3.348	–	–	Insoluble
$Na_5ScGe_4O_{12}$	3.476	–	–	Insoluble
$Na_5ScSi_4O_{12}$	2.743	–	–	Insoluble
$Na_5Y_4(SiO_4)_4F$	3.938	–	–	–
$Na_5YGe_4O_{12}$	3.548	–	–	Insoluble
$Na_5YSi_4O_{12}$	2.863	–	–	Insoluble
$NaAlSiO_4$	2.63	–	–	Insoluble
$NaBaPO_4$	4.270	1.5 (Mohs)	–	–
$NaGd(WO_4)_2$	7.184	–	–	–
$NaGdO_2$	6.162	–	–	Slightly soluble
$NaInO_2$	5.711	–	–	Slightly soluble
$NaLa(MoO_4)_2$	4.773	–	–	–
$NaLaO_2$	4.949	–	–	Soluble
$NaNO_3$	2.261	19.2(200)	(1010)-p	92 (25)
$NaSbBe_4O_7$	4.28	8 (Mohs)	(0001)-i	Insoluble
$NaScO_2$	3.515	–	–	Slightly soluble
$NaYF_4$	3.85	–	–	Insoluble
$NbCaAlO_4$	5.56	–	–	Insoluble
$Nd_xY_{1-x}Al_3\ (BO_3)_4$	–	8 (Mohs)		–
$NH_4Al(SeO_4)_2$	3.13	–	–	–
$NH_4Al(SO_4)_2$	2.472	–	–	–
$NH_4Ga(SeO_4)_2$	3.476	–	–	–
$NH_4Ga(SO_4)_2$	2.854	–	–	–
$NH_4H_2PO_4$	1.803	1 (Mohs)	(101)-p	36.8 (20)
Pb_2InNbO_6	8.567	.	.	Insoluble
$Pb_2ZnSi_2O_7$	–	–	(001)	Insoluble
$Pb_3Ca_2(AsO_4)_3Cl$	5.82	4.5 (Mohs)	(10$\underline{1}$1)-i	Insoluble
$Pb_3Ge_2O_7$	–	–	–	Insoluble
$Pb_5(AsO_4)\ _3F$	–	–	(10$\underline{1}$1)-i	Insoluble
$Pb_5(AsO_4)_3Cl$	7.28	3.5 (Mohs)	(10$\underline{1}$1)-i	Insoluble
$Pb_5(PO_4)_3Cl$	7.04	3.5 (Mohs)	(10$\underline{1}$1)-i	Insoluble
$Pb_5(PO_4)_3F$	6.868		(10$\underline{1}$1)-i	Insoluble
$Pb_5(VO_4)_3Cl$	6.88	3 (Mohs)	None	Insoluble
$Pb_5(VO_4)_3F$	7.155	–	(10$\underline{1}$1)-i	Insoluble
$PbAl_{12}O_{19}$	4.731	–	–	Insoluble
PbI_2	6.16	–	–	0.076 (25)
$PbMoO_4$	6.92	2.5–3 (Mohs)	(011)	Insoluble

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Physical Properties of Uniaxial Crystalline Materials—*continued*

Uniaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
PbO (litharge)	9.36	–	(110)-p	1.7×10^{-3} (20)
$PbTiO_3$	–	–	–	Insoluble
$PbWO_4$	8.23	2.5–3 (Mohs)	(001)-i	Insoluble
$Rb_2LaNb_5O_{15}$	5.35	–	–	Insoluble
Rb_2LiAlF_6	3.878	–	–	–
Rb_2LiGaF_6	4.258	–	–	–
Rb_2MgCl_4	2.791	–	–	–
Rb_2MgF_4	3.972	–	(001)-p	–
$Rb_2SnGe_3O_9$	4.850	–	–	Insoluble
$Rb_2SnSi_3O_9$	4.103	–	–	Insoluble
$Rb_2TiGe_3O_9$	4.425	–	–	Insoluble
$Rb_2TiSi_3O_9$	3.626	–	–	Insoluble
Rb_2ZnF_4	4.637	–	(001)-p	–
$Rb_3Gd(VO_4)_2$	4.50	–	–	Slightly soluble
$Rb_3Lu(VO_4)_2$	4.56	–	–	Slightly soluble
Rb_3NaBeF_8	3.376	–	–	–
$Rb_3Sc(VO_4)_2$	3.83	–	–	Slightly soluble
$Rb_3Y(VO_4)_2$	3.76	–	–	Slightly soluble
$RbAl(SeO_4)_2$	3.725	–	–	–
$RbAl(SO_4)_2$	3.126	–	–	–
$RbAlF_4$	3.792	–	–	–
$RbAlSi_2O_6$	2.893	–	–	Insoluble
$RbCdF_3$	4.836	–	–	–
$RbGa(SeO_4)_2$	4.088	–	–	–
$RbGa(SO_4)_2$	3.504	–	–	–
RbH_2AsO_4	–	1.5 (Mohs)	(101)-p	Very soluble
RbH_2PO_4	–	1.5 (Mohs)	(101)-p	Very soluble
$RbIn(MoO_4)_2$	3.88	–	$(10\underline{1}1)$-p	–
$RbIn(WO_4)_2$	5.19	–	$(10\underline{1}1)$-p	–
$RbSc(MoO_4)_2$	3.41	–	$(10\underline{1}1)$-p	–
$RbSc(WO_4)_2$	4.68	–	$(10\underline{1}1)$-p	–
$ScBO_3$	3.45	5 (Moh)	$(10\underline{1}1)$-p	Insoluble
$ScPO_4$	–	–	–	Insoluble
$ScVO_4$	–	–	–	–
Se	4.81	2.6 (Moh)	$(01\underline{1}2)$-i	Insoluble
SeO_2	4.16	–	–	–
α-SiC	3.219	3720	None	Insoluble
Si_3N_4	3.24	3400	None	Insoluble
SiO_2	2.65	741(500)	None	Insoluble
SnO_2	6.95	6.5 (Mohs)	(100)-i	Insoluble
$Sr_2Al_2SiO_7$	–	–	(001)	Insoluble
$Sr_2B_5O_9Cl$	3.250	–	–	Insoluble
$Sr_2Ga_2SiO_7$	–	–	(001)	Insoluble

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Physical Properties of Uniaxial Crystalline Materials—*continued*

Uniaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
$Sr_2MgGe_2O_7$	4.266	–	(001)	Insoluble
$Sr_2MgSi_2O_7$	–	–	(001)	Insoluble
$Sr_2ZnGe_2O_7$	–	–	(001)	Insoluble
$Sr_2ZnSi_2O_7$	4.027	–	(001)	Insoluble
$Sr_3(VO_4)_2$	4.464	–	–	–
$Sr_3B_2O_6$	4.257	–	–	Insoluble
$Sr_3Ga_2Ge_4O_{14}$	5.087	–	None	Insoluble
$Sr_3Ti_2O_7$	5.04	–	–	Insoluble
$Sr_5(AsO_4)_3F$	4.538	–	(10$\underline{1}$1)-i	Insoluble
$Sr_5(AsO_4)_3Cl$	4.525	–	–	Insoluble
$Sr_5(PO_4)_3Cl$	4.095	–	–	Insoluble
$Sr_5(PO_4)_3F$	4.14	380	(0001)-i	Insoluble
$Sr_5(VO_4)_3F$	4.13	–	(10$\underline{1}$1)-i	Insoluble
$Sr_5(VO_4)_3Cl$	4.122	–	(10$\underline{1}$1)-i	Insoluble
$Sr_5Nb_4O_{15}$	5.46	–	–	–
$Sr_5Ta_4O_{15}$	7.321	–	–	Insoluble
$SrAl_{12}O_{19}$	3.985	–	–	Insoluble
$SrAlF_5$	3.86	–	–	Insoluble
$(Sr_{0.6}Ba_{0.4})Nb_2O_6$	5.4	5.5 (Mohs)	–	Insoluble
$SrGaF_5$	4.40	–	–	Insoluble
$SrGdAlO_4$	6.602	–	(001)-p	Insoluble
$SrGdGa_3O_7$	5.64	–	–	Insoluble
$SrLa_4(SiO_4)_3O$	–	–	None	Insoluble
$SrLaAlO_4$	5.826	–	(001)-p	Insoluble
$SrLaBO_4$	4.802	–	–	Insoluble
$SrLaGaO_4$	5.372	–	(001)-p	Insoluble
$SrMg_2(VO_4)_2$	3.827	–	–	–
$SrMoO_4$	4.701	–	–	–
$SrSnB_2O_6$	–	–	–	Insoluble
$SrTiB_2O_6$	–	–	–	Insoluble
$SrWO_4$	6.354	–	–	Insoluble
$SrY_4(SiO_4)_3O$	–	–	None	Insoluble
$SrZrB_2O_6$	–	–	–	Insoluble
Ta_2O_5	8.2	–	–	Insoluble
$TaBO_4$	8.02	7.5 (Mohs)	(110)(010)	Insoluble
Te	6.25	18	None	Insoluble
$ThSiO_4$	6.7	4.5 (Mohs)	None	Insoluble
TiO_2	4.26	879 (500)	(110)-i	0.001
$Tl_2SnGe_3O_9$	6.617	–	–	Insoluble
$Tl_2TiGe_3O_9$	6.256	–	–	Insoluble
Tl_3AsS_3	7.18	–	–	Insoluble
Tl_3AsSe_3	7.834	–	–	Insoluble
$TlAl(SeO_4)_2$	4.894	–	–	–

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Physical Properties of Uniaxial Crystalline Materials—*continued*

Uniaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
$TlAl(SO_4)_2$	4.337	–	–	–
$TlAlF_4$	6.131	–	–	–
$TlGa(SeO_4)_2$	5.163	–	–	–
$TlGa(SO_4)_2$	4.719	–	–	–
$Y_2BeAl_2O_7$	–	–	(001)	Insoluble
$Y_2GeBe_2O_7$	4.810	–	(001)	Insoluble
$Y_2SiBe_2O_7$	4.423	–	(001)	Insoluble
$YAl_3(BO_3)_4$	3.724	1890	$(10\underline{1}1)$	Insoluble
$YAsO_4$	4.85	4.5 (Mohs)	–	Insoluble
YBO_3	–	–	–	Insoluble
$YCaAl_3O_7$	–	–	(001)	Insoluble
$YGa_3(BO_3)_4$	4.684	–	$(10\underline{1}1)$	Insoluble
$YInO_3$	6.032	–	–	–
YPO_4	4.31	4.5 (Mohs)	(110)-p	Insoluble
YVO_4	4.23	480	(110)-p	Insoluble
Zn_2GeO_4	4.781	–	–	Insoluble
Zn_2SiO_4	4.25	5.5 (Mohs)	(0001)-i	Insoluble
$ZnCO_3$	4.43	4 (Mohs)	$(10\underline{1}1)$-p	Insoluble
$ZnCl_2$	2.907	–	–	408 (25)
ZnF_2	4.95	–	–	1.62 (20)
$ZnGeP_2$	–	–	–	Insoluble
ZnO	5.606	4 (Mohs)	$(10\underline{1}0)$-p	1.6×10^{-4} (20)
$ZnSb_2O_6$	6.64	6.5 (Mohs)	–	–
$ZnSiP_2$	–	–	–	Insoluble
ZnS (wurtzite)	3.98	3.5 (Mohs)	$(11\underline{2}0)$-i	Insoluble
ZrO_2	5.861	–	–	Insoluble
$ZrSiO_4$	4.56	1000	(110)-i	Insoluble

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1.2.3 Biaxial Crystals

Physical Properties of Biaxial Crystalline Materials

Biaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
$Al_2(MoO_4)_3$	3.495	–	–	Insoluble
$Al_2(WO_4)_3$	5.079	–	(010)-p	Insoluble
$Al_2Ge_2O_7$	4.06	–	–	Insoluble
$Al_2SiO_4F_2$	3.57	8 (Mohs)	(001)-p	Insoluble
Al_2SiO_5-andalusite	3.13	6.5 (Mohs)	(110)	Insoluble
Al_2SiO_5-kyanite	3.6	4–7.5 (Mohs)	(100)-p	Insoluble
Al_2SiO_5-sillimanite	3.25	6.5 (Mohs)	(010)-p	Insoluble
$Al_4B_2O_9$	2.904	–	–	–
$Al_6Ge_2O_{13}$	3.662	–	–	Insoluble
$Al_6Si_2O_{13}$	3.19	1750	(010)-i	Insoluble
$AlHfTaO_6$	8.33	–	–	Insoluble
$AlNb_{11}O_{29}$	4.46	–	–	Insoluble
$AlNbO_4$	4.673	–	–	Insoluble
$AlTaO_4$	6.86	–	–	Insoluble
As_2S_3	3.49	1.5 (Mohs)	(010)-p	Insoluble
AsS	3.56	1.5 (Mohs)	(010)-i	Insoluble
$AsSbS_3$	3.92	1.5 (Mohs)	(001)-p	Insoluble
$Ba_2CaMgAl_2F_{14}$	4.204	3.5 (Mohs)	(001)-p	
$Ba_2CdMgAl_2F_{14}$	4.735	–	–	–
$Ba_2LiNb_5O_{15}$	–	–	–	Insoluble
$Ba_2NaNb_5O_{15}$	5.41	–	–	Insoluble
$Ba_2Zn_3F_{10}$	5.26	–	–	–
Ba_2ZnAlF_9	4.909	–	–	–
Ba_2ZnGaF_9	5.169	–	–	–
$Ba_3Al_2F_{12}$	4.37	–	–	–
$Ba_3TiAl_{10}O_{20}$	4.13	–	–	–
$BaAl_2B_2O_7$	3.559	–	–	–
$BaAl_2Ge_2O_8$	–	–	–	Insoluble
$BaAl_2Si_2O_8$	3.96	6–6.5 (Mohs)	(001)-p	Insoluble
$BaBe_2Si_2O_7$	4.00	7 (Mohs)	(001)(100)-p	Insoluble
$BaCa_2Mg(SiO_4)_2$	3.974	–	–	Insoluble
$BaCa_2Si_3O_9$	3.73	3.5 (Mohs)	(011)(010)-p	Insoluble
$BaCdAlF_7$	5.04	–	–	–
$BaCdGaF_7$	5.406	–	–	–
$BaCO_3$	4.31	3.5 (Mohs)	(010)-i	Very slightly soluble
$BaGaF_5$	5.104	–	–	–
$BaGe_2O_5$	5.85	–	–	Insoluble
$BaGeAl_6O_{12}$	4.031	–	–	–
$BaGeGa_6O_{12}$	5.201	–	–	–

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Physical Properties of Biaxial Crystalline Materials—*continued*

Biaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
$BaGeO_3$	5.072	–	–	Insoluble
$BaMgF_4$	4.538	–	–	–
$BaNb_2O_6$	–	–	–	Insoluble
$BaSO_4$	4.50	3 (Mohs)	(001)-p	Insoluble
$BaTa_2O_6$	7.824	–	–	Insoluble
$BaTi_4O_9$	4.52	–	–	Insoluble
$BaTiAl_6O_{12}$	3.791	–	–	–
$BaTiGa_6O_{12}$	4.981	–	–	–
BaY_2F_8	5.047	250–350	–	–
BaY_2O_4	5.806	–	–	–
$BaZnF_4$	5.178	–	–	–
β-$BaSi_2O_5$	3.77	5 (Mohs)	(001)	Insoluble
β-Ca_2SiO_4	3.31	6 (Mohs)	(100)-i	Insoluble
Be_2BO_3F	2.37	7.5 (Mohs)	(010)-p	Insoluble
$BeAl_2O_4$	3.75	1600–2300 (V)	None	Insoluble
$BeAl_6O_{10}$	3.75	–	–	–
β-Ga_2O_3	5.95	–	(010)-p	Insoluble
$Bi_2Al_4O_9$	6.229	–	–	–
Bi_2GeO_5	–	–	–	Insoluble
$Bi_2Mo_2O_9$	6.518	–	–	Insoluble
$Bi_2Mo_3O_{12}$	6.196	–	(100)-p	Insoluble
Bi_2O_3	9.37	–	–	Very slightly soluble
Bi_2SiO_5	–	–	–	Insoluble
Bi_2WO_6	7.35	3.5 (Mohs)	–	–
Bi_3TiNbO_9	–	–	–	Insoluble
$Bi_4B_2O_9$	8.185	–	–	–
$Bi_4Ti_3O_{12}$	8.045	313	–	Insoluble
γ-Bi_2MoO_6	7.068	–	–	–
BiB_3O_6	5.03	5–5.5 (Mohs)	–	Insoluble
$BiNbO_4$	–	–	–	Insoluble
$BiSbO_4$	8.48	–	–	Insoluble
$BiTaO_4$	8.958	–	–	Insoluble
$BiVO_4$-clinobisvanite	6.95	–	–	–
$BiVO_4$-pucherite	6.63	4 (Mohs)	(001)-p	–
$Ca(IO_3)_2$	4.48	3.5 (Mohs)	(011)-i	–
$Ca_2(AsO_4)Cl$	–	–	(010)-p	–
$Ca_2(PO_4)Cl$	–	–	(010)-p	–
$Ca_2(PO_4)F$	–	–	(010)-p	Insoluble
$Ca_2(VO_4)Cl$	3.075	–	(010)-p	–
$Ca_2Al_2O_5$	3.73	–	–	–
$Ca_2B_6O_{11}$	2.85	–	–	–
Ca_2BO_3Cl	2.766	–	–	–

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Physical Properties of Biaxial Crystalline Materials—*continued*

Biaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
$Ca_2Nb_2O_7$	–	–	–	Insoluble
$Ca_2Sb_2O_7$	5.204	–	–	Insoluble
$Ca_2V_2O_7$	3.36	5.5 (Mohs)	(110)-p	–
$Ca_3(VO_4)_2$	3.16	–	(110)(001)-p	–
$Ca_3Al_2O_6$	3.017	–	–	–
$Ca_3Ga_4O_9$	4.208	–	–	–
$Ca_3MgSi_2O_8$	3.31	6 (Mohs)	None	Insoluble
$Ca_3Si_2O_7$	2.96	5.5 (Mohs)	–	Insoluble
$Ca_5Al_6O_{14}$	3.03	–	(001)-p	–
$Ca_5Ga_6O_{14}$	4.18	5 (Mohs)	–	–
$CaAl_2F_8$	2.89	4.5 (Mohs)	(111)-p	Insoluble
$CaAl_2O_4$	2.942	–	–	–
$CaAl_2Si_2O_8$	2.76	6–6.5 (Mohs)	(001)-p	Insoluble
$CaAl_4O_7$	2.894	8.5 (Mohs)	–	–
$CaAlB_3O_7$	3.44	7.5 (Mohs)	None	Insoluble
$CaAlBO_4$	2.60	–	–	–
CaB_2O_4	2.702	–	–	–
$CaB_2Si_2O_8$	3.00	7 (Mohs)	None	Insoluble
CaB_3O_5F	2.729	–	–	Insoluble
CaB_4O_7	2.69	–	–	–
$CaBa(CO_3)_2$	3.67	4 (Mohs)	(110)-i	Very slightly soluble
$CaBe(PO_4)F$	2.95	5 (Mohs)	(110)-i	Insoluble
$CaBe_2(PO_4)_2$	2.89	6 (Mohs)	None	Insoluble
$CaCO_3$-aragonite	2.93	3.5–4 (Mohs)	(010)-i	Very slightly soluble
$CaGa_2O_4$	4.333	–	–	–
$CaGe_2O_5$	4.868	–	–	Insoluble
$CaIn_2O_4$	6.15	–	–	–
$CaMg(PO_4)F$	–	–	–	Insoluble
$CaMgAsO_4F$	3.77	5 (Mohs)	(101)-i	Very slightly soluble
$CaMgB_2O_5$	3.02	4.5 (Mohs)	(010)-p	Very slightly soluble
$CaMgGe_2O_6$	4.265	–	–	Insoluble
$CaMgSi_2O_6$	3.26	6.5 (Mohs)	(110)-i	Insoluble
$CaMgSiO_4$	3.06	5.5 (Mohs)	(010)-i	Insoluble
$CaNb_2O_6$	4.78	5.5 (Mohs)	None	Insoluble
$CaSc_2O_4$	3.897	–	–	Insoluble
$CaSiO_3$	2.9	5 (Mohs)	(100)-p	Insoluble
$CaSnO_3$	5.759	–	–	Insoluble
$CaSnSiO_5$	4.56	4 (Mohs)	–	Insoluble
$CaSO_4$	2.96	3.5 (Mohs)	(010)(100)	Very slightly soluble
$CaTa_2O_6$	–	–	–	Insoluble
$CaTiO_3$	4.04	–	–	Insoluble
$CaTiSiO_5$	3.53	5.5 (Mohs)	(110)-i	Insoluble
CaV_2O_6	3.59	–	(100)(001)-p	–

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Physical Properties of Biaxial Crystalline Materials—*continued*

Biaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
$CaYBO_4$	3.783	–	–	–
$CaZnGe_2O_6$	4.807	–	–	Insoluble
$CaZnSiO_4$	4.25	5 (Mohs)	(010)(100)	Insoluble
$CaZrSi_2O_7$	3.63	–	–	Insoluble
$CaZrTi_2O_7$	4.407	–	–	Insoluble
$Cd_2B_2O_5$	5.24	–	–	–
Cd_2GeO_4	6.313	–	–	Insoluble
CdB_4O_7	3.51	–	–	–
$CdWO_4$	8.005	–	–	–
Cs_2BeF_4	4.128	–	–	–
Cs_2CdBr_4	4.069	–	–	–
Cs_2HgI_4	4.357	–	–	–
Cs_2MgCl_4	2.952	–	–	–
Cs_2ZnBr_4	4.034	–	–	–
Cs_2ZnCl_4	3.357	–	–	–
CsB_3O_5	3.39	–	–	Soluble
$CsGd(MoO_4)_2$	–	–	(100)-p	–
CsLiBeF4	3.411	–	–	–
CsLiSO4	3.455	–	–	Very soluble
CsNbB2O6	–	–	(001)-p	Insoluble
$CsLiSO_4$	3.455	–	–	Very soluble
$CsNbB_2O_6$	–	–	(001)-p	Insoluble
$CsTiOAsO_4$	4.511	–	None	Insoluble
$CsZnAlF_6$	4.04	–	–	–
$Ga_2(WO_4)_3$	–	–	(010)-p	–
Ga_2GeO_5	4.97	–	–	Insoluble
$GaNbO_4$	5.01	–	–	Insoluble
$Gd(BO_2)_3$	4.84	–	–	–
$Gd_2(MoO_4)_3$	4.65	–	–	–
$Gd_2(WO_4)_3$	7.475	–	–	–
Gd_2GeO_5	–	–	–	Insoluble
Gd_2MoO_6	7.068	–	–	–
$Gd_2O_2SO_4$	6.483	–	–	–
Gd_2O_3	8.33	–	–	–
Gd_2SiO_5	6.77	6 (Mohs)	(100)-p	Insoluble
$Gd_2Sr_3(BO_3)_4$	5.266	–	–	–
Gd_2WO_6	8.339	–	–	–
Gd_3NbO_7	7.459	–	–	Insoluble
Gd_3TaO_7	8.414	–	–	Insoluble
$Gd_4Al_2O_9$	6.467	–	–	–
α-Ga_4GeO_8	5.65	–	–	Insoluble
$GdAlGe_2O_7$	–	–	–	Insoluble
$GdAlO_3$	7.437	–	–	Insoluble

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Physical Properties of Biaxial Crystalline Materials—*continued*

Biaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
$GdGaGe_2O_7$	6.08	–	–	Insoluble
$GdMgB_5O_{10}$	4.309	–	–	–
$GdNbO_4$	–	–	–	Insoluble
GdP_5O_{14}	3.55	–	–	Insoluble
$GdPO_4$	5.986	470	–	Insoluble
$GdScO_3$	6.642	–	–	Insoluble
HfO_2	10.11	–	–	Insoluble
$HgCl_2$	5.490	–	–	–
HgO	11.14	1.5–2.0 (Mohs)	(010)-p	–
HIO_3	4.637	–	–	–
$In_2(MoO_4)_3$	3.92	–	–	–
$In_2(WO_4)_3$	5.619	–	(010)-p	–
$InCaBO_4$	4.536	–	–	–
$InGaO_3$	6.447	–	–	–
$InNbO_4$	6.27	–	(010)-p	Insoluble
$InPO_4$	4.830	–	–	Insoluble
$InTaO_4$	8.296	–	(010)-p	Insoluble
$InVO_4$	4.50	–	–	Insoluble
K_2CaSiO_4	2.865	–	–	Insoluble
$K_3Gd(VO_4)_2$	3.15	–	–	Slightly soluble
$K_3La(PO_4)_2$	5.293	–	–	Insoluble
$K_3Lu(VO_4)_2$	3.15	–	–	Slightly soluble
$K_3Y(VO_4)_2$	3.15	–	–	Slightly soluble
$KAlSi_3O_8$	2.57	6 (Mohs)	(001)-p	Insoluble
$KAl_3Si_3O_{10}(OH)_2$	2.78	–	–	Insoluble
KBF_4	2.51	–	–	Slightly soluble
$KB_5O_8 \cdot 4H_2O$	1.740	2.5 (Mohs)	(010)-p	–
$KGaSi_3O_8$	2.887	–	–	Insoluble
$KIn(MoO_4)_2$	4.17	–	–	–
$KLaP_4O_{12}$	–	–	–	Insoluble
$KLu(WO_4)_2$	7.759	–	–	–
$KNbB_2O_6$	3.151	–	(001)-p	Insoluble
$KNbO_3$	4.617	–	–	Insoluble
KNO_3	2.11	2 (Mohs)	(011)-p	Soluble
KPb_2Cl_5	4.78	2.5 (Mohs)	–	Insoluble
$KTaB_2O_6$	4.262	–	(001)-p	Insoluble
$KTaO_3$	5.996 ?	–	–	Insoluble
KTi_3NbO_9	3.88	–	–	Insoluble
$KTiNbO_5$	3.82	–	–	Insoluble
$KTiOAsO_4$	3.454	–	None	Insoluble
$KTiOPO_4$	3.024	702	None	Insoluble
KVO_3	2.879	–	(010)-p	–
$KY(MoO_4)_2$	5.40	–	–	–

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Physical Properties of Biaxial Crystalline Materials—*continued*

Biaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
$KY(WO_4)_2$	6.56	–	–	–
LaB_3O_6	4.216	–	(010)-p	–
$La_2(WO_4)_3$	6.626	–	–	–
$La_2Ba_3(BO_3)_4$	5.353	–	–	–
$La_2Be_2O_5$	6.061	900(100)	(010)-i	Insoluble
$La_2Ca_3(BO_3)_4$	4.157	–	–	–
$La_2O_2SO_4$	5.467	–	–	–
La_2SiO_5	–	–	–	Insoluble
$La_2Sr_3(BO_3)_4$	4.783	–	–	–
$La_2Ti_2O_7$	5.782	648	(010)-p	Insoluble
La_2TiO_5	5.5	–	–	Insoluble
La_3NbO_7	6.25	–	–	Insoluble
La_3SbO_7	6.558	–	–	Insoluble
La_3TaO_7	7.139	–	–	Insoluble
$LaAlGe_2O_7$	5.18	–	–	Insoluble
$LaBMoO_6$	5.293	–	–	–
$LaBO_3$	5.304	–	–	–
$LaBWO_6$	6.185	–	–	–
$LaGaGe_2O_7$	–	–	–	Insoluble
$LaGaO_3$	7.21	–	–	Insoluble
$LaInO_3$	–	–	–	–
$LaMgB_5O_{10}$	3.923	–	–	–
$LaNb_5O_{15}$	6.264	–	–	Insoluble
$LaNbO_4$	5.914	–	–	Insoluble
LaP_5O_{14}	3.290	–	–	Insoluble
$LaPO_4$	5.067	5.5 (Mohs)	(100)-i	Insoluble
$LaSbO_4$	6.30	–	–	Insoluble
$LaScO_3$	5.79	–	–	Insoluble
$LaVO_4$	–	–	–	Insoluble
$LaY(WO_4)_3$	6.53	–	–	–
Li_2BeSiO_4	2.69	7 (Mohs)	(010)-i	Insoluble
Li_2CO_3	2.097	–	–	Slightly soluble
Li_2GeO_3	3.489	–	–	Insoluble
Li_2MgGeO_4	3.31	–	–	Insoluble
Li_2SiO_3	2.527	–	–	Insoluble
$Li_3La_2(BO_3)_3$	4.50	–	–	–
Li_3PO_4	2.48	4 (Mohs)	(010)-p	Insoluble
Li_3VO_4	2.645	–	–	Insoluble
$Li_3Y_2(BO_3)_3$	3.50	–	–	–
Li_5AlO_4	2.251	–	–	–
$Li_6Al_2(BO_3)_4$	2.58	–	–	–
$Li_6Lu(BO_3)_3$	3.538	–	–	–
$Li_6Y(BO_3)_3$	2.76	–	–	–

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Physical Properties of Biaxial Crystalline Materials—*continued*

Biaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
$LiAl(MoO_4)_2$	3.95	–	–	–
$LiAl(PO_4)F$	3.10	5.5 (Mohs)	(100)(110)-p	Insoluble
$LiAlGe_2O_6$	4.354	–	–	Insoluble
$LiAlSi_2O_6$	3.1	7 (Mohs)	(010)-p	Insoluble
$LiAlSi_4O_{10}$	2.40	6.5 (Mohs)	(001)-p	Insoluble
$LiBaAlF_6$	4.114	–	–	–
$LiBaGaF_6$	4.526	–	–	–
$LiBO_2$	2.883	–	–	–
LiB_3O_5	2.474	7 (Mohs)	None	Insoluble
$LiGa(WO_4)_2$	7.44	–	–	–
$LiGaGe_2O_6$	4.783	–	–	Insoluble
$LiGaO_2$	4.175	–	–	Insoluble
$LiGaSi_2O_6$	–	–	–	Insoluble
$LiGdO_2$	6.246	–	–	–
$LiGdP_4O_{12}$	–	–	–	Insoluble
$LiIn(MoO_4)_2$	4.149	–	–	–
$LiIn(WO_4)_2$	7.47	–	–	–
$LiInGe_2O_6$	5.041	–	–	Insoluble
$LiInSi_2O_6$	4.071	–	–	Insoluble
$LiInSiO_4$	4.160	–	–	Insoluble
$LiLa(MoO_4)_2$	4.551	–	–	–
$LiLaO_2$	6.18	–	–	Soluble
$LiLaP_4O_{12}$	–	–	–	Insoluble
$LiLu(WO_4)_2$	8.02	–	–	–
$LiLuGeO_4$	5.98	–	–	Insoluble
$LiLuP_4O_{12}$	–	–	–	Insoluble
$LiLuSiO_4$	5.46	–	–	Insoluble
$LiSc(WO_4)_2$	6.716	–	–	–
$LiScGe_2O_6$	4.157	–	–	Insoluble
$LiScGeO_4$	3.928	–	–	Insoluble
$LiScSi_2O_6$	3.090	–	–	Insoluble
$LiScSiO_4$	3.183	–	–	Insoluble
$LiVO_3$	2.971	–	(100)-p	Insoluble
$LiY(WO_4)_2$	6.83	–	–	–
$LiYGeO_4$	4.365	–	–	Insoluble
$LiYO_2$	6.258	–	–	–
$LiYSiO_4$	3.746	–	–	Insoluble
$LiZnBO_3$	3.64	–	–	–
Lu_2MoO_6	8.167	–	–	–
$Lu_2O_2SO_4$	7.854	–	–	–
Lu_2SiO_5	5.892	6.5 (Mohs)	None	Insoluble
Lu_2WO_6	9.718	–	–	–
$LuCaBO_4$	6.036	–	–	–

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Physical Properties of Biaxial Crystalline Materials—*continued*

Biaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
LuP_5O_{14}	3.72	–	–	Insoluble
$LuTaO_4$	9.761	–	–	Insoluble
$Mg_2(PO_4)F$	3.15	5 (Mohs)	(100)-i	Insoluble
$Mg_2B_2O_5$	2.910	5.5 (Mohs)	(hk0)-p	Insoluble
Mg_2BO_3F	2.784	–	–	Insoluble
Mg_2GeO_4	4.028	–	–	Insoluble
Mg_2SiO_4	3.22	7 (Mohs)	(010)-i	Insoluble
$Mg_3(PO_4)_2$	2.76	–	(100)(010)	Insoluble
$Mg_3B_2O_6$	3.04	6.5 (Mohs)	(110)-p	Insoluble
$Mg_3B_7O_{13}Cl$	2.95	7 (Mohs)	None	Slightly soluble
$Mg_3TiB_2O_8$	3.35	3.5 (Mohs)	(100)-p	Insoluble
$Mg_4Al_8Si_2O_20$	3.489	7.5 (Mohs)	(010)(001)-i	Insoluble
$Mg_4Ga_8Ge_2O_{20}$	–	–	–	Insoluble
$Mg_5(BO_3)_3F$	3.112	–	–	Insoluble
$MgAl_3BSiO_9$	2.98	7.5 (Mohs)	(100)-p	Insoluble
$MgAlBO_4$	3.45	7 (Mohs)	None	Insoluble
$MgGaBO_4$	4.285	–	–	Insoluble
$MgGeO_3$	4.282	–	–	Insoluble
$MgMoO_4$	3.809	–	–	–
$MgSiO_3$	3.21	5–6 (Mohs)	(110)-i	Insoluble
$MgTi(SO_4)_3$	2.82	–	–	–
$MgTi_2O_5$	3.649	–	–	Insoluble
$MgWO_4$	6.893	–	–	–
$Na(Sr,Ba)PO_4$	2.919	–	–	Insoluble
$Na_2BaTi_2Si_4O_{14}$	3.43	6 (Mohs)	(100)-i	Insoluble
Na_2BeF_4	2.482	–	–	–
$Na_2BeSi_2O_6$	2.70	6 (Mohs)	(100)-i	Insoluble
$Na_2Ca(PO_4)F$	2.88	–	–	Insoluble
$Na_2CaMg(PO_4)_2$	3.10	4.5 (Mohs)	–	Insoluble
Na_2GeO_3	3.319	–	–	Insoluble
$Na_2KTiNbSi_4O_{14}$	2.968	6.5 (Mohs)	–	Insoluble
Na_2LiAlF_6	2.98	–	(001)-p	Slightly soluble
$Na_2LiYSi_6O_{15}$	2.76	–	–	Insoluble
Na_2MgAlF_7	2.97	3.5 (Mohs)	(110)-i	Slightly soluble
Na_2MgGaF_7	3.359	–	–	–
Na_2MgInF_7	3.627	–	–	–
Na_2MgScF_7	2.853	–	–	–
Na_2MgSiO_4	2.75	–	–	Insoluble
$Na_2Si_2O_5$	–	–	(100)-p	Slightly soluble
Na_2SiO_3	2.64	–	–	Insoluble
$Na_2Ti_2Si_2O_9$	3.44	6 (Mohs)	(010)-i	Insoluble
Na_2ZnCl_4	2.382	–	–	–
Na_3AlF_6	2.90	2.5 (Mohs)	(001)-p	Slightly soluble

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Physical Properties of Biaxial Crystalline Materials—*continued*

Biaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
$Na_3GdSi_3O_9$	3.439	–	–	Insoluble
$Na_3La(BO_3)_2$	3.49	–	–	–
$Na_3La_2(BO_3)_3$	4.19	–	–	–
$Na_3ScSi_2O_7$	2.861	–	–	Insoluble
$Na_3YSi_3O_9$	2.962	–	–	Insoluble
$NaAl(AsO_4)F$	3.64	5 (Mohs)	(110)-i	Slightly soluble
$NaAl(PO_4)F$	3.126	4.5 (Mohs)	(111)-i	Insoluble
$NaAlGeO_4$	3.337	–	(010)-p	Insoluble
$NaAlSi_3O_8$	2.63	6–6.5 (Mohs)	(001)-p	Insoluble
$NaBePO_4$	2.81	5.5 (Mohs)	(010)-p	Insoluble
$NaBF_4$	2.53	3 (Mohs)	(100)(010)	Soluble
$NaCaPO_4$	3.117	3 (Mohs)	–	–
$NaCdPO_4$	4.10	–	–	–
$NaGaGe_2O_6$	4.864	–	–	Insoluble
$NaGaGeO_4$	4.028	–	(010)-p	Insoluble
$NaGaSiO_4$	3.336	–	(010)-p	Insoluble
$NaGdGeO_4$	5.366	–	–	Insoluble
$NaGdP_2O_7$	4.287	–	–	Insoluble
$NaGdP_4O_{12}$	3.45	–	–	Insoluble
$NaGdSiO_4$	–	–	–	Insoluble
$NaIn(MoO_4)_2$	4.02	–	–	–
$NaLaP_2O_7$	3.803	–	–	Insoluble
$NaLaP_4O_{12}$	3.4	–	–	Insoluble
$NaLiV_2O_6$	2.962	–	–	–
$NaLuGeO_4$	6.025	–	–	Insoluble
$NaLuP_2O_7$	4.114	–	–	Insoluble
$NaLuSiO_4$	5.435	–	–	Insoluble
$NaMgF_3$	3.06	–	–	–
$NaNbO_3$	4.57	5.5 (Mohs)	–	Insoluble
$NaScGeO_4$	3.39	–	–	Insoluble
$NaScSi_2O_6$	3.22	–	–	Insoluble
$NaSr_3Al_3F_{16}$	3.51	4 (Mohs)	None	Slightly soluble
$NaTaO_3$	7.123	–	–	Insoluble
$NaVO_3$	2.91	–	(110)-p	0.8
$NaYGeO_4$	4.302	–	–	Insoluble
$NaYO_2$	4.382	–	–	Slightly soluble
$NaYSiO_4$	4.083	–	–	Insoluble
$NaZnF_3$	4.105	–	–	–
$NH_4B_5O_8 \cdot 4H_2O$	1.57	2.5 (Mohs)	(100)-p	–
$Pb_2KNb_5O_{15}$	6.143	–	(001)	Insoluble
$Pb_2NaNb_5O_{15}$	–	–	–	Insoluble
$Pb_2V_2O_7$	6.46	3 (Mohs)	–	-
$Pb_3(PO_4)_2$	7.456	–	–	–

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Physical Properties of Biaxial Crystalline Materials—*continued*

Biaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
$Pb_3(VO_4)_2$	7.44	–	–	–
Pb_3GeO_5	–	–	–	Insoluble
$Pb_3MgNb_2O_9$	–	–	–	Insoluble
$Pb_3ZnNb_2O_9$	–	–	–	Insoluble
$PbBi_2Nb_2O_9$	6.684	–	–	Insoluble
$PbBr_2$	6.693	–	(001)-p	–
$PbCl_2$	5.85	31	(001)-p	0.99 (20)
$PbCO_3$	6.55	3 (Mohs)	(110)(021)-i	Very slightly soluble
$PbGeO_3$	6.968	–	–	Insoluble
PbO (massicot)	9.642		(100)-p	–
$PbNb_2O_6$	–	–	–	Insoluble
$PbSeO_3$	7.12	3.5 (Mohs)	(001)-p	–
$PbSeO_4$	7.08	3.5 (Mohs)	None	–
$PbSiO_3$	6.32	4.5 (Mohs)	(010)-p	Insoluble
$PbSO_4$	6.32	3.5 (Mohs)	(001)(210)	Insoluble
$PbTa_2O_6$	7.65	–	–	Insoluble
$PbTiP_2O_8$	–	–	–	Insoluble
$PbZnSiO_4$	6.13	3 (Mohs)	(120)-i	Insoluble
$RbAlSiO_4$	–	–	–	Insoluble
$RbB_5O_8 \cdot 4H_2O$	1.946	2.5 (Mohs)	–	–
Rb_2BeF_4	3.749	–	–	–
$RbBi(MoO_4)_2$	5.52	–	–	–
$RbGd_2Br_7$	4.79	–	–	Slightly soluble
$RbLa(WO_4)_2$	6.88	–	–	–
$RbNbB_2O_6$	3.584	–	(001)-p	Insoluble
$RbTaB_2O_6$	4.65	–	(001)-p	Insoluble
$RbTiOAsO_4$	4.018	–	None	Insoluble
$RbTiOPO_4$	3.647	–	None	Insoluble
$Sb2O_3$	5.83	2.5–3 (Mohs)	(110)-p	Insoluble
$SbNbO_4$	5.68	5.5 (Mohs)	(010)-i	Insoluble
$SbTaO_4$	7.53	5–5.5 (Mohs)	(010)-i	Insoluble
$Sc(PO_3)_3$	2.736	–	–	Insoluble
$Sc_2(MoO_4)_3$	3.102	–	–	–
$Sc_2(WO_4)_3$	4.566	–	(010)-p	Slightly soluble
$Sc_2Si_2O_7$	–	–	–	Insoluble
$(Sc,Y)_2Si_2O_7$	3.39	6.5 (Mohs)	(110)-i	Insoluble
Sc_2SiO_5	3.49	–	–	Insoluble
Sc_2TiO_5	3.611	–	–	Insoluble
$ScAlBeO_4$	–	–	None	Insoluble
$ScCaBO_4$	3.319	–	–	–
$ScGaO_3$	5.10	–	(010)-p	Insoluble
$ScGe_2O_5$	5.286	–	–	Insoluble
$ScMgBO_4$	3.287	–	–	–

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Physical Properties of Biaxial Crystalline Materials—*continued*

Biaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
$ScNbO_4$	4.843	–	(010)-p	Insoluble
$ScTaO_4$	6.90	–	(010)-p	Insoluble
$Sr_2(AsO_4)Cl$	–	–	(010)-p	–
$Sr_2(VO_4)Br$	4.342	–	–	–
$Sr_2(VO_4)Cl$	3.883	–	(010)-p	–
$Sr_2KNb_5O_{15}$	–	–	–	Insoluble
$Sr_2KTa_5O_{15}$	–	–	–	Insoluble
$Sr_2NaNb_5O_{15}$	5.19	–	–	Insoluble
$Sr_2Nb_2O_7$	5.204	–	–	Insoluble
$Sr_2Ta_2O_7$	7.074	–	–	Insoluble
$SrAl_2Ge_2O_8$	3.714	–	–	Insoluble
$SrAl_2O_4$	3.554	–	–	–
$SrAl_2Si_2O_8$	3.13	–	–	Insoluble
$SrAl_4O_7$	3.266	–	–	–
SrB_2O_4	3.350	–	–	–
$SrCO_3$	3.79	3.5 (Mohs)	(010)-i	Very slightly soluble
$SrGa_2O_4$	4.85	–	–	–
$SrGa_2Si_2O_8$	3.797	–	–	Insoluble
$SrGd_2O_4$	7.287	–	–	Insoluble
$SrIn_2O_4$	6.854	–	–	–
$SrLu_2O_4$	8.496	–	–	Insoluble
$SrNb_2O_6$	–	–	–	Insoluble
$SrSc_2O_4$	–	–	–	Insoluble
$SrSiO_3$	3.66	–	–	Insoluble
$SrSO_4$	3.97	3 (Mohs)	(001)-p	Insoluble
$SrTa_2O_6$	–	–	–	Insoluble
SrY_2O_4	5.344	–	–	–
$SrZnGe_2O_6$	–	–	–	Insoluble
TeO_2	6.00	2 (Mohs)	(010)-p	Very slightly soluble
$TlNbB_2O_6$	–	–	(001)-p	Insoluble
$TlTaB_2O_6$	–	–	(001)-p	Insoluble
V_2O_5	3.37	–	–	–
$Y_2(MoO_4)_3$	3.3	–	–	Very soluble
$Y_2(WO_4)_3$	–	–	(010)-p	Very soluble
Y_2BeO_4	4.582	–	–	Insoluble
Y_2GdSbO_7	6.443	–	–	Insoluble
Y_2GdTaO_7	7.102	–	–	Insoluble
Y_2GeO_5	–	–	–	Insoluble
$Y_2MgBe_2Si_2O_{10}$	4.152	6.5 (Mohs)	None	Insoluble
Y_2MoO_6	5.366	–	–	–
$Y_2O_2SO_4$	4.813	–	–	–
$Y_2Si_2O_7$	4.3	6 (Mohs)	None	Insoluble
Y_2SiO_5	4.543	6.5 (Mohs)	None	Insoluble

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Physical Properties of Biaxial Crystalline Materials—*continued*

Biaxial material	Density (g/cm^3)	Hardness (kg/mm^2)	Cleavage plane	Solubility (°C) ($g/100\ g\ H_2O$)
$Y_2Ti_2SiO_9$	–	–	–	Insoluble
Y_2WO_6	6.818	–	–	–
Y_3SbO_7	5.699	–	–	Insoluble
Y_3TaO_7	6.413	–	–	Insoluble
$Y_4Al_2O_9$	4.518	–	–	Insoluble
$YAlO_3$	5.35	1030–1450	(110)-p	Insoluble
$YCa_4O(BO_3)_3$	–	6–6.5 (Mohs)	None	Insoluble
$YCaGaBe_2Si_2O_{10}$	4.107	6.5 (Mohs)	None	Insoluble
YF_3	5.056	–	–	–
$YGd_2Nb_2O_9$	6.802	–	–	Insoluble
$YHfTaO_6$	8.13	–	–	Insoluble
$YNbO_4$	5.58	–	–	Insoluble
YP_5O_{14}	–	–	–	Insoluble
$YScO_3$	4.94	–	–	Insoluble
$YTaO_4$	7.579	–	–	Insoluble
$YTiTaO_6$	6.51	–	–	Insoluble
$Zn_3(AsO_3)_2$	4.27	5 (Mohs)	(110)-i	Insoluble
$Zn_3(BO_3)_2$	4.12	–	–	–
ZnB_4O_7	3.07	–	–	–
$ZnWO_4$	7.87	–	–	–
ZrO_2	5.82	6.5 (Mohs)	(001)-p	Insoluble

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1.3 Optical Properties*

The optical properties of crystals in this section are grouped into three tables: isotropic crystals, uniaxial crystals, and biaxial crystals. Materials are listed alphabetically in order of the chemical formulas. The following properties are included:

Transmission Range: Electronic and lattice absorption edges are given in terms of the wavelengths between which the transmission of a 1-mm-thick sample at 300 K is ≥ 10%. The values cited are approximate and are intended to as a general guide because many factors such as impurities, imperfections, temperature, crystallographic orientations, and compositional variations can affect the values.

Band Gap: Band gap data for transitions at room temperature unless noted otherwise. The energy gap depends on the structure of the material and varies with direction in anisotropic crystals. Optical transition: (D) – direct, (I) – indirect.

Refraction Index (n)**:** For isotropic crystals, there is only one refractive index. Uniaxial crystals with tetragonal, hexagonal, and trigonal (or rhombohedral) symmetry exhibit a unique index of refraction (symbolized as e or ε) when light vibrates parallel to the *c*-axis (the extraordinary ray). For light vibrating at 90° to the *c*-axis (the ordinary ray), the refractive indices are the same (symbolized as o or ω) in all 360° directions. Biaxial crystals with orthorhombic, monoclinic, and triclinic symmetry possess three significant indices of refraction, commonly symbolized as x, y, z or α, β, γ in the order from smallest to largest.

Unless specified, the refraction indices are the average values for standard daylight or are the values measured at 632.8 nm at room temperature (the differences in the daylight and He-Ne values are within 0.1%). In a few instances, e.g., tellurides, these materials are opaque to visible light so that the refractive indices are measured with an infrared light source. In these cases, the wavelength used is listed with parentheses.

Birefringence (Δn)**:** Birefringence of anisotropic materials is a measure of the maximum difference of the refractive indices within a crystal for a given wavelength.

Dispersion formulas: Refractive indices at specific wavelengths within specified ranges can be derived from dispersion formulas given in Section 1.3.4. Note that several different functional forms have been used to represent the dispersion of the refractive index.

Thermooptic coefficients (dn/dt): Thermooptic coefficients of optical crystals at various wavelengths are given in Section 1.3.5.

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* This section was adapted from "Optical crystals" by B. H. T. Chai, *Handbook of Laser Science and Technology, Suppl. 2, Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 3 ff (with additions).

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1.3.1 Isotropic Crystals

Optical Properties of Isotropic Crystalline Materials

Cubic material	Transmission (μm)	Band gap (eV)	Refractive index n
AgBr	0.49–35	2.7 (I), 4.3 (D)	2.242
AgCl	0.42–28	3.2 (I), 5.1 (D)	2.0568
AlAs	0.6 –15	2.153 (I)	2.87
$Al_{23}O_{27}N_5$ (ALON)	0.23–4.8	–	1.79
β-AlN	4.9	–	–
AlSb	–	1.63 (I), 2.22 (D)	–
As_2O_3	–	4–5	1.755
$Ba(NO_3)_2$	–	–	1.5714
BaF_2	0.14–13	9.1	1.4733
BaF_2-CaF_2	0.15–12	–	–
$Bi_{12}GeO_{20}$	0.47–7	–	2.5476
$Bi_{12}SiO_{20}$	0.52–	–	–
$Bi_{12}TiO_{20}$	–	–	2.5619
$Bi_4Ge_3O_{12}$	0.31–6	4.2	1.835
$Bi_4Si_3O_{12}$	–	–	2.051
BN	0.2–6	7.5 (I)	≈2.117
BP	0.5–6	2 (I)	2.8
$Ca_{12}Al_{14}O_{33}$	0.35–6	–	1.643
$Ca_3Al_2Si_3O_{12}$	–	–	1.734
$Ca_3Ga_2Ge_3O_{12}$	–	–	1.814
C (diamond)	0.24–2.7	5.47	2.4175
CaF_2	0.12–10	10	1.433
$CaLa_2S_4$	0.65–14.3	–	2.7
CaO	0.2–10	7.7	1.838
CdF_2	0.13–12	6	1.562
CdO	–	2.3	2.49
CdTe	0.9–30	1.56 (D)	2.817
CsBr	0.23–440	6.9	1.6929
CsCl	0.19–30	7.4	1.64
CsF	0.27–>15	10 (80 K)	1.48
CsI	0.25–62	6.2	1.7806
Cu_2O	–	2.1 (I), 2.6 (D)	–
CuBr	0.45–26	3.0 (80 K)	2.117
CuCl	0.4–19	3.3 (80 K)	1.97
CuI	–	3.1	2.346
GaAs	0.9–17.3	1.42 (D)	4.02
β-GaN	–	3.3	–
GaP	0.54–10.5	2.26 (I), 2.78 (D)	3.350
GaSb	1.7–20	0.726 (D)	3.82 (1.8 μm)
$Gd_2Ti_2O_7$	–	–	2.36
$Gd_3Ga_5O_{12}$	0.32–6	–	1.9637
$Gd_3Sc_2Al_3O_{12}$	–	–	1.901

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Optical Properties of Isotropic Crystalline Materials—*continued*

Cubic material	Transmission (μm)	Band gap (eV)	Refractive index n
$Gd_3Sc_2Ga_3O_{12}$	–	–	1.9628
Ge	1.8–15	0.664 (I)	4.052 (2.8 μm)
HgS	–	–	2.5
HgSe	2.1–20	0.6	–
HgTe	6–30	0.17 (D)	–
InAs	3.8–15	0.354 (D)	4.10
β-InN	4.98	–	–
InP	0.93–14	1.344 (D)	3.43
InSb	6–25	0.17	5.13
$K_2Mg_2(SO_4)_3$	–	–	1.53
K_2NaAlF_6	–	–	1.376
KBr	0.20–306	7.6 (D)	1.5566
KCl	0.18–25	8.5 (D)	1.4879
KF	0.146–16	10.9 (D)	1.362
KI	0.25–39	6.2 (D)	1.6581
$KMgF_3$	–	–	1.404
$KTaO_3$		3.5	2.2
$LiBaF_3$	–	–	1.544
LiBr	–	7.9 (D)	1.78
LiCl	–	9.3 (D)	1.66
LiF	0.12–6.6	13.6 (D)	1.3912
LiI	–	6 (D)	1.95
Lu_2O_3		3.9 (733 K)	–
$Lu_2Ti_2O_7$	–	–	2.57
$Lu_3Al_5O_{12}$	–	–	1.842
$Mg_3Al_2Si_3O_{12}$	–	–	1.713
$MgAl_2O_4$	0.21–5.3	–	1.715
$MgGa_2O_4$	–	–	1.879
MgO	0.16–9	7.8 (D)	1.735
MnO	–	3.7	2.18
$Na_3Li_3Al_2F_{12}$	0.15–13	–	1.3395
$Na_3Li_3Ga_2F_{12}$	0.15–13	–	–
$Na_3Li_3In_2F_{12}$	0.15–13	–	–
$Na_3Li_3Sc_2F_{12}$	0.15–13	–	–
$Na_8Al_6Si_6O_{24}Cl_2$	–	–	1.483
NaBr	0.2–24	7.5 (D)	1.64
NaCl	0.17–18	9.0 (D)	1.531
NaF	0.13–12	10.5	1.326
$5NaF\text{-}9YF_3$	–	–	1.470
NaI	0.26–24	5.9 (D)	1.77
$Pb(NO_3)_2$	–	–	1.780
PbF_2	0.29–12.5	5.0	1.7611
PbI_2	–	2.4	–
PbS	3–7	0.42 (D)	4.1 (3 μm)

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Optical Properties of Isotropic Crystalline Materials—*continued*

Cubic material	Transmission (μm)	Band gap (eV)	Refractive index n
PbSe	4.5–20	0.278 (D)	4.59 (3 μm)
PbTe	4–30	0.311 (D)	5.35 (3 μm)
RbBr	0.23–40	7.25 (D)	1.55
$RbCaF_3$	–	–	–
RbCl	0.2–30	8.3 (D)	1.49
RbF	–	10.4 (80 K)	–
RbI	0.26–50	5.83 (D)	1.64
Sb_2O_3	–	–	2.087
Sc_2O_3	–	–	1.964
Si	1.1–6.5	1.124 (I)	3.4777 (1.55 μm)
β-SiC	0.5–4	2.6 (I)	~2.6
SrF_2	0.13–12	9.4	1.4371
$SrSnO_3$	–	–	1.90
$SrTiO_3$	0.4–5.1	4.1	2.3878
ThO_2	0.22–9	5.7	2.07
Tl(Br,I)	0.58–42	–	2.573
Tl(Cl,Br)	0.42–27	–	2.329
Tl_2O_3	–	–	–
TlBr	0.44–38	3.1 (D)	2.384
TlCl	0.4–30	3.6	2.223
Y_2O_3	0.29–7.1	5.6	1.92
$Y_2Ti_2O_7$	–	–	2.34
$Y_3Al_5O_{12}$	0.21–5.2	–	1.8289
$Y_3Fe_5O_{12}$	–	–	2.25 (μm)
$Y_3Ga_5O_{12}$	–	–	1.913
$Y_3Sc_2Al_3O_{12}$	–	–	1.96
$ZnAl_2O_4$	–	–	1.7902
β-ZnS	0.4–12.5	3.68 (D)	2.3505
β-ZnS(CVD)	–	–	2.36
ZnSe	0.5–20	2.71 (D)	2.5907
ZnSe (CVD)	–	–	2.59
$ZnSiAs_2$	–	2.1	–
ZnTe	0.55–25	2.30 (D)	2.962
ZrO_2	0.35–7	5.0	2.1226
ZrO_2:Y_2O_3	0.38–6.0	~4.1	2.12

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1.3.2 Uniaxial Crystals

Optical Properties of Uniaxial Crystalline Materials

Uniaxial material	Transmission (μm)	Band gap (eV)	Refractive index n_e	Refractive index n_o	Birefringence Δn
Ag_3AsS_3	0.61–13.5	2.1	2.738	3.019	–0.281
Ag_3SbS_3	0.7–14	–	2.67	2.86	–0.19
$AgGaS_2$	0.5–13	2.6	2.507	2.554	–0.047
$AgGaSe_2$	0.78–18	1.7	2.676	2.700	–0.024 (1 μm)
β-AgI	–	2.9	2.21	2.22	–0.01
Al_2O_3	0.19–5.2	9.9	1.7579	1.7659	–0.008
AlF_3	–	–	1.3765	1.3770	–0.0005
α-AlN	–	6.23 (D)	2.13	2.20	–0.07
$AlPO_4$	0.2–3.6	–	1.5334	1.5243	0.0091
$Ba_2TiSi_2O_8$	0.3–5	–	1.765	1.775	–0.001
$Ba_2ZnSi_2O_7$	–	–	1.710	1.724	–0.014
$Ba_3(VO_4)_2$	0.3–5.6	–	–	–	–
$Ba_5(AsO_4)_3Cl$	–	–	1.880	1.884	0.004
$Ba_5(VO_4)_3Cl$	–	–	1.870	1.900	0.030
$BaAl_2O_4$	–	–	1.657	?	–
β-BaB_2O_4	0.19–3.5	6.2	1.54254	1.65510	0.11256
$BaBe(PO_4)F$	–	–	1.632	1.629	0.003
$BaGe_4O_9$	–	–	–	–	5.147
$BaSnSi_3O_9$	–	–	1.674	1.685	–0.011
$BaZrSi_3O_9$	–	–	1.6751	1.6850	–0.0099
Be_2GeO_4	–	–	1.720	1.734	–0.014
Be_2SiO_4	–	–	1.670	1.654	0.016
$Be_3Al_2Si_6O_{18}$	–	–	1.5682	1.5746	–0.0064
$Be_3Sc_2Si_6O_{18}$	–	–	1.607	1.627	0.02
$BeMg_3Al_8O_{16}$	–	–	1.717	1.722	0.005
BeO	0.11–4.5	10.6 (D)	1.7322	1.7166	0.0156
$Bi_2Ge_3O_9$	0.25–6.5	–	2.08	2.01	0.07
$Ca_2Al_2SiO_7$	–	–	1.658	1.669	–0.011
$Ca_2MgSi_2O_7$	–	–	1.64	1.632	0.008
$Ca_2Te_2O_5$	–	–	2.00	1.89	0.11
$Ca_2ZnSi_2O_7$	–	–	1.657	1.669	–0.012
$Ca_3Ga_2Ge_4O_{14}$	0.26–6.5	–	1.822	1.795	0.027
$Ca_5(AsO_4)_3F$	–	–	1.698	1.706	–0.008
$Ca_5(PO_4)_3Cl$	–	–	1.647	1.650	–0.003
$Ca_5(PO_4)_3F$	–	–	1.624	1.629	–0.005
$Ca_5(VO_4)_3Cl$	–	–	1.865	1.893	0.028
$CaAl_{12}O_{19}$	–	–	1.79	1.807	–0.017
$CaAl_2B_2O_7$	–	–	–	1.563	–
$CaCO_3$–calcite	0.2–5.5	5.9	1.486	1.658	–0.172

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Optical Properties of Uniaxial Crystalline Materials—*continued*

Uniaxial material	Transmission (μm)	Band gap (eV)	Refractive index n_e	Refractive index n_o	Birefringence Δn
$CaCO_3$–vaterite	–	–	1.65	1.55	0.10
$CaGdAlO_4$	0.35–7	–	1.9564	1.9331	0.0233
$CaGe_4O_9$	–	–	1.78	–	–
$CaLa_4(SiO_4)_3O$	–	–	1.7637	1.7915	–0.028
$CaLaAlO_4$	0.35–7	–	–	≈2.6	–
$CaMg(CO_3)_2$	–	–	1.503	1.680	–0.177
$CaMg_3(CO_3)_4$	–	–	1.609	1.708	0.099
$CaMoO_4$	–	–	1.9796	1.9703	0.0093
$CaSnB_2O_6$	–	–	1.660	1.778	–0.118
$CaWO_4$	0.13–5.6	–	1.9375	1.9208	0.017
$CaYAlO_4$	0.35–7	–	–	–	–
$CaZrBAl_9O_{18}$	–	–	1.7875	1.8159	–0.0284
$CdCl_2$	–	5.7	1.681	1.719	–0.038
$CdCO_3$	–	–	–	1.842	–
CdI_2	–	3.9	–	1.574	–
CdS	0.51–14.8	2.42 (D)	2.529	2.506	0.023
CdSe	0.75–20	1.70 (D)	2.557	2.537	0.02
CsD_2AsO_4	0.27–1.66	–	1.53	1.55	–0.02
CsD_2PO_4	0.27–1.66	–	–	–	–
$CsGa(SO_4)_2$	–	–	–	–	–
CsH_2AsO_4	0.26–1.43	–	1.53	1.55	–0.02
$CsLiB_6O_{10}$	0.18–2.7				
α-GaN	–	3.37 (D)	~2.25	~2.29	~0.04
GaS		2.3 (I), 3.8 (D)	–	–	–
GaSe	0.65–18	–	2.57	2.91	0.34 (1 μm)
$Gd_2GeBe2O_7$	–	–	–	–	–
$GdAl_3(BO_3)_4$	–	–	1.720	1.780	–0.060
$GdBO_3$	–	–	1.840	1.824	0.016
GeO_2	0.25–5	5.6	–	1.6045	–
Hg_2Br_2	0.4–30	2.6	–	–	–
Hg_2Cl_2	0.36–20	3.9	2.656	1.973	0.683
Hg_2I_2	0.45–40	2.4	–	–	–
HgI_2	–	2.1	–	–	–
HgS	0.6–28	2	3.232	2.885	0.347
InN	–	1.99	~2.09	–	–
In_2O_3	–	2.7 (I)	–	–	–
$InBO_3$	–	–	1.773	1.873	–0.100
$K_2Al_2B_2O_7$	0.18–3.6	–	–	–	–
$K_2BiNb_5O_{15}$	–	–	2.253	2.237	0.016
$K_2CaZr(SiO_3)_4$	–	–	1.655	1.625	0.03
$K_2Sr(SO_4)_2$	–	–	1.549	1.569	–0.020
$K_3LiNb_5O_{15}$	–	–	2.156	2.294	0.148
$KAlSi_2O_6$	–	–	1.509	1.508	0.001

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Optical Properties of Uniaxial Crystalline Materials—*continued*

Uniaxial material	Transmission (μm)	Band gap (eV)	Refractive index n_e	Refractive index n_o	Birefringence Δn
$KAlSiO_4$	–	–	1.5372	1.541	–0.0038
$KBe_2BO_3F_2$	0.155	–	1.406	1.472	–0.066
KD_2PO_4	0.20–1.5	–	1.46	1.49	0.03
KH_2PO_4	0.18–1.5	7.0	1.4669	1.5074	–0.0405
$KZnF_3$	–	–	–	–	–
$La_2GeBe_2O_7$	–	–	1.905	1.890	0.015
La_2O_3	–	2.9 (530 K)	–	–	–
La_2WO_6	–	–	2.18	2.16	0.02
$La_3Ga_5GeO_{14}$	0.24–7.5	–	1.940	1.925	0.015
$La_3Ga_5SiO_{14}$	0.35 –	–	1.9106	1.89965	0.01141
$La_3Nb_{0.5}Ga_{5.5}O_{14}$	0.29–6.7	–	1.896	1.955	0.059
$La_3Ta_{0.5}Ga_{5.5}O_{14}$	0.29–6.7	–	1.970	1.945	0.025
$LaAlO_3$	–	–	–	–	–
$LaBaGa_3O_7$	–	–	1.850	1.845	0.005
$LaBSiO_5$	–	–	1.7753	1.7843	–0.009
$LaCaGa_3O_7$	–	–	1.831	1.826	0.005
$LaCl_3$	–	–	1.8929	1.8265	0.0664
LaF_3	0.2–10	6.6	1.602	1.606	0.004
$LaSrGa_3O_7$	–	–	1.820	1.806	0.014
$Li_2B_4O_7$	–	–	1.560	1.605	–0.045
$LiAlSiO_4$	–	–	1.572	1.56	0.012
$LiCaAlF_6$	–	–	1.3852	1.3882	–0.003
$LiGdF_4$	–	–	1.474	1.502	–0.028
$LiIO_3$	0.38–5.5	4.0	1.7351	1.8815	–0.1464
$LiLuF_4$	–	–	1.468	1.494	–0.026
$LiNbO_3$	0.35–5.0	4.0	2.156	2.232	–0.076
$LiSrAlF_6$	–	–	1.384	1.380	0.004
$LiTaO_3$	–	–	2.188	2.183	–0.005
$LiYF_4$	0.12–8	~11	1.4762	1.4535	0.0227
$LuAl_3(BO_3)_4$	–	–	1.712	1.771	–0.059
$Mg_2Al_3(Si_5Al)O_{18}$	–	–	1.527	1.524	0.003
$MgCO_3$	–	–	1.510	1.700	–0.190
MgF_2	0.13–7.7	10.8	1.3886	1.3768	0.0118
$MgTiO_3$	–	–	1.95	2.31	–0.36
MnF_2	–	10.2	–	–	–
$Na_2Al_2B_2O_7$	–	–	1.504	1.540	–0.036
$Na(Li,Al)_3Al_6(BO_3)_3$ -$Si_6O_{18}(OH)$	variable	–	1.615–1.632	1.635–1.65	0.0180–0.0200
$NaNO_3$	0.35–3	–	1.3361	1.5874	–0.251
$NaSbBe_4O_7$	–	–	1.770	1.772	0.002
$NaScO_2$	–	–	–	–	–
$NH_4H_2PO_4$	0.19–1.5	6.8	1.48	1.53	–0.0458
$Pb_3Ca_2(AsO_4)_3Cl$	–	–	1.948	1.958	–0.010

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Optical Properties of Uniaxial Crystalline Materials—*continued*

Uniaxial material	Transmission (μm)	Band gap (eV)	Refractive index n_e	Refractive index n_o	Birefringence Δn
$Pb_5(AsO_4)_3Cl$	–	–	2.106	2.124	–0.018
$Pb_5(PO_4)_3Cl$	–	–	2.408	2.058	–0.010
$Pb_5(PO_4)_3F$	–	–	–	–	–
$Pb_5(VO_4)_3Cl$	–	–	2.350	2.416	–0.066
$PbAl_{12}O_{19}$	–	–	1.88	1.80	0.08
$PbMoO_4$	0.4–5.9	3.6	2.2584	2.3812	–0.123
PbO-litharge	–	2.8	2.535	2.655	0.130
$PbWO_4$	–	5.6	2.19	2.27	–0.08
RbH_2AsO_4	0.26–1.46	–	1.50	1.55	–0.05
RbH_2PO_4	0.22–1.4	–	1.47	1.50	–0.03
$ScBO_3$	–	–	1.780	1.872	–0.092
Se	1–30	1.7	3.61	2.79	0.82 (1μm)
α-SiC	0.5–4	2.8 (I)	~2.6	–	–
Si_3N_4	0.3–4.6	5	–	2.04	–
α-SiO_2	0.16–4.0	8.4	1.56	1.55	0.0095
SnO_2	– (4.3)	2.5 (I), 3.4 (D)	2.091	1.990	0.010
$Sr_2MgGe_2O_7$	–	–	1.800	1.816	–0.016
$Sr_3Ga_2Ge_4O_{14}$	0.26–6.8	–	1.85	1.8336	0.0164
$Sr_5(PO_4)_3F$	–	–	1.6252	1.6314	–0.062
$Sr_5(VO_4)_3F$	–	–	1.809	1.824	–0.015
$Sr_5(VO_4)_3Cl$	–	–	1.868	1.895	0.027
$SrAlF_5$	0.16–7	–	–	–	–
$(Sr_{0.6}Ba_{0.4})Nb_2O_6$	0.5–5.5	–	2.270	2.310	0.04
$SrGdGa_3O_7$	–	–	1.830	1.838	0.008
$SrLa_4(SiO_4)_3O$	–	–	1.8227	1.8567	–0.034
$SrMoO_4$	–	–	1.9110	1.9064	0.0046
Ta_2O_5	– (4.6)	–	2.21	2.20	0.01
$TaBO_4$	–	–	> 2.12	> 2.12	–
Te	3.5–32	0.33	4.929	6.372	–1.45 (4 μm)
$ThSiO_4$	–		1.79	1.78	0.01
TiO_2 (rutile)	0.42–4.0	3.5 (D)	2.872	2.584	0.288
Tl_3AsS_3	1.26–17	–	–	–	–
Tl_3AsSe_3	1.3–16	–	3.227	3.419	–0.192
$Y_2SiBe_2O_7$	–	–	1.80	1.83	–0.03
$YAl_3(BO_3)_4$	–	–	1.704	1.778	0.074
$YAsO_4$	–	–	1.879	1.783	0.096
YBO_3	–	–	1.802	1.788	0.014
YPO_4	–	–	1.816	1.827	–0.011
YVO_4	0.35–4.8	–	2.2148	1.9915	0.2233
Zn_2SiO_4	–	–	1.719	1.691	0.028
$ZnCO_3$	–	–	1.625	1.850	–0.275
$ZnCl_2$	~0.4–~15	–	–	–	–
ZnF_2	–	–	1.502	1.529	–0.027

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Optical Properties of Uniaxial Crystalline Materials—*continued*

Uniaxial material	Transmission (μm)	Band gap (eV)	Refractive index n_e	Refractive index n_o	Birefringence Δn
$ZnGeP_2$	0.74–15	–	3.28	3.23	0.05 (1 μm)
ZnO	0.37–	3.35 (D)	2.015	1.998	0.017
$ZnSb_2O_6$	–	–	>1.95	>1.95	–
α-ZnS	–	–	2.378	2.356	0.022
ZrO_2	–	4.99–	–	–	–
$ZrSiO_4$	0.4–	–	1.967	1.920	0.042

1.3.3 Biaxial Crystals

Optical Properties of Biaxial Crystalline Materials

Biaxial material	Transmission (μm) [Band gap (eV)]	Refractive index n_x	Refractive index n_y	Refractive index n_z	Birefringence Δn
$Al_2(WO_4)_3$	0.3–5.0	–	–	–	–
$Al_2SiO_4F_2$	–	1.630	1.631	1.638	0.008
Al_2SiO_5 (andalusite)	–	1.629	1.633	1.638	0.009
Al_2SiO_5 (kyanite)	–	1.712	1.720	1.727	0.015
Al_2SiO_5	–	1.653	1.654	1.669	0.023
$Al_4B_2O_9$	–	1.605	1.610	1.645	0.040
$Al_6Ge_2O_{13}$	–	1.72	–	1.758	0.046
$Al_6Si_2O_{13}$	0.21	1.642	1.644	1.654	0.012
$AlNb_{11}O_{29}$	–	2.20	–	2.22	0.02
$AlNbO_4$	–	1.985	–	2.005	0.02
As_2S_3	[2.5]	2.4	2.81	3.02	~0.6
AsS	–	2.538	2.684	2.704	0.116
$AsSbS_3$			>2.11	>2.73	>0.62
$Ba_2CaMgAl_2F_{14}$	–	1.441	1.442	1.444	0.003
$Ba_2NaNb_5O_{15}$	0.38–6.0	2.2177	2.3205	2.3222	0.1045
$BaAl_2Si_2O_8$	–	1.587	1.593	1.600	0.013
$BaBe_2Si_2O_7$	–	1.694	1.70	1.706	0.012
$BaCa_2Mg(SiO_4)_2$	–	1.731	–	1.752	0.021
$BaCa_2Si_3O_9$	–	1.668	1.684	1.685	0.017
$BaCO_3$	–	1.530	1.679	1.680	0.150
$BaMgF_4$	0.185–10	1.4496	1.4661	1.4738	0.0242
β-$BaSi_2O_5$	–	1.598	1.617	1.625	0.027
$BaSO_4$	–	1.6362	1.6373	1.6482	0.012
BaY_2F_8	0.2–9.5	1.5142	1.5232	1.5353	0.0211
Be_2BO_3F	–	1.554	1.587	1.628	0.074
$BeAl_2O_4$	–	1.746	1.748	1.756	0.010
BiB_3O_6	0.3–2.5	–	–	–	–

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Optical Properties of Biaxial Crystalline Materials—*continued*

Biaxial material	Transmission (μm) [Band gap (eV)]	Refractive index n_x	Refractive index n_y	Refractive index n_z	Birefringence Δn
$Bi_2Mo_3O_{12}$	0.42–5.2 [2.9]	2.254	2.306	2.497	0.243
Bi_2O_3	[2.8]	?	2.42	?	–
Bi_2WO_6	–	–	2.2	–	–
$BiSbO_4$	–	2.04	–	2.14	0.10
$BiTaO_4$	–	–	2.35	–	–
$BiVO_4$ (puucherite)	–	2.41	2.50	2.51	0.10
$Ca(IO_3)_2$	–	1.792	1.840	1.888	0.096
β-Ca_2SiO_4	–	1.707	1.715	1.730	0.023
$Ca_2(VO_4)Cl$	–	1.835	–	1.865	0.03
$Ca_2Al_2O_5$	–	1.96	2.01	2.04	0.08
$Ca_2V_2O_7$	–	1.942	2.00	2.132	0.19
$Ca_3(VO_4)_2$	–	1.864	1.885	1.890	0.026
$Ca_3(Zr,Ti)Si_2O_9$	–	1.735	1.737	1.758	0.023
$Ca_3MgSi_2O_8$	–	1.706	1.712	1.724	0.018
$Ca_3Si_2O_7$	–	1.641	1.644	1.650	0.009
$Ca_5Al_6O_{14}$	–	1.68	1.682	1.685	0.005
$Ca_5Ga_6O_{14}$	0.255–6.5	–	–	–	–
$CaAl_2F_8$	–	1.501	1.503	1.510	0.009
$CaAl_2Si_2O_8$	–	1.577	1.585	1.590	0.013
$CaAl_4O_7$	0.23–5.1	1.6178	1.6184	1.6516	0.0338
$CaAlB_3O_7$	–	1.712	1.717	1.726	0.014
$CaAlBO_4$	–	1.558	1.585	1.614	0.056
$CaB_2Si_2O_8$	–	1.630	1.633	1.635	0.005
CaB_3O_5F	–	1.612	1.636	1.653	0.041
$CaBa(CO_3)_2$	–	1.5261	1.6710	1.6717	0.146
$CaBe(PO_4)F$	–	1.580	1.600	1.610	0.030
$CaBe_2(PO_4)_2$	–	1.595	1.601	1.604	0.009
$CaCO_3$-α	–	1.530	1.6810	1.6854	0.1554
$CaGe_2O_5$	–	1.84	–	1.88	0.04
$CaMgAsO_4F$	–	1.640	1.660	1.675	0.035
$CaMgB_2O_5$	–	1.635	1.681	1.698	0.063
$CaMgSi_2O_6$	–	1.664	1.671	1.694	0.030
$CaMgSiO_4$	–	1.641	1.649	1.655	0.014
$CaNb_2O_6$	0.3–5.5	2.07	2.10	2.19	0.12
$CaSc_2O_4$	0.3–6.5	–	–	–	–
$CaSiO_3$	–	1.615	1.627	1.629	0.014
$CaSnSiO_5$	–	1.765	1.784	1.799	0.034
$CaSO_4$	–	1.570	1.575	1.614	0.044
$CaTiSiO_5$	–	1.84	1.870	1.943	0.103
CaV_2O_6	–	1.916	1.995	2.13	0.214
$CaZnSiO_4$	–	1.767	1.770	1.774	0.007
$CaZrSi_2O_7$	–	1.720	1.736	1.738	0.018
$Cd_2B_6O_{11}$	–	1.617	1.630	–	–

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Optical Properties of Biaxial Crystalline Materials—*continued*

Biaxial material	Transmission (μm) [Band gap (eV)]	Refractive index n_x	Refractive index n_y	Refractive index n_z	Birefringence Δn
CsB_3O_6	0.17–3.0	1.5294	1.5588	1.5864	0.0570
$CsNbO(SO_4)_2$	–	1.597	1.604	1.703	0.106
$CsTiOAsO_4$	0.35–5.3	1.8796	1.8961	1.9608	0.0812
β-Ga_2O_3	0.3–4.5	–	1.962	–	–
Gd_2O_3	[2.9, 933 K]	–	–	–	–
$Gd_2(MoO_4)_3$	0.32–5.2	1.8385	1.8390	1.8915	0.053
Gd_2SiO_5	0.2–5	1.871	1.884	1.910	0.039
GdP_5O_{14}	–	1.6094	1.6158	1.6298	0.0204
HfO_2	[5.5]	–	–	–	–
$HgCl_2$	–	1.725	1.859	1.965	0.240
HIO_3	0.3–1.8	2.37	2.5	2.65	0.280
$InPO_4$	–	1.608	1.618	1.623	0.015
$KAl_3Si_3O_{10}(OH)_2$	–	1.552	1.582	1.587	0.036
$KAlSi_3O_8$	–	1.518	1.520	1.523	0.005
KBF_4	–	1.324	1.325	1.325	0.001
$KB_5O_8 \cdot 4H_2O$	0.16–1.5	1.422	1.435	1.488	0.066
$KLaP_4O_{12}$	–	1.592	1.600	1.608	0.016
$KNbB_2O_6$	0.27–3.1	1.773	1.773	1.801	0.028
$KNbO_3$	0.4–4.5	2.168	2.279	2.329	0.161
KNO_3	–	1.332	1.505	1.509	0.172
KPbCl	0.3–20		n≈2		
$KTiOAsO_4$	0.35–3.0	1.8079	1.8138	1.9044	0.0965
$KTiOPO_4$	0.35–4.5 [3.5]	1.7614	1.7704	1.8636	0.1022
KVO_3	0.4–5.5	–	–	–	–
$La(BO_2)_3$	–	1.694	1.769	1.791	0.097
$La_2Be_2O_5$	0.3–4	1.9641	1.9974	2.0348	0.071
$La_2Ti_2O_7$	–	2.17	2.24	2.265	0.095
$LaBO_3$	–	1.800	1.877	1.882	0.082
LaP_5O_{14}	–	1.5956	1.6015	1.6145	0.0189
$LaPO_4$	–	1.774	1.77	1.828	0.054
Li_2BeSiO_4	–	1.622	1.633	1.638	0.016
Li_2CO_3	–	1.430	1.567	1.570	0.140
Li_2GeO_3	–	?	1.686	?	–
Li_3PO_4	–	1.550	1.557	1.566	0.016
Li_3VO_4	0.32 –	–	–	–	–
$LiAl(PO_4)F$	–	1.575	1.587	1.590	0.015
$LiAlSi_2O_6$	–	1.648	1.655	1.662	0.014
$LiAlSi_4O_{10}$	–	1.504	1.510	1.516	0.012
LiB_3O_5	0.16–2.6	1.5742	1.6014	1.6163	0.0421
$LiBO_2$	–	1.540	1.612	1.616	0.076
$LiGaO_2$	0.25–6	1.730	1.758	1.761	0.031
$LiVO_3$	0.5–5.5	1.850	1.970	2.13	0.28
Lu_2SiO_5	0.2–5	1.797	1.803	1.825	0.028

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Optical Properties of Biaxial Crystalline Materials—*continued*

Biaxial material	Transmission (μm) [Band gap (eV)]	Refractive index n_x	Refractive index n_y	Refractive index n_z	Birefringence Δn
LuP_5O_{14}	–	1.5950	1.6072	1.6125	0.0175
$Mg_2(PO_4)F$	–	1.569	1.570	1.580	0.011
$Mg_2B_2O_5$	–	1.596	1.639	1.670	0.074
Mg_2GeO_4	–	1.698	1.717	1.765	0.067
Mg_2SiO_4	–	1.635	1.651	1.670	0.035
$Mg_3(PO_4)_2$	–	1.540	1.544	1.559	0.015
$Mg_3B_2O_6$	–	1.652	1.653	1.673	0.021
$Mg_3B_7O_{13}Cl$	–	1.658	1.662	1.668	0.010
$Mg_3TiB_2O_8$	–	1.806	1.809	1.830	0.024
$Mg_4Al_8Si_2O_{20}$	–	1.701	1.703	1.705	0.004
$Mg_5(BO_3)_3F$	–	1.614	1.623	1.648	0.034
Mg_2SiO_4	–	1.635	1.651	1.670	0.035
$MgAl_3BSiO_9$	–	1.590	1.618	1.623	0.033
$MgAlBO_4$	–	1.667	1.697	1.705	0.038
$MgMoO_4$	–	1.82	1.83	1.84	0.02
$MgSiO_3$	–	1.654	1.655	1.665	0.011
$Na_2BaTi_2Si_4O_{14}$	–	1.727	1.732	1.789	0.062
$Na_2BeSi_2O_6$	–	1.544	1.549	1.549	0.005
$Na_2Ca(PO_4)F$	–	1.508	1.515	1.520	0.012
$Na_2CaMg(PO_4)_2$	–	1.598	1.605	1.608	0.010
Na_2MgAlF_7	–	1.346	1.348	1.350	0.004
Na_2MgSiO_4	–	1.534	1.536	1.543	0.009
$Na_2Si_2O_5$	–	1.507	1.517	1.521	0.014
$Na_2Ti_2Si_2O_9$	–	1.91	2.01	2.03	0.12
Na_3AlF_6	–	1.338	1.338	1.339	0.001
$NaAl(AsO_4)F$	–	1.634	1.672	1.685	0.051
$NaAl(PO_4)F$	–	1.545	1.554	1.565	0.020
$NaAlSi_3O_8$	–	1.527	1.531	1.538	0.011
$NaBe_2BO_3F_2$	~0.15–	1.370	1.474	1.474	0.104
$NaBePO_4$	–	1.552	1.558	1.561	0.009
$NaBF_4$	–	1.301	1.3012	1.3068	0.0058
$NaCaPO_4$	–	1.607	1.610	1.616	0.009
$NaMgF_3$	–	–	1.364	–	–
$NaNbO_3$	–	2.10	2.19	2.21	0.11
$NaScSi_2O_6$	–	1.683	1.715	1.724	0.041
$NaSr_3Al_3F_{16}$	–	1.429	1.433	1.436	0.007
$NaVO_3$	0.4–5.5	–	–	–	–
$NaZnF_3$	–	–	1.440	–	–
$NH_4B_5O_8{\bullet}4H_2O$	–	1.42	1.43	1.48	0.06
$Pb_2KNb_5O_{15}$	—	2.39	2.445	2.46	0.07
$Pb_2V_2O_7$	–		2.2–2.6		0.279
$PbBr_2$	0.36–30 [3.3]	–	–	–	–
$PbCl_2$	0.35–20	2.1992	2.2172	2.2596	0.0604

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Optical Properties of Biaxial Crystalline Materials—*continued*

Biaxial material	Transmission (μm) [Band gap (eV)]	Refractive index n_x	Refractive index n_y	Refractive index n_z	Birefringence Δn
$PbCO_3$	–	1.803	2.074	2.076	0.273
PbO (massicot)	[1.7]	2.51	2.61	2.71	0.200
$PbSeO_3$	–	2.12	2.14	2.14	0.02
$PbSeO_4$	–	1.96	1.97	1.98	0.02
$PbSiO_3$	–	1.947	1.961	1.968	0.021
$PbSO_4$	–	1.878	1.883	1.895	0.017
$PbZnSiO_4$	–	1.91	1.95	1.96	0.05
$RbNbB_2O_6$	0.27–3.0	1.751	1.771	1.795	0.044
$RbTiOAsO_4$	0.35–5.3	1.8294	1.838	1.9186	0.0892
$RbTiOPO_4$	0.35–4.3	1.7884	1.7992	1.8859	0.0975
Sb_2O_3	–	2.18	2.35	2.35	0.17
$SbNbO_4$	–	2.3977	2.4190	2.4588	0.061
$SbTaO_4$	–	2.3742	2.4039	2.4568	0.083
$Sc_2(WO_4)_3$	0.3–5.0	1.728	1.754	1.755	0.027
$Sc_2Si_2O_7$	–	1.754	1.785	1.803	0.049
Sc_2SiO_5	–	1.835	?	1.850	–
$(Sc,Y)_2Si_2O_7$	–	1.756	1.793	1.809	0.053
$Sr_2(VO_4)Cl$	–	1.785	–	1.816	0.03
$Sr_2Nb_2O_7$	–	1.85	2.044	2.05	0.20
$SrAl_2O_4$	–	1.638	–	1.656	0.018
$SrAl_4O_7$	0.2–5.5	1.620	1.636	1.644	0.024
SrB_2O_4	–	1.632	1.650	1.660	0.028
$SrCO_3$	–	1.517	1.663	1.667	0.150
$SrGa_2O_4$	–	1.737	–	1.767	0.03
$SrSO_4$	–	1.6215	1.6237	1.6308	0.0057
$SrZrO_3$	0.28–7.7	–	–	–	–
Ta_2O_5	[4.6]	–	–	–	–
TeO_2	0.33–5.0 [3]	2.00	2.18	2.35	0.35
V_2O_5	[~2.3]	2.42	?	–	–
Y_2BeO_4	–	1.840	–	1.855	0.015
$Y_2MgBe_2Si_2O_{10}$	–	1.78	1.80	1.82	0.04
$Y_2Si_2O_7$	–	1.731	1.738	1.744	0.013
Y_2SiO_5	0.2–5	1.780	1.784	1.811	0.031
$Y_4Al_2O_9$	–	1.826	1.830	1.832	0.006
$YAlO_3$	0.2–7	1.9243	1.9387	1.9478	0.0235
$Zn_3(AsO_3)_2$	–	1.74	1.79	1.82	0.08
ZrO_2	–	2.13	2.19	2.20	0.07

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1.3.4 Dispersion Formulas for Refractive Indices

Dispersion formulas for the refractive indices of crystals at room temperature are given in the following pages. Tabulated values of refractive indices at many wavelengths are given in Refs. 1–4 for most of the crystals below. Dispersion formulas for several organic materials are given in Refs. 1 and 3.

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Dispersion Formulas for Refractive Indices

Material	Dispersion formula (wavelength λ in μm)	Range (μm)	Ref.
Ag_3AsS_3	$n_o^2 = 7.483 + 0.474/(\lambda^2 - 0.09) - 0.0019\lambda^2$ $n_e^2 = 6.346 + 0.342/(\lambda^2 - 0.09) - 0.0011\lambda^2$	0.63–4.6 0.59–4.6	5
	$n_o^2 = 9.220 + 0.4454\lambda^2/(\lambda^2 - 0.1264) + 1733\lambda^2/(\lambda^2 - 1000)$ $n_e^2 = 7.007 + 0.3230\lambda^2/(\lambda^2 - 0.1192) + 660\lambda^2/(\lambda^2 - 1000)^2$	0.6–20	5
AgBr	$(n^2 - 1)/(n^2 - 2) = 0.452505 + 0.09939/(\lambda^2 - 0.070537) - 0.001509\lambda^2$	0.49–0.67	6
AgCl	$(n^2 - 1) = 2.062508\lambda^2/[\lambda^2 - (0.1039054)^2] + 0.9461465\lambda^2/[\lambda^2 - (0.2438691)^2] + 4.300785\lambda^2/[\lambda^2 - (70.85723)^2]$	0.54–21.0	7
$AgGaS_2$	$n_o^2 = 3.6280 + 2.1686\lambda^2/(\lambda^2 - 0.1003) + 2.1753\lambda^2/(\lambda^2 - 950)$ $n_e^2 = 4.0172 + 1.5274\lambda^2/(\lambda^2 - 0.1310) + 2.1699\lambda^2/(\lambda^2 - 950)$	0.49–12	8
$AgGaSe_2$	$n_o^2 = 4.6453 + 2.2057\lambda^2/(\lambda^2 - 0.1897) + 1.8377\lambda^2/(\lambda^2 - 1600)$ $n_e^2 = 5.2912 + 1.3970\lambda^2/(\lambda^2 - 0.2845) + 1.9282\lambda^2/(\lambda^2 - 1600)$	0.73–13.5	8
β-AgI	no = 2.184; n_e = 2.200 @ 0.659 μm n_o = 2.104; n_e = 2.115 @ 1.318 μm	—	9
Ag_3SbS_3	$n_o^2 = 1 + 6.585\lambda^2/[\lambda^2 - (0.4)^2] + 0.1133\lambda^2/[\lambda^2 - (15)^2]$ $n_e^2 = 1 + 5.845\lambda^2/[\lambda^2 - (0.4)^2] + 0.0202\lambda^2/[\lambda^2 - (15)^2]$	1.5–10.6	10
Al_2O_3	$n_o^2 = 1 + 1.43134936\lambda^2/[\lambda^2 - (0.0726631)^2] + 0.65054713\lambda^2/[\lambda^2 - (0.1193242)^2] + 5.3414021\lambda^2/[\lambda^2 - (18.028251)^2]$ $n_e^2 = 1 + 1.5039759\lambda^2/[\lambda^2 - (0.0740288)^2] + 0.55069141\lambda^2/[\lambda^2 - (0.1216529)^2] + 6.59273791\lambda^2/[\lambda^2 - (20.072248)^2]$	0.22–5.0	13
AlAs	$n^2 = 2.0729 + 6.0840\lambda^2/[\lambda^2 - 0.2822)^2] + 1.900\lambda^2/[\lambda^2 - 27.62)^2]$	0.56–2.2	11
AlN	$n_o^2 = 3.1399 + 1.3786\lambda^2/[\lambda^2 - (0.1715)^2] + 3.861\lambda^2/[\lambda^2 - (15.03)^2]$ $n_e^2 = 3.0729 + 1.6173\lambda^2/[\lambda^2 - (0.1746)^2] + 4.139\lambda^2/[\lambda^2 - (15.03)^2]$	0.22–5.0	12
ALON	$n^2 - 1 = 2.1375\lambda^2/[\lambda^2 - (0.10256)^2] + 4.582\lambda^2/[\lambda^2 - (18.868)^2]$	0.4–2.3	14

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BaB_2O_4	$n_o^2 = 2.7405 + 0.0184/(\lambda^2 - 0.0179) - 0.0155\lambda^2$ $n_e^2 = 2.3730 + 0.0128/(\lambda^2 - 0.0156) - 0.0044\lambda^2$	0.22–1.06	15
BaF_2	$n_o^2 = 1 + 0.643356\lambda^2/[\lambda^2 - (0.057789)^2] + 0.506762\lambda^2/[\lambda^2 - (0.10968)^2] + 3.8261^2/[\lambda^2 - (14.3864)^2]$	0.27–10.3	16
$BaTiO_3$	$n_o^2 = 1 + 4.187\lambda^2/[\lambda^2 - (0.223)^2]$ $n_e^2 = 1 + 4.064\lambda^2/[\lambda^2 - 0.211)^2]$	0.4–0.7	17
$BaMgF_4$	$n_x^2 = 2.1462 + 0.00736\lambda^2/(\lambda^2 - 0.0090)$ $n_y^2 = 2.007 + 0.0076\lambda^2/(\lambda^2 - 0.00799)$ $n_z^2 = 2.1238 + 0.0086\lambda^2/(\lambda^2 - 0)$	0.53–1.06	18
$Ba_2NaNb_5O_{12}$	$n_x^2 = 1 + 3.6008\lambda^2/(\lambda^2 - 0.032199)$ $n_y^2 = 1 + 3.9495\lambda^2/(\lambda^2 - 0.040140)$ $n_z^2 = 1 + 3.9495\lambda^2/(\lambda^2 - 0.040389)$	0.46–1.06	19, 20
BeO	$n_o^2 = 1 + 1.92274\lambda^2/[\lambda^2 - (0.07908)^2] + 1.24209\lambda^2/[\lambda^2 - (9.7131)^2]$ $n_e^2 = 1 + 1.96939\lambda^2/[\lambda^2 - (08590)^2] + 1.67389\lambda^2/[\lambda^2 - (10.4797)^2]$	0.44–7.0	38, 50
BiB_3O_6	$n_x^2 = 3.6545 + 0.0511\lambda^2/(\lambda^2 - 0.0371) - 0.0226\lambda^2$ $n_y^2 = 3.0740 + 0.03233\lambda^2/(\lambda^2 - 0.0316) - 0.01337\lambda^2$ $n_z^2 = 3.1685 + 00373\lambda^2/(\lambda^2 - 0.0346) - 0.01750\lambda^2$		117
$Bi_4Ge_3O_{12}$	$n^2 = 1 + 3.08959\lambda^2/(\lambda^2 - 0.01337)$	0.48–1.06	21
$Bi_{12}GeO_{20}$	$n^2 = 1 + 4.601\lambda^2/[\lambda^2 - (0.242)^2]$	0.48–0.7	22, 32
$Bi_{12}SiO_{20}$	$n^2 = 2.72777 + 3.01705\lambda^2/[\lambda^2 - (0.266)^2]$	0.4–0.7	23
BP	$n^2 = 1 + 6.841\lambda^2/[\lambda^2 - (0.267)^2]$	0.48–0.7	24
C (diamond)	$n^2 = 1 + 4.3356\lambda^2/[\lambda^2 - (0.1.60)^2] + 0.3306\lambda^2/[\lambda^2 - (0.1750)^2]$	0.225–∞	29

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Dispersion Formulas for Refractive Indices—*continued*

Material	Dispersion formula (wavelength λ in μm)	Range (μm)	Ref.
$Ca_2Al_2SiO_7$	$n_o^2 = 1 + 1.712/(\lambda^2 - 0.0196)$ $n_e^2 = 1 + 1.687/(\lambda^2 - 0.01133)$	0.31–1.06	26
$Ca_5(PO_4)_3F$	$n_o^2 = 2.626769 + 0.014626/(\lambda^2 - 0.012833) - 0.007653\lambda^2$ $n_e^2 = 2.620175 + 0.014703/(\lambda^2 - 0.011037) - 0.007544\lambda^2$	0.4–1.0	27
$CaCO_3$	$n_o = 1 + 0.8559\lambda^2/[\lambda^2 - (0.0588)^2] + 0.83913\lambda^2/[\lambda^2 - (0.141)^2] + 0.0009\lambda^2/[\lambda^2 - (0.197)^2] + 0.6845\lambda^2/[\lambda^2 - (7.005)^2]$ $n_e = 1 + 1.0856\lambda^2/[\lambda^2 - (0.07897)^2] + 0.0988\lambda^2/[\lambda^2 - (0.142)^2] + 0.317\lambda^2/[\lambda^2 - (1.468)^2]$	0.2–2.2	28
CaF_2	$n^2 = 1 + 0.5675888\lambda^2/[\lambda^2 - (0.050263605)^2] + 0.4710914\lambda^2/[\lambda^2 - (0.1003909)^2] + 3.8484723\lambda^2/[\lambda^2 - (34.649040)^2]$	0.23–9.7	45
$CaMoO_4$	$n_o^2 = 1 + 2.7840\lambda^2/[\lambda^2 - (0.1483)^2] + 1.2425\lambda^2/[\lambda^2 - (11.576)^2]$ $n_e^2 = 1 + 2.8045\lambda^2/[\lambda^2 - (0.1542)^2] + 1.0055\lambda^2/[\lambda^2 - (10.522)^2]$	0.45–3.8	30, 50
$CaWO_4$	$n_o^2 = 1 + 2.5493\lambda^2/[\lambda^2 - (0.1347)^2] + 0.9200\lambda^2/[\lambda^2 - (10.815)^2]$ $n_e^2 = 1 + 2.6041\lambda^2/[\lambda^2 - (0.11379)^2] + 4.1237\lambda^2/[\lambda^2 - (21.371)^2]$	0.45– 4.0	30, 50
$CdGeAs_2$	$n_o^2 = 10.1064 + 2.2988\lambda^2/(\lambda^2 - 1.0872) + 1.6247\lambda^2/(\lambda^2 - 1370)$ $n_e^2 = 11.8018 + 1.2152\lambda^2/(\lambda^2 - 2.6971) + 1.6922\lambda^2/(\lambda^2 - 1370)$	2.4–11.5	8
$CdGeP_2$	$n_o^2 = 5.9677 + 4.2286\lambda^2/(\lambda^2 - 0.2021) + 1.6351\lambda^2/(\lambda^2 - 671.33)$ $n_e^2 = 61573 + 4.0970\lambda^2/(\lambda^2 - 0.2330) + 1.4925\lambda^2/(\lambda^2 - 671.33)$	5.5–12.5	31
CdS	$n_o^2 = 1 + 3.96582820\lambda^2/[\lambda^2 - (0.23622804)^2] + 0.18113874\lambda^2/[\lambda^2 - (0.48285199)^2]$ $n_e^2 = 1 + 3.97478769\lambda^2/[\lambda^2 - (0.22426984)^2] + 0.26680809\lambda^2/[\lambda^2 - (0.46693785)^2]$ $+0.00074077\lambda^2/[\lambda^2 - (0.50915139)^2]$	0.51–1.4	93
CdSe	$n_o^2 = 4.2243 + 1.7680\lambda^2/(\lambda^2 - 0.2270) + 3.1200\lambda^2/(\lambda^2 - 3380)$ $n_e^2 = 4.2009 + 1.8875\lambda^2/(\lambda^2 - 0.2171) + 3.6461\lambda^2/(\lambda^2 - 3629)$	1–12	8

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CdTe	$n^2 = 1 + 6.1977889\lambda^2/[\lambda^2 - (0.317069)^2] + 3.22438216\lambda^2/[\lambda^2 - (72.0663)^2]$	6–22	33
CsB_3O_5	$n_x^2 = 2.2916 + 0.02105\lambda^2/(\lambda^2 - 0.06525) - 0.000031848\lambda^2$ $n_y^2 = 3.34498 + 1.04863\lambda^2/(\lambda^2 - 0.22044) - 0.01483\lambda^2$ $n_z^2 = 3.53666 + 1.10600\lambda^2/(\lambda^2 - 0.24988]) - 0.01711\lambda^2$	0.35–1.06	117
CsBr	$n^2 = 1 + 0.9533786\lambda^2/[\lambda^2 - (0.0905643)^2] + 0.8303809\lambda^2/[\lambda^2 - (0.1671517)^2] + 2.847172\lambda^2/[\lambda^2 - (119.0155)^2]$	0.36–39	34
CsCl	$n^2 = 1.33013 + 0.98369\lambda^2/[\lambda^2 - (0.119)^2] + 0.00009\lambda^2/[\lambda^2 - (0.137)^2] + 0.00018\lambda^2/[\lambda^2 - (145)^2]$ $+ 0.30914\lambda^2/[\lambda^2 - (0.162)^2] + 4.320\lambda^2/[\lambda^2 - (100.50)^2]$	0.18–40	35
CsD_2AsO_4	$n_o^2 = 1 + 1.40840\lambda^2/(\lambda^2 - 0.01299)$ $n_e^2 = 1 + 1.34731\lambda^2/(\lambda^2 - 0.01185)$	0.35–1.06	36
CsH_2AsO_4	$n_o^2 = 1 + 1.39961\lambda^2/(\lambda^2 - 0.01156)$ $n_e^2 = 1 + 1.34417\lambda^2/(\lambda^2 - 0.01155)$	0.35–1.06	36
CsI	$n^2 = 1 + 0.34617251\lambda^2/[\lambda^2 - (0.0229567)^2] + 1.0080886\lambda^2/[\lambda^2 - (0.1466)^2] + 0.28551800\lambda^2/[\lambda^2 - (0.1830)^2]$ $+ 0.39743178\lambda^2/[\lambda^2 - (0.2120)^2] + 3.3605359\lambda^2/[\lambda^2 - (161.0)^2]$	0.29–50	37
$CsLiB_6O_{10}$	$n_o^2 = 2.2049 + 0.0110259/(\lambda^2 - 0.0118119) - 0.0000695625\lambda^2$ $n_e^2 = 2.05936 + 0.00864948/(\lambda^2 - 0.0128929) - 0.0000267532\lambda^2$	0.24–0.63	118
	$n_o^2 = 2.14318 + 0.0158749/(\lambda^2 + 1.37559) - 0.00062375\lambda^2$ $n_e^2 = 2.04195 + 0.0273245/(\lambda^2 + 0.286672) - 0.000342718\lambda^2$	0.63–1.06	
$CsTiOAsO_4$	$n_x^2 = 3.74440 + 0.70733\lambda^2/(\lambda^2 - 0.26033) - 0.01526\lambda^2$ $n_y^2 = 3.34498 + 1.04863\lambda^2/(\lambda^2 - 0.22044) - 0.01483\lambda^2$ $n_z^2 = 3.53666 + 1.10600\lambda^2/(\lambda^2 - 0.24988) - 0.01711\lambda^2$	0.45–1.55	91
CuCl	$n^2 = 3.580 + 0.03162\lambda^2/(\lambda^2 - 0.1642) + 0.09288/\lambda^2$	0.43–2.5	25
$CuGaS_2$	$n_o^2 = 3.9064 + 2.3065\lambda^2/(\lambda^2 - 0.1149) + 1.5479\lambda^2/(\lambda^2 - 738.43)$ $n_e^2 = 4.3165 + 1.8692\lambda^2/(\lambda^2 - 0.1364) + 1.7575\lambda^2/(\lambda^2 - 738.43)$	0.55–11.5	39, 116

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Dispersion Formulas for Refractive Indices—*continued*

Material	Dispersion formula (wavelength λ in μm)	Range (μm)	Ref.
$CuGaS_2$	$n_o^2 = 3.9064 + 2.3065\lambda^2/(\lambda^2 - 0.1149) + 1.5479\lambda^2/(\lambda^2 - 738.43)$ $n_e^2 = 4.3165 + 1.8692\lambda^2/(\lambda^2 - 0.1364) + 1.7575\lambda^2/(\lambda^2 - 738.43)$	0.55–11.5	39, 116
GaAs	$n^2 = 3.5 + 7.4969\lambda^2/(\lambda^2 - 0.4082) + 1.9347\lambda^2/[(\lambda^2 - 37.17)^2]$	0.43–2.5	41
α-GaN	$n_o^2 = 3.6 + 1.75\lambda^2/[\lambda^2 - (0.256)^2] + 4.1\lambda^2/[\lambda^2 - (17.86)^2]$ $n_e^2 = 5.35 + 5.08\lambda^2/[\lambda^2 - (18.76)^2] + 1.0055\lambda^2/[\lambda^2 - (10.522)^2]$	<10	42
GaP	$n^2 = 1 + 1.390\lambda^2/[\lambda^2 - (0.172)^2] + 4.131\lambda^2/[\lambda^2 - (0.234)^2] + 2.570\lambda^2/[\lambda^2 - (345)^2] + 2.056\lambda^2/[\lambda^2 - (27.52)^2]$	0.8–10	43
GaSe	$n_o^2 = -0.05466\lambda^{-4} + 0.48605\lambda^{-2} + 7.8902 - 0.00824\lambda^2 - 0.00000276\lambda^4$ $n_e^2 = 6.0476 + 0.3423\lambda^2/(\lambda^2 - 0.16491) - 0.001042\lambda^2$	—	44
$Gd_2(MoO_4)_3$	$n_x^2 = 1 + 2.2450\lambda^2/(\lambda^2 - 0.022693)$ $n_y^2 = 1 + 2.24654\lambda^2/(\lambda^2 - 0.0226803)$ $n_z^2 = 1 + 2.41957\lambda^2/(\lambda^2 - 0.0245458)$	0.46–1.06	102
$Gd_3Ga_5O_{12}$	$n^2 = 3.749719 + 1.7083005/(39.509089\lambda^2 - 1) + 0.01048372\lambda^2/(0.001855744\lambda^2 - 1)$	0.40–1.06	46
$Gd_3Sc_2Al_3O_{12}$	$n^2 = 1 + 2.510\lambda^2/(\lambda^2 - 0.01537)$	0.54–0.64	47
$Gd_3Sc_2Ga_3O_{12}$	$n^2 = 3.743782 + 1.9139566/(43.240392\lambda^2 - 1) + 0.01067490\lambda^2/(0.01558170\lambda^2 - 1)$	0.40–1.06	48
Ge	$n^2 = 9.28156 + 6.72880\lambda^2/(\lambda^2 - 0.44105) + 0.21307\lambda^2/(\lambda^2 - 3870.1)$	2–12	49, 120
α–HgS	$n_o^2 = 6.9443 + 0.3665/(\lambda^2 - 0.1351) - 0.0019\lambda^2$ $n_e^2 = 8.3917 + 0.5405/(\lambda^2 - 0.1380) - 0.0027\lambda^2$	0.62–11	51
InAs	$n^2 = 11.1 + 0.71\lambda^2/[\lambda^2 - (2.551)^2] + 2.75\lambda^2/[\lambda^2 - (44.66)^2]$	3.7–31.3	
InP	$n^2 = 7.255 + 2.316\lambda^2/[\lambda^2 - (0.6263)^2] + 2.765\lambda^2/[\lambda^2 - (32.935)^2]$	0.95–10	53, 122

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$KB_5O_8 \cdot 4H_2O$	$n_x^2 = 1 + 1/(0.852497 - 0.0087588\lambda^2)$ $n_y^2 = 1 + 1/(0.972682 - 0.0087757\lambda^2)$ $n_z^2 = 1 + 1/(1.008157 - 0.0094050\lambda^2)$	0.23–0.76	54, 121
KBr	$n^2 = 1.39408 + 0.79221\lambda^2/[\lambda^2 - (0.146)^2] + 0.01981\lambda^2/[\lambda^2 - (0.173)^2] + 0.15587\lambda^2/[\lambda^2 - (0.187)^2]$ $+ 0.17673\lambda^2/[\lambda^2 - (60.61)^2] + 2.06217\lambda^2/[\lambda^2 - (87.72)^2]$	0.2–40	35
KCl	$n^2 = 1.26486 + 0.30523\lambda^2/[\lambda^2 - (0.100)^2] + 0.41620\lambda^2/[\lambda^2 - (0.131)^2] + 0.18870\lambda^2/[\lambda^2 - (0.162)^2]$ $+ 2.6200\lambda^2/[\lambda^2 - (70.42)^2]$	0.18–35	35
KF	$n^2 = 1.55083 + 0.29162\lambda^2/[\lambda^2 - (0.126)^2] + 3.60001\lambda^2/[\lambda^2 - (51.55)^2]$	0.15–22	35
KD_2PO_4	$n_o^2 = 1 + 1.2392348\lambda^2/(\lambda^2 - 0.83531147) + 14.78889\lambda^2/(\lambda^2 - 0.8851187)$ $n_e^2 = 1 + 1.125324\lambda^2/(\lambda^2 - 0.78980364) + 7.124567\lambda^2/(\lambda^2 - 1.190864)$	0.4–1.06	55, 56
KH_2AsO_4	$n_o^2 = 1 + 1.411981\lambda^2/(\lambda^2 - 1.1955269) + 28.100751\lambda^2/(\lambda^2 - 1.00681)$ $n_e^2 = 1 + 1.260916\lambda^2/(\lambda^2 - 1.1188613) + 5.258787\lambda^2/(\lambda^2 - 1.055210)$	0.4–1.06	55, 56
KH_2PO_4	$n_o^2 = 1 + 1.256618\lambda^2/(\lambda^2 - 0.84478168) + 33.89909\lambda^2/(\lambda^2 - 1.113904)$ $n_e^2 = 1 + 1.131091\lambda^2/(\lambda^2 - 0.8145980) + 5.75675\lambda^2/(\lambda^2 - 0.8117537)$	0.4–1.06	56
KI	$n^2 = 1.47285 + 0.16512\lambda^2/[\lambda^2 - (0.129)^2] + 0.41222\lambda^2/[\lambda^2 - (0.175)^2] + 0.44163\lambda^2/[\lambda^2 - (0.187)^2]$ $+ 0.16076\lambda^2/[\lambda^2 - (0.219)^2] + 0.33571\lambda^2/[\lambda^2 - (69.44)^2] + 1.92474\lambda^2/[\lambda^2 - (98.04)^2]$	0.25–50	35
$K_3Li_2Nb_5O_{15}$	$n_o^2 = 1 + 3.708\lambda^2/(\lambda^2 - 0.04601)$ $n_e^2 = 1 + 3.349\lambda^2/(\lambda^2 - 0.03564)$	0.45–0.68	57
$KNbO_3$	$n_x^2 = 1 + 2.49710\lambda^2/([\lambda^2 - (0.12909)^2] + 1.33660\lambda^2/[\lambda^2 - (0.25816)^2] - 0.025174\lambda^2$ $n_y^2 = 1 + 2.54337\lambda^2/([\lambda^2 - (0.13701)^2] + 1.44122\lambda^2/[\lambda^2 - (0.27275)^2] - 0.028450\lambda^2$ $n_z^2 = 1 + 2.37108\lambda^2/([\lambda^2 - (0.11972)^2] + 1.04825\lambda^2/[\lambda^2 - (0.25523)^2] - 0.019433\lambda^2$	0.40–3.4	59
$KTaO_3$	$n^2 = 1 + 3.591\lambda^2/([\lambda^2 - (0.193)^2]$	0.4–1.06	60

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Dispersion Formulas for Refractive Indices—*continued*

Material	Dispersion formula (wavelength λ in μm)	Range (μm)	Ref.
$KTiAsO_4$	$n_x^2 = 2.388887 + 0.77900\lambda^2/(\lambda^2 - (0.23784)^2 - 0.01501\lambda^2$ $n_y^2 = 2.11055 + 1.03177\lambda^2/[\lambda^2 - (0.21088)^2 - 0.01064\lambda^2$ $n_z^2 = 2.34723 + 1.10111\lambda^2/(\lambda^2 - (0.24016)^2 - 0.01739\lambda^2$	0.45–1.55	58, 91
$KTiOPO_4$	$n_x^2 = 2.16747 + 0.83733\lambda^2/([\lambda^2 - (0.04611)^2] - 0.01713\lambda^2$ $n_y^2 = 2.19229 + 0.83547\lambda^2/([\lambda^2 - (0.04970)^2] - 0.01621\lambda^2$ $n_z^2 = 2.25411 + 1.06543\lambda^2/([\lambda^2 - (0.05486)^2] - 0.02140\lambda^2$	0.4–1.06	61–64
$LaCl_3$	$n_o^2 = 1 + 2.235\lambda^2/(\lambda^2 - (0.01734)$ $n_e^2 = 1 + 2.469\lambda^2/(\lambda^2 - (0.017674)$	0.49–0.63	65
LaF_3	$n_o^2 = 1 + 1.53763\lambda^2/([\lambda^2 - (0.0881)^2]$ $n_e^2 = 1 + 1.5148\lambda^2/([\lambda^2 - (0.08781)^2]$	0.35–0.70	66
$La_2Be_2O_5$	$n_x^2 = 1 + 2.7990\lambda^2/(\lambda^2 + 0.01875)$ $n_y^2 = 1 + 2.9268\lambda^2/(\lambda^2 - 0.01918)$ $n_z^2 = 1 + 3.0725\lambda^2/(\lambda^2 - 0.01950)$	0.6–2	67
LiB_3O_5	$n_x^2 = 2.45768 + 0.0098877\lambda^2/([\lambda^2 - (0.026095)^2] - 0.013847\lambda^2$ $n_y^2 = 2.52500 + 0.017123\lambda^2/([\lambda^2 - (0.0060517)^2] - 0.0087838\lambda^2$ $n_z^2 = 2.58488 + 0.012737\lambda^2/([\lambda^2 - (0.016293)^2] - 0.016293\lambda^2$	0.29–1.06	68
$LiCaAlF_6$	$n_o^2 = 1.92552 + 0.00492/(\lambda^2 - 0.00569) - 0.00421\lambda^2$ $n_e^2 = 1.92155 + 0.00494/(\lambda^2 - 0.00617) - 0.00373\lambda^2$	0.4–1.0	69
LiF	$n^2 = 1 + 0.92549\lambda^2/[\lambda^2 - (0.7376)^2] + 6.96747\lambda^2/[\lambda^2 - (32.79)^2]$	0.1–10	35
$LiIO_3$	$n_o^2 = 2.03132 + 1.37623\lambda^2/(\lambda^2 - 0.0350823) + 1.06745\lambda^2/(\lambda^2 - 169.0)$ $n_e^2 = 1.83086 + 1.08807\lambda^2/(\lambda^2 - 0.0313810) + 0.554582\lambda^2/(\lambda^2 - 158.76)$	0.5–5	71

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$LiNbO_3$	$n_o^2 = 2.39198 + 2.51118\lambda^2/[\lambda^2 - (0.217)^2] + 7.1333\lambda^2/[\lambda^2 - (16.502)^2]$ $n_e^2 = 2.32468 + 2.25650\lambda^2/[\lambda^2 - (0.210)^2] + 14.503\lambda^2/[\lambda^2 - (25.915)^2]$	0.4–3.1	72
$LiSrAlF_6$	$n_o^2 = 1.97673 + 0.00309/(\lambda^2 - 0.00935) - 0.00828\lambda^2$ $n_e^2 = 1.98448 + 0.00235/(\lambda^2 - 0.10936) - 0.01057\lambda^2$	0.4–1.2	73
$LiYF_4$	$n_o^2 = 1.38757 + 0.70757\lambda^2/(\lambda^2 - 0.00931) + 0.18849\lambda^2/(\lambda^2 - 50.99741)$ $n_e^2 = 1.31021 + 0.84903\lambda^2/(\lambda^2 - (0.00876)^2 + 0.53607\lambda^2/(\lambda^2 - 134.9566)^2$	0.23–2.6	74
$Lu_3Al_5O_{12}$	$n^2 = 3.3275151 - 0.0149248\lambda^2 + 0.0178355\lambda^{-2} + 0.0046614\lambda^{-4} - 0.0009334\lambda^{-6} + 0.0000737\lambda^{-8}$	0.44–1.2	75
$MgAl_2O_4$	$n^2 = 1 + 1.8938\lambda^2/[\lambda^2 - (0.09942)^2] + 3.0755\lambda^2/[\lambda^2 - (15.826)^2]$	0.35–5.5	50, 76
MgF_2	$n_o^2 = 1 + 0.48755108\lambda^2/[\lambda^2 - (0.04338408)^2] + 0.39875031\lambda^2/[\lambda^2 - (0.09461442)^2] + 2.3120353\lambda^2/[\lambda^2 - (23.793604)^2]$ $n_e^2 = 1 + 0.41344023^2/[\lambda^2 - (0.03684262)^2] + 0.50497499\lambda^2/[\lambda^2 - (0.09076162)^2] + 2.4904862\lambda^2/[\lambda^2 - (12.771995)^2]$	0.4–3.1	77
MgO	$n^2 = 1 + 1.111033\lambda^2/[\lambda^2 - (0.0712465)^2] + 0.8460085\lambda^2/[\lambda^2 - (0.1375204)^2] + 7.808527\lambda^2/[\lambda^2 - (26.89302)^2]$	0.36–5.4	78
$NaBr$	$n^2 = 1.06728 + 1.10463\lambda^2/[\lambda^2 - (0.125)^2] + 0.18816\lambda^2/[\lambda^2 - (0.145)^2] + 0.00243\lambda^2/[\lambda^2 - (0.176)^2] + 0.24454\lambda^2/[\lambda^2 - (0.188)^2] + 3.7960\lambda^2/[\lambda^2 - (74.63)^2]$	0.21–34	35
$(Na,Ca)(Mg,Fe)_3B_3Al_6Si_6(O,OH,F)_{31}$ (tourmaline)	$n_o^2 = 1 + 1.6346\lambda^2/(\lambda^2 - 0.010734)$ $n_e^2 = 1 + 1.57256\lambda^2/(\lambda^2 - 0.011346)$	0.48–1.06	79
$NaBrO_3$	$n^2 = 1 + 1.3194\lambda^2/[\lambda^2 - (0.09)^2] + 0.2357\lambda^2/[\lambda^2 - (0.2)^2] - 0.0174\lambda^2$	—	80
$NaCl$	$n^2 = 1.00055 + 0.19800\lambda^2/[\lambda^2 - (0.050)^2] + 0.48398\lambda^2/[\lambda^2 - (0.100)^2] + 0.38696\lambda^2/[\lambda^2 - (0.128)^2] + 0.25998\lambda^2/[\lambda^2 - (0.158)^2] + 0.08796\lambda^2/[\lambda^2 - (40.50)^2] + 3.17064\lambda^2/[\lambda^2 - (60.98)^2] + 0.30038\lambda^2/[\lambda^2 - (120.34)^2]$	0.2–30	35
$NaClO_3$	$n^2 = 1 + 1.1825\lambda^2/[\lambda^2 - (0.09)^2] + 0.07992\lambda^2/[\lambda^2 - (0.185)^2] - 0.00864\lambda^2$	0.23–0.72	81
NaF	$n^2 = 1.41572 + 0.32785\lambda^2/[\lambda^2 - (0.117)^2] + 3.18248\lambda^2/[\lambda^2 - (40.57)^2]$	0.15–17	35

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Dispersion Formulas for Refractive Indices—*continued*

Material	Dispersion formula (wavelength λ in μm)	Range (μm)	Ref.
$[NH_4]_2CO$	$n_o^2 = 2.1823 + 0.0125\lambda^2/(\lambda^2 - 0.0300)$ $n_e^2 = 2.51527 + 0.0240\lambda^2/(\lambda^2 - 0.0300) + 0.020(\lambda - 1.52)/[(\lambda - 1.52)^2 + 0.8771$	0.3–1.06	82
$NH_4D_2AsO_4$	$n_o^2 = 1 + 1.418168\lambda^2/(\lambda^2 - 1.2246852) + 24.39162\lambda^2/(\lambda^2 - 1.175687)$ $n_e^2 = 1 + 1.262661\lambda^2/(\lambda^2 - 1.1728953) + 6.250606\lambda^2/(\lambda^2 - 0.9188848)$	0.4–1.06	55, 56
$NH_4H_2AsO_4$	$n_o^2 = 1 + 1.441185\lambda^2/(\lambda^2 - 1.2290244) + 30.08674\lambda^2/(\lambda^2 - 0.8843874)$ $n_e^2 = 1 + 1.274199\lambda^2/(\lambda^2 - 1.1750136) + 11.96164\lambda^2/(\lambda^2 - 1.041567)$	0.4–1.06	55, 56
$NH_4H_2PO_4$	$n_o^2 = 1 + 1.298990\lambda^2/(\lambda^2 - 0.0089232927) + 43.17364\lambda^2/(\lambda^2 - 1188.531)$ $n_e^2 = 1 + 1.162166\lambda^2/(\lambda^2 - 0.085932421) + 12.01997\lambda^2/(\lambda^2 - 831.8239)$	0.4–1.06	55, 56
NaI	$n^2 = 1.478 + 1.532\lambda^2/[\lambda^2 - (0.170)^2] + 4.27\lambda^2/[\lambda^2 - (86.21)^2]$	0.25–17	35
PbF_2	$n^2 = 1 + 0.66959342\lambda^2/[\lambda^2 - (0.00034911)^2] + 1.3086319\lambda^2/[\lambda^2 - (0.17144455)^2]$ $+ 0.01670641\lambda^2/[\lambda^2 - (0.28125513)^2] + 2007.8865\lambda^2/[\lambda^2 - (796.67469)^2]$	0.3–11.9	83
$PbMoO_4$	$n_o^2 = 1 + 3.54642\lambda^2/[\lambda^2 - (0.18518)^2] + 0.582703\lambda^2/[\lambda^2 - (0.33764)^2]$ $n_e^2 = 1 + 3.52555\lambda^2/[\lambda^2 - (0.17950)^2] + 0.20660\lambda^2/[\lambda^2 - (0.32537)^2]$	0.44–1.08	50, 84
$PbNb_4O_{11}$	$n_x^2 = 1 + 4.124\lambda^2/[(\lambda^2 - (0.202)^{2]}$ $n_y^2 = 1 + 4.139\lambda^2/[\lambda^2 - (0.2011)^{2]}$ $n_z^2 = 1 + 4.246\lambda^2/([\lambda^2 - (0.2014)^{2]}$	0.45–1.55	85
PbS	$n^2 = 1 + 15.9\lambda^2/([\lambda^2 - (0.77)^2] + 133.2\lambda^2/([\lambda^2 - (141)^2]$	3.5–10	86
PbSe	$n^2 = 1 + 21.1\lambda^2/([\lambda^2 - (1.37)^2]$	5–10	86
PbTe	$n^2 = 1 + 30.046\lambda^2/([\lambda^2 - (1.563)^2]$	4.0–12.5	87
$PbTiO_3$	$n_o^2 = 1 + 5.363\lambda^2/([\lambda^2 - (0.224)^2]$	0.45–1.15	

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	$n_e^2 = 1 + 5.366\lambda^2/([\lambda^2 - (0.0217)^2]$		
RbD_2AsO_4	$n_o^2 = 1 + 1.371661\lambda^2/(\lambda^2 - 1.1700309) + 16.30710\lambda^2/(\lambda^2 - 1.0114844)$ $n_e^2 = 1 + 1.269201\lambda^2/(\lambda^2 - 1.1202311) + 4.300136\lambda^2/(\lambda^2 - 1.149464)$	0.4–1.06	55, 56
RbD_2PO_4	$n_o^2 = 1 + 1.237455\lambda^2/(\lambda^2 - 0.8274984) + 17.69334\lambda^2/(\lambda^2 - 0.8839832)$ $n_e^2 = 1 + 1.154309\lambda^2/(\lambda^2 - 0.81539261) + 585751\lambda^2/(\lambda^2 - 0.8927180)$	0.4–1.06	55, 56
RbH_2AsO_4	$n_o^2 = 1 + 1.37723\lambda^2/(\lambda^2 - 0.01301)$ $n_e^2 = 1 + 1.272831\lambda^2/(\lambda^2 - 0.01157)$	—	89
RbH_2PO_4	$n_o^2 = 1 + 1.2068\lambda^2/(\lambda^2 - 0.01539)$ $n_e^2 = 1 + 1.15123\lambda^2/(\lambda^2 - 0.010048)$	0.48–1.06	90
$RbTiOAsO_4$	$n_x^2 = 1.97756 + 1.25726\lambda^2/[(\lambda^2 - (0.20448)^2] - 0.00865\lambda^2$ $n_y^2 = 2.22681 + 0.99616\lambda^2/[\lambda^2 - (0.21423)^2] - 0.01369\lambda^2$ $n_z^2 = 2.28779 + 1.20629\lambda^2/([\lambda^2 - (0.23484)^2] - 0.01583\lambda^2$	0.45–1.55	91
$RbTiOPO_4$	$n_x^2 = 2.38494 + 0.73603\lambda^2/([\lambda^2 - (0.23891)^2] - 0.01583\lambda^2$ $n_y^2 = 2.15559 + 0.93307\lambda^2/[\lambda^2 - (0.20994)^2] - 0.01452\lambda^2$ $n_z^2 = 2.27723 + 1.11030\lambda^2/([\lambda^2 - (0.23454)^2] - 0.01995\lambda^2$	0.45–1.55	91
Se	$n_o = 2.790$; $n_e = 3.608$ @ 1.06 μm $n_o = 2.64$; $n_e = 3.41$ @ 10.6 μm	—	92
Si	$n^2 = 1 + 10.66842933\lambda^2/[\lambda^2 - (0.3015116485)^2] + 0.003043475\lambda^2/[\lambda^2 - (1.13475115)^2]$ $+ 1.54133408\lambda^2/[\lambda^2 - (1104.0)^2]$	1.36–11	93, 94
α-SiC	$n_o^2 = 1 + 5.5515\lambda^2/([\lambda^2 - (0.16250)^2]$ $n_e^2 = 1 + 5.7382\lambda^2/([\lambda^2 - (0.16897)^2]$	0.49–1.06	95
β-SiC	$n^2 = 1 + 5.5705\lambda^2/([\lambda^2 - (0.1635)^2]$	0.47–0.69	96

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Dispersion Formulas for Refractive Indices—*continued*

Material	Dispersion formula (wavelength λ in μm)	Range (μm)	Ref.
SiO_2 (α-quartz)	$n_o^2 = 1 + 0.663044\lambda^2/[\lambda^2 - (0.060)^2] + 0.517852\lambda^2/[\lambda^2 - (0.106)^2] + 0.175912\lambda^2/[\lambda^2 - (0.119)^2] + 0.565380\lambda^2/[\lambda^2 - (8.844)^2] + 1.675299\lambda^2/[\lambda^2 - (20.742)^2]$ $n_e^2 = 1 + 0.665721\lambda^2/[\lambda^2 - (0.060)^2] + 0.503511\lambda^2/[\lambda^2 - (0.106)^2] + 0.214792\lambda^2/[\lambda^2 - (0.119)^2] + 0.539173\lambda^2/[\lambda^2 - (8.792)^2] + 1.807613\lambda^2/[\lambda^2 - (197.709)^2]$	0.18–0.71	97
SrF_2	$n^2 = 1 + 0.67805894\lambda^2/[\lambda^2 - (0.05628989)^2] + 0.37140533\lambda^2/[\lambda^2 - (0.10801027)^2] + 3.8484723\lambda^2/[\lambda^2 - (34.649040)^2]$	0.21–11.5	98
$SrMoO_4$	$n_o^2 = 1 + 2.4839\lambda^2/[\lambda^2 - (0.1451)^2] + 0.1015\lambda^2/[\lambda^2 - (4.603)^2]$ $n_e^2 = 1 + 2.4923\lambda^2/[\lambda^2 - (0.1488)^2] + 0.1050\lambda^2/[\lambda^2 - (4.544)^2]$	0.45–2.4	30
$SrTiO_3$	$n = 2.28355 + 0.035906/(\lambda^2 - 0.028) + 0.001666/(\lambda^2 - 0.028)^2 - 0.0061335\lambda^2 - 00001502\lambda^4$	0.4–5.4	99
$Sr_5(VO_4)_3F$	$n_o^2 = 3.29417 + 0.047212/(\lambda^2 - 0.048260) - 0.008518\lambda^2$ $n_e^2 = 3.24213 + 0.043872/(\lambda^2 - 0.053139) - 0.008773\lambda^2$	0.5–1.0	100
$Tb_2(MoO_4)_3$	$n_x^2 = 1 + 2.273955\lambda^2/(\lambda^2 - 0.02333)$ $n_y^2 = 1 + 2.2724\lambda^2/(\lambda^2 - 0.023359)$ $n_z^2 = 1 + 2.4430166\lambda^2/[\lambda^2 - 0.05133)$	0.46–1.06	101
Te	$n_o^2 = 18.5346 + 4.3289\lambda^2/(\lambda^2 - 3.9810) + 3.7800\lambda^2/(\lambda^2 - 11813)$ $n_e^2 = 29.5222 + 9.3068\lambda^2/(\lambda^2 - 2.5766) + 9.2350\lambda^2/(\lambda^2 - 13521)$	4–14	8
	$n_o^2 = 4.0164 + 18.8133\lambda^2/(\lambda^2 - 1.1572) + 7.3729\lambda^2/(\lambda^2 - 10000)$ $n_e^2 = 1.9041 + 36.8133\lambda^2/(\lambda^2 - 1.0803) + 6.2456\lambda^2/(\lambda^2 - 10000)$	8.5–30	8
TeO_2	$n_o^2 = 1 + 2.584\lambda^2/[\lambda^2 - (0.1342)^2] + 1.157\lambda^2/[\lambda^2 - (0.2638)^2]$ $n_e^2 = 1 + 2.823\lambda^2/[\lambda^2 - (0.1342)^2] + 1.542\lambda^2/[\lambda^2 - (0.2631)^2]$	0.4–1	103
TiO_2	$n_o^2 = 5.913 + 0.2441\lambda^2/(\lambda^2 - 0.0803)$	0.43–1.5	104

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rutile	$n_e^2 = 7.097 + 0.3322\lambda^2/(\lambda^2 - 0.0843)$		
TlBr	$(n^2 - 1)/(n^2 - 2) = 0.48484 + 0.10279/(\lambda^2 - 0.090000) - 0.0047896\lambda^2$	0.54–0.65	6
Tl[Br,Cl]	$n^2 = 1 + 3.821\lambda^2/[\lambda^2 - (0.02234)^2] - 0.000877\lambda^2$	0.6–24	106
Tl[Br,I]	$n^2 = 1 + 1.8293958\lambda^2/[\lambda^2 - (0.150)^2] + 1.6675593\lambda^2/[\lambda^2 - (0.250)^2] + 1.1210424\lambda^2/[\lambda^2 - (0.350)^2] + 0.04513366\lambda^2/[\lambda^2 - (0.450)^2] + 12.380234\lambda^2/[\lambda^2 - (164.59)^2]$	0.58–39.4	107
TlCl	$(n^2 - 1)/(n^2 - 2) = 0.47856 + 0.078588/(\lambda^2 - 0.08277) - 0.00881\lambda^2$	0.43–0.66	105
Tl_3AsSe_3	$n_o^2 = 1 + 10.210\lambda^2/[\lambda^2 - (0.444)^2] + 0.522\lambda^2/[\lambda^2 - (25.0)^2]$ $n_e^2 = 1 + 8.933\lambda^2/[\lambda^2 - (0.444)^2] + 0.308\lambda^2/[\lambda^2 - (25.0)^2]$	2–12	108
Y_2O_3	$n^2 = 1 + 2.578\lambda^2/[\lambda^2 - (0.1387)^2] + 3.935\lambda^2/[\lambda^2 - (22.936)^2]$	0.2–12	109
$YAlO_3$	$n_x^2 = 1 + 2.61960\lambda^2/(\lambda^2 + 0.012338)$ $n_y^2 = 1 + 2.67171\lambda^2/(\lambda^2 - 0.012605)$ $n_z^2 = 1 + 2.70381\lambda^2/(\lambda^2 - 0.012903)$	0.4–1.06	110
Y_2SiO_5	$n_x^2 = 3.0895 + 0.0334/(\lambda^2 + 0.0043) + 0.0199\lambda^2$ $n_y^2 = 3.1173 + 0.0283/(\lambda^2 - 0.0313)$ $n_z^2 = 3.1871 + 0.03022/(\lambda^2 - 0.138)$	0.44–0.64	111
YVO_4	$n_o^2 = 1 + 2.7665\lambda^2/(\lambda^2 - 0.026884)$ $n_e^2 = 1 + 3.5930\lambda^2/(\lambda^2 - 0.032103)$	0.5–1.06	112, 113
$Y_3Al_5O_{12}$	$n^2 = 1 + 2.293\lambda^2/[\lambda^2 - (0.1095)^2] + 3.705\lambda^2/[\lambda^2 - (17.825)^2]$	0.4– 4.0	30
$Y_3Ga_5O_{12}$	$n^2 = 1 + 2.5297\lambda^2/(\lambda^2 - 0.019694)$	0.46–0.63	48
$Y_3Sc_2Al_3O_{12}$	$n^2 = 1 + 2.4118\lambda^2/(\lambda^2 - 0.01477)$	0.53–0.65	115

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Dispersion Formulas for Refractive Indices—*continued*

Material	Dispersion formula (wavelength λ in μm)	Range (μm)	Ref.
$ZnGeP_2$	$n_o^2 = 4.4733 + 5.2658\lambda^2/(\lambda^2 - 0.1338) + 1.49090\lambda^2/(\lambda^2 - 662.55)$ $n_e^2 = 4.6332 + 5.3422\lambda^2/(\lambda^2 - 0.1426) + 1.4580\lambda^2/(\lambda^2 - 662.55)$	0.4–12	40
ZnO	$n_o^2 = 2.81419 + 0.87968\lambda^2/([\lambda^2 - (0.00569)^2] - 0.00711\lambda^2$ $n_e^2 = 2.80333 + 0.94470\lambda^2/([\lambda^2 - (0.3004)^2] - 0.00714\lambda^2$	0.45–4.0	30
α–ZnS	$n_o^2 = 4.4175 + 1.73968\lambda^2/([\lambda^2 - (0.2677)^2]$ $n_e^2 = 4.42643 + 1.7491\lambda^2/([\lambda^2 - (0.2674)^2]$	0.36–1.4	50, 105
β–ZnS	$n^2 = 1 + 0.3390426\lambda^2/([\lambda^2 - (0.31423026)^2] + 3.7606868\lambda^2/([\lambda^2 - (0.1759417)^2]$ $+ 2.7312353\lambda^2/([\lambda^2 - (33.886560)^2]$	0.55–10.5	98
ZnSe	$n^2 = 1 + 4.2980149\lambda^2/([\lambda^2 - (0.1920630)^2] + 0.62776557\lambda^2/([\lambda^2 - (0.37878260)^2]$ $+ 2.8955633\lambda^2/([\lambda^2 - (46.994595)^2]$	0.55–18	98
ZnTe	$n^2 = 9.921 + 0.42530\lambda^2/([\lambda^2 - (0.37766)^2] + 2.63580/([\lambda^2/(56.5)^2 - 1]$	0.55–30	114
ZrO_2: 12%Y_2O_3	$n^2 = 1 + 1.347091\lambda^2/([\lambda^2 - (0.062543)^2] + 2.117788\lambda^2/([\lambda^2 - (0.166739)^2] + 9.452943\lambda^2/([\lambda^2 - (24.320570)^2]$	0.36–5.1	116

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1.3.5 Thermooptic Coefficients

Thermooptic Coefficients

Material	Wavelength (nm)	dn/dt (10^{-6}/K)	Temperature (K)	Ref.
AgBr	3390	–61	RT	1
	10600	–50	RT	1
AgCl	610	–61	298	4
	633	–61	RT	1
	3390	–58	RT	1
	10600	–35	RT	1
$AgGaS_2$	600	258 (o)	RT	1
		255 (e)	RT	1
	1000	176 (o)	RT	1
		179 (e)	RT	1
	3390	154 (o)	RT	5
		155 (e)	RT	5
	10000	153 (o)	RT	1
		155 (e)	RT	1
$AgGaSe_2$	1064	98 (o)	RT	5
		66 (e)	RT	5
	3390	74 (o)	RT	5
		43 (e)	RT	5
	10600	58 (o)	RT	5
		46 (e)	RT	5
Al_2O_3	457.9	1.8 (o)	93	4
		1.9 (e)	93	4
		11.7 (o)	293	4
		12.8 (e)	293	4
		15.4 (o)	473	4
		16.9 (e)	473	4
	589	13.6 (o)	RT	1
		14.7 (e)	RT	1
	633	12.6	RT	1
$Al_{23}O_{27}N_5$	633	11.7	RT	1
BaB_2O_4	404.7	–16.4 (o)	RT	1
		–9.4 (e)	RT	1
	579	–16.6 (o)	RT	1
		–9.8 (e)	RT	1
	1014	–16.8 (o)	RT	1
		–8.8 (e)	RT	1
BaF_2	457.9	–7.8	90	4
		–15.6	293	4

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Thermooptic Coefficients—*continued*

Material	Wavelength (nm)	dn/dt (10^{-6}/K)	Temperature (K)	Ref.
BaF_2		–15.6	293	4
		–18.8	473	4
	632.8	–16.3	313	2
	1150	–8.1	90	4
		–16.2	293	4
		–19.3	473	4
	3390	–15.9	RT	1
	10600	–7.3	90	4
		–14.5	293	4
		–17.5	473	4
$Ba_2NaNb_5O_{15}$	1064	–25 (y)	RT	5
		80 (z)		5
$BeAl_2O_4$	1064	8	300	
BeO	458	8.2 (o)	RT	1
		13.4 (e)	RT	1
	633	8.2 (o)	RT	1
		13.4 (e)	RT	1
	1064	8.18 (o)	RT	5
		13.40 (e)	RT	5
$Bi_{12}GeO_{20}$	510	–34.5	RT	1
	650	–34.9	RT	1
C (diamond)	546	10.1	RT	1
	587	10	300	4
	30000	9.6	RT	1
$CaCO_3$	211	21.5 (o	334	4
		22.0 (e)	334	4
	365	3.6 (o)	RT	1
		14.4 (e)	RT	1
	441	3.2 (o	334	4
		13.2 (e)	334	4
	458	3.2 (o)	RT	1
		13.1 (e)	RT	1
	633	2.1 (o)	RT	1
		11.9 (e)	RT	1
CaF_2	254	–7.5	RT	1
	457.9	–3.9		
		–11.0	93	4
		13.4	293	4
	632.8	–11.5		
	663	–10.4	473	4
	1150	–4.1	313	2

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Thermooptic Coefficients—*continued*

Material	Wavelength (nm)	dn/dt (10^{-6}/K)	Temperature (K)	Ref.
CaF_2		–11.5	RT	1
		–14.1		
	3390	–8.1	93	4
			293	4
			473	4
			RT	1
$CaMoO_4$	587.6	–9.6 (o)	273–373	4
		–10.0 (e)	273–373	4
$Ca_5(PO_4)_3F$	500–1000	–10 (o)	293–338	3
		–8 (e)	293–338	3
$CaWO_4$	546.1	–7.1 (o)	293	4
	546.1	–10.2 (e)	293	2
CdF_2	457.9	–4.3	93	4
		–9.2	293	4
		–12.4	473	4
	1150	–5.7	93	4
		–11.5	293	4
		–15.1	473	4
	3390	–5.3	93	4
		–11.1	293	4
		–14.8	473	4
CdS	10600	58.6 (o)	RT	1
		62.4 (e)	RT	1
CdTe	1150	147	RT	1
	3390	98.2	RT	1
	10600	98.0	RT	1
CsBr	254	–82	RT	1
	288	–86	293	4
	400	–86	293	4
	633	–84.7	RT	1
	640	–85	293	4
	1150	–84	293	4
	3400	–84	293	4
	10600	–83	293	4
	17000	–82	293	4
	30000	–75.8	RT	1
CsCl	288	–79	293	4
	365	–78.7	293	1
	400	–78	293	4

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Thermooptic Coefficients—*continued*

Material	Wavelength (nm)	dn/dt (10^{-6}/K)	Temperature (K)	Ref.
CsCl	633	–77.4	293	1
	640	–77	293	4
	1150	–77	293	4
	3400	–76	293	4
	10600	–75	293	4
	17000	–72	293	4
	20000	–70.0	RT	1
CsF	288	–41	293	4
	400	–42	293	4
	640	–42	293	4
	1150	–42	293	4
	3400	–42	293	4
	10600	–39	293	4
	17000	–32	293	4
CsI	300	–79	288–307	4
	365	–87.5	RT	1
	633	–99.3	RT	1
	1000	–98.6	288–307	4
	10000	–91.7	288–307	4
	20000	–89.3	288–307	4
	30000	–88.0	288–307	4
	40000	–86.2	288–307	4
	50000	–78.5	288–307	4
GaAs	1150	250	RT	1
	3390	200	RT	1
	10600	200	RT	1
GaN	1150	61	RT	1
GaP	546	200	RT	1
	633	160	RT	1
GaSb	1550	380	80	4
	3700	312	100–400	4
$Gd_3Sc_2Al_3O_{12}$	543	8.9	298–308	3
	1152	5.05	308–313	3
$Gd_3Sc_2Ga_3O_{12}$	441.6	13.46	308–313	3
	543	13.3	298–308	3
	632.8	10.76	308–313	3
	1064	10.7	283–303	3
	1152	9.04	308–313	3
Ge	2500	462	RT	1
	5000	416	RT	1

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Thermooptic Coefficients—*continued*

Material	Wavelength (nm)	dn/dt (10^{-6}/K)	Temperature (K)	Ref.
Ge	20000	401	RT	1
InAs	3250	315	300–600	4
	4000	500	RT	1
	6000	400	RT	1
	10000	300	RT	1
InP	5000	83	RT	1
	10600	82	RT	1
	20000	77	RT	1
InSb	2000–40000	560	120–360	4
	5000–200000	460	100–400	4
KBr	457.9	–28.5	93	4
		–39.3	293	4
		–43.8	473	4
	1150	–30.5	93	4
		–41.9	293	4
		–46.3	473	4
	10600	30.6	93	4
		41.1	293	4
		45.6	473	4
KCl	457.9	–22.6	93	4
		–34.9	293	4
		–39.6	473	4
	1150	–23.5	93	4
		–36.2	293	4
		–41.1	473	4
	10600	–23.3	93	4
		–34.8	293	4
		–39.1	473	4
KF	254	–19.9	RT	1
	288	–21	293	4
	400	–22	293	4
	640	–23	293	4
	1150	–23	293	4
	3400	–23	293	4
	10600	–17	293	4
	17000	3	293	4
KH_2PO_4	624	–39.6 (o)	RT	1
		–38.2 (e)	RT	1
KI	288	268	293	4
	400	5	293	4

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Thermooptic Coefficients—*continued*

Material	Wavelength (nm)	dn/dt (10^{-6}/K)	Temperature (K)	Ref.
KI	458	–41.5	RT	1
	640	–49	293	4
	1150	–66	293	4
	3400	–72	293	4
	10600	–66	293	4
	17000	–52	293	4
	30000	–30.8	RT	1
$KNbO_3$	436	–67 (x)	RT	1
		–26 (y)	RT	1
		125 (z)	RT	1
	1064	23 (x)	RT	1
		–34 (y)	RT	1
		63 (z)	RT	1
	3000	21 (x)	RT	1
		–23 (y)	RT	1
		55 (z)	RT	1
$KTiOPO_4$	365	–6.5 (x)	RT	5
	532	–7.4 (x)	RT	5
		–0.9 (y)	RT	5
		–13.5 (z)	RT	5
LiB_3O_5	532	–1.9 (x)	RT	1
		–13.0 (y)	RT	1
		–7.4 (z)	RT	1
	1064	–1.9 (x)	RT	5
		–13.0 (y)	RT	5
		–8.3 (z)	RT	5
LiBr	288	56	293	4
	355	2	293	4
	640	–39	293	4
	1150	–48	293	4
	3400	–50	293	4
	10600	–37	293	4
	17000	–1	293	4
$LiCaAlF_6$	546, 764	–4.6 (o)	293–353	3
		–4.2 (e)	293–353	3
LiCl	288	9.9	293	4
	640	–32	293	4
	1150	–37	293	4
	3400	–38	293	4
	10600	–21	293	4
		–16	293	4

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Thermooptic Coefficients—*continued*

Material	Wavelength (nm)	dn/dt (10^{-6}/K)	Temperature (K)	Ref.
LiF	457.9	–3.3	93	4
		–21.6	473	4
	632.8	–17.0	313	2
	1150	–3.8	93	4
		–16.7	293	4
		–19.9	473	4
	3390	–4.0	93	4
		–14.5	293	4
		–18.0	473	4
LiI	288	268	293	4
	410	5	293	4
	640	–49	293	4
	1150	–66	293	4
	3400	–72	293	4
	10600	–66	293	4
	17000	–52	293	4
$LiIO_3$	400	–74.5 (o)	RT	1
		–63.5 (e)	RT	1
	1000	–84.9 (o)	RT	1
		–69.2 (e)	RT	1
$LiNbO_3$	660	4.4 (o)	RT	1
		37.9 (e)	RT	1
	3390	0.3 (o)	RT	1
		28.9 (e)	RT	1
$LiSrAlF_6$	900	–4.0 (o)	293–353	3
		–2.5 (e)	293–353	3
$LiTaO_3$	468	62 (o)	298	3
		12 (e)	298	3
	546	58 (o)	298	3
		7 (e)	298	3
	644	52 (o)	298	3
		5 (e)	298	3
$LiYF_4$	436	–0.54 (o)	RT	1
		–2.44	RT	1
	546	–0.67 (o)	RT	1
		–2.30 (e)	RT	1
	578	–0.91 (o)	RT	1
		–2.86 (e)	RT	1
$MgAl_2O_4$	589	9.0	RT	1
		1.8	93	4
		1.5	293	4

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Thermooptic Coefficients—*continued*

Material	Wavelength (nm)	dn/dt (10^{-6}/K)	Temperature (K)	Ref.
MgF_2	457.9	2.4	93	4
		0.9	293	4
		0.6	473	4
		0.1	473	4
	632.8	1.12 (o)	293	2
		0.58 (e)	293	2
	1150	2.0	93	4
		1.4	93	4
		0.9	293	4
		0.3	293	4
		–0.1	473	4
		–0.7	473	4
	3390	2.0	93	4
		1.5	93	4
		1.1	293	4
		0.6	293	4
		0.3	473	4
		–0.3	473	4
MgO	365	19.5	RT	1
	404.7	18.9	293	4
		19.1	303	4
		19.3	313	4
	546	16.5	RT	1
	589.3	15.3	293	4
		15.5	303	4
		15.7	313	4
	767.9	13.6	293	4
		13.8	303	4
		14.0	313	4
Mg_2SiO_4	488	2.8	298–313	3
NaBr	288	12.9	293	4
	350	–29	293	4
	365	–30.4	RT	1
	640	–39	293	4
	1150	–40	293	4
	3400	–40	293	4
	10600	–38	293	4
	17000	–32	293	4
NaCl	457.9	–20.6	93	4
		–34.2	293	4
		–39.2	473	4

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Thermooptic Coefficients—*continued*

Material	Wavelength (nm)	dn/dt (10^{-6}/K)	Temperature (K)	Ref.
NaCl	633	–35.4	RT	1
	1150	–22.2	93	4
		–36.4	293	4
		–41.4	473	4
	3390	22.4	93	4
		–36.6	293	4
		–41.8	473	4
NaF	457.9	–4.1	93	4
		–11.9	293	4
		–14.7	473	4
	632.8	–13.0	313	2
	1150	–4.5	93	4
		–13.2	293	4
		–15.9	473	4
	3390	–4.5	93	4
		–12.5	293	4
		–14.9	473	4
NaI	288	72	293	4
	325	3	293	4
	640	–46	293	4
	1150	–50	293	4
	3400	–50	293	4
	10600	–49	293	4
	17000	–44	293	4
$NH_4H_2PO_4$	624	–47.1 (o)	RT	1
		–4.3 (e)	RT	1
$PbMoO_4$	588	–75 (o)	273–373	4
		–41 (e)	273–373	4
PbS	3390	–2100	RT	1
	5000	–1900	RT	1
	10600	–1700	RT	1
PbSe	3390	–2300	RT	1
	5000	–1400	RT	1
	10600	–860	RT	1
PbTe	3390	–2100	RT	1
	5000	–1500	RT	1
	10600	–1200	RT	1
RbBr	288	–40	293	4
	400	–44	293	4
	640	–45	293	4

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Thermooptic Coefficients—*continued*

Material	Wavelength (nm)	dn/dt (10^{-6}/K)	Temperature (K)	Ref.
RbBr	1150	–45	293	4
	3400	–45	293	4
	10600	–44	293	4
	17000	–43	293	4
RbCl	288	–38	293	4
	400	–39	293	4
	640	–39	293	4
	1150	–39	293	4
	3400	–39	293	4
	10600	–38	293	4
	17000	–35	293	4
RbI	288	–37	293	4
	400	–55	293	4
	640	–56	293	4
	1150	–56	293	4
	3400	–56	293	4
	10600	–56	293	4
	17000	–55	293	4
Si	1407	206	291	4
	2500	166	RT	1
	3826	174	312	4
	5000	159	RT	1
	10600	157	RT	1
SiO_2 (α-quartz)	254	–2.9 (o)	RT	1
		–4.0 (e)	RT	1
	365	–5.4 (o)	RT	1
		–6.2 (e)	RT	1
	546	–6.2 (o)	RT	1
		–7.0 (e)	RT	1
$Sr_5(VO_4)_3F$	750–1000	–11 (o)	293–338	3
		–8 (e)	293–338	3
SrF_2	457.9	–54	93	4
		–12.0	293	4
		–13.4	473	4
	632.8	–12.5	313	2
	1150	–5.5	93	4
		–12.6	293	4
		–14.0	473	4
	10600	–3.5	93	4
		–9.8	293	4
		–12.0	473	4

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Thermooptic Coefficients—*continued*

Material	Wavelength (nm)	dn/dt (10^{-6}/K)	Temperature (K)	Ref.
TeO_2	436	30 (o)	RT	1
		25 (e)	RT	1
	644	9 (o)	RT	1
		8 (e)	RT	1
TiO_2 (rutile)	405	4 (o)	RT	1
		–9 (e)	RT	1
Tl[Br,I] KRS-5	576.9	–254	292–304	4
	1014	–240	292–304	4
	11035	–233	292–304	4
	25970	–202	292–304	4
	39380	–154	292–304	4
Tl_5AsSe_3	2–10	–45 (o)	RT	1
		36 (e)	RT	1
YVO_4	—	3.9 (o)	—	3
		8.5 (e)	—	3
YVO_4	—	3 (o)	—	3
		8.5 (e)	—	3
Y_2O_3	633	8.3	RT	1
Y_2SiO_5	546.1	9.05 (x)	298–343	3
		5.70 (y)	298–343	3
		6.73 (z)	298–343	3
$Y_3Al_5O_{12}$	457.9	11.89	303–318	2
	476.5	12.00	303–318	2
	488.8	11.60	303–318	2
	496.5	11.38	303–318	2
	501.7	11.37	303–318	2
	514.5	10.57	303–318	2
	543	9.7	298–308	3
	632.8	10.35	303–318	2
	1064.2	9.05	303–318	2
$YAlO_3$	1064	9.8 (a)	—	4
b–axis rod		14.5 (c)	—	4
$ZnGeP_2$	640	359 (o)	—	1
		376 (e)	—	1
	1000	212 (o)	—	1
		230 (e)	—	1
	10000	165 (o)	—	1
		170 (e)	—	1

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Thermooptic Coefficients—*continued*

Material	Wavelength (nm)	dn/dt (10^{-6}/K)	Temperature (K)	Ref.
β-ZnS	633	63.5	RT	1
	1150	35	93	4
		46	293	4
		49.8	RT	1
		50	473	4
	3390	28	93	4
		42	293	4
		46	473	4
	10600	27	93	4
		41	293	4
		47	473	4
β-ZnS (CVD)	633	63.5	RT	6
	1150	49.8	RT	6
	3390	45.9	RT	6
	10600	46.3	RT	6
ZnSe	633	76	93	4
		106	293	4
		121	473	4
	1150	59.7	RT	1
	3390	50	93	4
		62	293	4
		67	473	4
	10600	49	93	4
		61	293	4
		69	473	4
ZnSe (CVD)	633	1.6	RT	6
	1150	70	RT	6
	3390	62	RT	6
	10600	61	RT	6
ZrO_2:12%Y_2O_3			RT	1
	360	16	293–403	4
	458	10.0	RT	1
	633	7.9	RT	1
	800	7.2	293–403	4
	1690	6.2	293–403	4

(o) ordinary ray
(e) extraordinary ray
RT room temperature

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1.4 Mechanical Properties

1.4.1 Elastic Constants

The following tables are from the *CRC Handbook of Chemistry and Physics*, 82nd edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 2001), p. 12–37, with additions from the *Handbook of Optics*, Vol. 2 (McGraw–Hill, New York, 1999) and the *Handbook of Laser Science and Technology*, Vol. IV and Suppl. (CRC Press, Boca Raton, FL, 1995).

The elastic constants C_{ij} for single crystals are given in units of 10^{11} N/m^2 (equivalent to 100 GPa or 10^{12} dyn/cm^2). The values are for room temperature.

A useful compilation of published values from various sources may be found in Simmons, G., and Wang, H., *Single Crystal Elastic Constants and Calculated Aggregate Properties: A Handbook,* 2nd edition*,* (The MIT Press, Cambridge, MA, 1971). Temperature and pressure coefficients of the elastic constants for many materials are included in *Landolt–Börnstein, New Series*, III/11, Hellwege, K.–H. and Hellwege, A. M., Eds. (Springer–Verlag, New York, 1979).

Cubic Crystals

Material	Temperature (K)	Elastic constants (10^{11} N/m^2) C_{11}	C_{12}	C_{44}	Ref.
AgBr	300	0.5920	0.3640	0.0616	48
AlAs	RT	1.163	0.576	0.541	117
$Al_{23}O_{27}N_5$	RT	3.93	1.08	1.19	117
AlSb	300	0.8939	0.4427	0.4155	2
$Ba(NO_3)_2$	293	0.2925	0.2065	0.1277	7
BaF_2	298	0.9199	0.4157	0.2568	6
$Bi_4Ge_3O_{12}$	RT	1.250	0.324	0.249	117
$Bi_4Si_3O_{12}$	RT	1.298	0.297	0.247	117
BN	RT	7.83	1.46	4.18	117
BP	RT	3.15	1.00	1.60	117
C (diamond)	RT	10.40	1.70	5.50	117
CaF_2	298	1.6420	0.4398	0.8406	8
$CaLa_2S_4$	RT	0.98	0.47	0.50	117
CdTe	298	0.5351	0.3681	0.1994	9
CsBr	298	0.3063	0.0807	0.0750	11
CsCl	298	0.3644	0.0882	0.0804	11
CsI	298	0.2446	0.0661	0.0629	11
GaAs	298	1.1877	0.5372	0.5944	17
GaP	300	1.4120	0.6253	0.7047	18
GaSb	298	0.8839	0.4033	0.4316	16
$Gd_3Ga_5O_{12}$	RT	2.85	1.14	0.897	118
$Gd_3Sc_2Al_3O_{12}$	RT	2.99	1.01	0.89	119
$Gd_3Sc_2Ga_3O_{12}$	RT	2.77	1.049	0.8036	119

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Cubic Crystals—*continued*

Material	Temperature (K)	Elastic constants (10^{11} N/m^2) C_{11}	C_{12}	C_{44}	Ref.
Ge	298	1.2835	0.4823	0.6666	20
HgTe	290	0.548	0.381	0.204	36
InAs	293	0.8329	0.4526	0.3959	23
InP	RT	1.0220	0.5760	0.4600	24
InSb	298	0.6720	0.3670	0.3020	22
KBr	298	0.3468	0.0580	0.0507	11
KCl	298	0.4069	0.0711	0.0631	11
KCN	RT	0.1940	0.1180	0.0150	32
KF	295	0.6490	0.1520	0.1232	33
KI	300	0.2710	0.0450	0.0364	42
$KMgF_3$	RT	1.32	0.396	0.485	118
$KTaO_3$	RT	4.31	1.03	1.09	117
LiBr	RT	0.3940	0.1880	0.1910	32
LiCl	295	0.4927	0.2310	0.2495	33
LiF	RT	1.1397	0.4767	0.6364	34
LiI	RT	0.2850	0.1400	0.1350	32
$Lu_3Al_5O_{12}$	RT	3.39	1.14	1.13	119
$MgAl_2O_4$	298	2.9857	1.5372	1.5758	53
MgO	298	2.9708	0.9536	1.5613	20
MnO	298	2.23	1.20	0.79	35
NaBr	300	0.3970	0.1001	0.0998	33
$NaBrO_3$	RT	0.5450	0.1910	0.1500	32
NaCl	298	0.4947	0.1288	0.1287	11
$NaClO_3$	RT	0.4920	0.1420	0.1160	50
NaF	300	0.9700	0.2380	0.2822	51
NaI	300	0.3007	0.0912	0.0733	52
NH_4Br	300	0.3414	0.0782	0.0722	3
NH_4Cl	290	0.3814	0.0866	0.0903	4
$Pb(NO_3)_2$	293	0.3729	0.2765	0.1347	29
PbF_2	300	0.8880	0.4720	0.2454	28
PbS	RT	1.26	0.162	0.171	117
PbSe	RT	1.178	0.139	0.1553	117
PbTe	303.2	1.0795	0.0764	0.1343	30
RbBr	300	0.3152	0.0500	0.0380	45
RbCl	300	0.3624	0.0612	0.0468	45
RbI	300	0.2556	0.0382	0.0278	45
Si	298	1.6578	0.6394	0.7962	46
β-SiC	RT	3.50	1.42	2.56	117
$Sr(NO_3)_2$	293	0.4255	0.2921	0.1590	29
SrF_2	300	1.2350	0.4305	0.3128	54
SrO	300	1.601	0.435	0.590	55

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Cubic Crystals—*continued*

Material	Temperature (K)	Elastic constants (10^{11} N/m^2) C_{11}	C_{12}	C_{44}	Ref.
$SrTiO_3$	RT	3.4817	1.0064	4.5455	56
ThO_2	298	3.670	1.060	0.797	61
TiC	RT	5.00	1.13	1.75	107
TlBr	298	0.3760	0.1458	0.0757	59
TlCl	RT	0.403	0.155	0.0769	117
Tl[Br,I], KRS-5	RT	0.341	0.136	0.0579	117
Tl[Br,Cl], KRS-6	RT	0.397	0.149	0.0723	117
Y_2O_3	RT	2.33	1.01	0.67	117
$Y_3Al_5O_{12}$	RT	3.49	1.21	1.14	119
$Y_3Fe_2(FeO_4)_3$	298	2.680	1.106	0.766	19
$Y_3Sc_2Ga_3O_{12}$	RT	2.75	1.00	0.85	119
$Y_{2.25}Yb_{0.75}Al_5O_{12}$	RT	4.55	1.54	1.51	119
ZnS	298	1.0462	0.6534	0.4613	68
ZnSe	298	0.8096	0.4881	0.4405	68
ZnTe	298	0.7134	0.4078	0.3115	68
ZrC	298	4.720	0.987	1.593	63

Trigonal Crystals—Point Groups 32, 3m, –3m

Material	Temp. (K)	Elastic constants (10^{11} N/m^2) C_{11}	C_{12}	C_{13}	C_{14}	C_{33}	C_{44}	Ref.
Ag_3AsS_3	RT	0.570	0.318	—	—	0.364	0.090	117
Al_2O_3	300	4.9735	1.6397	1.1220	-0.2358	4.9911	1.4739	111
$AlPO_4$	RT	1.0503	0.2934	0.6927	-0.1271	1.3353	0.2314	73
β-$Ba_3B_6O_{12}$	RT	1.238	0.603	0.494	0.123	0.533	0.078	117
$CaCO_3$	300	1.4806	0.5578	0.5464	-0.2058	0.8557	0.3269	113
Fe_2O_3	RT	2.4243	0.5464	0.1542	-0.1247	2.2734	0.8569	82
$LiCaAlF_6$	RT	1.18	0.412	0.535	±0.192	1.07	0.504	119
$LiNbO_3$	RT	2.030	0.530	0.750	0.090	2.450	0.600	114
$LiSrAlF_6$	RT	1.17	—	—	—	0.94	—	119
LaF_3	RT	1.80	0.88	0.59	<0.005	2.22	0.34	117
$LiTaO_3$	RT	2.330	0.470	0.800	-0.110	2.750	0.940	114
$NaNO_3$	RT	0.8670	0.1630	0.1600	0.0820	0.3740	0.2130	12
Se	RT	0.198	0.066	0.202	|0.069|	0.836	0.183	117
α-SiO_2	298	0.8680	0.0704	0.1191	-0.1804	1.0575	0.5820	115
Te	RT	0.3257	0.0845	0.257	|0.1238|	0.717	0.3094	117
Tourmaline*	RT	2.7066	0.6927	0.0872	-0.0774	1.6070	0.6682	82

* $Na_3Al_6Si_6O_{18}(BO_3)_2(O,H,F)_4$

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Orthorhombic Crystals—Point Groups 222, m22, mmm

Material	Temp. (K)	Elastic constants (10^{11} N/m^2)									
		C_{11}	C_{12}	C_{13}	C_{22}	C_{23}	C_{33}	C_{44}	C_{55}	C_{66}	Ref.
$Al_2SiO_3(OH,F)_2$	RT	2.8136	1.2582	0.8464	3.8495	0.8815	2.9452	1.0811	1.3298	1.3089	82
$BaSO_4$	RT	0.8941	0.4614	0.2691	0.7842	0.2676	1.0548	0.1190	0.2874	0.2778	82
$BeAl_2O_4$	RT	4.32	—	—	4.64	—	5.11	1.45	1.52	1.42	120
$CaCO_3$	RT	1.5958	0.3663	0.0197	0.8697	0.1597	0.8503	0.4132	0.2564	0.4274	82
$CaSO_4$	RT	0.9382	0.1650	0.1520	1.845	0.3173	1.1180	0.3247	0.2653	0.0926	84
Cs_2SO_4	293	0.4490	0.1958	0.1815	0.4283	0.1800	0.3785	0.1326	0.1319	0.1323	81
HIO_3	RT	0.3030	0.1194	0.1169	0.5448	0.0548	0.4359	0.1835	0.2193	0.1736	73
K_2SO_4	293	0.5357	0.1999	0.2095	0.5653	0.1990	0.5523	0.195	0.1879	0.1424	81
$KB_5O_8{\cdot}4H_2O$	RT	0.582	0.229	0.174	0.359	0.231	0.255	0.164	0.046	0.057	71
$KNbO_3$	RT	2.26	0.96	—	2.70	—	2.80	0.743	0.250	0.955	117
$KTiOPO_4$	RT	1.59	—	—	1.54	—	1.75	—	—	—	117
$LiNH_4C_4H_4O_6{\cdot}4H_2O$	RT	0.3864	0.1655	0.0875	0.5393	0.2007	0.3624	0.1190	0.0667	0.2326	12
$(MgFe)SiO_3$	RT	1.876	0.686	0.605	1.578	0.561	2.085	0.700	0.592	0.544	78
$(MgFe)SiO_4$	RT	3.240	0.590	0.790	1.980	0.780	2.490	0.667	0.810	0.793	87
Mg_2SiO_4	298	3.2848	0.6390	0.6880	1.9980	0.7380	2.3530	0.6515	0.8120	0.8088	85
$MgSO_4{\cdot}7H_2O$	RT	0.325	0.174	0.182	0.288	0.182	0.315	0.078	0.156	0.090	86
$(Na,Al)SiO_3$	RT	0.716	0.261	0.297	0.632	0.297	1.378	0.196	0.248	0.423	78
$Na_2C_4H_4O_6{\cdot}2H_2O$	RT	0.461	0.286	0.320	0.547	0.352	0.665	0.124	0.031	0.098	12
$(NH_4)_2SO_4$	293	0.3607	0.1651	0.1580	0.2981	0.1456	0.3534	0.1025	0.0717	0.0974	81
$NaK(C_4H_4O_6)\cdot4H_2O$	RT	0.255	0.141	0.116	0.381	0.146	0.371	0.134	0.032	0.098	71
$NaNH_4C_4H_4O_6{\cdot}4H_2O$	RT	0.3685	0.2725	0.3083	0.5092	0.3472	0.5541	0.1058	0.0303	0.0870	12
$NiSO_4{\cdot}7H_2O$	RT	0.353	0.198	0.201	0.311	0.201	0.335	0.091	0.172	0.099	86
Rb_2SO_4	293	0.5029	0.1965	0.1999	0.5098	0.1925	0.4761	0.1626	0.1589	0.1407	81
$Sr(CHO_2)_2{\cdot}2H_2O$	RT	0.4391	0.1037	–0.149	0.3484	–0.014	0.3746	0.1538	0.1075	0.1724	12

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$SrSO_3$	RT	1.044	0.773	0.605	1.061	0.619	1.286	0.135	0.279	0.266	12
$TlSO_4$	293	0.4106	0.2573	0.2288	0.3885	0.2174	0.4268	0.1125	0.1068	0.0751	81
$ZnSO_4{\cdot}7H_2O$	RT	0.3320	0.1720	0.2000	0.2930	0.1980	0.3200	0.0780	0.1530	0.0830	86

Tetragonal Crystals—Point Groups 4, –4, 422, 4/m

Material	Temperature (K)	Elastic constants (10^{11} N/m^2)							Ref.
		C_{11}	C_{12}	C_{13}	C_{16}	C_{33}	C_{44}	C_{66}	
$CaMoO_4$	298	1.447	0.664	0.466	0.134	1.265	0.369	0.451	79
$CaWO_4$	RT	1.44	0.648	0.448	–0.142	1.26	0.369	0.461	117
$PbMoO_4$	RT	1.09	0.680	0.530	–0.140	0.920	0.267	0.335	117
$SrMoO_4$	RT	1.19	0.620	0.480	–0.120	1.04	0.349	0.420	117
$LiYF_4$	RT	1.21	0.609	0.526	–0.077	1.56	0.409	0.177	117

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Tetragonal Crystals—Point Groups 4mm, –42m, 422, 4/mmm

Material	Temperature (K)	Elastic constants (10^{11} N/m^2)						Ref.
		C_{11}	C_{12}	C_{13}	C_{33}	C_{44}	C_{66}	
$AgGaS_2$	RT	0.879	0.584	0.592	0.758	0.241	0.308	117
$BaTiO_3$	298	2.7512	1.7897	1.5156	1.6486	0.5435	1.1312	70
$CdGeAs_2$	RT	0.945	0.596	0.597	0.834	0.421	0.408	117
KH_2AsO_4	RT	0.530	–0.060	–0.020	0.370	0.120	0.070	12
KH_2PO_4	RT	0.7140	–0.049	0.1290	0.5620	0.1270	0.0628	71
MgF_2	RT	1.237	0.732	0.536	1.770	0.552	0.978	72
$NH_4H_2AsO_4$	298	0.6747	–0.106	0.1652	0.3022	0.0685	0.0639	69
$NH_4H_2PO_4$	293	0.6200	–0.050	0.1400	0.3000	0.0910	0.0610	69
$(NH_4)_3CO$	RT	0.217	0.089	0.24	0.532	0.0626	0.0045	117
$NiSO_4 \cdot 6H_2O$	RT	0.3209	0.2315	0.0209	0.2931	0.1156	0.1779	73
RbH_2PO_4	298	0.5562	–0.064	0.0279	0.4398	0.1142	0.0350	74
TeO_2	RT	0.5320	0.4860	0.2120	1.0850	0.2440	0.5520	76
TiO_2	298	2.7143	1.7796	1.4957	4.8395	1.2443	1.9477	75
$ZrSiO_4$	RT	2.585	1.791	1.542	3.805	0.733	1.113	78

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Monoclinic Crystals

Material	Temp. (K)	Elastic Constants (10^{11} N/m^2) C_{11}	C_{12}	C_{13}	C_{15}	C_{22}	Ref.
$(C_6H_5CH)_2$	RT	0.0930	0.0570	0.0670	-0.003	0.0920	94
$(CaMg)Si_2O_6$	RT	2.040	0.884	0.0883	-0.193	1.750	91
$C_{14}H_{10}$	RT	0.0852	0.0672	0.0590	-0.0192	0.1170	90
$CoSO_4 \cdot 7H_2O$	RT	0.335	0.205	0.158	0.016	0.378	86
$FeSO_4 \cdot 7H_2O$	RT	0.349	0.208	0.174	-0.020	0.376	86
$K_2C_4H_4O_6$	RT	0.3110	0.1720	0.1690	0.0287	0.3900	32
$KAlSi_3O_8$	RT	0.664	0.438	0.259	-0.033	1.710	92
$KHC_4H_4O_6$	RT	0.4294	0.1399	0.3129	-0.0105	0.3460	12
$Li_2SO_4 \cdot H_2O$	RT	0.5250	0.1715	0.1730	-0.0196	0.5060	32
$(NaFe)Si_2O_6$	RT	1.858	0.685	0.707	0.098	1.813	89
$(NH_2CH_2COOH)_3 \cdot H_2SO_4$ (TGS)	RT	0.4550	0.1720	0.1980	-0.030	0.3210	32
$Na_2S_2O_3$	RT	0.3323	0.1814	0.1875	0.0225	0.2953	12
Y_2SiO_5	RT	0.658	—	—	±0.706	1.85	119

Monoclinic Crystals—*continued*

Material	Elastic Constants (10^{11} N/m^2) C_{23}	C_{25}	C_{33}	C_{35}	C_{44}	C_{46}	C_{55}	C_{66}
$(C_6H_5CH)_2$	0.0485	-0.005	0.0790	-0.005	0.0325	0.0050	0.0640	0.0245
$(CaMg)Si_2O_6$	0.482	-0.196	2.380	-0.336	0.675	-0.113	0.588	0.705
$C_{14}H_{10}$	0.0375	-0.0170	0.1522	-0.0187	0.0272	0.0138	0.0242	0.0399
$CoSO_4 \cdot 7H_2O$	0.158	-0.018	0.371	-0.047	0.060	0.016	0.058	0.101
$FeSO_4 \cdot 7H_2O$	0.172	-0.019	0.360	-0.014	0.064	0.001	0.056	0.096
$K_2C_4H_4O_6$	0.1330	0.0182	0.5540	0.0710	0.0870	0.0072	0.1040	0.0826
$KAlSi_3O_8$	0.192	-0.148	1.215	-0.131	0.143	-0.015	0.238	0.361
$KHC_4H_4O_6$	0.1173	0.0176	0.6816	0.0294	0.0961	-0.0044	0.1270	0.0841
$Li_2SO_4 \cdot H_2O$	0.0368	0.0571	0.5400	-0.0254	0.1400	-0.0054	0.1565	0.2770
$(NaFe)Si_2O_6$	0.626	0.094	2.344	0.214	0.692	0.077	0.510	0.474
$(NH_2CH_2CO\text{-}OH)_3 \cdot H_2SO_4$	0.2080	-0.0036	0.2630	-0.0500	0.0950	-0.0026	0.1110	0.0620
$Na_2S_2O_3$	0.1713	0.0983	0.4590	-0.0678	0.0569	-0.0268	0.1070	0.0598
Y_2SiO_5	—	—	0.835	±0.330	0.465	±0.0014	1.87	0.656

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Hexagonal Crystals—Point Groups 6, –6, 622, 6mm, –62m, 6/mmm

Material	Temp. (K)	Elastic Constants (10^{11} N/m^2) C_{11}	C_{12}	C_{13}	C_{33}	C_{44}	Ref.
β-AgI	RT	0.293	0.213	0.196	0.354	0.0373	117
AlN	RT	3.45	1.25	1.20	3.95	1.18	117
$Be_3Al_2Si_6O_{18}$	RT	2.800	0.990	0.670	2.480	0.658	12
BeO	RT	4.70	1.68	1.19	4.94	1.53	96
$Ca_5(PO_4)3(OH,F,Cl)$	RT	1.667	0.131	0.655	1.396	0.663	12
CdS	298	0.8431	0.5208	0.4567	0.9183	0.1458	98
CdSe	298	0.7046	0.4516	0.3930	0.8355	0.1317	68
GaN	RT	2.96	1.30	1.58	2.67	2.41	117
$LiTiO_3$	RT	0.8124	0.3184	0.0925	0.529	0.1783	117
α-SiC	RT	5.02	0.95	056	5.65	1.69	117
TiB_2	RT	6.90	4.10	3.20	4.40	2.50	107
ZnO	298	2.0970	1.2110	1.0510	2.1090	0.4247	110
ZnS	298	1.2420	0.6015	0.4554	1.4000	0.2864	96

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1.4.2 Elastic Moduli

The mechanical response of a material to an applied force is described by various moduli. Young's modulus E (extension in tension) and the modulus of rigidity or shear G are related to Poisson's ratio μ (ratio of lateral to longitudinal strain under unilateral stress) by $\mu = E/2G) - 1$. The bulk modulus B (1/isothermal compressibility) is related to the above moduli by $B = E/3(1 - \mu)$.

Elastic Moduli

		Moduli		
Material	**Poisson's ratio**	**Young's E (GPa)**	**Rigidity G (GPa)**	**Bulk B (GPa)**
Ag_3AsS_3	0.38	28	10	37
AgBr	0.39	24.7	8.8	40.5
AgCl	0.41	22.9	8.1	44.0
$AgGaS_2$	0.37	52	19	67
β–AgI	0.4	12	4.4	24
AlAs	0.27	108	42.4	77.2
AlN	0.26	294	117	202
Al_2O_3	0.23	400	162	250
ALON	0.24	317	128	203
BaB_2O_4	0.41	30	11	60.6
BaF_2	0.31	65.8	25.1	57.6
$BaTiO_3$	0.36	145	53	174
$BeAl_2O_4$	—	469	—	—
BeO	0.23	395	162	240
$Bi_{12}GeO_{20}$	0.28	82	32	63.3
$Bi_{12}SiO_{20}$	0.28	84	33	63.1
BN	0.11	833	375	358
BP	0.19	324	136	172
C (diamond)	0.10	1100	500	460
$CaCO_3$	0.31	83	32	73.2
CaF_2	0.29	110	42.5	85.7
$CaLa_2S_4$	0.25	96	38.4	64
$CaMoO_4$	0.29	103	40	80
$CaWO_4$	0.29	96	37	78
$CdGeS_2$	0.32	74	28	70
CdS	0.38	42	15	59
CdSe	0.37	42	15.3	53
CdTe	0.35	8.4	14.2	42.9
CsBr	0.27	22	8.8	15.8
CsCl	0.27	25	10.0	18.2
CsI	0.26	18	7.3	12.6
CuCl	0.30	24.8	8.9	39.3
GaAs	0.24	116	46.6	75.0
GaN	0.25	294	118	195
GaP	0.24	140	56.5	89.3

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Elastic Moduli—*continued*

Material	Poisson's ratio	Moduli		
		Young's E (GPa)	Rigidity G (GPa)	Bulk B (GPa)
Ge	0.20	132	54.8	75.0
InAs	0.30	74	28	61
InP	0.30	89	34	72.7
KBr	0.30	18	7.2	15.2
KCl	0.29	22	8.5	18.4
KF	0.28	41	16	31.8
KH_2PO_4	0.26	38	15	28
KI	0.30	14	5.5	11.9
$KNbO_3$	0.22	250	71	95
$KTaO_3$	0.27	316	124	230
LaF_3	0.32	120	46	100
LiF	0.22	110	45	65.0
$LiIO_3$	0.23	55	22.4	33.5
$LiNbO_3$	0.25	170	68	112
$LiSrAlF_6$	0.3	109	—	—
$LiYF_4$	0.32	85	32	81
$MgAl_2O_4$	0.26	276	109	198
MgF_2	0.26	137	53.9	99.1
MgO	0.18	310	131	163
NaBr	0.26	29	11.6	19.9
NaCl	0.26	37	14.5	25.3
NaF	0.24	76	30.7	48.5
NaI	0.28	22	8.4	16.1
$[NH_4]_2CO$	0.41	~9	~3	17
$NH_4H_2PO_4$	0.32	29	11	27.9
PbF_2	0.33	59.8	22.4	60.5
$PbMoO_4$	0.35	66	24	72
PbS	0.28	70.2	27.5	52.8
PbSe	0.28	64.8	25.4	48.5
PbTe	0.26	56.9	22.6	39.8
Se	0.27	24	9	17
Si	0.22	162	66.2	97.7
α–SiC	0.16	455	197	221
β–SiC	0.17	447	191	224
β–SiC (CVD)	0.21	466	—	—
SiO_2, α–quartz	0.08	95	44	38
SrF_2	0.29	89	34.6	71.3
$SrMoO_4$	0.30	87	33	73
$SrTiO_3$	0.23	283	115	174
Te	0.25	35	14	24
TeO_2	0.33	45	17	46
TiO_2	0.27	293	115	215

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Elastic Moduli—*continued*

Material	Poisson's ratio	Moduli		
		Young's E (GPa)	Rigidity G (GPa)	Bulk B (GPa)
TlBr	0.32	24	8.9	22.4
Tl[Br,I] KRS-5	0.34	19.6	7.3	20.4
TlCl	0.33	25	9.3	23.8
Tl[Br,Cl], KRS-6	0.33	24	9.0	32.2
$Y_3Al_5O_{12}$	0.24	280	113	180
$Y_3Fe_5O_{12}$	0.29	200	—	—
Y_2O_3	0.30	173	67	145
ZnO	0.35	127	47	144
α-ZnS	0.30	87	33	74
β-ZnS	0.32	82.5	31.2	76.6
β-ZnS (CVD)	0.29	74.5	—	—
ZnSe	0.30	75.4	29.1	61.8
ZnSe (CVD)	0.28	70.3		
ZnTe	0.30	61.1	23.5	51.0
ZrO_2: 12%Y_2O_3	0.31	233	88.6	205

The above table was adapted from Tropf, W. J., Thomas, M. F., and Harris, T. J., Properties of crystals and glasses, *Handbook of Optics,* Vol. II (McGraw-Hill, New York, 1995), p. 33.48.

1.4.3 Engineering Data

The following engineering properties can depend on the production method and exhibit sample–to–sample variations. Material strength may also depend on subsurface damage resulting from grinding and polishing. Therefore, the data should be considered only as a guide.

Engineering Data

Material	Flexure strength (MPa)	Fracture toughness (MPa $m^{1/2}$)	Volume compressibility (Tpa^{-1})	Ref.
AgCl	26			1
AgSb			57.1	4
Al_2O_3	1200	3	1.36 || c	1
			1.22 || a	1
AlN	225	3		1
$Al_{23}O_{27}N_5$	310	1.4		1
α-AgI			41	4
BaB_2O_4		1.5		1
BaF_2	27			1
$Be_3Al_2Si_6O_{18}$			6.65	2
BeO	275			1
C (diamond)	2940	2.0		1

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Engineering Data—*continued*

Material	Flexure strength (MPa)	Fracture toughness (MPa $m^{1/2}$)	Volume compressibility (TPa^{-1})	Ref.
$Ca_5(PO_4)_3F$			13.2	2
CaF_2	90	0.5	11.64	1,2
$CaLa_2S_4$	81	0.68		1
$CaMoO_4$			12.5	2
$CaWO_4$			13.3	2
CdS	28			1
CdSe	21			1
$CdSiAs_2S_4$			4.3	4
CdTe	26			1
CsBr	8.4			1
CsI	5.6			1
GaAs	55		77.1	1,4
GaN	70			1
GaP	100	0.9	11.0	1,4
GaSbs			45.7	4
$Gd_2(MoO_4)_3$			27.2	2
$Gd_3Ga_5O_{12}$			5.88	2
$Gd_3Sc_2Ga_3O_{12}$		1.2		3
Ge	100	0.66		1
InAs			54.9	4
InP			73.5	4
InSb			44.2	4
KBr	11			1
KCl	10			1
$KMgO_3$			14.4	2
LaB_3O_6		1.9 (111)		
		0.38 (10–1)		
LaF_3	33			1
LiB_3O_5		2.0		
$LiCaAlF_6$		0.18 $\parallel$ c		3
		0.37 $\perp$ c		3
LiF	27		15.05	1,2
$LiNbO_3$			8.8	2
$LiSrAlF_6$		0.40 $\parallel$ c		3
$LiYF_4$	35			1
$Lu_3Al_5O_{12}$		1.1		3
$MgAl_2O_4$	170	1.5		1
MgF_2	100		10.1	1
MgO	130	1.0	6.2	1
MnF_2			4.3 $\parallel$ a	2
			2.0 $\perp$ c	2

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Engineering Data—*continued*

Material	Flexure strength (MPa)	Fracture toughness (MPa $m^{1/2}$)	Volume compressibility (TPa^{-1})	Ref.
NaCl	9.6			1
Si	130	0.95		1
β-SiC	250			1
β-SiC (CVD)		3.3		
$Sr_5(PO_4)_3F$		0.51		3
$Sr_5(VO_4)_3F$		0.36 || c		3
Te	11			1
Tl[Br,Cl], KRS-6	21			1
Tl[Br,I] KRS-5	26			1
$Y_{2.25}Yb_{0.75}Al_5O_{12}$		1.3		3
Y_2O_3	150	0.7		1
Y_2SiO_5		0.54 || a		3
		0.70 || b		3
		0.78 || c		3
$Y_3Al_5O_{12}$		1.0, 1.4		3
$Y_3Al_5O_{12}$			5.34	2
$Y_3Fe_5O_{12}$			6.15	2
$Y_3Ga_5O_{12}$			5.73	2
α-ZnS	69			1
β-ZnS (CVD)	60	0.8		1
ZnSe	55	0.32		1
ZnSe (CVD)	52	≈ 1		
ZnTe	24			1
ZrO_2: 12%Y_2O_3	200	2.0		1

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1.5 Thermal Properties

1.5.1 Melting Point, Heat Capacity, Thermal Expansion, and Thermal Conductivity

Values for the heat capacity and the thermal expansion coefficient are those at or near room temperature; thermal conductivity values are for the temperatures T indicated.

Thermal Properties

Material	Melting point (K)	Heat capacity (J/g K)	Thermal expansion (10^{-6} K)	Thermal conductivity (W/ m K)	T (K)	Ref.
Ag_3AsS_3	763					1
AgBr	705	0.2790	33.8	1.11	250	2
				0.93	300	2
				0.57	500	2
AgCl	728	0.3544	32.4	1.25	250	2
				1.12	295	1
				1.1	373	4
$AgGaS_2$	1269	0.40	28.5 || a	1.5	300	1
			–18.7 || c			1
$AgGaSe_2$	1129	0.30	35.5 || a	1.1	300	1
			–15.0 || c			1
$AgGaTe_2$	990			1.0	300	3
β-AgI	423p	0.242		0.4	300	2
Al_2O_3	2319	0.777	6.65 || a	58	250	2
			7.15 || c	46	300	2
				24.2	500	2
$Al_6Si_2O_{13}$	2190	0.75				2
AlAs	2013	0.452	3.5			1
			3.1	84	300	3
AlN	3273	0.796	5.27 || a	500	250	2
			4.15 || c	320	300	2
				150	500	2
ALON	2323	0.830	5.66	12.6	300	2
				7.0	500	2
AlP	2820			92	300	3
$AlPO_4$	>1730		2.9	~6	300	1
AlSb	1330		4.2	60	300	3

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Thermal Properties—*continued*

Material	Melting point (K)	Heat capacity (J/g K)	Thermal expansion (10^{-6} K)	Thermal conductivity (W/ m K)	T (K)	Ref.
BaB_2O_4	1200p	0.49	4 || a	1.2 || a	300	2
	1370		34 || c	1.6 || c	300	2
BaF_2	1550	0.4474	18.4	7.5	250	2
				12	300	2
				10.5	370	4
BaF_2-CaF_2	1330	0.13	21.0			1
$Ba_3Lu\ (BO_3)_3$	1540					
$BaTiO_3$	278p	0.439	16.8 || a	6	300	2
	406p		–9.07 || c			2
	1870					1
BaY_2F_8	1230		17 || a	6	300	5
			18.7 || b			5
			19.4 || c			5
$Ba_2NaNb_5O_{12}$	1710	28.5 || a	10.4 || a,b			5
		–18.7 || c	11.4 || c			5
$BeAl_2O_4$	2140	0.830	6.3 || a	23	300	5
			6.0 || b			5
			6.5 || c			5
Be_2SiO_4		0.84		3.3	300	2
$Be_3Al_2Si_6O_{18}$	1730	0.84	2.1 || a	5	300	1
			2.7 || c			1
BeO	2373p	1.028	5.64 || a	420	250	2
	2725		7.47 || c	350	300	2
				200	500	2
BiB_3O_6		0.5 (330 K)	48.1 (x)			
			44 (y)			
			–26.9 (z)			
$Bi_4Ge_3O_{12}$	1320		7			1
$Bi_{12}GeO_{20}$	1200		16.8			1
Bi_2Te_3	853			2.8	204	4
				3.6	303	4
				4.6	370	4
BN	1100p	0.513	3.5	760	300	2
	3240			36.2	1047	1,4
BP	1400d	0.71	3.65	460	250	2

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Thermal Properties—*continued*

Material	Melting point (K)	Heat capacity (J/g K)	Thermal expansion (10^{-6} K)	Thermal conductivity (W/ m K)	T (K)	Ref.
BP				360	300	2
C (diamond)	1770p	0.5169	1.25	2800	250	2
				2200	300	2
C (diamond)				1300	500	2
$Ca(NbO_3)_2$	1830					5
$Ca_2Al_2SiO_7$	1860		11.4 || a	3 || c	300	6
				4.4 ⊥ c	300	6
$Ca_3Gd_2(BO_3)_3$	1680					
$Ca_3Y_2(BO_3)_3$	1630					
$Ca_5(PO_4)_3F$	1920	0.745	9.4 || a			5
			10 || c			5
$CaCO_3$ (calcite)	323p	0.8820	–3.7 || a	5.1 || a	250	2
	1610		25.1 || c	6.2 || c	250	2
				4.5 || a	300	2
				5.4 || c	300	2
				3.4 || a	500	2
				4.2 || c	500	2
CaF_2	1424p	0.9113	18.9	39.0	83	5
	1630			13	250	2
				9.7	300	1,2
				5.5	500	2
$CaLa_2S_4$	2083	0.36	14.6	1.7	300	2
				1.5	500	2
$CaMoO_4$	1750	0.690	19 || a	3.95 || a	300	5
			25 || c	3.82 || c	300	5
CaO	2890	0.75		18	450	1
$CaTiO_3$	2250					7
$CaWO_4$	1855	0.396	6.35 || a	6	300	1,2
			12.38 || c	11.3	422	2,4
$CaY_4(SiO_4)O$	2320		7.1 || a			5
			5.1 || c			5
$CdCl_2$	781					1
CdF_2	1370		27			1
$CdGeS_2$	900p		8.4 || a			2
	943		0.25 || c			2

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Thermal Properties—*continued*

Material	Melting point (K)	Heat capacity (J/g K)	Thermal expansion (10^{-6} K)	Thermal conductivity (W/ m K)	T (K)	Ref.
CdI_2	760					1
CdS	1560	0.3814	4.6 || a	27	300	2
CdS			2.5 || c	13	500	2
CdSe	1580	0.272	4.9 || a	9	300	1,2
			2.9 || c			2
CdTe	1320	0.210	5.0	8.2	250	2
				6.3	300	2
CsBr	908	0.2432	47.2	1.2	223	4
				0.85	300	2
				0.77	373	4
CsCl	918	0.3116	45.0	0.84	360	3
CsF	955	0.33	32	4.2	300	2
CsI	898	0.2032	48.6	1.4	223	4
				1.05	300	2
				0.95	373	4
$CsLiB_6O_{10}$	1120					
Cu_2GeS_3	1210	0.51	7.2	1.2	300	3
Cu_2GeSe_3	1030	0.34	8.4	2.4	300	3
Cu_2SnS_3	1110	0.44	7.8	2.8	300	3
Cu_2SnSe_3	960	0.31	8.9	3.5	300	3
CuBr	777		19			1
CuCl	700	0.490	14.6	1.0	250	2
				0.8	300	2
				0.5	500	2
CuF	1181					3
$CuGaS_2$	1553	0.452	11.2 || a			2
			6.9 || c			2
$CuGase_2$	1970		5.4	4.2	300	3
$CuGaTe_2$	2400		6.9	2.7	300	3
$CuInSe_2$	1600		6.6	3.7	300	3
$CuInTe_2$	1660		7.1	4.9	300	3
$CuSnTe_3$	680			14.4	300	3
Ga_2O_3	2170	0.46				1

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Thermal Properties—*continued*

Material	Melting point (K)	Heat capacity (J/g K)	Thermal expansion (10^{-6} K)	Thermal conductivity (W/ m K)	T (K)	Ref.
Ga_2Se_3	1020		8.9	50	300	3
Ga_2Te_3	1063			47	300	3
GaAs	1511	0.345	5.0	65	250	2
				54	300	2
				27	500	2
α-GaN	1160d	0.49	3.17 || a	130 || c	300	2
	2370		5.59 || c			2
GaP	1740	0.435	5.3	120	250	2
				100	300	2
				45	500	2
GaS	1240					7
GaSe	1235					7
GaSb	720	0.079	6.9	44	300	1,2
$Gd_2(MoO_4)_3$	1410	0.42				5
$Gd_3Ga_5O_{12}$	2100			60	70	5
				9.0	300	1
$Gd_3Sc_2Al_3O_{12}$	2110	0.424	6.9	5.6	300	6
$Gd_3Sc_2Ga_3O_{12}$	2130	0.4023	7.32	6.1	300	6
Ge	1211	0.3230	5.7	74.9	250	2
				59.9	300	2
				33.8	500	2
GeO_2	1360	0.54	4.5			1
HgI_2	532					7
Hg_2I_2	563					7
$Gd_2(MoO_4)_3$	1410	0.42				5
$Gd_3Ga_5O_{12}$	2100			60	70	5
				9.0	300	1
$Gd_3Sc_2Al_3O_{12}$	2110	0.424	6.9	5.6	300	6
$Gd_3Sc_2Ga_3O_{12}$	2130	0.4023	7.32	6.1	300	6
Ge	1211	0.3230	5.7	74.9	250	2
Ge				59.9	300	2
				33.8	500	2
GeO_2	1360	0.54	4.5			1

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Thermal Properties—*continued*

Material	Melting point (K)	Heat capacity (J/g K)	Thermal expansion (10^{-6} K)	Thermal conductivity (W/ m K)	T (K)	Ref.
HgI_2	532					7
Hg_2I_2	563					7
HgInSe2	1053			3.0	300	3
HgInTe2	1053			3.0	300	3
HgS	857s	0.21				1
HgSe	Subl.		4.8	5.5	110	1
HgTe	943		4.8	12	100	1
InAs	1216	0.2518	4.4	50	250	2
				27.3	300	2
				15	500	2
α-InN	1373	0.32	2.9–3.8	55.6	300	3
InP	1345	0.3117	4.5	90	250	2
				68	300	2
				32	500	2
InSb	798	0.144	4.7	16	300	3
$KAl_3Si_3O_{10}(OH)_2$	1473–1573	0.87	27	0.25–0.59	293	8
KBr	1007	0.4400	38.5	5.5	250	2
				4.8	300	2
				2.4	500	2
KCl	104	0.6936	36.5	8.5	250	2
				6.7	300	2
				3.8	500	2
KF	1131	0.8659	31.4	8.3	300	2
KH_2PO_4	123p	0.88	22.0 || a	2.0	250	2
	450p		39.2 || c	2.1	300	2
	526					2
KI	954	0.3192	40.3	2.1	300	2
$KNbO_3$	223p		37			2
	498p					2
$KTaO_3$				0.2	250	2
$KTaO_3$				0.17	300	2
$KTiOPO_4$	1210p	0.728	11 || a	2.0 || a	300	2
	1423		9 || b	3.0 || b	300	2
			0.6 || c	3.3 || c	300	2

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Thermal Properties—*continued*

Material	Melting point (K)	Heat capacity (J/g K)	Thermal expansion (10^{-6} K)	Thermal conductivity (W/ m K)	T (K)	Ref.
K_2NaAlF_6	1210					6
$La_2B_6O_{10}$	1107p					2
$La_2Be_2O_5$	1630		7–7.9 ⊥	4.7	300	1
			9.50 || c			1
			10			
$LaAlO_3$	2350					
LaB_3O_6	1420					
LaF_3	1700	0.508	15.8 || a	5.4	250	2
			11.0 || c	5.1	300	2
$LaCl_3$	1130	0.422				5
La_2O_2S			6 || c			5
			3 || a			5
LiBr	823					1
$LiCaAlF_6$	1100	0.935	3.6 || c	5.14 || c	300	6
			22 || c	4.58 ⊥ c	300	6
LiCl	878	1.2	44			1
LiF	1115	1.6200	34.4	19	250	2
				14	300	2
				7.5	500	2
$LiGdF_4$	1010					
LiI	720		58			2
$LiIO_3$	520p		28 || a			2
	693		48 || c			2
$LiNbO_3$	1523	0.63	14.8 || a	5.6	300	2
			4.1 || c			2
$LiSrAlF_6$	1065		–10.0 || c	3.09 ||c		6
			18.8 || c			6
$LiTaO_3$	1932	0.42	4.1 || c			6
			16.1 || c			6
$LiYF_4$	1092	0.79	13.3 || a	6.3	300	2
$LiYF_4$			8.3 || c			2
$Lu_3Al_5O_{12}$	2260		8.8	31	300	6
$MgAl_2O_4$	2408	0.8191	6.97	30	250	2
				25	300	2

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Thermal Properties—*continued*

Material	Melting point (K)	Heat capacity (J/g K)	Thermal expansion (10^{-6} K)	Thermal conductivity (W/ m K)	T (K)	Ref.
Mg_2SiO_4	2160	0.74	8.7 || a			5
			15.4 || b			5
			13.3 || c			5
MgF_2	1536	1.0236	9.4 || a	30 || a	300	2
			13.6 || c	21 || c	300	2
MgO	3073	0.9235	10.6	73	250	2
				59	300	2
				32	500	2
MnF_2	1130	0.75	6.1			1
MnO	2112	0.67	13			1
Na_3AlF_6	1000					1
NaBr	1028	0.5046	41.8	5.6	300	2
NaCl	1074	0.8699	41.1	8	250	2
				6.5	300	2
				4	500	2
NaF	1266	1.1239	33.5	22	250	2
				17	500	2
NaI	934	0.3502	44.7	4.7	500	2
$NaNO_3$	580	1.05	11 || a			1
			12 || c			1
$[NH_4]_2CO$	408	1.551				1
$NH_4H_2PO_4$	148p	1.26	27.2 || a	1.26 || a	300	2
	463		10.7 || c	0.71 || c	300	1,2
$PbCl_2$	774	0.27	31			1
PbF_2	422p	0.3029	29.0	28	300	2
	1094					1
PbI_2	685	0.27	31			7
	1145d					
$PbMoO_4$	1338	0.326	8.7 || a			2
$PbMoO_4$			20.3 || c			2
PbO (massicot)	1160	2.0				1
PbS	1390	0.209	19.0	2.5	300	2
PbSe	1338	0.175	19.4	2	250	2
				1.7	300	2

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Thermal Properties—*continued*

Material	Melting point (K)	Heat capacity (J/g K)	Thermal expansion (10^{-6} K)	Thermal conductivity (W/ m K)	T (K)	Ref.
PbSe				1	500	2
PbTe	1190	0.151	19.8	2.5	250	2
				2.3	300	2
				1.8	500	2
$PbTiO_3$	763p			4	300	2
				2.8	500	2
RbBr	966	0.31		12.2	105	1
RbCl	991	0.42	36	7.6	124	1
RbI	920	0.24	39	9.9	84	1
Se	490	0.3212	69.0 || a	1.5 || a	250	2
			–0.3 || c	5.1 || c	250	2
				1.3 || a	300	2
				4.5 || c	300	2
Si	1680	0.7139	2.62	191	250	2
				140	300	2
				73.6	500	2
Si_3N_4	>2300		1.1 || a	33	300	1
			2.1 || c			1
SiO_2 (α-quartz)	845p	0.7400	12.38 || a	7.5 || a	250	2
			6.88 || c	12.7 || c	250	2
				6.2 || a	300	2
				10.4 || c	300	2
				3.9 || a	500	2
				6.0 || c	500	2
α-SiC	3110	0.690		450 || a	300	2
β-SiC	3103d	0.670	2.77	490	300	2
SrF_2	1710	0.6200	18.1	11	250	2
				8.3	300	2
$SrGaO_4$	1870					
$SrGdGa_3O_7$	1870					6
$SrLaAl\ O_4$	1920					
$SrMoO_4$	1763	0.619		4.0 || a	300	2
				4.2 || c	300	2
$SrTiO_3$	110p	0.536	8.3	12.5	250	2
	2358			11.2	300	2
$Sr_3Y(BO_3)_3$	1670					

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Thermal Properties—*continued*

Material	Melting point (K)	Heat capacity (J/g K)	Thermal expansion (10^{-6} K)	Thermal conductivity (W/ m K)	T (K)	Ref.
$Sr_3Y_4(SiO_4)_3O$	2270					
$Sr_5(PO_4)_3F$	2040	0.50		2.0	300	6
$Sr_5(VO_4)_3F$	1920	0.513	7.3 || a			6
			10.8 ⊥ c			6
Ta_2O_5	2140					1
Te	621p	0.202	27.5 || a	2.5 || a	250	2
	723		–1.6 || c	4.9 || c	250	2
				2.1 || a	300	2
				3.9 || c	300	2
				1.5 || a	500	2
				2.5 || c	500	2
TeO_2	1006	0.41	15.0 || a	3	295	1,2
			4.9 || c			2
ThO_2	3600	0.24	7.8	15	300	1
TiO_2	2128	0.6910	6.86 || a	8.3 || a	250	2
rutile			8.97 || c	11.8 || c	250	2
				7.4 || a	300	2
				10.4 || c	300	2
				5.5 || a	500	2
				8.0 || c	500	2
Tl[Br,Cl]	697	0.201	51	0.50	300	2
Tl[Br,I]	687	0.16	58	0.32	300	2
Tl_3AsSe_3	583	0.19	28 || a	0.35	300	2
			18 || c			2
TlBr	740	0.1778	51	0.53	300	2
TlCl	703	0.2198	52.7	0.74	300	2
Y_2O_3	2650	0.4567	6.56	13.5	300	2
$YAlO_3$	2140	0.42	4.3–9.5 ⊥ c	11	323	1
			11 || c			1
$YCa_4O(BO_3)_3$			7.38 (ave)	2.60 || a	300	
				2.33 || b	300	
				3.01 || c	300	
YVO_4	~2100		11.4 || a	5.1 || a	300	1,6
			4.4 ⊥ c	5.2 || c	300	1,6
$Y_3Al_5O_{12}$	2220	0.625	7.7	14.5	226	6
				13.4	300	1,2

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Thermal Properties—*continued*

Material	Melting point (K)	Heat capacity (J/g K)	Thermal expansion (10^{-6} K)	Thermal conductivity (W/ m K)	T (K)	Ref.
				9.5	322	6
$Y_3Fe_5O_{12}$	1830		10.4	41.0	70	5
				7.4	300	5
$Y_3Ga_5O_{12}$	2100			39	70	5
				9.0	300	5
$Y_3Sc_2Al_3O_{12}$	2170	0.57	6.5	11	300	6
$Y_3Sc_2Ga_3O_{12}$	2180	0.534	8.1	7.3	300	6
$ZnCl_2$	563	0.525		0.313	562.9	8
ZnF_2	1140	0.63	9.8			1
$ZnGeAs_2$	1150			11	300	3
$ZnGeP_2$	1225p		7.8 || a	18	300	3
	1300		5.0 || c			3
ZnO	2248	0.495	6.5 || a	30	300	2
			3.7 || c	15	500	2
α-ZnS	2100	0.4723	6.54 || a			2
			4.59 || c			2
β-ZnS	1293p	0.4732	6.8	16.7	300	2
ZnSe	1790	0.339	7.1	13	300	2
$ZnSnAs_2$	1048			15	300	3
$ZnSnSb_2$	870			7.6	300	3
ZnTe	1510	0.218	8.4	10	300	1
ZrO_2	~3000	0.42	8.8	10.5	260	1
ZrO_2:	3110	0.46	10.2	1.8	300	2
$12\%Y_2O_3$				1.9	500	2
$ZrSiO_4$	2820	2.7		6.3	300	1

p – phase change, d – decomposes

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1.5.2 Temperature Dependence of Heat Capacity for Selected Solids

Temperature dependence of the molar heat capacity at constant pressure for representative crystalline solids and semiconductors in the range 200 to 600 K.

Molar Heat Capacity C_p in J/mol K

Name	200 K	250 K	300 K	400 K	500 K	600 K
Al_2O_3	51.12	67.05	79.45	88.91	106.17	112.55
$CaCO_3$	66.50	75.66	83.82	91.51	104.52	109.86
CaO	33.64	38.59	42.18	45.07	49.33	50.72
CsCl	50.13	51.34	52.48	53.58	56.90	59.10
Cu_2O	34.80	—	42.41	44.95	49.19	50.83
$CuSO_4$	77.01	89.25	99.25	107.65	127.19	136.31
Ge	—	—	23.25	23.85	24.96	25.45
KCl	48.44	50.10	51.37	52.31	54.71	56.35
LiCl	43.35	46.08	48.10	49.66	53.34	55.59
MgO	—	—	37.38	40.59	45.56	47.30
NaCl	46.89	48.85	50.21	51.25	53.96	55.81
Si	15.64	18.22	20.04	21.28	23.33	24.15
SiO_2	32.64	39.21	44.77	49.47	59.64	64.42

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1.5.3 Debye Temperature

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Material	Debye temperature (K)	Ref.
AgBr	145	1
AgCl	162	1
$AgGaS_2$	255	1
$AgGaSe_2$	156	1
$AgGaTe_2$	212	2
β-AgI	116	1
Al_2O_3	1030	1
AlAs	417	2
AlN	950	1
AlP	588	2
AlSb	292	2
BaF_2	283	1
BeO	1280	1
BN	1900	1
BP	985	1
C (diamond)	2240	1
CaF_2	510	1
$CdGeS_2$	253	1
CdS	215	1
CdSe	181	1
$CdSiP_2$	282	2
$CdSnP_2$	195	2
CdTe	160	1
CsBr	145	1
CsCl	175	1
CsI	124	1
Cu_2GeS_3	254	2
Cu_2GeSe_3	168	2
Cu_2SnS_3	214	2
Cu_2SnSe_3	148	2
Cu_3AsSe_4	169	2
Cu_3SbSe_4	212	2
CuCl	179	1
$CuGaS_2$	356	1
$CuInTe_2$	195	2
GaAs	344	1
GaP	460	1
GaSb	320	2
Ge	380	1
HgTe	242	2
InP	321	2
InAs	249	2
InSb	144	2
KBr	174	1
KCl	235	1
KF	336	1
KI	132	1
$KTaO_3$	311	1
LaF_3	392	1
LiF	735	1
$LiNbO_3$	560	1
$MgAl_2O_4$	850	1
MgF_2	535	1
MgO	950	1
NaBr	225	1
NaCl	321	1
NaF	492	1
NaI	164	1
PbF_2	225	1
PbS	227	1
PbSe	138	1
PbTe	125	1
Se	151	1
Si	645	1
β-SiC	1000	1
SiO_2, α-quartz	271	1
SrF_2	378	1
Te	152	1
TiO_2	760	1
Tl[Br,Cl], KRS-6	120	1
Tl[Br,I] KRS-5	110	1
TlBr	116	1
TlCl	126	1
Y_2O_3	465	1
$Y_3Al_5O_{12}$	754	1
$ZnGeAs_2$	271	2
$ZnGeP_2$	428	1
ZnO	416	1
α-ZnS	351	1
β-ZnS	340	1
ZnSe	270	1
ZnTe	225	1
ZrO_2:12%Y_2O_3	563	1

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1.6 Magnetooptic Properties

1.6.1 Diamagnetic Materials

Verdet Constants V of Diamagnetic Crystals (room temperature)*

Crystal	Wavelength (nm)	V (rad/(m T))	CTE α (10^{-6}/K)	(1/V)dVdT + α (10^{-4}/K)	Ref.
AgBr	633	26.8			1
AgCl	633	22.8	30	3.2	1
Al_2O_3	546	4.0			3
	589	3.5			3
BaF_2	633	3.75	19	–0.2	1
$Ba(NO_3)_2$	633	2.9	17.5	0.7	1
$BaTaO_3$ (403 K)	427	276			16
	496	111			16
	620	52.4			16
	826	21.0			16
$BaTiO_3$	620	–51.0			3
$Bi_4Ge_3O_{12}$	442	84.1			4
	633	30.1		2.0	2
	633	28.8			4
	1064	7.6			4
	1064	7.5			4
$Bi_{12}GeO_{20}$	633	60.3			1
C (diamond)	589	6.8		1.4	5
	633	5.81	0.87		1
$CaCO_3$	589	5.6		0	6
CaF_2	589	5.6			4
	633	2.49	19	0.9	1
CsBr	633	10.8	47	0.8	1
CsCl	633	8.3	46	0.7	1
CsCN	633	5.51		3	1
CsF	633	4.71	33	0.3	1
CsH_2AsO_4	633	6.49			7
CsI	633	17.4	49	2.5	1
$CsNO_2$	633	4.24			1
CuCl	546	58.1			8
	633	31.9	30	3.0	1
Cu_2O	633	147	0	5.2	1
GaP	633	154	5.81	3.3	1
GaSe	633	22			9

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Verdet Constants of Diamagnetic Crystals—*continued*

Crystal	Wavelength (nm)	V (rad/(m T))	CTE α (10^{-6}/K)	(1/V)dVdT + α (10^{-4}/K)	Ref.
$Gd_3Al_5O_{12}$	633	13.3	3.35	–2.2	1
$Hg_3Te_2Cl_2$	633	83			1
$KAl(SO_4)$•12 H_2O	589	3.6			13
KBr	546	14.5			10
	589	12.4			10
	633	10.1			1
KCl	633	6.68	38.4	1.0	1
KCN	633	3.89	36.2	2.1	1
KH_2PO_4	633	3.72	49	0.5	7
KH_2AsO_4	633	69.3			7
KI	546	24.1			10
	589	20.4			10
	633	17.5		2.2	1
$KTaO_3$	352	128			13
	413	55			13
	496	28			13
	620	–14	43		3
	826	6.4			13
LaF_3	325	16			4
(H || c)	442	8.1			4
	633	3.5			4
	1064	1.8			4
$LiBaF_3$	633	3.72	27	0.7	1
LiBr	633	14.2	38	2	1
LiCl	633	9.3	35	1.3	1
LiF	633	2.33	25	3.0	1
LiH	633	24.6	32	1.7	1
$MgAl_2O_4$	589	6.1			14
	633	7.6	8.82	0.9	1
MgO	633	9.2	13	1.7	1
NaBr	546	18.1			13
	633	13.2		1.8	1
NaCl	546	11.9			10
	589	10.0			10
	633	8.5	39.8	1.2	1
$NaClO_3$	546	3.1			13
	589	2.4			13
NaI	633	22.5	43	1.9	1
NH_4	633	12.6	53	2	1
$NH_4Al(SO_4)$•12 H_2O	589	3.7			13
NH_4Br	589	14.7			13
	633	8.9	48	0.9	1

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Verdet Constants V of Diamagnetic Crystals—*continued*

Crystal	Wavelength (nm)	V (rad/(m T))	CTE α (10^{-6}/K)	(1/V)dVdT + α (10^{-4}/K)	Ref.
NH_4Cl	546	11.9			13
	589	10.5			13
	633	6.60			7
$NH_4H_2AsO_4$	633	69.3			15
$NH_4H_2PO_4$	633	40.2			15
NH_4I	633	18.3	37	3.0	1
$NiSO_4 \cdot H_2O$	546	7.4			14
	589	6.4			14
RbH_2PO_4	633	3.72			7
RbH_2AsO_4	633	6.17			7
SiO_2	546	5.6			11
	589	4.9			11
$Sm_3Ga_5O_{12}$	633	11.8	6.39	1.24	1
$SrTiO_3$	413	227			16
	496	90.2			16
	633	–49.0	9.4	–1.8	1
	826	–19.2			3
TiO_2	620	–45			3
$Y_3Ga_5O_{12}$	633	11.7	5	1.23	1
ZnS	546	83.4			5
	589	65.8			5
	633	52.8		10.0	1
ZnSe	476	436			12
	496	302			12
	514	244			12
	587	154			12
	633	118			12
ZnTe	633	188		3.7	1

* The above table was adapted from Deeter, M. N., Day, G. W., and Rose, A. H., Magnetooptic materials: crystals and glasses, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 367, with additions.

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1.6.2 Paramagnetic Materials

Verdet Constants for Representative Paramagnetic Crystals*

Crystal	Wavelength λ (nm)	Refractive index n	V (rad/(m T)	Ref.
$CaF_2:Ce^{3+}$(30%)	325	1.516	–278	1
	442	1.502	–86.4	1
	633	1.494	–32.3	1
	1064	1.489	–10.2	1
$CaF_2:Pr^{3+}$(5%)	266	1.471	–50.1	1
	325	1.461	–23.8	1
	442	1.451		1
	633	1.445	–4.9	1
	1064	1.441	–1.31	1
CeF_3	442	1.613	–306	1
	633	1.598	–118	1
	1064		–33	1
EuF_2	450		–1310	1
	500		–757	2
	550		–466	2
	600		–320	2
	633	1.544	–262	1
	650		–233	2
	1064	1.518	–55.3	1
$LiTbF_4$	325	1.493	–553	3
	442	1.481	–285	3
	633	1.473	–128	3
	1064	1.469	–38	3
NdF_3	442	1.60	–161	1
	633	1.59	–60.8	1
	1064	1.58	–28.2	1

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Verdet Constants for Representative Paramagnetic Crystals—*continued*

Crystal	Wavelength λ (nm)	Refractive index n	V (rad/(m T)	Ref.
KTb_3F_{10}	325	1.531	–633	3
	442	1.518	–272	3
	633	1.510	–112	3
	1064	1.505	–33.2	3
$Tb_3Ga_5O_{12}$	500		–278	4
	570		–169	4
	633	1.976	–134	1
	830		–61	4
	1064	1.954	–35	1

* The above table was adapted from Deeter, M. N., Day, G. W., and Rose, A. H., Magnetooptic materials: crystals and glasses, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 367, with additions.

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Rare Earth Aluminum Garnets

Material	Temp. (K)	Verdet constant V (rad/T m) at wavelength in nm 405	450	480	520	578	670	Ref.
$Tb_3Al_5O_{12}$	300	–659.4	–455.4	375.4	–302.3	–229	–158	1
	77	—	–29728	24284	–997	–757	–528	1
	4.2	—	—	—	–18860	–15650	–13140	2
	1.45	—	–58476	–50203	–40530	–32380	–27185	2
$Dy_3Al_5O_{12}$	300	–361	–274	–234	–194	–151	–104	1
$Ho_3Al_5O_{12}$	300	–206	–93.1	–75.7	–97.5	–87.0	–59.9	1
$Er_3Al_5O_{12}$	300	–55.0	–69.8	–44.8	–47.1	–42.2	–25.9	1
$Tm_3Al_5O_{12}$	300	43.9	30.0	27.1	22.1	17.2	—	1
$Yb_3Al_5O_{12}$	298	83.5	62.6	54.1	40.7	33.8	—	3
	77	209	157	140	114	87.9	—	3

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1.6.3 Ferromagnetic, Antiferromagnetic, and Ferrimagnetic Materials

The following symbols are used in the tables below:

T_c = Curie temperature
T_p = phase transition temperature
T_N = Neel temperature
T_∞ = compensation temperature
$4\pi M_S$ = saturation induction at 0 K, gauss
F = specific Faraday rotation, deg/cm
α = absorption coefficient (cm^{-1})
λ = measurement wavelength, nm

Transition Metals*

Material (structure)	Critical temp.	$4\pi M_S$ (gauss)	F (deg/cm)	Absorp. coeff. α (cm^{-1})	Temp. (K)	λ (nm)
Fe (bcc)	T_c = 1043	21800	4.4×10^5	6.5×10^5	300	500
			3.5×10^5	7.6×10^5	300	546
			6.5×10^5	5×10^5	300	1000
			7×10^5	4.2×10^5	300	1500
			7×10^5	3.5×10^5	300	2000
Co (hcp)	T_c = 1390	18200	2.9×10^5	—	300	500
			3.6×10^5	8.5×10^5	300	546
			5.5×10^5	6.1×10^5	300	1000
			5.5×10^5	4.5×10^5	300	1500
			4.8×10^5	3.6×10^5	300	2000
Ni (fcc)	T_c = 633	6400	0.8×10^5	—	300	500
			0.99×10^5	8.0×10^5	300	546
			2.6×10^5	5.8×10^5	300	1000
			1.5×10^5	4.8×10^5	300	1500
			1×10^5	4.1×10^5	300	2000
			7.2×10^5	4.2		4000

Binary Compounds*

Material (structure)	Critical temp.	$4\pi M_S$ (gauss)	F (deg/cm)	Absorp. coeff. α (cm^{-1})	Temp. (K)	λ (nm)
MnBi (NiAs)	T_c = 639	7700	4.2×10^5	6.1×10^5	300	450
		7500	5.0×10^5	5.8×10^5	300	500
		(300 K)	7.0×10^5	5.1×10^5	300	600
			7.7×10^5	4.5×10^5	300	700
			7.6×10^5	4.3×10^5	300	800
			7.5×10^5	4.2×10^5	300	900
			7.4×10^5	4.1×10^5	300	1000
MnAs (NiAs)	T_c = 313		0.44×10^5	5.0×10^5	300	500
			0.49×10^5	4.9×10^5	300	600

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Binary Compounds*—*continued*

Material (structure)	Critical temp.	$4\pi M_S$ (gauss)	F (deg/cm)	Absorp. coeff. α (cm^{-1})	Temp. (K)	λ (nm)
MnAs			0.78×10^5	4.5×10^5	300	800
			0.62×10^5	4.4×10^5	300	900
CrTe	$T_c = 334$		0.5×10^5	2.0×10^5	300	550
(NiAs)			0.4×10^5	1.2×10^5	300	900
			0.4×10^5	0.6×10^5	300	2500
FeRh	$T_p = 334$		0.9×10^5	3.3×10^5	348	700

Ferrites*

Material (structure)	Critical temp.	$4\pi M_S$ (gauss)	F (deg/cm)	Absorp. coeff. α (cm^{-1})	Temp. (K)	λ (nm)
$Y_3Fe_5O_{12}$	$T_N = 560$	2500	2400	1500	300	555
(garnet)			1750	1350	300	588
			1250	1400	300	625
			900	670	300	715
			800	1150	300	667
			750	450	300	770
			240	0.069	300	1200
			175	<0.06	300	5000–1500
$Gd_3Fe_5O_{12}$	$T_N = 564$	7300	–2000	6000	300	500
(garnet)	$T_\infty = 286$		–1050	900	300	600
			–450	400	300	700
			–300	100	300	800
			–220	230	300	900
			–80	70	300	1000
$NiFeO_4$	$T_N = 858$	3350	2.0×10^4	5.9×10^4	300	286
(spinel)			2.4×10^4	7.4×10^4	300	330
			-0.75×10^4	16×10^4	300	400
			-1.0×10^4	10×10^4	300	500
			0.12×10^4	1×10^4	300	660
			–120	38	300	1500
			40	32	300	2000
			75	15	300	3000
			110	15	300	4000
			110	32	300	5000
$CoFeO_4$	$T_N = 793$	4930	2.75×10^4	12×10^4	300	286
(spinel)			3.8×10^4	14×10^4	300	330
			3.6×10^4	17×10^4	300	400

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Ferrites*—*continued*

Material (structure)	Critical temp.	$4\pi M_S$ (gauss)	F (deg/cm)	Absorp. coeff. α (cm^{-1})	Temp. (K)	λ (nm)
			1.3×10^4	13×10^4	300	500
			-2.5×10^4	6×10^4	300	660
$MgFeO_4$			–60	100	300	2500
(spinel)			–40	40	300	3000
			0	12	300	4000
			30	4	300	5000
			35	6	300	6000
			50	13	300	7000
$BaFe_{12}O_{19}$			–50	38	300	2000
(hexagonal)			75	20	300	3000
			130	13	300	4000
			150	20	300	5000
			160	20	300	6000
			165	22	300	7000
$Ba_2Zn_2Fe_{12}O_{19}$			90	120	300	5000
(hexagonal)			80	70	300	6000
			75	65	300	7000
			70	85	300	8000

Halides*

Material (structure)	Critical temp.	$4\pi M_S$ (gauss)	F (deg/cm)	Absorp. coeff. α (cm^{-1})	Temp. (K)	λ (nm)
$RbNiF_3$	$T_N = 220$	1250	360	35	77	450
(perovskite)			210	12	77	500
			70	10	77	600
			–70	30	77	700
			310	70	77	800
			100	60	77	900
			75	25	77	1000
$RbFeF_3$	$T_p = 102$		3400	7	82	300
(perovskite)			160	3	82	400
			950	4.6	82	500
			620	1.5	82	600
			420	1.2	82	700
			300	2.5	82	800
FeF_3	$T_c = 365$	40	670	14	300	349
		(300 K)	415	8.2	300	404
			180	4.4	300	522.5

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Halides*—*continued*

Material (structure)	Critical temp.	$4\pi M_S$ (gauss)	F (deg/cm)	Absorp. coeff. α (cm^{-1})	Temp. (K)	λ (nm)
$CrBr_3$	$T_c = 32.5$	3390	3×10^5	3×10^3	1.5	478
(BiI_3)			1.6×10^5	1.4×10^4	1.5	500
$CrCl_3$	$T_c = 16.8$	3880	2000	20	1.5	410
(BiI_3)			–500	3	1.5	450
			–1000	30	1.5	590
CrI_3	$T_c = 68$	2690	1.1×10^5	6.3×10^3	1.5	970
(BiI_3)			0.8×10^5	3×10^3	1.5	1000

Borates*

Material (structure)	Critical temp.	$4\pi M_S$ (gauss)	F (deg/cm)	Absorp. coeff. α (cm^{-1})	Temp. (K)	λ (nm)
$FeBO_3$	$T_c = 115$	115	3200	140	300	500
(calcite)	(300 K)		2300	40	300	525
			1100	100	300	600
			450	38	300	700

Chalcogenides*

Material (structure)	Critical temp.	$4\pi M_S$ (gauss)	F (deg/cm)	Absorp. coeff. α (cm^{-1})	Temp. (K)	λ (nm)
EuO	$T_c = 69$	23700	-1.0×10^5	0.5×10^4	5	1100
(NaCl)		7500	3.2×10^5	7.5×10^4	5	800
			5×10^5	9.7×10^4	5	700
			3.6×10^5	9.7×10^4	5	600
			0.5×10^5	7.8×10^4	5	500
			3×10^4	$>0.5^5$	20	2500
			660	≥ 1.0	20	10600
EuS	$T_c = 16.3$		-1.6×10^5	~0	6	825
(NaCl)			-9.6×10^5	3.3×10^4	6	690
			5.5×10^5	1.2×10^5	6	563
			5.1×10^5	1.0×10^5	6	495
EuSe	$T_c = 7$	13200	1.45×10^5	80	4.2	750
(NaCl)			1.17×10^5	70	4.2	775
			0.95×10^5	60	4.2	800

* The data in the above tables are from Di Chen, Magnetooptical materials, *Handbook of Laser Science and Technology, Vol. IV, Optical Materials, Part 2* (CRC Press, Boca Raton, FL, 1986), p. 287.

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Room-Temperature Saturation Kerr Rotation Data for Ferromagnetic Materials

Material	T_c (K)	λ (nm)	θ_K (°)	Ref.
Fe	1043	633	–0.41	1
Co	1388	633	–0.35	1
Ni	627	633	–0.13	1
FeCo	NA	633	–0.54	1
MnBi	633	633	–0.70	2
PtMnSb	582	720	–1.27	3
CeSb[a]	16	2500	14	4

Measured at T = 2 K.

Faraday Rotation Data For Nonmetallic Ferro– and Antiferromagnetic Materials

Material	T_c (K)	$\mu_0 H$ (T)	λ (nm)	θ'_F (°/cm)	Ref.	Comments
EuO	69	2.1	660	4.9×10^5	5	1,4
EuSe	7	2.0	755	1.4×10^5	6	1,2,4,8
EuS	16	0.675	670	5.5×10^5	7	1,4
$CrBr_3$	36		493	1×10^5	8	1,5
$CdCr_2S_4$	84	0.6	1000	3800	9	1,5
$CdCr_2Se_4$	130	0.45	1050	5.5×10^4	10	1,4
$CoCr_2S_4$	221	0.4	10,600	320	11	ferri, 4
$YFeO_3$			600	$\sim 8 \times 10^3$	12	3,5,7
$FeBO_3$	348		525	2300	13	3,5,7
UO_2	30.8	4.0	276	4.8×10^4	14	2,4,8

Comments: (1) ferromagnetic; (2) antiferromagnetic; (3) canted antiferromagnetic; (4) electrically semiconducting; (5) electrically insulating; (6) electrically conducting; (7) birefringent; (8) measured in unsaturated state. (The ferrimagnet $CoCr_2S_4$ is included because of its chemical similarity to the ferromagnets $CdCr_2S_4$ and $CdCr_2Se_4$.)

Saturation Kerr Rotation/Ellipticity Data for Nonmetallic Ferromagnetic Materials

Material	T_c (K)	$\mu_0 H$ (T)	λ (nm)	$\theta_K[\varepsilon_K]$ (°)	Ref.	Comments
TmS	5.2	4	440	[–2.4]	15	1,6,8
TmSe	1.85	4	540	[–3.6]	15	1,6,8
US	177	4	350	[3.4]	16	1,6
USe	160	4	420	[4.0]	16	1,6
UTe	104	4	830	3.1	16	1,6
$CuCr_2Se_4$	432	2	1290	[–1.19]	17	1,6
$CoCr_2S_4$	221	1.5	1800	–4.6	18	ferri, 4

For materials which possess greater values of Kerr ellipticity than Kerr rotation, the ellipticity is reported in brackets [ ].

Comments: (1) ferromagnetic; (2) antiferromagnetic; (3) canted antiferromagnetic; (4) electrically semiconducting; (5) electrically insulating; (6) electrically conducting; (7) birefringent; (8) measured in unsaturated state.

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Room–Temperature Saturation Faraday Rotation and Absorption Data for Selected Iron Garnets at λ = 633 nm

Material	θ'_F(°/cm)	α (cm^{-1})	Growth technique	Ref.
$Y_3Fe_5O_{12}$	835	870	LPE	25
$Gd_3Fe_5O_{12}$	345	750	LPE	20
$Bi_3Fe_5O_{12}$	-5.5×10^4		sputtering	21
$Y_3Fe_{4.07}Ga_{0.93}O_{12}$	855	650	LPE	19
$Y_3Fe_{3.54}Ga_{1.46}O_{12}$	645	530	flux method	19
$Y_{2.3}Bi_{0.7}Fe_5O_{12}$	-1.25×10^4	1000	flux method	22
$Y_{0.5}Bi_{2.5}Fe_5O_{12}$	-7.5×10^4		MOCVD	23
$Y_{2.0}Ce_{1.0}Fe_5O_{12}$	2.2×10^4	540	sputtering	24

Room–Temperature Saturation Faraday Rotation and Absorption Data for Selected Iron Garnets at λ = 1064 nm

Material	θ'_F(°/cm)	α (cm^{-1})	Growth technique	Ref.
$Y_3Fe_5O_{12}$	280	9	flux method	25
$Pr_3Fe_5O_{12}$	65	10	flux method	26
$Nd_3Fe_5O_{12}$	535		flux method	26
$Sm_3Fe_5O_{12}$	15		flux method	25
$Eu_3Fe_5O_{12}$	107		flux method	25
$Gd_3Fe_5O_{12}$	65	10	flux method	25
$Tb_3Fe_5O_{12}$	535		flux method	25
$Dy_3Fe_5O_{12}$	310		flux method	25
$Ho_3Fe_5O_{12}$	135		flux method	25
$Er_3Fe_5O_{12}$	120		flux method	25
$Gd_{2.0}Bi_{1.0}Fe_5O_{12}$	–3300	< 10	flux method	27
$Y_{2.0}Ce_{1.0}Fe_5O_{12}$	–22000	1700	sputtering	24

Room–Temperature Saturation Faraday Rotation and Absorption Data for Selected Iron Garnets at λ = 1300 nm

Material	θ'_F(°/cm)	α (cm^{-1})	Growth technique	Ref.
$Y_3Fe_5O_{12}$	210	0.3	flux method	28
$Gd_3Fe_5O_{12}$	60	1.0	flux method	28
$Tb_3Fe_5O_{12}$	320		flux method	26
$Dy_3Fe_5O_{12}$	175		flux method	26
$Tm_3Fe_5O_{12}$	110		flux method	26
$Pr_3Fe_5O_{12}$	–1060	70	flux method	26
$Nd_3Fe_5O_{12}$	–690	< 50	LPE	26
$Y_{1.7}Bi_{1.3}Fe_5O_{12}$	–2100		LPE	29
$Gd_{2.0}Bi_{1.0}Fe_5O_{12}$	–2100	< 10	flux method	27
$Y_{2.0}Ce_{1.0}Fe_5O_{12}$	–120000	250	sputtering	24

LPE (liquid phase epitaxy), sputtering, and MOCVD (metal–organic chemical vapor deposition) are thin–film growth techniques. The flux method yields bulk crystals.

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The preceding tables were adapted from Deeter, M. N., Day, G. W., and Rose, A. H., Magnetooptic materials: crystals and glasses, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 367 (with additions).

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Faraday Rotation and Magnetooptic Properties of Orthoferrites[a]

		Intrinsic specific Faraday rotation (deg/cm) at 300 K						
Material	**$4\pi M_S$**[b] **(gauss)**	**600 nm**	**800 nm**	**1000 nm**	**1200 nm**	**1400 nm**	**1600 nm**	**Abs. coeff. (cm^{-1})** [c]
$EuFeO_3$	83							~38
$GdFeO_3$	94							~10
$TbFeO_3$	137							~29
$DyFeO_3$	128			|| c				~40
$HoFeO_3$	91	8000	2200	1000	800	700	600	~10
$ErFeO_3$	81							~15
$TmFeO_3$	140							~5
$YbFeO_3$	143							~12.5
$LuFeO_3$	119							~5
$SmFeO_3$	84							~50
$YFeO_3$	105			|| a				~10
$LaFeO_3$	83	3400	700	400	300	200	150	~10
$PrFeO_3$	71							~35
$NdFeO_3$	62							~10

[a] Strong natural birefringence interferes with the Faraday effect.
[b] Saturation induction.
[c] At a wavelength of 1250 nm.

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1.7 Electrooptic Properties

1.7.1 Linear Electrooptic Coefficients

The linear electrooptic effect occurs in acentric crystals. Only 21 acentric groups (those lacking a center of inversion) may have nonvanishing coefficients. Reduced electrooptic matrix forms are given in the two references below.

If the electrooptic coefficient r_{ij} is determined at constant strain (by making the measurement at high frequencies well above acoustic resonances of the sample) the crystal is clamped, as indicated by S. If the r_{ij} is determined at constant stress (at low frequencies well below the acoustic resonances of the sample) the sample is free, as indicated by T. The electrooptic coefficients are generally those for room temperature. Typical accuracies for r_{ij} are ±15%. Unless shown explicitly, the signs of r_{ij} have not been determined. As a rule, r_{ij} has little optical wavelength dependence in the transparent region of the crystal.

The following tables were adapted from:

> Kaminow, I. P., Linear Electrooptic Materials, *Handbook of Laser Science and Technology,* Vol. IV (CRC Press, Boca Raton, FL, 1986), p. 253.
>
> Holland, W. R. and Kaminow, I. P., Linear Electrooptic Materials, *Handbook of Laser Science and Technology, Suppl. 2* (CRC Press, Boca Raton, FL, 1995), p. 133.

A comprehensive table of electrooptic constants including extensive data on refractive indices and curves of wavelength and temperature dependence of electrooptic coefficients is given in Cook, W. R., Hearmon, R. F. S., Jaffe, H., and Nelson, D. F., Piezooptic and electrooptic coefficient constants, *Landolt-Börstein*, Group III, Vol. 11, Hellewege, K.-H. and Hellewege, A. M., Eds. (Springer-Verlag, New York, 1979), p. 495.

The following tables are divided according to the general structure of the electrooptic materials, i.e., tetrahedally coordinated binary AB compounds that are semiconductors, ABO_3-type compounds that are ferroelectric or pyroelectric, isomorphs of ferroelectric KH_2PO_4 and antiferroelectric $NH_4H_2PO_4$, other compounds that do not fit the previous categories, and organic compounds. Although nonlinear optic coefficients have been measured for many organic crystal and can be converted to equivalent electrooptic coefficients, only direct phase retardation measurements of the electrooptic effect are included in the last table.

AB-Type Compounds

Material	Symmetry	T/S	Electrooptic coeff.* r_{ij} (10^{-12} m/V)	Wavelength λ (μm)
CdS	6mm	T	$r_c = 4$	0.589
		T	$r_{51} = 3.7$	0.589
		T	$r_c = 5.5$	10.6
		S	$r_{33} = 2.4$	0.633
		S	$r_{13} = 1.1$	
		T	$r_c = 4.8 \pm 0.2$	
		T	$r_{42} = 1.6 \pm 0.2$	

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AB-Type Compounds—*continued*

Material	Symmetry	T/S	Electrooptic coeff.* r_{ij} (10^{-12} m/V)	Wavelength λ (μ*m*)
CdS		T	$r_{33} = 3.2 \pm 0.2$	1.15
		T	$r_{13} = 3.1 \pm 0.2$	
		T	$r_c = 6.2 \pm 0.2$	
		T	$r_{42} = 2.0 \pm 0.2$	
		T	$r_{33} = 2.9 \pm 0.1$	3.39
		T	$r_{13} = 3.5 \pm 0.1$	
		T	$r_c = 6.5 \pm 0.2$	
		T	$r_{42} = 2.0 \pm 0.2$	
		T	$r_{33} = 2.75 \pm 0.08$	10.6
		T	$r_{13} = 2.45 \pm 0.08$	
		T	$r_c = 5.2 \pm 0.3$	
		T	$r_{42} = 1.7 \pm 0.3$	
CdSe	6mm	S	$r_{33} = 4.3$	3.39
		S	$r_{13} = 1.8$	
$CdS_{0.75}Se_{0.25}$	6mm	T	$n_1^3 r_c = 70$	0.63
CdTe	-43m	T	$r_{41} = 6.8$	3.39
		T	$r_{41} = 6.8$	10.6
		T	$r_{41} = 5.5$	23.35
		T	$r_{41} = 5.0$	27.95
		S	$n_0^3 r_{41} = 100 \pm 10$	10.6
CuBr	-43m	T	$r_{41} = 0.85$	0.525
		S	$r_{41} = -2.5$	0.63
		S	$r_{41} = -3.0$	1.15
		S	$r_{41} = -3.0$	3.39
CuCl	-43m	T	$r_{41} = 3.6$	0.633
		T	$r_{41} = 3.2$	10.6
		S	$r_{41} = 2.35$	0.633
		S	$r_{41} = 2.20$	3.39
		S	$r_{41} = -2.35$	0.63
		S	$r_{41} = -2.5$	3.39
		T	$r_{41} = -5$	0.55
CuI	-43m	T	$n_0^3 r_{41} = 30$	0.63
GaAs	-43m	S	$r_{41} = 1.2$	0.9–1.08
		S	$r_{41} = -1.5$	3.39
		S + T	$r_{41} = 1.2 – 1.6$	1.0 – 3.0
		T	$r_{41} = 1.0 – 1.2$	2.0 – 12.0
		T	$r_{41} = 1.6$	10.6
		S	$r_{41} = -1.33$	1.06

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AB-Type Compounds—*continued*

Material	Symmetry	T/S	Electrooptic coeff.* r_{ij} (10^{-12} m/V)	Wavelength λ (μ*m*)
GaAs		T	r_{41} = 1.24 ± 0.04	3.39
		T	r_{41} = 1.51 ± 0.05	10.6
GaP	-43m	S	r_{41} = -1.07 – -0.97	0.56 – 3.39
		T	r_{41} = 0.79–0.80 (200 Hz)	0.552 – 1.15
		S	r_{41} = 0.95–0.87 (9.45 GHz)	
GaSe	-6m2	T	r_{22} = 22	0.63
		T	$n_1^3 r_{22}$ = 27.5	1.06
HgS	32	S	r_{11} = 3.1	0.633
		S	r_{41} = 1.4	0.633
		S	r_{11} = 4.2	3.39
		S	r_{41} = 2.4	3.39
InP	-43m	S	r_{41} = -1.34	1.06
		S	r_{41} = -1.68	1.50
β-SiC	43m	T	$r_{41,52,63}$ = 2.7±0.5	0.633
ZnO	6mm	S	r_{33} = +2.6	0.633
			r_{13} = -1.4	0.633
		S	r_{33} = +1.9	3.39
			r_{13} = +0.96	3.39
			r_{51} = -3.1	0.4
		T	r_{31} - r_{33} = -1.4	0.4
ZnS	-43m	T	r_{41} = 1.2	0.4
		T	r_{41} = 2.1	0.65
		S	r_{41} = 1.6	0.633
		S	r_{41} = 1.4	3.39
		T	r_{41} = -1.9	0.63
ZnS	6mm	T	r_{41} = 2.0	0.546
		S	r_{41} = 2.0	0.633
		T	r_{41} = 2.2	10.6
		T	r_{41} = 1.9	0.55
ZnTe	-43m	T	r_{41} = 4.45 – 3.95	0.59 – 0.69
		T	r_{41} = 1.4	10.6
		S	r_{41} = 4.3	0.633
		S	r_{41} = 3.2	3.39
		T	r_{41} = 4.2 ± 0.3	3.41
		T	r_{41} = 3.9 ± 0.2	10.6

* $r_c = r_{33} - (n_1^3 / n_3^3) r_{33}$

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ABO_3-Type Compounds

Material	Symmetry	T/S	Electrooptic coeff.* r_{ij} (10^{-12} m/V)	Wavelength λ (μ*m*)
$Ba_xNaNb_5O_{15}$	mm2		$r_C = 34$	0.633
			$r_{33} = 48$	
			$r_{42} = 92$	
			$r_{13} = 15$	
			$r_{33} = +29$	
			$42 = 75$	
			$r_{13} = 6.1$	
			$n_3^3 r_{33} = 265$	
			$n_1^3 r_{13} = 76$	
$Ba_{2-y}Sr_yK_xNa_{1-x}Nb_5O_{15}$ (0.5<*x*<0.75) (0.6<*y*<1.8)	4mm		$n_o^3 r_o = 730$	0.561
$Ba_{1.5}Sr_{0.5}K_{0.75}Na_{0.25}Nb_5O_{15}$	4mm		$r_{33} = 110$	
			$r_{51} = 250$	
$Ba_{0.5}Sr_{1.5}K_{0.5}Na_{0.75}Nb_5O_{15}$	4mm		$r_{33} = 180$	
			$r_{51} = 300$	
$Ba_{0.5}Sr_{1.5}K_{0.25}Na_{0.75}Nb_5O_{15}$	4mm		$r_{33} = 200$	
$BaTiO_3$	4mm	T	$r_{13} = 19.5 \pm 1$	0.5145
		T	$r_{33} = 97 \pm 7$	
		T	$r_c = 76 \pm 7$	
		T	$r_c = 108$	0.546
		T	$r_{51} = 1640$	
		S	$r_c = 23$	
		S	$r_{51} = 820$	
		S	$r_c = 19$	0.633
		S	$r_{33} = 28$	
		S	$r_{13} = 8$	
$KNbO_5$	mm2	S	$r_{33} = 25 \pm 8$	0.633
		S	$r_{42} = 270 \pm 40$	
		S	$r_{13} = 10 \pm 2$	
		S	$r_{51} = 23 \pm 3$	
		S	$r_{23} = 2 \pm 1$	
		T	$r_{33} = 64 \pm 5$	
		T	$r_{42} = 380 \pm 50$	
		T	$r_{13} = 28 \pm 2$	
		T	$r_{51} = 105 \pm 13$	
			$r_{23} = +1.3 \pm 0.5$	
$KSr_xNb_5O_{15}$	4mm or 4	T	$r_c = 130$	0.633

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ABO_3-Type Compounds—*continued*

Material	Symmetry	T/S	Electrooptic coeff.* r_{ij} (10^{-12} m/V)	Wavelength λ (μ*m*)
$LiIO_3$	6	S	$r_{33} = +6.4$	0.633
		S	$r_{41} = 1.4$	
		S	$r_{13} = +4.1$	
		S	$r_{51} = +3.3$	
$LiNbO_5$	3m	T	$r_c = 17.4$	0.633
		T	$r_{22} = 6.8$	
		T	$r_{51} = 32$	
		T	$r_{33} = +32.2$	
		T	$r_{13} = +10$	
		T	$r_c = 17$	1.15
		T	$r_{22} = 5.7$	
		T	$r_c = 16$	3.39
		T	$r_{22} = 3.1$	
		S	$r_{33} = +30.6$	0.633
		S	$r_{13} = +8.6$	
		S	$r_{51} = +28$	
		S	$r_{33} = 28$	3.39
		S	$r_{22} = 3.1$	
		S	$r_{13} = 65$	
		S	$r_{51} = 23$	
		S	$r_{33} = +28.8$	0.633
		S	$r_{51} = +18.2$	
		S	$r_{13} = +7.68$	
		S	$r_{33} = 27.2$	1.152
		S	$r_{13} = +6.65$	
		S	$r_{33} = +25.5$	3.391
		S	$r_{13} = +5.32$	
$LiTaO_5$	3m	T	$r_c = 22$	0.633
		S	$r_{33} = 30.3$	
		S	$r_{51} = 20$	
		S	$r_{33} = 27$	3.39
		S	$r_{51} = 15$	
		S	$r_{13} = 4.5$	
		S	$r_{22} = 0.3$	
		S	$r_{13} = 6.2$	
		S	$r_{33} = 26.7$	1.152
		S	$r_{51} = 8.9$	
		S	$r_{13} = 5.2$	
		S	$r_{33} = 25.2$	3.39
		S	$r_{13} = 4.4$	
		T	$r_{33} = 30.5 \pm 2$	0.633
		T	$r_{13} = 8.4 \pm 0.9$	

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ABO_3-Type Compounds—*continued*

Material	Symmetry	T/S	Electrooptic coeff.* r_{ij} (10^{-12} m/V)	Wavelength λ (μ*m*)
$K_5Li_2Nb_5O_{15}$	4mm		$r_{33} = 78$	0.633
			$r_{13} = 8.9$	
$KTa_xNb_{1-x}O_5$	4mm	T	$r_c = 450$	0.633
		T	$r_{51} = +50$	
$La_y(Sr_{.5}Ba_{0.5})_{1-1.5y}Nb_2O_6$ (0<*y*<.03)	4mm		$r_c = 145\text{-}669$	0.6328
			$r_c = r_{33}–(n_1/n_3)^3 r_{13}$	
$PbTiO_5$	4mm	S	$r_{33} = 5.9$	0.633
		S	$r_{13} = 13.8$	
$Sr_{0.61}Ba_{.0.39}Nb_2O_6$	4mm	T	$r_{13} = 47 \pm 5$	0.5145
		T	$r_{33} = 235 \pm 21$	
$Sr_{0.75}Ba_{.0.25}Nb_2O_6$	4mm	T	$r_c = 1410$	0.633
		T	$r_{33} = 1340$	
		T	$r_{51} = 42$	
		T	$r_{15} = 67$	
		S	$r_c = 1090$	
$Sr_{0.5}Ba_{.0.5}Nb_2O_6$	4mm	T	$r_c = 218$	0.633
$Sr_{0.46}Ba_{.0.54}Nb_2O_6$	4mm	T	$r_{33} = 35 \pm 3$	0.633
		T	$r_{13} = 180 \pm 30$	
$Sr_{0.3}Ba_{.0.79}Nb_2O_6$	4mm	T	$r_{13} = -266$	0.633
			$r_{33} = +113$	

* $r_c = r_{33} - (n_1^3 / n_3^3) r_{33}$

KDP- and ADP-Type Compounds

Material	Symmetry*	T/S	Electrooptic coeff. r_{ij} (10^{-12} m/V)	Wavelength λ (μ*m*)
KH_2PO_4 (KDP)	-42m	T	$r_{63} = 9.4 \pm 0.4$	0.633
		T	$r_{41} = +8.6$	
		S	$r_{63} = 8.8$	
KD_2PO_4 (DKDP)	-42m	T	$r_{63} = 23.8 \pm 0.6$	0.633
		T	$r_{41} = 8.8$	
		T	$r_{61} < 0$	
		S	$r_{63} = 24.0$	
KH_2AsO_4 (KDA)	-42m	T	$r_{63} = 10.9$	0.633
		T	$r_{41} = = 12.5$	
KD_2AsO_4 (DKDA)	-42m	T	$r_{63} = 18.2$	0.633

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KDP- and ADP-Type Compounds—*continued*

Material	Symmetry*	T/S	Electrooptic coeff. r_{ij} (10^{-12} m/V)	Wavelength λ (μ*m*)
RbH_2PO_4 (RDP)	-42m	T	r_{63}= 15.5	0633
		S	r_{63} = 0.91	
RbH_2AsO_4 (RDA)	-42m	T	r_{63} = 13.0	0.633
RbD_2AsO_4 (DRDA)	-42m	T	r_{63} = 21.4	0633
CsH_2AsO_4 (CDA)	-42m	T	r_{63} = 18.6	0633
CsD_2AsO_4 (DCDA)	-42m	T	r_{63} = 36.6	0633
$NH_4H_2PO_4$ (ADP)	-42m	T	r_{63} = -8.5	0633
		T	r_{41} = 24.5	
		S	r_{63} = 5.5	
$NH_4D_2PO_4$ (DADP)	-42m	T	r_{63} = 11.9	0633
$NH_4H_2AsO_4$ (ADa)	-42m	T	r_{63} = 9.2	0633

* Above T_c

Other Compounds

Material	Symmetry	T/S	Electrooptic coeff.. r_{ij} (10^{-12} m/V)	Wavelength λ (μ*m*)
$AgGaS_2$	-42m	T	r_{63} = 3.0	0.633
		T	r_{41} = 4.0	
$AgGaSe_2$	-42m	T	r_{63} = 6.9	1.15
		T	r_{41} = 4.5	
		T	$n^3 r_{63}$ = 76	
		T	$n^3 r_{41}$ = 85	
$(CH_3NH_3)_5Bi_2Br_{11}$	mm2	T	$1/2(n_3^3 r_{33} - n_2^3 r_{23})$=5.8±0.8	0.6328
		T	$1/2(n_3^3 r_{33} - n_1^3 r_{13})$=3.5±0.7	
BaB_2O_4 (BBO)	3m	T	r_{22} = 2.7±0.4	0.6328
		T	r_{31} = 0	
		T	r_{61} = 0.055	
		T	r_{22} = 2.5±0.1	
		T	r_c = 0.17±0.02	
		S	r_{22} = 2.1±0.3	
		S	r_c = 0.11±0.02	
$Bi_4Ge_3O_{20}$ (BGO)	23	T	r_{41} = 1.03	0.45–0.62
		T	r_{41} = 0.95	0.63
$Bi_4Si_3O_{20}$	23	T	r_{41} = 0.54	0.63
$Bi_{40}Ga_2O_{63}$	23	T	$n_0^3 r_{41}$ = 54.9	0.633

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Other Compounds—*continued*

Material	Symmetry	T/S	Electrooptic coeff.. r_{ij} (10^{-12} m/V)	Wavelength λ (μ*m*)
$Bi_{12}GeO_{20}$	23		$r_{41} = 3.67 \pm 0.11$	0.633
(BGO)			$r_{41} = 3.29 \pm 0.10$	0.850
$Bi_{12}SiO_{20}$	23	T	$r_{41} = 4.1 \pm 0.1$	0.650
(BSO)			$r_{41} = 4.25 \pm 0.13$	0.633
$Bi_{12}TiO_{20}$	23	T	$r_{41} = 5.75 \pm 0.10$	0.633
(BTO)			$r_{41} = 3.81 \pm 0.11$	
$Ca_2Nb_2O_7$	2	T	$r_{22} - (n_1/n_2)^3 r_{12} = 12$	0.63
		T	$r_{22} - (n_1/n_3)^3 r_{32} = 14$	
		S	$r_{22} - (n_3/n_2)^3 r_{32} = 0.6$	
		S	$r_{12} = 6.7$	
		S	$r_{22} = 25.5$	
		S	$r_{32} = 6.4$	
		S	$r_{13} = 0.37$	
		S	$r_{41} = 2.7$	
			$r_{52} = < 0.6$	
		S	$r_{63} = 0.9$	
$CdGaS_2$	-4	T	$r_{13} = 0.37$	0.50
		T	$r_{63} = 3.5$	
$CHI_3 \cdot 3S_8$	3m		$r_{12} = 4.4 \pm 2.5$	0.633
			$r_{13} = -0.512$	
			$r_{33} = 0.29 \pm 0.12$	
$Cs_3Sr[Cu_2(SCN)_9]$	42m	T	$r_{63} = +0.06 \pm .002$	0.633
$CuGaS_2$	-42m	S	$r_{63} = +1.35$	0.63
		S	$r_{41} = +1.76$	
		S	$r_{63} = +1.66$	1.15
		S	$r_{41} = +1.9$	
		S	$r_{63} n_0^3 r_{41}$	3.39
		S	$r_{41} = +1.1$	
$Gd_2(MoO_4)_3$ (450 K)	-42m	T	$n_1^3 r_{63} = 17$	0.633
$Gd_2(MoO_4)_3$ (30 K)	mm2	T	$n_1^3 r_{13} - n_3^3 r_{33} = 17.5$	0.633
$KTiOAsO_4$	mm2	T	$r_{33} = 40 \pm 1$	0.6328
(KTA)		T	$r_{33} = 21 \pm 1$	
		T	$r_{13} = 15 \pm 1$	
$KTiOPO_4$	mm2	T	$r_{13} = +9.5 \pm 0.5$	0.6328
(KTP)		T	$r_{23} = +15.7 \pm 0.8$	
		T	$r_{42} = 9.3 \pm 0.9$	
		S	$r_{13} = +8.8 \pm 0.8$	
		S	$r_{23} = +13.8 \pm 1.4$	

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Other Compounds—*continued*

Material	Symmetry	T/S	Electrooptic coeff.. r_{ij} (10^{-12} m/V)	Wavelength λ (μ*m*)
$KTiOPO_4$		S	r_{33} = +35.0±3.5	
		S	r_{51} = 6.9±1.4	
		S	r_{42} = 8.8±1.8	
$K_2Mg_2(SO_4)_3$	23	T	r_{41} = 0.40	0.546
$K_2Mn_2(SO_4)_3$	23	T	r_{41} = 2.0	0.453–0.642
$K_2Ni_2(SO_4)_3$	23	T	r_{41} = 0.4	0.453–0.642
$K_2S_2O_6$	32	T	r_{11} = 0.26	0.546
$LiInS_2$	mm2	T	$r_{33} - (n_1^3/n_3^3)r_{13}$ = +0.67 $r_{33} - (n_2^3/n_3^3)r_{23}$ = +0.60	0.63
$LiInSe_2$	mm2	T	$r_{33} - (n_1^3/n_3^3)r_{13}$ = +1.39 $r_{33} - (n_2^3/n_3^3)r_{23}$ = +1.55	0.63
$LiKSO_4$	6	T	r_c = 1.6	0.546
$LiNaSO_4$	3m	T	r_{22} = <0.02	0.546
$NaClO_3$	23	T	r_{41} = 0.4	0.589
$NaNO_2$	mm2	T	$r_{22} - (n_1/n))^3 r_{32}$ = 4.1	0.546
		T	$r_{32} - (n_1/n))^3 r_{12}$ = 4.2	
		T	$r_{22} - (n_1/n_2)^3 r_{12}$ = 0.6	
		T	r_{43} = -1.9	
		T	r_{61} = -3.0	
$Na_2SbS_4 \cdot 9H_2O$	23	T	$n_1^3 r_{41}$ = 5.66	0.42
		T	$n_1^3 r_{41}$ = 5.62	1.08
		T	r_{22} = 0.82	0.52
		T	r_{22} = 0.77	0.60
$(NH_4)_3Cd_2(SO_4)_3$	23	T	r_{41} = 0.70	0.546
$(NH_2)_2CO$	-42m	T	r_{63} = 0.52	0.63
		T	r_{41} = 0.50	
$(NH_4)_3Mn_2(SO_4)_3$	23	T	r_{41} = 0.53	0.546
$Pb_5Ge_3O_{11}$	3	T	r_{11} = 0.27	0.63
		T	r_{22} = 0.23	
		T	r_{13} = 10.5	
		T	r_{33} = 15.3	
		T	r_{41} = 0.6	
		T	r_{51} = 6	
		T	r_c = 5.3	

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Other Compounds—*continued*

Material	Symmetry	T/S	Electrooptic coeff.. r_{ij} (10^{-12} m/V)	Wavelength λ (μ*m*)
$Rb_2Mn_2(SO_4)_3$	23	T	r_{41} = 1.9	0.453–0.642
SbSI	mm2	T	r_{33} = 2x10^4 (293 K)	0.7
		T	r_{33} = 2000 (288 K)	
Se	32	S	$n_1^3 r_{11}$ = 89	1.15
		S	r_{11} = ~2.5	10.6
SiO_2	32	T	r_{11} = -0.47	0.409–0.605
		T	r_{41} = 0.20	
		S	r_{11} = 0.174	0.633
TeO_2	422	T	r_{41} = -0.76	0.63
		S	r_{41} = +0.62	
$Tl_2Mn_2(SO_4)_3$	23	T	r_{41} = 2.1	0.453–0.642
$Tl_2Cd_2(SO_4)_3$	23	T	r_{41} = 0.37	0.546
tourmaline	3m	T	r_{22} = 0.3	0.589
		S	r_{13} = 1.7	0.633
$ZnGeP_2$	-42m	S	r_{63} = -0.8	3.39
		S	r_{41} = +1.6	

Organic Compounds

Material	Symmetry	T/S	Electrooptic coeff. r_{ij} (10^{-12} m/V)	Wavelength λ (μ*m*)
$(CH_2)_6N_2$:HMT-	-43m	T	r_{41} = 0.72 ± 0.01	0.5
hexamethylenetetramine,		T	r_{41} = 0.78	0.633
hexamine		S	r_{41} = <0.14	
$C(CH_2OH)_4$	2	T	r_{52} = 1.45	0.46–0.70
		T	$\lvert r_{12} - r_{32} \rvert$ = 0.7	
$C_6H_4(NO_2)NH_2$	mm2	T	r_{33} = 16.7 ± 0.2	0.63
meta-nitroaniline		T	r_{23} = 0.1 ± 0.6	
		T	r_{13} = 7.4 ± 0.7	
$Cs_2C_4H_4O_6$	32	T	r_{11} = 1.0	0.546
DBNMNA	mm2	T	$n_a^3 r_{13} - n_c^3 r_{33}$ = 148	0.5145
2,6-dibromo-*N*-		T	r_{42} = 86	
methyl-4-nitroaniline		T	r_{51} = 83	
		T	$n_a^3 r_{13} - n_c^3 r_{33}$ = 32	0.6328
		T	r_{42} = 20.4	
		T	r_{51} = 41.4	

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Organic Compounds—*continued*

Material	Symmetry	T/S	Electrooptic coeff. r_{ij} (10^{-12} m/V)	Wavelength λ (μm)
DBNMNA		T	$n_a^3 r_{13} - n_c^3 r_{33} = 18.3$	0.810
		T	$r_{42} = 11.5$	
		T	$r_{51} = 31$	
MMONS	mm2	T	$r_{53} = 39.9 \pm 8$	0.6328
3-methyl-4-methoxy-		T	$r_{23} = 19.3 \pm 4$	
4;pr-nitrostilbene		T	$r_{c2} = 30.0 \pm 3$	
MNA	m	—	$r_{11} = 67 \pm 25$	0.6328
2-methyl-4-nitroaniline				
POM	222	*T*	$63 = 2.6 \pm 0.3$	0.63
3methyl 4-nitropyridine		T	$r_{52} = 5.1 \pm 0.4$	
1-oxide		T	$r_{41} = 3.6 \pm 0.6$	
PNP	2	T	$r_{12} = 20.2 \pm 0.3$	0.514
2-(*N*-Prolinol)-		T	$r_{22} = 28.3 \pm 0.4$	
5-nitropyridine		T	$r_{12} = 13.1 \pm 0.2$	
		T	$r_{22} = 13.1 \pm 0.2$	
SPCD	mm2	—	$r_{33} = 430$	0.6328
styrlpyridinium				
cyanine dye				

1.7.2 Quadratic Electrooptic Materials

Kerr Constants of Ferroelectric Crystals[1,2]

Material	T_{trans} (K)	λ (μm)	g_{11} (10^{10} esu)	g_{12} (10^{10} esu)	g_{11}-g_{12} (10^{10} esu)	g_{44} (10^{10} esu)
$BaTiO_3$	406	0.633	1.33	-0.11	1.44	—
$SrTiO_3$	—	0.633	—	—	1.56	—
$KTa_{0.65}Nb_{0.35}O_3$	330	0.633	1.50	-0.42	1.92	1.63
$KTaO_3$	13	0.633	—	—	1.77	1.33
$LiNbO_3$	1483	—	0.94	0.25	0.7	0.6
$LiTaO_3$	938	—	1.0	0.17	0.8	0.7
$Ba_{0.8}Na_{0.4}Nb_2O_6$	833	—	1.55	0.44	1.11	—

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1. Narasimhamurty, T. S., *Photoelastic and Electro-Optic Properties of Crystals*, Plenum Press, New York, 1981, p. 408.
2. Gray, D. E., Ed., *AIP Handbook of Physics*, McGraw Hill, New York, 1972, p. 6-241.

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1.8 Elastooptic Properties

1.8.1 Elastooptic Coefficients

The following tables of elastooptic coefficients (photoelastic constants) are from the *CRC Handbook of Chemistry and Physics*, 82nd edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 2001), p. 12–180. Materials are listed alphabetically by chemical composition. Data have been measured at room temperature, except for rare gas crystals.

Cubic Crystals; Point Groups 43m, 432, m3m

Material	Wavelength (μm)	Elastooptic coefficients				Ref.
		p_{11}	p_{12}	p_{44}	$p_{11}-p_{12}$	
C (diamond)	0.540–0.589	–0.278	0.123	–0.161	–0.385	13
CaF_2	0.55–0.65	0.038	0.226	0.0254	–0.183	11
CdTe	1.06	–0.152	–0.017	–0.057	–0.135	10
CuBr	0.633	0.072	0.195	–0.083	–0.123	12
CuCl	0.633	0.120	0.250	–0.082	–0.130	12
CuI	0.633	0.032	0.151	–0.068	–0.119	12
GaAs	1.15	–0.165	–0.140	–0.072	–0.025	15
GaP	0.633	–0.151	–0.082	–0.074	–0.069	15
$Gd_3Ga_5O_{12}$	0.514	–0.086	–0.027	–0.078	–0.059	23
Ge	3.39	–0.151	–0.128	–0.072	–0.023	14
KBr	0.589	0.212	0.165	–0.022	0.047	5
KCl	0.633	0.22	0.16	–0.025	0.06	4
KF	0.546	0.26	0.20	–0.029	0.06	1
KI	0.590	0.212	0.171	—	0.041	6
LiCl	0.589	—	—	–0.0177	–0.0407	3
LiF	0.589	0.02	0.13	–0.045	–0.11	5
NaBr	0.589	0.148	0.184	–0.0036	–0.035	1
NaCl	0.589	0.115	0.159	–0.011	–0.042	2
NaF	0.633	0.08	0.20	–0.03	–0.12	1
NaI	0.589	—	—	0.0048	–0.0141	3
NH_4Cl	0.589	0.142	0.245	0.042	–0.103	9
RbBr	0.589	0.293	0.185	–0.034	0.108	7,8
RbCl	0.589	0.288	0.172	–0.041	0.116	7,8
RbI	0.589	0.262	0.167	–0.023	0.095	7,8
SrF_2	0.633	0.080	0.269	0.0185	–0.189	16
$SrTiO_3$	0.633	0.15	0.095	0.072	—	17
Tl(Br,Cl)	0.633	–0.451	–0.337	–0.164	–0.114	19,20
Tl(Br,I)	0.633	–0.140	0.149	–0.0725	–0.289	18,20
$Y_3Al_5O_{12}$	0.633	–0.029	0.0091	–0.0615	–0.038	15
$Y_3Fe_5O_{12}$	1.15	0.025	0.073	0.041	—	15
$Y_3Ga_5O_{12}$	0.633	0.091	0.019	0.079	—	17
ZnS	0.633	0.091	–0.01	0.075	0.101	15

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Cubic Crystals; Point Groups 23, m3

Material	Wavelength (μm)	Elastooptic coefficients p_{11}	p_{12}	p_{44}	p_{13}	Ref.
$Ba(NO_3)_2$	0.589	—	$p_{11}-p_{22}$ = 0.992	–0.0205	$p_{11}-p_{13}$ = 0.713	13
$NaBrO_3$	0.589	0.185	0.218	–0.0139	0.213	26
$NaClO_3$	0.589	0.162	0.24	–0.0198	0.20	26
$Pb(NO_3)_2$	0.589	0.162	0.24	–0.0198	0.20	24,25
$Sr(NO_3)_2$	0.41	0.178	0.362	–0.014	0.316	27

Trigonal Crystals; Point Groups 3m, 32, –3m

Material	Wavelength (μm)	Elastooptic coefficients p_{11}	p_{12}	p_{13}	p_{14}	p_{31}
Ag_3AsS_3	0.633	±0.10	±0.19	±0.22		±0.24
Al_2O_3	0.644	–0.23	–0.03	0.02	0.00	–0.04
$CaCO_3$	0.514	0.062	0.147	0.186	–0.011	0.241
HgS	0.633			±0.445		
$LiNbO_3$	0.633	±0.034	±0.072	±0.139	±0.066	±0.178
$LiTaO_3$	0.633	–0.081	0.081	0.093	–0.026	0.089
$NaNO_3$	0.633		±0.21	±0.215	±0.027	±0.25
SiO_2	0.589	0.16	0.27	0.27	–0.030	0.29
Te	10.6	0.155	0.130	—	—	—

Trigonal Crystals; Point Groups 3m, 32, 3m —*continued*

Material	Wavelength (μm)	Elastooptic coefficients P_{33}	P_{41}	P_{44}	Ref.
Ag_3AsS_3	0.633	±0.20	—	—	38
Al_2O_3	0.644	–0.20	0.01	–0.10	15,32
$CaCO_3$	0.514	0.139	–0.036	–0.058	33
α–HgS	0.633	±0.115	—	—	36
$LiNbO_3$	0.633	±0.060	±0.154	±0.300	15,34
$LiTaO_3$	0.633	–0.044	–0.085	0.028	15,35
$NaNO_3$	0.633		0.055	–0.06	39
α–SiO_2	0.589	0.10	–0.047	–0.079	37
Te	10.6	—	—	—	15

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Tetragonal Crystals; Point Groups 4/mmm, –42m, 422

Material	Wavelength (μm)	Elastooptic coefficients p_{11}	p_{12}	p_{13}	p_{31}
$(NH_4)H_2PO_4$	0.589	0.319	0.277	0.169	0.197
$BaTiO_3$	0.633	0.425	—	—	—
CsH_2AsO_4	0.633	0.267	0.225	0.200	0.195
MgF_2	0.546	—	—	—	—
Hg_2Cl_2	0.633	±0.551	±0.440	±0.256	±0.137
KH_2PO_4	0.589	0.287	0.282	0.174	0.241
RbH_2AsO_4	0.633	0.227	0.239	0.200	0.205
RDP	0.633	0.273	0.240	0.218	0.210
$Sr_{0.75}Ba_{0.25}Nb_2O_6$	0.633	0.16	0.10	0.08	0.11
$Sr_{0.5}Ba_{0.5}Nb_2O_6$	0.633	0.06	0.08	0.17	0.09
TeO_2	0.633	0.0074	0.187	0.340	0.090
TiO_2 (rutile)	0.633	0.017	0.143	–0.139	–0.080

Tetragonal Crystals; Point Groups 4/mmm, –42m, 422—*continued*

Material	Wavelength (μm)	Elastooptic coefficients p_{33}	p_{44}	p_{66}	Ref.
$(NH_4)H_2PO_4$	0.589	0.167	–0.058	–0.091	40
$BaTiO_3$	0.633	—	—	—	41
CsH_2AsO_4	0.633	0.227	—	—	42
MgF_2	0.546	—	±0.0776	±0.0488	43
Hg_2Cl_2	0.633	–0.010	—	±0.047	44
KH_2PO_4	0.589	0.122	–0.019	–0.064	45
RbH_2AsO_4	0.633	0.182	—	—	41
RDP	0.633	0.208	—	—	41
$Sr_{0.75}Ba_{0.25}Nb_2O_6$	0.633	0.47	—	—	46
$Sr_{0.5}Ba_{0.5}Nb_2O_6$	0.633	0.23	—	—	46
TeO_2	0.633	0.240	–0.17	–0.046	47
TiO_2 (rutile)	0.633	–0.057	–0.009	–0.060	48

Tetragonal Crystals; Point Groups 4, –4, 4/m

Material	Wavelength (μm)	Elastooptic coefficients p_{11}	p_{12}	p_{13}	p_{16}	p_{31}
$CdMoO_4$	0.633	0.12	0.10	0.13	—	0.11
$PbMoO_4$	0.633	0.24	0.24	0.255	0.017	0.175
$NaBi(MoO_4)_2$	0.633	0.243	0.205	0.25	—	0.21

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Tetragonal Crystals; Point Groups 4, –4, 4/m —*continued*

Material	Wavelength (μm)	Elastooptic coefficients p_{33}	p_{44}	p_{45}	p_{61}	p_{66}	Ref.
$CdMoO_4$	0.633	0.18	—	—	—	—	49
$PbMoO_4$	0.633	0.300	0.067	–0.01	0.013	0.05	52
$NaBi(MoO_4)_2$	0.633	0.29	—	—	—	—	—

Hexagonal Crystals; Point Groups mmc, 6mm

Material	Wavelength (μm)	Elastooptic coefficients p_{11}	p_{12}	p_{13}	p_{31}	p_{33}	p_{44}	Ref.
$Be_3Al_2Si_6O_{18}$	0.589	0.0099	0.175	0.191	0.313	0.023	–0.152	28
CdS	0.633	–0.142	–0.066	–0.057	–0.041	–0.20	–0.099	2,15
ZnO	0.633	±0.222	±0.099	–0.111	±0.088	–0.235	0.0585	30
ZnS	0.633	–0.115	0.017	0.025	0.0271	–0.13	–0.0627	31

Orthorhombic Crystals; Point Groups 222, m22, mmm

Material	Wavelength (μm)	Elastooptic coefficients p_{11}	p_{12}	p_{13}	p_{21}	p_{22}	p_{23}
$Al_2SiO_4(OH,F)_2$	—	–0.085	0.069	0.052	0.095	–0.120	0.065
$BaSO_4$	0.589	0.21	0.25	0.16	0.34	0.24	0.19
HIO_3	0.633	0.302	0.496	0.339	0.263	0.412	0.304
$NaKC_4H_4O_6$	0.589	0.35	0.41	0.42	0.37	0.28	0.34
NH_4ClO_4	0.633	—	0.24	0.18	0.23	—	0.20
$(NH_4)_2SO_4$	0.633	0.26	0.19	±0.260	±0.230	±0.27	±0.254

Orthorhombic Crystals; Point Groups 222, m22, mmm —*continued*

Material	Elastooptic coefficients p_{31}	p_{32}	p_{33}	p_{44}	p_{55}	p_{66}	Ref.
$Al_2SiO_4(OH,F)_2$	0.095	0.085	–0.083	–0.095	–0.031	0.098	28
$BaSO_4$	0.28	0.22	0.31	0.002	–0.012	0.037	55
HIO_3	0.251	0.345	0.336	0.084	–0.030	0.098	54
$NaKC_4H_4O_6$	0.36	0.35	0.36	–0.030	0.0046	–0.025	53
NH_4ClO_4	0.19	0.18	±0.02	<±0.02	—	±0.04	51
$(NH_4)_2SO_4$	0.20	±0.26	0.26	0.015	±0.0015	0.012	52

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Rare Gas Crystals

Rare Gas	Elastooptic coefficients				Ref.
	p_{11}	p_{12}	p_{44}	$p_{11} - p_{12}$	
Ne (T = 24.3 K)	0.157	0.168	0.004	–0.011	59
Ar (T = 82.3 K)	0.256	0.302	0.015	–0.046	60
Kr (T = 115.6 K)	0.34	0.34	0.037	—	59
Xe (T = 160.5 K)	0.284	0.370	0.029	–0.086	60

Measured made at a wavelength of 488 nm.

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1.8.2 Acoustooptic Materials

A figure of merit for an acoustooptic material is $M = n^6p^2/\rho v^3$, where n is the refractive index, p is the photoelastic constant, ρ is the density, and ν is the sound velocity.

Properties of Selected Acoustooptic Materials

Material	Transparency range (μm)	Acoustic mode/ direction	Acoustic velocity ((km/s)	Figure of merit
Ge	2–20	L <111>	5.5	840
Hg_2Br_2	0.40–30	S <110>	0.273	2600
Hg_2Cl_2	0.36–20	S <110>	0.347	700
Hg_2I_2	0.45–40	S <110>	0.254	3200
$LiNbO_3$	0.35–5.0	L <100>	6.5	4.6
$PbBr_2$	0.36–60	S <010>	2.30	550
$PbCl_2$	0.35–20	S <001>	2.51	136
$PbMoO_4$	0.42–5.5	L <001>	3.63	36.3
SiO_2	0.12–4.5	L <100>	5.72	2.38
TeO_2	0.35–5.0	L <001>	4.2	34.5
		S <110>	0.62	793
Tl_3AsS_3	1.3–17	L <001>	2.15	416

All measurements at 0.633 μm, except for Ge at 10.6 μm; L = longitudinal, S = shear.

Reference:

Gottlieb, M. and Singh, N. B., Elastooptic materials*, Handbook of Laser Science and Technology*, *Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 416.

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1.9 Nonlinear Optical Properties

1.9.1 Nonlinear Refractive Index*

Nonlinear refraction is commonly defined either in terms of the optical field intensity I

$$n = n_0 + \gamma I$$

or in terms of the average of the square of the optical electric field $\langle E^2 \rangle$

$$n = n_0 + n_2 \langle E^2 \rangle,$$

where n_0 is the ordinary linear refractive index, γ is the nonlinear refractive coefficient, and n_2 is the nonlinear refractive index. The conversion between n_2 and γ is given by

$$n_2[\text{cm}^3/\text{erg}] = (cn_0/40\pi)\,\gamma[\text{m}^2/\text{W}] = 238.7\, n_0\, \gamma[\text{cm}^2/\text{W}],$$

where c is the speed (in m/s) of light in vacuum.

In terms of third-order susceptibility tensor $\chi^{(3)}(-\omega,\omega,\omega,-\omega)$ of the medium, the nonlinear refractive indices for a linearly polarized wave and a circularly polarized wave in an isotropic material are

$$n_2(\text{LP}) = (12\pi/n_0)\chi^{(3)}_{1111}(-\omega,\omega,\omega,-\omega)$$

and

$$n_2(\text{CP}) = (24\pi/n_0)\chi^{(3)}_{1122}(-\omega,\omega,\omega,-\omega).$$

Whereas in a cubic material the linear refractive index is isotropic, n_2 is not. If θ is the angle made by the electric field vector with the [100] axis for a wave propagating along, say, [001], the effective value of $\chi^{(3)}$ is given by

$$n_2(\theta) = 12\pi/n_0\{\chi^{(3)}_{1111}[1 + \sigma\sin(\theta)^2/2]\},$$

where

$$\sigma = [\chi^{(3)}_{1111} - \chi^{(3)}_{1122} + 2\chi^{(3)}_{1212}]/\chi^{(3)}_{1111}.$$

For a circularly polarized beam propagating along [100]

$$n_2(\text{CP},100) = 6\pi/n_0[\chi^{(3)}_{1111} + 2\chi^{(3)}_{1122} - \chi^{(3)}_{1212}]$$

and for a circularly polarized beam propagating along [111]

$$n_2(\text{CP},111) = 4\pi/n_0[\chi^{(3)}_{1111} + 4\chi^{(3)}_{1122} - \chi^{(3)}_{1212}].$$

The nonlinear refractive index is not a unique quantity for a given material because several physical mechanisms contribute to the polarization that is cubic in the applied optical elect-

* This section was adapted from Chase, L. L. and Van Stryland, E. W., Nonlinear Refractive index: inorganic materials, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 269.

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ric field. These physical mechanisms require a material response that can take place on various time scales. The mechanisms that contribute most strongly to n_2, and their characteristic time scales (in parentheses) are bound electrons (10^{-15} s), optically created free carriers (>10^{-12} s), Raman-active optical phonons (10^{-12} s), electrostriction (>10^{-9} s), and thermal excitation (~10^{-9} s).

Several methods listed below have been employed to measure n_2. The details of the measurements determine the relative contributions from the various possible physical mechanisms to the measured n_2. In general, experiments done with picosecond pulses and nondegenerate mixing are less likely to be affected by the "slow" electrostrictive or thermal effects than those done in the nanosecond pulse regime and with degenerate mixing. Most of the measurements include the effects of both electronic and vibrational (Raman) contributions to n_2.

Techniques for Measuring the Nonlinear Refractive Index

	Method	Ref.
DFWM	Degenerate four-wave mixing	2
DHG	Dynamic holographic grating	3
DTLC	Damage threshold for linear vs. circular polarization	4
ER	Ellipse rotation	5
KE	DC Kerr effect	6
NDFWM	Nondegenerate four-wave mixing	7,8
OKE	Optical Kerr effect	9
PDF	Power-dependent focus	10
PST	Power for self-trapping	11
RSS	Raman scattering spectroscopy	12
SFL	Self-focal length	13
SPA	Spatial profile analysis	14
SPM	Self-phase modulation	15
SSMG	Small-scale modulation growth	16
TBI	Two-beam interferometry	17
TII	Time-integrated interferometry	18
TRI	Time-resolved interferometry	19
TWR	Temporal waveform reshaping	20
WFC	Wavefront conjugation	21
ZS	Z-scan	22

In the following tables of nonlinear refractive parameters, values in parentheses were calculated by Chase and Van Stryland[1] from the quantities reported in the original references. Refractive indices in parentheses were obtained from extrapolation of available data. For noncubic crystals, or for cubic crystals where the polarization is not along a cube axis or is not specified in the original reference, the value tabulated for $\chi^{(3)}{}_{1111}$ is an effective value of $\chi^{(3)}$. Unless noted otherwise, measurements were made at room temperature.

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Measured Nonlinear Refractive Parameters

Crystals	Method	Pulse duration (ns)	Wavelength (nm)	Linear refractive index	χ_{1111} (10^{-13} cm^3 erg)	$n_{2,LP}$ (10^{-13} cm^3 erg)	γ_{LP} (10^{-16} cm^2/W)	Ref.
AgCl	NDFWM	3	1064	2.02	(1.25)	23.3	(48.3)	23[a]
Al_2O_3	PDF	0.17	308	(1.814)	(0.088)	(1.82)	4.2	24
Al_2O_3	ZS	0.02	532	1.8	(0.066)	(1.4)	3.3	25
Al_2O_3	ZS	0.028	1064	1.75	(0.056)	(1.2)	2.9	25
Al_2O_3	ZS	0.016	355	1.8	(0.076)	(1.6)	3.7	25
Al_2O_3	NDFWM	3	560, 590	(1.76)	(0.11)	2.4	(5.7)	8
Al_2O_3	PDF	0.030	1064	(1.76)	(0.060)	1.3	(3.1)	26
Al_2O_3 (E‖c)	NDFWM	3	1064	1.75	(0.060)	1.3	(3.11)	7
Al_2O_3 (E⊥c)	NDFWM	3	1064	1.75	(0.057)	1.23	(2.94)	7
Al_2O_3:Cr	TRI	~1	1064	1.76	(0.069)	1.48	(3.52)	27
AlGaAs	TRI	—	850–810	NA	—	–(2.2–3.3) × 10^4	—	28[b]
BaF_2	ZS	0.027	532	(1.476)	(0.031)	0.8	(2.27)	29
BaF_2	PDF	0.017	308	(1.500)	(0.077)	(1.94)	5.42	24
BaF_2	NDFWM	4	592, 575	(1.47)	0.069	(1.8)	(5.0)	30
BaF_2	TRI	0.125	1064	1.47	(0.39)	(1.00)	2.85	32
BaF_2 (100)	DFWM	0.3	1064	1.468	(0.026)	0.67	(1.91)	7
BaF_2 (100)	ZS	0.028	1064	1.47	0.019	(0.5)	1.4	25
BaF_2 (100)	ZS	0.02	532	1.48	0.029	(0.73)	2.1	25
BaF_2 (100)	ZS	0.016	355	1.5	0.039	(0.97)	2.7	25
$BeAl_2O_4$	NDFWM	3	1064	1.73	(0.67)	1.46	(3.54)	7
$Bi_{12}SiO_{20}$	OKE	1.5 × 10^{-4}	532	—	—	5	—	33
C (diamond)	NDFWM	4	545, 545-ε	(2.42)	0.46	(7.2)	(12.6)	31[n]
$CaCO_3$	NDFWM	3	560, 590	(1.66)	(0.14)	3.2	(8.1)	28[c]

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Measured Nonlinear Refractive Parameters—*continued*

Crystals	Method	Pulse duration (ns)	Wavelength (nm)	Linear refractive index	χ_{1111} (10^{-13} cm^3 erg)	$n_{2,LP}$ (10^{-13} cm^3 erg)	γ_{LP} (10^{-16} cm^2/W)	Ref.
$CaCO_3$ (E ‖ c)	NDFWM	3	1064	1.48	(0.033)	0.83	(2.35)	23
$CaCO_3$ (E ⊥c)	NDFWM	3	1064	1.643	(0.048)	1.11	(2.83)	23
CaF_2	PDF	0.017	308	(1.453)	(0.026)	(0.67)	1.92	24
CaF_2	NDFWM	4	592, 575	(1.43)	0.04	(1.1)	(3.1)	30
CaF_2	NDFWM	3	560, 590	(1.43)	(0.055)	1.46	(4.3)	8
CaF_2	TRI	0.125	1064	1.43	(0.025)	0.65	1.90	32,34
CaF_2	PDF	0.030	1064	1.43	0.105	2.8	(8.1)	10
$CaMg_2Si_2O_6$	NDFWM	3	1064	1.67	(0.077)	1.73	(4.34)	7
CaO (100)	NDFWM	3	1064	1.83	(0.25)	5.2	(11.9)	7
$CaWO_4$ (E ⊥ c)	NDFWM	3	1064	1.89	(0.25)	4.2	(9.3)	7
$CaWO_4$ (E ‖ c)	NDFWM	3	1064	1.91	(0.28)	5.6	(12.3)	7
CdF_2	NDFWM	4	575, 575-ε	(1.57)	0.145	(3.48)	(9.29)	31
CdF_2	TRI	0.125	1064	1.57	(0.061)	(1.46)	3.87	32
CdF_2 (100)	NDFWM	3	1064	1.56	(0.16)	3.95	(10.6)	7
CdS	ZS	0.03	532	2.34	(–211)	–3400	(–6090)	35
CdS	SPA	20	694	(2.42)	(130)	2×10^3	(3.5×10^3)	36
CdS (E‖c)	NDFWM	3	1064	2.34	(17.5)	283	(507)	7
CdS(E⊥c)	NDFWM	3	1064	2.33	(18.8)	304	(547)	7
$CdS_{0.18}Se_{0.82}$	SPA	20	694	(2.6)	(1500)	2.2×10^4	(3.5×10^4)	36
$CdS_{0.5}Se_{0.5}$	ZS	0.03	1064	2.45	(65)	1000	(1710)	35
$CdS_{0.5}Se_{0.5}$	SPA	20	694	(2.5)	(230)	3.5×10^3	(5.9×10^3)	36
CdSe	ZS	0.03	1064	2.56	(–6.1)	–90	(–147)	35
CdTe	ZS	0.04	1064	2.84	(–150)	–2000	(–3000)	35

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CdTe	DFWM	0.04	1064	2.84	±150	±2100	±3100	37[d]
CdTe	WFC	15	1064	~3	2.5×10^5	(3.1×10^6)	(4.4×10^6)	38
CeF_3	NDFWM	3	1064	~1.6	(0.055)	1.3	(3.4)	7
CeF_3	TRI	0.125	1064	~1.6	(0.066)	(1.55)	4.06	32
CsCl	NDFWM	0.006	1064, 532	(1.64)	0.086	(2.0)	(5.1)	39
CsCl	NDFWM	0.006	1064, 532	—	0.029	—	—	39[e]
CuCl	NDFWM	—	773, 694	(1.94)	33	640	1400	40[m]
Er_2O_3	NDFWM	3	1064	1.96	(0.24)	4.53	(9.7)	7
Ga_2O_3	NDFWM	3	1064	1.96	(0.30)	5.8	(12.4)	7
GaAs	ZS	0.03	1064	3.47	(~249)	~2700	(~3260)	35
GaAs	NDFWM	~200	9200–11800	(3.3)	120	(1.4×10^3)	(1.7×10^3)	41
GaP	TDFWM	2.7×10^{-3}	577	(3.396)	2.1×10^3	(2.33×10^4)	(2.87×10^4)	42
$Gd_3Ga_5O_{12}$	NDFWM	3	1064	1.945	(0.30)	5.8	(12.5)	7
$Gd_3Sc_2Al_3O_{12}$	NDFWM	3	1064	1.891	(0.20)	4.0	(8.9)	7
$Gd_3Sc_2Ga_3O_{12}$	NDFWM	3	1064	1.943	(0.28)	5.5	(11.9)	7
Ge	ZS	0.06	10600	3.47	(290)	2700	(2800)	35
Ge	NDFWM	~200	9200–11800	4.	1000	(9.4×10^3)	(9.9×10^3)	41
Ge	ER	2.3	10590	(4.)	250	(2.3×10^3)	(2.5×10^3)	43
Ge	NDFWM	—	10600	4.	—	—	—	44[f]
Ge	WFC	300	38000	4.0	400	(3.8×10^3)	(3.9×10^3)	45
HgCdTe	SPA	CW	10640	4.25	—	$[n = -7 \times 10^{-3}\ I^{1/3}]$	—	46[g]
InSb	SPA	CW	5313	(4)	$(-6. \times 10^{10})$	$(-6. \times 10^{11})$	-6×10^{11}	47[l]
InSb	SPA	CW	5405–5714	(4)	—	100	—	48[h]
InSb	NDFWM	—	10600	(4)	$\sim 2 \times 10^6$	$(\sim 2 \times 10^7)$	$(\sim 2 \times 10^7)$	49[i]
KBr	NDFWM	3	1064	1.544	(0.12)	2.93	(8.0)	7
KBr	PDF	0.030	1064	1.544	0.58	14.2	(38.5)	10
KCl	NDFWM	3	1064	1.479	(0.079)	2.01	(5.7)	7
KCl	PDF	0.030	1064	1.479	0.13	3.3	(9.3)	59

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Measured Nonlinear Refractive Parameters—*continued*

Crystals	Method	Pulse duration (ns)	Wavelength (nm)	Linear refractive index	χ_{1111} (10^{-13} cm^3 erg)	$n_{2,LP}$ (10^{-13} cm^3 erg)	γ_{LP} (10^{-16} cm^2/W)	Ref.
KF	NDFWM	0.006	1064, 532	(1.36)	0.014	(0.39)	(1.2)	39
KF	NDFWM	0.006	1064, 532	—	0.020	—	—	39[e]
KH_2PO_4	TRI	0.10	1064	(1.49)	(0.040)	1.0	(2.8)	34
KH_2PO_4	PDF	0.030	1064	1.49	0.14	3.6	(10)	7
KH_2PO_4 (‖c)	NDFWM	3	1064	1.460	(0.028)	0.72	(2.1)	7
KH_2PO_4 (⊥c)	NDFWM	3	1064	1.494	(0.031)	0.78	(2.2)	7
KI	NDFWM	0.006	1064, 532	(1.7)	0.38	(8.4)	(20)	39
KI	NDFWM	0.006	1064, 532		0.13	—	—	39[e]
KI	PDF	0.030	1064	1.638	0.49	11.2	(29)	10
$KTaO_3$	NDFWM	3	1064	2.25	(1.73)	29	(54)	7
$KTiOPO_4$	NDFWM	3	1064	1.74	(0.26)	5.73	(13.8)	7
$KTiOPO_4$	ZS	0.04	1064	1.78	(0.47)	(10)	24	50
$La_2Be_2O_5$:Nd	PDF	0.030	1064	(1.98)	(0.11)	2.1	(4.4)	26
$La_3Lu_2Ga_3O_{12}$	NDFWM	3	1064	1.930	(0.30)	5.8	(12.6)	10
LaF_3	TRI	0.125	1064	1.60(o)	(0.064)	1.51	3.95	86
LaF_3 (‖c)	NDFWM	3	1064	1.60	(0.059)	1.4	(3.7)	7
LAP, x + z	NDFWM	3	1064	1.51	(0.12)	3.0	(8.4)	7
LAP,y	NDFWM	3	1064	1.559	(0.077)	1.87	(5.0)	7
LiCl	NDFWM	0.006	1064,532	(1.67)	0.069	(1.56)	(3.9)	39
LiCl	NDFWM	0.006	1064,532	—	0.027	—	—	39[e]
LiF	ZS	0.028	1064	1.39	(0.01)	(0.27)	(0.81)	51
LiF	ZS	0.02	532	1.4	(0.011)	(0.3)	0.9	51
LiF	NDFWM	3	560, 590	(1.39)	(0.034)	0.92	(2.8)	8
LiF	TRI	0.125	1064	1.39	(0.013)	0.35	1.05	32,34

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$LiNbO_3$	NDFWM	5	577	(2.31(o))	—	—	—	52
$LiYF_4$	TRI	0.125	1064	1.45(o)	(0.023)	0.60	1.72	32
$MgAl_2O_4$	NDFWM	3	1064	1.72	(0.068)	1.5	(3.65)	7
MgF_2	NDFWM	3	1064	1.374	(0.0091)	0.25	(0.76)	7
MgF_2	ZS	0.028	1064	1.38	(0.0073)	(0.20)	0.61	51
MgF_2	ZS	0.02	532	1.38	(0.008)	(0.22)	0.67	51
MgF_2	ZS	0.016	355	1.4	(0.0085)	(0.23)	0.69	25
MgF_2	TRI	0.125	1064	1.37(o)	(0.011)	0.30	0.92	32,34
MgO	NDFWM	3	1064	1.72	(0.073)	1.61	(3.92)	7
NaBr	NDFWM	3	1064	1.623	(0.14)	3.26	(8.41)	7
NaBr	PDF	0.030	1064	1.62	0.41	9.6	(25)	10
NaCl	NDFWM	3	1064	1.531	(0.065)	1.59	(4.35)	7
NaCl	PDF	0.030	1064	1.532	0.26	6.5	(18)	10
NaF	NDFWM	3	1064	1.321	(0.012)	0.34	(1.1)	7
NaF	TRI	0.125	1064	1.32	(0.015)	0.43	1.37	32
NaF	PDF	0.030	1064	1.321	0.03	0.9	(2.9)	10
PbF_2	TRI	0.125	1064	1.76	(0.23)	4.94	11.7	32
Si	NDFWM	~200	9200–11800	(3.4)	60	660.	(820)	41
SiC	SPA,TWR	20	694	2.68	(36)	510	(800)	53
SiO_2 ($\perp$c)	NDFWM	3	1064	1.534	(0.046)	1.12	(3.06)	7
SiO_2 ($\parallel$c)	NDFWM	3	1064	1.543	(0.047)	1.16	(3.15)	7
SrF_2	NDFWM	3	1064	1.433	(0.019)	0.50	(1.46)	7
SrF_2	NDFWM	4	592, 575	(1.43)	0.052	(1.4)	(4.0)	30
SrF_2	TRI	0.125	1064	1.43	(0.023)	0.60	1.76	32
SrO (110)	NDFWM	3	1064	1.81	(0.24)	5.07	(11.7)	7
$SrTiO_3$	NDFWM	3	1064	2.31	(1.63)	26.7	(48)	7
TiO_2	NDFWM	3	1064	2.48	(3.67)	55.8	(94)	7
TiO_2	DFWM	0.08	1064	(2.48)	(7.75)	(118)	200	2

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Measured Nonlinear Refractive Parameters—*continued*

Crystals	Method	Pulse duration (ns)	Wavelength (nm)	Linear refractive index	χ_{1111} (10^{-13} cm^3 erg)	$n_{2,LP}$ (10^{-13} cm^3 erg)	γ_{LP} (10^{-16} cm^2/W)	Ref.
Y_2O_3	NDFWM	3	1064	1.92	(0.27)	5.33	(11.6)	7
$Y_3Al_5O_{12}$	TRI	0.15	1064	(1.83)	(0.15)	3.16	(7.2)	54[i]
$Y_3Al_5O_{12}$	NDFWM	3	560,590	(1.83)	(0.22)	4.5	(10)	8
$Y_3Al_5O_{12}$	TRI	~1	1064	1.83	(0.17)	3.47	(7.9)	27
$Y_3Al_5O_{12}$	ER	13	694	1.829	(0.21)	4.27	(9.8)	5[k]
$Y_3Al_5O_{12}$:Nd	PDF	0.030	1064	1.82	0.17	3.5	(8.1)	7
$Y_3Ga_5O_{12}$	NDFWM	3	1064	1.912	(0.26)	5.2	(11.4)	7
$YAlO_3$	NDFWM	3	1064	1.933	(0.17)	3.37	(7.3)	7
ZnO (E⊥χ)	NDFWM	3	1064	1.99	(1.32)	25	(53)	7
ZnO (E‖c)	NDFWM	3	1064	1.96	(1.20)	23	(49)	7
ZnS	ZS	0.03	1064	2.40	(3.1)	48	(84)	35
ZnS (E‖c)	NDFWM	3	1064	2.29	(2.98)	49	(90)	7
ZnS (E⊥c)	NDFWM	3	1064	2.29	(2.85)	47	(87)	7
ZnSe	ZS	0.03	1064	2.48	(11)	170	(290)	35
ZnSe	DFWM	0.04	1064	2.48	18	(270)	(460)	37
ZnSe	ZS	0.03	532	2.70	(–29)	–400	(–621)	35
ZnSe	DFWM	0.03	532	2.70	±30	(±420)	(±650)	37[d]
ZnTe	ZS	0.03	1064	2.79	(61)	830	(1250)	35
ZrO_2	SFL	0.045	1064	(1.92)	(0.41)	8	(17)	55
ZrO_2	SFL	0.03	1064	(1.92)	(0.31)	6	(12.9)	56
ZrO_2	NDFWM	3	1064	2.12	(0.33)	5.8	(11.5)	7

[a] polycrystalline sample; [b] wavelength dependent; [c] E ‖ optic axis; [d] absolute values measured; [e] in 5 mol/O acq. sc; [f] relative spect; impurity; 175 K, I in W/cm^2; [g] 175 K, I in W/cm^2; [h] 77 K, free electrons; [i] 4 K, free electrons; [j] 4 K ‖ [111]; [k] E ‖ [100]; [l] 5 K, free electrons; [m] 15 K; [n] dispersion also given.

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Dispersion of the Nonlinear Refractive Index*

Material	Energy gap (eV)	$n_2 \times 10^{-14}$ esu			
		266 nm	355 nm	532 nm	1064 nm
LiF	13.6	4.0 ± 1.0	1.9 ± 0.4	1.9 ± 0.4	2.5 ± 0.5
MgF_2	10.8	5.0 ± 1.0	2.2 ± 0.4	1.9 ± 0.4	1.9 ± 0.4
BaF_2	9.1	11 ± 2	9.7 ± 1.9	7.5 ± 1.5	5.0 ± 1.0
SiO_2	8.4	28 ± 6	8.5 ± 1.7	7.8 ± 1.6	7.4 ± 1.5
Al_2O_3	9.9	26 ± 5	16 ± 3	14 ± 3	13 ± 3
BaB_2O_4	6.2	1 ± 0.3	14 ± 3	21 ± 4	11 ± 2
KBr	7.6	—	—	47 ± 9	29 ± 6
$CaCO_3$	5.9	46 ± 9	14 ± 3	11 ± 2	11 ± 2
$LiNbO_3$	4.0	—	—	440 ± 70	48 ± 7
$KTiOPO_4$	3.5	—	—	98 ± 15	100 ± 20

* DeSalvo, R., Said, A. A., Hagan, D. J., Van Stryland, E. W., and Sheik-Bahae, M., Infrared to ultraviolet measurements of two-photon absorption and n_2 in wide bandgap solids, *IEEE J. Quantum Electron.* 32, 1324 (1996).

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1.9.2 Two-Photon Absorption*

Two-photon absorption (2PA) occurs in all materials at sufficiently high irradiance when the combined energy of two quanta of light matches a transition energy between two states of the same parity. The fundamental equation describing this loss of irradiance I with depth z in a material is

$$dI/dz + \beta I^2,$$

where β is the two-photon absorption coefficient. The coefficient β is proportional to the imaginary part of $\chi^{(3)}(-\omega,\omega,\omega,-\omega)$. The relationship between n_2, β, and $\chi^{(3)}$ is analogous to the relationship between n_0, the linear absorption coefficient α, and the linear susceptibility χ.

The two-photon absorption coefficient β depends not only on the frequency arguments but also on the state of polarization, propagation direction, and crystal symmetry as β is derived from the imaginary part of the third-order susceptibility tensor $\chi^{(3)}$. Relations for $\chi^{(3)}$ for cubic crystals for several polarization orientations are presented in reference 1. These relations are valid for both the real and imaginary parts of $\chi^{(3)}$. For a linear or circularly polarized wave:

$$\beta(\mathrm{LP}) = (32\pi^2\omega/n^2c^2)3\chi^{(3)}{}_{1111}$$

and

$$\beta(\mathrm{CP}) = (64\pi^2\omega/n^2c^2)3\chi^{(3)}{}_{1122}.$$

Because these equations are in cgs units (esu), β is in cm s/erg rather than the more common mixed unit of cm/W.

Several methods have been used to measure the two-photon absorption coefficient in solids. Direct transmission measurements as a function of irradiance have been the primary method to determine absolutely calibrated values of β as well as two-photon absorption spectra. Several other techniques have been utilized to obtain calibrated as well as relative measurements and two-photon absorption spectra. These are listed in the table to follow. Many of these methods require calibration. Direct transmission experiments are best suited for absolute calibration. Because to give a value for β a measurement of the absolute irradiance is needed, single-beam experiments are most easily calirated. Once absolute calibration is obtained at a single wavelength, relative measurements and spectral measurements can be calibrated.

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* This section was adapted from Van Stryland, E. W. and Chase, L. L., Two-photon absorption: inorganic materials, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 299.

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Techniques for Measuring Two-Photon Absorption

	Method	Ref.
AI1	Attenuation vs. irradiance for a single beam	3, 4
AI2	Attenuation vs. irradiance; two beams, usually one scanned in ω	5
AIS	Attenuation vs. irradiance; broad spectrum treated simultaneously	6
C	Calorimetry	7
CR	Comparison of 2-photon loss and Raman gain	8, 9
EPR	Elliptical polarization rotation	10
FCC	F-center coloration	11
GTA	Gain measurement in a 2-photon-pumped amplifier	12
IA	Intracavity absorption	13
L	Luminescence or fluorescence	14, 15
HGE	Harmonic generation efficiency	16
PA	Photoacoustics	17
PC	Photoconductivity or photo-Hall effect	18, 19
TCN	Two-channel normalization	20
TL	Thermal lensing	21
TRT	Time-resolved transmission	22
Z-scan	A propagation method to measure β and n_2	23

The experimental data on two-photon absorption coefficients (β in cm per GW) are presented in the following table. Materials are listed alphabetically. The method of measurement (using the above table), the pulse duration t_p, the input two-photon excitation energy $2\hbar\omega$ (or range of energies if spectra are given), band gap energy E_g (if given in the reference) or absorption cutoff energy for wide-gap materials, and linear index $n_0(\hbar\omega)$ are listed. The linear refractive indices are taken from reference 2.

The following shorthand notation is used in the table: Anisot. = anisotropy; β_l and $\beta_c = \beta$ measured with linearly or circularly polarized light, respectively; Cleartran = brand name of heat-treated ZnS that makes it water clear and is grown by CVD = chemical vapor deposition; Dir. = direct; K = Kelvin; L = length; Mag. = magnetic; Pol. = polarized; SHG = second harmonic generation; *T* = temperature; t = time; *E* for SHG, means that the electric field and propagation direction are aligned for SHG phase matching.

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Two-Photon Absorption Data

Material	Method	Pulse τ_p (ns)	Bandgap E_g (eV)	$2\hbar\omega$ (eV)	Index n_0 ($\hbar\omega$)	2PA coefficient (cm/GW)	Ref.	Additional information
Ag_3AsS_3	AI2	10	2.1	2.7–3.2	~2.7	Abs. spectr. (10 @ 3.1 eV)	24, 25	
Ag_3AsS_3	AI1	25		3.56	~2.7	20	26	
Ag_3AsS_3	AI1	20		2.34	~2.7	<3	26	
AgCl	L		3.2	4.0–4.4	2.0	Abs. spectr. (0.5 @ 4.3 eV)	27	Indirect gap
AgCl	L	9		6.6–7.6	2.07	Relative spectrum	28	77 K
AgCl	L	9		3.3–4.2		Relative spectrum	28	80 K
$AgGaSe_2$	AI1	~0.01	1.1	2.33	2.7	1.4	29	
α-AgI	A12		2.9	3.0–3.06		Relative spectrum	30	1.6 K
A1As-GaAs	L		1.7	1.65–1.8		Relative spectrum	191	
Al_2O_3	AI1	0.017	9.9	6.99	~1.79	<0.0016	3	
Al_2O_3	AI1	0.015		9.32	~1.84	0.27	3	
Al_2O_3	AI1	0.12		8.05	~1.8	0.0276	31	
As_2S_3	AI2	30	2.5	2.4–3.6	~2.6	Abs. spectr. (25 @ 3.4 eV)	32	
BaF_2	AI1	0.017	9.1	6.99	1.49	<0.0036	33	
BaF_2	AI1	0.015		9.32	~1.5	<0.0040	33	
BaF_2	AI1	0.0007		10.0	~1.5	0.11	34	
$BaTiO_3$	AI2	17	3.5	3.4–4.2		Abs. spectr. (4 @ 4 eV)	35	392 K
$BaTiO_3$	AI2	0.0012		4.16	~2.4	0.1	36	Photorefraction
$Bi_4Ge_3O_{12}$	L	~10	4.2	4.1–5.1	2.1	Relative spectrum	37	
$Bi_4Ge_3O_{12}$	L	9		4.27–4.83	2.1	Abs. spectr. (50 @ 4.5eV)	38	80 K
$Bi_4Ge_3O_{12}$	L	9		4.2–5	2.1	Relative spectrum	39	80 K
$Bi_4Ge_3O_{12}$	AI2	10		4.8–5.7		Abs. spectr. (10 @ 5.6 eV)	40	80 K
C (diamond)	CR	4.0	5.47	4.55	2.42	<0.003	9	
C (diamond)	AI1	0.021		4.66	2.42	<0.26	41	

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C (diamond)	AI1	0.000135		8.0	~2.5	0.74	42	Indirect gap
C (diamond)	Z-scan	0.015		6.99	~2.5	0.3	43	k ‖ [001]
$CaCO_3$	AI1	0.015	5.9	9.32	~1.5–1.8	0.24	3	
CaF_2	CR	4.0	10	4.31	1.43	<0.004	9	
CaF_2	AI1	0.015		9.32	1.46	<0.02	3	
CaF_2	AI1	0.0007		10.0	1.47	0.0083	34	
CaF_2	AI1	0.12		8.05	1.46	0.00092	31	
CdF_2	CR	4.0	6	4.31		<0.03	9	
CdF_2	AI1	0.017		6.99		<0.042	33	
CdF_2	AI1	0.015		9.32		1.6	33	
CdI_2	L	9	3.9	3.5–4.4		Relative spectrum	39	Indirect gap
CdP_2	TRT			2.34		160	44	
CdP_2	TRT			3.56		800	44	
CdP_2	AI2	15		2.4–3.2		Abs. spectr. (11 @ 2.9 eV)	45	
CdS	L	3×10^5	2.42	3.56	~2.42	12	46	123 K
CdS	AI2	30		2.5–3.5	2.35–2.42	Abs. spectr. (20 @ 2.8 eV)	47	
CdS	AI2	40		2.5–3.4	2.35–2.4	Abs. spectr. (14.7 @ 3.4 eV)	48	
CdS	AI1	30		3.56	~2.42	30	49	
CdS	AI2	30		2.5–3.5	2.3–2.4	Relative spectrum	50	Anisotropy
CdS	AI2			2.54–3.6	2.35–2.44	Abs. spectr. (30 @ 3.0 eV)	51	77 K
CdS	AI2			2.54–3.6	2.35–2.44	Abs. spectr. (30 @ 3.0 eV)	51	77 K
CdS	AI1	30		3.56	~2.42	100	52	β vs. length
CdS	AI2	30		2.65–3.45	2.35–2.4	Abs. spectr. (35 @ 4 eV)	53	
CdS	AI1	5		2.54–2.55	~2.35	Relative spectrum	54	
CdS	AI2	0.006		2.5–3.5	2.35–2.42	Abs. spectr. (18 @ 3.35 eV)	55	
CdS	L			2.550–2.554	~2.35	Relative spectrum	56	1.6 K
CdS	AI1	30		3.56	~2.42	15; 20	57	E ‖ c; E ⊥ c
CdS	AI2	300		2.5–2.6	~2.35	Abs. spect. (4000 @2.54 eV)	58	

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Two-Photon Absorption Data—*continued*

Material	Method	Pulse τ_p (ns)	Bandgap E_g (eV)	$2\hbar\omega$ (eV)	Index n_0 ($\hbar\omega$)	2PA coefficient (cm/GW)	Ref.	Additional information
CdS	L	~25	2.5	2.56–2.62	~2.35	Relative spectrum	107	
CdS	AI1	20	2.4	3.56	~2.42	56	106	Self-focusing
CdS	AI1	45	2.5	3.56	~2.42	120; 56	82	E ‖ c; E ⊥ c
CdS	AI2			2.5–3.6		Abs. spectr. (20 @ 3.2 eV)	62	β vs. pol.
CdS	PC	~10	2.58	~5.1–5.2	~2.8	Magnetospectra 0 < B < 10 Tesla	63	A-excitons 1.8 K
CdS	CR	8		3.91	~2.5	120; k ‖ c; 110 k ⊥ c, E ⊥ c 140 k ⊥ c, E ⊥ c	65	β vs. T and resistance
CdS	AI1			4.66		0.9; 1.8	66	E ‖ c; E ⊥ c
CdS	AI1	0.027		4.66	~2.64	5.5	67	
$CdS_{.25}S_{e.75}$	AI1	0.038	1.78	2.33	2.51	15	67	
$CdS_{0.5}Se_{0.5}$	C	11; 26		2.33		32;135	7	
$CdS_{0.5}Se_{0.5}$	AI1	0.038	1.93	2.33	2.45	10	67	
$CdS_{0.8}Se_{0.2}$	AI1	30		3.56		130	49	
$CdS_{0.9}Se_{0.1}$	AI1	30		3.56		70	49	
CdSe	AI1		1.7	2.33	2.56	950	68	
CdSe	AI1			2.33	2.56	900; 390	69	E ⊥ z; E ‖ z
CdSe	AI1			2.33	2.56	200	70	
CdSe	AI1	20		2.33	2.56	60–140	71	
CdSe	AI1	15		2.33	2.56	40	72	
CdSe	AI1	0.030		2.33	2.56	30	73	
CdSe	TRT	~20		1.88; 2.33	2.5; 2.56	2; <20	26	
CdSe	C	16		2.33	2.56	50	74	

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CdSe	C	11; 26		2.33	2.56	25; 38	7	
CdSe	PA	0.040		2.33	2.56	35	75	
CdSe	C	79		1.88	~2.5	67	7	
CdSe	AI1	0.038		2.33	2.56	18	67	
CdSe	AI1	~200		3.65	~2.6	$\sim 10^6$	76	4.2K, t resol.
CdSe	AI1	0.006		2.36	2.56	18	77	No dep. SHG
CdS_xSe_{1-x}	AI1	30	1.9–2.4	3.56		100–1700	78	300 K, 77 K
CdS_xSe_{1-x}	AI1			2.33, 3.56		Relative spectrum	79	
CdTe	AI1		1.56	2.33	2.84	200	70	
CdTe	AI1			2.33	2.84	180	80	300 K, 85 K,
CdTe	AI1	0.030		2.33	2.84	25	73	E ‖ z
CdTe	TCN	0.030		2.33	2.84	$\beta_{CdTe}/\beta_{GaAs} = 0.78$	20	
CdTe	C	16		2.33	2.84	130	74	
CdTe	C	11; 38		2.33	2.84	53; 78	7	
CdTe	C	79		1.88	~2.7	120	7	
CdTe	PA	0.040		2.33	2.84	50	75	
CdTe	TCN	20		2.33	2.84	170	81	
CdTe	AI1	0.005		2.34	2.84	12; 8	82	270 K; 100 K
CdTe	AI1	0.038		2.33	2.84	22; 15	67	Cryst., polycryst.
CdTe	AI1	0.035		2.33	2.84	8	83	
CdTe	Z-scan	0.040		2.33	2.84	26	84	Polycrystal
CsBr	AI2	~10	6.9	7.2–8.0	~1.8–1.9	Abs. spectr. (10 @ 7.5 eV)	85	20 K
CsD_2AsO_4	AI1	0.017		6.99	1.6	0.051; 0.080	3	E ‖ z; E ⊥ z
CsH_2AsO_4	AI1	0.017		6.99	1.6	0.028	3	
CsI	AI2	$\sim 10^6$	6.2	5.7–6.8	~1.8–1.9	Relative spectrum	86,87	

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Two-Photon Absorption Data—*continued*

Material	Method	Pulse τ_p (ns)	Bandgap E_g (eV)	$2\hbar\omega$ (eV)	Index n_0 ($\hbar\omega$)	2PA coefficient (cm/GW)	Ref.	Additional information
CsI	AI2	~10		6.2–6.8	~1.8–1.9	Abs. spectr. (40 @ 6.5 eV)	85	20 K
CsI	AI2			6.0–6.8	~1.8–1.9	Relative spectrum	88	20 K
CsI	L	5		7.0	1.89	Relative spectrum	89	
CsI	AI1	6		6.99	1.89	6	90	
CsI	AI1	0.00035		8.05	~1.9	4.5	91	3×10^{18} Na^+
Cu_2O	AI2	40	2.1	2.0–2.8		Relative spectrum	92	
Cu_2O	AI2	0.0005		3.4–3.9		Relative spectrum	93	20 K
Cu_2O	AI2			2.03–2.17		Relative spectrum	94	Excitons
CuBr	AI2	30	3	2.97–3.10	2.1	Relative spectrum	95	
CuBr	AI1	45		3.56	2.1	200	62	
CuCl	AI2	~10	3.3	3.2–4.25	~2	Relative spectrum	96	20 K
CuCl	AI2			3.21–3.56	1.97	Relative spectrum	97	4.2 K
CuCl	AI1	16		3.16–3.20	1.95	1×10^6	98	4 K, 77 K
CuCl	AI2	~5		3.16–3.18	1.95	~3×10^6	4	4.2 K
CuCl	AI1	45		3.56	1.97	45	62	
CuCl	AI2	~10		3.2–5.4	~2	Relative spectrum	99	
CuCl	AI2			3.2–5.4	~2	Relative spectrum	100	4.3 K, β vs Pol
CuCl	EPR	5		3.18–3.19	1.95	Relative spectrum	10	4 K
CuCl	L	9		3.34–4.1	1.92	Abs. spectr. (30 @ 3.5 eV)	38	80 K
CuCl	L	9		3.34–4.1	1.92	Relative spectrum	39	80 K
CuI	AI1	45	3.1	3.56	1.97	89	62	
$FeBO_3$	AI2	12	~2.5	2.6–3.6		Abs. spectr. (5 @ 3.4 eV)	101	108 K
GaAs	AI1		1.42	2.33	3.43	300	68	
GaAs	AI1			2.33	3.43	20	70	

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GaAs	AI1			2.33	3.43	800	49	n-type
GaAs	AI1, PC	22		2.33	3.43	360	102	
GaAs	AI1	~125		1.88	~3.4	33	103	
GaAs	AI1	30		2.33	3.43	230	104	
GaAs	AI1			2.33	3.43	80	80	300 K, 85 K
GaAs	AI1	~50		1.5–2.33	~3.4	Abs. spectr. (1100 @ 1.5eV)	105	
GaAs	AI1	15		2.33	3.43	60	72	
GaAs	AI1	0.030		2.33	3.43	28	46	E ‖ z
GaAs	AI1	~10		2.33	3.43	35; 78	106	
GaAs	L			1.4–1.8	~3.35	Abs. spectr. (5.1 @ 1.6eV)	107	
GaAs	L	5		2.33	3.43	70	108	
GaAs	AI1	0.008		2.33	3.43	15	109	
GaAs	C	0.030		2.33	3.43	30	7	
GaAs	AI1	30		2.33	3.43	100	110	
GaAs	AI1	~0.035		1.3–1.7		Relative spectrum	111	100 K
GaAs	AI1	0.038		2.33	3.43	23	67	
GaAs	AI1	0.045		2.33	3.43	26	112	
GaAs	AI2, L	0.005		2.34	3.43	45	113	295 K, 103 K
GaAs	AI2	0.035		2.33	3.43	27	114	Cross-pol.
GaAs	AI1	0.05		2.33	3.53	29	115	In Chinese
GaAs	A12	0.027		2.33	3.43	18, 22	116	
GaAs	AI1	0.08		2.33	3.43	26	117	
GaAs	Z-scan	0.040		2.33	3.43	26	84	No anisotropy
GaP	AI1	50	2.26	2.33	3.12	1.7	118	Indirect gap
GaP	AI1	0.030		2.33	3.12	0.2	73	E ‖ [110]
GaP	TCN			3.92	3.35	250	119	
GaP	CR			3.18	3.18	250	59	

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Two-Photon Absorption Data—*continued*

Material	Method	Pulse τ_p (ns)	Bandgap E_g (eV)	$2\hbar\omega$ (eV)	Index n_0 ($\hbar\omega$)	2PA coefficient (cm/GW)	Ref.	Additional information
GaS	AI1	20	2.8	3.56		100	120	Direct gap
GaS	PC	20	2.3	2.33		0.05	120	Indirect gap
GaSe	AI1	20	2.0	2.33		110	120	
Ge	AI1	80	0.66	1.06	~4	50	121	
Ge	AI1	100		0.8–1.0	~4	2500	122	
Ge	AI1; PC	~480		0.916	4.05	160	19	
$Hg_{0.78}Cd_{0.22}Te$	TRT	~200	0.17	0.233		14000	123	
$Hg_{0.78}Cd_{0.22}Te$	TRT	300		0.233		1×10^4, 3×10^4	124	300 K; 150 K
Hg_2Cl_2	L	2	3.9	4.7–5.2		Relative spectrum	125	8.5 K, E || *c*
Hg_2Cl_2	L, AI1	2		4.1–5.7		Relative spectrum	126	8.5 K
Hg_2Cl_2	L			4–5.5		Polarization dependence	127	8.5 K
InP	TRT	200	1.34	2.33	3.33	210	104	
InP	AI1, PC	22		2.33	3.33	260	102	
InP	AI1	30		2.33	3.33	1800	110	
InP	AI1	100		2.34	3.33	60	128	$\beta_l/\beta_c = 1.8$
InSb	PC	~200	0.17	0.233	3.95	59.6–119	129	77 K
InSb	PC	~200		0.233	3.95	0	129	2 K
InSb	PC	~200		0.257	3.95	1151–1419	129	77 K
InSb	AI1	~10		0.233	3.95	16000	130	
InSb	PC	~200		0.257	3.95	946–1850	129	2 K
InSb	AI1	30		0.233	3.95	15000	104	
InSb	AI1; PC	~150		0.233	3.95	220	19	
InSb	TRT	~200		0.233; 0258	3.95	8000; 14000	123	
InSb	TRT	300		0.233	3.95	4800	124	

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InSb	TRT	300		0.233	3.95	220	124	77 K
InSb	AI2	130		0.233	3.95	2000–5600	130	
InSb	PC	CW		0.26	3.95	2900	131	Magnetic field
InSb	AI1	0.045		0.234; 0.258	3.95	2500; 1700	132,133	300 K
KBr	AI1	15	7.6	7.12	~1.6	3.3	134	
KBr	AI2	~10		7.0–8.0	~1.6	Relative spectrum	135	20 K, 80 K
KBr	AI1	0.015		9.32	~1.6	2.0	3	
KBr	CR	15		6.7	~1.6	8.0	136	
KBr	AI1	10		7.18	~1.6	$\beta_{KBr} = 0.64\ \beta_{KI}$	137	
KCl	FCC	8	8.5	9.32	1.6	1.5	11	
KCl	AI1	0.015		9.32	1.6	2.2	3	
KCl	AI2	10		8.1–8.5	1.6	Abs. spectr. (400 @ 8.5eV)	138	20 K
KD_2AsO_4	AI1	0.017		6.99	~1.6	0.027	3	
KD_2PO_4	AI1	0.030		9.32	1.57–1.51	0.027	139	
KD_2PO_4	AI1	0.030	7.0	9.32	1.57–1.51	0.027	140	$k \perp c$
KD_2PO_4	AI1	0.017		6.99	1.53–1.49	0.0054	3	
KH_2AsO_4	AI1	0.017		6.99	~1.6	0.048	3	
KH_2PO_4	AI1	0.017	7.0	6.99	1.53–1.49	0.0059	3	
KH_2PO_4	AI1	0.015		9.32	1.57–1.51	0.27	3	
KH_2PO_4	Model	0.5		9.32	1.57–1.51	0.5	141	$E \perp$ opt.axis
KI	AI1	15		7.12	~1.9	4.4	134	
KI	AI2			6.0–7.5	~1.7–1.9	Relative spectrum	142	
KI	AI2			6.1–7.7	~1.7–1.9	Relative spectrum	88	20 K
KI	AI2			6.23–6.36	~1.7–1.8	Relative spectrum	143	
KI	PC	20		7.12	~1.9	10	144	
KI	AI1	0.017		6.99	~1.9	7.3	3	
KI	AI1	0.015		9.32	2.0	3.7	3	
KI	CR	15		6.7	~1.9	18	136	

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Two-Photon Absorption Data—*continued*

Material	Method	Pulse τ_p (ns)	Bandgap E_g (eV)	$2\hbar\omega$ (eV)	Index n_0 ($\hbar\omega$)	2PA coefficient (cm/GW)	Ref.	Additional information
KI	AI1	0.024		7.12	~1.9	8	145	
KI	AI1	10		7.12	~1.9	Relative value	137	
KI	AI2	10		6.0–6.7		Abs. spectr. (300 @ 6.5 eV)	138	20 K
KRS-V	C	38		2.33	2.44	1.6	7	
$KTa_{0.7}Nb_{0.3}O_3$	AI1	0.010		4.66		14	146	
$KTaO_3$	AI2	17	3.5	3.9–4.6		Abs. spectr. (1 @ 4.4 eV)	35	
KTP	Z-scan	0.019	3.5	4.66	1.8	0.1	147	E for SHG
LiF	AI1	0.015	13.6	9.32	1.4	<0.02	3	
$LiIO_3$	AI2	10	4.0	4.4–4.8	1.75–1.9	<0.4	148	
$LiNbO_3$	AI1	30	4.0	3.56	~2.2	10.	49	
$LiNbO_3$	AI1	0.025		4.66	2.3–2.2	3.4	149	
$LiNbO_3$	AI2	10		4.4–4.8	2.3–2.2	Abs. spectr. (1.5 @ 4.66 eV)	148	
$LiYF_4$	AI1	0.015	~11	9.32	1.5	<0.004	33	
MgF_2	AI1	0.017	10.8	6.99	1.4	<0.0062	33	
MgF_2	AI1	0.015		9.32	1.4	<0.0028	33	
NaBr	AI1	0.015	7.5	9.32	1.8	2.5	3	
NaCl	AI1	0.015	9.0	9.32	~1.64	3.5	3	
NaCl	AI2	10		8.1–8.6	~1.6	Abs. spectr. (200 @ 8.5 eV)	138	20 K
$NH_4H_2AsO_4$	AI1	0.017		6.99		0.035	3	
$NH_4H_2PO_4$	AI1	0.030	6.8	9.32	1.59–1.53	0.11	139	No pol., k ⊥ c
$NH_4H_2PO_4$	AI1	0.015		9.32	1.59–1.53	0.24	3	
$NH_4H_2PO_4$	AI1	0.017		6.99	1.55–1.50	0.0068	3	
$NH_4H_2PO_4$	Model	0.5		9.32	1.59–1.53	0.35	141	E ⊥ opt. axis
$NH_4H_2PO_4$	Model	0.5		4.67 + 5.83	~1.6	1	141	E for 5th harmonic

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$NH_4H_2PO_4$	Model	0.5		11.66	~1.6	9.5	141	E for 5th harmonic
PbI_2	AI1	20	2.4	3.56		250	120	
PbI_2	AI2	~10		2.46–2.55		Relative spectrum	150	1.6–300 K
$PbMoO_4$	AI2	50	3.6	3.2–4.2		Abs. spectr. (5 @ 4 eV)	151–52	80 K, 300 K
RbBr	AI2	~10	7.25	7.0–8.0	~1.6	Relative spectrum	135	20 K, 80 K
RbBr	AI1	0.017		6.99	1.6	2.43	3	
RbBr	AI1	0.015		9.32	1.7	2.18	3	
RbBr	CR	15		6.7	1.6	11	136	
RbBr	AI1	10		7.12	1.6	$\beta_{RbBr} = 0.55\ \beta_{KI}$	137	
RbCl	AI1	0.015	8.3	9.32	1.6	1.1	3	
RbH_2AsO_4	AI1	0.017		6.99		0.050	3	
RbH_2PO_4	AI1	0.017		6.99		0.059	3	
RbI	AI2	~10	5.83	6.1–7.0	1.7	Relative spectrum	135	20 K
RbI	AI1	0.017		6.99	1.73	5.1	3	
RbI	AI1	0.015		9.32	2.0	2.5	3	
RbI	AI1	10		7.12	1.73	$\beta_{RbBr} = 0.51\ \beta_{KI}$	137	
Si	AI1	200	1.12	2.33	3.52	40	153	
Si	AI1		“1.1”	2.33	3.52	7300	70	T dependence
Si	AI2	25		1.62–2.2	~3.5	Relative spectrum	154	
Si	AI1	0.020		2.33	3.52	1.9; 1.5	155	20 K; 100 K
Si	C	79		1.88	~3.5	21	7	
Si	AI1	0.004–0.1		2.33–2.34	3.52	1.5	156	
Si	AI2	0.00009		4–4.5; 4.0	~3.8	15–36; 34.6	156,157	Dir. $E_g = 3.43$
SiC	AI1	30	2.6	3.56	2.6	200	49	
SiC	L	20		3.0–4.6	~2.6	Relative spectrum	159	E || c; E $\perp$ c
SiO_2 (quartz)	AI1	0.015	8.4	9.32	1.6	<0.045	3	
SnO_2	AI2	~10	3.4	3.555–3.573		Relative spectrum	160	

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Two-Photon Absorption Data—*continued*

Material	Method	Pulse τ_p (ns)	Bandgap E_g (eV)	$2\hbar\omega$ (eV)	Index n_0 ($\hbar\omega$)	2PA coefficient (cm/GW)	Ref.	Additional information
SnO_2	AI1	45		3.56		300; 34	62	E ‖ c; E ⊥ c
SrF_2	AI1	0.017	9.4	6.99	1.45	<0.0057	33	
SrF_2	AI1	0.015		9.32	1.47	<0.0054	33	
SrF_2	AI1	0.0007		10.0	1.47	0.011	34	
$SrTiO_3$	AI1	~30	4.1	3.56	2.38	2.9	161	
$SrTiO_3$	CR			3.92	2.4	3	119	
$SrTiO_3$	AI2	17		3.2–4.4	~2.4	Abs. spectr. (4 @ 4.2 eV)	35,162	
$SrTiO_3$	AI2			4.1; 4.7; 5.0	2.4–2.5	1.3; 4.1; 10.2	163	
$SrTiO_3$	PA	5		3.2–5.5	~2.4–2.5	Abs. spectr. (5 @ 5.0 eV)	17	
$SrTiO_3$	AI2			3.3–4.2	~2.4	Abs. spectr (2 @ 4.1 eV)	164	
Te	AI2	200	0.33	0.342	~5–6	800	140	
TiO_2	AI2		3.5	3.3–4.1	~2.5–2.9	Abs. spectr. (300 @ 4 eV)	166	
TiO_2	AI1	0.004		4.66	~2.6–3	14	167	
TiO_2	AI1	0.004		3.96	~2.6–2.9	6.5	167	
TiO_2	CR			3.92	~2.6–2.9	23	119	
TiO_2	CR			4.1; 4.7; 5.0	~2.6–3	12.7; 87; 170.	163	
TiO_2	AI1	45		3.56	~2.5–2.9	150; 120	62	E ‖ c; E ⊥ c
TlCl	AI2	20	3.6	3.4–4.4	2.2–2.26	Abs. spectr. (0.45 @ 3.8 eV)	165	
TlCl	AI2	20		3.4–4.4	2.2–2.26	Abs. spectr. (4.7 @ 4.0 eV)	169	
TlCl	AI2	~10		3.39–3.56	2.2	Relative spectrum	170	4, 20, 77 K
V_2O_5	AI1	60	~2.3	3.56		720	171	E ‖ [001]
$Y_3Fe_5O_{12}$	AI2	17	2.66	2.5–3.5		Abs. spectr. (300 @ 3.51 eV)	172	T dep., β vs. pol.
$Zn_{.0.85}Cd_{0.15}Se$	AI1	10	2.65	3.56		56	173	
$Zn_{0.12}Cd_{0.88}Se$	AI1	10	1.92	3.56		620; 260	173	E ⊥ z; E ‖ z

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$Zn_{0.5}Cd_{0.5}S$	AI1	45	~3	3.56		60	62	
$Zn_{0.5}Cd_{0.5}S$	AI2	35	2.62	2.6–3.6		Abs. spectr. (20 @ 3.4 eV)	174	
$Zn_{0.5}Cd_{0.5}S$	AI2			2.6–3.4		Abs. spectr. (10 @ 3 eV)	63	β vs. pol.
ZnO	AI2	20	3.35	3.42–3.45	2.0	Relative spectrum	175	
ZnO	AI1:AI2			3.56		26; 21	176	$k \perp c$
ZnO	AI2			3.42–3.43	2.0	Abs. spectr. (2 @ 3.4 eV)	177	4.2 K in 42 kG field
ZnO	AI2	~10		3.42–3.48	2.0	Relative spectrum	88	1.6 K
ZnO	CR			4.1; 4.7; 5.0	2.0–2.1	19.8; 20.9; 47.8	163	
ZnO	AI1	45		3.56	2.0	34; 16	62	E ‖ c; E⊥c
ZnO	AI2	50		3.4–4.2	2.0	Abs. spectr. (10 @ 3.8 eV)	133	β vs. pol.
ZnO	AI1	0.027		4.67	2.05	5.0	67	
ZnO	L	9		3.4–4.2	2.0	Abs. Spectr. (10 @ 3.5 eV)	28,38	80 K
ZnP_2	TRT			2.34		120	44	
ZnP_2	TRT			3.56		650	44	
ZnP_2	AI2	15		2.4–3.2		Abs. spectr. (10 @ 2.9 eV)	45	
ZnP_2	AI2	25	2.22	2.2–2.7		Abs. spectr. (10 @ 2.6 eV)	179	
ZnP_2	AI2	15		2.4–3.4		Relative spectrum	180	Impurities
ZnS	AI2		3.68	3.7–4.2	~2.36	Abs. spectr. (2.3 @ 4.0 eV)	154	
ZnS	AI2			3.6–4.0	~2.35	Relative spectrum	181	
ZnS	PC	20		3.56	~2.35	4.3	18	Cu-doped
ZnS	AI1	45		3.56	~2.35	20; 0	62	E ‖ c; E ⊥ c
ZnS	PA	5		3.65–5.5	2.35–2.5	Relative spectrum	17	E ‖ z
ZnS	AI2			3.7–5.3		Abs. spectrum (2 @ 4.1 eV)	63	β vs. pol
ZnS	AI1	0.027		4.67	2.4	2.0; 3.5	67	Cleartran, CVD
ZnSe	AI1	30	2.71	3.56	~2.6	40	49	
ZnSe	AI1	10		3.56	~2.6	45	173	
ZnSe	AI2	40		2.6–3.6	~2.5–2.6	Abs. spectr. (4 @ 3.0 eV)	182	

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Two-Photon Absorption Data—*continued*

Material	Method	Pulse τ_p (ns)	Bandgap E_g (eV)	$2\hbar\omega$ (eV)	Index n_0 ($\hbar\omega$)	2PA coefficient (cm/GW)	Ref.	Additional information
ZnSe	AI2	40		2.75–3.45	~2.5–2.6	Abs.spectr. (13 @ 3.45 eV)	183	Impurity resonances
ZnSe	CR			3.18	~2.53	60	59	
ZnSe	AI1	45		3.56	~2.6	17000	62	300 K, cubic
ZnSe	AI2	15		2.7–3.75	~2.5–2.6	Abs. spectr. (10 @ 3.5 eV)	45	
ZnSe	TCN	20		3.56	~2.6	80	81	
ZnSe	AI2			2.7–3.8	~2.5–2.6	Abs. spectr. (10 @ 3.4 eV)	63	β vs. pol
ZnSe	AI2	15		2.9–3.7	~2.5–2.6	Abs. spectr. (10 @ 3.4 eV)	184	β vs Cu doped
ZnSe	AI1	20		3.56	~2.6	4–15	185	β vs Cu doped
ZnSe	AI1	0.027		4.67	2.7	5.5	67	
ZnSe	Z-scan	0.03		4.67	2.7	5.8	84	
ZnTe	AI1	30	2.3	2.33	2.79	34	104	
ZnTe	AI1			3.56	2.91	500	186	77 K
ZnTe	AI1	0.030		2.33	2.79	8.0	73	E || z
ZnTe	AI1, TCN	20		2.34; 3.56	2.79; 2.91	20; 300	187	T-tuned band gap
ZnTe	AI1	45		3.56	2.91	8000	62	Arb. pol.
ZnTe	AI2	30		2.8–4	~3	Abs. spectr. (4 @ 3.1 eV)	188	Time resolved
ZnTe	AI1	0.038		2.33	2.79	4.5	67	
ZnTe	Z-scan	0.040		2.33	2.79	4.2	84	
$Zn_xCd_{1-x}Se$	AI1		2.45–3.55	3.56		50–1	189	Anistropy
$Zn_{0.12}Cd_{0.88}Se$	AI1	10	1.92	3.56		620, 260	173	
$Zn_{0.5}Cd_{0.5}Se$	AI1	45	~3	3.5		60	62	
$Zn_{0.85}Cd_{0.15}Se$	AI1	10	2.65	3.56		56	173	
ZrO_2-(Y_2O_3)	AI1	0.03	~4.1	4.66	2.12	0.013	190	Independent of Y_2O_3

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1.9.3 Second Harmonic Generation Coefficients

Crystal System—Cubic

Cubic material	Symmetry class	d_{im} (pm/V)	Wavelength λ (μm)
$NaBrO_3$	23	$d_{14} = 0.19$	0.6943
$NaClO_3$	23	$d_{14} = 0.46$	0.6943
AlSb	–43m	$d_{14} = 49 \pm 36$	1.058
$Bi_4Ge_3O_{12}$	–43m	$d_{14} = 1.28$	1.064
CdTe	–43m	$d_{14} = 167.6 \pm 63$	10.6
		$d_{14} = 59.0 \pm 24$	28.0
CuBr	–43m	$d_{14} = 8.04 \pm 30\%$	10.6
		$d_{14} = -4.38 \pm 20\%$	1.318
		$d_{14} = -6.37 \pm 20\%$	1.064
		$d_{14} = -6.53 \pm 20\%$	0.946
CuCl	–43m	$d_{14} = 6.7 \pm 30\%$	10.6
		$d_{14} = -4.0 \pm 20\%$	1.318
		$d_{14} = -3.97 \pm 20\%$	1.064
		$d_{14} = -3.47 \pm 20\%$	0.946
CuI	–43m	$d_{14} = 8.04 \pm 30\%$	10.6
		$d_{14} = -5.47 \pm 20\%$	1.318
		$d_{14} = -6.08 \pm 20\%$	1.064
		$d_{14} = -6.04 \pm 20\%$	0.946
GaAs	–43m	$d_{14} = 134.1 \pm 41.9$	10.6
		$d_{14} = 209.5 \pm 13.3$	1.058
		$d_{14} = 256.5$	0.694
GaP	–43m	$d_{14} = 71.8 \pm 12.3$	1.058
		$d_{36} = 59.5 \pm 6.0$	1.318
		$d_{14} = +70.6$	3.39
GaSb	–43m	$d_{14} = +628 \pm 6.3$	10.6
InAs	–43m	$d_{14} = 364 \pm 47$	1.058
		$d_{14} = 249 \pm 62$	10.6
InP	–43m	$d_{14} = 143$	1.058
InSb	–43m	$d_{14} = 520 \pm 47$	1.058
		$d_{14} = 16345 \pm 503$	10.6
		$d_{14} = 560 \pm 230$	28
$N_4(CH_2)_6$	–43m	$d_{14} = 4.1$	1.06
β-ZnS	–43m	$d_{14} = 30.6 \pm 8.4$	10.6
		$d_{36} = 20.7 \pm 1.3$	1.058

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Crystal System—Cubic—*continued*

Cubic material	Symmetry class	d_{im} (pm/V)	Wavelength λ (μm)
ZnSe	–43m	$d_{14} = 78.4 \pm 29.3$	10.6
		$d_{36} = 26.6 \pm 1.7$	
ZnTe	–43m	$d_{14} = 92.2 \pm 33.5$	10.6
		$d_{14} = 83.2 \pm 8.4$	1.058
		$d_{36} = 89.6 \pm 5.7$	1.058

Crystal System—Hexagonal

Hexagonal material	Symmetry class	d_{im} (pm/V)	Wavelength λ (μm)
$LiIO_3$	6	$d_{31} = \pm 10.17 \pm 0.32$	0.5145
		$d_{33} = -5.15 \pm 0.32$	1.064
		$d_{31} = -4.96 \pm 0.32$	1.064
		$d_{33} = -5.54 \pm 0.61$	1.318
		$d_{31} = -6.82$	1.318
$LiKSO_4$	6	$d_{31} = 0.38$	0.6943
		$d_{33} = 0.71$	0.6943
GaS	6m2	$d_{16} = 135$	0.6943
GaSe	6m2	$d_{22} = 75.4 \pm 10.8$	10.6
		$d_{16} = 972$	0.6943
InSe	6m2	$d_{16} = 281$	0.6943
AgI	6mm	$d_{31} = +8.2 \pm 20\%$	1.318
		$d_{33} = -16.8 \pm 22\%$	1.318
AlN	6mm	$d_{31} = \leq 0.30$	1.064
		$d_{33} = 7.42 \pm 35\%$	1.064
BeO	6mm	$d_{33} = -0.20 \pm 0.01$	1.064
		$d_{31} = -0.15 \pm 0.01$	1.064
CdS	6 mm	$d_{33} = 25.8 \pm 1.6$	1.058
		$d_{31} = -13.1 \pm 0.8$	1.058
		$d_{15} = 14.4 \pm 0.8$	1.058
		$d_{33} = +44.0 \pm 12.6$	1.064
		$d_{31} = -26.4 \pm 6.31$	1.064
		$d_{15} = 28.9 \pm 7.1$	1.064
CdSe	6 mm	$d_{33} = 66.9 \pm 4.2$	1.064
		$d_{31} = -26.8 \pm 2.7$	1.064
		$d_{33} = 54.5 \pm 12.6$	1.064

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Crystal System—Hexagonal System—*continued*

Hexagonal material	Symmetry class	d_{im} (pm/V)	Wavelength λ (μm)
$LiClO_4 \cdot 3H_2O$	6mm	$d_{31} = +0.22 \pm 20\%$	1.064
		$d_{33} = +0.25 \pm 20\%$	1.064
		$d_{15} = +0.25 \pm 20\%$	1.064
SiC	6mm	$d_{31} = +8.6 \pm 0.9$	1.064
		$d_{33} = -14.4 \pm 1.3$	1.064
		$d_{15} = +8.0 \pm 0.9$	1.064
Zn_3AgInS_5	6mm	$d_{31} = +7.2 \pm 20\%$	1.064
		$d_{33} = \pm 15.9 \pm 20\%$	1.064
Zn_5AgInS_7	6mm	$d_{31} = +9.22 \pm 20\%$	1.064
		$d_{33} = +20.95 \pm 20\%$	1.064
ZnO	6mm	$d_{33} = -5.86 \pm 0.16$	1.058
		$d_{31} = 1.76 \pm 0.16$	1.058
		$d_{15} = 1.93 \pm 0.16$	1.058
α-ZnS	6mm	$d_{33} = 11.37 \pm 0.07$	1.058
		$d_{33} = 37.3 \pm 12.6$	10.6
		$d_{31} = -18.9 \pm 6.3$	10.6
		$d_{15} = 21.37 \pm 8.4$	10.6
		$d_{15} = 6.7 \pm 1.0$	1.064
		$d_{31} = -7.6 \pm 1.5$	1.064
		$d_{33} = +13.8 \pm 1.7$	1.064

Crystal System—Tetragonal

Tetragonal material	Symmetry class	d_{im} (pm/V)	Wavelength λ (μm)
$BaTiO_3$	4mm	$d_{33} = 6.8 \pm 1.0$	1.064
		$d_{31} = 15.7 \pm 1.8$	1.064
		$d_{15} = 17.0 \pm 1.8$	1.064
$Ba_6Ti_2Nb_8O_3$	4mm	$d_{31} = 9.7 \pm 1.8$	1.064
		$d_{33} = 13.2 \pm 1.8$	1.064
$K_3Li_2Nb_5O_{15}$	4mm	$d_{33} = 11.2 \pm 1.6$	1.064
		$d_{31} = 6.18 \pm 1.28$	1.064
		$d_{15} = 5.45 \pm 0.54$	1.064
$K_{0.8}Na_{0.2}Ba_2Nb_5O_{15}$	4mm	$d_{31} = 13.6 \pm 1.6$	1.064
$PbTiO_3$	4mm	$d_{33} = 7.5 \pm 1.2$	1.064
		$d_{31} = 37.6 \pm 5.6$	1.064
		$d_{15} = 33.3 \pm 5$	1.064

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Crystal System—Tetragonal System—*continued*

Tetragonal material	Symmetry class	d_{im} (pm/V)	Wavelength λ (μm)
$SrBaNb_5O_{15}$	4mm	$d_{33} = 11.3 \pm 3.3$	1.064
		$d_{31} = 4.31 \pm 1.32$	1.064
		$d_{15} = 5.98 \pm 2$	1.064
$AgGaS_2$	-42m	$d_{36} = 18 \pm 2.7$	10.6
		$d_{36} = 23.36 \pm 3.52$	1.064
$AgGaSe_2$	-42m	$d_{36} = 37.4 \pm 6.0$	10.6
		$d_{36} = 67.7 \pm 13$	2.12
$AgInSe_2$	-42m	$d_{36} = 55.9 \pm 10\%$	10.6
$CdGeAs_2$	-42m	$d_{36} = 351 \pm 105$	10.6
$BeSO_4 \cdot 4H_2O$	-42m	$d_{36} = 0.30$	0.6328
		$d_{36} = 0.29 \pm 0.03$	0.5321
$CdGeP_2$	-42m	$d_{36} = 162 \pm 30\%$	10.6
CsD_2AsO_4	-42m	$d_{36} = 0.40 \pm 0.05$	1.064
CsH_2AsO_4	-42m	$d_{36} = 0.22$	0.6943
		$d_{36} = 0.40 \pm 0.05$	1.064
$CuGaSe_2$	-42m	$d_{36} = 44.2 \pm 10\%$	10.6
$CuGaS_2$	-42m	$d_{36} = 14.5 \pm 15\%$	10.6
$CuInS_2$	-42m	$d_{36} = 10.6 \pm 15\%$	10.6
KD_2PO_4 (KD*P)	-42m	$d_{36} = 0.38 \pm 0.016$	1.058
		$d_{36} = 0.34 \pm 0.06$	0.694
		$d_{14} = 0.37$	1.058
KH_2PO_4 (KDP)	-42m	$d_{36} = 0.44$	1.064
		$d_{36} = 0.47 \pm 0.07$	0.694
KD_2AsO_4 (KD*A)	-42m	$d_{36} = 0.39$	1.064
KH_2AsO_4 (KDA)	-42m	$d_{36} = 0.43 \pm 0.025$	1.06
		$d_{36} = 0.39 \pm 0.4$	0.694
$ND_4H_2PO_4$ (AD*P)	-42m	$d_{36} = 0.495 \pm 0.07$	0.6943
$NH_4H_2PO_4$ (ADP)	-42m	$d_{36} = 0.762$	1.064
		$d_{36} = 0.85$	0.6943
		$d_{36} = 0.85$	0.694
$(NH_2)_2CO$ (urea)	-42m	$d_{36} = 1.35$	1.06
RbH_2AsO_4 (RDA)	-42m	$d_{36} = 0.39 \pm 0.04$	0.6943

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Crystal System—Tetragonal System—*continued*

Tetragonal material	Symmetry class	d_{im} (pm/V)	Wavelength λ (μm)
RbH_2PO_4 (RDP)	-42m	$d_{36} = 0.414 \pm 0.045$	0.6943
		$d_{36} = 0.38 \pm 0.04$	1.064
$ZnGeP_2$	-42m	$d_{36} = 111.2 \pm 30\%$	10.6
TeO_2	422	$d_{14} = 0.34 \pm 0.05$	1.318
		$d_{14} = 0.38 \pm 0.03$	1.064
		$d_{14} = 4.13 \pm 1.03$	0.659
$CdGa_2S_4$	-4	$d_{36} = 25.6 \pm 3.8$	1.064
$HgGa_2S_4$	-4	$d_{36} = 25.6 \pm 7.7$	1.064
$InPS_4$	-4	$d_{36} = 20.1 \pm 2.1$	1.064
		$d_{31} = 26.3 \pm 2.58$	1.064

Crystal System—Trigonal

Trigonal material	Symmetry class	d_{im} (pm/V)	Wavelength λ (μm)
$PbGe_3O_{11}$	3	$d_{11} = 0.96 \pm 0.16$	1.064
		$d_{22} = -2.1 \pm 0.3$	1.064
		$d_{31} = +0.51 \pm 0.07$	1.064
		$d_{33} = -0.79 \pm 0.12$	1.064
$AlPO_4$	32	$d_{11} = 0.35 \pm 0.03$	1.058
		$d_{14} < 0.008$	1.058
HgS	32	$d_{11} = 50.3 \pm 17$	10.6
		$d_{11} = 47.2 \pm 4$	1.32
$Nd_{0.2}Y_{0.8}Al_3(BO_3)_4$	32	$d_{11} = d_{12} = 1.36 \pm 0.16$	1.32
		$d_{14} = d_{12} < 0.01$	1.32
$PbS_2O_6 \cdot 4H_2O$	32	$d_{11} = 0.096$	1.0645
		$d_{11} = 0.15$	0.694
RbS_2O_6	32	$d_{11} = 0.081 \pm 0.03$	0.6943
Se	32	$d_{11} = 79.6 \pm 42$	10.6
$SrS_2O_6 \cdot 4H_2O$	32	$d_{11} = 0.06 \pm 0.02$	0.6943
Te	32	$d_{11} = 650 \pm 30$	10.6
SiO_2 (quartz)	32	$d_{11} = 0.335$	1.064
$(C_6H_5CO)_2$ (benzil)	32	$d_{11} = 3.6 \pm 0.5$	1.064

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Crystal System—Trigonal—*continued*

Trigonal material	Symmetry class	d_{im} (pm/V)	Wavelength λ (μm)
Ag_3AsS_3 (proustite)	3m	$d_{31} = 16.8 \pm 1$	10.6
		$d_{22} = 26.8 \pm 4$	10.6
		$d_{22} = 20.0$	1.152
		$d_{31} = 12.0$	1.152
Ag_3SbS_3 (pyrargerite)	3m	$d_{31} = 12.6 \pm 4$	10.6
		$d_{22} = 13.4 \pm 4$	10.6
β-BaB_2O_4 (BBO)	3m	$d_{22} = 13.4 \pm 4$	1.06
		$d_{31} = 12.6 \pm 4$	1.06
$(CN_3H_6)As(SO_4)_2$-•$6H_2O$ (GASH)	3m	$d_{22} = -1.05 \pm 0.017$	1.064
		$d_{31} = +0.008 \pm 0.017$	1.064
		$d_{33} = +0.020 \pm 0.003$	1.064
$LiNbO_3$	3m	$d_{33} = -34 \pm 8.6$	1.058
		$d_{31} = -4.88 \pm 0.7$	1.058
		$d_{22} = +2.58 \pm 0.25$	1.058
		$d_{31} = -4.35 \pm 0.4$	1.152
		$d_{22} = +2.1 \pm 0.8$	1.152
		$d_{33} = -31.8$	1.318
		$d_{31} = -29.1$	1.318
$LiTaO_3$	3m	$d_{33} = -16.4 \pm 2$	1.058
		$d_{31} = -1.07 \pm 0.2$	1.058
		$d_{22} = +1.7 \pm 0.2$	1.058
(Na,Ca)(Mg,Fe)$(BO_3)_3$-Al_6Si_6(OH,O,F) (tourmaline)	3m	$d_{15} = 0.24 \pm 0.04$	1.064
		$d_{31} = 0.14 \pm 0.03$	1.064
		$d_{22} = 0.07 \pm 0.01$	1.064
		$d_{33} = 0.50 \pm 0.06$	1.064
$TlIO_3$	3m	$d_{15} = 3.49 \pm 20\%$	1.064
		$d_{31} = 3.36 \pm 20\%$	1.064
		$d_{23} = 1.11 \pm 20\%$	1.064
		$d_{24} = 3.85 \pm 20\%$	1.064
		$d_{32} = 3.98 \pm 20\%$	1.064
		$d_{33} = 6.85 \pm 20\%$	1.064
SbI_3•$3S_8$	3m	d22 = 5.2	1.064
		d33 = 7.23	1.064
		d31 = 4.8	1.064

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Crystal System—Orthorhombic

Orthorhombic material	Symmetry class	d_{im} (pm/V)	Wavelength λ (μm)
$Ba(COOH)_2$	222	$d_{14} = 0.11 \pm 11\%$	1.064
		$d_{25} = 0.11 \pm 14\%$	1.064
		$d_{36} = 0.13 \pm 11\%$	1.064
α–HIO_3	222	$d_{36} = 5.15 \pm 0.16$	1.064
NO_2•$CH_3NOC_5H_4$ (POM)	222	$d_{36} = 6.4 \pm 1.0$	1.064
$Sr(COOH)_2$	222	$d_{34} = 0.51$	1.064
$BaMgF_4$	mm2	$d_{31} = 0.023 \pm 20\%$	1.064
		$d_{32} = \pm 0.035 \pm 12\%$	1.064
		$d_{33} = 0.0094 \pm 14\%$	1.064
		$d_{24} = 0.025 \pm 17\%$	1.064
$Ba_2NaNb_5O_{15}$	mm2	$d_{33} = -17.6 \pm 1.28$	1.064
		$d_{32} = -12.8 \pm 0.64$	1.064
		$d_{31} = -12.8 \pm 1.28$	1.064
$BaZnF_4$	mm2	$d_{32} = 0.08 \pm 20\%$	1.06
		$d_{15} = 0.011 \pm 20\%$	1.06
		$d_{33} = 0.035 \pm 20\%$	1.06
$C_6H_4(NO_2)_2$ [MDB]	mm2	$d_{33} = 0.74$	1.064
		$d_{32} = 2.7$	1.064
		$d_{31} = 1.78$	1.064
$Gd_2(MoO_4)_3$	mm2	$d_{33} = -0.044 \pm 0.008$	1.064
		$d_{32} = +2.42 \pm 0.36$	1.064
		$d_{31} = -2.49 \pm 0.37$	1.064
KB_5O_8•$4H_2O$	mm2	$d_{31} = 0.046$	0.4342
		$d_{32} = 0.003$	0.4342
KIO_2F_2	mm2	$d_{31} = \pm 0.57 \pm 25\%$	1.064
		$d_{32} = \pm 0.16 \pm 25\%$	1.064
		$d_{33} = \pm 2.79 \pm 25\%$	1.064
		$d_{15} = 0.49 \pm 25\%$	1.064
		$d_{24} = 0.25 \pm 25\%$	1.064
$K_2La(NO_3)_4$•$2H_2O$	mm2	$d_{31} = d_{15} = -1.13 \pm 0.15$	1.064
		$d_{32} = d_{24} = -1.10 \pm 0.1$	1.064
		$d_{33} = 0.13 \pm 0.1$	1.064
$KNbB_2O_6$	mm2	$d_{24} = 6.10$	1.064
		$d_{32} = 3.00$	1.064
		$d_{33} = 1.44$	1.064

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Crystal System—Orthorhombic—*continued*

Orthorhombic material	Symmetry class	d_{im} (pm/V)	Wavelength λ (μm)
$KNbO_3$	mm2	$d_{33} = -19.58 \pm 1.03$	1.064
		$d_{32} = +11.34 \pm 1.03$	1.064
		$d_{31} = -12.88 \pm 1.03$	1.064
$KTiOPO_4$ [KTP]	mm2	$d_{33} = 13.7$	1.06
		$d_{32} = \pm 5.0$	1.06
		$d_{31} = \pm 6.5$	1.06
		$d_{24} = 7.6$	1.06
		$d_{15} = 6.1$	1.06
LiB_3O_5	mm2	$d_{15} = +0.85$	1.064
		$d_{24} = -0.67$	
		$d_{33} = +0.04$	
$LiGaO_2$	mm2	$d_{31} = d_{15} = -1.13 \pm 0.15$	1.064
		$d_{33} = -0.59 \pm 0.06$	1.064
LiH_2PO_3	mm2	$d_{31} = 0.03$	1.064
		$d_{32} = 0.16$	1.064
		$d_{33} = 0.43$	1.064
		$d_{15} = 0.035$	1.064
		$d_{24} = 0.17$	1.064
$LiInO_2$	mm2	$d_{31} = 9.9 \pm 15\%$	1.064
		$d_{32} = 8.58 \pm 15\%$	1.064
		$d_{33} = 15.8 \pm 15\%$	1.064
Na(COOH)	mm2	$d_{15} = -0.22 \pm 0.11$	1.064
		$d_{32} = d_{15} \approx 0.22$	1.064
		$d_{33} = 0.33 \pm 0.16$	1.064
$NaNO_2$	mm2	$d_{31} = 0.074 \pm 0.008$	1.064
		$d_{32} = 1.89 \pm 0.25$	1.064
		$d_{33} = 0.094 \pm 0.008$	1.064
		$d_{15} = 0.04 \pm 0.008$	1.064
		$d_{24} = 1.80 \pm 0.25$	1.064
		$d_{31} = d_{15} = 0.18$	1.153
		$d_{32} = d_{24} = 0.76$	1.153
$NO_2 \cdot C_6H_4NH_2$ [mNA]	mm2	$d_{33} = 13.12 \pm 1.28$	1.064
		$d_{32} = 1.02 \pm 0.22$	1.064
		$d_{31} = 12.48 \pm 1.28$	1.064
$PbNb_2O_{11}$	mm2	$d_{31} = +6.5 \pm 0.97$	1.064
		$d_{32} = -5.87 \pm 0.88$	1.064
		$d_{33} = -8.88 \pm 1.32$	1.064
		$d_{15} = +5.89 \pm 0.88$	1.064
		$d_{24} = -5.42 \pm 0.39$	1.064

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Crystal System—Orthorhombic—*continued*

Orthorhombic material	Symmetry class	d_{im} (pm/V)	Wavelength λ (μm)
$RbNbB_2O_6$	mm2	$d_{24} = 2.40$	1.064
		$d_{32} = 2.30$	
		$d_{33} = 0.94$	
$Sr(COOH)_2$	222	$d_{34} = 0.51$	1.064
$SbNbO_4$	mm2	$d_{32} = 4.72 \pm 0.82$	1.058
$SbTaO_4$	mm2	$d_{32} = 4.1 \pm 0.82$	1.058
$Tb_2(MoO_4)_3$	mm2	$d_{31} = -2.99 \pm 0.35$	1.064
		$d_{32} = +2.22 \pm 0.33$	1.064
		$d_{33} = -0.11 \pm 0.03$	1.064
$Tb_2(MoO_4)_3$		$d_{15} = -2.52 \pm 0.38$	1.064
		$d_{24} = +2.55 \pm 0.35$	1.064

Crystal System—Monoclinic

Monoclinic material	Symmetry class	d_{im} (pm/V)	Wavelength λ (μm)
$GdCa_4O(BO_3)_4$	Cm	$d_{11} = 0.04$	1.064
		$d_{12} = 0.128$	1.064
		$d_{13} = -0.17$	1.064
		$d_{31} = 0.148$	1.064
		$d_{32} = 0.64$	1.064
		$d_{33} = 0.58$	1.064
$GdCa_4O(BO_3)_4$	Cm	$d_{11} = -0.104$	1.064
		$d_{12} = 0.015$	1.064
		$d_{13} = -0.253$	1.064
		$d_{31} = 0.12$	1.064
		$d_{32} = 1.36$	1.064
		$d_{33} = -0.93$	1.064
CH_3-NH_2–NO_2-C_6H_4 [MNA]	m	$d_{11} = 160 \pm 40$	1.064
		$d_{12} = 24 \pm 6$	1.064
4-$(CH_3)_2N$-C_6H_4 [DAST]	m	$d_{11} = 600 \pm 200$	1.064
		$d_{22} = 10 \pm 30$	1.064
		$d_{12} = 30 \pm 10$	1.064
$C_{10}H_{12}N_3O_6$ [MAP]	2	$d_{23} = 10.67 \pm 1.3$	1.064
		$d_{22} = 11.7 \pm 1.3$	1.064
		$d_{21} = 2.35 \pm 0.5$	1.064
		$d_{25} = -0.35 \pm 0.3$	1.064

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Crystal System—Monoclinic—*continued*

Monoclinic material	Symmetry class	d_{im} (pm/V)	Wavelength λ (μm)
$C_{14}H_{17}NO_2$ [DMC]	2	$d_{21} = 4.1$	1.06
		$d_{22} = 1.6$	1.06
		$d_{23} = 0.53$	1.06
N'-(4-nirophenyl)-(s)-proplinol (NPP)	2	$d_{21} = \sim 84$	1.06
		$d_{22} = 29$	1.06
$Li_2SO_4 \cdot H_2O$	2	$d_{22} = 0.4 \pm 0.06$	1.064
		$d_{23} = 0.29 \pm 0.04$	1.064
		$d_{34} = 0.25 \pm 0.04$	1.064
$(NH_2CH_2COOH)_3$-H_2SO_4 [TGS]	2	$d_{23} = 0.32$	0.694
$PbHPO_4$	2	$d_{31} = 0.11$	1.064
		$d_{11} = 0.4$	1.064
		$d_{33} = 0.23$	1.064

The above data are from tables of S. Singh, Nonlinear optical materials, *Handbook of Laser Science and Technology, Vol. III: Optical Materials, Part 1* (CRC Press, Boca Raton, FL, 1986), p. 54 ff and S. Singh, Nonlinear optical materials, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL 1995), p. 237 ff. These references list the original sources of the data; they also contain additional nonlinear coefficients for other organic materials and powders.

1.9.4 Third-Order Nonlinear Optical Coefficients

Crystal	Nonlinear optical process	Coefficient $C_{jn} \times 10^{20}$ m^2 V^{-2}	Wavelength (μm)
$Al_{0.2}Ga_{0.8}As$	$(-2\omega_2 - \omega_1; \omega_1, \omega_1, -\omega_2)$	$\chi^{(3)} = 116.7$	0.84
Al_2O_3	$(-2\omega_1 + \omega_2; \omega_1, \omega_1, -\omega_2)$	$C_{11} = 0.0159 \pm 0.002$	0.5250
	$(-\omega; \omega, \omega, -\omega)$	$C_{11} \leq 0.28$	0.6943
BaF_2	$(-2\omega_1 + \omega_2; \omega_1, \omega_1, -\omega_2)$	$C_{11} = 0.0387 \pm 0.00042$	0.5750
		$C_{18} = 0.0159 \pm 0.00014$	0.5750
$Bi_{1-x}Sb_x$	$(-2\omega_2 - \omega_1; \omega_1, \omega_1, -\omega_2)$	$\chi^{(3)} = 4.18 \times 10^8$	10.6
C (diamond)	$(-3\omega; \omega, \omega, -\omega)$	$C_{11} + 3C_{18} = 0.1456 \pm 10\%$	1.06
	$(-2\omega_1 + \omega_2; \omega_1, \omega_1, -\omega_2)$	$C_{11} + 3C_{18} = 0.163 \pm 0.046$	1.06
		$C_{11} + 3C_{18} = 0.0738 \pm 0.0019$	0.407
		$C_{18} = 0.01218 \pm 0.0009$	0.407
		$C_{11} = 0.02147$	0.545
		$C_{18} = 0.00803 \pm 0.0003$	0.545

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Third-Order Nonlinear Optical Coefficients—*continued*

Crystal	Nonlinear optical process	Coefficient $C_{jn} \times 10^{20}$ m^2 V^{-2}	Wavelength (μm)
$CaCO_3$	$(-2\omega_1+\omega_2;\ \omega_1, \omega_1, -\omega_2)$	$C_{11} = 0.0084 \pm 0.0037$	0.530
		$C_{11} = 0.0078 \pm 0.00033$	0.556
		$C_{33} = 0.0047 \pm 0.0009$	0.530
CaF_2	$(-2\omega_1+\omega_2;\ \omega_1, \omega_1, -\omega_2)$	$C_{11} = 0.002 \pm 0.0006$	0.575
		$C_{18} = 0.00089 \pm 0.00023$	0.575
		$C_{11} = 0.005$	0.6943
		$C_{18} = 0.0025$	0.6943
CdF_2	$(-2\omega_1+\omega_2;\ \omega_1, \omega_1, -\omega_2)$	$C_{11} = 0.0068 \pm 0.0010$	0.5750
		$C_{18} = 0.0022 \pm 0.0003$	0.5750
$CdGeAs_2$	$(-3\omega;\ \omega, \omega, \omega)$	$C_{11} = 182 \pm 84$	10.6
		$C_{16} = 175$	10.6
		$C_{18} = -35$	10.6
CdS	$(-2\omega_1+\omega_2;\ \omega_1, \omega_1, -\omega_2)$	$C_{11} = 2.24$	0.6943
GaAs	$(-2\omega_1+\omega_2;\ \omega_1, \omega_1, -\omega_2)$	$C_{11} = 16.80 \pm 10\%$	10.6
		$C_{18} = 4.2 \pm 0.168$	10.6
Ge	$(-2\omega_1+\omega_2;\ \omega_1, \omega_1, -\omega_2)$	$C_{11} = 140 \pm 50\%$	10.6
		$C_{18} = 85.4 \pm 2.8$	10.6
	$(-3\omega;\ \omega, \omega, -\omega)$	$C_{11} = 42.8 \pm 80\%$	10.6
		$C_{18} = 12 \pm 3.6$	10.6
HgCdTe	$(-2\omega_1+\omega_2;\ \omega_1, \omega_1, -\omega_2)$	$C_{11} = 1.75$	10.6
InAs	$(-2\omega_1+\omega_2;\ \omega_1, \omega_1, -\omega_2)$	$C_{11} = 63$	10.6
KBr	$(-2\omega_1+\omega_2;\ \omega_1, \omega_1, -\omega_2)$	$C_{11} = 0.042$	0.6943
		$C_{18} = 0.0154$	0.6943
	$(-3\omega;\ \omega, \omega, -\omega)$	$C_{11} = 0.0392$	1.06
KCl	$(-2\omega_1+\omega_2;\ \omega_1, \omega_1, -\omega_2)$	$C_{11} = 0.0266$	0.6943
		$C_{18} = 0.0081$	0.6943
	$(-3\omega;\ \omega, \omega, -\omega)$	$C_{11} = 0.0168$	1.06
KH_2PO_4	$(-3\omega;\ \omega, \omega, -\omega)$	$C_{11} - C_{18} = 0.04$	1.06
KI	$(-2\omega_1+\omega_2;\ \omega_1, \omega_1, -\omega_2)$	$C_{11} = 0.0035$	0.6943
		$C_{18} = 0.00216$	0.6943
LiF	$(-2\omega_1+\omega_2;\ \omega_1, \omega_1, -\omega_2)$	$C_{11} = 0.0048 \pm 0.0008$	0.5250
		$C_{11} = 0.0028$	0.6943
		$C_{18} = 0.00126$	0.6943
	$(-3\omega;\ \omega, \omega, -\omega)$	$C_{11} = 0.0014 \pm 0.00002$	1.89
		$C_{11} = 0.0042$	1.06

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Third-Order Nonlinear Optical Coefficients—*continued*

Crystal	Nonlinear optical process	Coefficient $C_{jn} \times 10^{20}$ $m^2 V^{-2}$	Wavelength (μm)
$LiIO_3$	$(-3\omega; \omega, \omega, -\omega)$	$C_{12} = 0.2285$	1.06
		$C_{35} = 6.66 \pm 1$	1.06
MgO	$(-2\omega_1+ \omega_2; \omega_1, \omega_1, -\omega_2)$	$C_{11} = 0.014$	0.6943
		$C_{18} = 0.0077$	0.6943
	$(-3\omega; \omega, \omega, -\omega)$	$C_{11} = 0.0336$	1.06
NaCl	$(-2\omega_1+ \omega_2; \omega_1, \omega_1, -\omega_2)$	$C_{11} = 0.0238$	0.6943
		$C_{18} = 0.0101$	0.6943
	$(-3\omega; \omega, \omega, -\omega)$	$C_{11} = 0.0168$	1.06
		$C_{18}/C_{11} = 0.4133$	1.06
NaF	$(-3\omega; \omega, \omega, -\omega)$	$C_{11} = 0.0035$	1.06
$NH_4H_2PO_4$	$(-3\omega; \omega, \omega, -\omega)$	$C_{11} = 0.0104$	1.06
		$C_{18} = 0.0098$	1.06
Si	$(-2\omega_1+ \omega_2; \omega_1, \omega_1, -\omega_2)$	$C_{11} = 8.4 \pm 10\%$	10.6
		$C_{18} = 4.03 \pm 0.252$	10.6
	$(-3\omega; \omega, \omega, -\omega)$	$C_{11} = 60.7 \pm 9.7$	1.06
α–SiO_2	$(-2\omega_1+ \omega_2; \omega_1, \omega_1, -\omega_2)$	$C_{11} = 0.014$	0.6943
		$C_{11} = 0.0059 \pm 50\%$	1.89
SrF_2	$(-2\omega_1+ \omega_2; \omega_1, \omega_1, -\omega_2)$	$C_{11} = 0.00205 \pm 0.0005$	0.575
		$C_{18} = 0.0014 \pm 0.00019$	0.575
$SrTiO_3$	$(-2\omega_1+ \omega_2; \omega_1, \omega_1, -\omega_2)$	$C_{11} = 5.6$	0.6943
		$C_{18} = 2.63$	0.6943
$Tb_3Al_5O_{12}$	$(-2\omega_1+ \omega_2; \omega_1, \omega_1, -\omega_2)$	$C_{11} = (3.1 \pm 0.62) \times 10^6$	4.0
		$C_{18} = (0.95 \pm 0.2) \times 10^6$	4.0
$Y_3Al_5O_{12}$	$(-2\omega_1+ \omega_2; \omega_1, \omega_1, -\omega_2)$	$C_{11} = 0.03052 \pm 0.0018$	0.5250
		$C_{18} = 0.0084$	0.694

The above data are from tables of S. Singh, Nonlinear optical materials, *Handbook of Laser Science and Technology, Vol. III: Optical Materials, Part 1* (CRC Press, Boca Raton, FL 1986), p. 54 ff and S. Singh, Nonlinear optical materials, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials*, (CRC Press, Boca Raton, FL, 1995), p. 237 ff. These references list the original sources of the data; they also contain additional nonlinear coefficients for other organic materials and powders.

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1.9.5 Optical Phase Conjugation Materials*

Photorefractive and semiconducting media are widely used for optical phase conjugation. Photorefractive materials are electrooptic photoconductors in which a refractive index grating can be written by charge generation, transport, and trapping. The most general interaction used to produce phase conjugation in photorefractive materials is degenerate four–wave mixing (DFWM).

Photorefractive materials may be classified into several major structural categories.[1]

Ferroelectric oxides, including $LiNbO_3$, $BaTiO_3$, $KNbO_3$, and $Sr_{1-x}Ba_xNb_2O_6$ (SBN). These materials have large electrooptic coefficients and are thus characterized by large values of diffraction efficiency, gain coefficient, and phase conjugate reflectivity. They are not effective photoconductors;, thus the response times in these materials with typical CW beams are slow.

Cubic oxides or sillenites, including $Bi_{12}SiO_{20}$ (BSO), $Bi_{12}GeO_{20}$ (BGO) and $Bi_{12}TiO_{20}$ (BTO). These materials have relatively small electrooptic coefficients, but they are good photoconductors, thus their response times are fast. In order to improve the phase conjugate reflectivity of the sillenites, applied DC or AC electric fields are generally used.

Bulk compound semiconductors, including GaAs, InP, and CdTe. These materials have small electrooptic coefficients but they are excellent photoconductors, with response times approaching the fundamental limit for bulk photorefractive materials. As with the sillenites, both DC and AC electric fields have been used to enhance the gain and phase conjugate reflectivity of semiconductor conjugators.

Other photorefractive materials include multiple quantum wells in the GaAs/AlGaAs or CdZnTe/ZnTe systems. These materials require an applied AC electric field; the periodic space charge field is due to periodic screening of the applied field. Photorefractive multiple quantum wells are faster than bulk semiconductors, but are relatively inefficient, because of the small thickness (typically 1 mm) of the active layers.

Organic crystals. Organic crystals are in principle easier to grow than inorganics, but they are also more difficult to handle. Only limited work on these materials has been performed.

Polymer films. These materials are simple and inexpensive to fabricate. In addition, there is great flexibility in modifying the structure to separately optimize the electro–optic properties and the charge transport properties.

[1] Fisher, R. A., Phase conjugation materials, *Handbook of Laser Science and Technology,* vol. V, *Optical Materials*, Part 3, (CRC Press, Boca Raton, FL 1987), p. 261.

* This section was adapted from Pepper, D. M., Minden, M. L., Bruesselbach, H. W., and Klein, M. B., Nonlinear optical phase conjugation materials, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 467.

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Semiconducting media possess a wide range of nonlinearities and materials are available at wavelengths from the visible spectral region to 10.6 μm and beyond. The variety of nonlinearities in semiconductors results from the presence of free carrier states, as well as the bound carrier states which are present in all optical materials. Large concentrations of free carriers can be created through doping or through optical excitation. Semiconductors are particularly useful materials in the infrared spectral region because in most cases the nonlinear susceptibility increases rapidly as the operating wavelength increases. In addition, the susceptibility is larger in materials with smaller values of band gap energy.

Nonlinear processes in semiconductors can be broadly divided into two categories: resonant and nonresonant. In general, nonresonant nonlinearities involve virtual transitions and are quite fast. By contrast, resonant nonlinearities involve real transitions (usually involving free carrier generation), and are thus slower. Nonlinear processes used for phase conjugation via DFWM in semiconductors include anharmonic response of bound electrons, nonlinear motion of free carriers, plasma generation by valence–to–conduction band transitions, interband population modulation through optically induced carrier temperature fluctuations, saturation of exciton absorption in multiple quantum wells, and saturation of intersubband transitions in multiple quantum wells.

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Semiconductor Phase Conjugate Materials

Material	Wavelength (μm)	Nonlinearity mechanism	Temp. (K)	Pulse width (ns)	Pump intensity (W/cm^2)	Reflectivity	$\chi^{(3)}$ (esu)	Ref.
Ge	10.6	AMBE	300	50	4×10^7	2%	2×10^{-10}	1
Ge	10.6	NLPlasma	300	1.5	1.2×10^8	800%	—	7
Ge	3.8	AMBE	300	—	1.2×10^7	0.14%	4×10^{-11}	3
Si	1.06	Plasma	300	10	10^6	1%**	—	4
Si	1.06	Plasma	300	15	10^7	150%	10^{-7}	5,6
Si	1.06	Plasma	300	15	7×10^6	100%	—	7
InAs	10.6	3PA-Plasma	300	~200	1.8×10^6	13%	2.5×10^{-7}	8,9
InSb	5.3	Plasma	5	CW	40	1%	—	10
InSb	5.3	Plasma	80	CW	1	20%	1.1	11
InSb	10.6	2PA-Plasma	300	~200	10^5	30%	2×10^{-5}	8,12,13
n-$Hg_{0.768}Cd_{0.232}Te$	10.6	CBNP	295	200	10^7	9%	4×10^{-8}	14
n-$Hg_{0.78}Cd_{0.22}Te$	10.6	Plasma	77	CW	1	8%	3×10^{-2}	15
n-$Hg_{0.78}Cd_{0.22}Te$	10.6	Plasma	120	CW	12	2%	5×10^{-2}	16
HgTe	10.6	Plasma*	300	~200	5×10^5	—	2×10^{-4}	17
CdTe	1.06	TSA-Plasma	300		10^7	200%		18
CdS	0.53	Plasma	300	15	2×10^7	—	3×10^{-9}	19
ZnSe	0.69	TSA-Plasma	300	15	5×10^7	200%	—	20

AMBE, anharmonic motion of bound electrons; Plasma, nonlinearity due to index change from free carriers; also known as band filling nonlinearity; NL Plasma, plasma nonlinearity induced by high-order nonlinear absorption; 2PA-Plasma, plasma nonlinearity induced by two-photon absorption; 3PA-Plasma, plasma nonlinearity induced by three-photon absorption; SIA, saturation of intersubband absorption; SEA, saturation of exciton absorption; CBNP, conduction band nonparabolicity; TSA-Plasma, plasma nonlinearity induced by two-step absorption via impurity states; *Fast (5 ps) interband population modulation; **Diffraction efficiency.

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Photorefractive Phase Conjugation Materials

Structural category and material	Wavelength (μm)	Gain coeff. (cm^{-1})	Response time(s)	Intensity (W/cm^2)	Interaction	Reflectivity	Ref.	Notes
Ferroelectric oxide								
$BaTiO_3$	0.515	—	—	—	DFWM	100 (10^4%)	1	
	1.09		500	1	Ring	17%	2	
	0.532	15	10^{-8}	2×10^6	TWM	—	3	b
	0.532		3×10^{-11}	3×10^8	—	3×10^{-6}	4	c
	0.515	—	10^{-3}	4	—	—	5	d
$BaTiO_3$:Co	0.515	—	—	—	SPBS	60%	6	
	0.85	—	—	—	Internal	70%	7	a
	0.515	38	0.021	1	—	—	8	e
SBN:Ce	0.442	—	0.3	0.5	Internal	30%	9	
SBN:Rh	0.532	—	10^{-8}	10^6	Internal	29%	10	
	0.515	60	10	1	TWM	—	11	f
BSKNN:Ce	0.458		100	1	Internal	28%	12	g
$KNbO_3$:Fe	0.488	—	5×10^{-5}	1	—	—	13	h
$KNbO_3$:Fe	0.488	14	10^{-3}	300	Ring	60%	14	i
Sillenite								
BSO	0.568		0.2	0.1	DFWM	270%	15	j
	0.568	12	0.2	0.1	TWM	—	16	k
BTO	0.633	9	—		Mutual	40%	17	l
	0.633	35	—	0.1	Ring	7%	18	m
	0.633	35	10	0.1	TWM	—	19	n

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Bulk semiconductor

InP:Fe	1.32	2.5	10^{-3}	0.1	Ring	11%	20	o
	1.064	11	0.1	0.07	Mutual	74%	21	p
	0.970	31	0.1	0.023	Ring	0.3%	18	q
GaP	0.633	0.4				0.3%	22	r
CdTe:V	1.32	10	10^{-3}	0.075	TWM	—	23	s
	1.5	2.4	2×10^{-3}	0.003	TWM	—	24	t
GaAs:Cr	1.064	6	0.040	0.050	TWM		25	u
GaAs	1.064	7.7	—	0.02	DFWM	500%	26	u
	1.064		—		Ring	3%	27	v
ZnTe:V	0.633	0.4	1.5×10^{-5}	4.7	TWM	—	28	

Organic crystal

COANP	0.676	0.1%	10^3	3.2	—	—	29	

[a] Reflectivity constant from 0.6–0.9 μm; [b] Experiment performed with 10-ns pulses; [c] Experiment performed with 30-ps pulses; [d] Samples operated at 120°C; [e] 45-degree cut sample; [f] Rhodium concentration = 0.07 wt %; [g] $Ba_{1.5}Sr_{0.5}K_{0.75}Na_{0.25}Nb_5O_{15}$ (BSKNN-1) and $Ba_{0.5}Sr_{1.5}K_{0.50}Na_{0.50}Nb_5O_{15}$ (BSKNN-2); [h] Electrochemically reduced sample; [i] Reflection grating geometry; [j] DC electric field (E=10 kV/cm) with moving grating; beam ratio=10^4; [k] DC electric field (E=10 kV/cm) with moving grating; beam ratio=10^5; [l] AC square-wave electric field (E=20 kV/cm; f=50 Hz); [m,n] AC square-wave electric field (E=10 kV/cm; f=60 Hz); beam ratio=10^5; [o] AC square-wave electric field (E=10 kV/cm); [p] DC electric field (E=13 kV/cm); temperature/intensity resonance; [q] DC electric field (E=10 kV/cm); beam ratio=10^6; [r] band edge resonance and temperature/intensity resonance; [s] AC square-wave electric field (E=23 kV/cm; f=230 kHz); [t] beam ratio=10^4; [u] DC electric field (E=5 kV/cm) with moving grating; beam ratio=10^4; [v] DC electric field (E=12 kV/cm).

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Section 2: Glasses

2.1 Introduction
2.2 Commercial Optical Glasses
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2.8 Electrooptic Properties
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Section 2

GLASSES

2.1 Introduction

Classification and Designation

Optical glasses are characterized and designated by their refractive index and dispersion. The most common measure is the refractive index at the wavelength of the He d line (587.6 nm) or the Na D line (589.3 nm). The difference in the refractive index at the hydrogen F (486.1 nm) and C (656.3 nm) lines, $n_F - n_C$ is called the average or principal dispersion. The ratio $(n_F - n_C)/(n_d - 1)$ is called the relative dispersion; the reciprocal of this quality is the Abbe number ν_d. i.e.,

$$\nu_d = (n_d - 1)/(n_F - n_C).$$

A useful code for finding information on a specific optical glass composition is the mil spec designation. This is a six-digit number where the first three digits designate the refractive index n_d with the preceding "l" omitted and the last three digits designate the Abbe number ν_d with the decimal point omitted. Thus a borosilicate glass BK 7 having an $n_d = 1.51680$ and $\nu_d = 64.17$ has a designation 517 642.

Glasses having $n_d > 1.60$, $\nu_d > 50$ or $n_d < 1.60$, $\nu_d > 55$ are called "crown" (K) glass; other glasses are called "flint" (F). These letters, plus others, are usually contained in the manufacturer's designation of optical glasses. Representative manufacturer's designations, glass types, and principal compositional components of commercial optical glasses are given in Table 2.1.1. Designations vary with the country of origin and some alternate designations are given in parentheses. "Light" or "dense" indicate the relative amounts of heavy metal oxides such as PbO or La_2O_3. Glasses with prefixes U or IR denote extended ultraviolet or infrared transmitting glasses. Other designators are used for glasses for special applications such as LG—laser glass, FR—Faraday rotator glass, and AO—acoustooptic glass.

Various manufacturers of multicomponent optical glass use their own designations. Table 2.1.2 relates these designations to actual composition in terms of major components. The table is comprehensive for Schott Optical Glass Inc. (Duryea, PA), Hoya Glass Works Ltd (Japan), Ohara Optical Glass Manufacturing Company, and Chance–Pilkington (England) glass designations. Corning Glass Works (France) uses another form of identification in which glass type does not play as signficant a role in the name. A cross-reference chart from Corning is presented in Table 2.1.2.

There are more than 200 types of optical glasses. Some are always available, others are generally available or available on short notice, and others are available on request. Section 2.2 presents properties of representative types of glasses that are generally preferred or standard glasses. Data are for Schott glasses; however, as indicated in Table 2.1.2, comparable glasses are offered by other companies. Most optical glasses are oxides; only a few non-oxide optical glasses such as heavy metal fluorides and chalcogenides are available commercially. Some of these are included as specialty glasses in Section 2.3.

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Table 2.1.1
Designation, Type, and Major Compositional Components of Optical Glasses

Designation	Glass Type	Composition[a]
FB	Fluoroberyllate	BeF_2-AF_3-RF-MF_2
FA	Fluoroaluminate	AlF_3-RF-MF_2-$(Y,La)F_3$
FP(FK)	Fluorophosphate	P_2O_5-AlF_3-RF-MF_2
FZ	Fluorozirconate	ZrF_4-RF-MF_2-$(Al,La)F_3$
FK(FC)	Fluorocrown	SiO_2-B_2O_3-K_2O-KF
BK(BSC)	Borosilicate crown	SiO_2-B_2O_3-R_2O-BaO
PK(PC)	Phosphate crown	P_2O_5-B_2O_3-R_2O-BaO
PSK(DPC, PCD)	Dense phosphate crown	P_2O_5-$(B,Al)_2O_3$-R_2O-MO
K(C)	Crown	SiO_2-R_2O-(Ca,Ba)O
ZK(ZC, ZnC)	Zinc crown	$SiO_2(B_2O_3)$-ZnO
BaK(BaC, LBC)	Barium crown	$SiO_2(B_2O_3)$-BaO-R_2O
SK(DBC, BCD)	Dense barium crown	SiO_2-B_2O_3-BaO
SSK(EDBC, BCDD)	Extra-dense barium crown	SiO_2-B_2O_3-BaO
LaK(LaC, LaCL)	Lanthanum crown	$B_2O_3(SiO_2)$-La_2O_3-ZnO-MO
LaSK	Dense lanthanum crown	$B_2O_3(SiO_2)$-La_2O_3-ZnO-MO
LgSK	Special long crown	B_2O_3-Al_2O_3-MF_2
TiK	Titanium crown	
TiF	Titanium flint	} $SiO_2(B_2O_3)$-TiO_2-Al_2O_3-KF
TiSF(FF)	Dense titanium flint	
KzF(CHD, SbF)	Short flint	SiO_2-B_2O_3-R_2O-Sb_2O_3
KzFS(ADF)	Dense short flint	$B_2O_3(Al_2O_3)$-PbO-MO
KF(CF, CHD)	Crown flint	
LLF(BLF, FEL)	Extra light flint	
LF(FL)	Light flint	} SiO_2-R_2O-PbO-MO
F(DF, FD)	Flint	
SF(EDF, FDS)	Dense flint	
SFS	Special dense flint	} SiO_2-R_2O-MO-TiO_2
BaLF(LBC, BCL)	Light barium flint	
BaF(BF, FB)	Barium flint	} SiO_2-B_2O_3-BaO-PbO-R_2O
BaSF(DBF, FBD)	Dense barium flint	
LaF(LaFL)	Lanthanum flint	$B_2O_3(SiO_2)$-La_2O_3-MO-PbO
LaSF	Dense lanthanum flint	$B_2O_3(SiO_2)$-La_2O_3-MO-PbO
TaK	Tantalum crown	
TaF	Tantalum flint	B_2O_3-La_2O_3-$(Gd,Y)_2O_3$-$(Ta,Nb)_2O_5$
TaSF	Dense tantalum flint	B_2O_3-La_2O_3-$(Gd,Y)_2O_3$-$(Ta,Nb)_2O_5$
NbF	Niobium flint	B_2O_3-La_2O_3-ZnO-Nb_2O_5
NbSF	Dense niobium flint	$B_2O_3(SiO_2)$-La_2O_3-ZnO-$(Ti,Zr)O_2$

[a] R and M denote one or more alkali or alkaline earth elements, respectively.

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Table 2.1.2
Designations for Equivalent Optical Glasses

Mil spec	Schott type	Hoya type	Corning type
465-657	FK 3	FC	A63-65
486-817	FK 52	PFC	A86-82
487-704	FK 5	FC	A87-70
510-635	BK 1	BSC	B10-63
511-604	K 7	C	B11-60
517-642	BK 7	BSC	B16-64
518-603	BaLK N3	C	B18-60
518-651	PK 2	BSC	B18-65
523-594	K 5	C	B23-59
529-518	KzF 2	CHD	B29-52
540-597	BaK 2	BCL	B39-59
548-457	LLF 1	FeL	B48-46
548-535	BaLF 5	FBL	B48-53
564-609	SK 11	BCD	B64-61
569-560	BaK 4	BCL	B69-56
573-575	BaK 1	BCL	B72-57
581-408	LF 5	FL	B81-41
589-612	SK 5	BCD	B89-61
604-381	F 5	FD	C04-38
606-439	BaF 4	FB	C06-44
607-566	SK 2	BCD	C07-57
609-590	SK 3	BCD	C09-59
613-443	KzFS N4	FSB	C13-44
613-585	SK 4	BCD	C13-58
614-564	SK 6	BCD	C13-56
618-551	SSK 4	BCD	C17-55
620-363	F 2	FD	C20-36
620-603	SK 16	BCD	C20-60
623-531	SSK 2	BCDD	C23-53
623-569	SK 10	BCD	C23-57
623-581	SK 15	BCD	C23-58
624-469	BaF 8	FB	C24-47
626-356	F 1	FD	C26-36
637-353	F 6	FD	C37-35
639-555	SK N18	BCD	C39-56

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Table 2.1.2—*continued*
Designations for Equivalent Optical Glasses

Mil spec	Schott type	Hoya type	Corning type
641-601	LaK 21	BCS	C41-60
648-339	SF 2	FDD	C48-34
650-392	BaSF 10	FBD	C51-39
651-559	LaK22	BCS	C51-56
652-585	LaK N7	BCS	C52-58
658-572	LaK11	BCS	C57-57
659-510	SSK N5	BCDD	C58-51
667-331	SF 19	FDD	C67-33
667-484	BaF N11	FB	C67-48
670-471	BaF N10	FB	C70-47
678-555	LaK N12	BCS	C78-56
689-312	SF 8	FeD	C89-31
689-496	LaF 23	FBS	C90-50
691-548	LaK N9	BCS	C90-55
697-554	LaK N14	BCS	C97-55
699-301	SF 15	FeD	C99-30
702-411	BaSF 52	FBD	D01-41
713-538	LaK 8	BCS	D13-54
717-295	SF 1	FeD	D17-29
717-480	LaF N3	FBS	D17-48L
720-503	LaK 10	BCS	D20-50
724-380	BaSF 51	FBD	D23-38
728-284	SF 10	FeD	D28-28
734-514	LaK N16	BCS	D34-51
740-281	SF 3	FeD	D40-28
744-448	LaF N2	FBS	D44-45
755-276	SF 4	FeD	D56-27
762-269	SF 55	FeD	D62-27
785-258	SF 11	FeD	D85-25
785-259	SF 56	FeD	D85-26
788-474	LaF 21	FBS	D88-47
803-464	LaSF N30	FBS	E03-47
805-255	SF 6	FeD	E05-25
878-385	LaSF 15	FBS	E78-38

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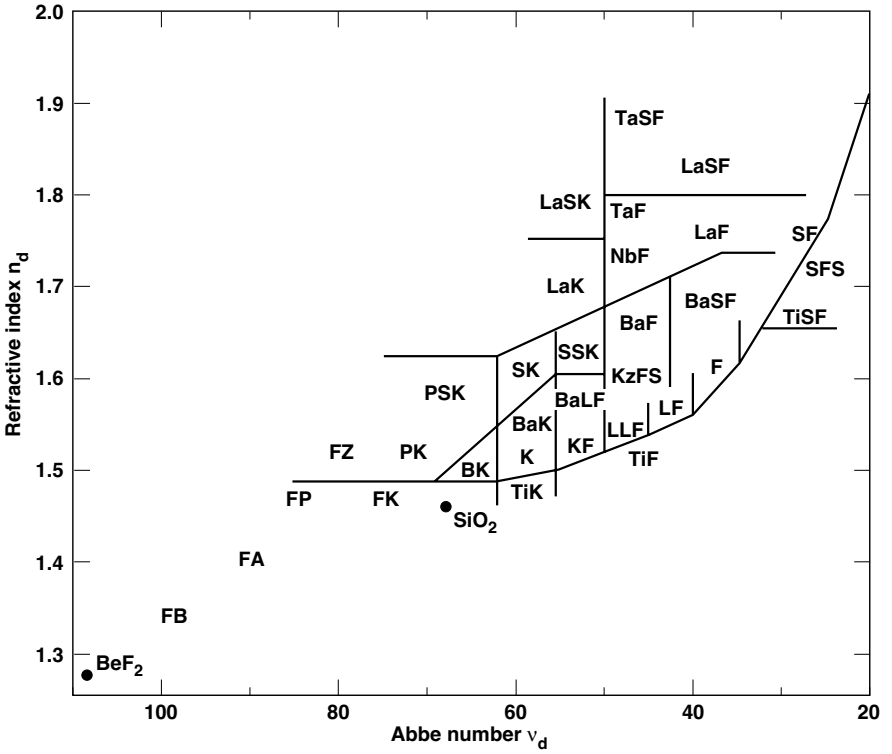

Figure 2.1.1 Glass map of the optical glass compositions in Table 2.1.1.

Refractive Index

Optical glasses cover a general range of refractive indices n_d = 1.4 to 2.0 and reciprocal dispersions ν_d = 20 to 90. These are almost exclusively oxide glasses. The location of the glasses is shown in the glass map above, where the lines divide the main compositional types. The range of $n_d - \nu_d$ in this figure is larger than that given in the ordinary glass catalogs so as to include low-index, low-dispersion fluoride glasses. Amorphous SiO_2 and BeF_2 are added to indicate the extrema for oxide and fluoride glasses. Many higher index chalcogenide glasses cannot be located in an $n_d - \nu_d$ plot because the absorption edge extends into the visible and it is not always possible to measure ν_d. Therefore for infrared materials, plots are made using a reciprocal dispersion based on measurements of refractive index at longer wavelengths.

Manufacturer's data sheets usually report the refractive index (the mean value for a number of melts) at a number of specific wavelengths. Wavelengths of a number of commonly used spectral lines and laser wavelengths are given in Table 2.1.3.

For interpolating values of the refractive index at the other wavelengths, glass manufacturers use an approximate dispersion formula derived from a power series expansion of the form

$$n^2 = A_0 + A_1{}^2 + A_2\,\lambda^{-2} + A_3\,\lambda^{-4} + A_4\,\lambda^{-6} + A_5\,\lambda^{-8},$$

where the constants A_i are determined from a least squared fit of the measured values.

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Table 2.1.3
Principal Wavelengths Used for Refractive Index Measurements

Wavelength (nm)	Spectral line	Element	Wavelength (nm)	Spectral line	Element
365.0	i	Hg	656.3	C	H
404.7	n	Hg	706.6	r	He
435.8	g	Hg	768.2	A'	K
480.0	F'	Cd	852.1	s	Cs
486.1	F	H	1014.0	t	Hg
546.1	e	Hg	1060.0	Nd glass laser	
587.6	d	He	1064	Nd:YAG laser	
589.3	D	Na	1529.6		Hg
632.8	He-Ne laser		1970.1		Hg
643.8	C'	Cd	2325.4		Hg

Using the above equation, refractive indices in the wavelength range 365-1014 nm can be calculated to an accuracy of ± 5 x 10^{-6} or better. The thermal coefficient of refractive index depends on the wavelength, temperature, and pressure.

Transmission

The transmission of optical glasses is frequently given in terms of the internal transmission T_i after correction for reflective losses R, that is, $T_i = T/R$. The deviation of T_i from 100% is a measure of absorption due to impurities and scattering due to defects. The internal transmittance is usually reported at a number of standard wavelengths from the ultraviolet to the infrared. The transmission (I/I_O) and the absorption coefficient α for a sample of length l are related by

$$\alpha l = \ln(I_0/I) = 2.303OD,$$

where $OD = \log_{10}(I_o/I)$ is the absorbance or optical density. The absorption cross section σ is derived from $\alpha = \sigma N$, where N is the number of absorbing centers to unit volume.

Glasses exist that are optically transparent in the vacuum ultraviolet and in the mid-infrared. Variations of the ultraviolet and infrared absorption edges of representative optical glasses are illustrated below.

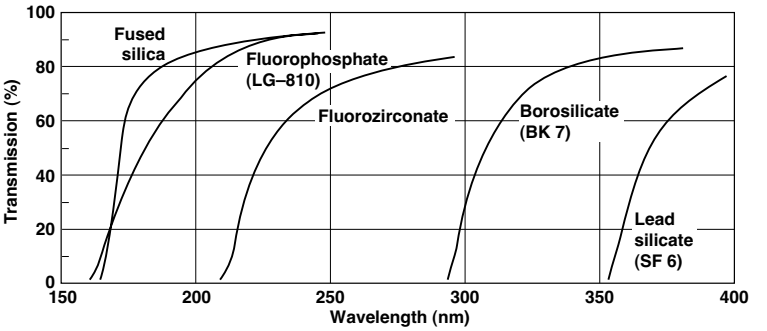

Figure 2.1.2. Ultraviolet absorption edge of representative optical glasses. Sample thicknesses: 5 mm except for SiO_2 and LG 810 which are 2 mm.

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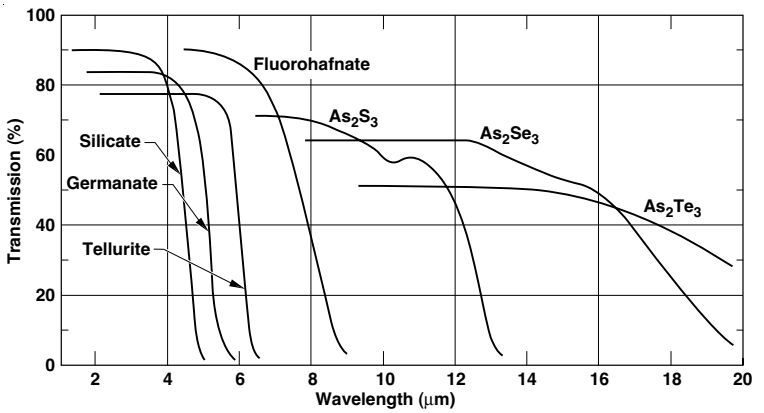

Figure 2.1.3. Infrared absorption edge of representative optical glasses. Sample thicknesses: 2 mm.

Thermal Properties

The temperature range in which a glass transforms from its solid state into a "plastic" state is called the transformation region. A transformation (annealing) temperature T_g is used to define this region and is determined from a standard thermal expansion measurement. The viscosity of the melt at T_g is approximately $10^{13.4}$ poise. The softening temperature is that temperature at which, in a standard test, the glass deforms under its own weight and corresponds to a melt viscosity of $10^{7.6}$ poise.

Thermal expansion varies the dimensions of glass and affects refractive optics subject to either uniform or gradient temperature variations. The coefficient of thermal expansion α of glass ranges from near zero for special low expansion glasses such as titania-doped SiO_2 and tailored glass ceramics to values greater than 20 x 10^{-6}/K. For optical glasses α ranges from about 4 to 16 x 10^{-6}/K. The thermal expansion coefficient increases with increasing temperature, exhibiting a nonlinear increase up to about room temperature, followed by an approximately linear range until the glass begins to exhibit plastic behavior, and then a rapid increase with increasing structural mobility in the glass. Therefore, mean thermal expansion coefficients are given for a specific temperature range.

Because of its disordered atomic structure, the thermal conductivity of glass is much lower than that for crystalline materials. The thermal conductivity of optical glasses ranges from about 0.5 to 1.5 W/m K, being high for silica and low for glasses containing large quantities of heavy elements such as lead, tantalum, barium, and lanthanum. The thermal conductivity of glass increases with temperature but only slightly above 300 K.

Mechanical Properties

The mechanical response of a glass to an applied force is described by various moduli. Optical glass catalogs usually list moduli such as Young's modulus E (extension in tension) and the modulus of rigidity or shear G which are important for thermal and mechanical stress determinations. These are related to Poisson's ratio μ (ratio of lateral to longitudinal strain under unilateral stress) by

$$\mu + 1 = E/2G.$$

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The bulk modulus B (1/isothermal compressibility) is related to the above moduli by

$$B = E/3(1 - \mu).$$

Elastic moduli can also be expressed in terms of the longitudinal and transverse sound velocities and the density.

The hardness of a glass is usually measured from the indentation of Knoop or Vickers penetrators. Values (Knoop) for oxide glasses range from ~250 for high-lead-content glasses to >600 kg/mm^2 for lanthanum crown glasses. The Knoop hardness generally correlates with Young's modulus.

The stress-optical coefficient K varies with glass type and wavelength. It is usually positive, although it can become negative (so-called Pockels glasses) for silicate glasses having a high lead content. The stress-optical coefficient is measured in units of 1 Brewster = $(\text{TPa})^{-1}$ = 10^{-12} m^2/N. Values of K are included in the table and generally range from $-2 < K < 4$ TPa^{-1} for oxide glasses to $-40 < K < 20$ TPa^{-1} for chalcogenide glasses.

Chemical Properties

An important consideration for many optical glasses is their chemical reactivity with slurries during cutting and polishing of components such as lenses, windows, and prisms and with its environment where it may be subject to chemical attack by water, water vapor, gases, acids, etc. Corrosion, dimming, and straining occur and vary greatly depending on the chemical composition of the glass. No simple test and parameter is sufficient to characterize chemical reactivity under all conditions. Thus many terms and tests are used to rank glasses with respect to their resistance to acids, straining, climate, weathering, etc. Manufacturers typically list several categories of acid and alkali resistance to cover the above ranges.

2.2 Commercial Optical Glasses

Data for selected commercial optical glasses representative of the various glass types are presented in Sections 2.2 and 2.3 are from manufacturers' catalogs and data sheets and from the *Handbook of Optics,* Vol. II (McGraw-Hill, New York, 1995), chapter 33, and references cited therein.

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2.2.1 Optical Properties

Glass type	Refractive index n_d	Abbe number ν_d	Dispersion $n_F - n_C (x10^{-3})$	dn/dT (10^{-6}/K)* 435.8 nm	1060 nm
FK 5	1.48749	70.41	6.924	−1.1	−1.8
FK 51	1.48656	84.47	5.760	−5.9	−6.4
PK 2	1.51821	65.05	7.966	3.7	2.3
PSK 3	1.55232	63.46	8.704	–	–
PSK 53	1.62014	63.48	9.769	−1.7	−2.6
BK 7	1.51680	64.17	8.054	3.4	2.3
BaLK N3	1.51849	60.25	8.606	3.1	1.9
K 5	1.52249	59.48	8.784	2.4	1.1
UK 50	1.52257	60.38	8.654	–	–
ZK 1	1.53315	57.98	9.196	4.4	2.8
ZK N7	1.50847	61.19	8.310	6.8	6.1
BaK 50	1.56774	57.99	9.790	8.7	7.7
SK 2	1.60738	56.65	10.721	5.6	3.9
SK 14	1.60311	60.60	9.952	3.6	2.3
KF 9	1.52341	51.49	10.166	5.1	3.3
BaLF 4	1.57957	53.71	10.790	6.3	4.3
SSK 4	1.61765	55.14	11.201	4.0	2.2
SSK N5	1.65844	50.88	12.940	–	–
LaK N7	1.65160	58.52	11.134	1.7	0.5
LaK 10	1.72000	50.41	14.282	5.8	3.8
LLF 6	1.53172	48.76	10.905	4.4	2.6
BaF 4	1.60562	43.93	13.787	5.1	2.6
BaF N10	1.67003	47.11	14.222	–	–
LF 5	1.58144	40.85	14.233	4.4	1.6
F 2	1.62004	36.37	17.050	5.9	2.8
BaSF 2	1.66446	35.83	18.545	–	–
BaSF 51	1.72373	38.11	18.991	12.1	8.1
LaF N2	1.74400	44.77	16.618	3.4	1.1
LaF N21	1.78831	47.39	16.633	6.1	3.8
LaSF 30	1.80318	46.45	17.292	–	–
LaSF 31	1.88067	41.10	21.429	6.2	3.5
SF 2	1.64769	33.85	19.135	−1.8	−2.6
SF 59	1.95250	20.36	46.774	–	–
SF N64	1.70585	30.30	22.295	4.3	0.9
TiK 1	1.47869	58.70	8.155	−1.8	−2.6
TiF 1	1.51118	51.01	10.022	−0.1	−1.5
TiF 6	1.61650	30.97	19.904	–	–
KzF N1	1.55115	49.64	11.103	5.0	3.1
KzFS N4	1.61340	44.30	13.848	6.2	4.4
LgSK 2	1.58599	61.04	9.600	−2.5	−4.0
NbF 1	1.74330	59.23	–	7.9 (633 nm)	–

* dn/dT in air; 0/+20˚C

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2.2.2 Internal transmittance (5 mm)

	Wavelength				
Glass type	**320 nm**	**400 nm**	**700 nm**	**1530 nm**	**2325 nm**
FK 5	0.975	0.998	0.999	0.993	0.91
FK 51	0.87	0.996	0.999	0.999	0.999
PK 2	0.84	0.998	0.999	0.999	0.975
PSK 3	0.85	0.997	0.999	0.996	0.91
PSK 53	0.05	0.96	0.997	0.985	0.94
BK 7	0.81	0.998	0.999	0.997	0.89
UBK 7	0.920	0.998	0.999	0.997	0.88
BaLK N3	0.82	0.998	0.999	0.997	0.91
K 5	0.78	0.997	0.999	0.998	0.91
UK 50	0.92	0.998	0.997	0.996	0.92
ZK 1	0.77	0.996	0.999	0.995	0.92
ZK N7	0.69	0.992	0.999	0.995	0.92
BaK 50	0.36	0.998	0.999	0.994	0.93
SK 2	0.71	0.995	0.999	0.998	0.952
SK 14	0.73	0.994	0.999	0.994	0.90
KF 9	0.41	0.996	0.999	0.999	0.90
BaLF 4	0.08	0.995	0.999	0.997	0.94
SSK 4	0.4	0.994	0.999	0.997	0.94
SSK N5	–	0.981	0.998	0.997	0.93
LaK N7	0.46	0.992	0.999	0.997	0.89
LaK 10	0.20	0.981	0.999	0.998	0.87
LLF 6	0.84	0.998	0.999	0.998	0.90
BaF 4	0.15	0.994	0.999	0.999	0.951
BaF N10	–	0.965	0.999	0.997	0.93
LF 5	0.60	0.998	0.999	0.999	0.92
F 2	0.20	0.998	0.999	0.999	0.93
BaSF 2	–	0.963	0.999	0.998	0.959
BaSF 51	–	0.956	0.998	0.999	0.89
LaF N2	0.02	0.968	0.999	0.996	0.93
LaF 21	–	0.975	0.999	0.999	0.88
LaSF 30	–	0.975	0.999	0.999	0.87
LaSF 31	0.13	0.93	0.999	0.998	0.961
SF 2	0.01	0.994	0.999	0.999	0.94
SF 59	–	0.60	0.994	0.999	0.950
SF N64	–	0.93	0.999	0.998	0.950
TiK 1	0.17	0.94	0.998	0.999	–
TiF 1	–	0.981	0.998	0.999	0.89
TiF 6	–	0.90	0.996	0.998	0.68
KzF 1	0.46	0.986	0.999	0.990	0.92
KzFS N4	0.50	0.988	0.999	0.996	0.790
LgSK 2	0.07	0.970	0.996	0.979	–

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2.2.3 Mechanical Properties

Glass type	Density (g/cm^3)	Young's modulus E (10^3 N/mm^2)	Poisson's ratio μ	Knoop hardness (kg/mm^2)	Stress-optical coefficient K $(TPa)^{-1}$
FK 5	2.45	62	0.205	450	2.91
FK 51	3.73	79	0.287	360	0.67
PK 2	2.51	84	0.209	520	–
PSK 3	2.91	84	0.226	510	–
PSK 53	3.60	77	0.287	370	–
BK 7	2.51	81	0.208	520	2.74
BaLK N3	2.61	72	0.212	470	–
K 5	2.59	71	0.227	450	–
UK 50	2.62	73	0.240	460	–
ZK 1	2.71	68	0.214	430	–
ZK N7	2.49	71	0.259	450	3.62
BaK 50	2.93	81	0.263	520	–
SK 2	3.55	78	0.261	460	–
SK 14	3.44	86	0.202	490	2.00
KF 9	2.71	67	0.244	440	–
BaLF 4	3.17	76	0.265	460	–
SSK 4	3.63	79	0.278	460	–
SSK N5	3.71	88	0.277	470	–
LaK N7	3.84	90	0.288	460	–
LaK 10	3.81	111	0.205	580	–
LLF 6	2.81	63	0.247	420	–
BaF 4	3.50	66	0.281	400	–
BaF N10	3.76	89	0.226	480	–
LF 5	3.22	59	0.225	410	2.81
F 2	3.61	58	0.245	370	–
BaSF 2	3.90	66	0.289	410	–
BaSF 51	4.31	80	0.293	450	–
LaF N2	4.54	87	0.294	450	1.65
LaF N21	4.44	120	0.290	630	–
LaSF 30	4.56	124	0.298	630	–
LaSF 31	5.24	123	0.231	620	–
SF 2	3.86	55	0.269	350	2.65
SF 59	6.26	51	0.250	250	–1.46
SF N64	3.00	93	0.254	500	–
TiK 1	2.39	40	0.239	330	–
TiF 1	2.47	58	0.263	440	–
TiF 6	2.79	65	0.225	410	–
KzF N1	2.71	60	0.276	500	–
KzFS N4	3.20	60	0.290	380	–
LgSK 2	4.15	76	0.308	340	–
NbF 1	4.17	108	–	675	–

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2.2.4 Thermal Properties

Glass type	Thermal expansion* (10^{-6}/K)	Thermal conductivity (W/m K)	Specific heat (J/g K)	Transform. temp. (˚C)	Softening temp. (˚C)
FK 5	9.2	0.925	0.818	464	672
FK 51	16.9	–	–	403	–
PK 2	6.9	1.149	0.80	568	721
PSK 3	7.4	0.990	0.682	602	736
PSK 53	10.7	0.612	0.603	614	–
BK 7	7.1	1.114	0.858	563	766
BaLK N3	9.0	1.029	0.749	562	738
K 5	8.2	0.950	0.783	583	720
UK 50	8.1	0.964		554	735
ZK 1	7.5	0.894	0.77	562	732
ZK N7	5.4	1.042	0.770	528	721
BaK 50	4.6	1.044	0.758	629	820
SK 2	7.0	0.776	0.595	654	823
SK 14	7.0	0.851	0.636	649	773
KF 9	638	1.01	0.75	445	661
BaLF 4	6.4	0.827	0.67	569	731
SSK 4	6.1	0.806	0.57	639	791
SSK N5	7.9	–	0.574	641	751
LaK N7	8.2	–	–	618	716
LaK 10	6.9	–	–	620	703
LLF 6	8.5	–	–	422	627
BaF 4	8.8	0.766	0.557	521	694
BaF N10	7.9	0.798	0.595	630	745
LF 5	9.1	0.866	0.657	419	585
F 2	8.2	0.780	0.557	432	593
BaSF 2	9.3	–	–	493	640
BaSF 51	6.4	0.722	0.536	522	630
LaF N3	9.1	0.670	0.481	616	736
LaF N21	6.9	–	–	667	–
LaSF 30	7.1	–	–	684	–
LaSF 31	7.9	–	–	753	–
SF 2	9.2	0.735	0.498	441	600
SF 59	10.3	0.506	0.306	362	–
SF N64	9.7			578	666
TiK 1	10.3	0.773	0.842	340	–
TiF 1	9.1	0.953	0.81	443	–
TiF 6	16.7	–	–	410	494
KzF N1	7.5	–	–	470	675
KzFS N4	5.5	0.769	0.64	492	594
LgSK 2	12.1	0.866	0.51	515	–
NbF 1	5.3	0.845	0.48	590	625

* 20/300˚C

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2.3 Specialty Optical Glasses

Designation	Glass type	Composition
Vycor® (Corning 7913)	silica	96% SiO_2
Pyrex® (Corning 7740)	borosilicate	SiO_2–B_2O_3–Na_2O–Al_2O_3
Ultraviolet transmitting glasses		
Corning 9741	alkali borosilicate	SiO_2–B_2O_3–Na_2O + . . .
Schott UBK 7	borosilicate	SiO_2–B_2O_3–Na_2O–CaO + . . .
ULTRAN 30 (Schott)		
Hoya UBS250		
Infrared transmitting glasses		
Fused germania	germanium oxide	100% GeO_2
Corning 9753	calcium aluminate	SiO_2–CaO–Al_2O_3
Corning 9754	calcium aluminate	GeO_2–CaO–Al_2O_3–BaO–ZnO
Barr&Stroud BS-39B	calcium aluminate	CaO–Al_2O_3–MgO
Kigre BGA	germanate	BaO–Ga_2O_3–GeO_2
Schott IRG 2	germanate	
Schott IRG 9	fluorophosphate	P_2O_5 + . . .
Schott IRG 11	calcium aluminate	CaO–Al_2O_3 + . . .
Schott IRG 100	chalcogenide	
Arsenic trisulfide	chalcogenide	100% As_2S_3
Arsenic triselenide	chalcogenide	100% As_2Se_3
AMTIR-1	chalcogenide	$Ge_{33}As_{12}Se_{55}$
AMTIR-3	chalcogenide	$Ge_{28}As_{12}Se_{60}$
Fluoride glass		
Ohara HTF-1	fluoride	
Low expansion glasses		
CLEARCERAM 55 (Ohara)	glass ceramic	
CLEARCERAM 63 (Ohara)	glass ceramic	
LE30 (Hoya)	glass ceramic	aluminosilicate
Zerodur (Schott)	glass ceramic	SiO_2–Al_2O_3–P_2O_5 + . . .
ULE (Corning 7971)	glass ceramic	SiO_2–TiO_2
Athermal glasses		
Schott PSK 54	dense phosphate crown	P_2O_5– $(B,Al)_2O_3$–R_2O–MO
Schott TiF 6	titanium flint	$SiO_2(B_2O_3)$ –TiO_2–Al_2O_3–KF
Acoustooptic glasses		
Hoya AOT-5	tellurite	TeO_2 + . . .
Hoya AOT-44B	tellurite	TeO_2 + . . .
Low nonlinear refractive index glass		
Schott FK 54	fluorophosphate	P_2O_5 + . .

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2.3.1 Optical Properties

Glass type	Transmission range (μm)	Refractive index n_d	Abbe number ν_d	dn/dT (10^{-6}/K)
Vycor® (Corning 7913)	0.3–2.4			
Pyrex® (Corning 7740)		1.474		
Ultraviolet transmitting glasses				
Corning 9741	0.25–	1.47	65	
Schott UBK 7	0.32–2.1	1.5168	64.3	
ULTRAN 30 (Schott)	0.28–	1.5483	74.3	–5.8 (546 nm)
Hoya UBS250	0.27–	1.472	65.8	
Infrared transmitting glasses				
Fused germania	0.30–4.9	1.60832 (n_D)	41.2	
Corning 9753	0.38–4.3	1.60475 (n_D))		
Corning 9754	0.36–4.8	1.6601 (n_D)	46.5	
Barr&Stroud BS-39B	0.38–4.9	1.6764 (n_D)	44.5	7.4 (589.3 nm)
Kigre BGA	0.5–5.0	1.663 (n_D)	45.6	12
Schott IRG 2	0.44–5.1	1.8918	30.0	
Schott IRG 9	0.38–4.1	1.4861	81.0	
Schott IRG 11	0.44–4.75	1.6809	44.2	
Schott IRG 100	0.93–13	2.7235 (n_1)		103 (2.5 μm)
Arsenic trisulfide	0.62–11.0	2.47773 (n_1)		85 (0.6 μm)
Arsenic triselenide	0.87–17.2	2.7728 (n_{12})		55 (0.83 μm)
AMTIR-1	0.75–14.5	2.6055 (n_1)		101 (1 μm)
AMTIR-3	0.93–16.5	2.6366 (n_3)		98 (3 μm)
Fluoride glass				
Ohara HTF-1	0.21–6.9	1.44296	92.5	
Low expansion glasses				
CLEARCERAM 55 (Ohara)	0.42–	1.547	55.0	
CLEARCERAM 63 (Ohara)	0.40–	1.547	55.1	
LE30 (Hoya)	0.35–	1.532		
Zerodur (Schott)	0.4–2.3	1.5424	56.1	15.7
ULE (Corning 7971)	0.23–3.9	1.5418	75.2	–5.5
Athermal glasses				
Schott PSK 54		1.5860	64.6	
Schott TiF 6	0.4–1.7	1.6165	31.0	
Acoustooptic glasses				
Hoya AOT-5		2.10238	18.10	
Hoya AOT-44B		1.97961	20.58	
Low nonlinear refractive index glass				
Schott FK 54	0.35–2.5	1.4370	90.7	–5.68 (546 nm)

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2.3.2 Mechanical Properties

Glass type	Density (g/cm^3)	Young's modulus E (10^3 N/mm^2)	Poisson's ratio μ	Knoop hardness (kg/mm^2)	Stress-optic coefficient K $(TPa)^{-1}$
Vycor® (Corning 7913)	2.18	68.8	0.19	487	
Pyrex® (Corning 7740)	2.23	62.8	0.200	418	3.9
Ultraviolet transmitting glasses					
Corning 9741	2.17	72	0.23		
Schott UBK 7	2.51	81	0.212	500	
ULTRAN 30 (Schott)	4.02	76	0.297	380	
Hoya UBS250	2.26	59.1	0.222	488	
Infrared transmitting glasses					
Fused germania	3.60	43.1	0.192		
Corning 9753	2.798	98.6	0.28	600	
Corning 9754	3.581	84.1	0.290	560	
Barr&Stroud BS-39B	3.1	104	0.29		
Kigre BGA	3.6	84.1	0.29	560	
Schott IRG 2	5.00	95.9	0.282	481	
Schott IRG 9	3.63	77.0	0.288	346	
Schott IRG 11	3.12	107.5	0.284	610	
Schott IRG 100	4.67	21	0.261	150	
Arsenic trisulfide	3.20	15.8	0.295	180	
Arsenic triselenide	4.69	18.3	0.288	120	
AMTIR-1	4.41	22.1	0.27	170	
AMTIR-3	4.67	21.4	0.26	150	
Fluoride glass					
Ohara HTF-1	3.94	64.2	0.28	320	
Low expansion glasses					
CLEARCERAM 55 (Ohara)	2.56	95.8	0.25	680	
CLEARCERAM 63 (Ohara)	2.57	95.5	0.25	660	
LE30 (Hoya)	2.58	75.4	0.159	657	2.9
Zerodur (Schott)	2.53	91	0.24	630	3.0
ULE (Corning 7971)	2.205	67.3	0.17	460	4.0
Athermal glasses					
Schott PSK 54	3.52			340	
Schott TiF 6	2.79	65	0.262	310	
Acoustooptic glasses					
Hoya AOT-5	5.87			290	
Hoya AOT-44B	5.06			226	
Low nonlinear refractive index glass					
Schott FK 54	3.18	76	0.286	320	

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2.3.3 Thermal Properties

Glass type	Thermal expansion (10^{-6}/K)	Thermal conduct. (W/m K)	Specific heat (J/g K)	Transform. temp. (K)	Softening temp. (K)
Vycor® (Corning 7913)	0.75	1.38	0.75	890	1200
Pyrex® (Corning 7740)	3.25	1.13	1.05	560	821
Ultraviolet transmitting glasses					
Corning 9741	3.8			733	978
Schott UBK 7	8.3			563	716
ULTRAN 30 (Schott)	13.9	0.667	0.58	513	600
Hoya UBS250	5.6	0.96		449	645
Infrared transmitting glasses					
Fused germania	6.3		0.746	800	
Corning 9753	6.0	2.3	0.795	1015	
Corning 9754	6.2	0.81	0.54	1008	1147
Barr&Stroud BS-39B	6.3		0.865		970
Kigre BGA	6.3			741	873
Schott IRG 2	8.8	0.91	0.495	975	
Schott IRG 9	16.1	0.88	0.695	696	
Schott IRG 11	8.2	1.13	0.749	1075	
Schott IRG 100	15.0	0.3		550	624
Arsenic trisulfide	26.1	0.17	0.473	436	573
Arsenic triselenide	24.6	0.20	0.349		345
AMTIR-1	12.0	0.25	0.293	635	678
AMTIR-3	13.5	0.22	0.276	550	570
Fluoride glass					
Ohara HTF-1	16.1			658	
Low expansion glasses					
CLEARCERAM 55 (Ohara)	0.2	1.62	0.76		
CLEARCERAM 63 (Ohara)	–2.1	1.62	0.73		
LE30 (Hoya)	0.4			690	921
Zerodur (Schott)	0.5	1.64	0.821		
ULE (Corning 7971)	0.03	1.31	0.776	1000	1490
Athermal glasses					
Schott PSK 54	11.9			486	568
Schott TiF 6	16.7			410	494
Acoustooptic glasses					
Hoya AOT-5	16.1			332	347
Hoya AOT-44B	20.1			296	314
Low nonlinear refractive index glass					
Schott FK 54	16.9			403	

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2.4 Fused (Vitreous) Silica*

Different types of silica have been commercially available from several suppliers (Corning Incorporated, Hereaus Amersil, Thermal Syndicate Ltd, General Electric Co., Quartz et Silice [France], Dynasil Corp. of America, NSG Quartz [Japan], Westdeutsche Quartzschmelze GmbH (Germany), Nippon Glass [Japan]). The glasses are compositionally the same except for metallic impurities, structural defects, and water content, but these differences and fabrication variations cause the properties of the silicas to differ significantly. The vitreous silicas can be distinguished by the source of raw material used and the process of melting or consolidating the raw material into bulk vitreous silica. It is produced commercially from naturally occurring quartz of high purity and from silicon tetrachloride liquid or vapor or from tetraethyl orthosilicate liquid. These precursors are processed in several different ways. Hetherington et al.[1] divided the different silicas into four types based on manufacturing method

In one method, naturally occurring quartz is purified to varying degrees by preselection of clean crystalline material, fragmented to a fine powder, and fused to bulk glass. The fusion is performed by electric melting in a refractory crucible or container under vacuum, an inert atmosphere, or a hydrogen atmosphere. This produces a type of vitreous silica designated as type I. If the same raw material is fused using an oxyhydrogen torch or an isothermal plasma torch, then the resultant vitreous silica is designated type II. The principal differences between these are the lower hydroxyl content and different impurities of type I.

Melting atmosphere influences the glass structure and properties. After fusion, various amounts of hot working are performed to homogenize the resultant silica glasses. The synthetic precursors, mainly $SiCl_4$, are fused to a solid glass with an oxyhydrogen torch producing a very pure but wet material denoted type III. These precursors also can be used to produce vitreous silica under relatively dry conditions such as those present using an oxygen or argon plasma torch. This material has been designated type IV. The principal difference between types III and IV fused silica is OH content which introduces strong absorption around 2.8 μm.

Using similar torches but depositing on a cooler bait, the synthetic material can also be formed into a porous boule that is subsequently consolidated to a fully dense silica boule in a furnace. Consolidation of the porous silica body can involve firing in different atmospheres and can be achieved at a temperature several hundred degrees below that used for fusion of the type III and type IV silica. The commercialization of this latter technology has occurred principally in the fabrication of optical fibers based on vitreous silica. Certain manufacturers have used this technology for the fabrication of bulk silica. This vitreous silica is similar to type III or IV depending on the method of consolidation, but the processing is sufficiently different that it should be considered in a class by itself. Although there is varied opinion on what kind of silica should be designated type V, there is general agreement that there are many types of vitreous silica which, because of the dependence on fabrication, do not fall into the earlier established four types. Fleming[2] has viewed the consolidated soot sufficiently close to type III and IV that it is designated type V in the following tables. Fluoride-doped, low-OH silica glass has recently been developed for deep UV and vacuum UV applications and is designated as modified silica.[3] Optical, mechanical, and thermal properties of the various types of silicas are compared below.

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* From Fleming, J. W., Optical glasses, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, 1995), p. 69 (with additions).

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Glass Type	Brand name	Source
SiO_2 I	IR-Vitreosil	4
	Infrasil	5
	Pursil 453, Ultra	6
	GE 104, 105, 201, 204, 124, 125	7
SiO_2 II	Herasil, Homosil, Ultrasil, Optosil	5
	Vitreosil 055, 066, 077	4
SiO_2 III	Suprasil	5
	Spectrosil	4
	7940, 7980 (HPFS)	8
	Dynasil	9
	Tetrasil	6
	NSG-ES	10
	GE 151	7
	Synsil	11
SiO_2 IV	Suprasil W	5
	Spectrosil WF	4
SiO_2 V	Nippon Sheet Glass	12
Sol gel SiO_2	Gelsil	13

Refractive Index Properties[14]

	Refractive index				dn/dT (10^{-6}/K)		
λ (nm)	Suprasil	Homosil/ Herasil/ Infrasil	HPFS 7980	λ (nm)	Suprasil	Homosil/ Herasil/ Infrasil	HPFS 7980
193	1.56077		1.560841	193			20.6
238				238	14.6	15.2	
248	1.50855		1.508601	248			14.2
308	1.48564		1.485663	308			12.1
365	1.47447	1.47462	1.474555	365	11.0	11.5	11.2
405	1.46962	1.46975	1.469628	405			10.8
436	1.46669	1.46681	1.466701	436			10.6
486	1.46313	1.46324	1.463132	486			10.4
546	1.46008	1.46018	1.460082	546	9.9	10.6	10.2
588	1.45846	1.45856	1.458467	588	9.8	10.5	10.1
633	1.45702		1.457021	633			10.0
644				644	9.6	10.4	
656	1.45637	1.45646	1.456370	656			9.9
1064			1.449633	1064			9.6
1500	1.44462	1.44473		1500			
2000	1.43809	1.43821		2000			
2500	1.42980	1.42995		2500			
3000	1.41925	1.41941		3000			
3500	1.40589	1.40605		3500			

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Optical Properties

Glass type	Data source	Transmission range (μm)	Refractive index n_d	Abbe number ν_d	dn/dT (10^{-6}/K)
SiO_2 I	4,5,7	0.21–2.8	1.45867	67.56	10.5
SiO_2 II	4,5	0.19–3.5	1.45857	67.6	
SiO_2 III	5,8	0.17–2.2	1.45847	67.7	9.9
SiO_2 IV	5	0.18–3.5	–	–	–
SiO_2 V	12	0.18–3.5	1.45847	67.7	9.9
Sol gel SiO_2	13, 15	0.17–3.5	1.458–1.463	66.4–67.8	–
Mod. SiO_2	16,17	0.155–3.5	1.65423 (157 nm)	–	39 (157 nm)

Resistance to humidity: fused silica exhibits no or very little surface deterioration due to climatic conditions.

Dispersion formula[18] (wavelength λ in μm)	Range (μm)
$n^2 = 1 + 0.6961663\lambda^2/[\lambda^2 - (0.0684043)^2] + 0.4079426\lambda^2/[\lambda^2 - (0.1162414)^2] + 0.8974794\lambda^2/[\lambda^2 - (9.896161)^2]$	0.21–3.71

Mechanical Properties

Glass type	Density (g/cm^3)	Young's modulus E (10^3 N/mm^2)	Poisson's ratio μ	Hardness (Knoop) (kg/mm^2)	Stress-optical coefficient K $(TPa)^{-1}$
SiO_2 I	2.203	72	0.17	570	3.5
SiO_2 II	2.203	70	0.17	600	–
SiO_2 III	2.201	70	0.17	610	–
SiO_2 IV	2.201	70	0.17	600	–
SiO_2 V	2.201	70	0.17	600	–
Sol gel SiO_2	2.204	73	–	–	–
Mod. SiO_2	2.201	69	0.17	–	–

Thermal Properties

Glass type	Thermal expansion (10^{-6}/K)	Thermal conductivity (W/m K)	Specific heat (J/g K)	Transformation temperature (°C)	Softening temperature (°C)
SiO_2 I	0.55	1.4	0.67	1215	1683
SiO_2 II	0.55	1.38	0.75	1175	1727
SiO_2 III	0.60	1.38	0.74	1080	1590
SiO_2 IV	0.55	1.38	0.75	1110	1650
SiO_2 V	0.60	1.38	0.74	1080	1590
Sol gel SiO_2	0.57	–	–	~1160	–
Mod. SiO_2	0.51*	1.37	0.77	–	–

* 0–300ºC

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Properties of Modified Silica[19]

	Refractive Index Data For Fluorine-Doped Silica Blanks					
Wavelength (nm)	**0% F**	**0.17 wt.% F**	**0.67 wt.% F**	**0.8 wt.% F**	**1.12 wt.%F**	**1.48 wt.%F**
435.8	1.4671	1.466	1.4638	1.4634	1.4618	1.4604
480	1.4639	1.4628	1.4606	1.4603	1.4586	1.4573
546.1	1.4605	1.4594	1.4573	1.4569	1.4553	1.4539
589.3	1.4588	1.4578	1.4556	1.4552	1.4537	1.4524
632.8	1.4576	1.4568	1.4546	1.4542	1.4529	1.4515
643.8	1.4572	1.4561	1.4539	1.4536	1.452	1.4507
777	1.4533	1.4526	1.4502	1.4499	1.4485	1.4474
1300	1.4472	1.4461	1.4444	1.4436	1.4423	1.4411
1541	1.4441	1.4433	1.4409	1.4405	1.4393	1.438
Coeff. thermal expansion (10^{-6}/K)	0.59	–	–	0.51	–	0.43
Anneal point (°C)	1094	962	883	866	833	807

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2.5 Fluoride Glasses

2.5.1 Fluorozirconate Glasses

Fluorozirconate Glass Compositions

Glass	Composition (mol %)								
	ZrF_4	BaF_2	GdF_3	LaF_3	YF_3	AlF_3	ThF_4	LiF	NaF
ZBL	62	33	–	5	–	–	–	–	–
ZBG	63	33	4	–	–	–	–	–	–
ZBGA	61	32	4	–	–	3	–	–	–
ZBT	60	33	–	–	–	–	7	–	–
ZTL	60			7		–	23	–	–
ZBAN	58	15				6			21
ZBLA	57	34	–	5	–	4	–	–	–
ZBGA	60	32	4	–	–	4	–	–	–
ZBLAL	52	20	–	5	–	3	–	20	–
ZBLYAL	49	22	–	3	3	3	–	20	–
ZBLAN	56	14	–	6	–	4	–	–	20

Optical Properties

Glass type	Transmission range (μm)	Refractive index n_D	Abbe number ν_d	dn/dT (10^{-6}/K) 435.8 nm	dn/dT (10^{-6}/K) 1060 nm
ZBL	0.25–7.0	1.523	–	–	–
ZBT	0.32–6.8	1.53	–	–	–
ZBLA	0.29–7.0	1.521	62	–	–
ZBLAN	0.25–6.9	1.480	64	−14.5 (633 nm)	–

Mechanical Properties

Glass type	Density (g/cm^3)	Young's modulus E	Poisson's ratio μ	Hardness (Knoop)	Stress-optical coeff. K $(TPa)^{-1}$
ZBL	4.78	60	0.31	228	–
ZBT	4.8	60	0.28	250	–
ZBLA	4.61	60.2	0.25	235	–
ZBLAN	4.52	60	0.31	225	–

Thermal Properties

Glass type	Thermal expansion (10^{-6}/K)	Thermal conductivity (W/m K)	Specific heat (J/g K)	Transformation temperature (K)	Softening temperature (K)
ZBL	18.8	–	0.538	580	–
ZBT	4.3	–	0.511	568	723
ZBLA	18.7	–	0.534	588	–
ZBLAN	17.5	0.4	0.520	543	–

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2.5.2 Fluorohafnate Glasses

Fluorohafnate Glass Composition (mol %)

Glass	HfF_4	BaF_2	LaF_3	AlF_3	ThF_4
HBL	62	33	5	–	–
HBT	60	33	–	–	7
HBLA	58	33	5	4	–

Optical Properties

Glass type	Transmission range (μm)	Refractive index n_D	Abbe number ν_d	dn/dT (10^{-6}/K) 435.8 nm	dn/dT (10^{-6}/K) 1060 nm
HBL	0.25–7.3	1.498	–	–	–
HBT	0.22–7.7	1.53	–	–	–
HBLA	0.29–7.3	1.504	–	–	–

Mechanical Properties

Glass type	Density (g/cm^3)	Young's modulus E	Poisson's ratio μ	Hardness (Knoop)	Stress-optical coeff. K $(TPa)^{-1}$
HBL	5.78	55	0.3	228	–
HBT	6.2	55	0.3	250	–
HBLA	5.88	56	0.3	240	–

Thermal Properties

Glass type	Thermal expansion (10^{-6}/K)	Thermal conductivity (W/m K)	Specific heat (J/g K)	Transformation temperature (K)	Softening temperature (K)
HBL	18.3	–	0.413	605	–
HBT	6.0	–	0.428	593	–
HBLA	17.3	–	0.414	580	–

Data in the tables of Sections 2.5.1 and 2.5.2 are from the *Handbook of Optics, Vol. II* (McGraw-Hill, New York, 1995), chapter 33, and references cited therein.

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2.5.3 Other Fluoride Glasses

Fluoroberyllate Glasses

Glass	Composition (mol %)						
	BeF_2	MgF_2	CaF_2	BaF_2	AlF_3	LiF	KF
BF	100	–	–	–	–	–	–
BLK	60	–	–	–	–	20	20
BACK	49	–	14	–	10	–	27
BAMCBa	35	19	10	14	22	–	–

Properties of Fluoroberyllate Glasses

Glass	Density (g/cm^3)	Refractive index n_D	Nonlinear index (m^2/W)	Abbe number	Hardness (kg/mm^2)
BF	2.122	1.275	0.75	105	300
BACK	2.621	1.3459	1.03	96	215
BAMCBa	3.247	1.3538	1.14 (calc.)	~95	315

Barium Indium Fluoride Glasses

Glass	Composition (mol %)						
	BaF_3	InF_3	GaF_3	ZnF_2	YbF_3	ThF_4	ZrF_4
BIZnYbT	30	30	–	20	10	10	–
BlG	30	18	12	20	10	6	4

Aluminofluoride Glasses

	Composition (mol %)										
	AlF_3	BaF_2	CaF_2	YF_3	SrF_2	MgF_2	CdF_2	LiF	NaF	ZrF_4	PbF_2
YABC	40	20	20	20	–	–	–	–	–	–	–
CLAP	30.6	–	–	–	–	–	26.1	10	–	–	33.3
ABC	30.2	9.9	19.2	8.3	12.4	3.5	–	–	3.8	10.2	2.5

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2.6 Chalcogenide Glasses

Chalcogenide Glass-Forming Systems

System	Example glass (atomic %)
As-S	As 40, S 60
As-Se	As 40, Se 60
Ge-S	Ge 20, S 80
Ge-Se	Ge 20, Se 80
Ge-As-S	Ge 25, As 15, S 60
Ge-As-Se	Ge 33, As 12, Se 55
Ge-As-Te	Ge 10, As 20, Te 70
Ge-Se-Te	Ge 22, Se 20, Te 58
Ge-Sb-Se	Ge 28, Sb 12, Se 60
Ge-P-S	Ge 70, P 5, S 25
Ge-As-Se-Te	Ge 30, As 13, Se 27, Te 30

Refractive Indices of Chalcogenide Glasses

Glass (atomic %)	Refractive Index (n_λ), λ in μm							$[dn/dT]_\lambda$
	n_2	n_3	n_4	n_5	n_8	n_{10}	n_{12}	($10^{-5}K^{-1}$)
As40, S60	2.4268	2.4152	2.4116	2.4074	2.3937	2.3822	–	$[0.9]_5$
As40, Se60	–	–	–	–	2.7789	2.7789	2.7738	–
Ge20, Se80	–	–	–	–	2.4071	2.4027	2.3973	–
Ge25, As15, Se60	2.22	–	–	–	–	–	–	–
Ge10, As20, Se70	–	–	–	–	2.4649	2.4594	2.4526	–
Ge10, As30, Se60	–	–	–	–	2.6256	2.6201	2.6135	–
Ge10, As40, Se50	–	–	–	–	2.6108	2.6067	2.6016	
Ge33, As13, Se55	2.5310	2.5184	2.5146	2.5112	2.5036	2.4977	2.4902	$[7.2]_{10.6}$
Ge10, As20, Te70	–	–	–	3.55	–	–	–	–
Ge28, Sb12, Se60	–	2.6266	2.6210	2.6173	2.6088	2.6023	2.5942	$[9.1]_{10}$
Ge30, As13, Se27, Te30	–	2.8818	2.8732	2.8688	2.8610	2.8563	2.8509	$[15]_{10}$

Physical Properties of Chalcogenide Glasses

Glass (atomic %)	T_g (°C)	Thermal expansion (10^{-6}/°C)	Density (g/cm^3)	Hardness (kg/mm^2)	Young's modulus (G Pa)	Fracture toughness ($N\ mm^{-3/2}$)
As40, S60	180	21.4	3.15	109(K)	15.9	–
As40, Se60	178	21.0	4.62	–	–	–
Ge20, Se80	154	24.8	4.37	147(V)	–	–
Ge25, As15, Se60	425	12.8	3.00	200(K)	–	–
Ge10, As20, Se70	159	24.8	4.47	154(V)	16.5	6.7 ± 0.4
Ge10, As30, Se60	210	190	4.51	176(V)	18.0	7.1 ± 0.6
Ge10, As40, Se50	222	20.9	4.49	173(V)	15.9	7.4 ± 0.8
Ge 33, As13, Se55	362	12.0	4.40	170(K)	22.1	–
Ge10, As20, Te70	–	18.0	–	111(K)	–	–
Ge28, Sb12, Se60	277	13.5	4.67	159(K)	21.5	–
Ge30, As13, Se27, Te30	262	12.8	4.91	226(V)	–	–

K, Knoop; V, Vickers

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Chalcohalide Glass-Forming Systems

As-based systems	Ge-based systems	Te-based systems	Other systems
As-S-Cl	Ge-S-Br	Te-Cl	Sb-S-Br
As-S-Br	Ge-S-I	Te-Br	Sb-S-I
As-S-I	Ge-S-Ag-I	Te-S-Cl	Sb-Se-I
As-Se-Br	Ge-As-S-I	Te-S-Br	Si-S-Cl
As-Se-I	Ge-Se-Br	Te-S-I	Si-S-I
As-Se-In-I	Ge-Se-I	Te-Se-Cl	Si-Se-I
As-Te-Br	Ge-Te-I	Te-Se-Br	Cs-Al-S-Cl
As-Te-I		Te-Se-I	Cs-Ga-S-Cl
		Te-Se-As-I	

Properties of Chalcohalide Glasses

Glass (atomic %)	T_g (°C)	Thermal expansion (10^{-6}/°C)	Density (g/cm^3)	Hardness (kg/mm^2)	n_λ (λ in μm)
As 30, S 60, Br 10	120	–	3.1	110	–
As 30, Se 60, Br 10	70	–	4.33	110	–
As 30, Te 60, Br 10	95	–	4.92	110	–
As 40, S 50, Cl 10	145	46.7	2.62	71	–
As 30, S 60, Cl 10	122	49.0	4.26	40	–
Ge 30, S 60, Br 10	322	–	–	–	1.883 (0.63)
Ge 30, S 60, I 10	370	–	2.90	–	2.0 (0.63)
Te 60, Cl 40	82	31.0	4.63	–	–
Te 60, Br 40	73	–	–	–	–
Te 60, I 40	44	–	–	–	–
Te 50, Sl6.7, Cl 33.3	80	33.0	–	–	–
Te 50, Se16.7, Cl 33.3	81	–	4.2	–	–
Te 30, S 50, Cl 20	73	74	–	–	–
Te 30, S 50, Br 20	64	60	–	–	–
Te 50, S 16.7, Br 33.3	71	33	–	–	–
Te 50, Se 30, Br20	–	–	–	–	2.86 (10.6)
Te10, Se 70, I 20	53	44.6	4.6	–	–
Te 30, Se 25, I 45	49	–	–	–	–
Te 30, Se 30, I 40	48	62.7	5.0	–	2.80 (10.6)
Te 20, Se 30, As 40 I 10	120	–	4.71	–	2.87 (10.6)

Tables in Section 2.6 are from Bruce, A. J., Optical waveguide materials:glasses, *Handbook of Laser Science and Technology, Suppl. 2* (CRC Press, Boca Raton, FL, 1998), p. 691.

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2.7 Magnetooptic Properties

2.7.1 Diamagnetic Glasses

Verdet Constants and Dispersion of Commercial Diamagnetic Glasses[1]

$$V = \frac{\pi}{\lambda}\frac{n^2(\lambda)-1}{n(\lambda)}\left(A + \frac{B}{\lambda^2 - \lambda_0^2}\right)$$

Glass type[a]	n	V (633 nm) (rad/(m T))	λ_o (nm)	A (10^{-7} rad/T)	B (10^{-19} m^2 rad/T)
FK 3	1.4630	4.1	95.3	7.2702	1.3333
FK 5	1.4860	4.7	92.3	7.3531	1.2647
FK 51	1.4853	3.5	84.7	5.4805	1.2695
FK 52	1.4848	3.2	86.2	4.1070	1.6842
PK 2	1.5165	4.7	96.4	7.1672	1.5350
BK 3	1.4967	4.4	96.1	6.8316	1.5282
BK 7	1.5151	4.9	97.0	5.5387	2.1116
BaLKN3	1.5167	5.2	100.0	5.9938	2.2601
K 3	1.5164	5.2	101.0	1.2978	3.8205
BaK 50	1.5657	5.8	102.6	7.2536	1.9887
SK 16	1.6182	5.5	101.2	5.5302	2.1438
SSK N 5	1.6557	5.8	110.6	8.3749	1.2103
LaKN12	1.6753	6.1	106.5	6.7875	1.8439
LaKN14	1.6941	4.9	106.5	6.4470	1.0542
LF 3	1.5793	8.4	120.4	9.4425	3.4867
F 2	1.6166	10.8	129.7	11.1061	4.0872
FN 11	1.6175	2.6	130.1	1.2158	1.2041
F 13	1.6188	10.8	130.4	10.6164	4.3176
LaSFN31	1.8762	5.5	125.4	7.0445	0.5728
LaSF 32	1.7981	2.6	143.9	0.9594	0.9845
SF 1	1.7124	15.4	144.7	13.4192	5.4231
SF 2	1.6438	11.6	134.6	7.0169	5.7546
SF 6	1.7988	20.1	156.4	15.7116	6.3430
SF 14	1.7561	15.1	152.8	12.3008	4.9536
SF 18	1.7165	15.7	145.2	12.2097	5.8514
SF 53	1.7232	15.1	146.7	11.0378	5.8444
SF 57	1.8396	21.8	161.7	16.7417	6.7168
SF 58	1.9091	27.1	170.5	18.2033	7.7697
SF 59	1.9432	28.5	175.3	22.6382	6.8410
SFN 64	1.7011	1.5	142.8	0.7433	37.1043
TiK 1	1.4770	4.7	100.8	9.1198	1.4464
TiF 3	1.5450	2.3	119.9	5.9402	0.0959
TiF 6	1.6125	2.3	140.6	0.9432	1.0387
KzFSN 4	1.6105	7.9	117.8	8.7691	2.8597
LgSK 2	1.5840	6.1	100.6	8.2800	1.7067

[a]Schott glass designations. Similar glasses are available from other sources.

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Verdet Constants V of Noncommercial Diamagnetic Glasses

Glass type	Composition (wt %)	V (rad/(m T), wavelength (nm)) 442	633	700	853	1060	Ref.
B_2O_3	100 B_2O_3	–	3.77	–	–	–	2
Bi_2O_3	95 Bi_2O_3, 5 B_2O_3	–	–	25.0	14.8	9.6	3
PbO	95 PbO, 5 B_2O_3	–	–	27.1	17.8	9.1	3
	82 PbO, 18 SiO_2	–	–	22.3	13.1	7.9	3
	50 PbO, 15 K_2O, 35 SiO_2	–	–	9.3	5.8	3.1	3
Tl_2O	95 Tl_2O, 5 B_2O_3	–	–	26.7	17.8	9.3	3
	82 Tl_2O, 18 SiO_2	–	–	29.1	19.5	12.6	3
	50 Tl_2O, 15 K_2O	–	–	10.5	6.5	3.5	3
SnO	76 SnO, 13 B_2O3, 11 SiO_2	–	–	20.6	13.4	7.5	3
CdO	47.5 CdO, 52.5 P_2O_5	9.6	6.5	–	–	–	4
ZnO	36.4 ZnO, 63.6 P_2O_5	12.7	5.8	–	–	–	4
TeO_2	75 TeO_2, 25 Sb_2O_3	–	–	22.2	15.2	9.3	3
	88.9 TeO_2, 11.1 P_2O_5	57.1	22.2	–	–	6.5	3
	80 TeO_2, 20 $ZnCl_2$	–	–	21.3	13.4	7.3	3
	84 TeO_2, 16 BaO	–	–	16.2	11.9	8.4	3
	70 TeO_2, 30 WO_3	–	–	15.2	10.1	6.5	3
	20 TeO_2, 80 PbO	–	–	37.2	21.8	14.0	3
Sb_2O_3	25 Sb_2O_3, 75 TeO_2	–	–	22.2	15.2	9.3	3
	75 Sb_2O_3, 20 Cs_2O, 5 Al_2O_3	–	–	21.5	12.7	7.3	3
	75 Sb_2O_3, 10 Cs_2O, 10 Rb_2O, 5 Al_2O_3		–	22.7	15.2	8.7	3
ZrF_4	63.1 ZrF_4, 14.9 BaF_2, 7.2LaF_3, 1.9 AlF_3, 9.1 PbF_2, 3.8 LiF		3.1	–	–	–	2

Chalcogenide glasses	V (rad/(m T), wavelength (nm)) 500	633	700	1000	Ref.
As_2S_3	–	0.28	0.21	0.081	5,6
$As_{20}S_{80}$	0.22	0.12	0.093		6
As_2Se_3	–	–	–	0.110	6
As_{40} S_{57} Se_3	–	0.31	0.23		6
Ge_{20} $As_{20}S_{60}$	–	0.20	0.155		6

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Verdet Constants of SiO_2

λ(nm)	V (rad/T m)	Ref.	λ(nm)	V (rad/T m)	Ref.
254	29.8	7	500	7.2	8
410	11.0	8	578	4.35	9
436	7.68	9		4.40	11
	8.38	10	620	4.5	8
	8.12	11	633	3.67	11,12

Wavelength Dependence of Verdet Constants (300 K)

Glass type	V (rad/(m T))			
	435.8 nm	546.1 nm	632.8 nm	1060 nm
SF 59	69.8	37.2	25.9	8.1
SF 58	63.1	34.3	23.9	7.6
SF 57	52.4	28.8	20.1	6.7
SF 6	45.1	25.3	17.6	6.1
SF 1	34.9	19.8	13.7	4.9
SF 5	29.7	16.9	11.9	4.1
SF 2	27.1	15.4	11.1	3.8
F 2	24.2	13.7	9.9	3.5
BK 7	9.6	5.8	4.1	1.7

From Schott Optical Glass, Technical Information Optical Glass, Tl. No. 11.

Temperature Dependence of the Faraday Effect in Several Glasses[13,14]

Glass	V (rad/(m T))	Theory $\frac{1}{V_0}\frac{dV}{dT}$ (10–4/K)	Experiment $\frac{1}{V_0}\frac{dV}{dT}$ (10^{-4}/K)	Experiment $\frac{1}{(VL)_0}\frac{d(VL)}{dT}$ (10^{-4}/K)	α (10^{-6}/K)
SF-57	21.8	1.29	1.26 ± 0.08	1.35 ± 0.08	9.2
SiO2	3.7	0.81	0.69 ± 0.03	0.69 ± 0.03	0.55
BK-7	4.9	0.56	0.63 ± 0.06	0.71 ± 0.06	8.3

Values for 633 nm.

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2.7.2 Paramagnetic Glasses

Verdet Constants V of Paramagnetic Glasses (295 K)

Rare earth ion Host glass	Ion conc. (10^{21}/cm^3)	V (rad/(m T), wavelength (nm) 400	500	633	700	1064	Ref.
Ce^{3+}							
aluminoborate	8.33	–	–	–64	–	–	1
phosphate	6	–196[a]	–94.9	–50.3[b]	–38.4	–	2
silicophosphate	4.8	–169	–	39.9	–	–9.0	3
Pr^{3+}							
aluminoborate	6.64	–178	–	–	–	–	3
borate	9.2	–	–	–	–59.1	–17.5	4
lanthanum borate	5.0	–111[a]	–64.0	–	–	–	5
metaphosphate	3.32	–	–125[c]	–39.6[b]	–	–12.3	6
phosphate	5.3	–130	–76.0	–43.7[b]	–35.8	–	1
silicate	3.79	–	–	–[ ]	–20.9	–7.9	4
Eu^{3+}							
aluminoborate	4.1	–343	–86.7	–32.9[d]	–26.5		7
Tb^{3+}							
aluminosilicate	6.6	–	–	–73.6	–	–20.1	8
fluoroberyllate	2.92	–	–25.2[c]	–10.7	–	–2.9	6
fluorophosphate	4.72	–	–52.4[c]	–23.3	–	–5.4	6
lanthanum borate	5.5	–149[a]	–83.8	–48.6[b]	–	–	5
phosphate	5.4	–163[a]	–94.0	–55.3[b]	–43.6	–	2
Dy^{3+}							
aluminoborate	8.6	–271	–	–70.1	–	–	3
borate	5.8	–127[a]	–79.4	–46.3[b]	–	–	5
phosphate	6.2	–157[a]	–96.3	–57.3[b]	–46.3	–	2
silicate	3.46	–	–	–	–19.5	–9.3	4

[a] 405 nm, [b] 635 nm, [c] 442 nm, [d] 650 nm.

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Verdet Constants of Commercial Paramagnetic Glasses (295 K)

Glass type	V (rad/(m T), wavelength (nm)					
	325	**442**	**532**	**633**	**1064**	**Ref.**
Hoya FR-4 (discontinued) (cerium phosphate)	–	–82.6	–	–30.5	–8.4	9
Hoya FR-5 (terbium borosilicate)	–444	–174	–	–71.0	–20.6	9
Hoya FR-7 (terbium fluorophosphate)	–	–82.3	–	–34.9	–9.6	6
Kigre M-18 (terbium boroaluminosilicate)	–	–	–74.8	–	–20.6	10
Kigre M-24 (terbium boroaluminosilicate)	–	–	–88.2	–	–26.1	10
Kigre M-32 (terbium boroaluminosilicate)	–	–	–98.4	–	–29.0	10
Ownes-Illinois EY-1 (discontinued) (terbium silicate)	–273	–98	—	–41.9	–11.9	6
Ownes-Illinois EY-2(discontinued) (terbium silicate)	–	–	–	–	–11	6

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2.8 Electrooptic Properties

Electric-field-induced birefringence, the DC electrooptic Kerr effect, is given by

$$n = n_{||} - n_{\perp} = \lambda B E^2,$$

where λ is the wavelength in centimeters, E is the applied electric field strength in volts per centimeter, $n_{||}$ and $n_{\perp}$ are the refractive indices in the directions parallel and perpendicular to the electric field, and B is the Kerr constant in centimeters per volt squared. In terms of the third-order nonlinear susceptibilities [in electrostatic units (esu)],

$$\chi_{\text{eff}}(-\omega,\omega,0,0) = \chi^{(3)}_{1111} - \chi^{(3)}_{1122} = (9\lambda B n/24\pi)\ 10^4.$$

A positive electrooptic constant is obtained when the induced index change in the direction of the applied field is larger than the induced index change for the perpendicular direction. A negative sign for B implies that the major effect is a large decrease in the refractive index in the direction of the electric field.

DC Electrooptic Kerr Constants[1,2]

		n_D	ε	$B(10^{-14}$ m/V$^2)$
Commercial glasses:				
Schott	SF 6	1.805	15.7	0.08
Schott	SF 57	1.847	16	0.11
Schott	SF 58	1.918	18	0.16
Schott	SF 59	1.962	23	0.30
Schott	LASF 7	1.850	19	–0.22
Corning	8310	–	–	0.07
Corning	8363	1.94	20	0.2
Corning	8391	–	–	0.06
Corning	8393	–	–	0.08
Corning	8427	–	–	0.09
Corning	8463	1.97	–	0.36
Arsenic trisulfide	As_2S_3	2.48	–	8.7
Experimental glasses (mol %):				
40 SiO_2 - 60 PbO		2.06	–	0.38
60 SiO_2 - 40 Tl_2O		2.0	–	1.10
54 SiO_2 - 41 Tl_2O - 5 PbO		–	–	0.96
76 SiO_2 - 9 Tl_2O - 15 K_2O		–	–	0.30
73 SiO_2 - 14 K_2O - 13 Ta_2O_5		–	–	–0.57
85 TeO_2 - 7.5 BaO - 7.5 ZnO		2.17	–	0.7
60 TeO_2 - 20 BaO - 20 ZnO		2.02	–	0.5
36 TeO_2 - 51 PbO - 12 SiO_2		–	–	1.1
32 Tl_2O - 28 Bi_2O_3 - 40 GeO_2		–	1.15	

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DC Electrooptic Kerr Constants[1,2]—*continued*

	n_D	ε	$B(10^{-14}$ m/V$^2)$
57 PbO - 25 Bi_2O_3 - 18 Ga_2O_3	2.46	28.4	1.4
34 Nb_2O_5 - 36 SiO_2 - 30 Na_2O	–	–	2.80
70 PbO - 12 Ga_2O_3 - 6 Tl_2O - 12 CdO	2.31	21	1.6
57 PbO - 18 Bi_2O_3 - 18 Ga_2O_3 - 7 Tl_2O	2.30	25.5	1.4
48 PbO - 14 Bi_2O_3 - 10 Ga_2O_3 - 14 Tl_2O - 14 CdO	2.27	23	1.4
43 SiO_2 - 15.5 Li_2O - 11.5 K_2O - 4 Al_2O_3 - 31 Ta_2O_5	1.81	17.4	–0.8
20 SiO_2 - 20 B_2O_3 - 20 Na_2O - 20 Na_2O - 20 Nb_2O_5 - 20 TiO_2	1.93	15.3	–1.23
41 B_2O_3 - 10 ZnO - 11 La_2O_3 - 22 ThO_2 - 5Ta_2O_5 - 11 Nb_2O_5	1.94	–	–0.18
23 PbO - 22 SiO_2 - 11 MgO - 14 BaO - 16 TiO_2 - 4 Al_2O_3 - 8Nb_2O_5	–	22	–0.4
46 PbO - 42 Bi_2O_3 - 11 Ga_2O_3- 9 Tl_2O	2.46	29	1.4
46 PbO - 33 Bi_2O_3 - 12 Ga_2O_3 - 9 Tl_2O	2.31	26	1.2
71.6 PbO - 26.5 SiO_2 - 0.5 Na_2O - 0.9 K_2O - 0.5 As_2S_3	1.79	16	0.14
66.5 PbO - 28.1 SiO_2 - 3.4 TiO_2 - 0.5 Na_2O - 1.0 K_2O - 0.5 As_2S_3	1.84	16	0
54.2 PbO - 32.0 SiO_2 - 11.6 TiO_2 - 0.6 Na_2O - 1.1 K_2O - 0.5 As_2S_3	1.82	16	-0.22
71.6 PbO - 26.5 SiO_2 – 3.4 TiO_2 - 0.6 Na_2O - 1.2 K_2O - 0.5 As_2S_3	1.86	16	0.25

Measured at 633 nm.

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1. Hall, D. W. and Borrelli, N. F., Nonlinear optical properties of glasses, *Optical Properties of Glass*, Kreidl, N. and Uhlmann, D. R., Eds., American Ceramic Society (1991), pp. 87–125.
2. Borrelli, N.F., Aitken, B.G., Newhouse, M.A., and Hall, D.W., Electric-field induced birefringence properties of high refractive under glasses exhibiting large Kerr nonlinearaties, *J. Appl. Phys.* 70, 2774 (1991).

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2.9 Elastooptic Properties

The stress optic coefficients are defined as

$$K_p = dn_p/dP$$

and

$$K_s = dn_s/dP,$$

where the ordinary and extraordinary indices of refractive are designated n_S and n_P, respectively, according as the light polarization is perpendicular (*s*) or parallel (*p*) to the pressure vector. The elastooptic coefficients can be calculated from the experimentally determined values of the stress optic coefficients through the relations

$$p_{11} = 2E[2\mu K_s + (1 - \mu)K_p]/[n^3(2\mu - 1)(\mu + 1)]$$

and

$$p_{12} = 2E[\mu K_p + K_s]/[n^3(2\mu - 1)(\mu + 1)],$$

where *E* is the elastic modulus and μ is Poisson's ratio.

The elastooptic coefficients for several representative glasses are given below.

Glass	Wavelength (μm)	Elastooptic Coefficients			Ref.
		p_{11}	p_{12}	p_{44}	
fused silica (SiO_2)	0.633	0.121	0.270	-0.075	1
tellurite glass	0.633	0.257	0.241	0.0079	2
As_2S_3	1.15	0.308	0.299	0.0045	1
$Ge_{33}Se_{55}As_{12}$	1.06	0.21	0.21	—	1
LaSF	0.633	0.088	0.147	-0.030	3
SF4	0.633	0.215	0.243	-0.014	3
TaFd7	0.633	0.099	0.138	-0.020	3

1. Pinnow, D. A., Elasto-optical materials, *CRC Handbook of Lasers*, Pressley, R. J., Ed. (The Chemical Rubber Co., Cleveland, OH, 1971).
2. Yano, T., Fukomoto, A., and Watanabe, A., Tellurite glass: a new acousto-optic material, *J. Appl. Phys*. 42, 3671 (1971).
3. Eschler, H. and Weidinger, F., *J. Appl. Phys.*, 46, 65 (1975).

Two acoustooptic figures of merit, M_1 and M_2, are:

$$M_{1i} = n^7 p_{1i}/\rho v_1$$

and

$$M_{2i} = n^6 p_{1i}/\rho v^3{}_1.$$

A compilation of these properties for most of the optical glasses carried in the Schott Optical Glass Catalog is given in Modification of the refractive index of optical glass by tensile and compressive stresses, *Schott Technical Information TI No. 20*, 4/88 and in Gottlied, M. and Singh, N. B., Elastooptic materials, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 415.

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Elastooptic Properties of Schott Glasses

Glass type	$-K_p$ [a]	$-K_s$ [a]	P_{11}	P_{12}	M_{11} [b]	M_{12b}	M_{21} [c]	M_{22} [c]
FK 3	1.0	4.9	0.15	0.24	3	7	1	2
FK 5	0.9	3.8	0.14	0.23	2	6	1	1
FK 51	1.1	1.8	0.17	0.20	2	3	1	1
FK 52	1.1	1.8	0.16	0.19	2	3	1	1
FK 54	0.8	1.6	0.14	0.17	1	2	0	0
PK 1	0.8	3.9	0.14	0.25	2	7	0	1
PK 2	0.4	3.1	0.11	0.22	1	6	0	1
PK 3	0.5	3.1	0.11	0.21	2	6	0	1
PK 50	1.2	3.4	0.14	0.21	3	6	1	1
PK 51A	1.4	1.9	0.16	0.18	3	3	1	1
PSK 2	0.6	2.9	0.13	0.21	2	6	0	1
PSK 3	0.8	3.3	0.14	0.23	3	7	0	1
PSK 50	1.2	3.1	0.16	0.21	3	6	1	1
PSK 52	1.0	2.4	0.14	0.18	3	5	1	1
PSK 53A	1.5	2.6	0.17	0.20	5	6	1	1
BK 1	0.6	3.4	0.12	0.21	2	6	0	1
BK 3	0.5	3.8	0.12	0.24	2	7	0	1
BK 6	0.4	2.9	0.11	0.20	1	5	0	1
BK 7	0.5	3.3	0.12	0.22	2	6	0	1
UBK 7	0.5	3.3	0.12	0.23	2	6	0	1
BK 8	0.4	3.1	0.11	0.21	1	5	0	1
BK 10	0.7	3.9	0.13	0.24	2	7	0	1
BaLK 1	1.4	4.1	0.17	0.26	4	9	1	2
BaLK N3	0.7	4.0	0.13	0.24	2	8	0	2
K 3	1.2	4.1	0.16	0.26	3	9	1	2
K 4	0.8	3.5	0.12	0.21	2	6	0	1
K 5	0.6	3.7	0.13	0.23	2	7	0	1
K 7	0.7	3.8	0.12	0.23	2	7	0	1
K 10	1.4	4.6	0.15	0.26	3	8	1	2
K 11	1.1	4.1	0.14	0.24	2	7	1	2
K 50	0.5	3.7	0.12	0.23	2	7	0	1
UK 50	0.5	3.8	0.13	0.24	2	7	0	1
K 51	1.0	4.6	0.15	0.27	3	9	1	2
ZK 1	0.3	4.0	0.13	0.24	2	8	0	2
ZK 5	0.3	3.8	0.12	0.22	2	7	0	2

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Elastooptic Properties of Schott Glasses—*continued*

Glass type	$-K_p$ [a]	$-K_s$ [a]	P_{11}	P_{12}	M_{11} [b]	M_{12b}	M_{21} [c]	M_{22} [c]
ZK N7	0.3	3.8	0.11	0.23	2	7	0	1
BaK 1	0.7	3.2	0.13	0.20	2	6	1	1
BaK 2	1.0	3.6	0.14	0.22	3	7	1	2
BaK 4	0.5	3.2	0.12	0.21	2	6	0	1
BaK 5	0.9	3.6	0.15	0.23	3	7	1	2
BaK 6	0.8	3.2	0.14	0.21	3	6	1	1
BaK 50	0.0	3.0	0.11	0.21	2	6	0	1
SK 1	0.7	3.0	0.13	0.20	3	6	1	1
SK 2	0.8	3.0	0.14	0.20	3	6	1	1
SK 3	0.7	2.6	0.12	0.18	2	5	0	1
SK 4	0.6	2.5	0.12	0.18	2	5	0	1
SK 5	0.8	2.8	0.14	0.21	3	6	1	1
SK 6	0.7	3.0	0.14	0.20	3	6	1	1
SK 7	0.8	2.6	0.13	0.19	3	5	1	1
SK 8	0.8	3.1	0.14	0.21	3	7	1	2
SK 9	0.8	3.1	0.14	0.21	3	7	1	2
SK 10	0.8	2.6	0.13	0.19	3	5	1	1
SK 11	0.7	3.2	0.13	0.22	2	6	0	1
SK 12	0.5	2.8	0.11	0.19	2	5	0	1
SK 13	0.9	3.2	0.15	0.22	3	7	1	2
SK 14	0.8	2.6	0.13	0.19	3	5	1	1
SK 15	0.8	2.7	0.14	0.20	3	6	1	1
SK 16	1.0	2.8	0.16	0.22	4	7	1	1
SK N18	0.5	2.4	0.13	0.19	3	6	1	1
SK 19	1.0	2.8	0.14	0.20	3	6	1	1
SK 20	0.6	3.0	0.12	0.20	2	5	0	1
SK 51	1.1	2.7	0.15	0.20	4	6	1	1
SK 52	0.0	2.3	0.10	0.18	2	5	0	1
SK 55	0.2	2.2	0.10	0.17	1	4	0	1
KF 1	1.3	4.3	0.16	0.25	3	9	1	2
KF 3	0.8	3.8	0.13	0.22	2	6	0	1
KF 6	1.2	4.1	0.14	0.23	2	7	1	2
KF 9	1.4	4.5	0.16	0.25	3	9	1	2
KF 50	1.1	4.3	0.14	0.23	3	8	1	2
BaLF 3	0.8	3.9	0.15	0.24	3	8	1	2

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Elastooptic Properties of Schott Glasses—*continued*

Glass type	$-K_p$[a]	$-K_s$[a]	P_{11}	P_{12}	M_{11}[b]	M_{12b}	M_{21}[c]	M_{22}[c]
BaLF 4	0.2	3.3	0.11	0.20	2	6	0	1
BaLF 5	0.9	4.0	0.14	0.23	3	7	1	2
BaLF 6	0.4	3.1	0.11	0.19	2	6	0	1
BaLF 8	0.8	3.7	0.12	0.21	2	6	1	2
BaLF 50	0.6	2.9	0.12	0.19	2	5	0	1
BaLF 51	0.9	3.3	0.13	0.21	3	6	1	1
SSK 1	0.9	3.1	0.14	0.21	3	7	1	2
SSK 2	1.2	3.4	0.16	0.22	4	8	1	2
SSK 3	0.9	3.2	0.14	0.20	3	6	1	2
SSK 4	0.8	2.9	0.13	0.20	3	6	1	1
SSK N5	0.5	2.3	0.11	0.17	2	5	0	1
SSK N8	0.7	3.1	0.13	0.21	3	7	1	1
SSK 50	0.9	2.7	0.14	0.19	3	6	1	1
SSK 51	1.1	3.3	0.16	0.23	4	8	1	2
SSK 52	–	–	–	–	–	–	–	–
LaK N6	1.0	2.6	0.15	0.20	3	6	1	1
LaK .N7	0.6	2.1	0.11	0.16	2	4	0	1
LaK 8	0.1	1.9	0.10	0.16	2	5	0	1
LaK 9	0.3	2.0	0.11	0.17	2	5	0	1
LaK 10	0.1	2.0	0.10	0.16	2	5	0	1
LaK 11	0.5	2.3	0.12	0.17	2	5	0	1
LaK N12	0.8	2.3	0.13	0.17	3	5	1	1
LaK L12	0.0	1.6	0.07	0.13	1	3	0	0
LaK N13	1.2	2.5	0.15	0.19	4	6	1	1
LaK N14	0.2	2.0	0.10	0.17	2	5	0	1
LaK 16A	– 0.1	1.8	0.08	0.15	1	4	0	1
LaK 21	1.0	2.8	0.16	0.22	4	7	1	1
LaK L21	0.0	2.0	0.09	0.17	1	5	0	1
LaK N22	0.7	2.5	0.13	0.18	3	5	1	1
LaK 23	0.7	2.2	0.12	0.16	2	4	1	1
LaK 28	0.2	2.0	0.11	0.17	2	6	0	1
LaK 31	0.1	1.7	0.09	0.15	1	4	0	1
LaK 33	0.3	1.7	0.10	0.15	2	5	0	1
LLF 1	1.7	4.7	0.15	0.23	3	8	1	2
LLF 2	1.6	4.6	0.15	0.23	3	8	1	2

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Elastooptic Properties of Schott Glasses—*continued*

Glass type	$-K_p$ [a]	$-K_s$ [a]	P_{11}	P_{12}	M_{11} [b]	M_{12b}	M_{21} [c]	M_{22} [c]
LLF 3	1.4	4.2	0.15	0.23	3	8	1	2
LLF 4	1.5	4.5	0.15	0.24	4	9	1	2
LLF 6	1.5	4.7	0.15	0.25	3	8	1	2
LLF 7	1.5	4.6	0.14	0.23	3	8	1	2
BaF 3	0.8	3.8	0.12	0.20	2	6	1	2
BaF 4	1.3	3.9	0.14	0.21	3	7	1	2
BaF 5	1.3	4.0	0.17	0.24	4	9	1	2
BaF N6	1.3	3.8	0.16	0.24	4	9	1	2
BaF 8	0.8	3.1	0.12	0.19	3	6	1	1
BaF 9	0.8	2.9	0.13	0.19	3	6	1	1
BaF N10	0.7	2.7	0.14	0.20	3	7	1	1
BaF N11	0.4	2.3	0.11	0.16	2	5	0	1
BaF 12	0.7	2.9	0.12	0.19	3	6	1	1
BaF 13	1.1	2.9	0.15	0.20	4	7	1	2
BaF 50	0.9	2.7	0.14	0.19	3	7	1	1
BaF 51	0.2	2.4	0.09	0.16	2	5	0	1
BaF 52	0.8	3.1	0.12	0.19	3	6	1	1
BaF 53	0.3	2.5	0.10	0.17	2	5	0	1
BaF 54	0.5	2.3	0.11	0.16	2	5	0	1
LF 1	1.9	4.9	0.17	0.24	4	9	1	3
LF 2	1.9	4.6	0.16	0.23	4	9	1	3
LF 3	1.8	4.6	0.16	0.23	4	9	1	3
LF 4	1.5	4.6	0.14	0.22	3	8	1	2
LF 5	2.3	5.2	0.18	0.25	6	11	2	3
LF 6	1.9	4.8	0.16	0.23	4	9	1	3
LF 7	2.2	5.3	0.18	0.25	5	10	2	3
LF 8	2.1	5.1	0.18	0.25	5	10	1	3
F 1	2.7	5.4	0.18	0.23	6	11	2	4
F 2	2.4	5.2	0.17	0.23	5	10	2	3
F 3	2.3	5.2	0.17	0.23	5	10	2	3
F 4	2.3	5.2	0.16	0.22	5	9	2	3
F 5	2.0	4.9	0.15	0.22	4	9	1	3
F 6	2.6	5.1	0.17	0.22	6	10	2	3
F 7	2.7	5.6	0.19	0.25	7	12	2	4
F 8	1.8	4.9	0.16	0.23	4	9	1	3

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Elastooptic Properties of Schott Glasses—*continued*

Glass type	$-K_p$[a]	$-K_s$[a]	P_{11}	P_{12}	M_{11}[b]	M_{12b}	M_{21}[c]	M_{22}[c]
F 9	2.0	4.7	0.16	0.23	5	9	1	3
F N11	0.3	3.4	0.10	0.20	2	7	0	1
F 13	2.9	5.8	0.19	0.25	7	12	2	4
F 14	1.9	4.9	0.15	0.22	4	9	1	3
F 15	2.4	5.3	0.17	0.24	5	10	2	3
BaSF 1	1.4	4.1	0.14	0.20	3	7	1	2
BaSF 2	1.7	4.1	0.15	0.20	4	8	1	3
BaSF 5	1.8	4.2	0.15	0.21	4	8	1	2
BaSF 6	1.2	3.2	0.15	0.20	4	8	1	2
BaSF 10	1.6	3.8	0.15	0.21	4	8	1	2
BaSF 12	1.4	3.5	0.15	0.20	4	8	1	2
BaSF 13	1.1	2.9	0.13	0.18	4	7	1	2
BaSF 14	1.8	3.8	0.17	0.22	6	10	2	3
BaSF 50	0.9	3.1	0.13	0.19	4	7	1	2
BaSF 51	0.6	2.8	0.12	0.17	3	6	1	1
BaSF 52	0.3	2.6	0.11	0.17	2	6	0	1
BaSF 54	2.5	3.9	0.18	0.21	8	11	2	3
BaSF 55	1.3	3.5	0.15	0.20	5	8	1	2
BaSF 56	1.9	4.3	0.17	0.22	5	10	2	3
BaSF 57	1.2	3.2	0.14	0.19	3	7	1	2
BaSF 64	– 0.1	2.4	0.09	0.17	1	6	0	1
LaF 2	0.7	2.2	0.11	0.15	3	5	1	1
LaF 3	0.6	2.1	0.11	0.15	2	5	0	1
LaF N7	1.2	2.9	0.13	0.17	4	7	1	2
LaF N8	0.2	2.2	0.10	0.16	2	5	0	1
LaF 9	3.5	4.3	0.19	0.21	11	13	4	4
LaF N10	0.2	1.9	0.10	0.15	2	5	0	1
LaF 11A	2.6	4.1	0.18	0.21	8	11	2	3
LaF 13	1.2	2.6	0.15	0.18	5	8	1	2
LaF 20	0.8	2.6	0.14	0.19	3	7	1	1
LaF N21	0.1	1.4	0.07	0.12	1	3	0	0
LaF 22A	0.5	2.0	0.09	0.14	2	4	0	1
LaF N23	1.2	2.8	0.15	0.19	4	7	1	2
LaF N24	– 0.2	1.6	0.06	0.13	1	3	0	0
LaF 25	– 0.5	1.6	0.05	0.11	0	3	0	0

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Elastooptic Properties of Schott Glasses—*continued*

Glass type	$-K_p$[a]	$-K_s$[a]	P_{11}	P_{12}	M_{11}[b]	M_{12b}	M_{21}[c]	M_{22}[c]
LaF 26	0.1	2.1	0.09	0.14	2	4	0	1
LaF N28	0.1	1.4	0.07	0.12	1	3	0	0
LaSF 3	0.0	1.8	0.08	0.14	2	5	0	1
LaSF 8	2.0	3.5	0.17	0.21	8	12	2	3
LaSF N9	0.3	2.1	0.09	0.14	2	6	0	1
LaSF N15	0.3	1.5	0.08	0.11	2	4	0	1
LaSF N18	0.3	1.6	0.08	0.11	2	4	0	1
LaSF N30	0.3	1.7	0.10	0.14	2	5	0	1
LaSF N31	0.6	1.7	0.10	0.14	3	5	1	1
LaSF 32	– 0.1	2.3	0.07	0.14	1	6	0	1
LaSF 33	0.7	2.5	0.11	0.16	3	7	1	1
SF 1	4.5	6.2	0.22	0.25	12	16	5	6
SF 2	3.3	5.9	0.19	0.25	8	13	3	5
SF 3	4.4	6.0	0.20	0.23	11	15	5	6
SF 4	4.6	5.9	0.20	0.23	12	15	5	6
SF 5	3.1	5.4	0.18	0.22	7	11	3	4
SF 6	6.0	6.8	0.24	0.25	19	21	8	9
SF L6	0.2	3.0	0.09	0.16	3	8	0	1
SF 7	2.7	5.5	0.17	0.23	6	11	2	4
SF 8	3.6	5.9	0.19	0.24	9	13	3	5
SF 9	3.2	5.8	0.20	0.25	8	13	3	5
SF 10	3.6	5.6	0.20	0.24	10	15	3	5
SF 11	3.8	5.0	0.19	0.21	10	13	4	5
SF 12	2.8	5.3	0.18	0.24	7	12	2	4
SF 13	3.3	5.2	0.18	0.22	9	13	3	4
SF 14	3.8	5.4	0.20	0.23	11	15	4	5
SF 15	3.0	5.1	0.18	0.22	7	11	3	4
SF 16	3.3	6.0	0.20	0.25	8	13	3	5
SF 17	3.3	6.1	0.20	0.25	8	13	3	5
SF 18	4.1	5.9	0.20	0.23	11	14	4	6
SF 19	3.1	5.5	0.18	0.23	7	12	3	4
SF 50	–	–	–	–	–	–	–	–
SF 51	2.3	4.7	0.16	0.21	5	9	2	3
SF 52	3.5	5.7	0.20	0.24	9	14	3	5
SF 53	3.8	5.4	0.19	0.22	10	13	4	5

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Elastooptic Properties of Schott Glasses—*continued*

Glass type	$-K_p$ [a]	$-K_s$ [a]	P_{11}	P_{12}	M_{11} [b]	M_{12b}	M_{21} [c]	M_{22} [c]
SF 54	4.7	6.4	0.22	0.26	14	18	5	7
SF 55	4.3	5.7	0.20	0.22	11	14	5	6
SF 56	4.8	5.8	0.21	0.22	13	16	5	6
SF L56	0.0	2.8	0.07	0.15	2	6	0	1
SF 57	6.7	6.7	0.23	0.23	20	20	9	9
SF 58	8.2	7.2	0.24	0.23	29	26	14	13
SF 59	9.0	7.6	0.25	0.24	34	30	17	15
SF 61	4.5	6.0	0.21	0.23	12	15	5	6
SF 62	3.5	5.8	0.19	0.24	8	13	3	5
SF 63	4.2	5.8	0.20	0.22	11	14	4	6
SF N64	0.2	3.1	0.10	0.18	2	8	0	1
TiK 1	2.3	6.1	0.19	0.27	5	10	2	3
TiF 1	1.1	4.2	0.15	0.23	3	7	1	2
TiF 2	1.1	4.5	0.15	0.25	4	9	1	2
TiF 3	1.1	4.4	0.15	0.24	4	9	1	2
TiF 4	0.9	4.2	0.14	0.23	3	9	1	2
TiF N5	0.6	3.9	0.12	0.21	3	8	1	2
TiF 6	0.7	3.0	0.11	0.16	2	5	0	1
KzF N1	1.0	4.2	0.13	0.21	3	7	1	2
KzF N2	1.3	5.0	0.14	0.24	3	9	1	2
KzF 6	1.7	5.8	0.16	0.26	4	10	1	3
KzFS1	1.0	4.2	0.15	0.21	4	8	1	2
KzFS N2	0.1	3.8	0.12	0.23	2	8	0	2
KzFS N4	0.6	3.8	0.13	0.20	3	7	1	2
KzFS N5	0.7	3.4	0.12	0.18	3	7	1	2
KzFS 6	0.6	4.0	0.14	0.22	3	8	1	2
KzFS N7	0.6	3.1	0.12	0.18	3	7	1	1
KzFS 8	1.5	3.7	0.15	0.20	5	9	1	2
KzFS N9	0.4	3.5	0.12	0.20	2	7	1	2
LgSK 2	1.1	2.2	0.15	0.18	3	4	1	1

[a] 10^{-6} mm^2/N; [b] 10^{-7} cm^2 s/g; [c] 10^{-18} s^3/g.

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2.10 Nonlinear Optical Properties

2.10.1 Nonlinear Refractive Index*

Nonlinear refraction is commonly defined either in terms of the optical field intensity I

$$n = n_0 + \gamma I$$

or in terms of the average of the square of the optical electric field $\langle E^2 \rangle$

$$n = n_0 + n_2 \langle E^2 \rangle,$$

where n_0 is the ordinary linear refractive index, γ is the nonlinear refractive coefficient, and n_0 is the nonlinear refractive index. The conversion between n_2 and γ is given by

$$n_2[\text{cm}^3/\text{erg}] = (cn_0/40\pi)\,\gamma[\text{m}^2/\text{W}] = 238.7\, n_0\, \gamma[\text{cm}^2/\text{W}],$$

where c is the speed(in m/s) of light in vacuum. In terms of third-order susceptibility tensor $\chi^{(3)}(-\omega,\omega,\omega,-\omega)$ of a medium, the nonlinear refractive indices for a linearly polarized wave and for a circularly polarized wave in an isotropic material are

$$n_2(\text{LP}) = (12\pi/n_0)\,\chi^{(3)}{}_{1111}(-\omega,\omega,\omega,-\omega)$$

and

$$n_2(\text{CP}) = (24\pi/n_0)\,\chi^{(3)}{}_{1122}(-\omega,\omega,\omega,-\omega).$$

The two-photon absorption coefficient β is proportional to the corresponding imaginary part of $\chi^{(3)}(-\omega,\omega,\omega,-\omega)$. The relationship between n_2, β, and $\chi^{(3)}$ is analogous to the relationship between n_0, the linear absorption coefficient α, and the linear susceptibility χ.

The nonlinear refractive index is not a unique quantity for a given material because a number of physical mechanisms contribute to the polarization that is cubic in the applied optical electric field. The mechanisms that contribute most strongly to n_2, and their characteristic time scales (in parentheses) are bound electrons (10^{-15} s), optically created free carriers ($>10^{-12}$ s), Raman-active optical phonons (10^{-12} s), electrostriction ($>10^{-9}$ s), and thermal excitation ($\sim 10^{-9}$ s).

Several methods listed below have been employed to measure n_2. The details of the measurements determine the relative contributions from the various possible physical mechanisms to the measured n_2. In general, experiments done with picosecond pulses and nondegenerate mixing are less likely to be affected by the "slow" electrostrictive or thermal effects than those done in the nanosecond pulse regime and with degenerate mixing. Most of the measurements include the effects of both electronic and vibrational (Raman) contributions to n_2.

In the following tables values of the parameters in parentheses were calculated by Chase and Van Stryland[1] from the quantities reported in the original references. Refractive indices in parentheses were obtained from extrapolation of available data. For noncubic crystals, or for cubic crystals where the polarization is not along a cube axis or is not specified in the original reference, the value tabulated for $\chi^{(3)}{}_{1111}$ is an effective value of $\chi^{(3)}$.

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* This section was adapted from Chase, L. L., and Van Stryland, E. W., Nonlinear refractive index: inorganic materials, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 269.

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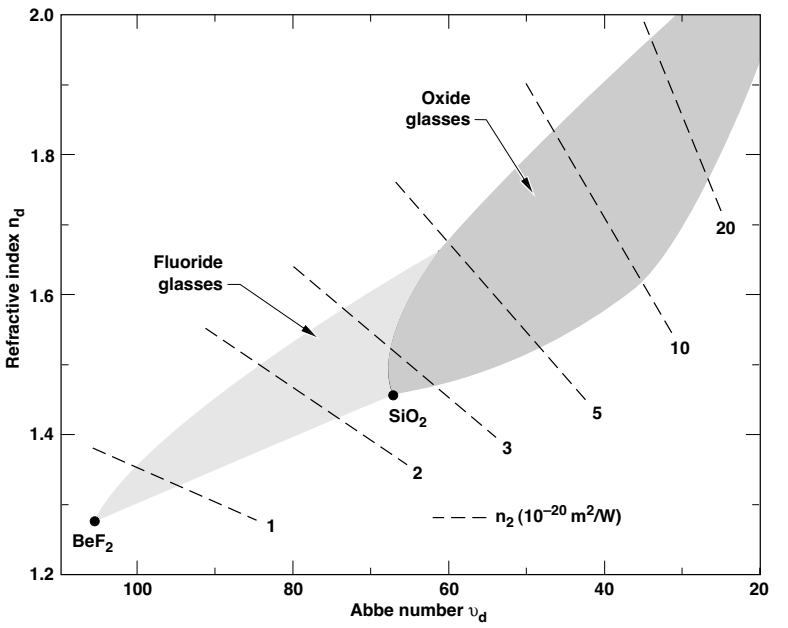
Techniques for Measuring the Nonlinear Refractive Index

	Method	Ref.
DFWM	Degenerate four-wave mixing	2
DTLC	Damage threshold for linear vs. circular polarization	3
ER	Ellipse rotation	4
NDFWM	Non-degenerate four-wave mixing	5, 6
OKE	Optical Kerr effect	7
PDF	Power-dependent focus	8
RSS	Raman scattering spectroscopy	9
SPM	Self-phase modulation	10
SSMG	Small-scale modulation growth	11
TII	Time-integrated interferometry	12
TRI	Time-resolved interferometry	13
TWM	Three-wave mixing	5
TWR	Temporal waveform reshaping	14

Boling, Glass, and Owyoung[15] derived an empirical formula relating n_2 at wavelengths much longer than the interband absorption to the linear refractive index and its dispersion. This formula for estimating n_2 is accurate to within about 25% for a wide range of crystals and glasses.[6,16] The equation is generally not applicable to chalcogenide glasses. Lines of constant n_2 predicted from this equation are plotted as a function of n_d and ν_d in the figure below and are superimposed on regions of known oxide and fluoride glasses.



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Measured Nonlinear Refractive Parameters of Glasses

Glass	Method	Pulse length (ns)	Wavelength (nm)	Refractive index	χ_{1111} (10^{-13} cm^{3}erg)	$n_{2,LP}$ (10^{-13} cm^{3}erg)	γ_{LP} (10^{-16} cm^2/W)	Ref.
Aluminate L-65	NDFWM	3	1064	(1.6637)	(.116)	2.64	(6.6)	16
Beryllium fluoride	TRI	0.15	1064	1.28	(0.0078)	0.26	(0.75)	17
Borate L-109	NDFWM	3	1064	(1.606)	(0.080)	1.88	(4.9)	16
Borosilicate BK-7	NDFWM	3	1064	(1.5168)	(0.052)	1.30	(3.59)	16
Borosilicate 517	DTLC	20	1064	1.51	(1.150)	1.24	(3.44)	3[a]
Borosilicate BK-7	ER	20	694	1.52	(0.056)	1.4	(3.86)	19[b]
Borosilicate BK-7	TRI	0.125	1064	1.52	(0.050)	1.24	3.43	13
Borosilicate BK-10	TRI	0.17	355	1.50	(0.024)	0.6	1.7	20
Borosilicate BSC	TWM	3	560,590	1.51	(0.092)	2.3	(6.4)	5
Borosilicate BSC-2	TWR	12.	694	(1.50)	(0.080)	2.0	(5.6)	21
Flint SF-55	DTLC	20	1064	1.73	(0.38)	8.3	(20.)	3
Fluoroberyllate:Nd	TRI	0.15	1064	1.34	(0.012)	0.33	(1.0)	17
Fluorophosphate E-115	NDFWM	3	1064	(1.4899)	(0.032)	0.80	(2.25)	16
Fluorophosphate E-131	NDFWM	3	1064	(1.4372)	(0.023)	0.61	(1.78)	16
Fluorophosphate E-132	NDFWM	3	1064	(1.4423)	(0.027)	0.70	(2.03)	16
Fluorophosphate E-133	NDFWM	3	1064	(1.4511)	(0.026)	0.68	(1.96)	16
Fluorophosphate K-1172	NDFWM	3	1064	(1.4364)	(0.025)	0.65	(1.90)	16
Fluorophosphate A86-82	TRI	0.125	1064	1.49	(0.028)	0.71	2.0	21
Fluorophosphate FK-51	TRI	0.125	1064	1.49	(0.027)	0.69	1.94	13
Fluorosilicate FC-5	TRI	0.125	1064	1.49	(0.042)	1.07	3.01	13
Fluorozirconate 9028	NDFWM	3	1064	(1.5314)	(0.049)	1.21	(3.31)	16
Gallate “RN”	DFWM	0.09	1064	2.48	4.2	(227)	(383)	22
Germanate Q-5	DFWM	0.09	1064	2.30	0.8	(15.7)	(29)	22
Germanate VIR-3	DFWM	0.09	1064	1.84	0.48	(9.66)	(22)	77

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Measured Nonlinear Refractive Parameters of Glasses—*continued*

Glass	Method	Pulse length (ns)	Wavelength (nm)	Refractive Index	χ_{1111} (10^{-13} cm^{3}erg)	$n_{2,LP}$ (10^{-13} cm^{3}erg)	γ_{LP} (10^{-16} cm^2/W)	Ref.
Phosphate:Ce FR-4	TRI	0.15	1064	(1.56)	(0.081)	1.95	(5.2)	23
Phosphate EV-1	TRI	0.125	1064	1.51	(0.036)	0.91	2.53	24
Phosphate LHG-5	NDFWM	3	1064	(1.51)	(0.058)	1.44	(4.0)	16
Phosphate:Nd LHG-5	TRI	0.125	1064	1.54	(0.047)	1.16	3.15	24
Phosphate LHG-6	NDFWM	3	1064	(1.53)	(0.045)	1.12	(3.07)	19
Posphate:Nd LHG-6	TRI	0.125	1064	1.53	(0.040)	1.01	2.76	24
Phosphate:Nd LHG-5	PDF	0.030	1064	1.54	(0.061)	1.5	(4.1)	25
Phosphate:Nd LHG-6	PDF	0.030	1064	1.53	(0.061)	1.5	(4.1)	25
Phosphate Q-88	NDFWM	3	1064	(1.5449)	(0.052)	1.27	(3.44)	16
Phosphate P-108	NDFWM	3	1064	(1.5312)	(0.052)	1.28	(3.50)	16
Phosphate 5037	NDFWM	3	1064	(1.5772)	(0.065)	1.56	(4.14)	16
Phosphate 5038	NDFWM	3	1064	(1.5915)	(0.072)	1.71	(4.50)	16
Silica (Dynasil 4000)	TRI	0.125	1064	1.46	(0.037)	0.95	2.73	13
Silica (fiber)	SPM	~0.15	514	(1.47)	(0.044)	1.14	(3.2)	10
Silica (Suprasil II)	TRI	0.17	355	1.50	(0.036)	0.9	2.5	20
Silica (Suprasil II)	SSMG	1.1	351	1.50	(0.024)	0.6	1.7	11
Silica, SiO_2	NDFWM	3	1064	(1.46)	(0.033)	0.85	(2.44)	16
Silica, SiO_2	OKE	10^{-4}	620	1.4519	0.024	0.62	(1.80)	26
Silica, SiO_2	TII	20	1064	(1.46)	0.044	(1.1)	(3.3)	27
Silica, SiO_2	TII/SPM/SS	0.004	249	(1.508)	(0.06–0.08)	1.5–2.0	(4.2–5.6)	28
Silica, SiO_2	PDF	0.17	308	(1.489)	(0.042)	(1.07)	3.0	29
Silica, SiO_2	ER	13	694	1.45	(0.039)	1.00	(2.88)	4
Silica, SiO_2	NDFWM	3	560,590	1.46	(0.070)	1.8	(5.2)	5
Silica, SiO_2	DTLC	20	1064	1.45	(0.036)	0.93	(2.7)	3[a]

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Silicate (Si-Nb-Ti-Na)	DFWM	0.08	1064	1.56–1.95	(0.072–0.97)	1.75–18.8	(4.7–40)	30
Silicate 8463	DFWM	0.09	1064	1.94	1.0	(19.4)	(42)	22
Silicate C835	TRI	~1	1064	1.50	(0.073)	1.83	(5.1)	31
Silicate C1020	TRI	~1	1064	1.50	(0.073)	1.83	(5.1)	31
Silicate C1020	RSS		647	1.51	(0.060)	1.5	(4.2)	9c
Silicate C-2828	NDFWM	3	1064	(1.5418)	(0.063)	1.54	(4.18)	16
Silicate C2828	TRI	~1	1064	1.53	(0.084)	2.08	(5.7)	31
Silicate E-0525	OKE	10^{-4}	620	1.8050	0.48	(10.0)	(23.)	26
Silicate E-1	DFWM	0.08	1064	1.93	(1.16)	(22.6)	49	2
Silicate ED-2	NDFWM	3	1064	(1.57)	(0.066)	1.58	(4.22)	16
Silicate ED-2	TRI	~1	1064	(1.57)	(0.064)	1.53	(4.1)	31
Silicate ED-2	TRI	0.125	1064	1.57	(0.059)	1.41	3.77	21
Silicate ED-2:Nd	TRI	0.125	1064	1.57	(0.059)	1.41	3.77	13
Silicate ED-2:Nd	RSS		647	(1.57)	(0.075)	1.8	(4.8)	9c
Silicate ED-2:Nd	TRI	0.15	1064	(1.57)	(0.063)	1.52	(4.1)	23
Silicate ED-3	NDFWM	3	1064	(1.5714)	(0.064)	1.53	(4.08)	16
Silicate ED-4	NDFWM	3	560,590	1.55	(0.011)	2.6	(7.0)	5
Silicate ED-4	PDF	0.030	1064	1.55	(0.086)	2.1	(5.7)	25
Silicate ED-4	ER	13	694	1.56	(0.072)	1.73	(4.6)	4
Silicate ED-8	NDFWM	3	1064	(1.6008)	(0.072)	1.69	(4.42)	16
Silicate EY-1	ER	13	694	1.61	(0.088)	2.06	(5.4)	32
Silicate EY-1	TRI	0.15	1064	(1.61)	(0.076)	1.77	(4.6)	3
Silicate FD-6	DFWM	0.08	1064	1.77	(0.61)	(13.1)	31	2
Silicate FD-60	DFWM	0.08	1064	1.77	(0.39)	(8.4)	20	2
Silicate FD-60	OKE	10^{-4}	620	1.8052	0.42	(8.77)	(20)	26
Silicate FDS-9	DFWM	0.08	1064	1.81	(0.46)	(9.5)	22	2
Silicate FR-5	NDFWM	3	1064			1.93		16
Silicate GLS-1	PDF	~1	1064			1.16		34

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Measured Nonlinear Refractive Parameters of Glasses—*continued*

Glass	Method	Pulse length (ns)	Wavelength (nm)	Refractive index	χ_{1111} (10^{-13} cm^{3}erg)	$n_{2,LP}$ (10^{-13} cm^{3}erg)	γ_{LP} (10^{-16} cm^2/W)	Ref.
Silicate La SF30	OKE	10^{-4}	620	1.8032	0.12	(2.51)	(5.83)	26
Silicate LG-650	NDFWM	3	1064	(1.5214)	(0.058)	1.44	(3.96)	16
Silicate K-8	TII	10	694		1.5			35
Silicate KGSS-1621	PDF	~1	1064			1.07		34
Silicate LGS-247	PDF	~1	1064			1.17	(3.25)	34
Silicate LSO	ER	13	694	1.51	(0.058)	1.44	(4.0)	4
Silicate Q-246	NDFWM	3	1064	(1.558)	(0.054)	1.31	(3.52)	16
Silicate "QR"	DFWM	0.09	1064	2.02	1.1	(20.7)	(43)	22
Silicate SF-56	DFWM	0.08	1064	1.75	(0.51)	(10.9)	26	2
Silicate SF-57	DFWM	0.08	1064	1.81	(0.85)	(17.7)	41	2
Silicate SF-57	OKE	10^{-4}	620	1.8467	0.51	(10.4)	(23.6)	26[d]
Silicate SF-58	DFWM	0.09	1064	1.88	0.52	(10.3)	(23)	22
Silicate SF-58	DFWM	0.08	1064	1.88	(1.10)	(22)	49	2
Silicate SF-59	DFWM	0.09	1064	1.91	0.75	(14.6)	(32)	22
Silicate SF-59	OKE	10^{-4}	620	1.9176	0.78	(15.3)	(33.5)	26[d]
Silicate SF-6	NDFWM	3	1064	(1.77)	(0.38)	8.0	(18.9)	16
Silicate SF-6	OKE	10^{-4}	620	1.8052	0.45	(9.40)	(21.8)	26[d]
Silicate SF-6	TRI	~1	1064	1.77	(0.42)	9.0	(21)	31
Silicate SF-7	ER	20	694	1.67	(0.093)	5.9	(15)	19[b]
Silicate:TB FR-5	TRI	0.125	1064			2.1	5.2	13
Silicate ZF-7	TII		532			0.7		35
Tellurite 3151	NDFWM	3	1064	2.05	(1.31)	24	(49)	16
Tellurite K-1261	NDFWM	3	1064	2.05	(1.25)	23	(47)	16

[a] total n_2; [b] electronic assumption; [c] also nuclear/electronic ratio; [d] low frequency assumption.

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2.10.2 Two-Photon Absorption

Two-Photon Absorption Data

Glass	Pulse width t_p (ns)	Band gap E_g (eV)	$2\hbar\omega$ (eV)	Index $n_0(\hbar\omega)$	2PA coeff. β (cm/GW)	Ref.
As_2S_3	~30	–	3.56	~2.58	14	1
As_2S_3	30	2.3	2.4–3.6	2.5–2.6	(a)	2
BK 3 (Schott)	1.2	4.4	4.67	–	0.0006	3
BK 7 (Schott)	1.1, 7	3.9	7.07	1.54	0.0060	4
BK 7 (Schott)	1.2	4.0	4.67		0.0029	3
BK 10 (Schott)	1.1, 7	4.1	7.07	1.52	0.0045	4
BK 10 (Schott)	1.2	4.5	4.67	–	0.0004	3
Holmium oxide	–	–	4.26–4.32	–	(b)	5
LG630:Nd (Schott)	0.006	–	2.33	–	0.004	6
Silica 7940 (Corning)	1.1, 7	7.8	7.07	~1.6	<0.0005	4
Silica (Suprasil)	0.017	7.8	6.99	~1.6	<0.0012	7
Silica (Suprasil)	0.015	7.8	9.32	~1.6	<0.045	7
Silica (Suprasil)	0.015	7.8	9.32	~1.6	0.017	8
Silica (Suprasil)	0.00045	7.8	10.0	~1.6	0.058	9
Silica (fused)	0.0007	7.8	10.0	~1.6	0.045	10
Silica (fused)	~10	–	12.8	–	0.11	11
Silica (fused)	0.008	–	10.0	~1.6	0.08	12
Silica (fused)	0.00028	7.8	10.0	~1.6	0.014	13
Silica (fused)	0.004	–	10.0	~1.6	0.06	14

(a) Relative spectrum, (b) Absorption spectrum (30 @ 3.1 eV)

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The preceding table was adapted from Van Stryland, E. W. and Chase, L. L., Two-photon absorption: inorganic materials, in *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 299.

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2.10.3 Third-Order Nonlinear Optical Coefficients

Glass	Nonlinear optical process	Coefficient C_{jn} x 10^{20} m^2 V^{-2}	Wavelength (μm)
BK–7	$(-\omega; \omega, \omega, -\omega)$	$C_{11} = 0.00257$	0.6943
Borosilicate	$(-2\omega_1+ \omega_2; \omega_1, \omega_1, -\omega_2)$	$C_{11} = 0.0018$	0.6943
ED–4 glass	$(-2\omega_1+ \omega_2; \omega_1, \omega_1, -\omega_2)$	$C_{11} = 0.01498 \pm 0.0011$	0.525
K-8	$(-\omega; \omega, \omega, -\omega)$	$C_{11} = 0.21 \pm 0.042$	0.6943
LaSF–7	$(-\omega; \omega, \omega, -\omega)$	$C_{11} = 0.014$	0.694
LSO-glass	$(-\omega; \omega, \omega, -\omega)$	$C_{11} = 0.0026$	0.694
SF–7	$(-\omega; \omega, \omega, -\omega)$	$C_{11} = 0.01108$	0.694
Silica, SiO_2	$(-2\omega_1+ \omega_2; \omega_1, \omega_1, -\omega_2)$	$C_{11} = 0.098$	0.6943
	$(-\omega; \omega, \omega,-\omega)$	$C_{18} = 0.0017$	0.694
		$C_{11} = 0.672 \pm 0.126$	0.6943
TF–7	$(-2\omega_1+ \omega_2; \omega_1, \omega_1, -\omega_2)$	$C_{11} = 0.42 \pm 0.098$	0.6943

Table adapted from Singh, S., Nonlinear optical materials, *Handbook of Laser Science and Technology, Vol. III: Optical Materials, Part 1* (CRC Press, Boca Raton, FL, 1986), p. 54.

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2.10.4 Brillouin Phase Conjugation

Glasses Used for Brillouin Phase Conjugation

Glass	Wavelength λ (nm)	Brillouin shift at λ (GHz)	Linewidth $\Delta\nu_B$ (MHz)	Gain g (cm/GW)	Ref.
Silica, SiO_2	1064		16	4.7, 5	1
			29–75(a)	2.5	2
			29	2.3	3
	532		43–162(b)	2.9	4
	488	25.18		4.48	5
Silicate glass	488	21.79–23.41	170–208	2.78–5.18	5
Borate glass	488	17.54–23.31	100–138	3.44–14.29	5
Halide glasses(c)					
ZBL	488	17.64	213.6	2.832	5
ZBLA	488	17.80	98.7	1.713	5
ZBLAN	488	18.82	96.0	3.608	5
HBL	488	15.83	151.4	1.127	5
HBLA	488	15.63	162.3	0.96	5
HBLAPC	488	17.82	179.5	1.023	5
BeF_2	488	17.19	52.5	16.06	5
$95BeF_2$-$5ThF_4$	488	17.61	74.8	11.54	5
$91BeF_2$-$9ThF_4$	488	19.33	42.8	12.44	5
$88BeF_2$-$12ThF_4$	488	18.40	21.3	24.69	5

(a) The authors report gain narrowing.
(b) The authors report the transverse and longitudinal linewidth, respectively.
(c) Gain calculated from the authors measurements of other parameters.

The above table was adapted from Pepper, D. M., Minden, M. L., Bruesselbach, H. W. and Klein, M. B., Nonlinear optical phase conjugation materials, in *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 467.

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2.11 Special Glasses

2.11.1 Filter Glasses

There are three general types of filter glasses: (1) colorless—optical glasses with different ultraviolet cutoffs, (2) ionically colored by heavy metal or rare earth ions, and (3) colloidically colored. The optical, thermal, and mechanical properties, chemical resistance, and internal quality of these glasses are carefully controlled and are generally similar to those of optical glasses. Manufacturer's catalogs should be consulted for specific transmission curves and transmittance. Several of the colored filter glasses exhibit photoluminescence [see W. H. Turner, Photoluminescence of color filter glasses, *Appl. Opt.* 12, 480 (1973) and tables later in this section].

Glass filters may be classified according to their optical properties—short wavelength cutoff, long wavelength cutoff, bandpass, band blocking, and neutral density. Filter glasses produced by major manufacturers are listed by groups in the following table.

Commercial Filter Glasses

	Corning			
	Glass no.	**C.S. no.**	**Hoya**	**Schott**
UV cutoff filters	7940 UV	9-57	—	—
(visible and IR transmitting)	7940	9-58	—	—
	7910	9-54	UV-22	WG-230
	7906	9-30	UV-28	WG-280
	7058	0-56	—	—
	—	—	UV-30	WG-395
	7740	0-53	—	WG-305
	—	—	UV-32	WG-320
	9754	9-56	UV-34	WG-335
	7953	9-55	—	WG-345
	7380	0-52	UV-36	WG-360
Near UV and visible cutoff filters	—	—	L-36	—
	—	—	L-38	GG-375
	3850	0-51	L-39	GG-385
	—	—	L-40	GG-395
	3060	3075		GG-400
	3391	3-74	L-42	GG-420
	—	3-144	—	—
	3389	3-73	L-44	GG-435
	3387	3-72	Y-46	GG-455
	—	—	Y-48	GG-475
	3385	3-71	Y-50	GG-495
	3384	3-70	Y-52	OG-515
	3486	3-69	O-54	OG-530
	3484	3-68	O-56	OG-550
	3482	3-67	—	—
	3480	3-66	O-58	OG-570

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Commercial Filter Glasses—*continued*

	Corning			
	Glass no.	**C.S. no.**	**Hoya**	**Schott**
Near UV and visible cutoff filters	2434	2-73	—	—
	2424	2-63	R-60	OG-590
	2418	2-62	—	RG-610
	2412	2-61	R-62	—
	2408	2-60	V	RG-630
	2404	2-59	—	—
	2403	2-58	R-64	RG-645
	2030	2-64	R-66	RG-665
			R-68	—
IR transmitting sharp cutoff filters	—	—	R-70	RG-695
	—	—	R-72	RG-715
	—	—	IR-76	—
	—	—	IR-80	RG-780
	—	—	IR-83	RG-830
	2550	7-57	IR-85	RG-850
	—	—	RM-86	—
	2563	7-99	RM-90	—
	2540	7-56	—	—
	—	—	RM-1000	RG-1000
	2600	7-69	—	—
UV transmitting, visible rejection	5970	7-51	B-370	UG-1
(variable IR transmission)	9863	7-54	U-330	UG-5
	—	—	U-340	UG-11
	5860	7-37	U-350	—
	5840	7-60	U-360	—
	5113	5-58	—	—
UV, IR transmitting, visible rejection	5073	7-64	M-30	UG-3
(blue-violet glass)	5071	7-63	M-50	—
	5330	1-64	B-380	BG-1
	5070	7-62	—	BG-1
	—	—	—	BG-3
	—	—	M-10	BG-24
	5030	5-57	M-30	—
	5113	5-58	M-50	—
	5850	7-59	—	—
	5874	7-39	—	—
	5031	5-56	B-410	—
Blue transmitting, red IR absorbing	5562	5-61	B-390	BG-12
	—	—	—	BG-25
	—	—	—	BG-37
	5900	1-62	LB-80	BG-34
	5900	1-62	LB-20	BG34

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Commercial Filter Glasses—*continued*

	Corning			
	Glass no.	**C.S. no.**	**Hoya**	**Schott**
Blue transmitting, red IR absorbing	5900	1-62	LB-40	BG-34
	5900	1-62	LB-60	BG34
	5900	1-62	LB-100	BG-34
	5900	1-62	LB-120	BG34
	5900	1-62	LB-145	BG-34
	5900	1-62	LB-165	BG34
	5900	1-62	LB-200	BG-34
	5433	5-59	B-430	—
	5543	5-60	B-440	—
	4308	4-70	—	BG-14
	4303	4-72	B-460	BG-23
	4305	4-71	—	BG-26
	—	—	B-480	BG-28
	—	—	—	BG-13
	4060	4-67	—	BG-7
	4-74	4-74	—	BG-7
Blue, green transmitting,	4309	4-39	CS-500	BG-38
red, IR absorbing	9788	4-97	C-500	—
	9782	4-96	CM-500	BG-39
	—	—	C-500	—
	—	—	CL-500	—
	—	—	CC-500	—
	—	—	—	BG-40
	9780	4-76	—	—
	4784	4-94	—	BG-18
Green transmitting	—	—	—	VG-4
	4015	4-65	—	VG-5
	5300	4-106	—	—
	—	—	—	VG-6
	—	—	G-530	—
	4010	4-64	G-5633	VG-9
	—	—	G-545	—
	—	—	G-550	VG-10
	—	—	—	VG-14
	—	—	—	GG-4
	—	—	—	GG-10
	4084	4-68	—	GG-19
	9830	4-77	—	—
IR absorbing, visible transmitting	3961	1-56	—	KG-1
	3962	1-57	—	KG-2
	3965	1-58	—	KG-3

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Commercial Filter Glasses—*continued*

	Corning			
	Glass no.	**C.S. no.**	**Hoya**	**Schott**
IR absorbing, visible transmitting	3966	1-59	HA-20	KG-4
	4605	1-75	HA-30	—
	—	—	HA-50	KG-5
IR transmitting, visible absorbing filters	2600	7-69	HA-60	RG-9
	2540	7-56	RT-830	RG-1000
	2550	7-57	RM-86	—
	—	—	RM-89	—
	—	—	RM-100	—
Neutral density filters	—	—	—	NG-1
	—	—	ND-03	NG-3
	—	—	ND-25	—
	8364	7-98	ND-40	NG-4
	—	—	ND-50	NG-5
	—	—		NG-9
	—	—	ND-13	
	3390	7-58	ND-0	NG-10
	—	—	ND-70	NG-4
	—	—	—	NG-12
Fluorescent color compensating filters	—	—	FLD-60	—
	—	—	FLW-85	—
Signal yellow and uranium yellow filters	3304	3-76	—	—
	3307	3-77	—	—
	3750	3-79	—	—
	3780	3-80	—	—
	3718	3-94	—	—
Color converion filters	5572	1-61	—	FG-3
	—	—	LA-20	—
	—	—		FG-6
	—	—	LA-40	FG-13
	—	—	LA-60	FG-15
	—	—		FG-16
	—	—	LA-80	—
	—	—	LA-100	—
	—	—	LA-120	—
	—	—	LA-140	—
	—	—	1-1B	—
Calibration filters	5121	1-60	—	—
	311	3-142	HY-1	—
	—	—	V-10	BG-20
	—	—	V-30	BG-36

Table from Cook, L. M. and Stokowski, S. E., Filter materials*, Handbook of Laser Science and Technology*, *Vol. IV, Optical Materials, Part 2* (CRC Press, Boca Raton, FL, 1986), p. 93.

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Fluorescence Data for Schott Filter Glasses

Filter type	Xenon-arc lamp		Mercury-arc lamp	
	Emission max. (nm)	Intensity relative to GG-17	Emission max. (nm)	Intensity relative to GG-17
UG-3	520	0.2	432	0.3
UG-10	515	2.7	450	1.4
BG-13	542	0.7	525	0.4
BG-14	522	1.9	490	0.8
BG-23	520	0.3	490	0.3
BG-38	520	4.1	505	2.8
BG-39	515	0.3	460	0.2
BG-39	480	0.1	510	0.2
BG-38	490	0.04	500	0.2
VG-3	515	0.5	520	0.05
VG-13	515	5.2	515	0.1
GG-17	532	100	532	100
GG-21	532	87	535	72
GG-375	432	2.5	460	0.5
GG-400	565	12.4	548	0.9
GG-420	570	30	575	4.1
GG-435	590	13	580	1.6
GG-455	620	30	580	1.7
GG-475	620	30	580	3.2
GG-495	630	19	590	1.9
OG-515	660	8.2	575	1.4
OG-530	670	4.5	585	0.4
OG-550	650	4.1	595	0.6
OG-570	670	2.1	605	0.6
OG-590	680	0.6	625	0.3
WG-9	440	21	460	0.6
WG-10	465	0.02	465	1.7
WG-230	540	0.03	420	1.6
WG-280	530	0.08	530	1.1
WG-295	515	0.08	525	1.0
WG-305	425	0.02	435	6.4
WG-320	430	0.2	455	2.8
WG-335	450	0.3	455	3.3
WG-345	460	0.1	500	0.5
WG-360	530	0.4	490	0.6
FG-1	555	0.05	610	0.2
FG-4	515	1.8	450	0.7
FG-5	515	0.9	460	0.5
FG-12	515	2.5	455	1.4
RG-610	660	0.6	660	0.2

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Fluorescence Data for Schott Filter Glasses—*continued*

Filter type	Xenon-arc lamp		Mercury-arc lamp	
	Emission max. (nm)	Intensity relative to GG-17	Emission max. (nm)	Intensity relative to GG-17
RG-630	660	0.8	660	0.18
RG-645	635	3.3	680	0.4
RG-665	690	0.3		
RG-695	710	0.08		
RG-715	680	1.0		

Fluorescence Data for Corning Filter Glasses

Filter number	Excitation wavelength (nm)	Emission peak (nm)	Fluorescence intensity
0-54	300	405	1.0
0-51	350	560	0.0031
0-52	345	420	0.286
0-53	225	420	0.077
3-75	350	560	0.0064
3-74	400	570	0.104
3-73	420	570	0.108
3-72	420	620	0.065
3-71	450	630	0.065
3-70	470	680	0.022
3-69	440	685	0.014
3-68	420	730	0.0024
3-67	440	735	0.0008
3-66	450	740	0.0005
2-73	450	740	0.0004
2-63	450	780	0.0003
2-62	450	780	0.0002
2-61	450	790	0.0002
3-79	300	535	1.513
3-94	400	535	0.098
4-69	345	510	0.0014
4-69	250	500	0.111
4-71	345	500	0.0059
9-30	250	390	0.314
9-54	250	395	0.154

Preceding two tables are from Cook, L. M. and Stokowski, S. E., Filter materials*, Handbook of Laser Science and Technology, Vol. IV, Optical Materials, Part 2* (CRC Press, Boca Raton, FL, 1986), p. 93.

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2.11.2 Laser Glasses

Compositions of commercial laser glasses are rarely published. Most current glasses are similar to the following:

- Silicate glasses of the Li_2O-CaO-SiO_2 or Li_2O-Na_2O-SrO-SiO_2 type. Examples of these glasses include the Schott LG-680, Kigre Q-246, and Hoya LSG-91H. These glasses generally have excellent physical properties and, because of their high Li_2O content, can be strengthened by ion exchange. Therefore, these glasses can be very resistant to thermal shock.
- Potassium-barium-phosphate glasses with a high cross section for stimulated emission. Examples of these glasses include Schott LG-760, Hoya LGH-80, and Kigre Q-98. These glasses are often modified with Na_2O, Li_2O, Al_2O_3, etc. to produce a glass with a near-zero optical distortion. Examples of these athermal glasses include Schott LG-LG-760, Hoya LGH-8, and Kigre Q-98.
- Lithium-aluminum-phosphate glasses with a relatively high thermal shock resistance for high average power applications. These glasses can usually be ion exchanged to further improve their resistance to breakage. Examples of these glasses include Schott APG-1 and Hoya HAP-4.
- Fluorophosphate glasses feature a low nonlinear refractive index which reduces spatial beam breakup due to small scale self-focusing. An example is Schott LG-810.

In addition to commercial laser glasses, a large number of different glasses have been used in experimental lasers. Below is a summary of the range of spectroscopic properties that have been obtained for the $^4F_{3/2}$–$^4I_{11/2}$ transition of Nd^{3+}. For additional data of glass lasers, see the *Handbook of Lasers* (CRC Press, Boca Raton, FL, 2000), p. 161.

Spectroscopic Properties for Nd^{3+} Observed in Different Glasses at 295 K

Host glass	Refractive index (n_d)	Cross section (pm^2)	Peak wavelength (μm)	Effective linewidth (nm)	Radiative lifetime (μs)
Oxides					
Silicate	1.46–1.75	0.9–3.6	1.057–1.088	34–55	170–1090
Germinate	1.61–1.71	1.7–2.5	1.060–1.063	36–43	300–460
Tellurite	2.0–2.1	3.0–5.1	1.056–1.063	26–31	140–240
Phosphate	1.49–1.63	2.0–4.8	1.052–1.057	22–35	280–530
Borate	1.51–1.69	2.1–3.2	1.054–1.062	34–38	270–450
Halides					
Beryllium fluoride	1.28–1.38	1.6–4.0	1.046–1.050	19–29	460–1030
Aluminum fluoride	1.39–1.49	2.2–2.9	1.049–1.050	28–32	540–650
Heavy metal fluoride	1.50–1.56	2.5–3.4	1.048–1.051	25–29	360–500
Chloride	1.67–2.06	6.0–6.3	1.062–1.064	19–20	180–220
Oxyhalides					
Fluorophosphate	1.41–1.56	2.2–4.3	1.049–1.056	27–34	310–570
Chlorophosphate	1.51–1.55	5.2–5.4	1.055	22–23	290–300
Chalcogenides					
Sulfide	2.1–2.5	6.9–8.2	1.075	21	64–100
Oxysulfide	2.4	4.2	1.075	28	92

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Properties of Hoya Laser Glasses

Glass designation	LHG-5	LHG-8	LHG-80
Glass type	**Nd-doped phosphate**	**Nd-doped phosphate**	**Nd-doped phosphate**
Lasing Properties			
Peak laser wavelength (nm)	1054	1054	1054
Stimulated emission cross section (pm^2)	4.1	4.2	4.8
Specific gain coefficient ($cm^{-1}/J/cm^3$)	0.217	0.223	0.255
Loss at lasing wavelength (cm^{-1})	0.0015	0.0015	0.0015
Fluorescence linewidth			
FWHM (nm)	22.0	21.8	20.2
Effective (nm)	–	–	–
Fluorescence lifetime (μs)	290	315	320
at $[Nd^{3+}]$ (10^{20} / cm^3)	3.2	3.1	3.1
Optical properties			
Refractive index at			
lasing wavelength (nm)	1.5308	1.5200	1.5329
633	1.5391	1.5279	1.5415
587 nm, n_d	1.5410	1.5296	1.5429
Abbe value	63.5	66.5	64.7
Nonlinear refractive index, n_2 (10^{-13} esu)	1.28	1.13	1.24
Temperature coefficient of refractive index, dn/dT (20–40°C) (10^{-6}/°C)	–0.4	–5.3	–3.8
Temperature coefficient of optical path length, w = CTE $(n-1)$ + dn/dT (20–40°C) (10^{-6}/°C)	4.2	0.6	1.8
Stress optical coefficient (nm/cm/kgf/cm^2)	2.26	1.93	1.77
Thermal Properties			
Coefficient of thermal expansion, dl/dT (10^{-6}/°C) (20–40°C)	8.4	11.2	10.2
(100–300°C)	9.8	12.7	13.0
Thermal conductivity (W/m K)	0.77	0.58	0.63
Specific heat (J/g K)	0.71	0.75	0.63
Glass transformation temperature, T_g (°C)	455	485	402
Other Properties			
Density (g/cm^3)	2.68	2.83	2.92
Young's modulus, E (kgf/mm^2)	6910	5110	5100
Poisson's ratio	0.237	0.258	0.267
Knoop hardness (kgf/mm^2)	429	350	342

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Properties of Hoya Laser Glasses—*continued*

Glass designation Glass type	LSG-91H Nd-doped silicate	HAP-4 Nd-doped phosphate	LEG-30 Er-doped phosphate
Lasing Properties			
Peak laser wavelength (nm)	1062	1054	1535
Stimulated emission cross section (pm^2)	2.7	3.6	0.77
Specific gain coefficient ($cm^{-1}/J/cm^3$)	0.144	0.197	–
Loss at lasing wavelength (cm^{-1})	0.0015	0.0015	–
Fluorescence linewidth			
FWHM (nm)	27.4	27.0	32.0
Effective (nm)	–	–	–
Fluorescence lifetime (μs)	300	350	8.7
at $[Nd^{3+}]$ (10^{20} / cm^3)	3.0	3.2	–
Optical properties			
Refractive index at			
lasing wavelength (nm)	1.5498	1.5331	1.527
632.8 nm	1.5590	1.5416	1.5402
587 nm, n_d	1.5611	1.5433	1.5419
Abbe value	56.6	64.6	65.4
Nonlinear refractive index, n_2 (10^{-13} esu)	1.58	1.25	1.22
Temperature coefficient of refractive index, dn/dT			
(20–40°C) (10^{-6}/°C)	1.6	1.8	–3.0
Temperature coefficient of optical path length,			
w = CTE $(n-1) + dn/dT$ (20–40°C) (10^{-6}/°C)	6.6	5.7	2.2
Stress optical coefficient (nm/cm/kgf/cm^2)	2.16	2.44	–
Thermal Properties			
Coefficient of thermal expansion, dl/dT (10^{-6}/°C)			
(20–40°C)	9.0	7.2	9.6
(100–300°C)	10.5	8.5	10.9
Thermal conductivity (W/m K)	1.03	1.02	–
Specific heat (J/g K)	0.63	0.71	0.55
Glass transformation temperature, T_g (°C)	465	486	515
Other Properties			
Density (g/cm^3)	2.81	2.70	3.09
Young's modulus, E (kgf/mm^2)	8890	7020	5640
Poisson's ratio	0.237	0.236	0.26
Knoop hardness (kgf/mm^2)	590	470	346

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Properties of Kigre Laser Glasses

Glass designation	**Q-88**	**Q-98**	**Q-100**
Glass type	**Nd-doped phosphate**	**Nd-doped phosphate**	**Nd-doped phosphate**
Lasing Properties			
Peak laser wavelength (nm)	1054	1053	1054
Stimulated emission cross section (pm^2)	4.0	4.5	4.4
Specific gain coefficient ($cm^{-1}/J/cm^3$)	–	–	–
Loss at lasing wavelength (cm^{-1})	0.0008	0.0008	0.0008
Fluorescence linewidth			
FWHM (nm)	21.9	21.1	21.2
Effective (nm)	26.3	25.5	25.1
Fluorescence lifetime (μs)	326	308	357
at $[Nd^{3+}]$ (10^{20} / cm^3)	–	–	–
Optical properties			
Refractive index at			
lasing wavelength (nm)	1.504	1.516	1.508
632.8 nm	1.513	1.524	1.514
587 nm, n_D	1.515	1.526	1.519
Abbe value	67.5	68.2	69.2
Nonlinear refractive index, n_2 (10^{-13} esu)	1.08	1.08	1.02
Temperature coefficient of refractive index, dn/dT (20–40°C) (10^{-6}/°C)	–3.2	–5.1	–6.8
Temperature coefficient of optical path length, w = CTE $(n-1) + dn/dT$ (20–40°C) (10^{-6}/°C)	2.3	0.8	–0.4
Stress optical coefficient (nm/cm/kgf/cm^2)	2.1	1.8	2.0
Thermal Properties			
Coefficient of thermal expansion dl/dT			
(10^{-6}/°C) (20–40°C)	10.9	11.4	12.5
(100–300°C)	–	–	–
Thermal conductivity (W/m K)	0.69	0.52	0.60
Specific heat (J/g K)	0.84	0.72	0.75
Glass transformation temperature, T_g (°C)	458	450	350
Other Properties			
Density (g/cm^3)	2.63	2.83	2.60
Young's modulus, E (kgf/mm^2)	6181	5110	5477
Poisson's ratio	0.243	0.256	0.267
Knoop hardness (kgf/mm^2)	320	290	310

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Properties of Kigre Laser Glasses—*continued*

Glass designation	**Q-246**	**MM-2**	**QE-7S**
Glass type	**Nd-doped phosphate**	**Er-doped phosphate**	**Er-doped phosphate**
Lasing Properties			
Peak laser wavelength (nm)	1054.5	1535	1.535
Stimulated emission cross section (pm^2)	3.5	0.8	0.8
Specific gain coefficient ($cm^{-1}/J/cm^3$)	0.186	–	–
Loss at lasing wavelength (cm^{-1})	0.0015	–	0.002
Fluorescence linewidth			
FWHM (nm)	23.0	55	30
Effective (nm)	26.65		
Fluorescence lifetime (μs)	350	7900	8000
at $[Nd^{3+}]$ (10^{20} / cm^3)	2.0	–	–
Optical properties			
Refractive index at			
lasing wavelength (nm)	1.526	1.53	1.531
632.8 nm	1.535	–	–
587 nm, n_D	1.537	1.54	1.542
Abbe value	67.7	–	–
Nonlinear refractive index, n_2 (10^{-13} esu)	1.13	–	–
Temperature coefficient of refractive index, dn/dT (20–40°C) (10^{-6}/°C)	1.2	-3.8	6.3
Temperature coefficient of optical path length, w = CTE (n–1) + dn/dT (20–40°C) (10^{-6}/°C)	5.2	3.3	0.3
Stress optical coefficient (nm/cm/kgf/cm^2)	2.2	2.1	
Thermal Properties			
Coefficient of thermal expansion dl/dT			
(10^{-6}/°C) (20–40°C)	7.6	7.3	11.4
(100–300°C)	–	8.4	–
Thermal conductivity (W/m K)	0.83	0.85	0.82
Specific heat (J/g K)	0.84		0.80
Glass transformation temperature, T_g (°C)	450	506	462
Other Properties			
Density (g/cm^3)	2.64	2.70	2.94
Young's modulus, E (kgf/mm^2)	7242	7100	7210
Poisson's ratio	0.239	0.24	0.24
Knoop hardness (kgf/mm^2)	315	435	556

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Properties of Kigre Laser Glasses—*continued*

Glass designation	**QX/Nd**	**QX/Er**	**QX/Yb**
Glass type	**Nd-doped phosphate**	**Nd-doped phosphate**	**Nd-doped phosphate**
Lasing Properties			
Peak laser wavelength (nm)	1054	1535	1025-1060
Stimulated emission cross section (pm^2)	3.8	0.8	1.4
Specific gain coefficient ($cm^{-1}/J/cm^3$)	–	–	–
Loss at lasing wavelength (cm^{-1})	–	–	–
Fluorescence linewidth	–	–	–
FWHM (nm)	27.2	55.0	56.5
Effective (nm)	–	–	–
Fluorescence lifetime (μs)	353	7900	2000
at $[Nd^{3+}]$ (10^{20} / cm^3)	–	–	–
Optical properties			
Refractive index at			
lasing wavelength (nm)	1.53	1.521	1.52
632.8 nm	–	–	–
589.3 nm, n_D	1.538	1.538	1.535
Abbe value	66.0	64.5	61.1
Nonlinear refractive index, n_2 (10^{-13} esu)	1.17	1.22	1.22
Temperature coefficient of refractive index dn/dT (20–40°C) (10^{-6}/°C)	–0.4	0	0
Temperature coefficient of optical path length, w = CTE $(n-1)$ + dn/dT (20–40°C) (10^{-6}/°C)	5.1	3.3	3.3
Stress optical coefficient (10^{-6} mm^2/N)	2.1	2.3	2.3
Thermal Properties			
Coefficient of thermal expansion dl/dT			
(10^{-6}/°C) (20–40°C)	7.2	8.2	8.3
(20–100°C)	8.4	9.4	9.5
Thermal conductivity (W/m K)	0.85	0.85	0.85
Specific heat (J/g K)	–	–	–
Glass transformation temperature, T_g (°C)	–	–	–
Other Properties			
Density (g/cm^3)	2.66	2.90	2.81
Young's modulus, E (10^3 N/ mm^2)	7100	6700	6700
Poisson's ratio	0.24	0.24	0.24
Knoop hardness (kgf/mm^2)	503	435	435

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Properties of Schott Laser Glasses

Glass designation	LG-700	LG-750	LG-760
Glass type	**Nd-doped phosphate**	**Nd-doped phosphate**	**Nd-doped phosphate**
Lasing Properties			
Peak laser wavelength (nm)	1053	1053.5	1053.5
Stimulated emission cross section (pm^2)	3.7	4.0	4.2
Specific gain coefficient ($cm^{-1}/J/cm^3$)	0.195	0.212	0.223
Loss at lasing wavelength (cm^{-1})	0.0015	0.0020	–
Fluorescence linewidth			
FWHM (nm)	22.3	21.5	19.6
Effective (nm)	26.6	25.5	23.6
Fluorescence lifetime (μs)	350	360	350
at $[Nd^{3+}]$ (10^{20} / cm^3)	2.0	2.0	2.0
Optical properties			
Refractive index at			
lasing wavelength (nm)	1.504	1.516	1.508
632.8 nm	1.513	1.524	1.514
587 nm, n_d	1.515	1.526	1.519
Abbe value	67.5	68.2	69.2
Nonlinear refractive index, n_2 (10^{-13} esu)	1.08	1.08	1.02
Temperature coefficient of refractive index dn/dT (20–40°C) (10^{-6}/°C)	–3.2	–5.1	–6.8
Temperature coefficient of optical path length, w = CTE $(n-1)$ + dn/dT (20–40°C) (10^{-6}/°C)	2.3	0.8	–0.4
Stress optical coefficient (nm/cm/kgf/cm^2)	2.1	1.8	2.0
Thermal Properties			
Coefficient of thermal expansion dl/dT			
(10^{-6}/°C) (20–40°C)	10.9	11.4	12.5
(100–300°C)	–	–	–
Thermal conductivity (W/m K)	0.69	0.52	0.60
Specific heat (J/g K)	0.84	0.72	0.75
Glass transformation temperature, T_g (°C)	458	450	350
Other Properties			
Density (g/cm^3)	2.63	2.83	2.60
Young's modulus, E (10^3 N/mm^2)	6181	5110	5477
Poisson's ratio	0.243	0.256	0.267
Knoop hardness (N/mm^2)	320	290	310

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Properties of Schott Laser Glasses–*continued*

Glass designation Glass type	LG-660 Nd-doped silicate	LG-670 (ED-2) Nd-doped silicate	LG-680 (ED-3) Nd-doped silicate
Lasing Properties			
Peak laser wavelength (nm)	1057	1061	1061
Stimulated emission cross section (pm^2)	2.0	2.7	2.9
Specific gain coefficient ($cm^{-1}/J/cm^3$)	0.106	0.144	0.155
Loss at lasing wavelength (cm^{-1})	0.002	<0.003	0.002
Fluorescence linewidth			
FWHM (nm)	24.9	27.8	28.2
Effective (nm)	33.3	34.4	34.7
Fluorescence lifetime (μs)	480	330	≥350
at $[Nd^{3+}]$ (10^{20} / cm^3)	1.4	1.4	2.0
Optical properties			
Refractive index at			
lasing wavelength (nm)	1.509	1.561	1.560
632.8 nm	1.517	1.570	1.568
587 nm, n_d	1.519	1.572	1.570
Abbe value	58.2	57.5	57.7
Nonlinear refractive index, n_2 (10^{-13} esu)	1.34	1.41	1.6
Temperature coefficient of refractive index			
dn/dT (20–40°C) (10^{-6}/°C)	1.1	2.9	2.9
Temperature coefficient of optical path length,			
w = CTE $(n-1)$ + dn/dT (20–40°C) (10^{-6}/°C)	6.5	8.0	8.1
Stress optical coeff. (546 nm) (nm/cm/N/mm^2)	29	21.0	20
Thermal Properties			
Coefficient of thermal expansion dl/dT			
(10^{-6}/°C) (20–40°C)	10.7	9.26	9.3
(100–300°C)	12.2	10.3	–
Thermal conductivity (W/m K)	1.05	1.35	1.35
Specific heat (J/g K)	0.72	0.92	0.92
Glass transformation temperature, T_g (°C)	395	468	468
Other Properties			
Density (g/cm^3)	2.60	2.54	2.54
Young's modulus, E (10^3 N/mm^2)	69.4	90.1	9190
Poisson's ratio	0.233	0.242	0.242
Knoop hardness (N/mm^2)	4415	5876	599

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Properties of Schott Laser Glasses—*continued*

Glass designation **Glass type**	**APG-1** **Nd-doped phosphate**	**LG-810** **Nd-doped fluoro-phosphate**	**LG-812** **Nd-doped fluoro-phosphate***
Lasing Properties			
Peak laser wavelength (nm)	1054.5	1051	1051
Stimulated emission cross section (pm^2)	3.5	2.6	2.7
Specific gain coefficient ($cm^{-1}/J/cm^3$)	0.186	0.138	0.15
Loss at lasing wavelength (cm^{-1})	0.0015	<0.002	0.005
Fluorescence linewidth			
FWHM (nm)	23.0	26.1	22
Effective (nm)	26.65	31.0	–
Fluorescence lifetime (µs)	350	470	400
at $[Nd^{3+}]$ ($1020 / cm^3$)	2.0	1.4	2.86
Optical properties			
Refractive index at			
lasing wavelength (nm)	1.526	1.429	1.428
632.8 nm	1.535	1.434	–
587 nm, nd	1.537	1.435	1.435
Abbe value	67.7	91	91.0
Nonlinear refractive index, n^2 (10^{-13} esu)	1.13	0.52	0.5
Temperature coefficient of refractive index			
dn/dT (20–40°C) (10^{-6}/°C)	1.2	−7.7	−7.7
Temperature coefficient of optical path length,			
w = CTE $(n - 1)$ + dn/dT (20–40°C) (10^{-6}/°C)	5.2	−1.4	−1.4
Stress optical coeff. (546 nm) ($nm/cm/N/mm^2$)	2.2	9.3	9.3
Thermal Properties			
Coefficient of thermal expansion dl/dT			
(10^{-6}/°C) (20–40°C)	7.6	14.5**	14.5**
(100–300°C)	–	16.5	–
Thermal conductivity (W/m K)	0.83	1.06	1.06
Specific heat (J/g K)	0.84	0.71	0.71
Glass transformation temperature, T_g (°C)	450	395	401
Other Properties			
Density (g/cm^3)	2.64	3.19	3.19
Young's modulus, E (10^3 N/mm^2)	7242	75.3	75.3
Poisson's ratio	0.239	0.275	0.275
Knoop hardness (N/mm^2)	315	3237	330

* Properties are not final.
** −30–+70°C

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2.11.3 Faraday Rotator Glasses

Diamagnetic Glasses

The Verdet constant of diamagnetic glasses is proportional to the dispersion of the refractive index, dn/dλ. Thus high index, large dispersion glasses are generally used for Faraday rotation applications. Data for representative diamagnetic glasses are given below.*

	Wavelength (nm)				
Schott BK 7	**435.8**	**480.0**	**546.1**	**632.8**	**1060**
Verdet constant, V(rad/T m)	9.6	7.6	5.8	4.1	1.7
Loss coefficient, α (cm^{-1})	0.0017	—	0.0016	—	—
Index of refraction, n	1.5267	1.5228	1.5187	1.5151	1.5067

	Wavelength (nm)				
Schott SF 6	**435.8**	**480.0**	**546.1**	**632.8**	**1060**
Verdet constant, V(rad/T m)	48.1	34.9	25	18	6.1
Loss coefficient, α (cm^{-1})	0.024	0.008	0.002	—	—
Index of refraction, n	1.8470	1.8297	1.8126	1.7988	1.7738

	Wavelength (nm)				
Schott SF 57	**435.8**	**480.0**	**546.1**	**632.8**	**1060**
Verdet constant, V(rad/T m)	52.4	39.6	29	20	6.7
Loss coefficient, (cm^{-1})	0.0205	—	0.002	0.002	0.002
Index of refraction, n	1.8939	1.8742	1.8550	1.8396	1.8118

	Wavelength (nm)				
Schott SF 59	**435.8**	**480.0**	**546.1**	**632.8**	**1060**
Verdet constant, V(rad/T m)	69.8	—	37.2	25.9	8.1
Loss coefficient, α (cm^{-1})	—	—	—	—	—
Index of refraction, n	2.0156	1.9890	1.9635	1.9432	1.9078

	Wavelength (nm)				
As_2S_3	**435.8**	**480.0**	**546.1**	**632.8**	**1060**
Verdet constant, V(rad/T m)	86.7	56.4	38.7	19	13
Loss coefficient, α (cm^{-1})	—	—	—	—	—
Index of refraction, n	2.636	2.562	2.521	2.465	2.448

* Schott glass designations. Similar glasses are available from other sources.

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Paramagnetic Glasses

Data from manufacturer's data sheets.

	Wavelength (nm)			
Hoya FR 4 (discontinued)	**325**	**442**	**632.8**	**1064**
Verdet constant, V(rad/T m)	—	–82.6	–30.5	–8.4
Loss coefficient, α (cm^{-1})	—		0.00597	0.0054
Index of refraction, n	—	1.584	1.570	1.561

	Wavelength (nm)			
Hoya FR 5	**325**	**442**	**632.8**	**1064**
Verdet constant, V(rad/T m)	–444	–174	–71.0	–20.6
Loss coefficient, α (cm^{-1})	—	—	0.0291	0.0086
Index of refraction, n	1.731	1.701	1.684	1.673

	Wavelength (nm)			
Hoya FR 7	**325**	**442**	**632.8**	**1064**
Verdet constant, V(rad/T m)	—	–82.3	–34.9	–9.6
Loss coefficient, α (cm^{-1})	—	—	—	—
Index of refraction, n	—	1.540	1.530	1.524

	Wavelength (nm)			
Kigre M-18	**543.1**	**632.8**	**830.0**	**1064**
Verdet constant, V(rad/T m)	–103	–70.9	–37.9	–21.3
Loss coefficient, α (cm^{-1})	—	—	—	—
Index of refraction, n	—	1.6845 (n_D)	—	1.664

Verdet constant relative to FR 5 measured at 21.7 rad/T m.

	Wavelength (nm)	
Kigre M-24	**532**	**1064**
Verdet constant, V(rad/T m)	–87	–26
Loss coefficient, α (cm^{-1})	—	—
Index of refraction, n	1.701 (n_D)	1.687

	Wavelength (nm)	
Kigre M-32	**532**	**1064**
Verdet constant, V(rad/T m)	–98	–29
Loss coefficient, α (cm^{-1})	—	—
Index of refraction, n	1.727 (n_D)	1.713

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O-I EY-1 (discontinued)	Wavelength (nm 325	442	632.8	1064
Verdet constant, V(rad/T m)	−273	−98.0	−41.9	–11.9
Loss coefficient, α (cm^{-1})	—	—	—	<0.005
Index of refraction, n	1.665	1.639	1.624	1.615

O-I EY-2 (discontinued)	Wavelength (nm) 325	442	632.8	1064
Verdet constant, V(rad/T m)	—	—	—	−11
Loss coefficient, α (cm^{-1})	—	—	—	<0.010
Index of refraction, n	—	—	—	1.607

Optical Properties of Paramagnetic Faraday Rotator Glasses

Glass type	Transmission range (μm)	Refractive index n_D	Abbe number ν_D	dn/dT (10^{-6}/K)	Nonlinear index n_2 calc. (10^{-13}esu)
FR-4	~0.4–2.0	1.5732	58.0	2.8	1.59
FR-5	~0.4–1.5*	1.6864	53.5	7.5	2.45
FR-7	~0.4–1.5*	1.5316	74.9	–	0.95
M-18	~0.4–1.5*	1.682	48.8	7.5	2.7
M-24	~0.4–1.5*	1.701	52.0	–	2.6
M-32	~0.4–1.5*	1.727	51.1	–	2.9

* Tb^{3+} absorption line at ~0.54 μm.

Mechanical and Thermal Properties of Paramagnetic Faraday Rotator Glasses

Glass type	Density (g/cm^3)	Young's modulus E (10^3 N/mm^2)	Poisson's ratio μ	Knoop hardness (N/mm^2)	Thermal expansion (10^{-6}/°C)	Transform. temp (°C)
FR-4	3.10	65.2	0.244	6020	98	625
FR-5	4.28	108	0.22	7310	47	756
FR-7	4.32	–	–	5070	17.1	398
M-18	4.33	113	0.339	7380	5.63	757
M-24	4.45	121	0.326	7500	5.59	775
M-32	4.85	120	0.306	7930	6.00	774

Data from manufactures' sheets.

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2.11.4 Gradient-Index Glasses

Gradient-index (GRIN) glasses are ones in which the index of refraction varies spatially within the glass. A radial gradient is one that is symmetric about a line; therefore the surfaces of constant index of refraction are cylinders. There are two commonly used mathematical representations for such gradients. The first, used to specify products manufactured by Nippon Sheet Glass, is $N(r) = N_0(1 - Ar^2/2 + h_4r^4 + h_6r^6 + \ldots)$; the second is $N(r) = N_{00} + N_{10}r^2 + N_{20}r^4 + \ldots$). In both cases, the quadratic coefficient determines the focal length, numerical aperture, and other first-order properties of the lens. The higher-order coefficients determine the image quality.

The tables below present catalog data for Nippon Sheet Glass (NSG) materials and those of Gradient Lens Corporation(GLC) together with calculated maximum numerical aperture (NA) and quarter-pitch length. Other diameters and numerical apertures may be available; the reader should contact the appropriate vendor for current data.

NSG Radial Gradient Lenses (Selfoc)

	SLS	SLS	SLW	SLW	SLW	SLW	SLH
Numerical aperture	0.37	0.37	0.46	0.46	0.46	0.46	0.6
Diameter (mm)	1	2	1	1.8	2	31.8	
Wavelength (μm)	0.63	0.63	0.63	0.63	0.63	0.63	0.634
	2.49E^{-1}	6.10E^{-2}	3.70E^{-1}	1.15E^{-1}	9.24E^{-2}	4.24E^{-2}	1.85E^{-1}
Square root A	0.499	0.247	0.608	0.339	0.304	0.206	0.43
N_{00}	1.5637	1.5637	1.6075	1.6075	1.6075	1.6075	1.6576
N_{10}	–1.95E^{-1}	–4.77E^{-2}	–2.97E^{-1}	–9.24E^{-2}	–7.43E^{-2}	–3.41E^{-2}	–1.53E^{-1}
ΔN	–4.87E^{-2}	–4.77E^{-2}	–7.43E^{-2}	–7.48E^{-2}	–7.43E^{-2}	–7.67E^{-2}	–1.24E^{-1}
Index at edge	1.515	1.516	1.5332	1.5326	1.5332	1.5307	1.5334
Quarter-pitch length	3.15	6.36	2.58	4.63	5.17	7.63	3.65

Data from SELFOC Product Guide, NSG America, Inc., Somerset, NJ 08873.

GLC Radial Gradient Lenses (BIG GRINS)

	BG 30	BG 40	BG 50
Numerical aperture	0.19	0.19	0.19
Diameter (mm)	3	4	5
Wavelength (μm)	0.63	0.63	0.63
A	5.78E^{-3}	3.25E^{-3}	2.12E^{-3}
Square root A	0.076	0.057	0.046
N_{00}	1.643	1.643	1.643
N_{10}	–4.74E^{-3}	–2.67E^{-3}	–1.74E^{-3}
ΔN	–1.07E^{-2}	–1.07E^{-2}	–1.09E^{-2}
Index at edge	1.6323	1.6323	1.6321
Quarter-pitch length	20.67	27.56	34.15

Data from Gradient Lens Corporation Data Sheets, Rochester, NY 14608.

Tables from Moore, D. T., Gradient-index materials, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, 1995), p. 499.

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2.11.5 Mirror Substrate Glasses

Properties of Mirror Substrate Glasses

Material (supplier)	Density (g/cm^3)	Thermal expansion coefficient ($10^{-6}/K$)	Knoop hardness (kg/mm^2)	Stress-optical coefficient (TPa^{-1})
BK 7 (various)	2.51	8.3	520	2.7
fused silica*	2.20	0.55	635	3.5
LE30 (Hoya)	2.58	0.4	657	2.9
Pyrex (Corning)	2.23	3.2	418	3.9
ULE (Corning)	2.21	0.03	460	4.0
Zerodur® (Schott)	2.53	0.10	630	3.0

* For a list of suppliers, see the section on fused silica.

2.11.6 Athermal Glasses

Athermal glass compositions are selected such that the optical path length, defined as the refractive index times the actual geometric distance the light traverses in the glass, is independent of temperature. The change in optical path length ΔW with temperature is

$$\Delta W = s[\alpha(n - 1) + dn/dT]\Delta T = sGT,$$

where s is the actual distance in the glass, α is the coefficient of thermal expansion, n is the refractive index, and T is the temperature. G is the thermo-optical coefficient. For Δw to approach zero, the gradient of the refractive index as a function of temperature must be negative. Examples of glasses with this property can be found in the FK, PK, PSK, SSK, BaLF, F, TiF, and BaSF families on the glass map. Data for several representative athermal optical and laser glasses are given in the table (see, also, sections 2.2.2 and 2.9.2).

Properties of Athermal Glasses

Glass type	n_d	ν_d	Thermal expansion coefficient α ($10^{-6}/K$)*	dn/dT ($10^{-6}/K$)**
Optical glasses				
Ultran (Schott)	1.5483	74.2	11.9	–6.5
PSK 54 (Schott)	1.5860	64.6	11.9	–7.0
TiF 6 (Schott)	1.6165	31.0	13.9	–6.4
FK 54 (Schott)	1.4370	90.7	14.6	–5.9
ATF4 (Hoya)	1.65376	44.72	12.9	–6.6
Nd-doped laser glasses				
LHG-8 (Hoya)	1.530	66.5	11.2	–5.3
Q-98 (Kigre)	1.555	63.6	9.9	–4.5
LG-760 (Schott)	1.519	69.2	12.5	–6.8
LG-810 (Schott)	1.537	67.7	14.5	–7.7

* –30 – +70°C; ** +20 – +40°C

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2.11.7 Acoustooptic Glasses

Acoustic waves create a time-varying refractive index grating in a material via the photoelastic effect. The grating spacing is equal to the acoustic wavelength; the grating depth is determined by the drive power of the transducer. A light beam traversing the medium is deflected by the grating at the Bragg angle Θ_B from the normal to the sound propagation direction given by

$$\sin \Theta_B = (1/2)\lambda/\Lambda,$$

where λ and Λ are the wavelengths of the light and sound beams. The diffraction efficiency for a transducer of height H and interaction length L is

$$I/I_0 = (\pi^2/2)(L/H)(n^6p^2/\nu n^3)P_a/\lambda^2$$

where P_a is the acoustic power, p is the photoelastic constant, ρ is the density, and ν is the sound velocity. Thus an acoustooptic material, in addition to having low losses at the acoustic and optical wavelengths, should also have a large index of refraction and small sound velocity.

A figure of merit for an acoustooptic material is $M = n^6p^2/\rho v^3$. Properties and figures of merit for several glasses are compared below.

Properties of Acoustooptic Glasses

Glass	Transmission range (μm)	Acoustic wave polar.	Sound velocity (km/sec)	Optical wave polar.	Refract. index (632.8 nm)	Relative merit[(a)]
fused silica (SiO_2)	0.2–4.0	long.	5.96	$\perp$	1.46	1.0
lead silicate (Schott SF 4)	0.38–1.8	long.	3.63	$\perp$	1.62	3.0
lead silicate (Schott SF 59)	0.46–2.5	long.	3.20	$\parallel$ or $\perp$	1.95	12.6
tellurite (Hoya AOT 5)	0.47–2.7	long. shear	3.40 1.96	$\perp$ $\parallel$ or $\perp$	2.090	23.9
tellurite (Hoya AOT 44B)	0.43–2.5	long.	3.33	$\parallel$	1.971	20.9
arsenic trisulfide (As_2S_3)	0.6–11	long.	2.6	$\parallel$	2.61	256
$Ge_{55}As_{12}S_{33}$	1.0–14	2.52	2.52	$\perp$		54

(a) Figure of merit relative to that of SiO_2.

Data from Gottlieb, M., Elastooptic materials, *Handbook of Laser Science and Technology*, Vol. 4 (CRC Press, Boca Raton, FL, 1986), p. 319.

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2.11.8 Abnormal Dispersion Glass

Various relative partial dispersions

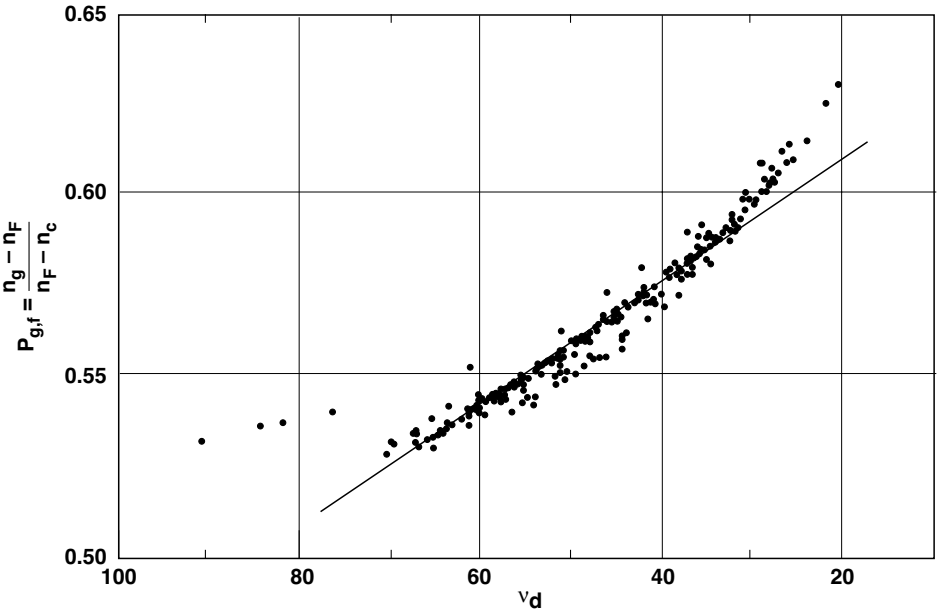
$$P_{x,y} = (n_x - n_y)/(n_F - n_C)$$

are defined for other wavelengths x and y. The relative partial dispersion of most glasses obeyed a linear relationship on ν_d of the form

$$P_{x,y} \approx a_{xy} + b_{xy}\,\nu_d\,,$$

where a and b are constants. It is not possible to correct for second-order chromatic aberrations using so-called "normal" glasses that satisfy this equation. Because of the linear relationship between the relative partial dispersions and Abbe number, the difference in partial dispersions will always be the same for normal glasses.

Correction for second-order chromatic aberration (secondary spectrum) is accomplished using glasses with equal partial dispersions for different Abbe values (the corrected systems are called apochromats). These abnormal dispersion glasses depart from the "normal line" and the linear relationship above. The relative dispersion $(n_g - n_F)/(n_F - n_C)$ of optical glasses is plotted in the figure below and shows the magnitude of the deviations from the normal line that are possible. The deviations can be either positive or negative. Optical glass catalogs list deviations of the relative partial dispersions from the normal for glasses covering a wide range of ν_d values.



Deviation of the relative partial dispersion $P_{g,f}$ of optical glasses from the normal line (Schott Optical Glass Catalog).

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Section 3: Polymeric Materials

3.1 Optical Plastics
3.2 Index of Refraction
3.3 Nonlinear Optical Properties
3.4 Thermal Properties
3.5 Engineering Data

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Section 3

POLYMERIC MATERIALS

Of the large number of known polymers, several exhibit useful optical properties. Various properties of optical plastics are compared with those of glasses below. The documentation of optical properties and the accuracy of data on plastics are generally not comparable to that of optical glasses. In addition, mechanical and chemical resistance properties should be checked with the material supplier because they may vary widely within a polymer group. Numerous caveats about the use and application of plastics in optical systems are noted in reference 1.

Property	Plastic	Glass
Optical		
Refractive index (n_d)	1.31–1.65	1.28–1.95
Abbe number (v_d)	92–20	91–20
Index homogeneity	$\pm 1 \times 10^{-4}$	$\pm 1 \times 10^{-6}$
Index change with temperature (10^{-6} K^{-1})	−143 to −100	−8.5 to 6.0
Birefringence (nm/cm)	60–80,000	5
Transmission range (nm)	200–2500	150–3500
Mechanical		
Density (g/cm^3)	0.83–1.46	2.3–6.3
Young modulus (10^3 N/mm^2)	1–10	46–129
Poisson's ratio		0.192–0.309
Thermal		
Expansion coefficient (10^{-6} K^{-1})	25–130	3.7–14.6
Heat capacity (J g^{-1} K^{-1})	1–2	0.31–0.89
Thermal conductivity (W m^{-1} K^{-1})	0.1–0.3	0.51–1.28
Softening temperature (°C)	360–430	750–1100

From Cook, L. M. and Stokowski, S. E., Filter materials, *Handbook of Laser Science and Technology, Volume IV: Optical Materials, Part 2* (CRC Press, Boca Raton, FL, 1995), p. 151.

Common optical plastics include:

polymethyl methacrylate (PMMA) (acrylic)
polystyrene (styrene) (PS)
methyl methacrylate styrene copolymer (NAS)
stryrene acrylonitrile (SAN), acrylic/styrene copolymer
polycarbonate (PC)
polymethylpentene (TPX)
acrylonitrile, butadienne, and styrene terpolymer (ABS)
nylon, amorphous polyamide
polyetherimide (PEI)
polysulfone
allyl diglycol carbonate (CR-39)
Telfon (Telfon AF®) (TPFE), fluorinated-(ethylenic-cyclo oxyaliphatic substituted ethylenic) copolymer

In the following tables properties of these and other optical plastics are given in order of decreasing index of refraction.

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3.1 Optical Plastics

Properties of Optical Plastics–I

Polymer	Trade name	Manufacturer	Density (g/cm^3)	Index n_D	Abbe ν_D
Polyetherimide (PEI)	Ultem	G.E. Plastics	1.27	1.658	
Polyarylsulfone	Radel	Amoco Performance	1.37	1.651	
Polyurethane	Isoplast 301	Dow	1.2	1.64–1.65	
Polysulfone	Udel P-1700	Amoco Performance	1.24	1.633	22.5
Polyarylate	Durel 400	Hoecsht Celanese	1.21	1.61	
	Ardel D-100	Amoco Performance	1.21	1.61	
Poly α-methylstyrene	Resin 18	Amoco Chemical	1.075	1.61	
Polyamide, amorphous nylon Aliphatic/aromatic	Durethan T40	Miles Inc. (Bayer AG)	1.185	1.590	
Polystyrene (PS)	Styron	Dow	1.06	1.589	31
Polyamide, amorphous nylon	Zytel 330	DuPont	1.18	1.588	
Polycarbonate (PC)	Calibre	Dow	1.20	1.586	30
	Lexan	G.E. Plastics	1.20	1.586	30.3
	Makrolon	Miles Inc.	1.2	1.586	30
Polystyrene co-maleic anhydride (SMA)	Dylark 232	Arco	1.08	1.586	31.8
Modified polyestercarbonate	Lexan SP	G.E. Plastics	1.18	1.582	
Polystyrene-butadiene copolymer	K Resin	Phillips 66	1.01	1.571	
Polystyrene-coacrylonitrile (SAN)	Lustran	Monsanto	1.07	1.57	35.3
	Lustran Sparkle	Monsanto	1.07	1.57	
	Tyril 990	Dow	1.07	1.57	
Polyester (PETG)	Kodar 6763	Eastman	1.27	1.567	
Polyamide, amorphous (nylon type 6/3)	Trogamid T	Huls-America	1.12	1.566	
Polystyrene co-methyl-methacrylate (2:1) (SMMA)	NAS 30	Novacor	1.09	1.564	35
Epoxy casting resin	OS-4000	Dexter Corp. (Hysol)	A = 1.15 B = 1.22	A = 1.563 B = 1.565	
Amorphous polyolefin from dicyclopentadiene	APO	Mitsui Petrochem.	1.05	1.54	
Acrylonitrile-butadiene-styrene terpolymer (ABS)	Cycolac CTBZ	G.E. Plastics	1.07	1.536	35
Polyamide, amorphous (nylon type 12)	Grilamid	EMS-America-Grilon	1.06	1.535	
Polystyrene co-methylmethacrylate (1:2) (SMMA)	NAS-55	Novacor	1.13	1.535	41.15
Amorphous polyolefin (APO)	ZEONEX	Zeon Chemicals	1.01	1.528	55.7

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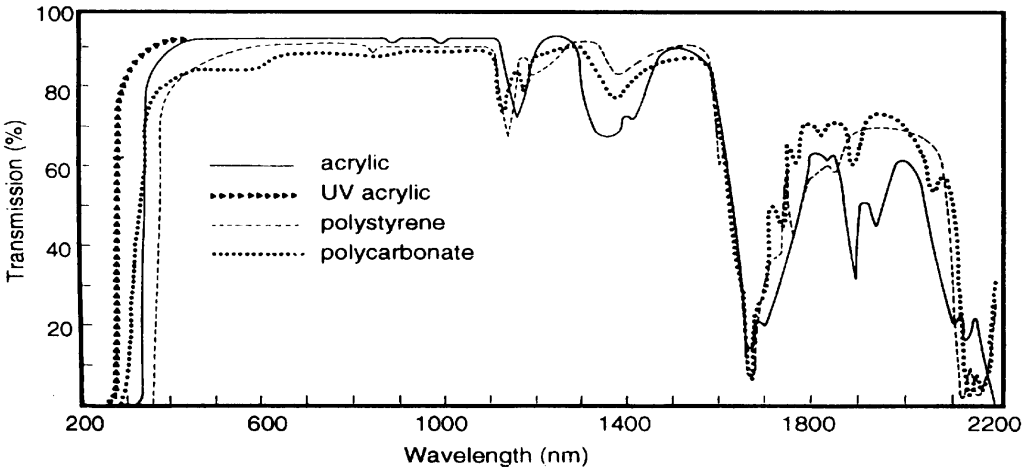
Properties of optical plastics–I—*continued*

Polymer	Trade name	Manufacturer	Density (g/cm^3)	Index n_D	Abbe ν_D
Dicyclopolyolefin	Telene	B F Goodrich	1.0	1.528	55.3
Epoxy molding compound	MG-18	Dexter Corp. (Hysol)	1.35	1.52	
Tricyclodecyl co-methacrylate (TCDMA)	OZ-1000	Hitachi Chemical	1.16	1.500	57
Low moisture acrylic	WF-201	Mitsubishi Rayon		1.495	58
Allyl diglycol carbonate	CR-39	PPG Industries	1.32	1.498	59.3
Polymethylmethacrylate	Plexiglas	Rohm and Haas	1.19	1.491	57.4
PMMA, acrylic	Acrylite	Cyro	1.19	1.491	57.4
	CP	ICI	1.18	1.491	57.4
	Perspex	ICI	1.18	1.491	57.4
	Shinkolite P	Mitsubishi Rayon	1.19	1.491	57.4
Polymethylmethacrylate impact modified, 20%	MI-7	Rohm and Haas	1.17	1.49	
impact modified, 40%	DR-G	Rohm and Haas	1.15	1.49	
Poly(4-methylpentene-1)	TPX RT-18	Mitsui Plastics	0.833	1.463	56.3
Cellulose acetate butyrate (CAB)	Tenite	Eastman	1.15–1.2	1.46–1.49	51.9
Fluoropolymer (TPFE)	Teflon AF 1600	DuPont	1.8	1.32	92

Optical Transmission

Optical plastics transmit well in the visible and the near infrared, but absorb strongly in the ultraviolet (fluoropolymers are an exception) and throughout the infrared. Most plastics degrade somewhat both in physical and optical properties when exposed to ultraviolet radiation.



Transmission spectra of optical plastics. sample thickness: 3.2 mm.

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Properties of Optical Plastics–II

Polymer	Relative haze[a]	Hue[b]	Deflect.[c] temp. (°C)	Comments
Polyetherimide (PEI)	light	amber	200	Good thermal/chemical resistance, high color but good in near IR
Polyarylsulfone	light	yellow	204	Tough
Polyurethane	light	colorless	88	Can be custom tailored, good chemical resistance
Polysulfone	light	yellow	174	Good thermal and moisture stability, high temperature
Polyarylate	noticeable	light straw	158	High temperature, good UV resistance
Poly α-methylstyrene	slight	colorless	n/a	Brittle, can be modifier for K resin
Polyamide, amorphous nylon	slight	light straw	110	Tough, hard
Polystyrene (PS)	low	colorless	82110	Low haze grades available
Polyamide, amorphous nylon	noticeable	colorless	123	Good abrasion resistance, moisture sensitive
Polycarbonate (PC)	slight	light straw	123129	Very tough, high impact
Polystyrene co-maleic anhydride (SMA)	slight	colorless	96	Brittle
Modified polyestercarbonate	slight	light straw	107	Processes at lower temperature
Polystyrene-butadiene copolymer	noticeable	light straw	76	Tough
Polystyrene-coacrylonitrile ∂8 (SAN)	slight	light straw	93104	Tougher than polystyrene
Polyester (PETG)	slight	light straw	70	Film extruding
Polyamide, amorphous (nylon type 6/3)	noticeable	straw	124	Good abrasion resistance
Polystyrene co-methyl-methacrylate (2:1) (SMMA)	slight	colorless	98	Optical quality
Amorphous polyolefin from dicyclopentadiene	n/a	n/a	T_g = 141	Optical quality, very low moisture
Acrylonitrile-butadiene-styrene terpolymer (ABS)	noticeable	yellow	79	Tough
Polyamide, amorphous (nylon type 12)	noticeable	straw	150	Good abrasion resistance
Polystyrene co-methyl-ethacrylate (1:2) (SMMA)	slight	colorless	99	Optical quality
Amorphous polyolefin (APO)	slight	light straw	123	Optical quality
Dicyclopolyolefin	slight	light straw	107	Very low moisture (0.01%)
Epoxy molding compound	slight	colorless	120	Semiconductor embedment
Epoxy casting resin			T_g = 110	Two-part casting resin
Tricyclodecyl co-methacrylate (TCDMA)	low	colorless		Lower moisture than PMMA (1.2%)
Low moisture acrylic	sligth	light straw	103	Optical quality
Allyl diglycol carbonate	low	light straw	91	Cast thermoset, hard
			55–65	Ophthalmic use

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Properties of optical plastics–II—*continued*

Polymer	Relative haze[a]	Hue[b]	Deflect.[c] temp. (°C)	Comments
Polymethylmethacrylate PMMA, acrylic	low to slight	light straw to colorless	72–102	Optical quality, hard, widely used, scratch resistant
Impact modified, 20%	light	colorless	85	Tougher than PMMA
Impact modified, 40%	light	colorless	79	Tough, will creep with mild force
Poly(4-methylpentene-1)	slight	colorless	90 at 66 psi	Unusual properties, lowest density of all thermoplastics, infrared transmission, very tough
Cellulose acetate butyrate (CAB)	noticeable	light straw	43–88	Tough
Fluoropolymer (TPFE)	noticeable	colorless	154	Very low index of refraction, good ultraviolet transmission.

[a]Relative haze estimates: low (<0.7%); slight (to 1.5 %); light (to 3%); noticeable (>3%).

[b]Hue (yellowness) estimates: colorless, light straw, straw, yellow, amber.

[c]Heat deflection temperature at 264 psi.

The above tables are from D. Keyes, Optical plastics, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), pp. 85–94.

Loss Contributions (in dB/km) for PS, PMMA, and PMMA-d8 Core Fibers

Core material	PS				PMMA			PMMA-d8		
Wavelength (nm)	**552**	**580**	**624**	**672**	**518**	**567**	**650**	**680**	**780**	**850**
Total loss	162	138	129	114	57	55	128	20	25	50
Absorption	0	4	22	24	1	7	88	0	9	36
Electronic transition tail	22	11	4	2	0	0	0	0	0	0
Rayleigh scattering	95	78	58	43	28	20	12	10	6	4
Structural imperfections	45	45	45	45	28	28	28	10	10	10
Loss limit	117	93	84	69	29	27	100	10	15	40

Source: Kaino, T., Fujiki, M., and Jinguji, K., Preparation of plastic optical fibers, *Rev. Electr. Commun. Lab.* 32, 478 (1984).

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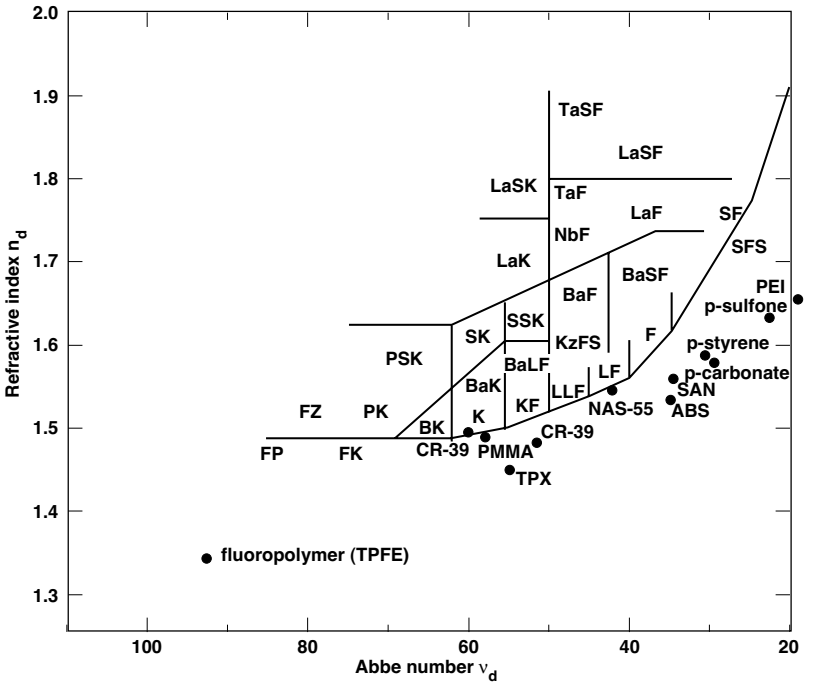
3.2 Index of Refraction

Index of Refraction of Common Optical Plastics

Wavelength (nm)	PMMA	Poly-styrene	Poly-carb.	SAN	PEI	NAS	TPFE
365.0	1.5136	1.6431	1.6432	1.6125	—	—	—
404.7	1.5066	1.6253	1.6224	1.5971	—	—	—
435.8	1.5026	1.6154	1.6115	1.5886	—	—	—
480.0	1.4983	1.6052	1.6007	1.5800	1.687	—	—
486.1	1.4978	1.6041	1.5994	1.5790	—	1.574	—
546.1	1.4938	1.5950	1.5901	1.5713	1.668	—	—
587.6	1.4918	1.5905	1.5855	1.5674	1.660	—	—
589.3	1.4917	1.5903	1.5853	1.5673		10564	1.31
643.9	1.4896	1.5858	1.5807	1.5634	1.651	—	—
656.3	1.4892	1.5849	1.5799	1.5627	—	1.558	—
706.5	1.4878	1.5820	1.5768	1.5601	—	—	—
852.1	1.4850	1.5762	1.5710	1.5551	—	—	—
1014.0	1.4831	1.5726	1.5672	1.5519	—	—	—
Abbe number	57.4	30.9	29.9	34.8	18.3	34.7	92

Adapted from a table of J. D. Lytle, *Handbook of Optics*, Vol. II (McGraw-Hill, New York, 1995), Chapter 34 (with additions).

Being carbon-based materials, the index of refraction and dispersion of polymers differ significantly from those of glasses and crystals. The locations of optical plastics relative to optical glasses are shown in the refractive index–Abbe number diagram below.



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3.3 Nonlinear Optical Properties

Abbreviations	Material
3-BCMUr	Red form of poly-3-BCMU
3-DDCTP	Poly(3-dodecylthiophene)
4-BCMUr	Red form of poly-4-BCMU
4-BCMUy	Yellow form of poly-4-BCMU
AO	Acridine orange
AY	Acridine yellow
BBB	Poly(6,9-dihydro-6,9-dioxobisbenzimidazo[2,1*b*:1',2'*j*]benzo[1*mn*][3,8]phenanthroline-3,12-diyl)
BBL	Poly{(7-oxo-7,10H-benz[de]imidazo[4',5':5,6]benzimidazo[2,1-*a*]isoquinoline 3,4:10,11-tetrayl)-10-carbonyl}
BBPEN	Bis[*n*-butyl, 2-phenyl-1,2-ethenedithiolato(2-)-*S*,*S*'] nickel
BSQ	1,3-Bis(4'-*N*,*N*-dibutylamino-2'-hydroxyphenyl)-cyclobutene-2,4-dione
DCV	4-*N*,*N*-Diethylamino-4'-*b,b*-dicyanovinyl (azobenzene)
DEANS	4-Diethylamino-4'-nitrostilbene
DNBA	4-Nitrobenzylidenyl (4'-*N*,*N*-dimethylaminoanilide)
DNTA	4-Nitrothenylidenyl (4'-*N*,*N*-dimethylaminoanilide)
DR1	Disperse red 1
ISQ	1,3-Bis(3',3'-dimethyl-2'-indoleninylidenyl)-cyclobutene-2,4-dione
LTFPG	Lead-tin fluorophosphate glass
MDCB	*m*-Dicyanobenzene
MDNB	*m*-Dinitrobenzene
Mg:OPTAP	Magnesium octaphenyl tetra-azaporphyrin
MNA	2-Methyl-4-nitroaniline
MV757	MV757 commercial epoxy resin
NFAI	5-Nitro(2-furanacroleindenyl (4'-*N*,*N*-dimethylaminoanilide)
NPCV	4-*N*,*N*-Dibutylamino-4'-(b-cyano-b-(4≤-nitrophenyl) vinyl) (azobenzene)
OMPS	Poly(*n*-octylmethylpolysilane
PBT	Poly-*p*-phenylenebenzobisthiazole
PC	Polycarbonate
PDES	Polydiethynylsilane
PDTT	Polydithieno(3,2-*b*,2',3'-*b*)thiophene
PMMA	Poly(methyl) methacrylate
PPMS	Polyphenylmethylsilane
PPV	Poly (*p*-phenylene vinylene)
PS	Polysilane
PT	Polythiophene
PTS	Bis-(*p*-toluene sulfonate) of 2,4-hexadiyne-1,6 diol (polydiacetylene)
PTS-PDA	Single crystal poly PTS polydiacetylene
PVK	Poly-*N*-ninyl carbazole
rB	Rhodamine B
SiNc	Silicon naphthalocyanine
SiPc	Silicon phthalocyanine
TCDU:	Bis-(phenylurethane) of 5,7-dodecadiyne-1,2-diol (polydiacetylene)
TCV	4-*N*,*N*-Diethylamino-4'-tricyanovinyl (azobenzene)
TNF	2,4,7-Trinitrofluorenone
TPO-N	Thiophene oligomer with N units

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Bulk Two-Photon Absorption Coefficients

Material	Excitation duration(ns)	Applied two-photon energy (eV)	Two-photon cross section (cm/GW)	Ref.	Additional information
3-BCMU	0.033	2.33	0.52	33	Benzene chloride 2.3% blue gel
4-BCMU	0.033	2.33	0.76	33	Benzene chloride 1.7% red gel
4-BCMU	0.033	2.33	<0.1	33	14% yellow form solution in DMF
4-BCMU	0.06	1.88	<0.25	34	Polymer waveguide
PPV	0.00006	4	6.8	35	PPV in silica sol-gel
PTS	0.015	2.28	28	36	Pump @1.17 eV
PTS	0.015	2.55	300	36	Pump @1.17 eV
PTS	0.015	2.78	500	36	Pump @1.17 eV
PTS	0.015	2.96	900	36	Pump @1.17 eV
TCDU	0.015	2.2	1	36	Pump @0.81 eV
TCDU	0.015	2.3	14	36	Pump @1.17 eV
TCDU	0.015	2.4	3	36	Pump @0.81 eV
TCDU	0.015	2.6	6.4	36	Pump @0.81 eV
TCDU	0.015	2.6	54	36	Pump @1.17 eV
TCDU	0.015	2.9	80	36	Pump @1.17 eV

From Garito, A. E. and Kuzyk, M. G., Two-photon absorption: organic materials, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 329.

Techniques for Measuring Nonlinear Refraction

Abbreviation	Method	Ref.
DFWM	Degenerate four-wave mixing	1
KE	DC Kerr effect	2
MSI	Modified Sagnac interferometry	3
OKE	Optical Kerr effect	4
SA	Saturated absorption	5
TBC	Two-beam coupling	5
TRI	Time-resolved interferometry	6

All measurements in the following tables were made at room temperature.

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Nonlinear Refraction Data for Polymers

Material	Meth.	Pulse duration (ns)	Wavelength (nm)	Linear index n	$\chi^{(3)}_{1111}$ (10^{-12} cm^3/erg)	$\chi^{(3)}_{1111} - \chi^{(3)}_{1122}$ (10^{-12} cm^3/erg)	Ref.
3-DDCTP	DFWM	0.0004	620		330		7
3-DDCTP	DFWM	0.00006	620		55		7
3-DDCTP[a]	DFWM	0.00035	590	1.585	450		8
3-DDCTP[a]	DFWM	0.00035	602	1.585	330		8
3-DDCTP[a]	DFWM	0.00035	705	1.585	40		8
3-DDCTP[b]	DFWM	0.00035	590	1.61	700		8
3-DDCTP[b]	DFWM	0.00035	602	1.61	500		8
3-DDCTP[b]	DFWM	0.00035	705	1.61	40		8
4-BCMUr	DFWM	0.0005	605		400		9
4-BCMUy	DFWM	0.0005	605		25		9
4-BCMUy	DFWM	0.033	1064			$\chi^{(3)}_{1212} = 1.4$	10
4-BCMUy	DFWM	0.033	1064			$\chi^{(3)}_{1212} = 9.0$	10
4-BCMUy	DFWM	0.033	1064			$\chi^{(3)}_{1212} = 13$	10
BBB	DFWM	0.035	1064		5.5	3.7	11
BBL	DFWM	0.025	532		2000	1300	11
BBL	DFWM	0.035	1064		15	10	11
BBL[c]	DFWM	0.035	1064		20	13	11
OMPS	DFWM	10	532		2.9		12
PBT	DFWM	0.0005	585–604		9		13
PDES	DFWM	0.00009	620		3000		14
PDTT	DFWM	0.008	530	2	11,400		15
PDTT	DFWM	0.008	585	2	7,700		15
PDTT	DFWM	0.008	605	2	5,500		15
PDTT	DFWM	0.008	630	2	1,300		15
PDTT	DFWM	0.008	1060	2	30		15
Poly(4-BCMU)	TRI	0.06	1319		0.456		16
PPMS	OKE	0.003	1060,532		2.0		17
PS	OKE	0.008	1060,532		2		18
PT	DFWM	0.008	530	2	6,680		15
PT	DFWM	0.008	585	2	5,000		15
PT	DFWM	0.008	605	2	3,000		15
PT	DFWM	0.008	630	2	700		15
PT	DFWM	0.008	1060	2	30		15
PTS-PDA	DFWM	0.006	651.5	3	9,000		19
PTS-PDA	DFWM	0.006	661	3	7,275		19
PTS-PDA	DFWM	0.006	671	3	2,317		19
PTS-PDA	DFWM	0.006	681	3	1,025		19
PTS-PDA	DFWM	0.006	691	3	380		19
PTS-PDA	DFWM	0.006	701.5	3	500		19
PTS-PDA	MSI	0.06	1060	3	1250		3
PTS-PDA[a]	TRI	0.1	1060	3	6840		20
TPO-1	DFWM	0.0004	602	1.529	0.14		21
TPO-2	DFWM	0.0004	602		0.50		21
TPO-3	DFWM	0.0004	602	1.562	2.6		21
TPO-4	DFWM	0.0004	602	1.581	11		21
TPO-5	DFWM	0.0004	602	1.600	30		21
TPO-6	DFWM	0.0004	602	1.623	100		21

[a] Chemically prepared; [b] Electrochemically prepared; [c] Electrochemically doped; [d] Single crystal waveguides.

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Nonlinear Refraction Data for Solid Solutions and Copolymers

Dye	Host	Dye density (10^{22} cm^{-3})	Meth.	Pulse (ns)	Wavelength (nm)	Linear index	$\chi^{(3)}_{1111}$ (10^{-12} cm^3/erg)	Ref.
AO	LTFPG	0.00008	SA	15,000	514	1.77	3 x 10^{10}	22
AO	LTFPG	0.00008	TBC	15,000	514	1.77	4 x 10^{10}	22
AY	LTFPG	0.000077	SA	15,000	514	1.77	6 x 10^{10}	22
AY	LTFPG	0.000077	TBC	15,000	514	1.77	2 x 10^{10}	22
BBPEN	PMMA	saturation	DFWM	0.1	1064	1.49	29.9	23
BEPEN	PMMA	saturation	DFWM	0.1	1064	1.49	131	23
BSQ	PMMA	0.0028	MSI[b]	0.06	1064	1.48	2.8	24
BSQ	PMMA	0.0028	KE	8 kHz	799	1.5	0.97[a]	25
DCV	PMMA	0.0148	KE	8 kHz	632.8	1.5	1.8[a]	26
DCV	PMMA	0.0148	KE	8 kHz	676	1.5	0.53[a]	26
DCV	PMMA	0.0148	KE	8 kHz	799	1.5	0.156[a]	26
DEANS	PC	17	KE	500 Hz	597		6	27
DNBA	PMMA	0.0137	KE	8 kHz	632.8	1.5	0.093[a]	26
DNTA	PMMA	0.0276	KE	8 kHz	632.8	1.5	0.282[a]	26
DR1	PMMA	0.01	KE	8 kHz	632.8	1.5	0.23[a]	26
DR1	PMMA	0.0244	KE	8 kHz	632.8	1.5	0.51[a]	26
DR1	PMMA	0.04	KE	8 kHz	632.8	1.5	0.84[a]	26
ISQ	PMMA	0.0019	KE	8 kHz	479	1.5	0.263[a]	26
ISQ	PMMA	0.0019	KE	8 kHz	570	1.5	0.341[a]	26
ISQ	PMMA	0.0019	KE	8 kHz	632.8	1.5	0.155[a]	26
ISQ	PMMA	0.0019	KE	8 kHz	680	1.5	0.418[a]	26
ISQ	PMMA	0.0019	KE	8 kHz	799	1.5	0.387[a]	26
MDCB	PMMA	0.109	KE	8 kHz	632.8	1.5	0.0274[a]	26
MDNB	PMMA	0.124	KE	8 kHz	632.8	1.5	0.0205[a]	26
Mg:OPTAP	PMMA	5 wt%	DFWM	0.001	598	1.48	11.7	28
MNA	PMMA	0.143	OKE[b]		1064	1.5	2.08	29
NFAI	PMMA	0.0240	KE	8 kHz	632.8	1.5	0.471[a]	26
NPCV	PMMA	0.0119	KE	8 kHz	632.8	1.5	0.315[a]	26
PPV	Sol-gel silica	1:1 by weight	DFWM	0.00006	620		45	30
PPV	Sol-gel silica	1:1 by weight	DFWM	0.0004	608		91	30
PPV	Sol-gel silica	1:1 by weight	OKE	0.00006	620		38	30
rB	MV757	0.0077 M/l	DFWM	0.00035	595	1.81	10.7	31
SiNc	PMMA	30 wt%	DFWM	0.001	598	1.434	20.9	28
SiPc[c]	PMMA	10 wt%	DFWM	0.001	598	1.42	94	28
TCV	PMMA	0.0218	KE	8 kHz	632.8	1.5	3.9[a]	26
TNF	PVK	1:2 molar ratio	DFWM	0.002	602		20	32
TNF	PVK	1:4 molar ratio	DFWM	0.002	602		12	32
TNF	PVK	1:8 molar ratio	DFWM	0.002	602		7.4	32
TNF	PVK	1:16 molar ratio	DFWM	0.002	602		3.4	32
TNF	PVK	1:32 molar ratio	DFWM	0.002	602		2.0	32

[a] Assumes $\chi^{(3)}_{1111} = 3\,\chi^{(3)}_{1133}$. [b] Waveguide measurement; [c] Copolymer.

From Garito, A. E. And Kuzyk, M. G., Nonlinear refractive index: organic materials, *Handbook of Laser Science and Technology, Suppl. 2* (CRC Press, Boca Raton, FL 1995), p. 289.

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3.4 Thermal Properties

Thermal Properties of Common Plastics

Material	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	Linear thermal expansion ($10^{-5}\ K^{-1}$)	Refractive index dn/dT ($10^{-4}\ K^{-1}$)	Maximum service temp. (K)
polymethylmethacrylate	0.16–0.24	3.6–6.5	–1.05	360
polystyrene	0.10–0.13	6.0–8.0	–1.2– –1.4	350
NAS	0.18	5.6–6.5		360
styrene acrylonitrile (SAN)	0.11	6.4–6.7	–1.1	350
polycarbonate	0.19	6.6–7.0	–1.07– –1.43	390
polymethyl pentene (TPX)	0.16	11.7		385
polyamide (Nylon)	0.2–0.23	8.2		350
polyarylate	0.28	6.3		
polysulfone	0.11	2.5		430
polystyrene co-butadiene		7.8–12		
polyallyl diglycol carbonate	0.20	12.0		370
cellulose acetate butyrate	0.16–0.32			
polyethersulfone	0.13–0.17	5.5		470
polychloro-trifluoroethelyne	0.25	4.7		470
polyvinylidene fluoride		7.4–13		420
polyetherimide		5.6		440

From a table of J. D. Lytle, *Handbook of Optics,* Vol. II (McGraw-Hill, New York, 1995), Chapter 34 (with additions).

3.5 Engineering Data

Engineering Data for Transparent Polymers–I

Generic family	Trade name	Manufacturer	Tensile strength yield psi	Tensile modulus 10^5, psi	Flexural modulus 10^5, psi	Impact strength (Izod)
Transparent ABS	Magnum	Dow	7300	3.8	4.2	2
	Cycolac	GE Plastics				
Acrylic (PMMA)	Plexiglas	Rohm & Haas	9400–10800	4.5–4.7	2.5–4.5	0.4–1.2
	CP	ICI				
	Acrylite	CYRO				
	Lucite	Dupont				
Allyl diglycol carbonate	CR-39	PPG	5500	3	2.5–3.3	0.2–0.4
Cellulosics (acetate, butyrate, proponiate)	Tenite	Eastman	2000–7800	0.6–2.15	1.5–3.4	1.5–7.8
Nylon, amorphous	Zytel 330	Dupont	9800–11000	4. 05	3.86	1.8–2.8
	Grilamid	EMS				
	Trogamid T	Huls America				

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Engineering Data for Transparent Polymers–I—*continued*

Generic family	Trade name	Manufacturer	Tensile strength yield psi	Tensile modulus 10^5, psi	Flexural modulus 10^5, psi	Impact strength (Izod)
PET	Kodapak	Eastman	8500–10500	4–6	3.5–4.5	0.25–0.7
	Petlon	Miles Inc.				
	Selar	Dupont				
PETG	Kodar	Eastman	7100	2.5	2.9	1.7
Polyarylate	Durel	Hoescht Celanese	9500–10500	2.9–3.05	3.3	4.2–5.5
	Arylon	Dupont				
	Ardel	Amoco Performance				
Polycarbonate	Calibre	Dow	9000–10500	3.4	3.5	14–18
	Markrolon	Miles Inc. (Bayer)				
	Lexan	GE Plastics				
Polyetherimide	Ultem	GE Plastics	15200	4.3	4.8	0.6–1.0
Polyester (polypthalate) carbonate	Lexan PPC	GE Plastics	9500	n/a	2.94–3.38	10
Polyethersulfone	Victrex	ICI	12200	n/a	3.73	1.6
Poly-4-methylpentene-1	TPX	Mitsui Plastics	3000	2	n/a	2.0–3.0
Polyphenylsulfone	Radel	Amoco Performance	10400	3.1	0.124	12
Polystyrene	Styron	Dow	5000–12000	4–5	4–4.7	0.25–0.4
	Polystyrol	BASF				
	Hostyren	Hoescht Celanese				
	Bapolan	Bamberger				
	polystyrene	Chevron				
	polystyrene	Dart, Mobil				
	polystyrene	Amoco, Novacor				
	polystyrene	Huntsman				
Polysulfone	Udel	Amoco	10200	3.6	3.9	1.3
PVC, rigid	Geon	B.F. Goodrich	6000–7700	3.6–3.7	3.6–5	0.5–1.6
	PVC, rigid	Georgia Gulf				
	Oxyblend	Occidental				
	Unichem	Colorite				
Styrene acronylitrile)	Tyril	Dow	9000–1200	4–5.6	5–5.5	0.35–0.5
(SAN	Lustran	Monsanto				
	Luran	BASF				
	Blendex	GE Plastics				
Styrene butadiene	K Resin	Phillips	4000	1.8	2.4	0.25–0.40
Styrene maleic anhydride	Dylark	Arco	7400	4.4	4.6–4.9	0.4
Styrene methylmethacrylat	NAS	Novacorp	9000	4.5–5.0	3.5–3.9	0.2–0.3
Thermoplastic polyurethane, rigid	Isoplast 301	Dow	9000	2.6	3.4	1.5

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Engineering Data for Transparent Polymers–II

Generic family	Trade name	Chemical resistance					
		Aliph. HC	Arom. HC	Conc. base	Dilute base	Conc. inorg. acid	Dilute inorg. acid
Transparent ABS	Magnum Cycolac	F	P	G	G	P	G
Acrylic (PMMA)	Plexiglas CP Acrylite Lucite	G	P	F/P	G	P	G
Allyl diglycol carbonate	CR-39	G	G	G	G	G	G
Cellulosics (acetate, butyrate, proponiate)	Tenite	F	P	P	F	P	F
Nylon, amorphous	Zytel 330 Grilamid Trogamid T	EX	EX	G	EX	P	F
PET	Kodapak Petlon Selar	G	P/F	P	F	G/F	G
PETG	Kodar	G	P/F	P	F	G/F	G
Polyarylate	Durel Arylon Ardel	P/F	P	P	N/A	F	G
Polycarbonate	Calibre Markrolon Lexan	F	P	P	P/F	F	G
Polyetherimide	Ultem	EX	EX	N/A	N/A	EX	EX
Polyester (polypthalate) carbonate	Lexan PPC	F	F/P	P	F	F	G
Polyethersulfone	Victrex	G	F	G	G	G	G
Poly-4-methylpentene-1	TPX	F	P	EX	EX	EX	EX
Polyphenylsulfone	Radel	G	P	G	G	N/A	N/A
Polystyrene	Styron Polystyrol Hostyren Bapolan polystyrene	P	P	G	G	EX	G
Polysulfone	Udel	P/F	P	EX	EX	EX	EX
PVC, rigid	Geon Oxyblend Unichem	G	P	EX	EX	G	EX

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Engineering Data for Transparent Polymers–II—*continued*

Generic family	Trade name	Chemical resistance					
		Aliph. HC	Arom. HC	Conc. base	Dilute base	Conc. inorg. acid	Dilute inorg. acid
Polyarylate	Durel Arylon Ardel	P/F	P	P	N/A	F	G
Polycarbonate	Calibre Markrolon Lexan	F	P	P	P/F	F	G
Polyetherimide	Ultem	EX	EX	N/A	N/A	EX	EX
Polyester (polypthalate) carbonate	Lexan PPC	F	F/P	P	F	F	G
Polyethersulfone	Victrex	G	F	G	G	G	G
Poly-4-methylpentene-1	TPX	F	P	EX	EX	EX	EX
Polyphenylsulfone	Radel	G	P	G	G	N/A	N/A
Polystyrene	Styron Polystyrol Hostyren Bapolan polystyrene	P	P	G	G	EX	G
Polysulfone	Udel	P/F	P	EX	EX	EX	EX
PVC, rigid	Geon PVC, rigid Oxyblend Unichem	G	P	EX	EX	G	EX
Styrene acronylitrile (SAN)	Tyril Lustran Luran Blendex	G	P	G	G	G	G
Styrene butadiene	K Resin	P	P	P	F/G	P	F/G
Styrene maleic anhydride (SMA)	Dylark	F/G	P	G	P	F	G
Styrene methylmethacrylate (SMMA)	NAS	F/P	P	F	G	F	G
Thermoplastic polyurethane, rigid	Isoplast 301	EX	EX	EX	EX	F/G	EX

Chemical resistance codes: Aliphatic hydrocarbons; aromatic hydrocarbons; concentrated base; dilute base; concentrated inorganic acid; dilute inorganic acid. Excellent; Good; Fair; Poor.

The above tables are from Keyes, D., Optical plastics, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), pp. 85–94.

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Section 4: Metals

4.1 Physical Properties of Selected Metals
4.2 Optical Properties
4.3 Mechanical Properties
4.4 Thermal Properties
4.5 Mirror Substrate Materials

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Section 4

METALS

Metals are used in optical systems as reflective optical components, optical thin films, structural elements, and mirror substrates. For these optical applications only a limited number of metals are useful. The materials and properties included in this section are therefore necessarily selective.

Depending upon the application, various physical, optical, mechanical, and thermal properties are of interest; for example, structural stiffness with low mass, thermal diffusivity to reduce thermal gradients and associated distortions, and smooth surface finish to accept of optical coatings. Thermal, elastic, electrical and magnetic properties may be anisotropic, thus crystal structure is also important.

4.1 Physical Properties of Selected Metals

Metal	Symbol	Crystal structure	Space group	Atomic weight	Density (g/cm^3)
Aluminum	Al	cubic	Fm3m	26.98	2.70
Beryllium	Be	hexagonal	$P6_3/mmc$	9.01	1.85
Chromium	Cr	cubic	Im3m	52.00	7.15
Copper	Cu	cubic	Fm3m	63.55	8.96
Germanium	Ge	cubic	Fd3m	72.61	5.32
Gold	Au	cubic	Fm3m	196.97	19.3
Iridium	Ir	cubic	Fm3m	192.22	22.5
Iron	Fe	cubic	Im3m	55.85	7.87
Magnesium	Mg	hexagonal	$P6_3/mmc$	24.30	1.74
Molybdenum	Mo	cubic	Im3m	95.94	10.2
Nickel	Ni	cubic	Fd3m	58.69	8.9
Niobium	Nb	cubic	Im3m	92.91	8.57
Osmium	Os	hexagonal	$P6_3/mmc$	190.23	22.59
Palladium	Pd	cubic	Fm3m	106.42	12.0
Platinum	Pt	cubic	Fm3m	195.08	21.5
Rhenium	Re	cubic	Fm3m	186.21	20.8
Rhodium	Rh	cubic	Fm3m	102.91	12.4
Silicon	Si	cubic	Fd3m	28.09	2.33
Silver	Ag	cubic	Fm3m	107.87	10.50
Tantalum	Ta	cubic	Im3m	180.95	16.4
Tin	Sn	tetragonal	Fd3m	118.71	7.28
Titanium	Ti	cubic	Im3m	47.88	4.5
Tungsten	W	cubic	Im3m	183.84	19.3
Zinc	Zn	hexagonal	$P6_3/mmc$	65.39	7.14
Zirconium	Zr	hexagonal	$P6_3/mmc$	91.22	6.51

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Electrical Resistivity of Pure Metals (nohm m)

Temp. (K)	10	20	80	200	300	400	600
Aluminum	0.0010	0.00755	2.45	15.87	27.33	38.7	61.3
Beryllium	0.332	0.336	0.75	12.9	376	67.6	132
Chromium	—	—	—	77	127	158	247
Copper	0.0200	0.0280	2.15	10.46	17.25	24.02	37.92
Gold	0.226	0.35	4.81	14.62	22.71	31.07	48.7
Iron	0.238	0.287	6.93	52.0	99.8	161	329
Molybdenum	0.0089	0.0261	4.82	31.3	55.2	80.2	131
Nickel	0.057	0.140	5.45	36.7	72.0	118	255
Palladium	0.0242	0.0563	1.75	6.88	10.80	14.48	21.2
Platinum	0.154	1.17	19.22	67.7	108	146	219
Silver	0.0115	0.042	2.89	10.29	16.29	22.41	35.3
Tantalum	1.02	1.46	26.2	86.6	135	182	274
Tungsten	0.00137	0.0196	6.06	31.8	54.4	78.3	130
Zinc	0.112	0.387	11.5	38.3	60.6	83.7	134.9
Zirconium	0.253	0.357	6.64	26.3	43.3	60.3	91.5

From the *CRC Handbook of Chemistry and Physics*, 82nd edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 2001), p. 12-45. Values of resistivity at other temperatures are given in this reference.

4.2 Optical Properties

The following tables list the index of refraction n, the extinction coefficient k, and the normal incidence reflection $R(\phi = 0)$ as a function of photon energy E expressed in electron volts (eV). The dielectric function $\varepsilon = \varepsilon_1 + i\varepsilon_2$ can be computed from the complex index of refraction $N = n + ik$ using $\varepsilon_1 = n^2 - k^2$ and $\varepsilon_2 = 2nk$.

The tables are from Weaver, J. H. and Frederikse, H. P. R., Optical properties of selected elements, in *CRC Handbook of Chemistry and Physics*, 82nd edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 2001), p. 12-133. The optical constants in these tables are abridged from three more extensive tabulations.[1-3] For critical applications the reader should refer to the original work. References for individual metals are listed at the end of the tables. Generally tabulated values for the optical properties are accurate to better than 10%. Data in parentheses are extrapolated or interpolated values. For most elements the spectral range covered is from the far infrared (0.010 or 0.10 eV) to the far ultraviolet (10, 30, or 300 eV). The intervals between successive energies in the tables are chosen in such a way that the major spectral features are preserved.

Tables of n, k, and $R(\phi = 0)$ are given for the following metals:

Aluminum	Iron	Palladium	Tantalum
Chromium	Magnesium	Platinum	Titanium
Copper	Molybdenum	Rhenium	Tungsten
Germanium	Nickel	Rhodium	Zinc
Gold	Niobium	Silicon	Zirconium
Iridium	Osmium	Silver	

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Aluminum[4]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.040	98.595	203.701	0.9923	4.400	0.244	3.380	0.9249
0.050	74.997	172.199	0.9915	4.600	0.223	3.222	0.9249
0.060	62.852	150.799	0.9906	4.800	0.205	3.076	0.9249
0.070	53.790	135.500	0.9899	8.000	0.072	1.663	0.9269
0.080	45.784	123.734	0.9895	8.500	0.063	1.527	0.9272
0.090	39.651	114.102	0.9892	9.000	0.056	1.402	0.9277
0.100	34.464	105.600	0.9889	9.500	0.049	1.286	0.9282
0.125	24.965	89.250	0.9884	10.000	0.044	1.178	0.9286
0.150	18.572	76.960	0.9882	10.500	0.040	1.076	0.9293
0.175	14.274	66.930	0.9879	11.000	0.036	0.979	0.9298
0.200	11.733	59.370	0.9873	11.500	0.033	0.883	0.9283
0.250	8.586	48.235	0.9858	12.000	0.033	0.791	0.9224
0.300	6.759	40.960	0.9844	12.500	0.034	0.700	0.9118
0.350	5.438	35.599	0.9834	13.000	0.038	0.609	0.8960
0.400	4.454	31.485	0.9826	13.500	0.041	0.517	0.8789
0.500	3.072	25.581	0.9817	14.000	0.048	0.417	0.8486
0.600	2.273	21.403	0.9806	14.200	0.053	0.373	0.8312
0.700	1.770	18.328	0.9794	14.400	0.058	0.327	0.8102
0.800	1.444	15.955	0.9778	14.600	0.067	0.273	0.7802
0.900	1.264	14.021	0.9749	14.800	0.086	0.211	0.7202
1.000	1.212	12.464	0.9697	15.000	0.125	0.153	0.6119
1.100	1.201	11.181	0.9630	15.200	0.178	0.108	0.4903
1.200	1.260	10.010	0.9521	15.400	0.234	0.184	0.3881
1.300	1.468	8.949	0.9318	15.600	0.280	0.073	0.3182
1.400	2.237	8.212	0.8852	15.800	0.318	0.065	0.2694
1.500	2.745	8.309	0.8678	16.000	0.351	0.060	0.2326
1.600	2.625	8.597	0.8794	16.200	0.380	0.055	0.2031
1.700	2.143	8.573	0.8972	16.400	0.407	0.050	0.1789
1.800	1.741	8.205	0.9069	16.750	0.448	0.045	0.1460
1.900	1.488	7.821	0.9116	17.000	0.474	0.042	0.1278
2.000	1.304	7.479	0.9148	17.250	0.498	0.040	0.1129
2.200	1.018	6.846	0.9200	17.500	0.520	0.038	0.1005
2.400	0.826	6.283	0.9228	17.750	0.540	0.036	0.0899
2.600	0.695	5.800	0.9238	18.000	0.558	0.035	0.0809
2.800	0.598	5.385	0.9242	18.500	0.591	0.032	0.0664
3.000	0.523	5.024	0.9241	19.000	0.620	0.030	0.0554
3.200	0.460	4.708	0.9243	19.500	0.646	0.028	0.0467
3.400	0.407	4.426	0.9245	20.000	0.668	0.027	0.0398
3.600	0.363	4.174	0.9246	20.500	0.689	0.025	0.0342
3.800	0.326	3.946	0.9247	21.000	0.707	0.024	0.0296
4.000	0.294	3.740	0.9248	21.500	0.724	0.023	0.0258
4.200	0.267	3.552	0.9248	22.000	0.739	0.022	0.0226
4.400	0.244	3.380	0.9249	22.500	0.753	0.021	0.0199
4.600	0.223	3.222	0.9249	23.000	0.766	0.021	0.0177
4.800	0.205	3.076	0.9249	23.500	0.778	0.020	0.0157
4.000	0.294	3.740	0.9248	24.000	0.789	0.019	0.0140
4.200	0.267	3.552	0.9248	24.500	0.799	0.018	0.0126

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Aluminum[4]—*continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
25.000	0.809	0.018	0.0113	85.000	1.007	0.028	0.0002
25.500	0.817	0.017	0.0102	90.000	1.005	0.031	0.0002
26.000	0.826	0.016	0.0092	95.000	0.999	0.036	0.0003
27.000	0.840	0.015	0.0076	100.000	0.991	0.030	0.0002
28.000	0.854	0.014	0.0063	110.000	0.994	0.025	0.0002
29.000	0.865	0.014	0.0053	120.000	0.991	0.024	0.0002
30.000	0.876	0.013	0.0044	130.000	0.987	0.021	0.0001
35.000	0.915	0.010	0.0020	140.000	0.989	0.016	0.0001
40.000	0.940	0.008	0.0010	150.000	0.990	0.015	0.0001
45.000	0.957	0.007	0.0005	160.000	0.989	0.014	0.0001
50.000	0.969	0.006	0.0003	170.000	0.989	0.011	0.0001
55.000	0.979	0.005	0.0001	180.000	0.990	0.010	0.0000
60.000	0.987	0.004	0.0000	190.000	0.990	0.009	0.0000
65.000	0.995	0.004	0.0000	200.000	0.991	0.007	0.0000
70.000	1.006	0.004	0.0000	220.000	0.992	0.006	0.0000
72.500	1.025	0.004	0.0002	240.000	0.993	0.005	0.0000
75.000	1.011	0.024	0.0002	260.000	0.993	0.004	0.0000
77.500	1.008	0.025	0.0002	280.000	0.994	0.003	0.0000
80.000	1.007	0.024	0.0002	300.000	0.995	0.002	0.0000

Chromium[5]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.06	21.19	42.00	0.962	2.80	1.80	4.06	0.703
0.10	11.81	29.76	0.955	3.00	1.54	3.71	0.695
0.14	15.31	26.36	0.936	3.20	1.44	3.40	0.670
0.18	8.73	25.37	0.953	3.40	1.39	3.24	0.657
0.22	5.30	20.62	0.954	3.60	1.26	3.12	0.661
0.26	3.91	17.12	0.951	3.80	1.12	2.95	0.660
0.30	3.15	14.28	0.943	4.00	1.02	2.76	0.651
0.42	3.47	8.97	0.862	4.20	0.94	2.58	0.639
0.54	3.92	7.06	0.788	4.40	0.90	2.42	0.620
0.66	3.96	5.95	0.736	4.50	0.89	2.35	0.607
0.78	4.13	5.03	0.680	4.60	0.88	2.28	0.598
0.90	4.43	4.60	0.650	4.70	0.86	2.21	0.586
1.00	4.47	4.43	0.639	4.80	0.86	2.13	0.572
1.12	4.53	4.31	0.631	4.90	0.86	2.07	0.557
1.24	4.50	4.28	0.629	5.00	0.85	2.01	0.542
1.36	4.42	4.30	0.631	5.10	0.86	1.94	0.523
1.46	4.31	4.32	0.632	5.20	0.87	1.87	0.503
1.77	3.84	4.37	0.639	5.40	0.93	1.80	0.466
2.00	3.48	4.36	0.644	5.60	0.95	1.74	0.443
2.20	3.18	4.41	0.656	5.80	0.97	1.74	0.437
2.40	2.75	4.46	0.677	6.00	0.94	1.73	0.444
2.60	2.22	4.36	0.698	6.20	0.89	1.69	0.446

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Chromium[5]—*continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
6.40	0.85	1.66	0.447	16.50	0.31	0.75	0.134
6.60	0.80	1.59	0.444	17.00	0.90	0.73	0.132
6.80	0.75	1.51	0.439	17.50	0.88	0.72	0.130
7.00	0.74	1.45	0.425	18.00	0.87	0.70	0.129
7.20	0.71	1.39	0.414	18.50	0.84	0.69	0.130
7.40	0.69	1.33	0.404	19.00	0.82	0.68	0.131
7.60	0.66	1.23	0.378	20.00	0.77	0.64	0.130
7.80	0.67	1.15	0.347	20.5	0.76	0.63	0.129
8.00	0.68	1.07	0.315	21.0	0.74	0.58	0.121
8.20	0.71	1.00	0.278	21.5	0.72	0.55	0.116
8.50	0.74	0.92	0.235	22.0	0.71	0.52	0.112
9.0	0.83	0.81	0.170	22.5	0.70	0.50	0.109
9.50	0.92	0.74	0.132	23.0	0.69	0.48	0.105
10.00	0.98	0.73	0.120	23.5	0.68	0.45	0.101
10.50	1.01	0.72	0.112	24.0	0.68	0.43	0.096
11.00	1.05	0.69	0.103	24.5	0.67	0.39	0.089
11.50	1.09	0.69	0.100	25.0	0.68	0.36	0.080
12.00	1.13	0.70	0.101	25.5	0.68	0.33	0.072
12.50	1.15	0.73	0.108	26.0	0.70	0.31	0.063
13.00	1.15	0.77	0.119	26.5	0.71	0.28	0.055
13.50	1.12	0.80	0.128	27.0	0.72	0.26	0.048
14.00	1.09	0.82	0.135	27.5	0.73	0.25	0.043
14.50	1.03	0.82	0.142	28.0	0.75	0.23	0.037
15.00	1.00	0.82	0.143	29.0	0.77	0.22	0.032
15.50	0.96	0.80	0.141	30.0	0.78	0.21	0.030
16.00	0.92	0.77	0.139				

Copper[6]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.10	29.69	71.57	0.980	3.00	1.18	2.21	0.509
0.50	1.71	17.63	0.979	3.20	1.23	2.07	0.468
1.00	0.44	8.48	0.976	3.40	1.27	1.95	0.434
1.50	0.26	5.26	0.965	3.60	1.31	1.87	0.407
1.70	0.22	4.43	0.958	3.80	1.34	1.81	0.387
1.75	0.21	4.25	0.956	4.00	1.34	1.72	0.364
1.80	0.21	4.04	0.952	4.20	1.42	1.64	0.336
1.85	0.22	3.85	0.947	4.40	1.49	1.64	0.329
1.90	0.21	3.67	0.943	4.60	1.52	1.67	0.334
2.00	0.27	3.24	0.910	4.80	1.53	1.71	0.345
2.10	0.47	2.81	0.814	5.00	1.47	1.78	0.366
2.20	0.83	2.60	0.673	5.20	1.38	1.80	0.380
2.30	1.04	2.59	0.618	5.40	1.28	1.78	0.389
2.40	1.12	2.60	0.602	5.60	1.18	1.74	0.391
2.60	1.15	2.50	0.577	5.80	1.10	1.67	0.389
2.80	1.17	2.36	0.545	6.00	1.04	1.59	0.380

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Copper[6] — *continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
6.50	0.96	1.37	0.329	38.00	0.93	0.18	0.010
7.00	0.97	1.20	0.271	39.00	0.93	0.17	0.009
7.50	1.00	1.09	0.230	40.00	0.93	0.17	0.009
8.00	1.03	1.03	0.206	41.00	0.94	0.16	0.008
8.50	1.03	0.98	0.189	42.00	0.94	0.16	0.007
9.00	1.03	0.92	0.171	43.00	0.94	0.15	0.007
9.50	1.03	0.87	0.154	44.00	0.95	0.15	0.007
10.00	1.04	0.82	0.139	45.00	0.95	0.15	0.006
11.00	1.07	0.75	0.118	46.00	0.95	0.15	0.006
12.00	1.09	0.73	0.111	47.00	0.95	0.14	0.006
13.00	1.08	0.72	0.109	48.00	0.95	0.14	0.006
14.00	1.06	0.72	0.111	49.00	0.95	0.14	0.005
14.50	1.03	0.72	0.111	50.00	0.95	0.13	0.005
15.00	1.01	0.71	0.111	51.00	0.95	0.13	0.005
15.50	0.98	0.69	0.109	52.00	0.95	0.13	0.005
16.00	0.95	0.67	0.106	53.00	0.96	0.12	0.004
17.00	0.91	0.62	0.097	54.00	0.96	0.12	0.004
18.00	0.89	0.56	0.084	55.00	0.96	0.12	0.004
19.00	0.88	0.51	0.071	56.00	0.96	0.11	0.004
20.00	0.88	0.45	0.059	57.00	0.96	0.11	0.004
21.00	0.90	0.41	0.048	58.00	0.96	0.11	0.004
22.00	0.92	0.38	0.040	59.00	0.97	0.11	0.003
23.00	0.94	0.37	0.035	60.00	0.97	0.11	0.003
24.00	0.96	0.37	0.035	61.00	0.97	0.11	0.003
25.00	0.96	0.40	0.040	62.00	0.97	0.11	0.003
26.00	0.92	0.40	0.044	63.00	0.96	0.10	0.003
27.00	0.88	0.38	0.043	64.00	0.96	0.10	0.003
28.00	0.86	0.35	0.039	65.00	0.97	0.10	0.003
29.00	0.85	0.30	0.032	66.00	0.97	0.10	0.003
30.00	0.86	0.26	0.025	67.00	0.97	0.09	0.003
31.00	0.88	0.24	0.020	68.00	0.97	0.09	0.002
32.00	0.89	0.22	0.017	69.00	0.97	0.09	0.002
33.00	0.90	0.21	0.015	70.00	0.97	0.09	0.002
34.00	0.91	0.20	0.014	75.00	0.98	0.09	0.002
35.00	0.92	0.20	0.013	80.00	0.98	0.09	0.002
36.00	0.92	0.19	0.012	85.00	0.97	0.09	0.002
37.00	0.92	0.19	0.011	90.00	0.96	0.08	0.002

Germanium[7]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.01240	(4.0065)	3.00E-03	0.361	0.01736	(4.0060)	1.50E-03	0.361
0.01364	4.0063	2.40E-03	0.361	0.01860		1.50E-03	
0.01488	(4.0060)	1.70E-03	0.361	0.01984		1.60E-03	
0.01612	(4.0060)	1.55E-03	0.361	0.02108		1.60E-03	

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Germanium[7]*—continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.02232		1.55E-03		0.08266	4.0013	9.78E-05	0.360
0.02356		1.53E-03		0.08551	4.0015	5.77E-05	0.360
0.02480		1.50E-03		0.08920		3.98E-05	
0.02604		1.25E-03		0.09460		4.59E-05	
0.02728		8.50E-04		0.09840		3.51E-05	
0.02852		6.50E-04		0.1	4.0063	3.70E-05	0.361
0.02976		7.00E-04		0.2	4.0108		0.361
0.03100	3.9827	8.50E-04	0.358	0.3	4.0246		0.362
0.03224		1.55E-03		0.4	4.0429		0.364
0.03348		2.75E-03		0.5	(4.074)		0.367
0.03472		3.55E-03		0.6	(4.104)	6.58E-07	0.370
0.03596	(3.9900)	3.05E-03	0.359	0.7	4.180	1.27E-04	0.377
0.03720		2.75E-03		0.8	4.275	5.67E-03	0.385
0.03844		2.70E-03		0.9	4.285	7.45E-02	0.386
0.03968	(3.9930)	2.90E-03	0.359	1.0	4.325	8.09E-02	0.390
0.04092		2.95E-03		1.1	4.385	0.103	0.395
0.04215		3.20E-03		1.2	4.420	0.123	0.398
0.04339		6.30E-03		1.3	4.495	0.167	0.405
0.04463		3.40E-03		1.4	4.560	0.190	0.411
0.04587	(3.9955)	2.50E-03	0.360	1.5	4.635	0.298	0.418
0.04711		2.10E-03		1.6	4.763	0.345	0.428
0.04835		2.00E-03		1.7	4.897	0.401	0.439
0.04959		8.00E-04		1.8	5.067	0.500	0.453
0.05083		1.40E-03		1.9	5.380	0.540	0.475
0.05207		1.35E-03		2.0	5.588	0.933	0.495
0.05331		1.10E-03		2.1	5.748	1.634	0.523
0.05455		8.00E-04		2.2	5.283	2.049	0.516
0.05579		6.00E-04		2.3	5.062	2.318	0.519
0.05703		9.0 E-04		2.4	4.610	2.455	0.508
0.05827		6.5 E-04		2.5	4.340	2.384	0.492
0.05951		4.6 E-04		2.6	4.180	2.309	0.480
0.06075		4.0 E-04		2.7	4.082	2.240	0.471
0.06199	3.9992	3.98E-04	0.360	2.8	4.035	2.181	0.464
0.06323		4.0 E-04		2.9	4.037	2.140	0.461
0.06447		4.3 E-04		3.0	4.082	2.145	0.463
0.06571		4.4 E-04		3.1	4.141	2.215	0.471
0.06695	(4.0000)	4.3 E-04	0.360	3.2	4.157	2.340	0.482
0.06819		3.1 E-04		3.3	4.128	2.469	0.490
0.06943		3.3 E-04		3.4	4.070	2.579	0.497
0.07067		3.8 E-04		3.5	4.020	2.667	0.502
0.07191		3.3 E-04		3.6	3.985	2.759	0.509
0.07315		2.5 E-04		3.7	3.958	2.863	0.517
0.07439		1.9 E-04		3.8	3.936	2.986	0.527
0.07514		1.58E-04		3.9	3.920	3.137	0.539
0.07749	4.0009	9.55E-05	0.360	4.0	3.905	3.336	0.556
0.07999	4.0011	1.71E-04	0.360	4.1	3.869	3.614	0.579

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Germanium[7]*—continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
4.2	3.745	4.009	0.612	6.5	1.10	2.05	0.489
4.3	3.338	4.507	0.659	7.0	1.00	1.80	0.448
4.4	2.516	4.669	0.705	7.5		1.60	
4.5	1.953	4.297	0.713	8.0	0.92	1.40	0.348
4.6	1.720	3.960	0.702	8.5	0.92	1.20	0.282
4.7	1.586	3.709	0.690	9.0	0.92	1.14	0.262
4.8	1.498	3.509	0.677	9.5		1.00	
4.9	1.435	3.342	0.664	10.0	0.93	0.86	0.167
5.0	1.394	3.197	0.650	20.0		0.237	
5.1	1.370	3.073	0.636	22.0		0.179	
5.2	1.364	2.973	0.622	24.0		0.144	
5.3	1.371	2.897	0.609	26.0		0.110	
5.4	1.383	2.854	0.600	28.0		0.0747	
5.5	1.380	2.842	0.598	30.0		0.1020	
5.6	1.360	2.846	0.602	32.0		0.0999	
5.7	1.293	2.163	0.479	34.0		0.0856	
5.8	1.209	2.873	0.632	36.0		0.0740	
5.9	1.108	2.813	0.641	38.0		0.0651	
6.0	1.30	2.34	0.517	40.0		0.0604	

Gold[8]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.10	8.17	82.83	0.995	2.90	1.50	1.79	0.368
0.20	2.13	41.73	0.995	3.00	1.54	1.80	0.369
0.30	0.99	27.82	0.995	3.10	1.54	1.81	0.371
0.40	0.59	20.83	0.995	3.20	1.54	1.80	0.368
0.50	0.39	16.61	0.994	3.30	1.55	1.78	0.362
0.60	0.28	13.78	0.994	3.40	1.56	1.76	0.356
0.70	0.22	11.75	0.994	3.50	1.58	1.73	0.349
0.80	0.18	10.21	0.993	3.60	1.62	1.73	0.346
0.90	0.15	9.01	0.993	3.70	1.64	1.75	0.351
1.00	0.13	8.03	0.992	3.80	1.63	1.79	0.360
1.20	0.10	6.54	0.991	3.90	1.59	1.81	0.366
1.40	0.08	5.44	0.989	4.00	1.55	1.81	0.369
1.60	0.08	4.56	0.986	4.10	1.51	1.79	0.368
1.80	0.09	3.82	0.979	4.20	1.48	1.78	0.367
2.00	0.13	3.16	0.953	4.30	1.45	1.77	0.368
2.10	0.18	2.84	0.925	4.40	1.41	1.76	0.370
2.20	0.24	2.54	0.880	4.50	1.35	1.74	0.370
2.40	0.50	1.86	0.647	4.60	1.30	1.69	0.364
2.50	0.82	1.59	0.438	4.70	1.27	1.64	0.354
2.60	1.24	1.54	0.331	4.80	1.25	1.59	0.344
2.70	1.43	1.72	0.356	4.90	1.23	1.54	0.332
2.80	1.46	1.77	0.368	5.00	1.22	1.49	0.319

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Gold[8]*—continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
5.20	1.21	1.40	0.295	10.00	1.37	0.80	0.126
5.40	1.21	1.33	0.275	10.20	1.36	0.80	0.127
5.60	1.21	1.27	0.256	10.40	1.35	0.80	0.125
5.80	1.21	1.20	0.236	10.60	1.34	0.79	0.123
6.00	1.22	1.14	0.218	10.80	1.34	0.77	0.120
6.20	1.24	1.09	0.203	11.00	1.34	0.76	0.116
6.40	1.25	1.05	0.190	11.20	1.34	0.74	0.113
6.60	1.27	1.01	0.177	11.40	1.35	0.73	0.111
6.80	1.30	0.97	0.167	11.60	1.36	0.72	0.109
7.00	1.34	0.95	0.162	11.80	1.38	0.71	0.108
7.20	1.36	0.95	0.161	12.00	1.39	0.71	0.109
7.40	1.38	0.96	0.164	12.40	1.44	0.73	0.115
7.60	1.38	0.98	0.169	12.80	1.45	0.79	0.127
7.80	1.35	0.99	0.171	13.20	1.42	0.84	0.137
8.00	1.31	0.96	0.165	13.60	1.37	0.86	0.140
8.20	1.30	0.92	0.155	14.00	1.33	0.86	0.140
8.40	1.30	0.89	0.147	14.40	1.29	0.86	0.139
8.60	1.31	0.88	0.144	14.80	1.26	0.84	0.135
8.80	1.31	0.86	0.140	15.20	1.24	0.83	0.132
9.00	1.30	0.83	0.133	15.60	1.22	0.81	0.127
9.20	1.31	0.81	0.126	16.00	1.21	0.79	0.123
9.40	1.33	0.78	0.122	16.40	1.20	0.78	0.119
9.60	1.36	0.78	0.121	16.80	1.19	0.76	0.116
9.80	1.37	0.79	0.124	17.20	1.19	0.75	0.114
5.60	1.21	1.27	0.256	17.60	1.19	0.74	0.111
5.80	1.21	1.20	0.236	18.00	1.19	0.74	0.109
6.00	1.22	1.14	0.218	18.40	1.19	0.73	0.109
6.20	1.24	1.09	0.203	18.80	1.20	0.74	0.110
6.40	1.25	1.05	0.190	19.20	1.21	0.76	0.116
6.60	1.27	1.01	0.177	19.60	1.21	0.80	0.125
6.80	1.30	0.97	0.167	20.00	1.18	0.83	0.133
7.00	1.34	0.95	0.162	20.40	1.14	0.85	0.141
7.20	1.36	0.95	0.161	20.80	1.10	0.87	0.149
7.40	1.38	0.96	0.164	21.20	1.05	0.88	0.156
7.60	1.38	0.98	0.169	21.60	1.00	0.88	0.162
7.80	1.35	0.99	0.171	22.00	0.94	0.86	0.164
8.00	1.31	0.96	0.165	22.40	0.89	0.83	0.163
8.20	1.30	0.92	0.155	22.80	0.85	0.79	0.157
8.40	1.30	0.89	0.147	23.20	0.82	0.75	0.149
8.60	1.31	0.88	0.144	23.60	0.80	0.70	0.138
8.80	1.31	0.86	0.140	24.00	0.80	0.66	0.125
9.00	1.30	0.83	0.133	24.40	0.80	0.62	0.113
9.20	1.31	0.81	0.126	24.80	0.80	0.58	0.101
9.40	1.33	0.78	0.122	25.20	0.82	0.56	0.090
9.60	1.36	0.78	0.121	25.60	0.83	0.54	0.084
9.80	1.37	0.79	0.124	26.00	0.84	0.52	0.079

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Gold[8]—*continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
26.40	0.85	0.51	0.074	28.40	0.88	0.48	0.062
26.80	0.85	0.50	0.071	28.80	0.88	0.48	0.062
27.20	0.86	0.49	0.068	29.20	0.88	0.48	0.062
27.60	0.86	0.49	0.065	29.60	0.87	0.48	0.064
28.00	0.87	0.48	0.063	30.00	0.86	0.48	0.064

Iridium[9]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.10	28.49	60.62	0.975	3.40	1.53	3.05	0.610
0.15	15.32	45.15	0.973	3.60	1.52	2.81	0.573
0.20	9.69	35.34	0.972	3.80	1.61	2.69	0.541
0.25	6.86	28.84	0.969	4.00	1.64	2.68	0.535
0.30	5.16	24.25	0.967	4.20	1.58	2.71	0.549
0.35	4.11	20.79	0.964	4.40	1.45	2.68	0.561
0.40	3.42	18.06	0.960	4.60	1.31	2.60	0.567
0.45	3.05	15.82	0.954	4.80	1.18	2.49	0.570
0.50	2.98	14.06	0.944	5.00	1.10	2.35	0.559
0.60	2.79	11.58	0.925	5.20	1.04	2.22	0.543
0.70	2.93	9.78	0.895	5.40	1.00	2.09	0.522
0.80	3.14	8.61	0.862	5.60	0.98	1.98	0.499
0.90	3.19	7.88	0.840	5.80	0.96	1.86	0.474
1.00	3.15	7.31	0.822	6.00	0.95	1.78	0.454
1.10	3.04	6.84	0.808	6.20	0.94	1.68	0.427
1.20	2.96	6.41	0.791	6.40	0.94	1.59	0.401
1.30	2.85	6.07	0.779	6.60	0.94	1.50	0.375
1.40	2.72	5.74	0.767	6.80	0.95	1.42	0.345
1.50	2.65	5.39	0.750	7.00	0.97	1.34	0.318
1.60	2.68	5.08	0.728	7.20	0.99	1.27	0.290
1.70	2.69	4.92	0.716	7.40	1.02	1.20	0.262
1.80	2.64	4.81	0.710	7.60	1.03	1.14	0.241
1.90	2.57	4.68	0.704	7.80	1.08	1.06	0.208
2.00	2.50	4.57	0.699	8.00	1.13	1.03	0.191
2.10	2.40	4.48	0.697	8.20	1.18	1.00	0.179
2.20	2.29	4.38	0.695	8.40	1.22	0.98	0.171
2.30	2.18	4.26	0.692	8.60	1.26	0.96	0.164
2.40	2.07	4.14	0.689	8.80	1.29	0.95	0.160
2.50	1.98	4.00	0.682	9.00	1.33	0.94	0.157
2.60	1.91	3.86	0.673	9.20	1.36	0.95	0.159
2.70	1.85	3.73	0.665	9.40	1.39	0.95	0.161
2.80	1.81	3.61	0.655	9.60	1.42	0.97	0.163
2.90	1.77	3.51	0.646	9.80	1.44	0.99	0.169
3.00	1.73	3.43	0.640	10.00	1.45	1.01	0.175
3.20	1.62	3.26	0.629	10.20	1.45	1.04	0.182

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Iridium[9]—*continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
10.40	1.44	1.07	0.187	19.60	1.15	1.05	0.197
10.60	1.43	1.09	0.193	20.00	1.10	1.06	0.205
10.80	1.41	1.12	0.200	20.50	1.04	1.05	0.210
11.00	1.38	1.13	0.206	21.00	0.99	1.04	0.215
11.20	1.34	1.14	0.208	21.50	0.94	1.02	0.220
11.40	1.31	1.13	0.208	22.00	0.89	1.00	0.222
11.60	1.28	1.12	0.206	22.50	0.84	0.99	0.228
11.80	1.25	1.10	0.203	23.00	0.79	0.96	0.232
12.00	1.24	1.08	0.199	23.50	0.76	0.92	0.228
12.40	1.21	1.05	0.191	24.00	0.73	0.87	0.223
12.80	1.19	1.01	0.181	24.50	0.70	0.83	0.218
13.20	1.18	0.98	0.173	25.00	0.69	0.79	0.209
13.60	1.17	0.95	0.165	25.50	0.68	0.76	0.200
14.00	1.16	0.91	0.155	26.00	0.67	0.72	0.192
14.40	1.17	0.88	0.147	26.50	0.67	0.69	0.181
14.80	1.18	0.87	0.142	27.00	0.66	0.66	0.174
15.20	1.19	0.84	0.136	27.50	0.66	0.63	0.166
15.60	1.20	0.83	0.133	28.00	0.66	0.61	0.158
16.00	1.21	0.83	0.131	28.50	0.66	0.59	0.151
16.40	1.23	0.82	0.129	29.00	0.65	0.57	0.148
16.80	1.25	0.82	0.127	29.50	0.64	0.55	0.145
17.20	1.28	0.83	0.131	30.00	0.64	0.53	0.140
17.60	1.30	0.87	0.140	32.00	0.62	0.44	0.119
18.00	1.30	0.93	0.154	34.00	0.64	0.35	0.091
18.40	1.27	0.97	0.166	36.00	0.69	0.27	0.059
18.80	1.24	1.00	0.176	38.00	0.73	0.24	0.044
19.20	1.20	1.03	0.187	40.00	0.76	0.22	0.034

Iron[10]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.10	6.41	33.07	0.978	1.20	3.24	4.26	0.641
0.15	6.26	22.82	0.956	1.30	3.16	4.07	0.626
0.20	3.68	18.23	0.958	1.40	3.12	3.87	0.609
0.26	4.98	13.68	0.911	1.50	3.05	3.77	0.601
0.30	4.87	12.05	0.892	1.60	3.00	3.60	0.585
0.36	4.68	10.44	0.867	1.70	2.98	3.52	0.577
0.40	4.42	9.75	0.858	1.80	2.92	3.46	0.573
0.50	4.14	8.02	0.817	1.90	2.89	3.37	0.563
0.60	3.93	6.95	0.783	2.00	2.85	3.36	0.563
0.70	3.78	6.17	0.752	2.10	2.80	3.34	0.562
0.80	3.65	5.60	0.725	2.20	2.74	3.33	0.563
0.90	3.52	5.16	0.700	2.30	2.65	3.34	0.567
1.00	3.43	4.79	0.678	2.40	2.56	3.31	0.567
1.10	3.33	4.52	0.660	2.50	2.46	3.31	0.570

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Iron[10]*—continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
2.60	2.34	3.30	0.576	9.50	0.90	1.02	0.226
2.70	2.23	3.25	0.575	9.67	0.90	1.00	0.221
2.80	2.12	3.23	0.580	9.83	0.89	0.99	0.218
2.90	2.01	3.17	0.580	10.00	0.88	0.97	0.213
3.00	1.88	3.12	0.583	10.17	0.87	0.94	0.203
3.10	1.78	3.04	0.580	10.33	0.87	0.91	0.196
3.20	1.70	2.96	0.576	10.50	0.87	0.89	0.189
3.30	1.62	2.87	0.572	10.67	0.88	0.87	0.179
3.40	1.55	2.79	0.565	10.83	0.89	0.85	0.170
3.50	1.50	2.70	0.556	11.00	0.91	0.83	0.162
3.60	1.47	2.63	0.548	11.17	0.92	0.83	0.159
3.70	1.43	2.56	0.542	11.33	0.93	0.84	0.159
3.83	1.38	2.49	0.534	11.50	0.93	0.84	0.160
4.00	1.30	2.39	0.527	11.67	0.93	0.84	0.162
4.17	1.26	2.27	0.510	11.83	0.92	0.84	0.163
4.33	1.23	2.18	0.494	12.00	0.91	0.84	0.163
4.50	1.20	2.10	0.482	12.17	0.90	0.84	0.165
4.67	1.16	2.02	0.470	12.33	0.89	0.83	0.164
4.83	1.14	1.93	0.451	12.50	0.98	0.83	0.165
5.00	1.14	1.87	0.435	12.67	0.87	0.82	0.166
5.17	1.12	1.81	0.425	12.83	0.86	0.81	0.166
5.33	1.11	1.75	0.408	13.00	0.85	0.80	0.162
5.50	1.09	1.17	0.401	13.17	0.84	0.79	0.161
5.67	1.09	1.65	0.383	13.33	0.84	0.78	0.160
5.83	1.10	1.61	0.373	13.50	0.83	0.77	0.159
6.00	1.09	1.59	0.366	13.67	0.82	0.76	0.157
6.17	1.08	1.57	0.365	13.83	0.81	0.75	0.154
6.33	1.04	1.55	0.365	14.00	0.81	0.73	0.151
6.50	1.02	1.51	0.358	14.17	0.80	0.72	0.149
6.67	1.00	1.47	0.351	14.33	0.80	0.71	0.146
6.83	0.97	1.43	0.346	14.50	0.79	0.79	0.144
7.00	0.96	1.39	0.333	14.67	0.79	0.69	0.141
7.17	0.94	1.35	0.327	14.83	0.78	0.67	0.138
7.33	0.94	1.30	0.311	15.00	0.78	0.66	0.135
7.50	0.94	1.26	0.298	15.17	0.78	0.65	0.131
7.67	0.94	1.23	0.288	15.33	0.78	0.64	0.238
7.83	0.94	1.21	0.279	15.50	0.77	0.63	0.126
8.00	0.94	1.18	0.272	15.67	0.77	0.62	0.123
8.17	0.94	1.16	0.265	15.83	0.77	0.61	0.119
8.33	0.94	1.14	0.258	16.00	0.77	0.60	0.116
8.50	0.94	1.12	0.251	16.17	0.78	0.58	0.112
8.67	0.94	1.10	0.246	16.33	0.78	0.58	0.110
8.83	0.92	1.08	0.240	16.50	0.78	0.57	0.107
9.00	0.93	1.07	0.236	16.67	0.77	0.56	0.106
9.17	0.92	1.06	0.233	16.83	0.78	0.55	0.103
9.33	0.91	1.04	0.231	17.00	0.78	0.55	0.102

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Iron[10]—*continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
17.17	0.78	0.54	0.100	21.67	0.72	0.38	0.071
17.33	0.78	0.54	0.098	21.83	0.72	0.37	0.070
17.50	0.77	0.53	0.097	22.00	0.72	0.36	0.068
17.67	0.77	0.52	0.095	22.17	0.71	0.35	0.067
17.83	0.78	0.51	0.092	22.33	0.72	0.34	0.064
18.00	0.78	0.51	0.091	22.50	0.72	0.34	0.063
18.17	0.78	0.51	0.090	22.67	0.72	0.33	0.062
18.33	0.78	0.50	0.089	22.83	0.72	0.32	0.059
18.50	0.77	0.50	0.089	23.00	0.72	0.31	0.058
18.67	0.77	0.50	0.088	23.17	0.72	0.30	0.056
18.83	0.77	0.49	0.087	23.33	0.72	0.29	0.054
19.00	0.77	0.49	0.087	23.50	0.73	0.28	0.050
19.17	0.76	0.49	0.088	23.67	0.73	0.28	0.049
19.33	0.76	0.48	0.087	23.83	0.74	0.27	0.047
19.50	0.75	0.47	0.086	24.00	0.74	0.27	0.045
19.67	0.75	0.47	0.085	24.17	0.74	0.26	0.044
19.83	0.75	0.46	0.084	24.33	0.74	0.26	0.043
20.00	0.74	0.45	0.083	24.50	0.74	0.25	0.042
20.17	0.74	0.44	0.081	24.67	0.75	0.25	0.040
20.33	0.74	0.44	0.081	24.83	0.75	0.24	0.039
20.50	0.74	0.42	0.080	25.00	0.75	0.24	0.038
20.67	0.73	0.43	0.079	26.00	0.76	0.21	0.031
20.83	0.73	0.42	0.078	27.00	0.78	0.18	0.026
21.00	0.73	0.41	0.077	28.00	0.79	0.16	0.021
21.17	0.72	0.40	0.076	29.00	0.81	0.14	0.017
21.33	0.72	0.39	0.074	30.00	0.82	0.13	0.014
21.50	0.72	0.38	0.073				

Magnesium[11] (evaporated)

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
2.145	0.48	3.71	0.880	5.636	0.15	1.50	0.832
2.270	0.57	3.47	0.843	6.200	0.20	1.40	0.765
2.522	0.53	2.92	0.805	6.889	0.25	1.30	0.693
2.845	0.52	2.65	0.777	7.750	0.20	1.20	0.722
3.064	0.52	2.05	0.681	8.857	0.15	0.95	0.730
5.167	0.10	1.60	0.894	10.335	0.25	0.40	0.419

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Molybdenum[12]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.10	18.53	68.51	0.985	3.50	3.06	3.21	0.543
0.15	8.78	47.54	0.985	3.60	3.05	3.23	0.546
0.20	5.10	35.99	0.985	3.70	3.04	3.27	0.550
0.25	3.36	28.75	0.984	3.80	3.04	3.31	0.554
0.30	2.44	23.80	0.983	3.90	3.04	3.40	0.564
0.34	2.00	20.84	0.982	4.00	3.01	3.51	0.576
0.38	1.70	18.44	0.980	4.20	2.77	3.77	0.610
0.42	1.57	16.50	0.978	4.40	2.39	3.88	0.640
0.46	1.46	14.91	0.975	4.60	2.06	3.84	0.658
0.50	1.37	13.55	0.971	4.80	1.75	3.76	0.678
0.54	1.35	12.36	0.966	5.00	1.46	3.62	0.695
0.58	1.34	11.34	0.960	5.20	1.22	3.42	0.706
0.62	1.38	10.44	0.952	5.40	1.07	3.20	0.706
0.66	1.43	9.67	0.942	5.60	0.96	2.99	0.700
0.70	1.48	8.99	0.932	5.80	0.89	2.80	0.688
0.74	1.51	8.38	0.921	6.00	0.85	2.64	0.674
0.78	1.60	7.83	0.906	6.20	0.81	2.50	0.660
0.82	1.64	7.35	0.892	6.40	0.79	2.36	0.641
0.86	1.70	6.89	0.876	6.60	0.78	2.24	0.619
9.90	1.74	6.48	0.859	6.80	0.78	2.13	0.592
1.00	1.94	5.58	0.805	7.00	0.80	2.04	0.568
1.10	2.15	4.85	0.743	7.20	0.81	1.98	0.548
1.20	2.44	4.22	0.671	7.40	0.81	1.95	0.542
1.30	2.77	3.74	0.608	7.60	0.75	1.90	0.552
1.40	3.15	3.40	0.562	7.80	0.71	1.81	0.542
1.50	3.53	3.30	0.550	8.00	0.69	1.73	0.530
1.60	3.77	3.41	0.562	8.20	0.67	1.65	0.512
1.70	3.84	3.51	0.570	8.40	0.66	1.57	0.495
1.80	3.81	3.58	0.576	8.60	0.65	1.49	0.475
1.90	3.74	3.58	0.576	8.80	0.65	1.41	0.450
2.00	3.68	3.52	0.571	9.00	0.65	1.33	0.420
2.10	3.68	3.45	0.565	9.20	0.67	1.25	0.385
2.20	3.76	3.41	0.562	9.40	0.69	1.19	0.355
2.30	3.79	3.61	0.578	9.60	0.71	1.12	0.320
2.40	3.59	3.78	0.594	9.80	0.74	1.05	0.285
2.50	3.36	3.73	0.591	10.00	0.77	0.99	0.250
2.60	3.22	3.61	0.582	10.20	0.81	0.93	0.217
2.70	3.13	3.51	0.573	10.40	0.86	0.88	0.188
2.80	3.08	3.42	0.565	10.60	0.91	0.83	0.162
2.90	3.05	3.33	0.566	10.80	0.98	0.79	0.138
3.00	3.04	3.27	0.550	11.00	1.05	0.77	0.125
3.10	3.03	3.21	0.544	11.20	1.12	0.78	0.123
3.20	3.05	3.18	0.540	11.40	1.18	0.80	0.125
3.30	3.06	3.18	0.540	11.60	1.23	0.85	0.135
3.40	3.06	3.19	0.541	11.80	1.25	0.89	0.145

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Molybdenum[12]—*continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
12.00	1.26	0.92	0.154	23.60	0.58	0.53	0.166
12.40	1.25	0.98	0.168	24.00	0.58	0.49	0.151
12.80	1.23	1.00	0.178	24.60	0.60	0.43	0.124
13.20	1.20	1.02	0.185	25.00	0.62	0.39	0.106
13.60	1.17	1.02	0.187	25.60	0.66	0.35	0.085
14.00	1.15	1.01	0.185	26.00	0.68	0.33	0.072
14.40	1.13	1.00	0.182	26.50	0.71	0.31	0.060
14.80	1.13	0.99	0.179	27.00	0.73	0.29	0.050
15.00	1.14	0.99	0.179	27.50	0.76	0.28	0.041
15.60	1.15	1.01	0.184	28.00	0.79	0.27	0.036
16.00	1.14	1.04	0.194	28.50	0.81	0.26	0.031
16.60	1.10	1.10	0.216	29.00	0.83	0.26	0.028
17.00	1.04	1.12	0.233	29.50	0.86	0.26	0.025
17.60	0.94	1.14	0.257	30.00	0.88	0.26	0.023
18.00	0.87	1.12	0.270	31.00	0.92	0.29	0.024
18.60	0.77	1.08	0.283	32.00	0.92	0.32	0.030
19.00	0.71	1.02	0.284	33.00	0.90	0.33	0.032
19.60	0.66	0.94	0.275	34.00	0.91	0.34	0.034
20.00	0.64	0.89	0.264	35.00	0.87	0.37	0.043
20.60	0.62	0.81	0.245	36.00	0.82	0.34	0.043
21.00	0.61	0.77	0.234	37.00	0.81	0.30	0.038
21.60	0.61	0.71	0.215	38.00	0.81	0.27	0.033
22.00	0.60	0.69	0.207	39.00	0.82	0.25	0.029
22.60	0.59	0.63	0.195	40.00	0.83	0.23	0.025
23.00	0.58	0.60	0.185				

Nickel[13]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.10	9.54	45.82	0.983	1.20	2.85	5.10	0.721
0.15	5.45	30.56	0.978	1.30	2.74	4.85	0.708
0.20	4.12	22.48	0.969	1.40	2.65	4.63	0.695
0.25	4.25	17.68	0.950	1.50	2.53	4.47	0.688
0.30	4.19	15.05	0.934	1.60	2.43	4.31	0.679
0.35	4.03	13.05	0.918	1.70	2.28	4.18	0.677
0.40	3.84	11.43	0.900	1.80	2.14	4.01	0.670
0.50	4.03	9.64	0.864	1.90	2.02	3.82	0.659
0.60	3.84	8.35	0.835	2.00	1.92	3.65	0.649
0.70	3.59	7.48	0.813	2.10	1.85	3.48	0.634
0.80	3.38	6.82	0.794	2.20	1.80	3.33	0.620
0.90	3.18	6.23	0.774	2.30	1.75	3.19	0.605
1.00	3.06	5.74	0.753	2.40	1.71	3.06	0.590
1.10	2.97	5.38	0.734	2.50	1.67	2.93	0.575

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Nickel[13]*—continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
2.60	1.65	2.81	0.557	10.40	0.95	0.80	0.145
2.70	1.64	2.71	0.542	10.60	0.97	0.76	0.129
2.80	1.63	2.61	0.525	10.80	0.99	0.75	0.123
2.90	1.62	2.52	0.509	11.00	1.01	0.73	0.115
3.00	1.61	2.44	0.495	11.25	1.04	0.72	0.111
3.10	1.61	2.36	0.480	11.50	1.05	0.71	0.109
3.20	1.61	2.30	0.467	11.75	1.07	0.71	0.108
3.30	1.61	2.23	0.454	12.00	1.07	0.71	0.108
3.40	1.62	2.17	0.441	12.25	1.07	0.71	0.107
3.50	1.63	2.11	0.428	12.50	1.08	0.71	0.106
3.60	1.64	2.07	0.416	12.75	1.08	0.71	0.106
3.70	1.66	2.02	0.405	13.00	1.08	0.71	0.105
3.80	1.69	1.99	0.397	13.25	1.08	0.71	0.105
3.90	1.72	1.98	0.393	13.50	1.07	0.70	0.105
4.00	1.73	1.98	0.392	13.75	1.07	0.70	0.105
4.20	1.74	2.01	0.396	14.00	1.07	0.71	0.106
4.40	1.71	2.06	0.409	14.25	1.06	0.70	0.106
4.60	1.63	2.09	0.421	14.50	1.05	0.70	0.106
4.80	1.53	2.11	0.435	14.75	1.04	0.70	0.107
5.00	1.40	2.10	0.449	15.00	1.03	0.70	0.107
5.20	1.27	2.04	0.454	15.25	1.02	0.69	0.106
5.40	1.16	1.94	0.449	15.50	1.01	0.69	0.105
5.60	1.09	1.83	0.435	15.75	1.00	0.68	0.104
5.80	1.04	1.73	0.417	16.00	0.99	0.67	0.103
6.20	1.00	1.54	0.371	16.50	0.98	0.66	0.101
6.40	1.01	1.46	0.345	17.00	0.96	0.64	0.098
6.60	1.01	1.40	0.325	17.50	0.94	0.63	0.096
6.80	1.02	1.35	0.308	18.00	0.92	0.61	0.092
7.00	1.03	1.30	0.291	18.50	0.91	0.58	0.087
7.20	1.03	1.27	0.282	19.00	0.90	0.56	0.082
7.40	1.03	1.24	0.273	19.50	0.90	0.54	0.077
7.60	1.02	1.22	0.265	20.00	0.89	0.51	0.071
7.80	1.01	1.18	0.256	20.50	0.89	0.49	0.066
8.00	1.01	1.15	0.248	21.00	0.90	0.47	0.061
8.20	1.00	1.13	0.242	21.50	0.91	0.46	0.057
8.40	0.99	1.11	0.235	22.00	0.91	0.45	0.055
8.60	0.98	1.08	0.228	22.50	0.91	0.44	0.053
8.80	0.97	1.05	0.220	23.00	0.92	0.44	0.051
9.00	0.97	1.01	0.211	23.50	0.91	0.44	0.052
9.20	0.96	0.99	0.203	24.00	0.90	0.43	0.051
9.40	0.95	0.96	0.194	24.50	0.90	0.43	0.051
9.60	0.95	0.93	0.185	25.00	0.89	0.42	0.050
9.80	0.95	0.89	0.175	26.00	0.88	0.39	0.046
10.00	0.95	0.87	0.166	27.00	0.87	0.37	0.042
10.20	0.95	0.83	0.155	28.00	0.87	0.35	0.040

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Nickel[13]—*continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
29.00	0.86	0.34	0.037	65.00	0.98	0.09	0.002
30.00	0.86	0.32	0.034	68.00	0.96	0.12	0.004
35.00	0.86	0.24	0.022	70.00	0.94	0.11	0.004
40.00	0.87	0.18	0.014	75.00	0.94	0.09	0.003
45.00	0.88	0.13	0.008	80.00	0.94	0.07	0.002
50.00	0.92	0.10	0.004	90.00	0.94	0.06	0.002
60.00	0.96	0.08	0.002				

Niobium[14]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.12	15.99	53.20	0.979	3.00	2.51	2.68	0.485
0.20	7.25	34.14	0.976	3.10	2.48	2.60	0.475
0.24	5.47	28.88	0.975	3.20	2.45	2.53	0.465
0.28	4.26	24.95	0.974	3.30	2.44	2.45	0.453
0.35	3.11	20.03	0.970	3.40	2.46	2.38	0.442
0.45	2.28	15.58	0.964	3.50	2.48	2.33	0.435
0.55	1.83	12.67	0.956	3.60	2.52	2.29	0.428
0.65	1.57	10.59	0.947	3.70	2.56	2.27	0.426
0.75	1.41	9.00	0.935	3.80	2.59	2.28	0.427
0.85	1.35	7.74	0.918	3.90	2.62	2.29	0.429
0.95	1.35	6.70	0.893	4.00	2.64	2.33	0.434
1.05	1.44	5.86	0.857	4.20	2.64	2.42	0.447
1.15	1.55	5.18	0.814	4.40	2.53	2.56	0.467
1.25	1.65	4.63	0.768	4.60	2.39	2.56	0.470
1.35	1.76	4.13	0.715	4.80	2.32	2.52	0.465
1.45	1.95	3.68	0.650	5.00	2.26	2.57	0.475
1.55	2.15	3.37	0.595	5.20	2.16	2.62	0.487
1.65	2.36	3.13	0.552	5.40	2.00	2.68	0.505
1.75	2.54	2.99	0.527	5.60	1.81	2.67	0.518
1.85	2.69	2.89	0.510	5.80	1.63	2.60	0.522
1.95	2.82	2.86	0.505	6.00	1.49	2.49	0.520
2.05	2.89	2.87	0.505	6.20	1.38	2.38	0.512
2.15	2.92	2.87	0.505	6.40	1.31	2.25	0.496
2.25	2.93	2.87	0.505	6.60	1.26	2.14	0.480
2.35	2.92	2.88	0.506	6.80	1.24	2.04	0.460
2.45	2.89	2.90	0.509	7.00	1.23	1.96	0.441
2.55	2.83	2.92	0.512	7.20	1.22	1.91	0.430
2.65	2.74	2.90	0.511	7.40	1.20	1.88	0.427
2.75	2.66	2.86	0.507	7.60	1.14	1.85	0.430
2.85	2.58	2.80	0.500	7.80	1.07	1.78	0.428

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Niobium[14]—*continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
8.00	1.02	1.69	0.412	17.80	0.75	0.87	0.217
8.20	1.00	1.60	0.390	18.00	0.74	0.85	0.209
8.40	0.99	1.51	0.365	18.60	0.73	0.77	0.185
8.60	0.99	1.43	0.340	19.00	0.72	0.72	0.170
8.70	0.99	1.39	0.328	19.60	0.72	0.66	0.150
8.80	1.00	1.36	0.315	20.00	0.72	0.62	0.137
9.00	1.01	1.29	0.290	20.60	0.71	0.55	0.119
9.20	1.04	1.22	0.265	21.00	0.72	0.50	0.100
9.40	1.07	1.18	0.245	21.60	0.75	0.43	0.075
9.60	1.10	1.13	0.227	22.00	0.78	0.40	0.063
9.80	1.13	1.09	0.209	22.60	0.82	0.35	0.045
10.00	1.18	1.05	0.194	23.00	0.85	0.33	0.038
10.20	1.23	1.04	0.187	23.60	0.88	0.30	0.029
10.40	1.27	1.04	0.185	24.00	0.91	0.29	0.025
10.60	1.30	1.06	0.190	24.60	0.94	0.28	0.022
10.80	1.32	1.08	0.195	25.00	0.96	0.27	0.020
11.00	1.32	1.10	0.200	25.60	0.99	0.26	0.018
11.20	1.31	1.12	0.204	26.00	1.00	0.26	0.017
11.40	1.30	1.13	0.207	26.60	1.03	0.25	0.016
11.60	1.28	1.13	0.209	27.00	1.04	0.25	0.015
11.80	1.27	1.13	0.210	27.60	1.06	0.25	0.015
12.00	1.25	1.12	0.209	28.00	1.08	0.24	0.015
12.40	1.24	1.10	0.204	28.60	1.11	0.24	0.016
12.80	1.24	1.09	0.200	29.00	1.13	0.25	0.017
13.20	1.24	1.09	0.201	29.60	1.16	0.26	0.020
13.60	1.23	1.12	0.208	30.00	1.18	0.28	0.023
14.00	1.20	1.13	0.216	31.00	1.18	0.31	0.026
14.40	1.16	1.15	0.225	32.00	1.20	0.34	0.031
14.80	1.11	1.16	0.234	33.00	1.21	0.38	0.038
15.00	1.08	1.16	0.238	34.00	1.20	0.42	0.044
15.60	0.99	1.14	0.247	35.20	1.17	0.47	0.051
16.00	0.92	1.11	0.250	36.00	1.15	0.50	0.056
16.60	0.85	1.04	0.245	37.50	1.07	0.53	0.064
17.00	0.80	0.99	0.240	39.50	0.95	0.50	0.063
17.20	0.79	0.96	0.236	40.50	0.92	0.47	0.059
17.40	0.77	0.93	0.230				

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Osmium (polycrystalline)[15]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.10	4.08	50.23	0.994	4.40	2.24	3.44	0.599
0.15	2.90	33.60	0.990	4.60	2.01	3.31	0.598
0.20	2.44	25.11	0.985	4.80	1.88	3.19	0.592
0.25	2.35	19.99	0.977	5.00	1.74	3.12	0.596
0.30	2.23	16.54	0.969	5.20	1.58	3.00	0.597
0.35	2.33	14.06	0.955	5.40	1.46	2.88	0.593
0.40	2.45	12.32	0.940	5.60	1.36	2.77	0.589
0.45	2.43	11.02	0.927	5.80	1.27	2.65	0.582
0.50	2.41	9.97	0.913	6.00	1.20	2.54	0.575
0.55	2.33	9.12	0.901	6.20	1.13	2.44	0.571
0.60	2.21	8.37	0.890	6.40	1.06	2.33	0.562
0.65	2.11	7.68	0.877	6.60	1.01	2.21	0.548
0.70	2.02	7.04	0.862	6.80	0.97	2.11	0.532
0.75	2.00	6.46	0.842	7.00	0.95	2.00	0.514
0.80	2.00	5.95	0.820	7.20	0.92	1.91	0.497
0.85	2.01	5.51	0.796	7.40	0.91	1.81	0.476
0.90	2.03	5.10	0.769	7.60	0.90	1.72	0.451
0.95	2.05	4.74	0.742	7.80	0.90	1.63	0.426
1.00	2.09	4.41	0.712	8.00	0.91	1.55	0.400
1.10	2.15	3.84	0.651	8.20	0.91	1.48	0.375
1.20	2.16	3.35	0.592	8.40	0.94	1.40	0.344
1.30	2.25	2.77	0.506	8.60	0.96	1.34	0.319
1.40	2.49	2.23	0.419	8.80	0.98	1.29	0.296
1.50	2.84	1.80	0.369	9.00	1.01	1.24	0.274
1.60	3.36	1.62	0.379	9.20	1.04	1.19	0.255
1.70	3.70	1.75	0.411	9.40	1.08	1.16	0.238
1.80	3.78	1.83	0.423	9.60	1.10	1.14	0.229
1.90	3.81	1.75	0.418	9.80	1.13	1.11	0.217
2.00	3.98	1.60	0.418	10.00	1.16	1.10	0.209
2.10	4.26	1.54	0.432	10.20	1.19	1.08	0.203
2.20	4.58	1.62	0.457	10.30	1.20	1.08	0.201
2.30	4.84	1.76	0.479	10.40	1.22	1.08	0.200
2.40	5.10	2.01	0.506	10.50	1.23	1.09	0.201
2.50	5.28	2.38	0.532	10.60	1.24	1.10	0.203
2.60	5.36	2.82	0.557	10.80	1.25	1.11	0.206
2.70	5.30	3.29	0.580	11.00	1.24	1.13	0.213
2.80	5.07	3.78	0.603	11.20	1.23	1.14	0.217
2.90	4.65	4.18	0.624	11.40	1.19	1.15	0.223
3.00	4.05	4.40	0.639	11.60	1.17	1.12	0.216
3.20	3.29	3.96	0.614	11.80	1.16	1.10	0.211
3.40	2.93	3.79	0.607	12.00	1.15	1.08	0.205
3.60	2.75	3.45	0.577	12.40	1.14	1.03	0.191
3.80	2.73	3.32	0.562	12.80	1.15	1.01	0.183
4.00	2.71	3.34	0.565	13.20	1.16	0.98	0.174
4.20	2.53	3.44	0.584	13.60	1.17	0.97	0.170

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Osmium (polycrystalline)[15] — *continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
14.00	1.17	0.96	0.169	24.00	0.73	0.84	0.209
14.40	1.16	0.94	0.165	24.40	0.72	0.82	0.207
14.80	1.16	0.91	0.156	24.80	0.70	0.80	0.205
15.20	1.17	0.89	0.148	25.20	0.69	0.77	0.202
15.60	1.20	0.86	0.140	25.60	0.67	0.75	0.199
16.00	1.25	0.87	0.140	26.00	0.66	0.72	0.195
16.40	1.28	0.90	0.147	26.40	0.65	0.69	0.189
16.80	1.28	0.94	0.157	26.80	0.63	0.66	0.183
17.20	1.27	0.97	0.167	27.20	0.65	0.62	0.165
17.60	1.26	1.01	0.178	28.00	0.64	0.59	0.156
18.00	1.23	1.04	0.189	28.40	0.64	0.57	0.148
18.40	1.19	1.08	0.200	28.80	0.65	0.55	0.140
18.80	1.14	1.10	0.210	29.20	0.65	0.53	0.134
19.20	1.10	1.10	0.219	29.60	0.65	0.51	0.128
19.60	1.05	1.11	0.227	30.00	0.65	0.49	0.121
20.00	0.96	1.10	0.239	31.00	0.65	0.45	0.111
20.40	0.93	1.09	0.240	32.00	0.66	0.41	0.095
20.80	0.89	1.05	0.240	33.00	0.68	0.37	0.079
21.20	0.86	1.02	0.237	34.00	0.70	0.34	0.068
21.60	0.83	0.99	0.235	35.00	0.72	0.31	0.057
22.00	0.80	0.96	0.230	36.00	0.74	0.29	0.048
22.40	0.78	0.93	0.226	37.00	0.77	0.27	0.040
22.80	0.77	0.90	0.220	38.00	0.79	0.26	0.035
23.20	0.75	0.88	0.217	39.00	0.81	0.26	0.031
23.60	0.75	0.86	0.211	40.00	0.84	0.26	0.026

Palladium[15]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.10	4.13	54.15	0.994	1.20	2.65	6.10	0.790
0.15	3.13	35.82	0.990	1.30	2.50	5.78	0.781
0.20	3.07	26.59	0.983	1.40	2.34	5.50	0.774
0.26	3.11	20.15	0.971	1.50	2.17	5.22	0.767
0.30	3.56	17.27	0.955	1.60	2.08	4.95	0.755
0.36	3.98	14.41	0.932	1.70	2.00	4.72	0.745
0.40	4.27	13.27	0.916	1.80	1.92	4.54	0.737
0.46	4.27	12.11	0.902	1.90	1.82	4.35	0.729
0.50	4.10	11.44	0.896	2.00	1.75	4.18	0.721
0.56	3.92	10.49	0.883	2.10	1.67	4.03	0.714
0.60	3.80	9.96	0.876	2.20	1.60	3.88	0.707
0.72	3.51	8.70	0.854	2.30	1.53	3.75	0.700
0.80	3.35	8.06	0.840	2.40	1.47	3.61	0.693
1.00	2.99	6.89	0.811	2.50	1.41	3.48	0.685
1.10	2.81	6.46	0.800	2.60	1.37	3.36	0.676

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Palladium[15]—*continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
2.70	1.32	3.25	0.668	8.80	1.04	0.65	0.094
2.80	1.29	3.13	0.658	9.00	1.07	0.64	0.090
2.90	1.26	3.03	0.648	9.50	1.12	0.65	0.089
3.00	1.23	2.94	0.639	10.00	1.14	0.65	0.088
3.10	1.20	2.85	0.630	10.50	1.16	0.65	0.087
3.20	1.17	2.77	0.622	11.00	1.18	0.64	0.086
3.30	1.14	2.68	0.613	11.50	1.19	0.65	0.087
3.40	1.12	2.60	0.602	12.00	1.20	0.66	0.089
3.50	1.10	2.52	0.591	12.50	1.19	0.67	0.091
3.60	1.08	2.45	0.581	13.00	1.18	0.67	0.091
3.70	1.07	2.38	0.570	13.50	1.18	0.67	0.092
3.80	1.06	2.31	0.558	14.00	1.17	0.67	0.093
3.90	1.05	2.25	0.547	14.50	1.15	0.68	0.095
4.00	1.03	2.19	0.537	15.00	1.13	0.69	0.098
4.20	1.04	2.09	0.510	15.50	1.10	0.68	0.096
4.40	1.03	2.01	0.493	16.00	1.08	0.66	0.092
4.60	1.03	1.94	0.476	16.50	1.06	0.63	0.086
4.80	1.01	1.90	0.470	17.00	1.07	0.61	0.081
5.00	0.96	1.86	0.472	17.50	1.06	0.61	0.080
5.20	0.90	1.79	0.474	18.00	1.07	0.59	0.077
5.40	0.85	1.70	0.463	18.50	1.07	0.59	0.077
5.60	0.81	1.62	0.449	19.00	1.08	0.59	0.077
5.80	0.78	1.54	0.437	19.50	1.08	0.61	0.080
6.00	0.76	1.45	0.418	20.00	1.07	0.65	0.090
6.20	0.74	1.37	0.397	20.50	1.03	0.67	0.098
6.40	0.73	1.29	0.375	21.00	0.99	0.67	0.103
6.60	0.72	1.21	0.350	21.50	0.95	0.66	0.103
6.80	0.73	1.13	0.316	22.00	0.91	0.64	0.103
7.00	0.73	1.05	0.287	22.50	0.88	0.62	0.101
7.20	0.75	0.98	0.255	23.00	0.86	0.59	0.097
7.40	0.77	0.91	0.223	23.50	0.85	0.56	0.091
7.60	0.79	0.85	0.195	24.00	0.84	0.54	0.086
7.80	0.83	0.78	0.163	25.00	0.81	0.51	0.084
8.00	0.88	0.73	0.133	26.40	0.80	0.43	0.066
8.20	0.94	0.70	0.117	27.80	0.81	0.38	0.052
8.40	0.96	0.70	0.114	29.20	0.82	0.35	0.046
8.60	1.00	0.65	0.097				

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Platinum[16]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.10	13.21	44.72	0.976	4.40	1.43	2.04	0.432
0.15	8.18	31.16	0.969	4.60	1.39	1.95	0.415
0.20	5.90	23.95	0.962	4.80	1.38	1.85	0.392
0.25	4.70	19.40	0.954	5.00	1.36	1.76	0.372
0.30	3.92	16.16	0.945	5.20	1.36	1.67	0.350
0.35	3.28	13.66	0.936	5.40	1.36	1.61	0.332
0.40	2.81	11.38	0.922	5.60	1.36	1.54	0.315
0.45	3.03	9.31	0.882	5.80	1.36	1.47	0.295
0.50	3.91	7.71	0.813	6.00	1.38	1.40	0.276
0.55	4.58	7.14	0.777	6.20	1.39	1.35	0.261
0.60	5.13	6.75	0.753	6.40	1.42	1.29	0.246
0.65	5.52	6.66	0.746	6.60	1.45	1.26	0.236
0.70	5.71	6.83	0.751	6.80	1.48	1.24	0.231
0.75	5.57	7.02	0.759	7.00	1.50	1.24	0.230
0.80	5.31	7.04	0.762	7.20	1.50	1.25	0.231
0.85	5.05	6.98	0.763	7.40	1.49	1.23	0.228
0.90	4.77	6.91	0.765	7.60	1.48	1.22	0.225
0.95	4.50	6.77	0.763	7.80	1.48	1.20	0.221
1.00	4.25	6.62	0.762	8.00	1.47	1.18	0.216
1.10	3.86	6.24	0.753	8.20	1.47	1.17	0.212
1.20	3.55	5.92	0.746	8.40	1.47	1.15	0.209
1.30	3.29	5.61	0.736	8.60	1.47	1.14	0.205
1.40	3.10	5.32	0.725	8.80	1.47	1.13	0.202
1.50	2.92	5.07	0.716	9.00	1.48	1.12	0.200
1.60	2.76	4.84	0.706	9.20	1.49	1.11	0.198
1.70	2.63	4.64	0.697	9.40	1.49	1.12	0.200
1.80	2.51	4.43	0.686	9.60	1.49	1.13	0.203
1.90	2.38	4.26	0.678	9.80	1.48	1.15	0.207
2.00	2.30	4.07	0.664	10.00	1.46	1.15	0.209
2.10	2.23	3.92	0.654	10.20	1.43	1.16	0.211
2.20	2.17	3.77	0.642	10.40	1.40	1.15	0.210
2.30	2.10	3.67	0.636	10.60	1.37	1.14	0.207
2.40	2.03	3.54	0.626	10.80	1.35	1.12	0.203
2.50	1.96	3.42	0.616	11.00	1.33	1.10	0.199
2.60	1.91	3.30	0.605	11.20	1.31	1.08	0.194
2.70	1.87	3.20	0.595	11.40	1.30	1.06	0.188
2.80	1.83	3.10	0.585	11.60	1.29	1.04	0.183
2.90	1.79	3.01	0.575	11.80	1.29	1.01	0.177
3.00	1.75	2.92	0.565	12.00	1.29	1.00	0.173
3.20	1.68	2.76	0.546	12.40	1.29	0.97	0.165
3.40	1.63	2.62	0.527	12.80	1.29	0.94	0.158
3.60	1.58	2.48	0.507	13.20	1.31	0.93	0.155
3.80	1.53	2.37	0.491	13.60	1.31	0.93	0.155
4.00	1.49	2.25	0.472	14.00	1.31	0.93	0.155
4.20	1.45	2.14	0.452	14.40	1.30	0.93	0.156

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Platinum[16] — *continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
14.80	1.27	0.93	0.157	22.50	0.81	0.98	0.235
15.20	1.27	0.93	0.155	23.00	0.77	0.92	0.226
15.60	1.25	0.92	0.151	23.50	0.75	0.87	0.213
16.00	1.24	0.89	0.146	24.00	0.74	0.82	0.201
16.50	1.24	0.87	0.142	24.50	0.73	0.77	0.187
17.00	1.25	0.86	0.138	25.00	0.73	0.73	0.174
17.50	1.27	0.85	0.135	25.50	0.73	0.70	0.162
18.00	1.31	0.88	0.142	26.00	0.74	0.67	0.150
18.50	1.30	0.94	0.157	26.50	0.74	0.65	0.142
19.00	1.28	0.99	0.171	27.00	0.74	0.63	0.136
19.50	1.23	1.03	0.184	27.50	0.74	0.62	0.130
20.00	1.18	1.06	0.197	28.00	0.75	0.60	0.125
20.50	1.11	1.09	0.212	28.50	0.75	0.59	0.121
21.00	1.03	1.10	0.226	29.00	0.75	0.58	0.118
21.50	0.94	1.08	0.238	29.50	0.74	0.58	0.120
22.00	0.87	1.04	0.240	30.00	0.73	0.58	0.124

Rhenium (single crystal)[8] E || c

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.10	6.06	51.03	0.991	1.60	2.59	3.49	0.587
0.15	4.66	33.96	0.984	1.70	2.70	3.27	0.557
0.20	4.16	25.36	0.975	1.80	2.82	3.10	0.535
0.25	4.03	20.10	0.962	1.90	2.90	3.00	0.520
0.30	4.37	16.69	0.943	2.00	2.97	2.91	0.510
0.35	4.50	14.53	0.925	2.10	3.03	2.86	0.504
0.40	4.53	12.96	0.909	2.20	3.06	2.84	0.501
0.45	4.53	11.78	0.893	2.30	3.07	2.82	0.499
0.50	4.53	10.88	0.878	2.40	3.06	2.81	0.498
0.55	4.50	10.26	0.867	2.50	3.02	2.80	0.497
0.60	4.29	9.75	0.861	2.60	2.96	2.77	0.493
0.65	4.07	9.35	0.856	2.70	2.89	2.68	0.482
0.70	3.80	8.94	0.853	2.80	2.89	2.57	0.468
0.75	3.48	8.55	0.850	2.90	2.99	2.47	0.457
0.80	3.21	8.10	0.846	3.00	3.11	2.57	0.470
0.85	2.96	7.68	0.841	3.20	2.90	2.68	0.482
0.90	2.73	7.24	0.835	3.40	2.83	2.50	0.459
0.95	2.56	6.79	0.826	3.60	2.93	2.48	0.457
1.00	2.45	6.36	0.813	3.80	2.86	2.56	0.467
1.10	2.38	5.61	0.778	4.00	2.81	2.51	0.460
1.20	2.35	5.02	0.742	4.20	2.86	2.55	0.466
1.30	2.39	4.54	0.702	4.40	2.81	2.74	0.489
1.40	2.44	4.13	0.662	4.60	2.56	2.83	0.504
1.50	2.50	3.79	0.624	4.80	2.41	2.71	0.493

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Rhenium (single crystal)[8] E || c—*continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
5.00	2.39	2.68	0.488	16.40	1.19	1.27	0.259
5.20	2.34	2.75	0.500	16.80	1.14	1.29	0.269
5.40	2.20	2.81	0.515	17.00	1.12	1.30	0.275
5.60	2.02	2.84	0.530	17.40	1.07	1.30	0.286
5.80	1.83	2.80	0.538	18.00	0.99	1.30	0.300
6.00	1.65	2.71	0.541	18.40	0.93	1.29	0.311
6.20	1.54	2.59	0.532	18.80	0.87	1.28	0.321
6.40	1.45	2.50	0.526	19.20	0.81	1.25	0.330
6.80	1.32	2.31	0.508	19.60	0.77	1.21	0.332
7.00	1.26	2.23	0.500	20.00	0.73	1.18	0.333
7.20	1.20	2.15	0.493	20.40	0.70	1.14	0.332
7.40	1.16	2.06	0.480	20.80	0.67	1.11	0.332
7.60	1.12	1.99	0.470	21.20	0.64	1.08	0.334
7.80	1.08	1.89	0.454	21.60	0.61	1.04	0.335
8.00	1.05	1.80	0.435	22.00	0.58	1.01	0.340
8.20	1.05	1.71	0.411	22.40	0.55	0.97	0.341
8.40	1.05	1.62	0.386	22.80	0.53	0.93	0.338
8.60	1.06	1.55	0.360	23.20	0.51	0.89	0.334
8.80	1.09	1.48	0.336	23.60	0.50	0.85	0.329
9.00	1.11	1.43	0.317	24.00	0.48	0.80	0.319
9.20	1.13	1.39	0.301	24.40	0.48	0.76	0.207
9.40	1.16	1.34	0.281	24.80	0.47	0.72	0.296
9.60	1.18	1.32	0.274	25.20	0.47	0.68	0.282
9.80	1.20	1.29	0.264	25.60	0.47	0.65	0.270
10.00	1.23	1.26	0.252	26.00	0.47	0.61	0.255
10.20	1.25	1.25	0.246	26.40	0.48	0.57	0.240
10.40	1.28	1.25	0.242	26.80	0.48	0.54	0.225
10.60	1.29	1.25	0.242	27.20	0.49	0.51	0.208
10.80	1.30	1.26	0.244	27.60	0.50	0.48	0.193
11.00	1.30	1.27	0.247	28.00	0.51	0.45	0.176
11.20	1.29	1.28	0.249	29.00	0.54	0.39	0.145
11.40	1.28	1.28	0.252	30.00	0.57	0.33	0.114
11.60	1.26	1.28	0.252	31.00	0.62	0.29	0.086
11.80	1.24	1.26	0.249	32.00	0.66	0.26	0.065
12.00	1.23	1.24	0.244	33.00	0.68	0.24	0.054
12.40	1.22	1.21	0.237	34.00	0.72	0.21	0.041
12.80	1.21	1.18	0.230	35.00	0.76	0.20	0.031
13.20	1.22	1.16	0.222	36.00	0.79	0.20	0.025
13.60	1.22	1.13	0.215	37.00	0.82	0.19	0.021
14.00	1.24	1.12	0.209	38.00	0.85	0.20	0.018
14.40	1.27	1.11	0.204	39.00	0.89	0.21	0.016
14.80	1.29	1.15	0.213	40.00	0.88	0.26	0.022
15.20	1.29	1.19	0.225	42.00	0.88	0.26	0.022
15.60	1.26	1.22	0.236	44.00	0.89	0.29	0.026
16.00	1.23	1.25	0.248	46.00	0.85	0.32	0.035

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Rhenium (single crystal)[8] E || c —*continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
48.00	0.82	0.30	0.036	54.00	0.72	0.30	0.055
50.00	0.80	0.30	0.038	56.00	0.66	0.24	0.061
52.00	0.78	0.30	0.044	58.00	0.65	0.16	0.055

Rhenium (single crystal)[8] E ⊥ c

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.10	4.25	42.83	0.991	2.90	3.49	2.75	0.497
0.15	3.28	28.08	0.984	3.00	3.53	2.71	0.493
0.20	3.28	20.66	0.971	3.20	3.55	2.84	0.506
0.25	3.47	16.27	0.951	3.40	3.34	2.88	0.508
0.30	3.73	13.44	0.926	3.60	3.25	2.83	0.501
0.35	3.93	11.54	0.900	3.80	3.24	2.84	0.502
0.40	3.99	10.15	0.875	4.00	3.19	2.94	0.513
0.45	4.17	9.03	0.846	4.20	3.05	3.06	0.526
0.50	4.34	8.26	0.821	4.40	2.88	3.15	0.539
0.55	4.45	7.73	0.801	4.60	2.67	3.18	0.548
0.60	4.53	7.40	0.788	4.80	2.44	3.17	0.554
0.65	4.44	7.26	0.784	5.00	2.25	3.12	0.556
0.70	4.13	7.09	0.784	5.20	2.10	3.04	0.555
0.75	3.77	6.75	0.779	5.40	1.96	2.96	0.553
0.80	3.55	6.32	0.766	5.60	1.84	2.88	0.551
0.85	3.39	5.95	0.752	5.80	1.73	2.81	0.549
0.90	3.26	5.61	0.737	6.00	1.61	2.74	0.549
0.95	3.17	5.27	0.719	6.20	1.51	2.64	0.545
1.00	3.09	4.96	0.701	6.40	1.42	2.56	0.541
1.10	3.05	4.39	0.658	6.80	1.28	2.37	0.526
1.20	3.08	3.89	0.613	7.00	1.22	2.28	0.517
1.30	3.20	3.56	0.578	7.20	1.16	2.19	0.508
1.40	3.23	3.38	0.559	7.40	1.12	2.08	0.493
1.50	3.23	3.12	0.532	7.60	1.12	1.98	0.468
1.60	3.29	2.88	0.507	7.80	1.08	1.93	0.463
1.70	3.38	2.72	0.491	8.00	1.05	1.83	0.443
1.80	3.47	2.59	0.480	8.20	1.05	1.74	0.418
1.90	3.54	2.50	0.473	8.40	1.05	1.66	0.397
2.00	3.63	2.43	0.469	8.60	1.06	1.58	0.372
2.10	3.74	2.40	0.470	8.80	1.07	1.52	0.351
2.20	3.83	2.38	0.472	9.00	1.09	1.46	0.327
2.30	3.93	2.44	0.481	9.20	1.11	1.41	0.309
2.40	4.00	2.55	0.492	9.40	1.14	1.36	0.290
2.50	4.01	2.70	0.505	9.60	1.17	1.31	0.273
2.60	3.90	2.84	0.514	9.80	1.20	1.27	0.258
2.70	3.74	2.92	0.517	10.00	1.24	1.24	0.244
2.80	3.57	2.88	0.511	10.20	1.29	1.22	0.234

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Rhenium (single crystal)[8] E ⊥ c —*continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
10.40	1.33	1.23	0.233	23.20	0.53	0.89	0.322
10.60	1.36	1.25	0.238	23.60	0.52	0.85	0.317
10.80	1.38	1.28	0.245	24.00	0.50	0.82	0.314
11.00	1.37	1.31	0.253	24.40	0.49	0.79	0.309
11.20	1.36	1.33	0.259	24.40	0.49	0.79	0.309
11.40	1.33	1.34	0.264	24.80	0.48	0.75	0.303
11.60	1.31	1.34	0.266	25.20	0.47	0.72	0.295
11.80	1.28	1.33	0.266	25.60	0.47	0.68	0.286
12.00	1.26	1.32	0.264	26.00	0.46	0.64	0.276
12.40	1.23	1.29	0.257	26.40	0.46	0.61	0.263
12.80	1.22	1.26	0.251	26.80	0.46	0.57	0.249
13.20	1.20	1.23	0.245	27.20	0.47	0.53	0.231
13.60	1.19	1.20	0.236	27.60	0.48	0.50	0.216
14.00	1.20	1.16	0.225	28.00	0.49	0.47	0.198
14.40	1.22	1.13	0.214	29.00	0.51	0.41	0.164
14.80	1.27	1.12	0.207	30.00	0.55	0.34	0.129
15.20	1.31	1.17	0.218	31.00	0.59	0.29	0.097
15.60	1.31	1.23	0.234	32.00	0.64	0.26	0.072
16.00	1.28	1.28	0.251	33.00	0.67	0.24	0.060
16.40	1.24	1.33	0.270	34.00	0.70	0.22	0.047
16.80	1.17	1.37	0.288	35.00	0.74	0.20	0.036
17.00	1.14	1.38	0.297	36.00	0.77	0.19	0.029
17.40	1.06	1.39	0.314	37.00	0.80	0.19	0.023
18.00	0.95	1.38	0.334	38.00	0.84	0.19	0.018
18.40	0.88	1.36	0.346	39.00	0.88	0.21	0.016
18.80	0.82	1.33	0.355	40.00	0.87	0.25	0.023
19.20	0.76	1.29	0.360	42.00	0.87	0.25	0.023
19.60	0.72	1.25	0.363	44.00	0.88	0.28	0.026
20.00	0.67	1.21	0.369	46.00	0.84	0.31	0.035
20.40	0.64	1.15	0.364	48.00	0.82	0.30	0.036
20.80	0.61	1.10	0.357	50.00	0.80	0.30	0.039
21.20	0.60	1.06	0.349	52.00	0.77	0.30	0.044
21.60	0.58	1.02	0.342	54.00	0.71	0.29	0.055
22.00	0.57	0.98	0.336	56.00	0.66	0.23	0.061
22.40	0.56	0.95	0.328	58.00	0.64	0.16	0.055

Rhodium[9]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.10	18.48	69.43	0.986	0.70	3.67	11.72	0.908
0.20	8.66	37.46	0.977	0.80	3.63	10.34	0.887
0.30	5.85	25.94	0.967	0.90	3.62	9.36	0.867
0.40	4.74	19.80	0.955	1.00	3.71	8.67	0.848
0.50	4.20	16.07	0.941	1.10	3.67	8.26	0.837
0.60	3.87	13.51	0.925	1.20	3.51	7.94	0.832

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Rhodium[9]*—continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
1.30	3.26	7.63	0.829	7.80	0.68	1.20	0.363
1.40	3.01	7.31	0.827	8.00	0.69	1.12	0.329
1.50	2.78	6.97	0.823	8.20	0.71	1.04	0.288
1.60	2.60	6.64	0.818	8.40	0.74	0.97	0.252
1.70	2.42	6.33	0.813	8.60	0.78	0.89	0.212
1.80	2.30	6.02	0.805	8.80	0.83	0.83	0.179
1.90	2.20	5.76	0.798	9.00	0.88	0.77	0.148
2.00	2.12	5.51	0.789	9.20	0.95	0.73	0.125
2.10	2.05	5.30	0.780	9.40	1.01	0.71	0.110
2.20	2.00	5.11	0.772	9.60	1.07	0.69	0.102
2.30	1.94	4.94	0.765	9.80	1.12	0.69	0.098
2.40	1.90	4.78	0.756	10.00	1.17	0.69	0.098
2.50	1.88	4.65	0.748	10.60	1.26	0.73	0.106
2.60	1.85	4.55	0.743	11.00	1.29	0.76	0.113
2.70	1.80	4.49	0.742	11.60	1.32	0.80	0.124
2.90	1.63	4.36	0.748	12.00	1.32	0.82	0.127
3.00	1.53	4.29	0.753	12.60	1.32	0.82	0.129
3.10	1.41	4.20	0.760	13.00	1.32	0.83	0.131
3.20	1.30	4.09	0.764	13.60	1.32	0.85	0.134
3.30	1.20	3.97	0.767	14.00	1.32	0.86	0.138
3.40	1.11	3.84	0.769	14.60	1.30	0.89	0.144
3.50	1.04	3.71	0.768	15.00	1.28	0.90	0.147
3.60	0.99	3.58	0.764	15.60	1.25	0.90	0.147
3.70	0.95	3.45	0.759	16.00	1.24	0.89	0.147
3.80	0.91	3.34	0.753	16.50	1.23	0.88	0.145
3.90	0.88	3.23	0.747	17.00	1.22	0.88	0.144
4.00	0.86	3.12	0.739	17.50	1.22	0.87	0.143
4.20	0.83	2.94	0.722	18.00	1.23	0.88	0.145
4.40	0.80	2.76	0.706	18.50	1.25	0.92	0.155
4.60	0.78	2.60	0.684	19.00	1.24	0.98	0.172
4.80	0.79	2.46	0.659	19.50	1.18	1.05	0.193
5.00	0.79	2.34	0.635	20.00	1.10	1.09	0.213
5.20	0.79	2.23	0.613	20.50	1.00	1.09	0.230
5.40	0.80	2.14	0.591	21.00	0.91	1.05	0.234
5.60	0.80	2.06	0.573	21.50	0.86	1.00	0.228
5.80	0.79	2.00	0.561	22.00	0.83	0.95	0.219
6.00	0.76	1.93	0.556	22.50	0.81	0.92	0.214
6.20	0.73	1.85	0.544	23.00	0.79	0.90	0.213
6.40	0.70	1.77	0.534	23.50	0.75	0.87	0.214
6.60	0.68	1.69	0.518	24.00	0.73	0.84	0.210
6.80	0.67	1.60	0.498	24.50	0.70	0.81	0.208
7.00	0.66	1.52	0.476	25.00	0.69	0.77	0.202
7.20	0.66	1.43	0.452	25.50	0.67	0.74	0.195
7.40	0.66	1.35	0.423	26.00	0.66	0.70	0.188
7.60	0.67	1.27	0.394	26.50	0.65	0.66	0.176

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Rhodium[9] — *continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
27.00	0.65	0.64	0.168	33.00	0.60	0.37	0.110
27.50	0.65	0.61	0.159	34.00	0.65	0.30	0.074
28.00	0.65	0.59	0.152	35.00	0.69	0.28	0.058
29.00	0.65	0.54	0.137	36.00	0.73	0.27	0.049
30.00	0.66	0.51	0.127	37.00	0.74	0.28	0.047
31.00	0.64	0.49	0.127	38.00	0.74	0.27	0.045
32.00	0.61	0.44	0.126	39.00	0.75	0.25	0.041

Silicon (single crystal)[17]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.01240	0.65	2.90E-04	0.300	0.2170		4.05E-07	
0.01488	3.4190	2.30E-04	0.300	0.2232		3.94E-07	
0.01736	3.4192	1.90E-04	0.300	0.2294		3.26E-07	
0.01984	3.4195	1.70E-04	0.300	0.2356		2.97E-07	
0.02480	3.4197		0.300	0.2418		2.82E-07	
0.03100	3.4199		0.300	0.2480	3.4261	1.99E-07	0.300
0.04092	3.4200		0.300	0.3100	3.4294		0.301
0.04463		1.08E-04		0.3626	3.4327		0.301
0.04959	3.4201	9.15E-05	0.300	0.4568	3.4393	2.50E-09	0.302
0.05703		1.56E-04		0.6199	3.4490		0.303
0.06199	3.4204	2.86E-04	0.300	0.8093	3.4784		0.306
0.06943		3.84E-04		1.033	3.5193		0.311
0.07439		7.16E-04		1.1	(3.5341)	1.30E-05	0.312
0.08059	(3.4207)	1.52E-04	0.300	1.2		1.80E-04	
0.08679		1.02E-04		1.3		2.26E-03	
0.09299		2.59E-04		1.4		7.75E-03	
0.09919		1.77E-04		1.5	3.673	5.00E-03	0.327
0.1054		1.53E-04		1.6	3.714	8.00E-03	0.331
0.1116		2.02E-04		1.7	3.752	1.00E-02	0.335
0.1178		1.22E-04		1.8	3.796	0.013	0.340
0.1240	3.4215	6.76E-05	0.300	1.9	3.847	0.016	0.345
0.1364		5.49E-05		2.0	3.906	0.022	0.351
0.1488		2.41E-05		2.1	3.969	0.030	0.357
0.1612		2.49E-05		2.2	4.042	0.032	0.364
0.1736	(3.4230)	1.68E-05	0.300	2.3	4.123	0.048	0.372
0.1798		2.45E-05		2.4	4.215	0.060	0.380
0.1860		2.66E-06		2.5	4.320	0.073	0.390
0.1922		1.74E-06		2.6	4.442	0.090	0.400
0.1984		8.46E-07		2.7	4.583	0.130	0.412
0.2046		5.64E-07		2.8	4.753	0.163	0.426
0.2108	(3.4244)	4.17E-07	0.300	2.9	4.961	0.203	0.442

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Silicon (single crystal)[17]—*continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
3.0	5.222	0.269	0.461	5.7	1.180	3.112	0.673
3.1	5.570	0.387	0.486	5.8	1.133	3.045	0.672
3.2	6.062	0.630	0.518	5.9	1.083	2.982	0.673
3.3	6.709	1.321	0.561	6.0	1.010	2.909	0.677
3.4	6.522	2.705	0.592	6.5	0.847	2.73	0.688
3.5	5.610	3.014	0.575	7.0	0.682	2.45	0.691
3.6	5.296	2.987	0.564	7.5	0.563	2.21	0.693
3.7	5.156	3.058	0.563	8.0	0.478	2.00	0.691
3.8	5.065	3.182	0.568	8.5	0.414	1.82	0.688
3.9	5.016	3.346	0.577	9.0	0.367	1.66	0.683
4.0	5.010	3.587	0.591	9.5	0.332	1.51	0.672
4.1	5.020	3.979	0.614	10.0	0.306	1.38	0.661
4.2	4.888	4.639	0.652	12.0	0.257	0.963	0.590
4.3	4.086	5.395	0.703	14.0	0.275	0.641	0.460
4.4	3.120	5.344	0.726	16.0	0.345	0.394	0.297
4.5	2.451	5.082	0.740	18.0	0.455	0.219	0.159
4.6	1.988	4.678	0.742	20.0	0.567	0.0835	0.079
4.7	1.764	4.278	0.728	22.14	0.675	0.0405	0.038
4.8	1.658	3.979	0.710	24.31	0.752	0.0243	0.020
4.9	1.597	3.749	0.693	26.38	0.803	0.0178	0.012
5.0	1.570	3.565	0.675	28.18	0.834	0.0152	0.008
5.1	1.571	3.429	0.658	30.24	0.860	0.0138	0.006
5.2	1.589	3.354	0.646	31.79	0.877	0.0132	0.004
5.3	1.579	3.353	0.647	34.44	0.899	0.0121	0.003
5.4	1.471	3.366	0.663	36.47	0.913	0.0113	0.002
5.5	1.340	3.302	0.673	38.75	0.925	0.0104	0.002
5.6	1.247	3.206	0.675	40.00	0.930	0.0100	0.001

Silver[6]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.10	9.91	90.27	0.995	3.60	0.23	1.13	0.671
0.20	2.84	45.70	0.995	3.70	0.30	0.77	0.475
0.30	1.41	30.51	0.994	3.77	0.53	0.40	0.154
0.40	0.91	22.89	0.993	3.80	0.73	0.30	0.053
0.50	0.67	18.32	0.992	3.90	1.30	0.36	0.040
1.00	0.28	9.03	0.987	4.00	1.61	0.60	0.103
1.50	0.27	5.79	0.969	4.10	1.73	0.85	0.153
2.00	0.27	4.18	0.944	4.20	1.75	1.06	0.194
2.50	0.24	3.09	0.914	4.30	1.73	1.13	0.208
3.00	0.23	2.27	0.864	4.50	1.69	1.28	0.238
3.25	0.23	1.86	0.816	4.75	1.61	1.34	0.252
3.50	0.21	1.42	0.756	5.00	1.55	1.36	0.257

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Silver[6]—*continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
5.50	1.45	1.34	0.257	29.00	0.92	0.56	0.079
6.00	1.34	1.28	0.246	30.00	0.93	0.54	0.074
6.50	1.25	1.18	0.225	31.00	0.93	0.53	0.072
7.00	1.18	1.06	0.196	32.00	0.92	0.53	0.072
7.50	1.14	0.91	0.157	33.00	0.90	0.51	0.071
8.00	1.16	0.75	0.114	34.00	0.88	0.49	0.067
9.00	1.33	0.56	0.074	35.00	0.86	0.45	0.061
10.00	1.46	0.56	0.082	36.00	0.89	0.44	0.055
11.00	1.52	0.56	0.088	38.00	0.89	0.39	0.043
12.00	1.61	0.59	0.100	40.00	0.90	0.37	0.039
13.00	1.66	0.64	0.112	42.00	0.90	0.35	0.036
14.00	1.72	0.78	0.141	44.00	0.90	0.33	0.033
14.50	1.64	0.88	0.152	46.00	0.90	0.32	0.031
15.00	1.56	0.92	0.156	48.00	0.89	0.31	0.030
16.00	1.42	0.91	0.151	50.00	0.88	0.29	0.027
17.00	1.33	0.86	0.139	52.00	0.89	0.28	0.024
18.00	1.28	0.80	0.124	54.00	0.88	0.17	0.024
19.00	1.27	0.75	0.111	56.00	0.87	0.26	0.024
20.00	1.29	0.71	0.103	58.00	0.87	0.24	0.021
21.00	1.35	0.75	0.112	60.00	0.87	0.22	0.018
21.50	1.37	0.80	0.124	62.00	0.88	0.21	0.016
22.00	1.34	0.87	0.141	64.00	0.88	0.21	0.016
22.50	1.26	0.93	0.157	66.00	0.88	0.21	0.016
23.00	1.17	0.94	0.163	68.00	0.87	0.21	0.017
23.50	1.10	0.93	0.165	70.00	0.83	0.20	0.021
24.00	1.04	0.90	0.165	72.00	0.85	0.18	0.016
24.50	0.99	0.87	0.160	74.00	0.85	0.17	0.014
25.00	0.95	0.83	0.154	76.00	0.85	0.16	0.013
25.50	0.91	0.78	0.144	78.00	0.85	0.15	0.013
26.00	0.90	0.74	0.133	80.00	0.85	0.14	0.012
26.50	0.89	0.69	0.121	85.00	0.85	0.11	0.011
27.00	0.89	0.65	0.109	90.00	0.85	0.08	0.009
27.50	0.89	0.62	0.099	95.00	0.86	0.06	0.007
28.00	0.90	0.59	0.090	100.00	0.87	0.04	0.005

Tantalum[12]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.10	10.14	66.39	0.9380	0.50	1.37	14.26	0.974
0.15	9.45	46.41	0.983	0.58	1.15	12.19	0.970
0.20	5.77	35.46	0.982	0.70	0.96	9.92	0.962
0.26	3.67	27.53	0.981	0.78	0.89	8.77	0.956
0.30	2.87	23.90	0.980	0.90	0.84	7.38	0.942
0.38	2.03	18.87	0.978	1.00	0.89	6.47	0.996

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Tantalum[12] *–continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
1.10	0.93	5.75	0.899	8.60	1.14	1.45	0.317
1.20	0.98	5.14	0.872	8.80	1.17	1.41	0.301
1.30	1.00	4.62	0.842	9.00	1.19	1.40	0.294
1.40	1.04	4.15	0.805	9.20	1.21	1.38	0.289
1.50	1.09	3.73	0.762	9.40	1.21	1.38	0.287
1.60	1.15	3.33	0.707	9.60	1.21	1.38	0.285
1.70	1.24	2.95	0.640	9.80	1.21	1.37	0.285
1.80	1.35	2.60	0.560	10.00	1.20	1.37	0.286
1.90	1.57	2.24	0.460	10.20	1.19	1.37	0.286
2.00	1.83	1.99	0.388	10.40	1.18	1.37	0.287
2.10	2.10	1.84	0.354	10.60	1.16	1.36	0.288
2.20	2.36	1.81	0.351	10.80	1.15	1.36	0.289
2.30	2.56	1.86	0.365	11.00	1.13	1.35	0.290
2.40	2.68	1.92	0.378	11.20	1.11	1.35	0.292
2.50	2.75	1.98	0.388	11.40	1.09	1.34	0.293
2.60	2.80	2.02	0.395	11.60	1.07	1.33	0.294
2.70	2.84	2.08	0.405	11.80	1.05	1.32	0.295
2.80	2.85	2.14	0.412	12.00	1.02	1.31	0.296
2.90	2.84	2.20	0.420	12.20	1.00	1.29	0.295
3.00	2.81	2.24	0.425	12.40	0.98	1.28	0.294
3.20	2.73	2.31	0.432	12.60	0.96	1.26	0.292
3.40	2.61	2.33	0.435	12.80	0.94	1.24	0.289
3.60	2.49	2.30	0.430	13.00	0.93	1.22	0.286
3.80	2.40	2.22	0.418	13.60	0.91	1.16	0.272
4.00	2.36	2.14	0.406	14.00	0.90	1.15	0.272
4.20	2.35	2.06	0.392	14.60	0.85	1.15	0.285
4.40	2.39	2.01	0.384	15.00	0.80	1.13	0.293
4.60	2.45	2.00	0.384	15.60	0.72	1.08	0.301
4.80	2.53	2.06	0.394	16.00	0.68	1.04	0.304
5.00	2.58	2.20	0.416	16.60	0.63	0.97	0.301
5.20	2.52	2.44	0.450	17.00	0.60	0.92	0.296
5.40	2.31	2.61	0.480	17.60	0.60	0.92	0.296
5.60	2.06	2.67	0.501	18.00	0.55	0.79	0.274
5.80	1.83	2.63	0.510	18.60	0.53	0.71	0.254
6.00	1.63	2.56	0.515	19.00	0.53	0.65	0.236
6.20	1.48	2.45	0.512	19.60	0.53	0.57	0.207
6.40	1.37	2.33	0.504	20.00	0.54	0.52	0.185
6.60	1.29	2.22	0.492	20.60	0.55	0.44	0.152
6.80	1.23	2.11	0.478	21.00	0.57	0.39	0.127
7.00	1.18	2.01	0.462	21.60	0.64	0.34	0.089
7.20	1.15	1.91	0.445	22.00	0.64	0.32	0.081
7.40	1.13	1.82	0.425	22.60	0.69	0.27	0.058
7.60	1.12	1.75	0.406	23.00	0.73	0.24	0.043
7.80	1.11	1.68	0.390	23.60	0.80	0.26	0.033
8.00	1.11	1.61	0.370	24.00	0.80	0.26	0.034
8.20	1.12	1.55	0.350	24.60	0.82	0.25	0.029
8.40	1.13	1.50	0.332	25.00	0.83	0.25	0. 026

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Tantalum[12] *–continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
25.60	0.86	0.24	0.022	31.00	0.97	0.23	0.014
26.00	0.88	0.25	0.022	32.00	0.98	0.24	0.015
26.60	0.87	0.26	0.023	33.00	0.98	0.25	0.015
27.00	0.87	0.25	0.022	34.00	0.99	0.25	0.016
27.60	0.89	0.23	0.019	35.00	0.99	0.26	0.017
28.00	0.90	0.23	0.017	36.00	0.99	0.27	0.018
28.60	0.91	0.22	0.015	37.00	0.99	0.28	0.019
29.00	0.92	0.22	0.014	38.00	0.98	0.28	0.021
29.60	0.94	0.22	0.014	39.00	0.97	0.29	0.022
30.00	0.95	0.22	0.014	40.00	0.95	0.29	0.023

Titanium (polycrystalline)[18]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.10	5.03	23.38	0.965	2.30	1.86	2.56	0.495
0.15	3.00	15.72	0.954	2.40	1.81	2.47	0.483
0.20	2.12	11.34	0.939	2.50	1.78	2.39	0.471
0.25	2.05	8.10	0.890	2.60	1.75	2.34	0.462
0.30	6.39	9.94	0.833	2.70	1.71	2.29	0.456
0.35	2.74	6.21	0.792	2.80	1.68	2.25	0.451
0.40	2.49	4.68	0.708	2.90	1.63	2.21	0.447
0.45	3.35	3.25	0.545	3.00	1.59	2.17	0.444
0.50	4.43	3.22	0.555	3.10	1.55	2.15	0.442
0.60	4.71	3.77	0.597	3.20	1.50	2.12	0.442
0.70	4.38	3.89	0.603	3.30	1.44	2.09	0.442
0.80	4.04	3.82	0.596	3.40	1.37	2.06	0.443
0.90	3.80	3.65	0.582	3.50	1.30	2.01	0.443
1.00	3.62	3.52	0.570	3.60	1.24	1.96	0.441
1.10	3.47	3.40	0.560	3.70	1.17	1.90	0.436
1.20	3.35	3.30	0.550	3.80	1.11	1.83	0.430
1.30	3.28	3.25	0.546	3.85	1.08	1.78	0.423
1.40	3.17	3.28	0.549	3.90	1.06	1.73	0.413
1.50	2.98	3.32	0.557	4.00	1.04	1.62	0.389
1.60	2.74	3.30	0.559	4.20	1.05	1.45	0.333
1.70	2.54	3.23	0.557	4.40	1.13	1.33	0.284
1.80	2.36	3.11	0.550	4.60	1.17	1.29	0.265
1.90	2.22	2.99	0.540	4.80	1.21	1.23	0.244
2.00	2.11	2.88	0.530	5.00	1.24	1.21	0.236
2.10	2.01	2.77	0.520	5.20	1.27	1.20	0.228
2.20	1.92	2.67	0.509	5.40	1.17	1.16	0.228

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Titanium (polycrystalline)[18] *–continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
5.60	1.24	1.21	0.234	14.40	0.77	0.42	0.069
5.80	1.21	1.22	0.241	14.80	0.79	0.38	0.058
6.00	1.15	1.21	0.244	15.20	0.79	0.36	0.052
6.20	1.11	1.18	0.240	15.60	0.79	0.32	0.045
6.40	1.08	1.14	0.232	16.00	0.83	0.31	0.037
6.60	1.04	1.06	0.212	16.40	0.84	0.28	0.030
6.80	1.05	1.02	0.198	16.80	0.87	0.27	0.025
7.00	1.06	0.97	0.182	17.20	0.90	0.25	0.020
7.20	1.07	0.95	0.175	17.60	0.93	0.25	0.017
7.40	1.11	0.94	0.167	18.00	0.94	0.24	0.165
7.60	1.09	0.92	0.165	18.40	0.94	0.23	0.017
7.80	1.11	0.93	0.165	18.80	0.95	0.24	0.016
8.00	1.10	0.94	0.169	19.20	0.96	0.25	0.016
8.20	1.10	0.95	0.171	19.60	0.97	0.25	0.017
8.40	1.08	0.95	0.175	20.00	0.98	0.27	0.018
8.60	1.04	0.96	0.181	20.40	0.98	0.27	0.019
8.80	1.02	0.95	0.181	20.60	1.00	0.29	0.020
9.00	1.00	0.94	0.182	21.20	0.99	0.31	0.023
9.20	0.97	0.93	0.182	21.60	0.99	0.31	0.024
9.40	0.95	0.91	0.181	22.00	0.98	0.32	0.025
9.60	0.94	0.90	0.179	22.40	0.98	0.33	0.027
9.80	0.91	0.88	0.179	22.80	0.97	0.33	0.028
10.00	0.89	0.88	0.180	23.20	0.96	0.34	0.030
10.20	0.86	0.85	0.178	23.60	0.95	0.35	0.031
10.40	0.85	0.83	0.175	24.00	0.92	0.35	0.033
10.60	0.81	0.79	0.167	24.5	0.91	0.34	0.032
10.80	0.80	0.76	0.162	25.0	0.91	0.33	0.032
11.00	0.79	0.72	0.152	25.5	0.89	0.33	0.032
11.20	0.81	0.69	0.139	26.0	0.89	0.33	0.032
11.40	0.81	0.69	0.139	26.5	0.88	0.32	0.032
11.60	0.79	0.68	0.139	27.0	0.86	0.31	0.032
11.80	0.78	0.67	0.137	27.5	0.85	0.30	0.033
12.00	0.77	0.65	0.132	28.0	0.84	0.29	0.033
12.80	0.76	0.55	0.106	28.5	0.82	0.26	0.029
13.20	0.76	0.52	0.097	29.0	0.83	0.25	0.027
13.60	0.76	0.48	0.087	30.0	0.84	0.22	0.022
14.00	0.77	0.45	0.077				

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Tungsten[19]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.10	14.06	54.71	0.983	3.40	3.39	2.66	0.485
0.20	3.87	28.30	0.981	3.50	3.24	2.70	0.488
0.25	2.56	22.44	0.980	3.60	3.13	2.67	0.482
0.30	1.83	18.32	0.979	3.70	3.05	2.62	0.476
0.34	1.71	15.71	0.973	3.80	2.99	2.56	0.468
0.38	1.86	13.88	0.963	3.90	2.96	2.50	0.460
0.42	1.92	12.63	0.954	4.00	2.95	2.43	0.451
0.46	1.69	11.59	0.952	4.20	3.02	2.33	0.440
0.50	1.40	10.52	0.952	4.40	3.13	2.32	0.442
0.54	1.23	9.45	0.948	4.60	3.24	2.41	0.455
0.58	1.17	8.44	0.938	4.80	3.33	2.57	0.475
0.62	1.28	7.52	0.917	5.00	3.40	2.85	0.505
0.66	1.45	6.78	0.888	5.20	3.27	3.27	0.548
0.70	1.59	6.13	0.856	5.40	2.92	3.58	0.586
0.74	1.83	5.52	0.810	5.60	2.43	3.70	0.618
0.78	2.12	5.00	0.759	5.80	2.00	3.61	0.637
0.82	2.36	4.61	0.710	6.00	1.70	3.42	0.643
0.86	2.92	4.37	0.661	6.20	1.47	3.24	0.646
0.90	3.11	4.44	0.660	6.40	1.32	3.04	0.640
0.94	3.15	4.43	0.658	6.60	1.21	2.87	0.631
0.98	3.15	4.36	0.653	6.80	1.12	2.70	0.619
1.00	3.14	4.32	0.649	7.00	1.06	2.56	0.607
1.10	3.05	4.04	0.627	7.20	1.01	2.43	0.593
1.20	3.00	3.64	0.590	7.40	0.98	2.30	0.573
1.30	3.12	3.24	0.545	7.60	0.95	2.18	0.556
1.40	3.29	2.96	0.515	7.80	0.93	2.06	0.533
1.50	3.48	2.79	0.500	8.00	0.94	1.95	0.505
1.60	3.67	2.68	0.494	8.20	0.94	1.86	0.481
1.70	3.84	2.79	0.507	8.40	0.96	1.76	0.449
1.80	3.82	2.91	0.518	8.60	0.99	1.70	0.422
1.90	3.70	2.94	0.518	8.80	1.01	1.65	0.401
2.00	3.60	2.89	0.512	9.00	1.01	1.60	0.388
2.10	3.54	2.84	0.506	9.20	1.02	1.55	0.369
2.20	3.49	2.76	0.497	9.40	1.03	1.50	0.352
2.30	3.49	2.72	0.494	9.60	1.05	1.44	0.329
2.40	3.45	2.72	0.493	9.80	1.09	1.38	0.307
2.50	3.38	2.68	0.487	10.00	1.13	1.34	0.287
2.60	3.34	2.62	0.480	10.20	1.19	1.33	0.274
2.70	3.31	2.55	0.472	10.40	1.24	1.34	0.270
2.80	3.31	2.49	0.466	10.60	1.27	1.36	0.274
2.90	3.32	2.45	0.461	10.80	1.29	1.39	0.282
3.00	3.35	2.42	0.459	11.00	1.28	1.42	0.290
3.10	3.39	2.41	0.460	11.20	1.27	1.44	0.297
3.20	3.43	2.45	0.465	11.40	1.25	1.46	0.305
3.30	3.45	2.55	0.476	11.60	1.22	1.48	0.313

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Tungsten[19] *—continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
11.80	1.20	1.48	0.318	22.80	0.49	0.69	0.272
12.00	1.16	1.48	0.323	23.20	0.49	0.66	0.263
12.40	1.10	1.47	0.329	23.60	0.48	0.62	0.252
12.80	1.04	1.44	0.333	24.00	0.49	0.57	0.234
13.20	0.98	1.40	0.332	24.40	0.50	0.53	0.213
13.60	0.94	1.35	0.325	24.80	0.51	0.49	0.191
14.00	0.91	1.28	0.312	25.20	0.53	0.46	0.171
14.40	0.90	1.23	0.296	25.60	0.55	0.43	0.150
14.80	0.90	1.17	0.276	26.00	0.57	0.40	0.132
15.20	0.93	1.13	0.255	26.40	0.59	0.38	0.117
15.60	0.97	1.12	0.246	26.80	0.61	0.37	0.105
16.00	0.98	1.14	0.249	27.00	0.62	0.36	0.099
16.40	0.97	1.17	0.260	27.50	0.64	0.34	0.085
16.80	0.94	1.19	0.273	28.00	0.67	0.32	0.073
17.20	0.90	1.21	0.289	28.50	0.69	0.31	0.065
17.60	0.85	1.21	0.304	29.00	0.71	0.30	0.057
18.00	0.80	1.20	0.317	29.50	0.73	0.30	0.052
18.40	0.74	1.18	0.330	30.00	0.75	0.29	0.047
18.80	0.69	1.15	0.340	31.00	0.78	0.29	0.042
19.20	0.64	1.11	0.347	32.00	0.79	0.29	0.040
19.60	0.60	1.07	0.353	33.00	0.82	0.28	0.033
20.00	0.56	1.02	0.354	34.00	0.84	0.29	0.032
20.40	0.54	0.97	0.350	35.00	0.85	0.31	0.033
20.80	0.52	0.92	0.342	36.00	0.85	0.32	0.036
21.20	0.50	0.87	0.331	37.00	0.84	0.33	0.039
21.60	0.50	0.82	0.318	38.00	0.83	0.33	0.040
22.00	0.49	0.77	0.303	39.00	0.81	0.33	0.042
22.40	0.49	0.73	0.287	40.00	0.80	0.33	0.045

Zinc, E || c[20]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.7514	1.9241	7.5619	0.883	1.377	2.9459	3.5761	0.584
0.827	1.7921	6.9973	0.874	1.459	3.2523	4.2447	0.640
0.866	1.5571	6.7753	0.881	1.550	3.8086	4.6212	0.657
0.952	1.4824	6.2296	0.868	1.653	3.7577	4.6239	0.659
0.992	1.5762	5.8843	0.847	1.722	3.5908	4.4614	0.650
1.033	1.5407	5.3192	0.823	1.823	3.4234	4.3232	0.642
1.078	1.5853	4.9013	0.793	1.937	3.0132	3.9974	0.624
1.127	1.7768	4.5307	0.748	1.984	1.8562	3.9706	0.690
1.181	1.9808	4.2004	0.701	2.066	1.4856	4.0555	0.737
1.240	2.8821	3.4766	0.575	2.094	1.2525	3.9961	0.762
1.305	3.2039	3.0042	0.520	2.119	1.0017	3.8683	0.789

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Zinc, E || c[20]—*continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
2.275	0.7737	3.9129	0.832	3.220	0.3069	2.5088	0.847
2.445	0.6395	3.4013	0.821	3.594	0.2737	2.1737	0.828
2.666	0.4430	3.1379	0.851	4.065	0.2510	1.8528	0.799
2.917	0.3589	2.8140	0.853	4.678	0.2354	1.6357	0.776

Zinc, E ⊥ c[20]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.751	1.4469	7.4158	0.905	1.722	3.9369	4.6356	0.657
0.827	1.4744	6.9688	0.892	1.823	3.7549	4.3042	0.635
0.866	1.3628	6.6886	0.892	1.937	3.4512	4.1942	0.631
0.952	1.3165	6.2212	0.881	1.984	3.2515	4.2980	0.644
0.992	1.3835	5.8910	0.863	2.066	2.0802	4.7231	0.738
1.033	1.2889	5.4001	0.850	2.094	1.7084	4.7923	0.774
1.078	1.3095	4.9025	0.822	2.119	1.3329	4.4751	0.791
1.127	1.6897	4.4062	0.746	2.275	0.9725	4.2879	0.825
1.181	1.9701	4.0176	0.684	2.255	0.7568	3.7627	0.824
1.240	2.8717	3.2873	0.555	2.666	0.5470	3.4277	0.845
1.305	3.3991	2.7684	0.497	2.917	0.4774	3.0476	0.834
1.377	3.1807	3.4709	0.569	3.220	0.3911	2.7463	0.835
1.459	3.5064	4.1994	0.630	3.594	0.3147	2.3041	0.821
1.550	4.1241	4.7768	0.664	4.06	0.3013	2.0077	0.789
1.653	4.0269	4.8027	0.667	4.678	0.2806	1.7997	0.770

Zirconium (polycrystalline)[20]

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
0.10	6.18	1.76	0.300	0.50	4.13	1.44	0.175
0.15	3.37	1.30	0.123	0.56	5.01	1.58	0.231
0.20	2.34	1.08	0.058	0.60	5.18	1.61	0.242
0.26	2.24	1.06	0.052	0.70	4.54	1.51	0.202
0.30	2.59	1.14	0.073	0.80	4.03	1.42	0.168
0.36	3.17	1.26	0.110	0.90	3.74	1.37	0.149
0.40	3.09	1.24	0.105	0.96	3.69	1.36	0.145
0.46	3.36	1.30	0.123	1.00	3.66	1.35	0.143

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Zirconium (polycrystalline)[20] *—continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
1.10	3.65	1.35	0.142	8.00	1.66	0.91	0.026
1.20	3.53	1.33	0.134	8.20	0.67	0.91	0.026
1.30	3.25	1.27	0.116	8.40	1.68	0.92	0.026
1.40	3.10	1.25	0.106	8.60	1.68	0.92	0.026
1.50	3.02	1.23	0.100	8.80	1.66	0.91	0.026
1.60	2.88	1.20	0.091	9.00	1.65	0.91	0.025
1.70	2.68	1.16	0.078	9.20	1.63	0.90	0.025
1.80	2.49	1.12	0.067	9.40	1.60	0.89	0.024
2.00	2.14	1.03	0.047	9.60	1.57	0.89	0.023
2.10	1.99	1.00	0.040	9.80	1.52	0.87	0.021
2.20	1.87	0.97	0.034	10.00	1.47	0.86	0.020
2.30	1.78	0.94	0.030	10.20	1.42	0.84	0.018
2.40	1.71	0.92	0.027	10.40	1.35	0.82	0.016
2.50	1.62	0.90	0.024	10.50	1.32	0.81	0.016
2.60	1.54	0.88	0.022	10.60	1.28	0.80	0.015
2.70	1.46	0.86	0.019	10.80	1.23	0.78	0.014
2.80	1.40	0.84	0.018	11.00	1.19	0.77	0.014
2.90	1.34	0.82	0.016	11.20	1.16	0.76	0.013
3.00	0.30	0.81	0.016	11.40	1.13	0.75	0.013
3.10	1.26	0.80	0.015	11.60	1.11	0.74	0.013
3.30	1.19	0.77	0.014	11.80	1.09	0.74	0.013
3.40	1.16	0.76	0.013	12.00	1.08	0.73	0.013
3.50	1.13	0.75	0.013	12.40	1.05	0.72	0.012
3.60	1.10	0.74	0.013	12.80	1.01	0.71	0.012
3.70	1.07	0.73	0.013	13.20	0.98	0.70	0.012
3.80	1.04	0.72	0.012	13.60	0.95	0.69	0.013
3.90	1.01	0.71	0.012	14.00	0.92	0.68	0.013
4.00	0.98	0.70	0.012	14.40	0.89	0.67	0.013
4.20	0.94	0.68	0.013	14.80	0.90	0.67	0.013
4.40	0.89	0.67	0.013	15.20	0.92	0.68	0.013
4.60	0.85	0.65	0.014	15.60	0.95	0.69	0.013
4.80	0.81	0.64	0.014	16.00	0.98	0.70	0.012
5.00	0.78	0.63	0.015	16.40	1.01	0.71	0.012
5.20	0.77	0.62	0.016	16.80	1.04	0.72	0.012
5.40	0.77	0.62	0.016	16.40	1.01	0.71	0.012
5.60	0.80	0.63	0.014	16.80	1.04	0.72	0.012
5.80	0.87	0.66	0.013	17.20	1.09	0.74	0.013
6.00	1.00	0.71	0.012	17.60	1.13	0.75	0.013
6.20	1.11	0.75	0.013	18.00	1.17	0.76	0.014
6.40	1.23	0.78	0.014	18.40	1.21	0.78	0.014
6.60	1.33	0.81	0.016	18.80	1.24	0.79	0.014
6.80	1.42	0.84	0.018	19.20	1.27	0.80	0.015
7.00	1.49	0.86	0.020	19.60	1.29	0.80	0.015
7.20	1.54	0.88	0.022	20.00	1.30	0.81	0.015
7.40	1.58	0.89	0.023	20.60	1.29	0.80	0.015
7.60	1.61	0.90	0.024	21.00	1.27	0.80	0.015
7.80	1.63	0.90	0.025	21.60	1.23	0.78	0.014

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Zirconium (polycrystalline)[20]—*continued*

Energy eV	n	k	R(ϕ = 0)	Energy eV	n	k	R(ϕ = 0)
22.00	1.20	0.77	0.014	26.60	0.91	0.67	0.013
22.60	1.15	0.76	0.013	27.00	0.88	0.66	0.013
23.00	1.12	0.75	0.013	27.60	0.84	0.65	0.014
23.60	1.08	0.73	0.013	28.00	0.83	0.64	0.014
24.00	1.05	0.73	0.013	28.60	0.82	0.64	0.014
24.60	1.02	0.71	0.012	29.00	0.81	0.64	0.014
25.00	1.00	0.71	0.012	29.60	0.82	0.64	0.014
25.60	0.97	0.69	0.012	30.00	0.82	0.64	0.014
26.00	0.95	0.69	0.013				

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Spectra

Spectra of n and k and of the normal incidence absorptance A and reflectance R are shown graphically in Figures 4.2.1–4.2.24 for the following metals [figures are from Lynch, D. W., Mirror and reflector materials, *Handbook of Laser Science and Technology, Vol. IV, Optical Materials, Part 2* (CRC Press, Boca Raton, FL, 1986), p. 185].

Aluminum	Gold	Nickel	Silicon
Copper	Iron	Niobium	Silver
Germanium	Molybdenum	Platinum	Tungsten

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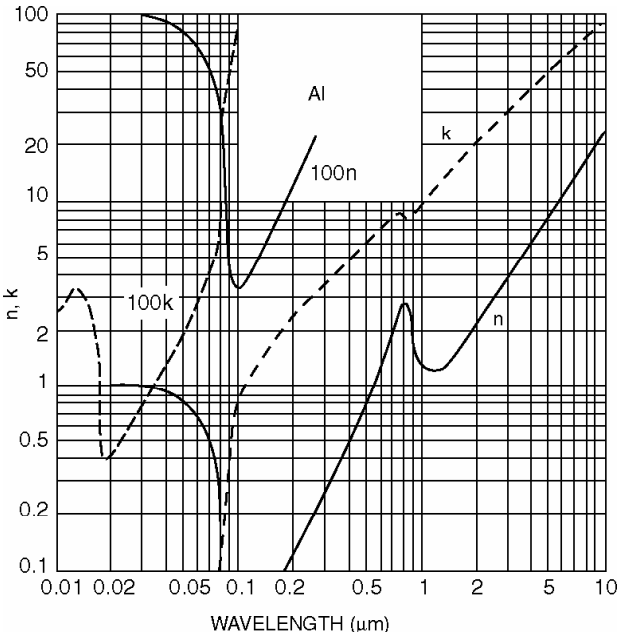

Figure 4.2.1 Real (n) and imaginary (k) part of the index of refraction for aluminum.

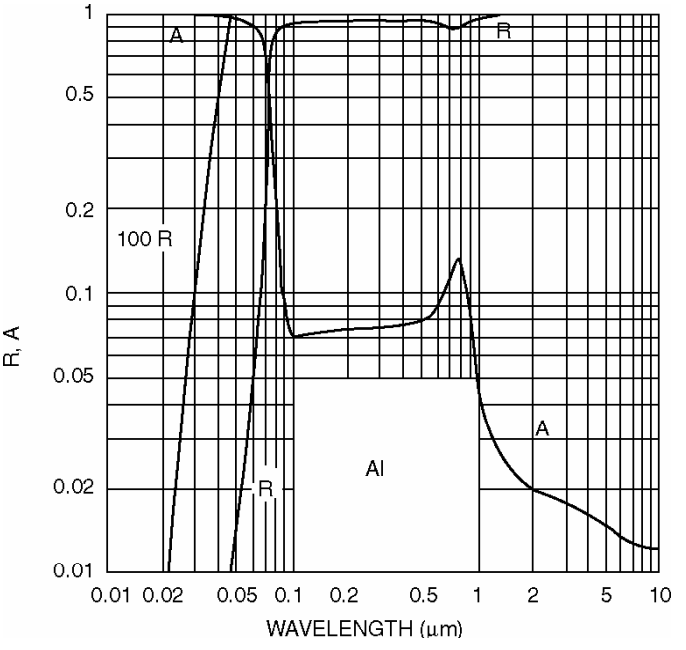

Figure 4.2.2 Reflectance and absorptance (A) for aluminum calculated for normal incidence from the data of Figure 4.2.1. Note that A = 1 – R and a semi-infinite sample is assumed, i.e., the sample is thick enough to be opaque.

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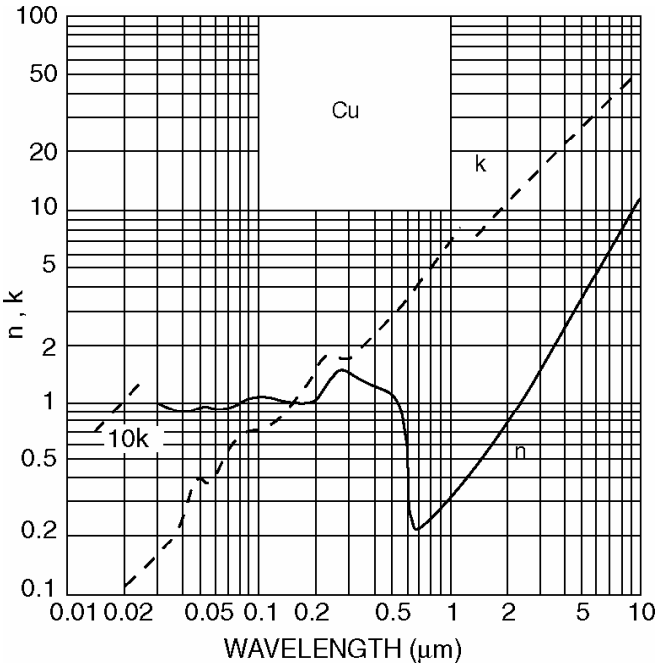

Figure 4.2.3 Real (n) and imaginary (k) part of the index of refraction for copper.

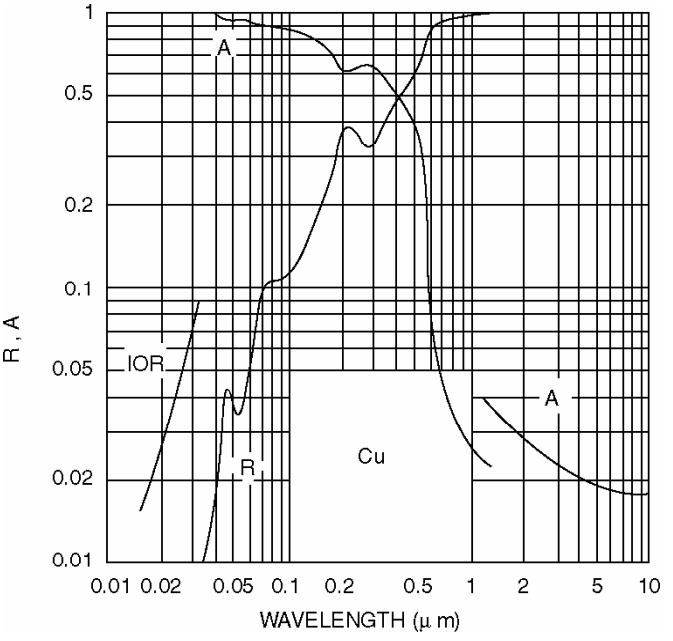

Figure 4.2.4 Reflectance and absorptance (A) for copper calculated for normal incidence from the data of Figure 4.2.3. Note that A = 1 – R and a semi-infinite sample is assumed, i.e., the sample is thick enough to be opaque.

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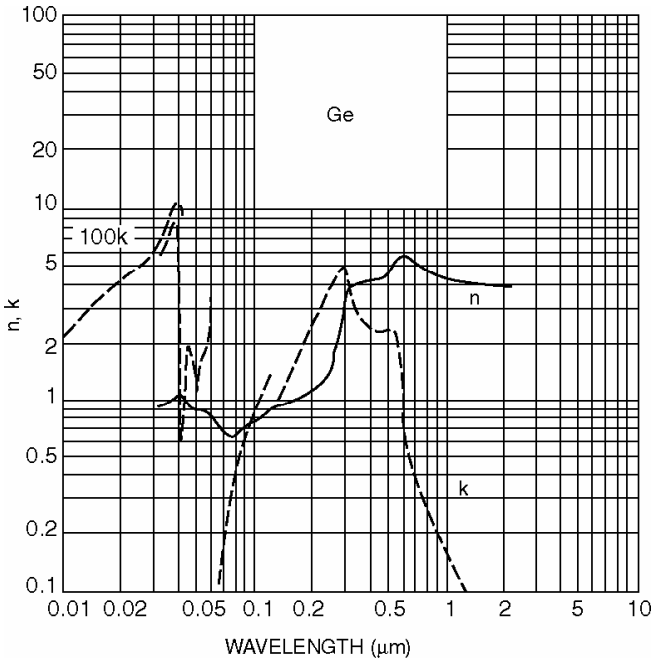

Figure 4.2.5 Real (n) and imaginary (k) part of the index of refraction for germanium.

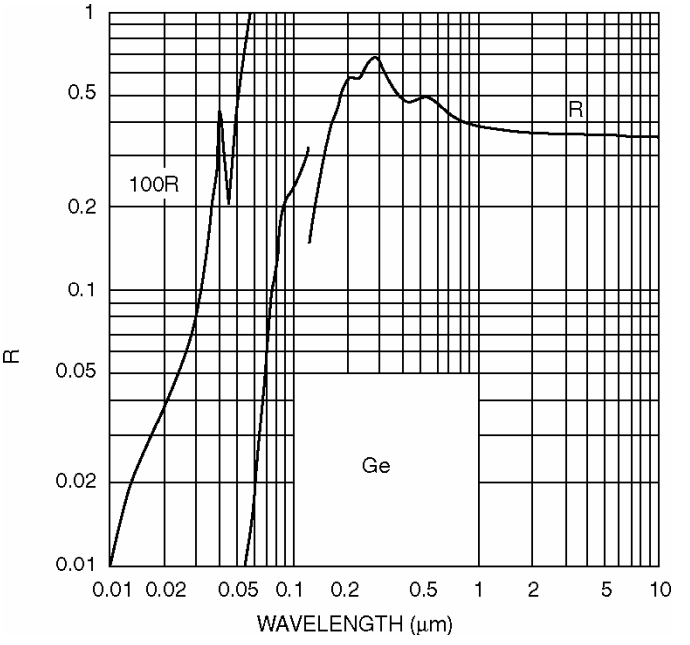

Figure 4.2.6 Reflectance (R) for germanium calculated for normal incidence from the data of Figure 4.2.4. Germanium is transparent for wavelengths >1.8 μm and no effect from a second surface has been considered in calculating R.

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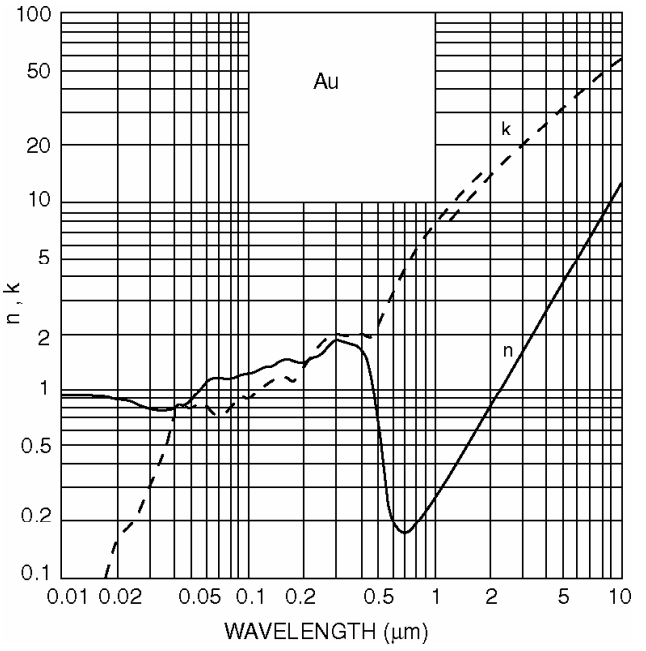

Figure 4.2.7 Real (n) and imaginary (k) part of the index of refraction for gold.

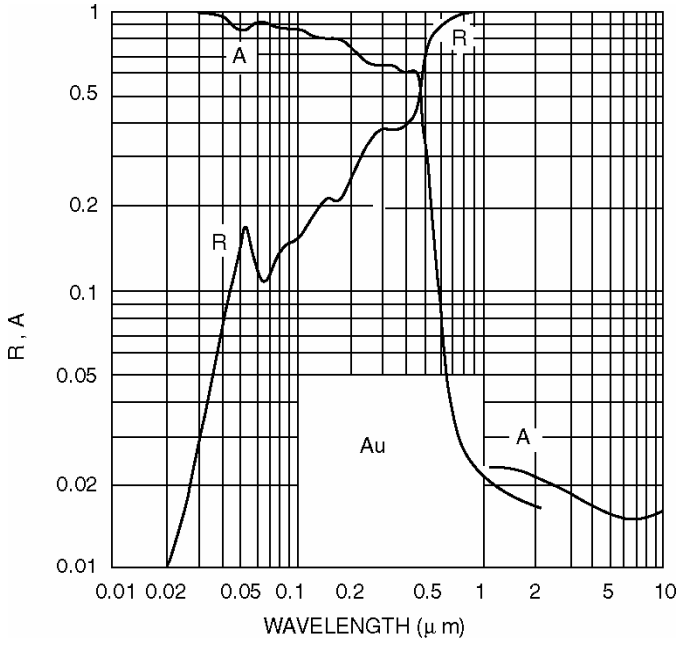

Figure 4.2.8 Reflectance and absorptance (A) for gold calculated for normal incidence from the data of Figure 4.2.7. Note that A = 1 – R and a semi-infinite sample is assumed, i.e., the sample is thick enough to be opaque.

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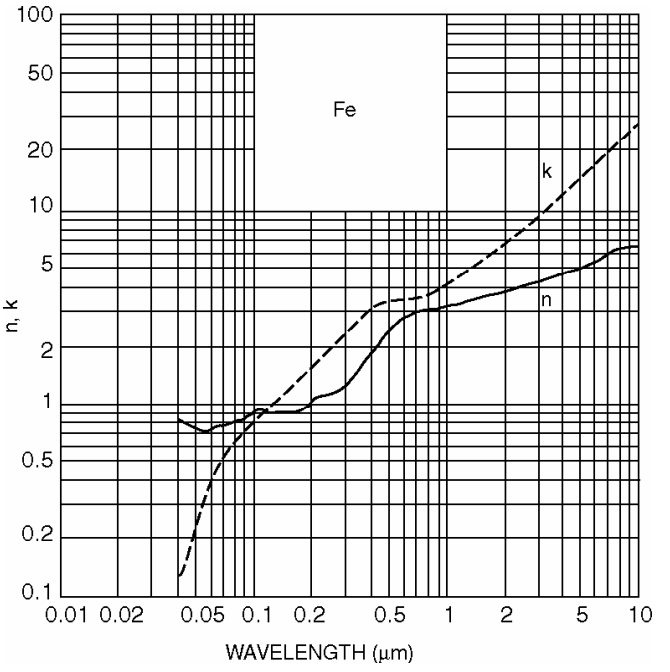

Figure 4.2.9 Real (n) and imaginary (k) part of the index of refraction for iron.

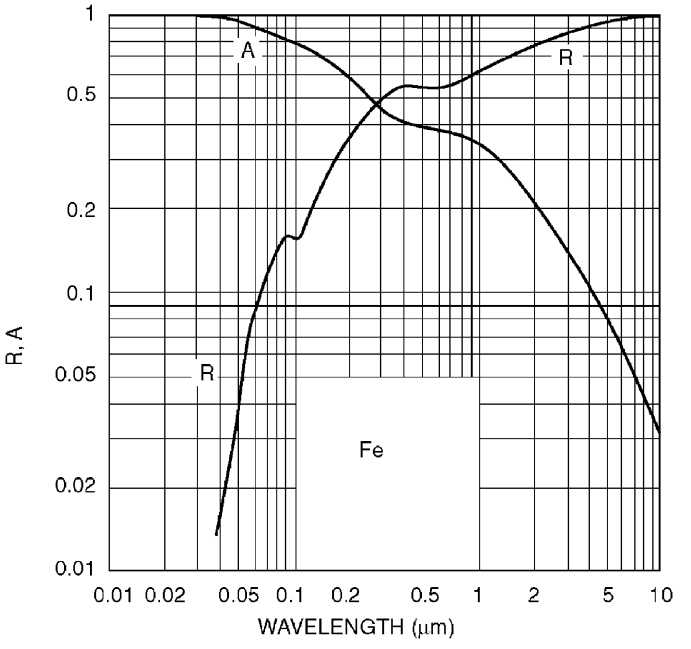

Figure 4.2.10 Reflectance and absorptance (A) for iron calculated for normal incidence from the data of Figure 4.2.9. Note that A = 1 – R and a semi-infinite sample is assumed, i.e., the sample is thick enough to be opaque.

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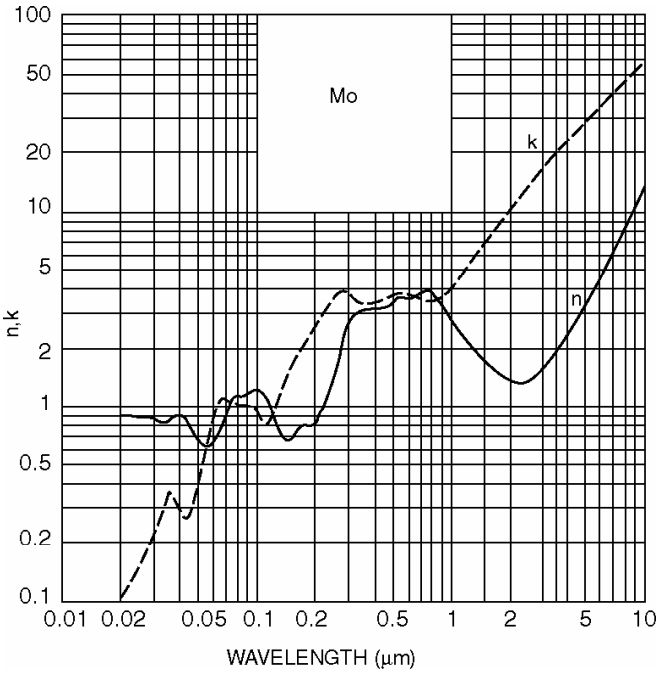

Figure 4.2.11 Real (n) and imaginary (k) part of the index of refraction for molybdenum.

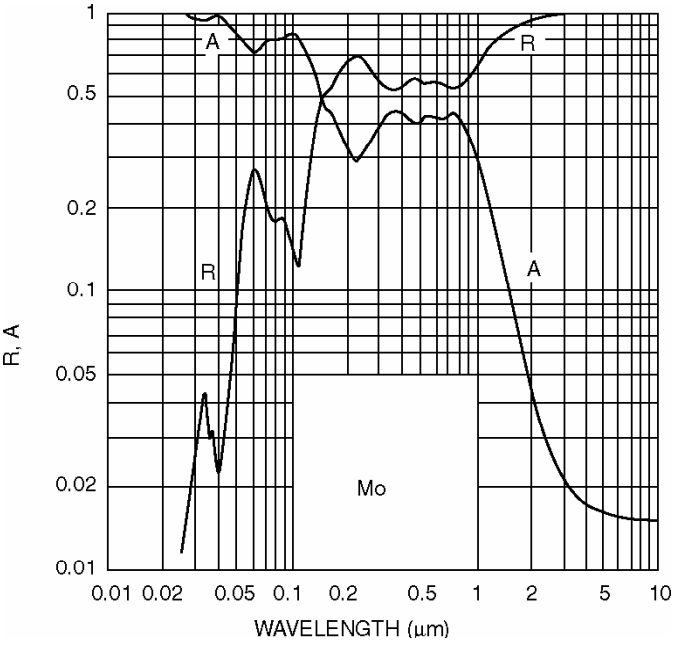

Figure 4.2.12 Reflectance and absorptance (A) for molybdenum calculated for normal incidence from the data of Figure 4.2.11. Note that A = 1 – R and a semi-infinite sample is assumed, i.e., the sample is thick enough to be opaque.

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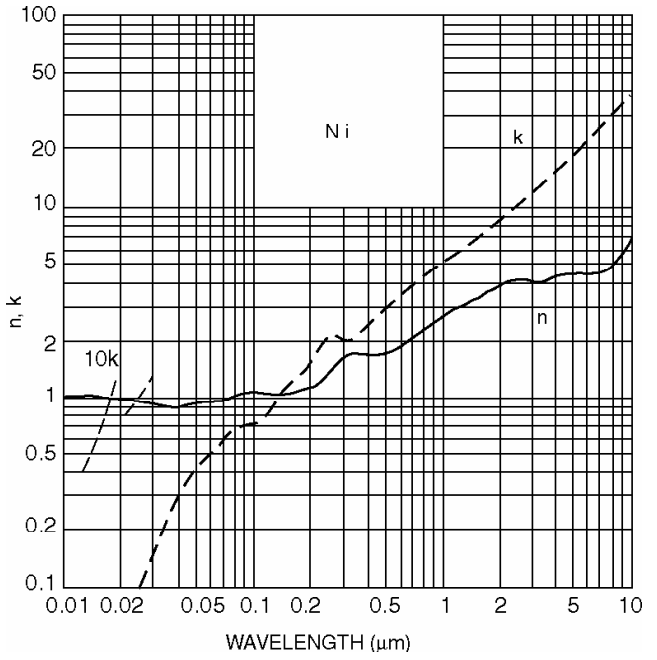

Figure 4.2.13 Real (n) and imaginary (k) part of the index of refraction for nickel.

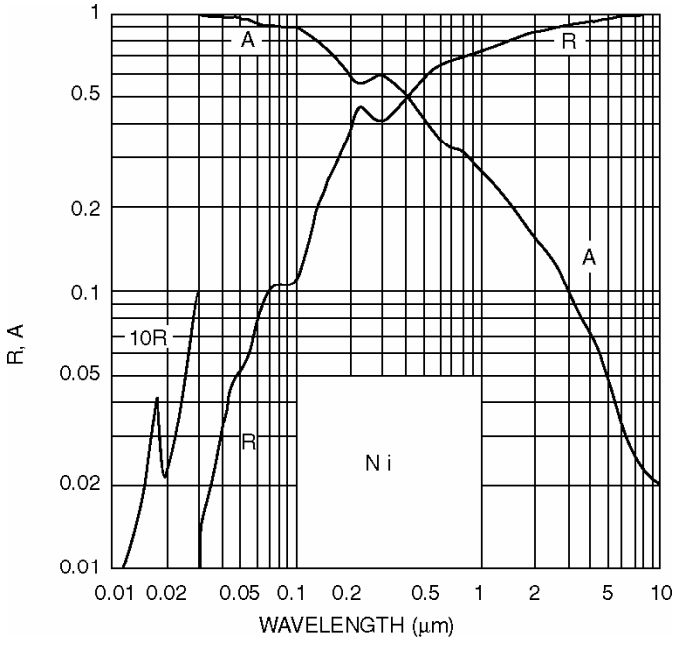

Figure 4.2.14 Reflectance and absorptance (A) for nickel calculated for normal incidence from the data of Figure 4.2.13. Note that A = 1 – R and a semi-infinite sample is assumed, i.e., the sample is thick enough to be opaque.

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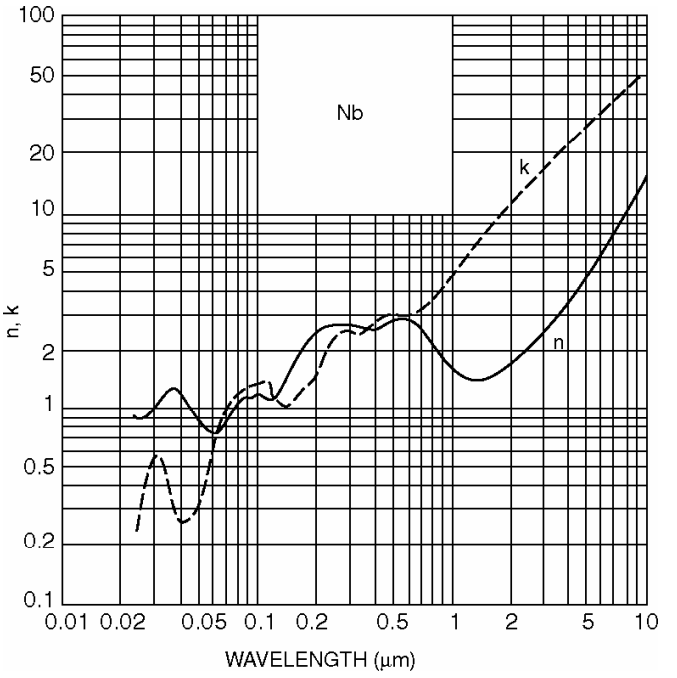

Figure 4.2.15 Real (n) and imaginary (k) part of the index of refraction for niobium.

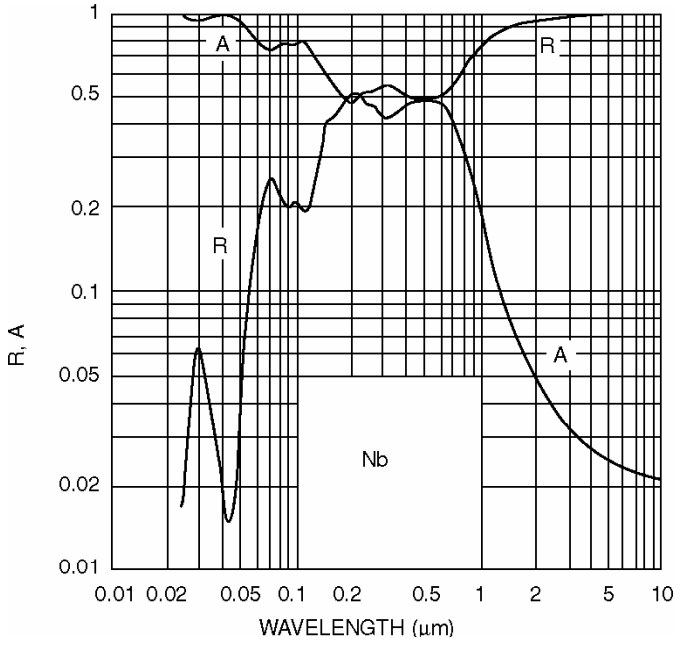

Figure 4.2.16 Reflectance and absorptance (A) for niobium calculated for normal incidence from the data of Figure 4.2.15. Note that A = 1 – R and a semi-infinite sample is assumed, i.e., the sample is thick enough to be opaque.

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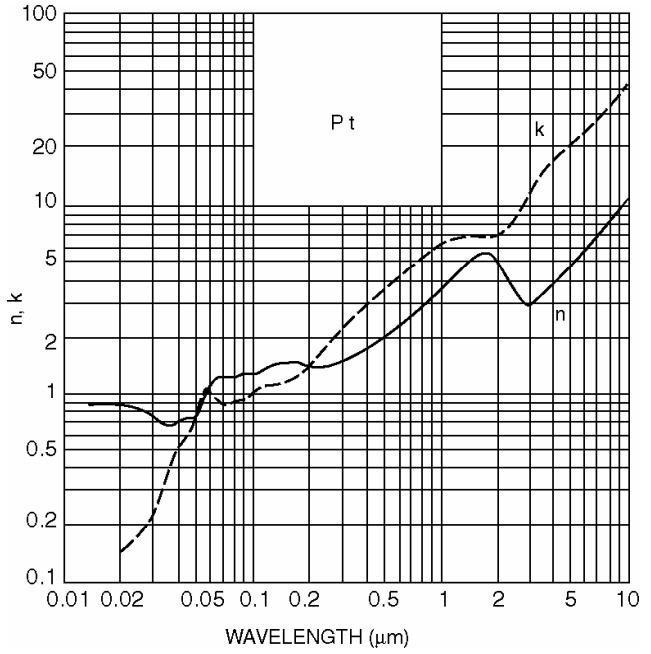

Figure 4.2.17 Real (n) and imaginary (k) part of the index of refraction for platinum.

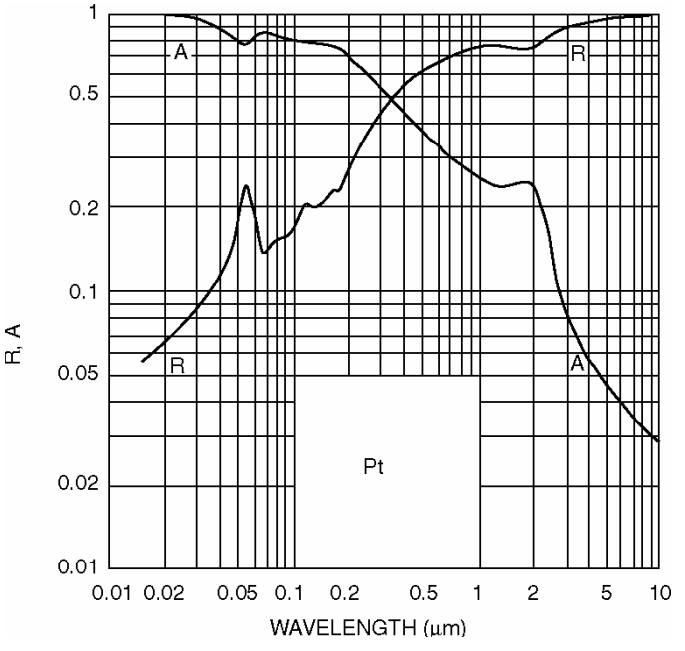

Figure 4.2.18 Reflectance and absorptance (A) for platimum calculated for normal incidence from the data of Figure 4.2.17. Note that A = 1 – R and a semi-infinite sample is assumed, i.e., the sample is thick enough to be opaque.

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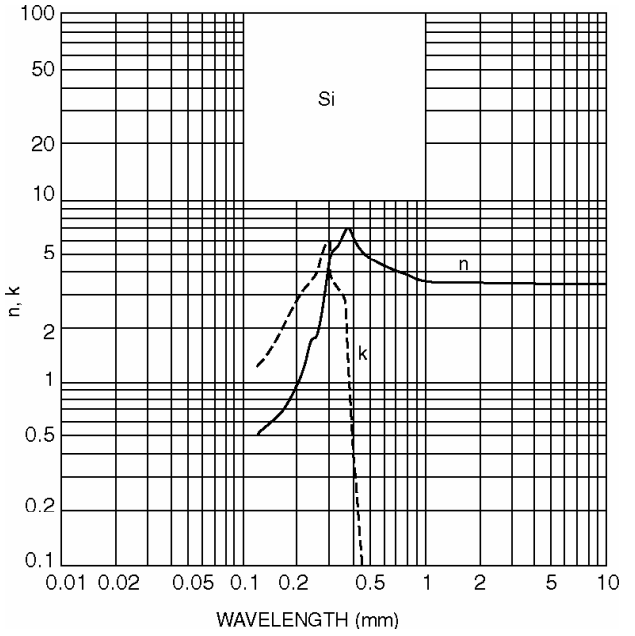

Figure 4.2.19 Real (n) and imaginary (k) part of the index of refraction for silicon.

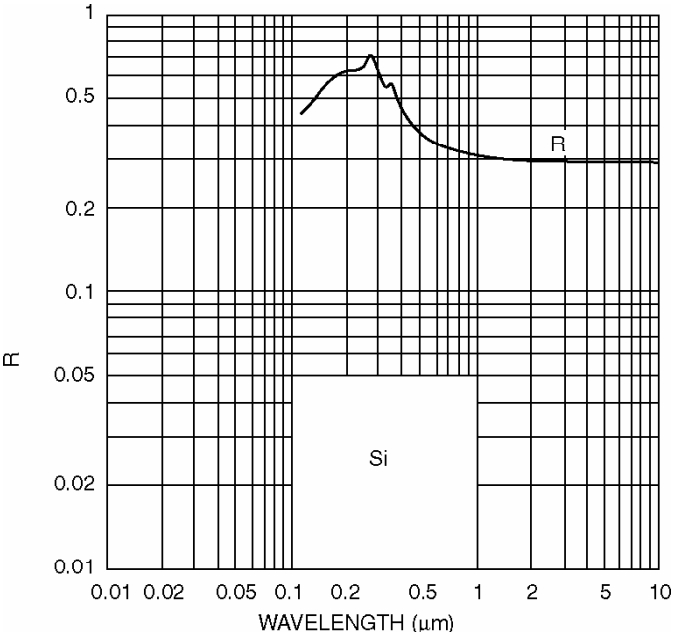

Figure 4.2.20 Reflectance and absorptance (A) for silicon calculated for normal incidence from the data of Figure 4.2.19. Silicon is transparent for wavelengths > 1.2 μm and no effect from a second surface has been considered in calculating R.

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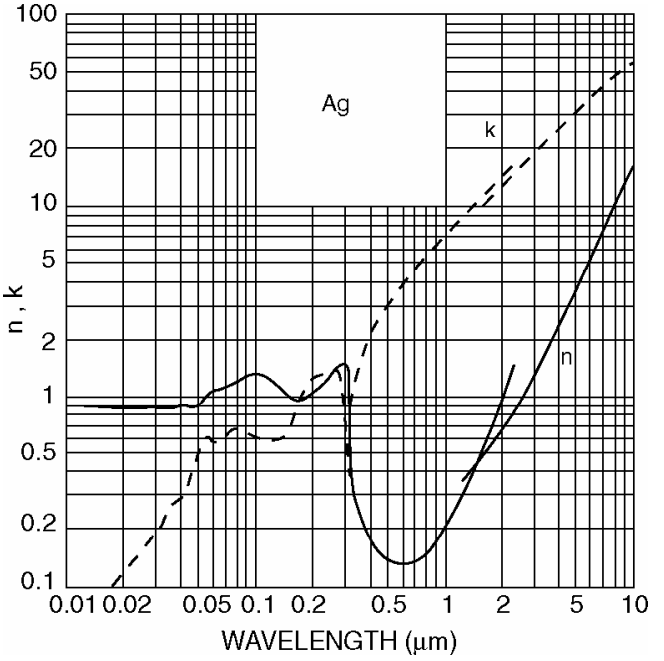

Figure 4.2.21 Real (n) and imaginary (k) part of the index of refraction for silver.

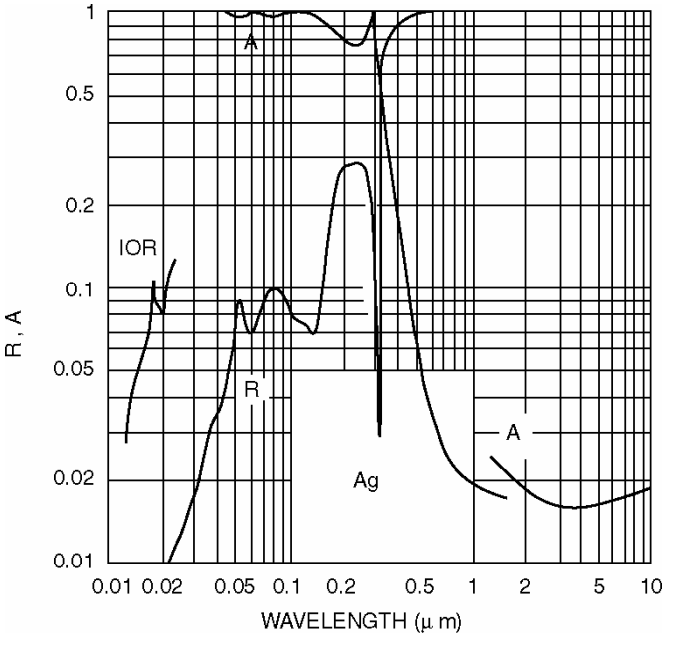

Figure 4.2.22 Reflectance and absorptance (A) for silver calculated for normal incidence from the data of Figure 4.2.21. Note that A = 1 – R and a semi-infinite sample is assumed, i.e., the sample is thick enough to be opaque.

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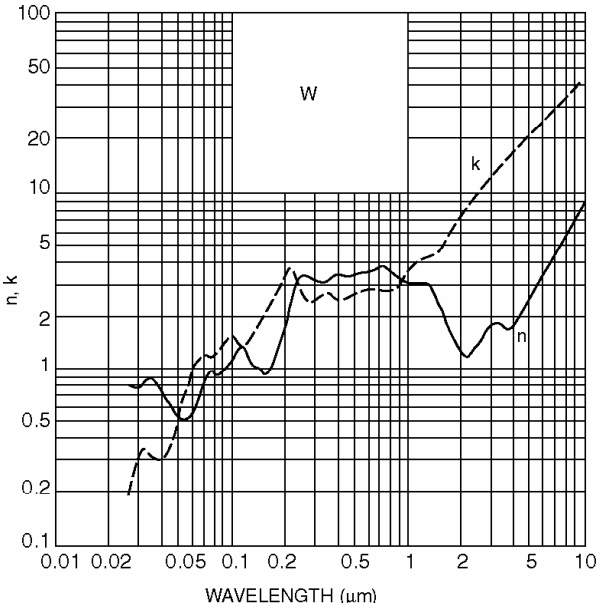

Figure 4.2.23 Real (n) and imaginary (k) part of the index of refraction for tungsten.

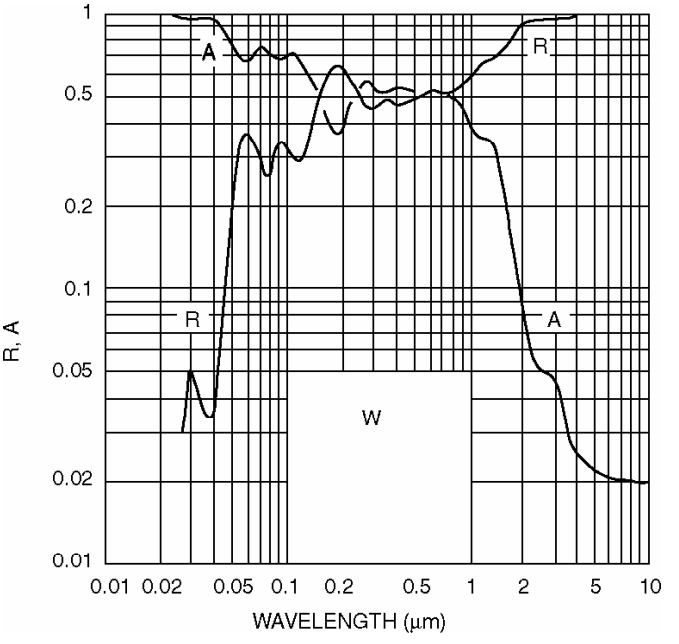

Figure 4.2.24 Reflectance and absorptance (A) for tungsten calculated for normal incidence from the data of Figure 4.2.23. Note that A = 1 – R and a semi-infinite sample is assumed, i.e., the sample is thick enough to be opaque.

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Emittance

Emittance is the ratio of radiated emitted power of a surface (W/m^2) to the emissive power of a blackbody at the same temperature. The total emittance is an integral over all wavelengths; the spectral emittance is given as a function of wavelength at constant temperature.

Normal Spectral Emittance (650 nm)

Metal	Emissivity
Beryllium	0.61
Chromium	0.34
Copper	0.10
Gold	0.14
Iron	0.35
Iron (cast)	0.37
Molybdenum	0.37
Nickel	0.36
Nickel (80) -chromium (20)	0.35
Palladium	0.33
Platinum	0.30
Silver	0.07
Steel	0.35
Tantalum	0.49
Titanium	0.63
Tungsten	0.43
Zirconium	0.32

From the *CRC Handbook of Chemistry and Physics*, 75th edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 1994), p. 10-296.

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Total Emittance

Metal	Temperature (˚C)	Emissivity
Aluminum		
polished	50–500	0.04–0.06
oxidized	200	0.11
	600	0.19
Chromium		
polished	50	0.1
	500–1000	0.28–0.38
Copper		
oxidized	50	0.6–0.7
	500	0.88
unoxidized	100	0.02
polished	50–100	0.02
Gold		
carefully polished	200–600	0.02–0.03
unoxidized	100	0.02
Iron, cast		
oxidized	200	0.64
	600	0.78
unoxidized	100	0.21
Molybdenum	600–1000	0.08–0.13
Nickel		
polished	200–400	0.07–0.09
unoxidized	25	0.045
	100	0.06
	500	0.12
	1000	0.19
Nickel (80)		
-chromium (20)	100	0.87
	600	0.87
Platinum		
polished	200–600	0.05–0.1
unoxidized	25	0.017
	100	0.047
	500	0.096
Silver		
polished	200–600	0.02–0.03
unoxidized	100	0.02
	500	0.035
Steel		
8%Ni, 18%Cr	500	0.35
cast, polished	750–1050	0.52–0.56
oxidized	200–600	0.8
unoxidized	100	0.08
Tantalum		
unoxidized	1500	0.21
Tungsten		
unoxidized	25	0.024
	100	0.032
	500	0.071
Zinc		
polished	200–300	0.04–0.05
unoxidized	300	0.05

From the *CRC Handbook of Chemistry and Physics*, 75th edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 1994), p. 10-295.

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Reflectance of Freshly Evaporated Mirror Coatings

	Normal Incidence Reflectance (%)					
λ (nm)	Aluminum	Copper	Gold	Platinum	Rhodium	Silver
220	91.5	40.4	27.5	40.5	57.8	28.0
240	91.9	39.0	31.6	46.9	63.2	29.5
260	92.2	35.5	35.6	51.5	67.7	29.2
280	92.3	33.0	37.8	54.9	70.7	25.2
300	92.3	33.6	37.7	57.6	73.4	17.6
320	92.4	36.3	37.1	60.0	75.5	8.9
340	92.5	38.5	36.1	62.0	76.9	72.9
360	92.5	41.5	36.3	63.4	78.0	88.2
380	92.5	44.5	37.8	64.9	78.1	92.8
400	92.4	47.5	38.7	66.3	77.4	95.6
450	92.2	55.2	38.7	69.1	76.0	97.1
500	91.8	60.0	47.7	71.4	76.6	97.9
550	91.5	66.9	81.7	73.4	78.2	98.3
600	91.1	93.3	91.9	75.2	79.7	98.6
650	90.5	96.6	95.5	76.4	81.1	98.8
700	89.7	97.5	97.0	77.2	82.0	98.9
750	88.6	97.9	97.4	77.9	82.6	99.1
800	86.7	98.1	98.0	78.5	83.1	99.2
850	86.7	98.3	98.2	79.5	83.4	99.2
900	89.1	98.4	98.4	80.5	83.6	99.3
950	92.4	98.4	98.5	80.6	83.9	99.3
1000	94.0	98.5	98.6	80.7	84.2	99.4
1500	97.4	98.5	99.0	81.8	87.7	99.4
2000	97.8	98.6	99.1	81.8	91.4	99.4
3000	98.0	98.6	99.3	90.6	95.0	99.4
4000	98.2	98.7	99.4	93.7	95.8	99.4
5000	98.4	98.7	99.4	94.9	96.4	99.5
6000	98.5	98.7	99.4	95.6	96.8	99.5
7000	98.6	98.7	99.4	95.9	97.0	99.5
8000	98.7	98.8	99.4	96.0	97.2	99.5
9000	98.7	98.8	99.4	96.1	97.4	99.5
10000	98.7	98.9	99.4	96.2	97.6	

Reference: Hass, G., in *Applied Optics and Optical Engineering*, vol. III, Kingslake, R., Ed., (Academic Press, New York, 1965), p. 309. See also, Palmer, J. M., *Handbook of Optics* (McGraw-Hill, New York, 1995), Chapter 25 and references cited therein.

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4.3 Mechanical Properties

Elastic Constants

Metal	Elastic stiffness constants (10^{11} N/m^2)				
Cubic crystals	C_{11}	C_{12}	C_{44}		
Aluminum	1.0675	0.6041	0.2834		
Chromium	3.398	0.586	0.990		
Copper	1.683	1.221	0.757		
Germanium	1.2835	0.4823	0.6666		
Gold	1.9244	1.6298	0.4200		
Iridium	5.80	2.42	2.56		
Iron	2.26	1.40	1.16		
Molybdenum	4.637	1.578	1.092		
Nickel	2.841	1.529	1.242		
Niobium	2.4650	1.3450	0.2873		
Palladium	2.2710	1.7604	0.7173		
Platinum	3.4670	2.5070	0.7650		
Silicon	1.6578	0.6394	0.7962		
Silver	1.2399	0.9367	0.4612		
Tantalum	2.6023	1.5446	0.8255		
Tungsten	5.2239	2.0437	1.6083		
Hexagonal crystals	C_{11}	C_{12}	C_{13}	C_{33}	C_{55}
Beryllium	2.923	0.267	0.140	3.364	1.625
Magnesium	0.5950	0.2612	0.2180	0.6155	0.1635
Zinc	1.6368	0.3640	0.5300	0.6347	0.3879
Zirconium	1.434	0.728	0.657	1.648	0.320

Reference: Frederikse, H. P. R., Elastic constants of single crystals, *Handbook of Chemistry and Physics*, 82nd edition (CRC Press, Boca Raton, FL, 1994), p. 12-37.

Elastic Moduli and Poisson's Ratio

Material	Young's modulus (GN/m^2)	Shear modulus (GN/m^2)	Bulk modulus (GN/m^2)	Poisson's ratio
Aluminum				
5086-O	71.0	26.4	—	0.33
6061-T6	68.9	25.9	—	0.33
Beryllium (I-701-H)	315.4	148.4	115.0	0.043
Copper	129.8	48.3	137.8	0.343
Germanium	79.9	29.6	—	0.32
Gold	78.5	26.0	171.0	0.42
Invar 36	144.0	26.0	99.4	0.259
Iron	211.4	57.2	169.8	0.293

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Elastic Moduli and Poisson's Ratio—*continued*

Material	Young's modulus (GN/m^2)	Shear modulus (GN/m^2)	Bulk modulus (GN/m^2)	Poisson's ratio
Molybdenum	324.8	81.6	261.2	0.293
Nickel	199.5	125.6	177.3	0.312
Platinum	170.0	76.0	276.0	0.39
Silicon	113.0	60.9	—	0.42
Silicon carbide				
CVD	461.0	39.7		0.21
reaction sintered	413.0	—	—	0.24
Silver	82.7	30.3	103.6	0.367
Stainless steel		77.0		
304	193.0	83.9	—	0.27
416	215.0	80.0	166.0	0.283
430	200	62.2	—	0.27
Tantalum	185.7	160.2	196.3	0.342
Tungsten	411		311.0	0.28

Table adapted from Palmer, J. M., *Handbook of Optics,* Vol.II (McGraw-Hill, New York, 1995), p. 35.73.

Strength Properties

Material	Yield strength (MN/m^2)	Microyield strength (MN/m^2)	Elongation (in 50 mm) %	Hardness
Aluminum				
5086-O	115	40	22	55 (Rockwell B)
6061-T6	276	160	15	95 (Rockwell B)
Beryllium (I-701-H)	276	30	4	80 (Rockwell B)
Copper	195	12	42	10 (Rockwell B)
Gold	125		30	30 (Knoop*)
Invar 36	276	37	35	70 (Rockwell B)
Molybdenum	600		47	150 (Knoop*)
Nickel	148		35	109 (Rockwell B)
Platinum	150			40 (Knoop*)
Silver	130		47	32 (Knoop*)
Stainless steel				
304	241		60	80 (Rockwell B)
416	950		12	41 (Rockwell C)
430	380		25	86 (Rockwell B)
Tantalum	220		30	120 (Knoop*)
Tungsten	780		2	350 (Knoop*)

* kg/mm^2

Table adapted from Palmer, J. M., *Handbook of Optics,* Vol.II (McGraw-Hill, New York, 1995), p. 35.74.

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4.4 Thermal Properties

Thermal Properties

Metal	Density[(a)] (g/cm^3)	Melting point (°C)	Coeff. linear expansion[(a)] (10^{-6} K^{-1})	Specific heat capacity (J/g K)	Thermal conductivity[(b)] (W/m K)
Aluminum	2.70	660.3	23.1	0.897	237
Beryllium	1.85	1287	11.3	1.825	200
Chromium	7.15	1907	4.9	0.449	93.7
Copper	8.96	1084.6	16.5	0.385	401
Gold	19.3	1064.3	14.2	0.129	317
Iridium	22.5	2446	6.4	0.131	147
Iron	7.87	1538	11.8	0.449	80.2
Magnesium	1.74	650	24.8	1.023	156
Molybdenum	10.2	2623	4.8	0.251	138
Nickel	8.9	1455	13.4	0.444	90.7
Niobium	8.57	2477	7.3	0.265	53.7
Osmium	22.59	3033	5.1	0.130	87.6
Palladium	12.0	1555	11.8	0.246	71.8
Platinum	21.5	1768.4	8.8	0.133	71.6
Rhenium	20.8	3186	6.2	0.137	47.9
Rhodium	12.4	1964	8.2	0.243	150
Silver	10.5	961.8	18.9	0.235	429
Tantalum	16.4	3017	6.3	0.140	57.5
Tin	7.28	231.9	22.0	0.228	66.6
Titanium	4.5	1668	8.6	0.523	21.9
Tungsten	19.3	3422	4.5	0.132	174
Zinc	7.14	419.5	30.2	0.388	116
Zirconium	6.52	1855	5.7	0.278	27.7

(a) 25°C, (b) 27°C. From the *CRC Handbook of Chemistry and Physics*, 82nd edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 2001), p. 12-219.

Temperature Dependence of Linear Thermal Expansion Coefficient (ppm/K)

Temperature (K)	100	200	293	400	500	600
Aluminum (6061)	12.2	20.9	22.5	25.0	27.5	30.1
Beryllium	1.32	7.00	11.3	13.6	15.1	16.6
Copper	10.3	15.2	16.5	17.6	18.3	18.9
Gold	11.8	13.7	14.2	14.8	15.4	15.9
Iron	506	10.1	11.8	13.4	14.4	15.1
Molybdenum	2.8	4.6	4.8	4.9	5.1	5.3
Nickel	6.6	11.3	13.4	14.5	15.3	15.9
Silicon	-0.4	1.5	2.6	3.2	3.5	3.7
Silicon carbide (α)	0.14	1.5	3.3	4	4.2	4.5
Silver	14.2	17.8	18.9	19.7	20.6	21.5
Stainless steel (304)	11.4	13.2	14.7	16.3	17.5	18.6
Stainless steel (416)	6	7.9	9.5	10.9	12.1	12.9

Adapted from Palmer, J. M., Properties of metals, in *Handbook of Optics, Vol.II* (McGraw-Hill, New York, 1995), p. 35.60.

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Temperature Dependence of Molar Heat Capacity (J/mol K)

Temp. (K)	200	250	300	350	400	500	600
Aluminum	21.33	23.08	24.25	25.11	25.78	26.84	27.89
Beryllium	9.98	13.58	16.46	18.53	19.95	21.94	23.34
Chromium	19.86	22.30	23.47	24.39	25.23	26.63	27.72
Copper	22.63	23.77	24.48	24.95	25.33	25.91	26.48
Germanium	—	—	23.25	23.85	24.31	24.96	25.45
Gold	—	—	25.41	25.37	25.51	26.06	26.65
Iron	21.95	23.94	25.15	26.28	27.39	29.70	32.05
Magnesium	22.72	24.02	24.90	25.57	26.14	27.17	28.18
Silicon	15.64	18.22	20.04	21.28	22.14	23.33	24.15
Silver			25.36	25.55	25.79	26.36	26.99
Tantalum	24.08	24.86	25.31	25.60	25.84	26.35	26.84
Titanium	22.37	24.07	25.28	26.17	26.86	27.88	28.60
Tungsten	22.49	23.69	24.30	24.65	24.92	25.36	25.79
Zinc	24.05	25.02	25.45	25.88	26.35	27.39	28.59
Zirconium	23.87	24.09	25.22	25.61	25.93	26.56	27.28

From the *CRC Handbook of Chemistry and Physics*, 82nd edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 2001), p. 12-218.

Temperature Dependence of Thermal Conductivity (W/m K)

Temp. (K)	4	20	80	200	300	400	600
Aluminum	15700	11700	432	237	237	240	231
Chromium	160	593	184	111	93.7	90.9	80.7
Copper	16200	10800	557	413	401	393	379
Germanium	877	1490	325	96.8	59.9	43.2	27.3
Gold	2090	1580	332	323	317	311	298
Iron	677	1540	175	94	80.2	69.5	54.7
Nickel	859	1650	210	107	90.7	80.2	65.6
Platinum	880	495	81.5	72.6	71.6	71.8	73.2
Silicon	297	4810	1340	264	148	98.9	61.9
Silver	14700	5100	471	430	429	425	412
Tin	18100	320	91.5	73.3	66.6	62.2	—
Titanium	5.75	27.5	32.6	24.5	21.9	20.4	19.4
Tungsten	5630	4050	229	185	174	159	137

From the *CRC Handbook of Chemistry and Physics*, 82nd edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 2001), p. 12-221.

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4.5 Mirror Substrate Materials

Tables adapted from Palmer, J. M., Properties of metals, in *Handbook of Optics*, Vol.II (McGraw-Hill, New York, 1995), p. 35.11.

Mirror Substrate Materials

Material	Density (g/cm^3)	Young's modulus (GN/m^2)	Specific stiffness (arbitrary units)
Fused silica	2.19	72	33
Beryllium (I-70)	1.85	287	155
Aluminum (6061)	2.70	68	25
Copper	8.94	117	13
Stainless steel (304)	8.00	193	24
Invar (36)	8.05	141	18
Silicon	2.33	131	56
Silicon carbide (30% Si)	2.89	330	114
Silicon carbide CVD)	3.21	465	145

Thermal Properties of Substrate Materials

Material	Coeff. linear expansion (10^6 K^{-1})	Specific heat capacity (J/g K)	Thermal conductivity (W/m K	Thermal diffusivity (10^{-6} m^2/s)
Fused silica	0.50	750	1.4	0.85
Beryllium (I-70)	11.3	1925	216	57.2
Aluminum (6061)	22.5	896	167	69
Copper	16.5	385	391	115.5
Stainless steel (304)	14.7	500	16.2	4.0
Invar (36)	1.0	515	10.4	2.6
Silicon	2.6	710	156	89.2
Silicon carbide (30% Si)	2.6	670	155	81.0
Silicon carbide CVD)	2.4	733	198	82.0

Thermal Distortion of Substrate Materials

Material	Steady state distortion coefficient[(a)] (μm/W)	Transient distortion coefficient[(b)] (s/m^2 K)
Fused silica	0.36	0.59
Beryllium (I-70)	0.05	0.20
Aluminum (6061)	0.13	0.33
Copper	0.53	0.14
Stainless steel (304)	0.91	3.68
Invar (36)	0.10	0.38
Silicon	0.02	0.03
Silicon carbide (30% Si)	0.02	0.03
Silicon carbide CVDi)	0.01	0.03

(a) Linear expansion coefficient/thermal conductivity.
(b) Linear expansion coefficient/thermal diffusivity.

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Section 5: Liquids

5.1 Introduction
5.2 Water
5.3 Physical Properties of Selected Liquids
5.4 Index of Refraction
5.5 Nonlinear Optical Properties
5.6 Magnetooptic Properties
5.7 Commercial Optical Liquids

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Section 5

LIQUIDS

5.1 Introduction

Liquids in this section include water (H_2O), heavy water (D_2O), and the following selected organic materials (CAS – Chemical Abstract Service Registry Number):

CAS no.	Liquid	CAS no.	Liquid
100	acetic acid, $C_2H_4O_2$	5672	ethanol, C_2H_6O
10411	acetone, C_3H_6O	5569	ethylene glycol, $C_2H_6O_2$
867	benzene, C_6H_6	10186	glycerine (glycerol), $C_3H_8O_3$
998	bromobenzene, C_6H_5Br	6355	heptane, C_7H_{16}
3993	carbon disulfide, CS_2	6632	hexadecane, $C_{16}H_{34}$
7540	carbon tetrachloride, CCl_4	6731	hexane, C_6H_{14}
7554	chloroform, $CHCl_3$	7581	methanol, CH_4O
4305	cyclohexane, C_6H_{12}	4426	methylcyclohexane, C_7H_{14}
5529	1,2-dichloroethane, $C_2H_4Cl_2$	7915	1-methylnaphthalene, $C_{11}H_{10}$
7499	dichloromethane, CH_2Cl_2	2049	nitrobenzene, $C_6H_5NO_2$
7529	dimethylsulfoxide, C_2H_6OS	1947	toluene, C_7H_8
5187	1,4-dioxane, $C_4H_8O_2$	8848	2,2,4-trimethylpentane, C_8H_{18}

5.2 Water

5.2.1 Physical Properties

Density, specific heat capacity at constant pressure (C_p), viscosity, vapor pressure, thermal conductivity, dielectric constant, and surface tension of water. All values (except vapor pressure) at for a pressure of 100 kPa (1 bar)**.** Temperature scale is IPTS-68.

Temp. (°C)	Density (g/cm^3)	C_p (J/g K)	Visc. (μPa s)	Vapor press. (kPa)	Therm. cond. (mW/m K)	Diel. const.	Surf. tens. (mN/m)
0	0.99984	4.2176	0.6113	1793	561.0	87.90	75.64
10	0.99970	4.1921	1.2281	1307	580.0	83.96	74.23
20	0.99821	4.1818	2.3388	1002	598.4	80.20	72.75
30	0.99565	4.1784	4.2455	797.7	615.4	76.60	71.20
40	0.99222	4.1785	7.3814	653.2	630.5	73.17	69.60
50	0.98803	4.1806	12.344	547.0	643.5	69.88	67.94
60	0.98320	4.1843	19.932	466.5	654.3	66.73	66.24
70	0.97778	4.1895	31.176	404.0	663.1	63.73	64.47
80	0.97182	4.1963	47.373	354.4	670.0	60.86	62.67
90	0.96535	4.2050	70.117	314.5	675.3	587.12	60.82
100	0.95840	4.2159	101.325	281.8	679.1	55.51	58.91

From the *CRC Handbook of Chemistry and Physics*, 82nd edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 2001), p. 6-3.

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5.2.2 Absorption

Linear Absorption Coefficient α of Water*

λ (nm)	α (10^{-4} cm^{-1})	Ref.	λ (nm)	α (10^{-4} cm^{-1})	Ref.
185	14600	1	660	40.7	2
186	9700	1	665	41.9	2
187	6000	1	670	42.5	2
188	3800	1	675	43.8	2
189	2300	1	680	44.7	2
190	1400	1	685	46.7	2
400	5.8	2	690	49	4
410	4.7	2	690	51.5	2
420	3.8	2	694.2	52.6	3
430	4.0	2	695	56.9	2
440	3.2	2	700	64.8	2
450	3.3	2	702	69	4
460.7	2.11	3	705	75.0	2
469.4	2.05	3	710	90.4	2
480.7	1.86	3	714	98	4
490.1	1.89	3	715	111.4	2
499.9	2.33	3	720	137.5	2
510.1	3.13	3	725	134	4
520.7	3.80	3	725	175.6	2
529.0	4.09	3	730	230.9	2
540.4	4.80	3	735	238	4
546.3	5.28	3	735	260.8	2
574.5	8.05	3	740	269.8	2
580	10.9	2	745	271.2	2
585	11.9	2	746	275	4
590	17.2	2	750	268.3	2
595	21.4	2	752	281	4
598.6	19.25	3	755	269.6	2
600	27.2	2	758	272	4
602.2	23.2	3	760	268.5	2
605	29.3	2	769	251	4
610	29.3	2	770	251.9	2
615	30.0	2	780	234.6	2
620	30.9	2	781	230	4
625	30.5	2	790	205.2	2
630	32.0	2	794	210	4
635	32.5	2	806	195	4
640	33.4	2	813	191	4
645	33.9	2	820	199	4
649.2	32.3	3	833	308	4
650	35.1	2	847	387	4
655	38.7	2	862	428	4

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Linear Absorption Coefficient α of Water*—*continued*

λ (nm)	α (10^{-4} cm^{-1})	Ref.	λ (nm)	α (10^{-4} cm^{-1})	Ref.
877	506	4	1370	54500	4
893	609	4	1389	91300	4
909	750	4	1408	215000	4
926	1190	4	1429	310000	4
935	1580	4	1443	317000	4
943	2140	4	1471	285000	4
952	3220	4	1493	217000	4
962	4710	4	1515	156000	4
973	5140	4	1538	121000	4
980	5020	4	1563	96800	4
990	4690	4	1587	80700	4
1000	4160	4	1613	68000	4
1010	3510	4	1639	60700	4
1020	2850	4	1667	56500	4
1031	2310	4	1695	56500	4
1042	1900	4	1724	62300	4
1053	1640	4	1754	76000	4
1070	1480	4	1786	91800	4
1087	1660	4	1802	94800	4
1099	1920	4	1818	94400	4
1111	2320	4	1852	108000	4
1124	3230	4	1887	575000	4
1136	5480	4	1927	1240000	4
1149	9700	4	1961	1090000	4
1163	11800	4	2000	692000	4
1176	12300	4	2041	450000	4
1190	12500	4	2083	310000	4
1205	12500	4	2128	236000	4
1220	12200	4	2198	193000	4
1235	11700	4	2273	230000	4
1250	11100	4	2326	293000	4
1266	10700	4	2381	418000	4
1282	11300	4	2439	635000	4
1299	13400	4	2500	957000	4
1316	16700	4	2564	1110000	4
1333	22500	4	2632	1930000	4
1351	38700	4			

* Measurements made at room temperature (Ref. 1 – 298 K; Ref. 2 – 296 ± 1.5 K; Ref. 4 – 300 K).

References:

1. Barrett, J. and Mansell, A. L., Ultra-violet absorption spectra of the molecules H_2O, HDO and D_2, *Nature* 187, 138 (1960).

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2. Sullivan, S. A., Experimental study of the absorption in distilled water, artificial sea water, and heavy water in the visible region of the spectrum, *J. Opt. Soc. Am*. 53, 962 (1963). This reference contains additional values of α at wavelengths intermediate to those given above.
3. Tam, A. C. and Patel, C. K. N., Optical absorption of light and heavy water by laser optoacoustic spectroscopy, *Appl. Opt.* 18, 3348 (1979).
4. Palmer, K. F. and Williams, D., Optical properties of water in the near infrared, *J. Opt. Soc. Am.* 64, 1107 (1974).

Absorption Coefficient α for Water in the Infrared (T = 298 K)

λ (nm)	α (cm^{-1})	λ (nm)	α (cm^{-1})	λ (nm)	α (cm^{-1})
0.700	0.00602	3.45	481	7.1	566
0.725	0.0159	3.50	338	7.2	560
0.750	0.0261	3.6	180	7.3	554
0.775	0.0240	3.7	122	7.4	550
0.800	0.0196	3.8	112	7.5	546
0.825	0.0277	3.9	122	7.6	542
0.850	0.0433	4.0	145	7.7	540
0.875	0.0562	4.1	172	7.8	540
0.900	0.0678	4.2	206	7.9	539
0.925	0.144	4.3	247	8.0	539
0.950	0.374	4.4	294	8.2	538
0.975	0.449	4.5	374	8.4	540
1.00	0.363	4.6	402	8.6	544
1.20	1.04	4.7	420	8.8	550
1.40	12.4	4.8	393	9.0	557
1.60	67.2	4.9	351	9.2	567
1.80	80.3	5.0	312	9.4	579
2.00	69.1	5.1	274	9.6	594
2.20	16.5	5.2	244	9.8	614
2.40	50.1	5.3	232	10.0	639
2.60	153	5.4	240	10.5	793
2.65	318	5.5	265	11.0	1110
2.70	845	5.6	319	11.5	1550
2.75	2700	5.7	448	12.0	2080
2.80	5120	5.8	715	12.5	2600
2.85	8160	5.9	1330	13.0	2950
2.90	11600	6.0	2240	13.5	3190
2.95	12700	6.1	2700	14.0	3320
3.00	11400	6.2	1800	14.5	3360
3.05	9890	6.3	1140	15.0	3370
3.10	7780	6.4	882	15.5	3360
3.15	5390	6.5	758	16.0	3320
3.20	3630	6.6	678	16.5	3260
3.25	2360	6.7	632	17.0	3170
3.30	1400	6.8	604	17.5	3060
3.35	979	6.9	579	18.0	2970
3.40	720	7.0	575	18.5	2860

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Absorption Coefficient α for Water in the Infrared (T = 298 K)—*continued*

λ (nm)	α (cm^{-1})	λ (nm)	α (cm^{-1})	λ (nm)	α (cm^{-1})
19.0	2740	32	1270	90	749
19.5	2600	34	1220	100	669
20.0	2470	36	1200	110	607
21.0	2290	38	1190	120	551
22	2130	40	1210	130	497
23	2010	42	1220	140	449
24	1890	44	1250	150	415
25	1780	46	1260	160	390
26	1690	48	1280	170	367
27	1600	50	1290	180	348
28	1520	60	1230	190	331
29	1440	70	1030	200	317
30	1370	80	859		

Reference:

Hale, G M. and Querry, M. R., Optical constants of water in the 200-nm to 200-_m wavelength region, *Appl. Opt.* 12, 555 (1973).

Heavy Water

Absorption Coefficient α for Heavy water*

λ (nm)	α (10^{-4} cm^{-1})	λ (nm)	α (10^{-4} cm^{-1})	λ (nm)	α (10^{-4} cm^{-1})
400	31.8	540	6.3	680	3.2
410	28.5	550	5.8	690	3.3
420	26.3	560	5.3	700	4.5
430	23.4	570	5.4	710	5.1
440	20.8	580	4.9	720	5.4
450	18.2	590	4.4	730	5.9
460	15.6	600	4.2	740	6.7
470	14.1	610	4.0	750	6.9
480	13.1	620	4.0	760	6.9
490	11.6	630	3.3	770	6.5
500	10.1	640	3.2	780	6.7
510	8.9	650	3.4	790	7.4
520	8.6	660	2.9		
530	7.4	670	3.5		

Temperature: 296 ± 1.5 K
* 99.7% D_2O

Reference:

Sullivan, S. A., Experimental study of the absorption in distilled water, artificial sea water, and heavy water in the visible region of the spectrum, *J. Opt. Soc. Am*. 53, 962 (1963). This reference contains additional values of α at wavelengths intermediate to those given above.

5.2.3 Index of Refraction

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Index of Refraction n of Water (298 K)

λ (μm)	n(λ)	λ (μm)	n(λ)	λ (μm)	n(λ)
0.200	1.396	2.70	1.188	6.0	1.265
0.225	1.373	2.75	1.157	6.1	1.319
0.250	1.362	2.80	1.142	6.2	1.363
0.275	1.354	2.85	1.149	6.3	1.357
0.300	1.349	2.90	1.201	6.4	1.347
0.325	1.346	2.95	1.292	6.5	1.339
0.350	1.343	3.00	1.371	6.6	1.334
0.375	1.341	3.05	1.426	6.7	1.329
0.400	1.339	3.10	1.467	6.8	1.324
0.425	1.338	3.15	1.483	6.9	1.321
0.450	1.337	3.20	1.478	7.0	1.371
0.475	1.336	3.25	1.467	7.1	1.314
0.500	1.335	3.30	1.1450	7.2	1.312
0.525	1.334	3.35	1.432	7.3	1.309
0.550	1.333	3.40	1.420	7.4	1.307
0.575	1.333	3.45	1.410	7.5	1.304
0.600	1.332	3.50	1.400	7.6	1.302
0.625	1.332	3.6	1.385	7.7	1.299
0.650	1.331	3.7	1.374	7.8	1.297
0.675	1.331	3.8	1.364	7.9	1.294
0.700	1.331	3.9	1.357	8.0	1.291
0.725	1.330	4.0	1.351	8.2	1.286
0.750	1.330	4.1	1.346	8.4	1.281
0.775	1.330	4.2	1.342	8.6	1.275
0.800	1.329	4.3	1.338	8.8	1.269
0.825	1.329	4.4	1.334	9.0	1.262
0.850	1.329	4.5	1.332	9.2	1.255
0.875	1.328	4.6	1.330	9.4	1.247
0.900	1.328	4.7	1.330	9.6	1.239
0.925	1.328	4.8	1.330	9.8	1.229
0.950	1.327	4.9	1.328	10.0	1.218
0.975	1.327	5.0	1.325	10.5	1.185
1.00	1.327	5.1	1.322	11.0	1.153
1.20	1.324	5.2	1.317	11.5	1.126
1.40	1.321	5.3	1.312	12.0	1.111
1.60	1.317	5.4	1.305	12.5	1.123
1.80	1.312	5.5	1.298	13.0	1.146
2.00	1.306	5.6	1.289	13.5	1.177
2.20	1.296	5.7	1.277	14.0	1.210
2.40	1.279	5.8	1.262	14.5	1.241
2.60	1.242	5.9	1.248	15.0	1.270
2.65	1.219	6.0	1.265	15.5	1.197

Index of Refraction n of Water (298 K)—*continued*

λ (μm)	n(λ)	λ (μm)	n(λ)	λ (μm)	n(λ)

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15.5	1.197	26	1.539	60	1.703
16.0	1.325	27	1.545	70	1.821
16.5	1.351	28	1.549	80	1.886
17.0	1.376	29	1.551	90	1.924
17.5	1.401	30	1.551	100	1.957
18.0	1.423	32	1.546	110	1.966
18.5	1.443	34	1.536	120	2.004
19.0	1.461	36	1.527	130	2.036
19.5	1.476	38	1.522	140	2.056
20.0	1.480	40	1.519	150	2.069
21.0	1.487	42	1.522	160	2.081
22	1.500	44	1.530	170	2.094
23	1.511	46	1.541	180	2.107
24	1.521	48	1.555	190	2.119
25	1.531	50	10587	200	2.130

Reference:

Hale, G M. and Querry, M. R., Optical constants of water in the 200-nm to 200-μm wavelength region, *Appl. Opt.* 12, 555 (1973).

Index of refraction n of water (300 K)

λ (nm)	n	Ref.	λ (nm)	n	Ref.
214.44	1.4032	1	746	1.332	3
303.4	1.3581	1	752	1.332	3
360	1.353	3	758	1.332	3
404.66	1.342742	2	769	1.331	3
408	1.344	3	781	1.331	3
435.84	1.340210	2	794	1.331	3
449	1.337	3	806	1.331	3
486.13	1.337123	2	813	1.331	3
508.6	1.3360	1	820	1.330	3
546.07	1.334466	2	833	1.330	3
556	1.333	3	847	1.330	3
587.56	1.333041	2	862	1.330	3
589.3	1.332988	2	877	1.330	3
632.8	1.331745	2	893	1.329	3
656.28	1.331151	2	909	1.329	3
670.8	1.3308	1	926	1.329	3
690	1.332	3	935	1.329	3

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Index of Refraction n of Water (300 K)—*continued*

λ (nm)	n	Ref.	λ (nm)	n	Ref.
990	1.328	3	1471	1.321	3
1000	1.328	3	1493	1.320	3
1010	1.328	3	1515	1.320	3
1020	1.328	3	1538	1.319	3
1031	1.328	3	1563	1.319	3
1042	1.328	3	1587	1.318	3
1053	1.328	3	1613	1.318	3
1070	1.328	3	1639	1.317	3
1087	1.327	3	1667	1.316	3
1099	1.327	3	1695	1.315	3
1111	1.327	3	1724	1.314	3
1124	1.327	3	1754	1.314	3
1136	1.326	3	1786	1.313	3
1149	1.326	3	1802	1.312	3
1163	1.326	3	1818	1.312	3
1176	1.326	3	1852	1.311	3
1190	1.325	3	1887	1.310	3
1205	1.325	3	1927	1.309	3
1220	1.325	3	1961	1.307	3
1235	1.325	3	2000	1.306	3
1250	1.324	3	2041	1.305	3
1266	1.324	3	2083	1.303	3
1282	1.324	3	2128	1.301	3
1299	1.324	3	2198	1.296	3
1316	1.324	3	2273	1.291	3
1333	1.323	3	2326	1.285	3
1351	1.323	3	2381	1.281	3
1370	1.323	3	2439	1.276	3
1389	1.322	3	2500	1.268	3
1408	1.322	3	2564	1.257	3
1429	1.321	3	2632	1.239	3
1443	1.321	3			

References:

1. Kaye, G. W. and Laby, T. H., *Tables of Physical and Chemical Constants* (Longmans, Green & Co., London, 1959).
2. James, A. M. and Lord, M. P., *Macmillan's Chemical and Physical Data* (Macmillan, London, 1992).
3. Palmer, K. F. and Williams, D., *J. Opt. Soc. Am.* 64, 1107 (1974).

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Index of Refraction of Water at Different Temperatures and Wavelengths

	Wavelength (nm)					
T (°C)	**226.50**	**361.05**	**404.41**	**589.00**	**632.80**	**1013.98**
0	1.39450	1.34896	1.34415	1.33432	1.33306	1.32612
10	1.39422	1.34870	1.34389	1.33408	1.33282	1.32591
20	1.39336	1.34795	1.34315	1.33336	1.33211	1.32524
30	1.39208	1.34682	1.34205	1.33230	1.33105	1.32424
40	1.39046	1.34540	1.34065	1.33095	1.32972	1.32296
50	1.38854	1.34373	1.33901	1.32937	1.32814	1.32145
60	1.38636	1.34184	1.33714	1.32757	1.32636	1.31974
70	1.38395	1.33974	1.33508	1.32559	1.32438	1.31784
80	1.38132	1.33746	1.33284	1.32342	1.32223	1.31576
90	1.37849	1.33501	1.33042	1.32109	1.31991	1.31353
100	1.37547	1.33239	1.32784	1.31861	1.31744	1.31114

Reference:

From Schiebener, P., Straub, J. Levelt Sengers, J. M. H., and Gallagher, J. S., *J. Phys. Chem. Ref. Data* 19, 677 (1990) and the *CRC Handbook of Chemistry and Physics*, 75th edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 1994).

Temperature Derivative of the Index of Refraction n of Water

λ (nm)	**dn/dT × 10^6 (K^{-1})**	**Ref.**	**λ (nm)**	**dn/dT × 10^6 (K^{-1})**	**Ref.**
226.50	–128 (293–303 K)	1	589.3	–80 (293 K)	4
361.05	–113 (293–303 K)	1		–97 (293–298 K)	2
404.41	–110 (293–303 K)	1	632.8	–96 (293–298 K)	2
404.66	–101 (293–298 K)	2		–98.5 (298 K)	3
435.84	–100 (293–303 K)	1		–106 (293–303 K)	1
486.13	–99 (293–298 K)	2	656.28	–96 (293–298 K)	2
546.07	–98 (293–298 K)	2	706.52	–95 (293–298 K)	2
	–100 (298 K)	3	1013.98	–100 (293–303 K)	1
587.56	–97 (293–298 K)	2			

References:

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5.3 Physical Properties of Selected Liquids

Data in the following tables are in large part from the *CRC Handbook of Chemistry and Physics*, 82nd edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL). Physical and chemical property data for many additional organic and inorganic liquids are given in this reference.

Liquid	Molecular weight	Density (g/cm^3)	Dielectric constant ε	Electric dipole moment (D)
acetic acid, $C_2H_4O_2$	60.05	1.0492	6.20	1.74
acetone, C_3H_6O	58.08	0.7856	21.01	2.88
benzene, C_6H_6	78.11	0.8765	2.2825	0
bromobenzene, C_6H_5Br	157.01	1.4950	5.45	—
carbon disulfide, CS_2	76.14	1.2556	2.6320	0
carbon tetrachloride, CCl_4	153.82	1.5833	2.2379	0
chloroform, $CHCl_3$	119.38	1.4800	4.8069	1.01
cyclohexane, C_6H_{12}	84.16	0.7731	2.0243	0
1,2–dichloroethane, $C_2H_4Cl_2$	98.96	1.2457	10.10	—
dichloromethane, CH_2Cl_2	84.93	1.3266	8.93	1.6
dimethylsulfoxide, C_2H_6OS	78.14	1.0955	47.24	3.96
1,4–dioxane, $C_4H_8O_2$	88.11	1.0286	2.2189	—
ethanol, C_2H_6O	46.07	0.7873	25.3	1.69
ethylene glycol, $C_2H_6O_2$	76.10	0.9598	41.4	2.28
glycerine (glycerol), $C_3H_8O_3$	92.10	1.2567	46.53	—
heptane, C_7H_{16}	100.20	0.6837	1.9209	≈ 0
hexadecane, $C_{16}H_{34}$	226.45	0.7733	2.0460	—
hexane, C_6H_{14}	86.18	0.6563	1.8865	—
methanol, CH_4O	32.04	0.7872	33.0	1.70
methylcyclohexane, C_7H_{14}	98.19	0.7694	2.024	≈ 0
1–methylnaphthalene, $C_{11}H_{10}$	142.20	1.0202	2.915	—
nitrobenzene, $C_6H_5NO_2$	123.11	1.1985	35.6	—
toluene, C_7H_8	92.14	0.8647	2.379	—
2,2,4–trimethylpentane, C_8H_{18}	114.23	0.6877	1.943	—
water, H_2O	18.01528	0.99705	80.100	—
heavy water, D_2O	20.02748	1.1044	79.754	—

Density at 298 K.
1 D = 3.33564×10^{-30} C m

Dielectric Strength of Liquids*

Liquid	Dielectric strength (kV/mm)	Ref.
carbon tetrachloride, CCl_4	5.5	1
chlorobenzenze, C_6H_5Cl	7.1	1
helium, He, liquid, 4.2 K	10	2
carbon tetrachloride, CCl_4	16.0	3

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Dielectric Strength of Liquids*—*continued*

Liquid	Dielectric strength (kV/mm)	Ref.
chlorobenzenze, C_6H_5Cl	18.8	3
nitrogen, N_2, liquid, 77 K:		
coaxial cylinder electrodes	20	4
sphere to plane electrodes	60	4
cyclohexane, C_6H_{12}	42–48	5
hexane, C_6H_{14}	42.0	5
water, H_2O	65–70	6
2,2,4–trimethylpentane, C_8H_{18}	140	7,8
benzene, C_6H_6	163	7,8
heptane, C_7H_{16}	166	7,8
toluene, $C_6H_5C\,H_3$:	199	7,8
	46	5
	20.4	3
	12.0	1

* The dielectric strength (or breakdown voltage) of a material depends on the specimen thickness, the electrode shape, and the rate of the applied voltage increase.

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Physical Properties

Liquid	Melting point (°C)	Boiling point (°C)	Specific heat capacity (J/g K)	Volume thermal expan. coeff. B_t (10^3 K^{-1})
acetic acid, $C_2H_4O_2$	16.6	117.9	2.05	1.1
acetone, C_3H_6O	–94.8	56.05	2.17	1.43
benzene, C_6H_6	5.53	80.09	1.74	1.23
bromobenzene, C_6H_5Br	–30.6	156	—	—
carbon disulfide, CS_2	–111.5	46	1.00	1.19
carbon tetrachloride, CCl_4	–23	76.8	0.85	1.22
chloroform, $CHCl_3$	–63.6	61.17	0.96	1.28
cyclohexane, C_6H_{12}	6.6	80.73	1.84	1.1[a]
1,2–dichloroethane, $C_2H_4Cl_2$	–35.5	83.5	1.30	1.16[a]

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Physical Properties—*continued*

Liquid	Melting point (°C)	Boiling point (°C)	Specific heat capacity (J/g K)	Volume thermal expan. coeff. β_t (10^3 K^{-1})
dichloromethane, CH_2Cl_2	–95.1	40	1.19	—
dimethylsulfoxide, C_2H_6OS	—	—	1.96	—
1,4–dioxane, $C_4H_8O_2$	11.8	101.5	4.9	1.03[a]
ethanol, C_2H_6O	–114.1	78.29	2.44	1.10
ethylene glycol, $C_2H_6O_2$	–13		2.39	0.566
glycerine (glycerol), $C_3H_8O_3$	18.2		2.38	0.53
heptane, C_7H_{16}	–90.6	98.5	2.24	—
hexadecane, $C_{16}H_{34}$	18.1	286.8	—	—
hexane, C_6H_{14}	–95.3	68.73	2.26	1.35
methanol, CH_4O	–97.68	64.6	2.53	1.19
methylcyclohexane, C_7H_{14}	–126.6	100.9	1.88	—
1–methylnaphthalene, $C_{11}H_{10}$	–30.4	244.7	—	—
nitrobenzene, $C_6H_5NO_2$	5.7	210.8	1.51	0.83
toluene, C_7H_8	–94.99	110.63	1.71	1.06
2,2,4–trimethylpentane, C_8H_{18}	–107.3	99.2	—	—
water, H_2O	0.00	100.00	4.1818	0.256
heavy water, D_2O	3.82	101.42	—	—

Specific heat capacity and volume thermal expansion coefficients measured at 298 K except for [a] measured at 293 K.

5.3.1 Thermal conductivity

Thermal conductivity values correspond to a nominal pressure of 1 atmosphere. The values for water, benzene, and toluene are particularly well determined and can be used for calibration purposes.

	Thermal conductivity (W/m K)					
Liquid	–25°C	0°C	25°C	50°C	75°C	100°C
acetic acid, $C_2H_4O_2$			0.158	0.153	0.149	0.144
acetone, C_3H_6O		0.169	0.161			
benzene, C_6H_6			0.1411	0.1329	0.1247	
carbon disulfide, CS_2		0.154	0.149			
carbon tetrachloride, CCl_4		0.104	0.099	0.093	0.088	
chlorobenzene, C_6H_5Cl	0.136	0.131	0.127	0.122	0.117	0.112
chloroform, $CHCl_3$	0.127	0.122	0.117	0.112	0.107	0.102
cyclohexane, C_6H_{12}	0.137	0.129	0.121	0.113		
dibromomethane, CH_2Br_2	0.120	0.114	0.108	0.103	0.097	
1,4–dioxane, $C_4H_8O_2$			0.159	0.147	0.135	0.123
ethanol, C_2H_6O		0.176	0.169	0.162		
ethylene glycol, $C_2H_6O_2$		0.256	0.256	0.256	0.256	0.256

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Thermal conductivity (W/m K)—*continued*						
Liquid	**–25ºC**	**0ºC**	**25ºC**	**50ºC**	**75ºC**	**100ºC**
glycerine (glycerol), $C_3H_8O_3$			0.292	0.295	0.297	0.300
heavy water, D_2O				0.618		0.636
heptane, C_7H_{16}	0.1378	0.1303	0.1228	0.1152	0.1077	
hexadecane, $C_{16}H_{34}$	0.144	0.140	0.136	0.133	0.129	0.125
hexane, C_6H_{14}	0.137	0.128	0.120	0.111	0.102	0.093
methanol, CH_4O	0.214	0.207	0.200	0.193		
nitrobenzene, $C_6H_5NO_2$						
toluene, C_7H_8	0.1461	0.1386	0.1311	0.1236	0.1161	
water, H_2O		0.5610	0.6071	0.6435	0.6668	0.6791

From the table in *CRC Handbook of Chemistry and Physics*, 75th edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 1994), p. 6–249. Thermal conductivity data for additional organic and inorganic liquids are given in this reference.

5.3.2 Viscosity

	Viscosity (mPa s)					
Liquid	**–25ºC**	**0ºC**	**25ºC**	**50ºC**	**75ºC**	**100ºC**
acetic acid, $C_2H_4O_2$			1.056	0.786	0.599	0.464
acetone, C_3H_6O	0.540	0.395	0.306	0.247		
benzene, C_6H_6		0.604	0.436	0.335		
bromobenzene, C_6H_5Br			10.74	0.798	0.627	0.512
carbon disulfide, CS_2		0.429	0.352			
carbon tetrachloride, CCl_4		1.0321	0.908	0.656	0.494	
chloroform, $CHCl_3$	0.988	0.706	0.537	0.427		
cyclohexane, C_6H_{12}			0.894	0.615	0.447	
1,2–dichloroethane, $C_2H_4Cl_2$			0.464	0.362		
dichloromethane, CH_2Cl_2	0.727	0.533	0.413			
dimethylsulfoxide, C_2H_6OS			1.987	1.290		
1,4–dioxane, $C_4H_8O_2$			1.177	0.787	0.569	
ethanol, C_2H_6O	3.262	1.786	1.074	0.694	0.476	
ethylene glycol, $C_2H_6O_2$			16.1	6.554	3.340	1.975
glycerine (glycerol), $C_3H_8O_3$			934	152	39.8	14.8
heptane, C_7H_{16}	0.757	0.523	0.378	0.301	0.243	
hexadecane, $C_{16}H_{34}$				2.487	1.609	1.132
hexane, C_6H_{14}		0.405	0.300	0.240		
methanol, CH_4O	1.258	0.793	0.544			
methylcyclohexane, C_7H_{14}		0.991	0.679	0.501	0.390	0.316
nitrobenzene, $C_6H_5NO_2$		3.036	1.863	1.262	0.918	0.704
toluene, C_7H_8	1.165	0.778	0.560	0.424	0.333	0.270
water, H_2O		1.793	0.890	0.547	0.378	0.282

Viscosity values correspond to a nominal pressure of 1 atmosphere.

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5.3.3 Surface Tension

Liquid	Surface tension σ (mN/m)				
	10°C	25°C	50°C	75°C	100°C
acetic acid, $C_2H_4O_2$		27.10	24.61	22.13	
acetone, C_3H_6O		23.46	20.66		
benzene, C_6H_6		28.22	25.00	21.77	
bromobenzene, C_6H_5Br	36.98	35.24	32.34	29.44	26.54
carbon disulfide, CS_2	33.81	31.58	27.87		
carbon tetrachloride, CCl_4		26.43	23.37	20.31	17.25
chloroform, $CHCl_3$		26.67	23.44	20.20	
cyclohexane, C_6H_{12}	26.43	24.65	21.68		
1,2–dichloroethane, $C_2H_4Cl_2$		31.86	28.29	24.72	
dichloromethane, CH_2Cl_2		27.20			
dimethylsulfoxide, C_2H_6OS		42.92	40.06		
1,4–dioxane, $C_4H_8O_2$		32.75	29.28	25.80	22.32
ethanol, C_2H_6O	23.22	21.97	19.89		
ethylene glycol, $C_2H_6O_2$		47.99	45.76	43.54	41.31
heptane, C_7H_{16}	21.12	19.65	17.20	14.75	
hexadecane, $C_{16}H_{34}$		27.05	24.91	22.78	20.64
hexane, C_6H_{14}	19.42	17.89	15.33		
methanol, CH_4O	23.23	22.07	20.14		
methylcyclohexane, C_7H_{14}	24.989	23.29	20.46		
nitrobenzene, $C_6H_5NO_2$			40.56	37.66	34.77
toluene, C_7H_8	29.71	27.93	24.96	21.98	19.01
water, H_2O	74.23	71.99	67.94	63.57	58.91

5.3.4 Absorption

Ultraviolet Absorption of Pure Liquids:

The following tables present data on the UV absorption edge of several common liquids. The data were obtained using a 1.00–cm pathlength cell and a water reference. From Bruno, T. J. and Svoronos, P. D. N., *CRC Handbook of Basic Tables for Chemical Analysis* (CRC Press, Boca Raton, FL, 1989), p. 213.

Acetone	
Wavelength (nm)	Maximum absorbance
330	1.000
340	0.060
350	0.010
375	0.005
400	0.005

Benzene	
Wavelength (nm)	Maximum absorbance
278	1.000
300	0.020
325	0.010
350	0.005
400	0.005

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Carbon tetrachloride

Wavelength (nm)	Maximum absorbance
263	1.000
275	0.100
300	0.005
350	0.005
400	0.005

Chloroform

Wavelength (nm)	Maximum absorbance
245	1.000
250	0.300
275	0.005
300	0.005
400	0.005

Cyclohexane

Wavelength (nm)	Maximum absorbance
200	1.000
225	0.170
250	0.020
300	0.005
400	0.005

Dimethyl sulfoxide

Wavelength (nm)	Maximum absorbance
268	1.000
275	0.500
300	0.200
350	0.020
400	0.005

1,4–Dioxane

Wavelength (nm)	Maximum absorbance
215	1.000
250	0.300
300	0.020
350	0.005
400	0.005

Hexadecane

Wavelength (nm)	Maximum absorbance
190	1.000
200	0.500
250	0.020
300	0.005
400	0.005

Hexane

Wavelength (nm)	Maximum absorbance
195	1.000
225	0.050
250	0.010
275	0.005
300	0.005

Methanol

Wavelength (nm)	Maximum absorbance
205	1.000
225	0.160
250	0.020
300	0.005
400	0.005

Toluene

Wavelength (nm)	Maximum absorbance
284	1.000
300	0.120
325	0.020
350	0.005
400	0.005

Water

Wavelength (nm)	Maximum absorbance
190	0.010
200	0.010
250	0.005
300	0.005
400	0.005

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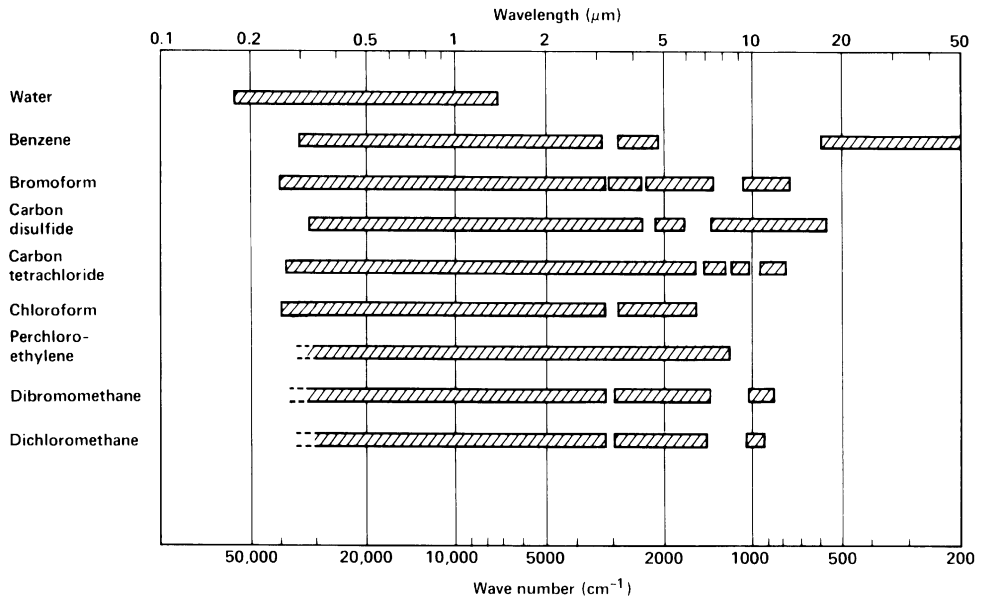
Transmission Limits*

Liquid	Limit (nm)	Liquid	Limit (nm)
acetone, C_3H_6O	200	heptane, C_7H_{16}	196
benzene, C_6H_6	270	*n*–hexane, C_6H_{14}	202
carbon tetrachloride, CCl_4	2250	methanol, CH_4O	183
chloroform, $CHCl_3$	220	methylcyclohexane, C_7H_{14}	206
cyclohexane, C_6H_{12}	211	1–octene, C_6H_{16}	210
n–decane, $C_{10}H_{22}$	173	*n*–pentane, C_5H_{12}	205
p–dioxane, $C_4H_8O_2$	203	toluene, C_7H_8	274
ethanol, C_2H_6O	189	water, H_2O	178

* Transmission limits are the wavelengths of the last visible blackening on a spectrogram for reasonable exposure and development time. From Klevens, H. B. and Platt, J. R., Ultraviolet transmission limits of some liquids and solids, *J. Am. Chem. Soc.* 69, 3055 (1947).



Spectral transmission ranges of several fluids used for liquid filters. The end points are for 50% transmission through 1 mm of the liquid [from Cook, L. M. and Stokowski, S. E., Filter materials, in *Handbook of Laser Science and Technology, Volume IV: Optical Materials, Part 2* (CRC Press, Boca Raton, 1995), p. 151].

For other organic and inorganic filter solutions, see Pellicori, S. F., Transmittances of some optical materials for use between 1900 and 3400 A, *Appl. Opt.* 3, 361 (1964); Bass, A. M., Short wavelength cut–off filters for the ultraviolet, *J. Opt. Soc. Am.* 38, 977 (1948); Ingersoll, K. A., Liquid filters for the visible and near infrared, *Appl. Opt.* 10, 2473 (1971); Ingersoll, K. A., Liquid filters for the ultraviolet, visible, and near infrared, *Appl. Opt.* 11, 2781 (1972).

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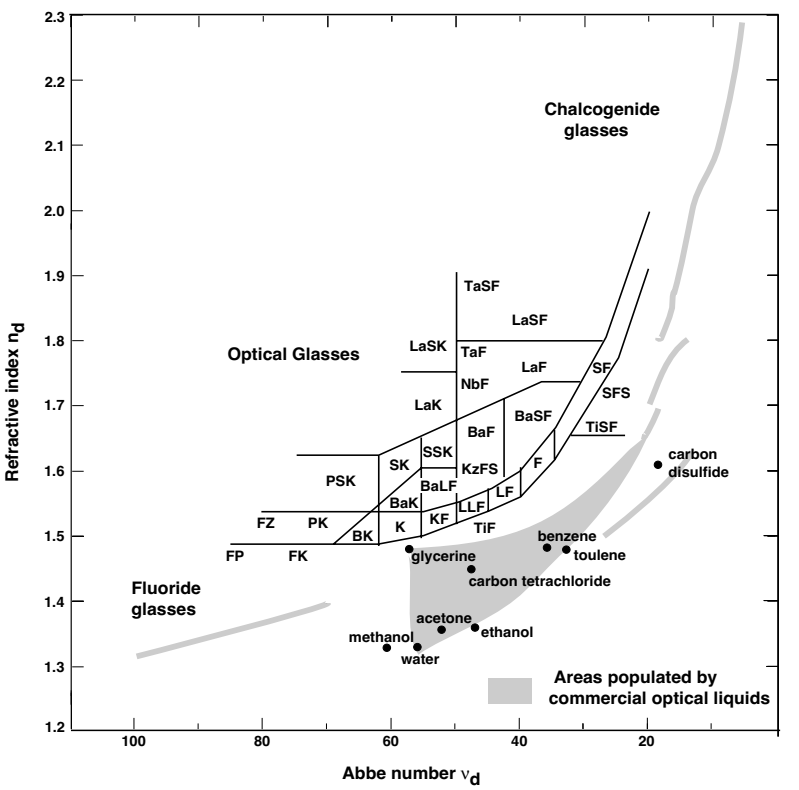
5.4 Index of Refraction

5.4.1 Organic Liquids

Index of Refraction of Selected Liquids (293 K)

Liquid	n_D	Liquid	n_D
methanol, CH_4O	1.3288	ethylene glycol, $C_2H_6O_2$	1.4318
acetone, C_3H_6O	1.3588	hexadecane, $C_{16}H_{34}$	1.4345
ethanol, C_2H_6O	1.3611	1,2–dichloroethane, $C_2H_4Cl_2$	1.4448
acetic acid, $C_2H_4O_2$	1.3720	chloroform, $CHCl_3$	1.4459
hexane, C_6H_{14}	1.3749	carbon tetrachloride, CCl_4	1.4601
heptane, C_7H_{16}	1.3878	glycerine (glycerol), $C_3H_8O_3$	1.4746
2,2,4–trimethylpentane, C_8H_{18}	1.3915	toluene, C_7H_8	1.4961
dimethylsulfoxide, C_2H_6OS	1.4170	benzene, C_6H_6	1.5011
1,4–dioxane, $C_4H_8O_2$	1.4224	nitrobenzene, $C_6H_5NO_2$	1.5562
methylcyclohexane, C_7H_{14}	1.4231	bromobenzene, C_6H_5Br	1.5597
dichloromethane, CH_2Cl_2	1.4242	1–methylnaphthalene, $C_{11}H_{10}$	1.6170
cyclohexane, C_6H_{12}	1.4266	carbon disulfide, CS_2	1.6319

Measured at a wavelength of 589 nm (sodium D line).



Comparison of selected liquids and optical glasses in an index of refraction Abbe number plot.

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Index of Refraction n of Selected Liquids

Acetic acid[1]

λ (nm)	n (296.05 K)
434.05	1.38003
486.13	1.37610
589.3	1.37152
656.28	1.36944

Acetone[1]

λ (nm)	n (292.55 K)
434.05	1.36750
486.13	1.36366
589.3	1.35886
656.28	1.35672

Carbon tetrachloride[1]

λ (nm)	n (285.45 K)
434.05	1.4835
486.13	1.4726
589.3	1.4656
656.28	1.4599

Benzene[1]

λ (nm)	n (293.15 K)
276.3	1.625
298.1	1.598
313.3	1.582
361.0	1.548
434.05	1.52361
486.13	1.51327
508.6	1.509
589.3	1.50144
656.28	1.49663
0.8	1.489
1.0	1.485
1.5	1.480
1.85	1.478

Carbon disulfide[1]

λ (nm)	n (291.15 K)
361.0	1.740
394.4	1.704
434.05	1.67665
441.6	1.673
479.99	1.656
486.13	1.6539
508.6	1.647
533.8	1.640
589.3	1.6295
656.28	1.62011

Toluene[2]

λ (nm)	n (293.15 K)
404.66	1.526120
434.05	1.51970
435.84	1.517830
479.99	1.509285
486.13	1.508315
546.07	1.500715
589.3	1.49693
632.8	1.493680
656.28	1.49365
706.52	1.489795

Chloroform[1]

λ (nm)	n (293.15 K)
265.5	1.5051
289.4	1.4911
313.1	1.4806
486.13	1.45024
589.3	1.44432
656.28	1.44189

Cyclohexane[1]

λ (nm)	n (293.15 K)
265.5	1.4741
289.4	1.4631
313.1	1.4549
486.13	1.36662
589.3	1.36242
656.28	1.36062

1,4–Dioxane[2]

λ (nm)	n (293.15 K)
265.5	1.4699
289.4	1.4583
313.1	1.4500
546.07	1.4330
589.3	1.4311

1,2-Dichloroethane[2]

λ (nm)	n (293.15 K)
434.05	1.45528
486.13	1.45024
589.3	1.44432
656.28	1.44189

Ethanol[1]

λ (nm)	n (291.5 K)
434.05	1.37011
486.13	1.36662
589.3	1.36242
656.28	1.36062

Ethylene glycol[2]

λ (nm)	n (293.15 K)
435.83	1.4400
546.07	1.4330
589.3	1.4311

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Index of Refraction n of Selected Liquids—*continued*

Glycerine[1]		Hexane[1]		Methanol[1]	
λ (nm)	n (293.15 K)	λ (nm)	n (293.15 K)	λ (nm)	n (287.65 K)
434.05	1.4839	434.05	1.38365	434.05	1.33801
486.13	1.4795	486.13	1.37988	486.13	1.33490
589.3	1.4740	589.3	1.37536	589.3	1.33118
656.28	1.4717	656.28	1.37337	656.28	1.32948

Nitrobenzene[1]	
λ (nm)	n (293.15 K)
486.13	1.57124
589.3	1.55291
656.28	1.54593

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2. James, A. M. and Lord, M. P., *Macmillan's Chemical and Physical Data* (Macmillan, London, 1992).

Temperature Derivative of the Index of Refraction

Methanol			Ethanol		
λ (nm)	$dn/dT \times 10^4$ (K^{-1})	Ref.	λ (nm)	$dn/dT \times 10^4$ (K^{-1})	Ref.
434.05	–3.90 (T = 288 K)	1			
486.13	–4.00 (T = 288 K)	1			
546.07	–4.05 (T = 298 K)	2	546.07	–4.05 (T = 298 K)	2
600	–4.68 (T = 278–298 K)	3	600	–4.38 (T = 278–298 K)	3
632.8	–4.00 (T = 288 K)	2	632.8	–4.00 (T = 298 K)	2
656.28	–4.00 (T = 298 K)	1			

Ethylene glycol			Glycerine		
λ (nm)	$dn/dT \times 10^4$ (K^{-1})	Ref.	λ (nm)	$dn/dT \times 10^4$ (K^{-1})	Ref.
486.13	–2.70 (T = 288 K)	1	486.13	–2.30 (T = 288 K)	1
600	–3.06 (T = 278–298 K)	3			
656.28	–2.60 (T = 288 K)	1	656.28	–2.20 (T = 288 K)	1

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Temperature Derivative of the Index of Refraction—*continued*

Hexane

λ (nm)	dn/dT × 10^4 (K^{-1})	Ref.
434.05	–5.60 (T = 298 K)	1
486.13	–5.50 (T = 298 K)	1
546.07	–5.43 (T = 298 K)	2
632.8	–5.40 (T = 298 K)	2
656.28	–5.30 (T = 298 K)	1

Cyclohexane

λ (nm)	dn/dT × 10^4 (K^{-1})	Ref.
434.05	–5.60 (T = 298 K)	1
486.13	–5.50 (T = 298 K)	1
546.07	–5.46 (T = 298 K)	2
589.3	–5.40 (T = 298 K)	3
632.8	–5.43 (T = 298 K)	2
656.28	–5.40 (T = 298 K)	1

Benzene

λ (nm)	dn/dT × 10^4 (K^{-1})	Ref.
434.05	–6.70 (T = 293 K)	4
486.13	–6.60 (T = 293 K)	4
546.07	–6.42 (T = 298 K)	2
589.3	–6.50 (T = 293 K)	4
632.8	–6.40 (T = 298 K)	2
656.28	–6.40 (T = 293 K)	4

Carbon tetrachloride

λ (nm)	dn/dT × 10^4 (K^{-1})	Ref.
434.05	–5.60 (T = 288 K)	1
486.13	–5.60 (T = 288 K)	1
546.07	–5.99 (T = 298 K)	2
589.3	–5.50 (T = 288 K)	1
632.8	–5.98 (T = 298 K)	2
656.28	–5.40 (T = 288 K)	1

Carbon disulfide

λ (nm)	dn/dT × 10^4 (K^{-1})	Ref.
267.7	–17.50 (T = 291 K)	4
274.9	–15.00 (T = 291 K)	4
361.0	–9.60 (T = 291 K)	4
394.4	–9.00 (T = 291 K)	4
434.1	–8.70 (T = 291 K)	4
441.6	–8.60 (T = 291 K)	4
467.8	–8.40 (T = 291 K)	4
479.99	–8.30 (T = 291 K)	4
508.6	–8.20 (T = 291 K)	4
533.8	–8.10 (T = 291 K)	4
546.07	–7.96 (T = 298 K)	2
589.3	–8.00 (T = 291 K)	4
632.8	–7.96 (T = 298 K)	2
656.28	–7.80 (T = 291 K)	4

Toluene

λ (nm)	dn/dT × 10^4 (K^{-1})	Ref.
404.66	–5.97 (T = 293 K)	5
435.84	–5.88 (T = 293 K)	5
479.99	–5.77 (T = 293 K)	5
486.13	–5.76 (T = 293 K)	5
546.07	–5.65 (T = 293 K)	5
587.56	–5.60 (T = 293 K)	5
589.00	–5.60 (T = 293 K)	5
589.59	–5.60 (T = 293 K)	5
632.8	–5.56 (T = 293 K)	5
	–5.55 (T = 298 K)	2
643.85	–5.55 (T = 293 K)	5
656.28	–5.54 (T = 293 K)	5
706.52	–5.51 (T = 293 K)	5

Acetic acid

λ (nm)	dn/dT × 10^4 (K^{-1})	Ref.
486.13	–3.80 (T = 288 K)	1
656.28	–3.70 (T = 288 K)	1

Chloroform

λ (nm)	dn/dT × 10^4 (K^{-1})	Ref.
546.07	–5.98 (T = 298 K)	2
632.8	–5.98 (T = 298 K)	2
656.28	–5.30 (T = 298 K)	1

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Acetone			Nitrobenzene		
λ (nm)	dn/dT × 10^4 (K^{-1})	Ref.	λ (nm)	dn/dT × 10^4 (K^{-1})	Ref.
486.13	–5.00 (T = 288 K)	1	486.13	–4.80 (T = 288 K)	1
546.07	–5.31 (T = 298 K)	2	546.07	–4.68 (T = 298 K)	2
589.3	–5.00 (T = 288 K)	1			
632.8	–5.31 (T = 298 K)	2	632.8	–4.68 (T = 298 K)	2
656.28	–4.90 (T = 288 K)	1	656.28	–4.60 (T = 288 K)	1

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5.4.2 Inorganic Liquids

Name	Formula	Temperature (°C)	n_D (589 nm)
ammonium	NH_3	–77	1.3944 (578 nm)
antimony pentachloride	$SbCl_5$	22	1.5925
argon	Ar	–188	1.2312
arsenic trichloride	$AsCl_3$	16	1.604
bromine tribromide	BrF_3	16	1.312
carbon disulfide	CS_2	20	1.62774
germanium tetrabromide	$GeBr_4$	26	1.6269
germanium tetrachloride	$GeCl_4$	25	1.4614
helium	He	–269	1.02451 (546 nm)
hydrogen peroxide	H_2O_2	28	1.4061
oxygen	O_2	–183	1.2243 (578 nm)
phosphorus tribromide	PBr_3	25	1.687
phosphorus trichloride	PCl_3	21	1.5122
sulfur dichloride	SCl_2	14	1.557
sulfur trioxide	SO_3	20	1.40965
tetrabromosilane	$SiBr_4$	31	1.5685
tetrachlorosilane	$SiCl_4$	25	1.41156
tin tetrabromide	$SnBr_4$	31	1.6628
tin tetrachloride	$SnCl_4$	25	1.5086
xenon	Xe	–112	1.3918 (578 nm)

Reference:

Wohlfarth, C. and Wohlfarth, B., *Landolt-Börnstein, Numerical Data and Functional Relationships in Science and Technology, New Series*, III/38A, Martienssen, W., Ed. (Springer-Verlag, Heidelberg, 1996). The index of refraction at other temperatures and wavelengths may be found in this reference.

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5.4.3 Calibration Liquids

The six liquids below are available in highly pure form and their index of refraction has been accurately measured as a function of wavelength and temperature. They are therefore useful for calibration of refractometers. The estimated uncertainties in the values are:

2,2,4-Trimethylpentane	±0.00003
Hexadecane	±0.00008
trans-Bicyclo[4.0.0]decane	±0.00008
1-Methylnaphthalene	±0.00008
Toluene	±0.00003
Methylcyclohexane	±0.00003

Further details are given in the references below. This table is reprinted from Reference 1 by permission of the Intemational Union of Pure and Applied Chemistry.

References:

1. Marsh, K. N., Ed., *Recommended Reference Materials for the Realization of Physicochemical Properties* (Blackwell Scientific Publications, Oxford, 1987).
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	2,2,4-Trimethylpentane			**Hexadecane**		
λ (nm)	**20°C**	**25°C**	**30°C**	**20°C**	**25°C**	**30°C**
667.81	1.38916	1.38670	1.38424	1.43204	1.43001	1.42798
656.28	1.38945	1.38698	1.38452	1.43235	1.43032	1.42829
589.26	1.39145	1.38898	1.38650	1.43453	1.43250	1.43047
546.07	1.39316	1.39068	1.38820	1.43640	1.43436	1.43232
501.57	1.39544	1.39294	1.39044	1.43888	1.43684	1.43480
486.13	1.39639	1.39389	1.39138	1.43993	1.43788	1.43583
435.83	1.40029	1.39776	1.39523	1.44419	1.44213	1.44007

	***trans*-Bicyclo[4.0.0]decane**			**1-Methylnaphthalene**		
λ (nm)	**20°C**	**25°C**	**30°C**	**20°C**	**25°C**	**30°C**
667.81	1.46654	1.46438	1.46222	1.60828	1.60592	1.60360
656.28	1.46688	1.46472	1.46256	1.60940	1.60703	1.60471
589.26	1.46932	1.46715	1.46498	1.61755	1.61512	1.61278
546.07	1.47141	1.46923	1.46705	1.62488	1.62240	1.62005
501.57	1.47420	1.47200	1.46980	1.63513	1.63259	1.63022
486.13	1.47535	1.47315	1.47095	1.63958	1.63701	1.63463
435.83	1.48011	1.47789	1.47567		1.65627	1.65386

	Toluene			**Methylcyclohexane**		
λ (nm)	**20°C**	**25°C**	**30°C**	**20°C**	**25°C**	**30°C**
667.81	1.49180	1.48903	1.48619	1.42064	1.41812	1.41560
656.28	1.49243	1.48966	1.48682	1.42094	1.41#42	1.41591
589.26	1.49693	1.49413	1.49126	1.42312	1.42058	1.41806
546.07	1.50086	1.49803	1.49514	1.42497	1.42243	1.41989
501.57	1.50620	1.50334	1.50041	1.42744	1.42488	1.42233
486.13	1.50847	1.50559	1.50265	1.42847	1.42590	1.42334
435.83	1.51800	1.51506	1.51206	1.43269	1.43010	1.42752

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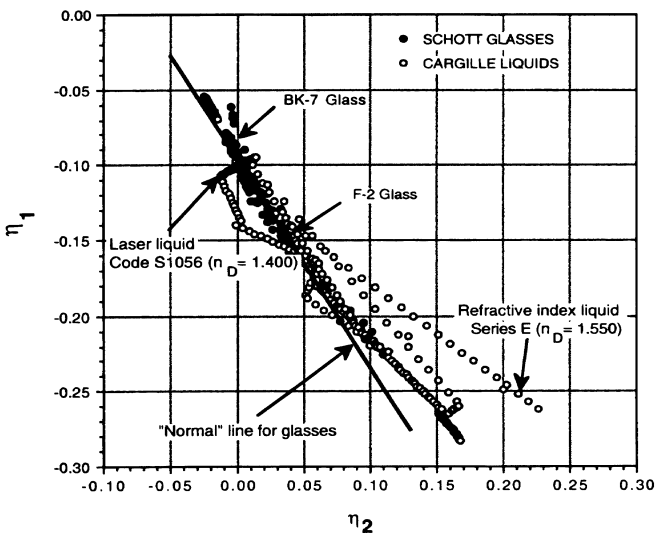
5.4.4 Abnormal Dispersion Liquids

Chromatic aberrations in complex lens systems can be corrected by combining lenses made of materials having different refractive indices and dispersions. When the partial dispersion of a material (refractive index for a pair of wavelengths) is plotted versus its Abbe number, most materials lie along a straight line, the so-called "normal" line. (Plots of relative dispersions showing the deviation of various glass types from the normal curve are included in most optical glass catalogs.) To correct for the secondary spectrum in apochromatic lens system (one corrected for three wavelengths), at least one of the materials must have an abnormal dispersion, that is, one lying off the normal line.

The wavelength dependence of the refractive index of a material can be described by the Buchdahl equation $N(\omega) = N_0 + \nu_1\omega + \nu_2\omega^2 + \ldots \nu_j\omega^j$, where N_0 is the refractive index at the wavelengths λ, ν_1, ν_2, . . . characterize the dispersion, and ω is the chromatic coordinate $\omega = (\lambda - \lambda_0/[1 + 5/2(\lambda - \lambda_0)]$. The dispersive power of a material in this model is given by

$$D(\lambda) = \delta N(\lambda) /(N_0 - 1) = \sum_{i=1}^{n} \eta_i\omega,$$

where n is the order of the Buchdahl dispersion equation. The dispersion coefficients η are defined by $\eta_i = \nu_i/(N_0 - 1)$. Below is a plot of the primary and secondary dispersion properties of 178 Schott optical glasses and 300 Cargille optical liquids (courtesy of R. D. Sigler).



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5.5 Nonlinear Optical Properties

Abbreviations for Materials

Abbreviations	Material
4-BCMUy	Yellow form of poly-4-BCMU
4ABP	4-Aminobiphenyl
123TB	1,2,3-Trimethyl benzene
124TB	1,2,4-Trimethyl benzene
1234TB	1,2,3,4-Tetramethyl benzene
1235TB	1,2,3,5-Tetramethyl benzene
α-NPA	a-NPO (2-(1-naphthyl)-5-phenyloxazole)
BBPEN	Bis[*n*-butyl, 2-phenyl-1,2-ethenedithiolato(2-)-*S*,*S*′] nickel
BEEDT	Bis(1,2-diethyl-1,2-ethenedithiolato(2-)-*S*,*S*') nickel
bis-MSB	*p*-Bis(*o*-methylstyryl)benzene
BP4B	Benzopurpurin 4B
BPDDT	*trans*-(Bis-(1-decyl-2-phenylethenedithiolato-*S*,*S*') nickel
BRD	Bacteriorhodopsin
BSQ	1,3-Bis(4'-*N*,*N*-dibutylamino-2'-hydroxyphenyl)-cyclobutene-2,4-dione
BTMSF	Bis (trimethylsilyl) ferocene
DCV	4-*N*,*N*-Diethylamino-4'-*b,b*-dicyanovinyl (azobenzene)
DEANS	4-Diethylamino-4'-nitrostilbene
DMF	Dimethylformamide
DMSM	4'-Dimethylamino-*N*-methyl-4-stilbazolium methylsulfate
DNTA	4-Nitrothenylidenyl (4'-*N*,*N*-dimethylaminoanilide)
DPA	Diphenyl amine
DQCI	1,3'-Diethyl 1-2,2-quinolythiacarbocyanice iodide
DR1	Disperse red 1
ISQ	1,3-Bis(3',3'-dimethyl-2'-indoleninylidenyl)-cyclobutene-2,4-dione
MDCB	*m*-Dicyanobenzene
MDNB	*m*-Dinitrobenzene
Mg:OPTAP	Magnesium octaphenyl tetraazaporphyrin
MNA	2-Methyl-4-nitroaniline
MNTPM	Zinc meso-tetra-(*p*-methoxphenyl) tetrabenzporphyrin
MNTPMP	Zinc meso-tetra-(*p*-methylphenyl) tetrabenzporphyrin
MOMT	Magnesium octamethyltetrabenzporphyrin
NFAI	5-Nitro(2-furanacroleindenyl (4'-*N*,*N*-dimethylaminoanilide)
NPCV	4-*N*,*N* -Dibutylamino-4'-(b-cyano-b-(4'-nitrophenyl) vinyl) (azobenzene)
P(4ABP)	Poly(4-amino biphenyl) with 1.5% tetrafluoroborate doping
P(DPA)	Poly(diphenyl amine) with 1.5% tetrafluoroborate doping
PBPC	Pb-phthalocyanine
PMTBQ	Nonconjugated derivative of a polythiophene
PPV	Poly (*p*-phenylene vinylene)
PTPC	Pt-phthalocyanine
R6G	Rhodamine 6G
RB	Rhodamine B
rB	Rhodamine B

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Abbreviations for Materials—*continued*

Abbreviations	Material
Retinal	6-*s*-*cis* and completelty *trans* retinal
retinal	*trans*-Retinal, malononitrile Knoevenagel adduct
Retinyl acetate	6-*s*-*cis* and completety *trans* retinyl 1,2-
SiNc	Silicon naphthalocyanine
SiPc	Silicon phthalocyanine
TBPP	Tetrabenzporphyrin
TCV	4-*N*,*N*-Diethylamino-4'-tricyanovinyl (azobenzene)
TKCPPC	Tetrakis(cumylphenoxy)phthalocyanines
TNF	2,4,7-Trinitrofluorenone
ZHDFT	Zinc hexadecafluorotetrabenzporphyrin
ZMTM	Zinc meso-tetramethyltetrabenzporphyrin
ZMTMF	Zinc meso-tetra-(*m*-fluorophenyl) tetrabenzporphyrin
ZMTP	Zinc meso-tetraphenyltetrabenzporphyrin
ZMTPDMAP	Zinc meso-tetra-(*p*-dimethylaminohenyl) tetrabenzporphyrin

Experimental Methods

Abbreviation	Method	Ref.
AFRS	anharmonic forced Rayleigh scattering	1
AI1	attenuation vs. irradiance for a single beam	2,3
DFWM	degenerate four-wave mixing	4
ID	ionization decay	5
KE	DC Kerr effect	6
L	luminescence or fluorescence	7,8
MSI	modified Sagnac interferometry	9
OKE	optical Kerr effect	10
OL	optical limiting	11
PS	polarization spectroscopy	12
PST	power for self-trapping	13
SA	saturated absorption	14
SFL	self-focal length	15
TBC	two-beam coupling	14
TL	thermal lensing	16
TPDR	two-photon double resonance spectroscopy	17
TPIF	two-photon induced fluorescence	18
TRI	time-resolved interferometry	19

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5.5.1 Two-Photon Absorption Cross Sections

The two-photon absorption cross section σ_2 is related to the two-photon absorption coefficient β by $\sigma_2 = (h\nu/N)\beta$, where N is the number density of molecules.

Two-Photon Absorption Coefficient β

Liquid	Wavelength (nm)	Pulse length (ns)	$\beta \times 10^{11}$ (m/W)	Ref.
benzene, C_6H_6	354.7	5	1.5	1
	532.1	5	4.5×10^{-5}	1
cyclohexane, C_6H_{12}	694.3	14	1.9	2
toluene, C_7H_8	354.7	5	1.2	1
	532.1	5	6.3×10^{-4}	1

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Two-Photon Absorption Cross Sections

Material	Method	Excitation duration (ns)	Applied two–photon energy (eV)	Two–Photon cross section σ_2 10^{-50}cm^4 s/ phot. mol.	Ref.
123TB	TPIF	5	4.66	0.0021	1
124TB	TPIF	5	4.66	0.075	1
1234TB	TPIF	5	4.66	0.076	1
1235TB	TPIF	5	4.66	0.18	1
α-NPA	L	0.002–0.003	3.57–4.62	Relative spectrum	2
Aniline	TL		3.96–5.69	Relative spectrum (8.8 × benzene @ 4.10 eV)	3
Anthracene	L	40	3.57	14	4
Azulene	AFRS	42–67	4.66	1070	5
Benzene	TL		4.46–5.69	Relative spectrum (49.0 × benzene @ 4.98 eV)	3
	TPIF	5	4.66	0.00025	1
Bis-MSB	L	0.002–0.003	3.57–4.62	Relative spectrum (690 @ 4.24 eV)	2
BRD	TPDR	6	2.07	169	6
	TPDR	6	2.12	207	6
	TPDR	6	2.16	247	6
	TPDR	6	2.21	289	6
	TPDR	6	2.30	288	6
	TPDR	6	2.36	244	6
	TPDR	6	2.56	201	6
	TPDR	6	2.70	167	6
	TPDR	6	2.78	127	6
	TPDR	6	2.92	174	6
	TPDR	6	3.02	199	6
Fluorobenzene	TL		4.46–5.69	Relative spectrum (1.5 × benzene @ 4.65 eV and 5.5 × benzene @ 5.69 eV)	3
Mesitylene	TPIF	5	4.66	0.096	1
m-Xylene	TPIF	5	4.66	0.028	1
o-Xylene	TPIF	5	4.66	0.035	1
p-Xylene	TPIF	5	4.66	0.052	1

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Two-Photon Absorption Cross Sections—*continued*

Material	Method	Excitation duration (ns)	Applied two–photon energy (eV)	Two–Photon cross section σ_2 10^{-50}cm^4 s/ phot. mol.	Ref.
Phenol	TL		4.21–5.69	Relative spectrum (0.8 x benzene @ 4.39 eV and 8.6 × @ 5.45 eV)	3
Pyridine	TL		4–6.2	Relative spectrum (0.27 @ 4.5 eV)	7
R6G	AI1	0.015	3.57	180	8
RB	AI1	0.015	3.57	120	8
Retinal	L	40	3.57	27 (in ethanol)	4
Retinyl acetate	L	40	3.57	26 (in n-hexane)	4
	L	40	3.57	29 (in EPIP	4
Toluene	TL		4.46–5.69	Relative spectrum (2.1 × benzene @ 4.59 eV and 3.3 × @ 5.62 eV)	3
	TPIF	5	4.66	0.0036	1

Table from Garito, A. F. and Kuzyk, M G., Two-photon absorption, organic materials, in *Handbook of Laser Science and Technology, Supplement 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 329.

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5.5.2 Nonlinear Refraction

Nonlinear Refractive Index γ

Liquid	Wavelength (μm)	$\gamma \times 10^{20}$ (m^2/W)	Ref.
acetic acid, $C_2H_4O_2$	0.6943	22.6	1
acetone, C_3H_6O	0.6943	13.3	1
benzene,* C_6H_6	0.57	38	4,7
	0.6943	35	1
carbon disulfide,* CS_2	0.53	310 ± 30	3
	0.6943	390 ± 50	4
	1.0642	290 ± 30	5
	1.32	330	4
	10.6	390 ± 150	6
carbon tetrachloride, CCl_4	0.53	10.2	4,7
	0.56-0.59	8.0	8
	0.6943	5.8	1
chloroform, $CHCl_3$	0.53	20	4,7
	0.6943	17	1
cyclohexane, C_6H_{12}	0.53	7.6	4,7
	0.55-0.58	12.3 ± 0.9	9
1,2-dichloroethane, $C_2H_4Cl_2$	0.53	24	4,7
ethanol, C_2H_6O	0.53	5.2	4,7
glycerine (glycerol), $C_3H_8O_3$	0.53	4.7	4,7
heavy water, D_2O	1.06	6.4	10
methanol, CH_4O	0.53	4.7	4,7
nitrobenzene, $C_6H_5NO_2$	0.53	450	4,7
	0.6943	240	1
toluene, C_7H_8	0.53	113	4,7
	0.6943	85	1
water, H_2O	0.53	2.7	4,7
	0.6943	2.8	1
	1.0642	5.4(?)	10

Measurements made at room temperature.

* Materials used for liquid optics based on nonlinear self-focusing [Ramanthan, D. and Molian, P. A., Laser micromachining using liquid optics, *Appl. Phys. Lett.* 78, 1484 (2001)].

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Nonlinear Refraction Data for Solutions

Material	Solvent	Dye weight fract.(%)	Method	Pulse length (ns)	Wave-length (nm)	Linear refract. index	$\chi^{(3)}_{1111}$,$\chi^{(3)}_{1212}$ (10^{-12}cm^3/erg)	Ref.
4-BCMUy	DMF	14	DFWM	0.033	1064	1.43	1.4	7
DEANS	DMF	3	OKE	6	700, 830		[a]0.2	8
DMSM	Ethanol	5	OKE	6	700, 830		0.46	8
DMSM	Formamide	20	OKE	6	700, 830		3	8
MNA	Ethanol	5	OKE	6	700, 830		[a]0.2	8
P(4ABP)	DMF	10^{-2}–10^{-3} M/l	DFWM	0.040	1064	1.43	0.31, 0.17	9
P(DPA)	DMF	10^{-2}–10^{-3} M/l	DFWM	0.040	1064	1.43	0.48, 0.22	9
PBPC[a]	$CHCl_3$	0.73 M/l	DFWM	0.035	1064		200	10
PMTBQ[a]	DCM	100	DFWM	0.030	532		4600	11
PTPC[a]	$CHCl_3$	0.73 M/l	DFWM	0.035	1064		20	10
Retinal	DMSO	10^{-3} M/l	DFWM	6	532		4.3	12
TKCPPC[a]	$CHCl_3$	0.73 M/l	DFWM	0.035	1064		4.0	10

[a]Extrapolated from solution measurement.

Nonlinear Refraction Data for Dye Solutions

Dye	Solvent	Dye conc. (10^{22}cm^{-3})	Method	Pulse length (ns)	Wave-length (nm)	Linear refract. index	$\chi^{(3)}_{1111}$ (10^{-20}m^2/V^2)	Ref.
A9860	1,2-dichl-oroethane	0.58	DFWM	0.16	532	1.45	1.8	2,3
b-Carotene	EtOH	20	DFWM	0.16	532	1.3	0.2	1,3
BDN	Toluene	1.6	DFWM	0.16	532	1.49	1.7	2,3
BEEDT	Dichl-oromethane	0.0001	DFWM	0.1	1064		0.36	4
BPDDT	Dichl-oromethane	0.0001	DFWM	0.1	1064		1.36	4
DNTPC	MtOH	4.3	DFWM	0.16	532	1.3	1.0	2,3
DTTC	MtOH	25	DFWM	0.16	532	1.3	0.8	2,3
IR5	1,2-Dichl-oroethane	1	DFWM	0.16	532	1.45	2.1	2,3
Nigrosine	H_2O	42	DFWM	0.16	532	1.33	2.6	2,3
S501	*o*-Dichl-orobenzene	0.5	DFWM	0.16	532	1.55	1.25	2,3

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Nonlinear Refraction Data for Dye Solutions—*continued*

Dye	Solvent	Absorption coeff. $\alpha(cm^{-1})$	Method	Pulse length (ns)	Wave-length (nm)	$\chi^{(3)}_{1111}$ (10^{-20} m^2/V^2)	$\chi^{(3)}_{1212}$,$\chi^{(3)}_{1221}$ ($10^{-12}$$cm^3$/erg)	Ref.
BP4B	Acetone	0.39	DFWM	20	532	89		5
BP4B	Ethanol	0.67	DFWM	20	532	151		5
BP4B	Glycerol	2.28	DFWM	20	532	130		5
BP4B	Methanol	0.74	DFWM	20	532	146		5
Chrysoidin[a]	Acetone	0.21	DFWM	20	532	83.1		5
Chrysoidin	Ethonal	0.67	DFWM	20	532	113		5
Chrysoidin	Methonal	0.66	DFWM	20	532	146		5
DQCI	Acetone	92	PS	6	590		8000	6
DQCI	Acetone	16.1	PS	6	590		1600	6
DQCI	Acetone	267	PS	6	590		20000	6
Malachite green	Acetone	27.6	PS	6	610		8800	6
Malachite green	Acetone	82.8	PS	6	610		4000	6
Malachite green	Acetone	175	PS	6	610		7000	6

[a]Linear refractive index = 1.33.

Dye	Solvent	Dye conc. (10^{-4} M/l)	Method	Pulse length (ns)	Wave-length (nm)	Linear refract. index	$\chi^{(3)}_{1111}$ (10^{-20} m^2/V^2)	Ref.
BDN	Toluene	*	DFWM	0.18	1064	1.5	91	2
*Co*TPP	Toluene	0.727	DFWM	0.08–0.2	532		10	2
H_2TPP	Toluene	3.86	DFWM	0.08–0.2	532		40	2
IR5	1,2–Dich-loroethane	*	DFWM	0.18	1064	1.45	62	2
S501	1,2–Dich-loroethane	*	DFWM	0.18	1064	1.45	59	2
Z_nTPP	Toluene	2.29	DFWM	0.08–0.2	532		20	2

*Dye concentration adjusted for 50% transmission in a 2-mm cell.

Dye	Solvent	Dye conc. (10^{-4} g/ml)	Method	Pulse length (ns)	Wave-length (nm)	Linear refract. index	$\chi^{(3)}_{1111}$ (10^{-12} cm^3/erg)	Ref.
MNTPM	THF	0.1–1.0	DFWM	17	532		14000	1
MNTPMP	THF	0.1–1.0	DFWM	17	532		12000	1
MOMT	THF	0.1–1.0	DFWM	17	532		8000	1
TBPP	THF	0.1–1.0	DFWM	17	532		3000	1
ZHDFT	THF	0.1–1.0	DFWM	17	532		2000	1
ZMTM	THF	0.1–1.0	DFWM	17	532		15000	1
ZMTMF	THF	0.1–1.0	DFWM	17	532		13000	1
ZMTP	THF	0.1–1.0	DFWM	17	532		3000	1
ZMTPDMAP	THF	0.1–1.0	DFWM	17	532		28000	1

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Nonlinear Refraction Data for Liquids

Liquid	Method	Pulse length (ns)	Wave-length (nm)	Linear refract. index	$\chi^{(3)}_{1111}$ ·$\chi^{(3)}_{1212}$ (10^{-12} cm^3/erg)	$\chi^{(3)}_{1111}$ (10^{-12} cm^3/erg)	Ref.
4ABP	DFWM	0.040	1064		$<\chi^{(3)}> = 3$		9
α-Picoline	TRI	0.025	532		0.045	0.05	13
Benzene	OKE	0.03	1064, 459	1.52[a]	0.057		14
Benzene	OKE	0.03	1064, 472	1.52[a]	0.057		14
Benzene	OKE	0.03	1064, 496	1.51[a]	0.068		14
Benzene	OKE	0.03	1064, 517	1.51[a]	0.059		14
Benzene	OKE	0.03	1064, 590	1.50[a]	0.070		14
Benzene	TRI	0.025	532	1.51	0.036	0.049	13
Benzene chloride	DFWM	0.033	1064		$\chi^{(3)}_{1212} = 0.11$		7
BTMSF	OL	10	1060	1.55		0.20	15
CCl_4	TRI	0.025	532	1.45	0.008	0.009	16
CH_3COCH_3	TRI	0.025	532		0.009	0.010	16
Chloroform	TRI	0.025	532	1.45	0.015	0.019	16
CS_2	DFWM	0.033	1064		$\chi^{(3)}_{1212} = 0.32$		7
CS_2	PST	130	10600	1.63		8.75	16
CS_2	TRI	0.025	532	1.63	0.60	0.68	13
CS_2	SFL	3	10600	1.63		0.83	17
Cyclohexane	RTI	0.025	532	1.43	0.007	0.009	13
DMF	DFWM	0.033	1064		$\chi^{(3)}_{1212} = 0.033$		7
DPA	DFWM	0.040	1064		$<c^{(3)}> = 3$		9
Molten ferrocene	OL	10	1060	1.55		0.17	15
Nitrobenzene	OKE	0.03	1064, 459	1.58[a]	0.13		14
Nitrobenzene	OKE	0.03	1064, 472	1.58[a]	0.168		14
Nitrobenzene	OKE	0.03	1064, 496	1.57[a]	0.146		14
Nitrobenzene	OKE	0.03	1064, 517	1.56[a]	0.132		14
Nitrobenzene	OKE	0.03	1064, 590	1.55[a]	0.084		14
Nitrobenzene	OL	10	1060	1.56		0.20	15
Nitrobenzene	TRI	0.025	532	1.55	0.11	0.13	13
P(4ABP)	DFWM	0.040	1064		$<c^{(3)}> = 100$		9
P(DPA)	DFWM	0.040	1064		$<c^{(3)}> = 100$		9
PPV	DFWM	0.0004	602,580		400		18
Toluene	RTI	0.025	532	1.49	0.018	0.038	13

[a] Refractive index of probe beam.

The tables above are from Garito, A. F. and Kuzyk, M G., Two-photon absorption, organic materials, *Handbook of Laser Science and Technology, Supplement 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995) , p. 289.

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5.5.3 Kerr Constants

DC Kerr Constants of Pure Liquids

Liquid	DC Kerr constant B_0 (10^{-16} (m/V^2))	Liquid	DC Kerr constant B_0 (10^{-16} (m/V^2))
acetone, C_3H_6O	1814	cyclohexane, C_6H_{12}	8.2
benzene, C_6H_6	66	ethanol, C_2H_6O	85.5
carbon disulfide, CS_2	358.9	hexane, C_6H_{14}	5.0
carbon tetrachloride, CCl_4	8.2	methanol, CH_4O	107.9
bronobenzene, C_6H_5Br	1012	nitrobenzene, $C_6H_5NO_2$	28500
cyclohexane, C_6H_{12}	8.2	toluene, C_7H_8	83.3

Measurements made at a wavelength of 589.3 nm and 293 K.

Reference:

1. Shen, Y. R., Electrostriction, optical Kerr effect and self-focusing of laser beams, *Phys. Lett*. 20, 378–380 (1966).

DC Kerr Response of Binary Liquids

Material A	Material B	Molar fraction A	Wave-length (nm)	Linear refract. index	Temp. (°C)	$n^{(2)}_{1111} - n^{(2)}_{1122}$ (10^{-20} m^2/V^2)
Benzene	Chlorobenzene	0	632.8	1.524	25	9.15
Benzene	Chlorobenzene	0.3	632.8		25	6.21
Benzene	Chlorobenzene	0.6	632.8		25	3.28
Benzene	Chlorobenzene	1.0	632.8	1.501	25	0
Cyclohexane	Nitrobenzene	0	632.8	1.556	25	28.2
Cyclohexane	Nitrobenzene	0.2	632.8		25	16.4
Cyclohexane	Nitrobenzene	0.4	632.8		25	9.32
Cyclohexane	Nitrobenzene	0.8	632.8		25	1.41
Cyclohexane	Nitrobenzene	1.0	632.8	1.427	25	0
Nitromethane	Chlorobenzene	0	632.8	1.524	25	9.15
Nitromethane	Chlorobenzene	0.4	632.8		25	10.7
Nitromethane	Chlorobenzene	0.7	632.8		25	12.3
Nitromethane	Chlorobenzene	1.0	632.8	1.382	25	8.28
Pyridine	2,6-Lutidine	0	632.8	1.495	25	8.28
Pyridine	2,6-Lutidine	0.6	632.8		25	11.9
Pyridine	2,6-Lutidine	1.0	632.8	1.509	25	14.5

Reference:

Piazza, R., Degiorgio, V., and Bellini, T., Kerr effect in binary liquids, *J. Opt. Soc. Am.* B 3, 1642 (1986).

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DC Kerr Response of Binary Liquids

Material A	Material B	Weight Percent of A (%)	Wavelength (nm)	Linear refractive Index	Temp. (°C)	$n^{(2)}_{1111} - n^{(2)}_{1122}$ (10^{-20} m^2/V^2)
Lutidine	H_2O	0	632.8	1.33	23–32.8	24.0
Lutidine	H_2O	35	632.8		23	10.2
Lutidine	H_2O	35	632.8		32	21.9
Lutidine	H_2O	35	632.8		32.8	38.0
Lutidine	H_2O	100	632.8		32	8.76
Lutidine	H_2O	100	632.8		32.8	8.76
Lutidine	H_2O	100	632.8	1.495	23	8.76

Reference:

Piazza, R., Degiorgio, V., and Bellini, T., Kerr effect in binary liquids, *J. Opt. Soc. Am.* B 3, 1642 (1986).

The tables above are from Garito, A. F. and Kuzyk, M. G., Two-photon absorption, organic materials, *Handbook of Laser Science and Technology, Supplement 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 289.

Optical Kerr Constant

The laser-induced Kerr constant is given by $B_0 = (2\pi/n\lambda_p)(\chi^{(3)}_{1212} + \chi^{(3)}_{1221})$, where λ_p is the linearly polarized probe beam wavelength.

Optical Kerr Constants of Pure Liquids

Liquid	Wavelength (nm)	Optical Kerr constant B_0 (10^{-16} m/V^2)
acetic acid	532	33.0
	694	22.9
	1064	21.5
acetone, C_3H_6O	694	8.2
benzene, C_6H_6	532	79
	694	70
	1064	51
carbon disulfide, CS_2	694	470
	1064	360
carbon tetrachloride, CCl_4	694	8.9
	1064	3.3
chlorobenzene, C_6H_5Cl	1064	89.9
chloroform, $CHCl_3$	694	23
	1064	18

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Optical Kerr Constants of Pure Liquids—*continued*

Liquid	Wavelength (nm)	Optical Kerr constant B_0 (10^{-16} m/V^2)
cyclohexane, C_6H_{12}	694	6.8
m-dichlorobenzene, $C_6H_4Cl_2$	694	170
o-dichlorobenzene, $C_6H_4Cl_2$	694	179
ethanol, C_2H_6O	694	5.22
	1064	5.1
heavy water, D_2O	1064	2.9
heptane, C_7H_{16}	694	11.3
	1064	7.6
hexadecane, $C_{16}H_{34}$	694	20.2
hexane, C_6H_{14}	694	9.9
	1064	6.9
methanol, CH_4O	694	4.76
	1064	3.3
methylcyclohexane, C_7H_{14}	694	7.7
nitrobenzene, $C_6H_5NO_2$	694	420
	1064	260
tetrachloroethylene, C_2Cl_4	694	148
toluene, C_7H_8	694	120
	1064	99
water, H_2O	694	4.6
	1064	2
o-xylene, C_8H_{10}	694	130
m-xylene, C_8H_{10}	694	125
po-xylene, C_8H_{10}	694	120

Measurements at room temperature.

Reference:

1. Harrison, N. J. and Jennings, B. R., Laser-induced Kerr constants for pure liquids, *J. Phys. Chem. Ref. Data* 21, 157–163 (1992).

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5.5.4 Third-Order Nonlinear Optical Coefficients

Liquid	Nonlinear optical process	Coefficient $C_{jn} \times 10^{20}$ m^2 V^{-2}	Wavelength (μm)
acetone, C_3H_6O	$(-\omega; \omega, \omega, -\omega)$	$C_{11} = 0.252 \pm 0.056$	0.6943
benzene, C_6H_6	$(-\omega; \omega, \omega, -\omega)$	$C_{11} = 0.518 \pm 0.07$	0.6943
		$C_{18} = 0.098$	0.5000
		$C_{18} = 0.0782$	0.6943
		$C_{18} = 0.091$	0.694
	$(-\omega_1; \omega_1, \omega_2, -\omega_2)$	$C_{18} = 0.028$	0.4880
	$(-2\omega_1+ \omega_2; \omega_1, \omega_1, -\omega_2)$	$C_{11} = 0.56$	0.694
		$C_{11} = 0.242 \pm 0.024$	0.5250
		$C_{11} = 0.00859 \pm 0.00037$	0.545
		$C_{18} = 0.252 \pm 0.00014$	0.545
	$(3\omega; \omega, \omega, \omega)$	$C_{11} = 0.0184 \pm 0.056$	1.89
	$(-2\omega; \omega, \omega, 0)$	$C_{11} = 0.02215 \pm 15\%$	1.06
		$C_{11} = 0.02215 \pm 15\%$	1.318
bromobenzene, C_6H_5Br	$(-2\omega_1+ \omega_2; \omega_1, \omega_1, -\omega_2)$	$C_{11} = 0.084$	0.6943
		$C_{11} = 0.0196 \pm 15\%$	1.06
carbon disulfide, CS_2	$(-\omega; \omega, \omega,-\omega)$	$C_{18} = 0.476$	0.694
		$C_{18} = 0.560$	0.500
	$(-\omega_1; \omega_1, \omega_2, -\omega_2)$	$C_{18} = 0.266$	0.4880
	$(-2\omega; \omega, \omega, 0)$	$C_{11} = 0.06233 \pm 15\%$	1.06
carbon tetrachloride, CCl_4	$(-\omega; \omega, \omega,-\omega)$	$C_{18} = 0.0168 \pm 30\%$	0.694
	$(-2\omega; \omega, \omega, 0)$	$C_{11} = 0.0182 \pm 15\%$	1.06
chloroform, $CHCl_3$	$(-\omega; \omega, \omega,-\omega)$	$C_{18} = 0.07 \pm 30\%$	1.06
1,2-dichloroethane, $C_2H_4Cl_2$	$(-2\omega; \omega, \omega, 0)$	$C_{11} = 0.042 \pm 15\%$	1.06
1,4-dioxane, $C_4H_8O_2$	$(-2\omega; \omega, \omega, 0)$	$C_{11} = 0.01351 \pm 15\%$	1.06
ethanol, C_2H_6O	$(-\omega; \omega, \omega,-\omega)$	$C_{18} = 0.0315$	0.694
		$C_{11} = 0.196 \pm 0.042$	0.6943
glycerine (glycerol), $C_3H_8O_3$	$(-\omega; \omega, \omega,-\omega)$	$C_{11} = 0.196 \pm 0.07$	0.6943
heptane, C_7H_{16}	$(-2\omega; \omega, \omega, 0)$	$C_{11} = 0.84 \pm 15\%$	1.06
hexane, C_6H_{14}	$(-2\omega; \omega, \omega, 0)$	$C_{11} = 0.7105 \pm 15\%$	1.06
methanol, CH_4O	$(-2\omega; \omega, \omega, 0)$	$C_{11} = 0.301 \pm 15\%$	1.06
methylbenzene, C_6H_8	$(-2\omega; \omega, \omega, 0)$	$C_{11} = 0.056$	0.6943
nitrobenzene, $C_6H_5NO_2$	$(-\omega; \omega, \omega,-\omega)$	$C_{18} = 0.42$	0.500
		$C_{18} = 0.322$	0.6943
		$C_{11} = 1.148 \pm 0.140$	0.6943
	$(-\omega_1; \omega_1, \omega_2, -\omega_2)$	$C_{18} = 0.182$	0.4880
	$(-2\omega; \omega, \omega, 0)$	$C_{11} = 0.585 \pm 15\%$	1.318
		$C_{11} = 0.360 \pm 15$	1.06
nitromethane, CH_3NO_2	$(-2\omega; \omega, \omega, 0)$	$C_{11} = 0.042 \pm 0.093$	0.6943
toluene, C_7H_8	$(-2\omega; \omega, \omega, 0)$	$C_{11} = 0.0238 \pm 15\%$	1.06
water, H_2O	$(-2\omega; \omega, \omega, 0)$	$C_{11} = 0.0616 \pm 15\%$	1.06

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Data in the preceding table are from S. Singh, Nonlinear optical materials, *Handbook of Laser Science and Technology, Vol. III: Optical Materials, Part 1* (CRC Press, Boca Raton, FL, 1986), p. 54 ff. Data for additional liquids are included in this reference.

5.5.5 Stimulated Raman Scattering

Observed SRS Lineshifts ω of Liquids

Substance	ω (cm^{-1})	Ref.
bromoforrn	222	1
tetrachloroethylene	448	2
carbon tetrachloride[a]	460	3
ethyl iodide	497	4
hexafluorobenzene[a]	515	3
bromoform	539	1
chlorine	552	5
methylene bromide	580	3
trichloroethylene	640	1
carbon disulfide	655	6
ethylene bromide	660	7
chloroform	667	1
α-xylene	730	8
FC104[b]	757	9
sulfur hexafluoride	775	10
α-dimethylphenethylamine	836	11
dioxane	836	1
morpholine[a]	841	3
thiophenol[a]	916	3
nitromethane[a]	927	3
deuterated benzene	944	12
potassium dihydrogen phosphate	980	13
cumene[a]	990	3
pyridine	991	12
1,3-dibromobenzene	992	2
benzene	992	12
aniline	997	14
styrene	998	15
m-toluidine[a]	999	3
acetophenone	999	16
bromobenzene	1000	14
chlorobenzene[a]	1001	3
tert-butylbenzene	1000	2
benzaldehyde[a]	1001	2
ethylbenzoate	1001	16
benzonitrile	1002	14
ethylbenzene	1002	8
toluene	1004	12

Observed SRS Lineshifts ω of Liquids—*continued*

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Substance	ω (cm^{-1})	Ref.
fluorobenzene	1012	17
γ-picoline	1016	3
m-cresol[a]	1029	3
m-dichlorobenzene[a]	1034	3
1-fluoro-2-chlorobenzene[d]	1034	2
1-fluoro-2-chlorobenzene[d]	1034	2
iodo-benzene[a]	1070	3
benzoyl chloride[a]	1086	3
benzaldehyde[a]	1086	3
anisole[a]	1097	3
pyrrole[a]	1178	3
furan[a]	1180	3
nitrous oxide	1289	10
styrene	1315	15
nitrobenzene	1344	12
1-bromonaphthalene	1363	12
1-chloronaphthalene	1374	18
2-ethylnaphthalene	1382	2
m-nitrotoluene[a]	1389	3
carbon dioxide	1392	10
quinoline[a]	1427	3
homocyclohexane	1438	4
furan[a]	1522	3
methyl salicylate[a]	1612	3
cinnamaldehyde	1624	18
styrene	1631	15
3-methylbutadiene	1638	19
pentadiene	1655	19
isoprene	1792	11
1-hexyne	2116	2
dimethyl sulfoxide[c]	2128	20
α-dichlorobenzene[a]	2202	3
benzonitrile	2229	18
acetonitrile	2250	4
1,2-dimethylaniline	2292	3
nitrogen	2327	21
hydrobromic acid	2493	9
hydrochloric acid	2814	9
methylcyclohexane	2817	3
methanol	2831	1
cis trans, 1,3-dimethylcyclohexane	2844	2
tetrahydrofuran	2849	18
cyclohexane	2852	12
cis- l,2-dimelhylcyclohexane	2853	2

Observed SRS Lineshifts ω of Liquids—*continued*

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Substance	ω (cm^{-1})	Ref.
α-dimethylphenethylamine	2856	11
dioxane	2856	1
decahydronaphthalene	2860	9
cyclohexane	2863	1
cyclohexanone	2863	8
cis. trans-1,3-dimethylcyclohexane	2866	2
cyclohexane	2884	1
dichloromethane[a]	2902	3
dimethyl sulfoxide	2916	20
morpholine	2902	3
cargille 5610[f]	2908	9
2,3-dimethyl-1,5-hexadiene	2910	2
limonene	2910	11
o-xylene	2913	8
1-hexyne	2916	2
cis-2-heptene	2916	2
2-octene	2918	2
acetonitrile	2920	9
mesitylene	2920	11
2-bromopropane	2920	2
acetone	2921	8
ethanol	2921	1
cis-1,2-dimethylcyclohexane	2921	2
carvone	2922	11
cis, trans-1,3-dimethylcyclohexane	2926	2
2-chloro-2-methylbutane	2927	2
dimethylformamide	2930	1
m-xylene	2933	8
1,2-diethyl tartrate	2933	11
o-xylene	2933	8
piperidine	2933	8
1,2-diethylbenzene	2934	2
1-bromopropane	2935	2
piperidine	2936	8
tetrahydrofuran	2939	18
decahydronaphthalene	2940	9
piperidine	2940	8
cyclohexanone	2945	8
2-nitropropane	2945	2
1,2 diethyl carbonate[a]	2955	3
1,2 dichloroethane[a]	2956	3
trans-dichloroethylene	2956	1
methyl fluoride	2960	10
1-bromopropane	2962	2

Observed SRS Lineshifts ω of Liquids—*continued*

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Substance	ω (cm^{-1})	Ref.
2-chloro-2-methylbutane	2962	2
α-dimethylphenethylamine	2967	11
dioxane	2967	1
methyl chloride	2970	10
cyclohexanol[a]	2982	3
cyclopentane[a]	2982	3
cyclopentanol[a]	2982	3
bromocyclopentane[a]	2982	3
o-dichlorobenzene	2982	3
p-chlorotoluene	2982	3
a-picoline[a]	2982	3
p-xylene	2988	8
o-xylene	2992	8
dibutyl-phthalate[a]	2992	3
1, 1, 1-trichloroethane	3018	1
ethylene chlorohydrin[a]	3022	3
isophorone[a]	3022	3
nitrosodimethylamine[a]	3022	3
propylene glycol[a]	3022	3
cyclohexane[a]	3038	3
styrene	3056	15
pyridine	3058	2
benzene	3064	12
tert-butylbenzene	3065	2
1-fluoro-2-chlorobenzene	3082	2
turpentine[a]	3090	3
pseudocumene[a]	3093	3
acetic acid[a]	3162	3
acetonylacetone[a]	3162	3
methyl methacrylate[a]	3162	3
γ-picoline[a]	3182	3
aniline	3300	14
water[a]	3651	3

a Observed at low resolution
b Product of 3M Co., St. Paul, MN
c 1:1 mixture with tetrachloroethylene
d Very weak and diffuse
e Deuterated
f Product of Cargille Laboratories, Cedar Falls, NJ

Table from Milanovich, F. P., Stimulated Raman scattering, *Handbook of Laser Science and Technology, Vol. III: Optical Materials* (CRC Press, Boca Raton, FL, 1986), p. 283.

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5.5.6 Stimulated Brillouin Scattering

Brillouin Gain Parameters for Selected Liquids

Material	Pump wavelength (nm)	Frequency shift (GHz)	Δν (MHz)	τ_B (ns)	g_B (cm/GW)	n	Density (g/cm^3)	Ref.
Acetone	1059	2.987	119 ± 5	1.34	15.8	1.355	0.791	1
	532	5.93	361	0.44	12.9	1.359 (Na_D)		2
	532	6.0	320	0.497	20			3
Benzene	1059	4.124	228	0.7	9.6	1.4837	0.879	1
	532	8.33	515	0.31	12.3	1.501 (Na_D)	0.874	2
Benzyl alcohol	532	9.38	2120	0.08	5.75	1.54 (Na-D)	1.045	2
Butyl acetate	532	6.23	575	0.28	9.13	1.394 (Na_D)	0.882	2
CS_2	1060	3.761	50	3.2	68	1.595	1.262	1
	532	7.7	120	1.9	130			3
CCl_4	1060	2.772	528	0.3	3.8	1.452	1.595	1
	532	5.72	890	0.18	8.77	1.4595	1.594	2
Chloroform	532	5.75	635	0.25	11.7	1.446 (Na_D)	1.492	2
Cyclohexane	532	7.19	1440	0.11	5.8	1.426 (Na_D)	0.779	2
N,*N*-Dimethyl formamide	532	7.93	615	0.26	7.8	1.431 (Na_D)	0.944	2
Dichloromethane	532	5.92	255	0.62	16.8	1.424	1.325	2
o-Dichlorobenzene	532	8.03	1340	0.12	4.7	1.551	1.306	2
Ethanol	532	5.91	546	0.29		1.36	0.785	2
Ethylene glycol	532	10.2	3630	0.04	0.85	1.431	1.113	2
Freon 113	532	3.72	81	0.18	5.5	1.3578	1.575	2
n-Hexane	532	5.64	580	0.27	8.8	1.379	0.67	2
Nitrobenzene	1060	4.255	396	0.4	7.2	1.5297	1.206	1
Methanol	532	5.47	325	0.49	10.6	1.329	.791	2
	530	5.6	210	0.334	13			3
Pyridine	532	8.92	746	0.21	14	1.51	0.978	2
Tin tetrachloride	1064	2.21 ± 0.02	182 ± 12	0.874	11.2 ± 0.5	1.36	2.226	4
	532	4.71	357	0.45				2
Titanium tetrachloride	1060	3.070	216	0.735	14.2	1.577	1.73	1
Toluene	532	7.72	1314	0.12	8.4	1.496	0.867	2
Trichloroethylene	532	5.94	765	0.21	12	1.4755	1.464	2
Water	1060	3.703	170	0.935	3.8	1.324	1	1
	532	7.4	607	0.26	2.94	1.333	1	2
Xylenes	532	7.74	1211	0.13	9.3	1.497	0.86	2

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Brillouin Materials Used for Phase Conjugation

Liquids	Temp. (K)	Wave-length λ (nm)	Refract. index	Sound speed v_s (km/s)	Brillouin shift at λ (GHz)	Phonon lifetime τ_p (ns)	Line width $\Delta\nu_b$ (MHz)	Gain g (cm/GW)	Density ρ (g/cm^3)	Ref.
Acetic acid					5.05					1
	295	633			5.64		400			2
Acetone		694		1.40	4.61		235			3
		1064			3.1					4
		1064	1.36	1.19		4	40	18		5
		1064			2.97	1.8	90	12.9		6
		1064			5.93	0.44	361	12.9		7
		532			5.00			12.9		7
	295	633			5.05		260			2
	293	1064	1.355	1.168	2.987	2.67	119[a]	15.8	0.791	8
		694					180	20		9
		694		1.19	4.600		175	18		11
Acetonitrile		633			5.52		300			2
BCl_3		1064								6
Benzene		694		1.5			245	18		11
		632		1.50	7.10		340			3
		532			8.33	0.31	515	12.3		7
					7.03		520			2
					7.08					1
		1064	1.5	1.5		3		18		5
	293	1060	1.4837	1.473	4.124	1.40	228[a]	9.6	0.879	8
	323	1060	1.4648	1.359	3.757	1.07	297			8

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Benzene		694			6.470		289[a]	18		9
Benzyl alcohol		532			9.38	0.08	2120	5.75		7
Butanol		633			5.63		720			2
Butyl acetate		532			6.23	0.28	575	9.13		7
$C_2Cl_3F_3$		532			3.72	0.18	865–880	5.50		7
(Freon 113)		1064	1.36	0.728	1.86	0.72	220	5.5		6
Carbon disulfide,		694		1.25			55	45		11
CS_2		694		1.142	5.85		80		1.263	3
		1064	1.62		3.8	7	23	50	1.263	5
	293	1060	1.593	1.250	3.76	6.4		68		8
	300	1060				4.9				8
		1064				6.7				4
		694				2.1		130		10
		633			6.45		140			2
	301	633			6.24		132			11
	162	633			9.05		396			11
Carbon tetra-		694		0.92	4.41		630		1.595	3
chloride, CCl_4		694	1.46	1.05			430	8		11
			1.46	1.05		1.3		6		5
		1064		1.04?	2.9		122	3.8	1.591	6
		532			5.72	0.18	890	8.77		7
		633			4.82		1260			2

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Brillouin Materials Used for Phase Conjugation—*continued*

Liquids	Temp. (K)	Wave-length λ (nm)	Refract. index	Sound speed v_s (km/s)	Brillouin shift at λ (GHz)	Phonon lifetime τ_p (ns)	Line width $\Delta\nu_b$ (MHz)	Gain g (cm/GW)	Density ρ (g/cm^3)	Ref.
Carbon tetra-chloride, CCl_4	293		1.452	1.012	2.772	0.60	528[a]	3.8	1.595	8
		1060								12
					4.390		650	6		9
								8		9
Chloroform		532			5.75	0.25	635	11.7		7
		633			4.88		840			2
Cyclohexane		532			7.19	0.11	1440	5.8		7
		1064	1.43	1.35		1		7		5
		694			5.550		774[b]	6.8		9
		694		1.35			670	6.8		11
Dichloromethane, CCl_2H_2		532			5.92	0.62	255	16.8		7
					2.96	2.5	64	16.9		4
Ethanol		532			5.91	0.29	546			7
		633			5.04		600			2
		694			4.550		353[b]	12[c]		9
Ethylene glycol		532			10.2	0.04	3630	0.85		7
Germanium tetrachloride, $GeCl_4$			1.46					12	1.87	6
Glycerol	298				2.8					11
	245				3.3		382			11

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	166				3.7		42		11
Methanol		1064	1.33	1.12		3.7		13	5
		532			5.47	0.49	325	10.6	7
		633			4.68		260		2
		694			4.250		250[b]	13	9
		694	1.33	1.118			200	13.2	11
N,*N*-Dimethyl formamide		532			7.93	0.26	615	7.8	7
n-Hexanes		532			5.64	0.27	580	8.80	7
		1064	1.37	1.11		3.5		19	5
		694					220	26	9
		694	1.37	1.113			212	19	11
		694					212	10	9
Nitrobenzene		694		1.56			900	4.5	11
		1064	1.56	1.56		0.8		4.5	5
	293	1060	1.530	1.474	4.255	0.80	396[a]	7.2	1.206	8
	313	1060	1.521	1.414	4.057	0.77	416			8
o-Dichlorobenzene		532			8.03	0.12	1340	4.70		7
PCl_3									8.6	6
Pyridine		532			8.92	0.21	746	14.00		7
		633			7.38					13
		633			7.36		780			2

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Brillouin Materials Used for Phase Conjugation—*continued*

Liquids	Temp. (K)	Wavelength λ (nm)	Refract. index	Sound speed v_s (km/s)	Brillouin shift at λ (GHz)	Phonon lifetime τ_p (ns)	Line width $\Delta\nu_b$ (MHz)	Gain g (cm/GW)	Density ρ (g/cm^3)	Ref.
Silicon tetrachloride, $SiCl_4$			1.41					10	1.48	6
Tin tetrachloride, $SnCl_4$			1.51	0.830					11	
	308	1064			2.21	1.7	182	11.2		14
		532			4.71	0.45	357			7
		1064			2.36	1.8	89			7
		1064								6
Titanium tetrachloride, $TiCl_4$		1064	1.62	1.05	3.2	2	80	14	1.73	5
		532			4.71	0.45	357			7
		1064								15
		1064					2.0		20 ± 4	6
	293	1060	1.577	1.032	3.070	1.47	216[a]	14.2	1.73	8
Toluene		694	1.38			480		13		11
		532			7.72	0.12	1314	8.4		7
		633			6.41	1000				2
		1064	1.5	1.4		1.5		10		5
Trichloroethylene		532			5.94	.21	765	12.00		7
Water, H_2O		1064	1.33	1.48	3.7					
		1064			3.7	1.1	152	2.94		7
		532			7.4	0.26	607	2.94		7
		633			6.23		440			2

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		1064	1.33	1.49		3.4		4.8		5
	293	1060	1.324		3.703	1.87[a]	170[a]	3.8	0.997	8
				1.482						16
		694	1.33	1.488			220	4.8		11
		694			5.69		317[b]	4.8		9
Water, D_2O			1.33	1.38	3.46	3.4	47	3.1	1.1	
Xylenes		532			7.74	0.13	1211	9.30		
26 Organic liquids		XeCl laser								17
30 Organic liquids		532								18

[a]These authors assume that lifetime = $1/(\pi \times$ linewidth); [b]This is the spontaneous scattering linewidth; these authors report different values for the spontaneous and stimulated scattering linewidth; [c]This is a theoretically calculated, not an experimental, number; [d]Density in amagats rather than pressure in atmospheres.

Table from Pepper, D. M., Minden, M. L., Bruesselbach, H. W. and Klein, M. B., Nonlinear optical phase conjugation materials, in *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 467.

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5.6 Magnetooptic Properties

The following tables and figure are from Munin, E., Magnetooptic materials: organic and inorganic liquids, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, 1995), p. 403.

5.6.1 Verdet Constants of Inorganic Liquids

Verdet Constants V of Inorganic Liquids

Liquid	λ(nm)	T(°C)	n	V(rad/T·m)	Ref.
$AsCl_3$	589		1.60	12.4	1
$COCl_2$	589	3		3.93	1
D_2O	578	19.7		3.819	1
	589	19.7		3.656	1
H_2O	578	11.5		3.971	1
	589	10		3.811	1
N_2	589	–195.5		1.21	2
NH_3	578	–40	1.35	5.47	3
O_2	589	–182.5		2.27	2
P[a]	589	33	2.07	38.7	1
PBr_3	578	20	1.70	17.6	1
PCl_3	578	26	1.511	8.78	1
P_4S	589	16		32.0	2
S[a]	589	114	1.93	23.5	1
SO_2	589	–10	1.39	5.23	2
$SbCl_5$	589	16		20.5	2
S_2Cl_2	589	16		12.2	2
$SiCl_4$	589	16		5.50	2
$SnCl_4$	578	28	1.516	13.0	1
$TiBr_4$	578	46		–15.4	5
$TiCl_4$	578	17	1.612	–4.80	6

[a]Fused.

5.6.2 Verdet Constants of OrganicLiquids

Verdet Constants V of Organic Liquids (from Ref. 7)

Formula	Name	λ (nm)	T(°C)	V (rad/T m)
CCl_4	tetrachloromethane	589	25.1	4.65
$CHCl_3$	trichloromethane	589	20.0	4.72
CH_2Br_3	tribromomethane	589	17.9	9.10
CH_2O_2	formic acid	589	20.8	3.04
CH_2Cl_2	dichloromethane	589	11.9	4.65
CH_2Br_2	dibromomethane	589	15.9	7.97
CH_2I_2	diiodomethane	589	15.0	4.39
CH_3Cl	monochloromethane	589	23	3.99
CH_3Br	monobromomethane	589	1.5	5.93
CH_3I	monoiodomethane	589	19.5	9.74
CH_4O	methyl alcohol	589	18.7	2.79
CH_3O_2N	mononitromethane	589	9.9	2.40

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Verdet Constants V of Organic Liquids (from Ref. 7)—*continued*

Formula	Name	λ (nm)	T(°C)	V (rad/T m)
C_2H_3Br	vinylbromide	589	7.8	6.11
C_2H_4O	ethyleneoxide (1,2-epoxiethane)	589	8.0	2.68
C_2H_4O	acetaldehyde (ethanal)	589	16.3	2.91
$C_2H_4O_2$	acetic acid	589	21.0	3.04
$C_2H_4O_2$	methylformate	589	16.5	2.79
$C_2H_4Cl_2$	1,1-dichloroethane	589	14.4	4.39
$C_2H_4Cl_2$	1,2-dichloroethane	589	14.4	4.80
$C_2H_4Br_2$	1,2-dibromoethane	589	15.2	7.74
C_2H_5Cl	monochloroethane	589	5.0	3.96
C_2H_5Br	monobromoethane	589	19.7	5.29
C_2H_5I	monoiodoethane	589	18.1	8.58
C_2H_6O	ethyl alcohol	589	16.8	3.29
$C_2H_6O_2$	glycol (1,2-ethanediol)	589	15.1	3.64
C_2H_6S	ethylmercaptan	578	16.0	5.38
$C_2H_2O_2Cl_2$	dichloroacetic acid	589	13.5	4.42
$C_2H_3O_2Cl$	chloroacetic acid (cloroethanoic acid)	589	64.5	3.87
$C_2H_3O_2Cl_3$	chloralhydrate	589	54.6	4.80
$C_2H_5O_2N$	mononitroethane	589	10.2	2.75
C_3H_4O	acrolein (propenal)	578	20.0	5.12
$C_3H_4O_3$	pyruvic acid (2-oxopropanoic acid)	589	14.5	3.52
C_3H_6O	allyl alcohol	589	18.3	4.65
C_3H_6O	propyl alcohol (1-propanol)	589	13.6	3.17
C_3H_6O	acetone (2-propanone)	589	20	3.24
$C_3H_6O_2$	propionic acid (propanoic acid)	589	20.3	3.20
$C_3H_6O_2$	formic acid ethyl ester (ethylmethanoate)	589	18.8	3.05
$C_3H_6O_2$	acetic acid methyl ester (methyl acetate)	589	20.0	3.00
C_3H_7Cl	propylchloride (1-chloropropane)	589	16.1	3.90
C_3H_7Cl	isopropylchloride (2-chloropropane)	589	17.2	3.90
C_3H_7Br	propylbromide (1-bromopropane)	589	19.2	5.21
C_3H_7Br	isopropylbromide (2-bromopropane)	589	17.1	5.15
C_3H_7I	propyliodide (1-iodopropane)	589	18.1	7.82
C_3H_7I	isopropyliodide (2-iodopropane)	589	26.3	7.65
C_3H_8O	*n*-propyl alcohol (1-propanol)	589	15.6	3.49
C_3H_8O	isopropyl alcohol (2-propanol)	589	20.0	3.58
$C_3H_8O_3$	glycerine (1,2,3-propanetriol)	589	16.0	3.87
C_3H_9N	*n*-propylamine	589	9.6	3.87
$C_3H_5O_9N_3$	nitroglycerine	589	13.5	2.62
$C_3H_7O_2N$	1-nitropropane	589	18.9	2.96
C_4H_6	1,3-butadiene (erythrene)	589	15.0	6.28
C_4H_8	1-butene (a-butylene)	589	15.0	4.04
C_4H_8	*cis*-2-butene (b-butylene)	589	15.0	4.01
C_4H_8	*trans*-2-butene	589	15.0	3.75
C_4H_{10}	butane	589	15.0	3.17
C_4H_{10}	isobutane (2-methylpropane)	589	15.0	3.23
C_4H_4O	furan (furfuran)	589	20.0	5.18
C_4H_4S	thiophene (thiofuran)	589	20.0	8.23
$C_4H_6O_3$	acetic anhydride (ethanoic anhydride)	589	20.0	3.24

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Verdet Constants V of Organic Liquids (from Ref. 7)—*continued*

Formula	Name	λ (nm)	T(°C)	V (rad/T m)
$C_4H_8O_2$	*n*-butyric acid (butanoic acid)	589	18.8	3.35
$C_4H_8O_2$	ethyl acetate (ethyl ethanoate)	589	20.0	3.14
$C_4H_8O_2$	propionic acid methyl ester	589	20.0	3.11
$C_4H_{10}O$	ethyl ether (ethoxyethane)	589	20.0	3.17
$C_4H_{10}O$	*n*-butyl alcohol (1-butanol)	589	20.0	3.58
$C_4H_{10}O$	isobutyl alcohol (2-methyl-1-propanol)	589	17.7	3.69
$C_4H_{10}O$	*sec*-butyl alcohol (methylethylcarbinol)	589	20.0	3.69
C_5H_6	cyclopentadiene	589	15.0	5.88
C_5H_8	1,3-pentadiene	589	15.0	6.05
C_5H_8	isoprene (2-methyl-1,3-butadiene)	589	15.0	6.05
C_5H_8	cyclopentene	589	15.0	4.42
C_5H_{10}	1-pentene	589	15.0	4.04
C_5H_{10}	isopentane (2-methyl-1-butane)	589	15.0	4.04
C_5H_{10}	cyclopentane	589	20.0	3.58
C_5H_{12}	pentane	589	15.0	3.35
C_5H_{12}	isopentane (2-methylbutane)	589	15.0	3.40
$C_5H_4O_2$	furfural (2-furancarbonal)	578	20.0	5.99
C_5H_5N	pyridine	589	11.9	7.50
$C_5H_{10}O_2$	propionic acid ethyl ester	589	20.0	3.29
$C_5H_{10}O_2$	acetic acid propylester	589	15.7	3.29
$C_5H_{14}N_2$	cadaverine (1,5-pentanediamine)	589	14.7	4.45
C_6H_6	benzene	589	15.0	8.73
C_6H_{12}	cyclohexane	589	20.0	3.61
C_6H_{14}	hexane	589	15.0	3.49
$C_6H_4Cl_2$	1,4-dichlorobenzene (*p*-dichlorobenzene)	589	64.5	7.82
C_6H_5F	fluorobenzene (phenylfluoride)	589	19.0	7.30
C_6H_5Cl	chlorobenzene (phenylchloride)	589	15.0	8.49
C_6H_5Br	bromobenzene (phenylbromide)	589	15.0	9.48
C_6H_5I	iodobenzene (phenyliodide)	589	15.0	11.8
C_6H_6O	phenol (hydroxibenzene)	589	39.0	9.34
C_6H_7N	aniline (aminobenzene)	589	15.0	12.2
$C_6H_{11}Cl$	chlorocyclohexane (cyclohexylchloride)	589	13.0	4.25
$C_6H_{12}O_3$	paraldehyde (paraacetaldehyde)	589	17.3	3.46
$C_6H_{14}O$	2-hexanol (butylmethylcarbinol)	589	20.0	3.81
$C_6H_{14}O$	3-hexanol (ethylpropylcarbinol)	589	20.0	3.78
$C_6H_{14}O$	2-methyl-3-pentanol	589	20.0	3.84
$C_6H_4O_4N_2$	1,3-dinitrobenzene (*m*-dinitrobenzene)	589	17.1	6.31
$C_6H_5O_2N$	nitrobenzene	589	15.0	6.31
C_7H_8	toluene (methylbenzene)	589	15.0	7.88
C_7H_{14}	1-heptene (a-heptylene)	589	18.0	4.16
C_7H_{16}	heptane	589	15.0	3.58
C_7H_5N	benzonitrile (benzenecarbonitrile)	589	15.7	7.97
C_7H_7Cl	*o*-chlorotoluene (2-chloro-1-methylbenzene)	589	15.4	8.58
C_7H_7Cl	*p*-chlorotoluene (4-chloro-1-methylbenzene)	589	15.2	7.71
C_7H_7Br	*o*-bromotoluene (2-bromo-1-methylbenzene)	589	16.7	8.96
C_7H_7Br	*p*-bromotoluene(4-bromo-1-methylbenzene)	589	39.0	8.38
C_7H_8O	*o*-cresol (*o*-methylphenol)	589	16.0	8.93

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Verdet Constants V of Organic Liquids (from Ref. 7)—*continued*

Formula	Name	λ (nm)	T(°C)	V (rad/T m)
C_7H_8O	*m*-cresol (*m*-methylphenol)	589	17.9	8.41
C_7H_8O	*p*-cresol (*p*-methylphenol)	589	17.0	8.46
C_7H_9N	*o*-toluidine (*o*-methylaniline)	589	17.3	11.0
C_7H_9N	*m*-toluidine (*m*-methylaniline)	589	15.0	10.4
C_7H_9N	*p*-toluidine (*p*-methylaniline)	589	50.0	9.80
$C_7H_{14}O$	enanthaldehyde (heptanal)	589	16.2	3.67
$C_7H_{16}O$	1-heptanol (*n*-heptylalcohol)	589	12.6	3.87
$C_7H_{16}O$	2-heptanol (amylmethylcarbinol)	589	20.0	3.84
$C_7H_{16}O$	3-heptanol (butylethylcarbinol)	589	20.0	3.99
$C_7H_7O_2N$	*o*-nitrotoluene	589	18.0	6.28
$C_7H_7O_2N$	*p*-nitrotoluene	589	54.3	5.73
C_8H_{10}	ethylbenzene (phenylethane)	589	15.0	8.14
C_8H_{10}	*o*-xilene (1,2-dimethylbenzene)	589	15.0	7.62
C_8H_{10}	*m*-xilene (1,3-dimethylbenzene)	589	15.0	7.18
C_8H_{10}	*p*-xilene (1,4-dimethylbenzene)	589	15.0	7.16
C_8H_{16}	1-octene (a-octylene)	589	15.0	4.19
C_8H_{16}	2-octene (b-octylene)	589	15.0	4.16
C_8H_{18}	octane	589	15.0	3.67
$C_8H_{18}O$	1-octanol (*n*-octyl alcohol)	589	20.0	3.87
$C_8H_{18}O$	2-octanol (methylhexylcarbinol)	589	20.0	3.90
$C_8H_{18}O$	3-octanol (ethylamylcarbinol)	589	20.0	3.87
C_9H_{12}	*o*-ethyltoluene (1-ethyl-2-ethylbenzene)	589	15.0	6.75
C_9H_{12}	*m*-ethyltoluene (1-ethyl-3-ethylbenzene)	589	15.0	8.46
C_9H_{12}	*p*-ethylbenzene (1-ethyl-4-ethylbenzene)	589	15.0	6.89
C_9H_{12}	mesitylene (1-3-5-trimethylbenzene)	589	15.0	6.63
C_9H_{20}	nonane	589	15.0	3.72
$C_{10}H_8$	naphthalene	589	89.5	13.0
$C_{10}H_{20}$	1-decene (*n*-decylene)	589	21.0	4.22
$C_{10}H_{22}$	decane	589	15.0	3.78
$C_{10}H_7Cl$	1-chloronaphthalene (*a*-chloronaphthalene)	578	18.0	14.3
$C_{10}H_7Br$	1-bromonaphthalene (*a*-bromonaphthalene)	578	20.0	15.1
$C_{10}H_8O$	*b*-naphthol (2-hydroxinaphthalene)	578	13.6	14.0
$C_{10}H_9N$	1-naphthylamine (*a*-naphthylamine)	589	32.6	19.9
$C_{10}H_{12}O_2$	isoeugenol (4-propenylguaiacol)	589	19.3	10.33
$C_{10}H_{12}O_2$	eugenol (4-allylguaiacol)	589	15.4	8.38
$C_{10}H_{12}O_2$	benzoic acid propylester (*n*-propylbenzoate)	589	15.4	6.40
$C_{10}H_{12}O_2$	*o*-toluic acid ethyl ester	589	15.2	6.54
$C_{10}H_{12}O_2$	*p*-toluic acid ethyl ester	589	15.0	6.34
$C_{10}H_{12}O_2$	*a*-toluic acid ethyl ester (ethylphenylacetate)	589	14.0	6.54
$C_{10}H_{12}O_2$	methylsaliciclic acid ethylester	589	18.6	7.27
$C_{10}H_{18}O$	*a*-terpineol	589	16.0	4.54
$C_{10}H_{18}O$	Citronellal	589	14.5	4.39
$C_{10}H_{18}O_4$	dipropylsuccinate	589	11.4	3.55
$C_{10}H_{10}O_6$	tartaric acid dipropyl ester (propyltartrate)	589	15.4	3.61
$C_{10}H_{20}O$	menthol	589	45.2	4.07
$C_{11}H_{24}$	undecane	589	20.5	3.81
$C_{12}H_{26}$	dodecane	589	21.5	3.84

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Verdet Constants V of Organic Liquids (from Ref. 7)—*continued*

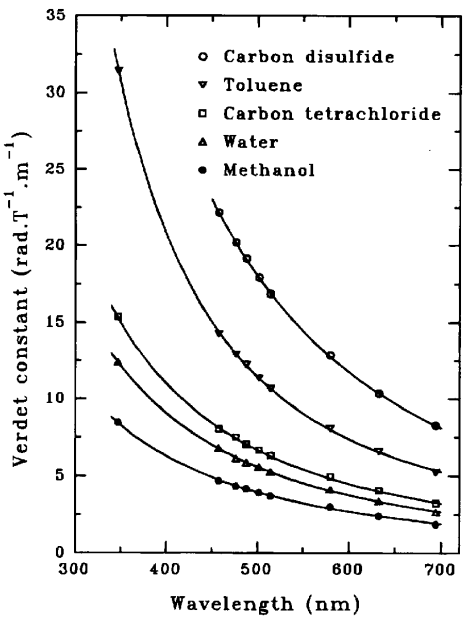
Formula	Name	λ (nm)	T(°C)	V (rad/T m)
$C_{14}H_{10}$	phenanthrene	578	100.0	17.0
$C_{16}H_{34}$	hexadecane	589	15.0	3.93
$C_{18}H_{14}$	1,2-diphenylbenzene	589	15.0	13.7
$C_{18}H_{22}$	1,6-diphenylhexane	589	20.0	8.00

5.6.3 Dispersion of the Verdet Constants

Dispersion of the Verdet Constant V in the Near Ultraviolet and Visible

		V(λ)(rad/T·m), λ(nm)						
Formula	**Name**	**347.1**	**457.9**	**488.0**	**514.5**	**580.0**	**632.8**	**694.3**
CH_3NO_2	nitromethane		4.07	3.58	3.26	2.60	2.15	1.67
CH_4O	methanol	8.46	4.68	4.16	3.69	3.00	2.40	1.88
$C_2H_4O_2$	acetic acid	9.75	5.29	4.65	4.13	3.29	2.71	2.09
C_2H_6O	ethanol	10.5	5.61	4.95	4.45	3.49	2.90	2.30
C_3H_6O	acetone	10.5	5.64	4.95	4.45	3.46	2.84	2.79
H_2O	water	12.4	6.78	5.85	5.24	4.10	3.35	2.66
CCl_4	carbon tetrachloride	15.4	8.03	7.04	6.31	4.95	4.04	3.23
$C_6H_5NO_2$	nitrobenzene		10.7	9.60	8.41	6.66	5.41	4.33
C_7H_8	toluene	31.4	14.3	12.2	10.7	8.09	6.60	5.24
C_6H_6	benzene		16.0	13.6	12.1	9.13	7.39	5.93
CS_2	carbon disulfide		22.2	19.2	16.8	12.9	10.4	8.26

Liquids are listed in increasing order of the Verdet constant.[8]



Dispersion of the Verdet constant for several liquids listed in the table above

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Dispersion of the Verdet Constant V in the Near Infrared[2]

		Vλ) (rad/T·m), λ(μm)				
Formula	**Name**	**0.6**	**0.8**	**1.0**	**1.5**	**2.0**
H_2O	water	3.67	2.04	1.28	(0.844 at 1.25 _m)	
$SnCl_4$	tin tetrachloride	11.9	6.31	3.93	1.75	0.902
$TiCl_4$	titanium tetrachloride	–3.81	–1.45	–0.756	–0.291	–0.145
CCl_4	carbon tetrachloride	4.68	2.59	1.66	0.727	0.378
CS_2	carbon disulfide	11.5	6.23	3.93	1.69	0.902
$CHCl_3$	chloroform	4.51	2.50	1.63	0.698	0.378
CH_3I	methyl iodide	9.25	5.18	3.26	1.40	0.785
CH_2I_2	methylene iodide	13.8	7.80	4.92	2.12	1.16
CH_4O	methyl alcohol	2.71	1.48	0.931	0.553	0.378
C_2H_5I	ethyl iodide	8.12	4.39	2.82	1.19	0.698
C_2H_6O	ethyl alcohol	3.23	1.75	1.11	0.553	0.291
C_3H_6O	acetone	3.00	1.77	1.16	0.495	0.262
$C_4H_{10}O$	ethyl ether	2.97	1.69	1.05	0.465	0.233
$C_4H_{10}O$	*n*-butyl alcohol	3.49	1.95	1.25	0.524	0.407
C_6H_6	benzene	8.17	4.45	2.76	1.13	0.640
$C_6H_5NO_2$	nitrobenzene	6.08	3.32	2.12	0.902	0.524
C_7H_8	toluene	7.50	3.99	2.53	1.02	0.582
C_7H_{16}	*n*-heptane	3.46	1.92	1.25	0.524	0.262
C_8H_{10}	xilene	6.75	3.72	2.33	1.02	0.553
$C_{10}H_7Br$	α-bromonaphthalene	13.4	7.13	4.42	1.83	1.02

Temperature = 23°C.

References:

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5.7 Commercial Optical Liquids

Cargille Refractive Index Liquids are examples of commercially available liquids having a wide range of known property values for optical applications. Specific refractive index and dispersion values are maintained by exacting quality control. These liquids are sold individually or in sets covering certain refractive index ranges at 25ºC and 589.3 nm:

Series AAA	1.300–1.395
Series AA	1.400–1.458
Series A	1.460–1.640
Series B	1.642–1.700
Series M	1.705–1.800
Series H	1.81–2.00
Series EH	2.01–2.11
Series FH	2.12–2.21
Series GH	2.22–2.31

Other Cargille liquids are available with special properties of dispersion, transmittance, compatibility, fluorescence, stability, toxicity, etc. for special applications.

Whereas evaporation of a pure substance will not change the index of refraction, liquids that are mixtures of substances with different indices of refraction and different volatilities change refractive index through evaporation.

Typical optical liquids transmit well in the visible, begin to absorb in the near-UV and are characterized by a series of absorption bands from 800 to 1600 nm. Exceptions to this pattern are Cargille Laser Liquids Code 433 and Code 3421 which do not reach a UV cutoff until below 240 nm and which are highly transparent, without peaks and valleys in the IR out to 2500 nm.

The best optical liquids with refractive index above 1.810 are arsenic based, highly toxic, and corrosive (Cargille Refractive Index Liquids Series H, EH, FH, and GH).

Properties of representative Cargille optical immersion and laser liquids are given in the following three tables. For a discussion of the optical, physical, and chemical properties of liquids, see R. Sacher and W. Sacher, Optical liquids, *Handbook of Laser Science and Technology*, *Suppl. 2, Optical Materials* (CRC Press, Boca Raton, FL, 1995).

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Properties of representative Cargille immersion liquids

Representative liquid			1	2	3	4	5	6	7	8	9	10	11	12
Formula code				S1050				5040			40BN		BNDN	
Refractive index range for code (n_D 25°C)				1.400–1.458				1.459–1.570			1.571–1.656		1.657–1.698	
Refractive	290		1.433	1.461	1.499	–	–	–	–	–	–	–	– –	
index @25°C			67%	73%	82%	0%	0%	0%	0%	0%	0%	0%	0%0%	
and percent	365	l	1.418	1.444	1.478	1.500	1.531	–	–	–	1.711	1.750	1.776	–
transmittance through			98%	98%	99%	17%	1%	0%	0%	0%	1%	50%	12%	0%
1 cm at representative	404.7	h	1.4127	1.4382	1.4719	1.4920	1.5214	1.5625	1.6036	1.6437	1.6832	1.7174	1.7408	1.7690
wavelengths			99%	99%	99%	85%	67%	49%	35%	45%	58%	72%	17%	2%
(nm)	486.1	F	1.4054	1.4306	1.4637	1.4819	1.5086	1.5460	1.5833	1.6170	1.6504	1.6794	1.7001	1.7250
			100%	100%	100%	98%	96%	92%	89%	90%	90%	90%	64%	40%
Calibrated	589.3	D	1.4000	1.4250	1.4580	1.4750	1.5000	1.5350	1.5700	1.6000	1.6300	1.6560	1.6750	1.6980
at n_D 25°C			100%	100%	100%	100%	99%	99%	99%	99%	99%	99%	98%	96%
±0.0005	656.3	C	1.3977	1.4227	1.4557	1.4722	1.4966	1.5307	1.5648	1.5936	1.6224	1.6473	1.6657	1.6881
			100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	99%	99%
	1064.8		1.392	1.417	1.450	1.465	1.488	1.520	1.552	1.578	1.605	1.628	1.645	1.666
			96%	96%	95%	96%	96%	97%	97%	98%	99%	99%	99%	99
	1300		1.390	1.415	1.449	1.464	1.487	1.518	1.550	1.576	1.602	1.624	1.641	1.662
			97%	94%	90%	90%	90%	91%	91%	93%	94%	96%	96%	97%
	1550		1.390	1.415	1.448	1.463	1.486	1.517	1.549	1.574	1.600	1.622	1.639	1.659
			75%	79%	84%	84%	85%	86%	86%	89%	92%	94%	94%	94%
Abbe ν, $(n_D - 1)/(n_F - n_C)$			52	54	57	49	42	35	31	26	22	20	2019	
Temp. Coeff., dn_D/dt (°C)			–.000412	–.000402	–.000388	–.000393	–.000401	–.000411	–.000421	–.000438	–.000454	–.000468	–.000473	–.000479
Viscosity, cSt, @25°C			10	13	17	22	31	50	82	29	10	4	4 4	
Density g/cm^3 @25°C			0.930	0.887	0.831	0.855	0.894	0.948	1.003	1.184	1.359	1.511	1.608	1.722
Thermal exp. cm^3/cm^3/°C			0.0010	0.0009	0.0008	0.0008	0.0008	0.0007	0.0007	0.0006	0.0006	0.0006	0.0006	
Flash point, °C				>138				>138			>113		>93	
Pour point, °C				<–7				<–7			<6		<6	
Boiling point, °C				>200				>262			>279		>279	
Toxicity (request MSDS)				Low				Low			Moderate		Moderate	

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Representative liquid *(cont.)* **1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Compatible (c) and incompatible (i)											
Acrylic	c			c			c			c	
Polycarbonate	na			c			i			na	
Polyethylene	c			c			c			c	
Polypropylene	c			c			c			c	
Polystyrene	c			i			i			i	
Latex rubber	i			i			i			i	
Neoprene rubber	c			i			i			i	
Silicone rubber	i			i (some)			c			c	
Aluminum	c			c			c			c	
Copper	c			c			i			i	
Steel	c			c			c			i	
Color stability in sun	Very high			Moderate			Low to moderate			Low	
Best solvents	ethyl ether, naphtha, xylene, toluene, heptane, methylene chloride, turpentine						Acetone, ethyl ether, naphtha, xylene, methylene chloride, toluene, heptane, turpentine				

na = not available; MSDS=materials specification data sheet.

Table from Sacher, R. and Sacher, W., Optical Liquids, *Handbook of Laser Science and Technology, Supplement 2:Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 97.

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Properties of representative special Cargille optical immersion liquids

Representative liquid			1	2	3	4	5	6	7	8	9	10	11	12
Formula code			4550*	4501	50350*		1160		50BN*		5095		OHGL*	OHZB
Refractive index range for code (n_D 25°C)			1.452–1.457	1.452–1.470	1.458–1.475		1.482–1.538		1.459–1.656		1.458–1.580		1.333–1.470	1.333–1.556
Refractive	290		1.489	–	1.518	–	–	–	–	–	–	–	1.503	–
index @25°C			56%	0%	72%	0%	0%	0%	0%	0%	0%	0%	59%	0%
and percent	365	l	1.471	1.500	1.496	1.512	1.535	1.584	1.673	1.715	1.536	1.647	1.488	1.598
transmittance through			100%	53%	99%	90%	90%	90%	75%	71%	94%	85%	97%	78%
1 cm at representative	404.7	h	1.4655	1.4902	1.4894	1.5024	1.5237	1.5686	1.6481	1.6853	1.5244	1.6243	1.4832	1.5847
wavelengths			100%	96%	100%	95%	95%	95%	80%	76%	98%	95%	98%	91%
(nm)	486.1	F	1.4577	1.4779	1.4809	1.4902	1.5094	1.5501	1.6185	1.6511	1.5097	1.5972	1.4757	1.5679
			100%	100%	100%	99%	99%	99%	93%	92%	100%	100%	100%	97%
Calibrated	589.3	D	1.4520	1.4700	1.4750	1.4820	1.5000	1.5380	1.6000	1.6300	1.5000	1.5800	1.4700	1.5560
at n_D 25°C			100%	100%	100%	100%	100%	100%	99%	99%	100%	100%	100%	99%
±0.0005	656.3	C	1.4497	1.4670	1.4726	1.4788	1.4963	1.5333	1.5931	1.6221	1.4962	1.5735	1.4676	1.5512
			100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	1064.8		1.444	1.460	1.467	1.471	1.487	1.522	1.577	1.604	1.487	1.558	1.461	1.539
			94%	95%	93%	97%	97%	97%	98%	99%	96%	98%	80%	93%
	1300		1.442	1.459	1.466	1.469	1.486	1.520	1.574	1.601	1.485	1.555	1.460	1.537
			88%	85%	87%	92%	93%	94%	94%	95%	92%	95%	58%	60%
	1550		1.442	1.458	1.465	1.468	1.485	1.519	1.573	1.599	1.484	1.554	–	–
			81%	84%	81%	87%	88%	90%	91%	93%	86%	90%	0%	0%
Abbe ν, $(n_D - 1)/(n_F - n_C)$		57	43	58	42	38	32	24	22	37	25	58	33	
Temp. Coeff., dn_D/d_t (°C)			–.000394	–.000488	–.000360	–.000348	–.000349	–.000350	–.000446	–.000458	–.000398	–.000416	–.000377	–.000330
Viscosity, cSt @25°C			11	0.4	112	41	41	41	6	5	14	10	679	9
Density, g/cm^3 @25°C			0.816	0.840	0.867	0.969	1.016	1.115	1.322	1.426	0.881	0.981	1.254	2.498
Thermal Exp., cm^3/cm^3/°C			0.00080.0010	0.0007	0.0007	0.0007	0.0006	0.0007	0.0007	0.0008	0.0007	0.0008	0.0006	
Flash point, °C			>135	>47	>138		>199		>113		>138		>165	None
Pour point, °C			<2	<2	<–7		<–45		<6		<–7		<18	<1
Boiling point, °C			>244	>178	>262		>370		>262		>262		>212	>212
Toxicity (request MSDS)			None	Moderate	None		Low		ModerateModerate			Low	Moderate	

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Representative liquid *(cont.)*	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Compatible (c) and incompatible (i)												
Acrylic	c	na	c		c		c		c		c	c
Polycarbonate	c	na	c		c		i		c		c	na
Polyethylene	c	na	c		c		c		c		c	c
Polypropylene	c	na	c		c		c		c		c	c
Polystyrene	c	na	c		i		i		i		c	c
Latex rubber	i	na	i		c		i		i		c	c
Neoprene rubber	c	na	c		i		i		i		c	c
Silicone rubber	i (some)	na	i (some)		c		c		i (some)		c	c
Aluminum	c	na	c		c		c		c		i	i
Copper	c	na	c		c		c		c		i	i
Steel	c	na	c		c		c		c		i	c
Color stability in sun	Very high	Moderate	Very high		High		Low to moderate		Moderate		na	Moderate
Best solvents	Ethyl ether, naphtha, xylene, methylene chloride toluene, heptane, turpentine				Ethanol, acetone, ethyl, ether, naphtha, xylene methylene chloride, toluene			Ethyl ether, naphtha xylene, methylene chloride toluene, heptane, turpentine			Water, ethanol	Water, ethanol, acetone

*=very low fluorescence 356 nm excitation; na = not available; MSDS = materials specification data sheet.

Table from Sacher, R. and Sacher, W., Optical Liquids, in *Handbook of Laser Science and Technology, Supplement 2:Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 97.

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Properties of representative Cargille laser liquids

Representative liquid			1	2	3	4	5	6		7	8	9	10	11	12
Formula code			433	3421		S1056		5610		5610		1074	1057	5763	
Refractive index range for code (n_D 25°C)			1.295–1.319	1.320–1.400		1.398–1.459		1.460–1.535		1.460–1.535		1.535–1.557	1.558–1.578	1.579–1.630	
Refractive	240		1.31	1.33	1.44	1.45	–	–	290	1.579	1.633	–	–	–	–
index @25°C			34%	11%	22%	8%	0%	0%		42%	34%	0%	0%	0%	0%
and percent	365	l	1.301	1.327	1.414	1.418	1.483	1.507	365 l	1.537	1.579	1.608	1.631	1.663	1.705
transmittance through			100%	100%	100%	98%	95%	95%		93%	92%	80%	80%	15%	2%
1cm at representative	486.1	F	1.2970	1.3222	1.4041	1.4055	1.4631	1.4840	404.7 h	1.5252	1.5639	1.5909	1.6139	1.6416	1.6795
wavelengths			100%	100%	100%	100%	100%	100%		96%	95%	97%	92%	82%	70%
(nm)	589.3	D	1.2950	1.3200	1.4000	1.4000	1.4550	1.4750	486.1 F	1.5102	1.5457	1.5704	1.5923	1.6163	1.6491
			100%	100%	100%	100%	100%	100%		99%	99%	99%	97%	96%	96%
Calibrated	656.3	C	1.2941	1.3190	1.3983	1.3977	1.4518	1.4713	589.3 D	1.5000	1.5340	1.5570	1.5780	1.6000	1.6300
at n_D 25°C			100%	100%	100%	100%	100%	100%		100%	100%	100%	99%	99%	99%
±0.0002	1064.8		1.292	1.316	1.394	1.392	1.444	1.462	656.3 C	1.4960	1.5295	1.5518	1.5724	1.5937	1.6229
			100%	100%	100%	96%	96%	96%		100%	100%	100%	100%	100%	100%
	1300		1.291	1.316	1.393	1.390	1.442	1.460	1064.8	1.486	1.519	1.539	1.559	1.579	1.606
			100%	100%	100%	97%	95%	95%		96%	97%	99%	100%	99%	99%
	1550		1.291	1.315	1.392	1.390	1.441	1.459	1300	1.484	1.517	1.537	1.556	1.576	1.603
			100%	100%	100%	75%	74%	75%		95%	95%	95%	97%	96%	95%
	2500		1.29	1.31	1.39	–	–	–	1550	1.483	1.516	1.535	1.555	1.574	1.602
			89%	90%	95%	0%	0%	0%		77%	80%	84%	83%	87%	92%
Abbe ν: $(n_D - 1)/(n_F - n_C)$		101	100	69	51	40	38		35	33	30	29	27	24	
Temp. Coeff., dn_D/dt (°C)			–.000351	–.000326	–.000346	–.000412	–.000414	–.000407		–.000397	–.000383	–.000414	–.000426	–.000425	–.000423
Viscosity, cSt @25°C			3	30	18	10	22	46		125	484	40	177	454	1734
Density, g/cm^3 @25°C			1.896	1.982	1.903	0.933	0.981	1.011		1.049	1.101	1.062	1.092	1.135	1.196
Thermal Exp., cm^3/cm^3/°C		0.0012	0.0010	0.0009	0.0010	0.0009	0.0008		0.0008	0.0007	0.0007	0.0007	0.0006	0.0006	
Flash point, °C			None	None		>121		>121		>121		>221	>243	>243	
Pour point, °C			<–20	<–20		<–70		<–22		<–22		<–20	<–6	<5	
Boiling point, °C			>174	>215		>149		>149		>149		>288	>288	>476	
Toxicity (request MSDS)			Low	None		Low		None		None		None	None	Low	

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Representative liquid *(cont.)*	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Compatible (c) and incompatible (i)												
Acrylic	c		c	c		c	c		c	c		c
Polycarbonate	na		na	c		c	c		c	c		c
Polyethylene	c		c	c		c	c		c	c		c
Polypropylene	c		c	c		c	c		c	c		c
Polystyrene	c		c	c		c	c		c	c		c
Latex Rubber	c		c	c		c	c		c	c		c
Neoprene Rubber	c		c	c		c	c		c	c		c
Silicone Rubber	c		i (some)	i (some)		i (some)	i (some)		c	c		i (some)
Aluminum	c		i	c		c	c		c	c		c
Copper	c		c	c		c	c		c	c		c
Steel	c		c	c		c	c		c	c		c
Color stability in sun	Very high		Very high	Very high		Very high	Very high		Very high	Very high		Low
Best solvents chloride,	Freon TF and other chlorofluorocarbons; also remove with soap and water			Ethyl ether, naphtha, xylene, methylene Chloride		Acetone, ethyl, ether, naphtha, xylene, methylene chloride			Acetone, ethyl, ether, xylene, methylene toluene, turpentine			

na = not available; MSDS=materials specification data sheet.

Table from Sacher, R. and Sacher, W., Optical Liquids, in *Handbook of Laser Science and Technology, Supplement 2:Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 97.

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Section 6: Gases

6.1 Introduction
6.2 Physical Properties of Selected Gases
6.3 Index of Refraction
6.4 Nonlinear Optical Properties
6.5 Magnetooptic Properties
6.6 Atomic Resonance Filters

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Section 6

GASES

6.1 Introduction

Gases included in this section:

Hydrogen, H_2	Noble gases
Deuterium, D_2	Helium, He
Nitrogen, N_2	Neon, Ne
Oxygen, O_2	Argon, Ar
Carbon monoxide, CO	Krypton, Kr
Carbon dioxide, CO_2	Xenon, Xe
Nitrous oxide, N_2O	
Nitric oxide, NO	
Methane, CH_4	
Ammonia, NH_3	

Composition of Air

Molecular weights and assumed fractional-volume composition of sea-level dry air:

Gas species	Molecular weight (kg/kmol)	Fractional volume (percent)
N_2	28.0134	0.78084
O_2	31.9988	0.209476
Ar	39.948	0.00934
CO_2	44.00995	0.000314
Ne	20.183	0.00001818
He	4.0026	0.00000524
Kr	83.80	0.00000114
Xe	131.30	0.000000087
CH_4	16.04303	0.000002
H_2	2.01594	0.0000005
N_2O	44.0129	0.0000005

From the "U.S. Standard Atmosphere, 1976," National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration and the United States Air Force, 1976. The U.S. Standard Atmosphere, 1976, is an idealized, steady-state representation of the earth's atmosphere from the surface to 1000 km, as it is assumed to exist in a period of moderate solar activity The air is assumed to be dry, and at heights sufficiently below 86 km, the atmosphere is assumed to be homogeneously mixed with a relative-volume composition leading to a mean molecular weight.

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Mean Free Path of Gases

Gas	Pressure 1 mm Hg (293 K)	Pressure 760 mm Hg (273 K)	Gas	Collision frequency (293 K)
Argon	4.73×10^{-5} m	6.30×10^{-8} m	Ammonia	9150×10^{6}
Helium	13.32	17.4	Argon	4000
Hydrogen	8.81	11.1	Carbon monoxide	5100
Krypton	3.63	4.8	Carbon dioxide	6120
Neon	9.4	12.4	Helium	4540
Nitrogen	4.5	5.9	Hydrogen	10060
Oxygen	4.82	6.3	Nitrogen	5070
Xenon	2.62	3.5	Oxygen	4430

6.2 Physical Properties of Selected Gases

Values of all properties in this section are for atmospheric pressure, P = 101.325 kPa.

Physical Properties

Gas	Specific gravity (kg/m^3)	Molecular mass	Mole fraction solubility* in H_2O ($\times 10^5$)
Noble gases			
He	0.17846	4.0026	0.6997
Ne	0.90035	20.180	0.8152
Ar	1.7839	39.948	2.519
Kr	3.745	83.80	4.512
Xe	5.8971	131.29	7.890
Other gases			
H_2	0.08988	2.01588	1.411
D_2	—	4.0282	1.460
O_2	1.42897	31.9988	2.293
CO	1.2504	28.0104	1.774
N_2	1.2506	28.0134	1.183
CO_2	1.97693	44.0098	6.1.5
CH_4	0.5547	16.0428	2.552
NO	1.3402	30.0061	3.477
N_2O	1.977	44.0129	43.67
NH_3	0.7710	17.031	—
air	1.205	28.966	—

* Mole fraction solubility is at 298 K.

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Physical Properties—*continued*

Gas	Ionization potential (eV)	Permittivity ε	Polarizability 10^{-24} cm^3	Dipole moment μ/D	Dielectic strength*
Noble gases					
He	24.5874	1.0000650	—	0	0.15[1]
Ne	21.5645	1.00013	0.3956	0	0.16,[2] 0.25[1]
Ar	15.7596	1.0005172	1.6411	0	0.18[2]
Kr	13.9996	1.00078	2.4844	0	—
Xe	12.1299	1.00126	4.044	0	—
Other gases					
H_2	15.4259	1.0002538	0.8042	0	0.50[1,2]
D_2	15.46	—	0.7954	0	—
O_2	12.07	1.0004947	1.5812	0	0.92[2]
N_2	15.581	1.0005480	1.7403	0	1.00
CO	14.014	1.00262	1.95	0.110	1.02,[1] 1.05[2]
CO_2	13.723	1.000922	2.911	0	0.82,[2] 0.88[1]
CH_4	12.71	1.00081	2.593	0	1.00,[1] 1.13[2]
NO	9.264	1.00060	1.70	0.159	
N_2O	12.886	1.00104	3.03	0.161	1.24[2]
NH_3	10.2	1.00622	2.81	—	—
air	—	1.0005364	—	—	0.97[3]
					3.0 kV/mm[4]
					~0.5 V/mm[5]
					1.4 kV/mm[6]

Values for the permittivity (dielectric constant) and the average electric dipole polarization for ground state molecules are for 293 K.

Debye unit: 1 D = 3.33564 x 10^{-30} C m.

* Relative to nitrogen. The dielectric strength (or breakdown voltage) of a material depends on the specimen thickness, the electrode shape, and the rate of the applied voltage increase. Values are given for standard conditions.

References:

CRC Handbook of Chemistry and Physics, 82nd edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 2001). Gas properties at other temperatures are also given in this reference.

1. Vijh, A. K., *IEEE Trans*. EI-12, 313 (1997).
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Physical Properties—*continued*

Gas	Thermal conductivity κ(W/m K)	Heat capacity at 288 K C_p(J/kg K)	Viscosity at 300 K (μPa)
Noble gases			
He	0.1567*	5192	20.0
Ne	0.0498*	1030	32.1
Ar	0.0179*	519.2	22.9
Kr	0.0095*	247.0	25.6
Xe	0.0055*	158.3	23.2
Other gases			
H_2	0.1869	14277	9.0
D_2		7250	12.6
O_2	0.0263	917	20.8
N_2	0.0260	1043	17.9
CO	0.0250*	1031	17.8
CO_2	0.0166	843.2	15.0
CH_4	0.0341	2226	11.2
NO	0.0259	—	19.2
N_2O	0.0174	—	15.0
NH_3	0.0244	2091	—
air	0.0262	1005	18.6

* Low pressure limiting value. In general values differ by less than 1% at atmosphere pressure.

Reference:
CRC Handbook of Chemistry and Physics, 75th edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 1994). Values of properties at other temperatures are also given in this reference.

Thermal Conductivity at Different Temperatures

Thermal Conductivity (mW/m K)

Gas	100 K	200 K	300 K	400 K	500 K	600 K	Ref.
Noble gases							
He*	75.5	119.3	156.7	190.6	222.3	252.4	1
Ne*	22.3	37.6	49.8	60.3	69.9	78.7	1
Ar*	6.2	12.4	17.9	22.6	26.8	30.6	1,2
Kr*	3.3	6.4	9.5	12.3	14.8	17.1	1
Xe*	2.0	3.6	5.5	7.3	8.9	10.4	1

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Thermal Conductivity (mW/m K)—*continued*

Gas	100 K	200 K	300 K	400 K	500 K	600 K	Ref.
Other gases							
H_2	68.6	131.7	186.9	230.4			3
O_2	9.3	18.4	26.3	33.7	41.0	48.1	4
CO*			25.0	32.3	39.2	45.7	5
N_2	9.8	18.7	26.0	32.3	38.3	44.0	6
CO_2		9.6	16.8	25.1	33.5	41.6	7
CH_4		22.5	34.1	49.1	66.5	84.1	8,9
NO		17.8	25.9	33.1	39.6	46.2	10
N_2O		9.8	17.4	26.0	34.1	41.8	10
air	9.4	18.4	26.2	33.3	39.7	45.7	11

* Low pressure limiting value. In general values differ by less than 1% at atmosphere pressure.

References:

1. Kestin, J. et al., Equilibrium and transport properties of the noble gases and their mixtures at low density, *J. Phys. Chem. Ref. Data* 13, 299 (1984).
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Viscosity

Gas	Viscosity in micropascal seconds (μPa s) 100 K	200 K	300 K	400 K	500 K	600 K	Ref.
Noble gases							
He*	9.7	15.3	20.0	24.4	28.4	32.3	1
Ne*	14.4	24.3	32.1	38.9	45.0	50.8	1
Ar*	8.0	15.9	22.9	28.8	34.2	39.0	1,2
Kr*	8.8	17.1	25.6	33.1	39.8	45.9	1
Xe*	8.3	15.4	23.2	30.7	37.6	44.0	1
Other gases							
H_2*	4.2	6.8	9.0	10.9	12.7	14.4	3
D_2*	5.9	9.6	12.6	15.4	17.9	20.3	4
O_2*	7.5	14.6	20.8	26.1	30.8	35.1	5
CO	6.7	12.9	17.8	22.1	25.8	29.1	6
N_2*		12.9	17.9	22.2	26.1	29.6	5
CO_2		10.0	15.0	19.7	24.0	28.0	7,8
CH_4		7.7	11.2	14.3	17.0	19.4	8
NO		13.8	19.2	23.8	28.0	31.9	6
N_2O		10.0	15.0	19.4	23.6	27.4	6
air		13.3	18.6	23.1	27.1	30.8	9

* Low pressure limiting value. In general values differ by less than 1% at atmosphere pressure.

References:

1. Kestin, J. et al., Equilibrium and transport properties of the noble gases and their mixtures at low density, *J. Phys. Chem. Ref. Data* 13, 299 (1984).
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6.3 Index of Refraction

Index of Refraction n of Helium, He

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
0.092		1.0000485	1
O.1000		1.0000453	1
0.1100		1.0000426	1
0.1200		1.0000407	1
0.1300		1.0000396	1
0.1400		1.0000389	1
0.1500		1.0000383	1
0.1600		1.0000378	1
0.1700		1.0000374	1
0.1800		1.0000373	1
0.1820		1.00003720	3
0.184949		1.00003718	3
0.194232		1.00003690	3
0.213923		1.00003634	3
0.228872		1.00003601	3
0.253728		1.00003549	3
	0.275278	1.00003573	3,4
	0.289360	1.00003562	3,4
	0.292541	1.00003559	3,4
	0.296728	1.00003557	3,4
	0.302150	1.00003553	3,4
	0.312566	1.00003547	3,4
	0.334148	1.00003536	3,4
	0.366328	1.00003523	3,4
	0.390641	1.00003516	3,4
	0.404656	1.00003512	3,4
	0.435835	1.00003505	3,4
	0.479992	1.00003498	5
	0.508582	1.00003494	5
	0.521007	1.00003493	3
0.546226	0.546074	1.00003490	3
0.577120	0.576959	1.00003486	3
0.579227	0.579065	1.00003486	3
0.644025	0.643847	1.00003481	3
	0.742511	1.00003477	5
	0.826452	1.00003474	5
	0.912296	1.00003472	5
	1.013979	1.00003470	5

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Index of Refraction n of Helium, He—*continued*

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
	1.371857	1.00003466	5
	1.529596	1.00003465	5
	2.058128	1.00003464	5

References:

1. Huber, M. C. E. and Tondello, G., Refractive index of He in the region 920 AA, *J. Opt. Soc. Am*. 64, 390 (1974).
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5. Mansfield, C. R. and Peck, E. R., Dispersion of helium, *J. Opt. Soc. Am.* 59, 199 (1969).

Dispersion formula [λ (μm) in vacuum at T = 273 K]	Range (μm)
$n = 1 + 0.01470091\lambda^2/423.98\lambda^2 - 1$	0.48–2.06

Reference: Mansfield, C. R. and Peck, E. R., Dispersion of helium, *J. Opt. Soc. Am.* 59, 199 (1969).

Index of Refraction n of Neon, Ne

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
0.1404		1.00007736	1
0.1525		1.00007520	1
0.1641		1.00007317	1
0.1702		1.00007280	1
0.180731		1.00007221	1
0.184949		1.00007190	1
0.194232		1.00007095	1
0.213923		1.00007017	1
0.228872		1.00006941	1
0.253728		1.00006872	1
	0.289360	1.00006860	2,3
	0.296728	1.00006850	2,3
	0.302150	1.00006843	2,3
	0.313183	1.00006831	2,3
	0.334148	1.00006812	2,3
	0.366328	1.00006788	2,3
	0.390641	1.00006773	2,3
	0.404656	1.00006766	2,3
	0.407781	1.00006765	2,3
	0.435835	1.00006753	2,3
	0.479992	1.00006739	2

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Index of Refraction n of Neon, Ne—*continued*

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
	0.491604	1.00006736	2,3
	0.508582	1.00006731	2
	0.521007	1.00006729	2
0.546226	0.546074	1.00006724	2
0.577120	0.576959	1.00006718	2
0.579227	0.579065	1.00006718	2
0.644025	0.643847	1.00006711	2

References:

1. Bideau-Mehu, A., Guern, R., Abjean, Y., and Johannin-Gilles, A., Measurement of refractive indexes of He, Ar, Kr, and Xe in the 253.7–140.4 nm wavelength range. Dispersion relation and estimated oscillator strength of the resonance lines, *J. Quant. Spectrosc. Radiat. Transfer* 25, 395 (1981).
2. Leonard, P. J., *Atomic Data and Nuclear Data Tables* 14, 21 (1974).
3. Cuthbertson, C. and Cuthbertson, M., *Proc. Roy. Soc. A* 135, 40 (1932).

Dispersion formula [λ (μm) in vacuum at T = 273 K]	Range (μm)
$n = 1 + 0.012055[0.1063\lambda^2/(184.661\lambda^2 - 1) + 182.90\lambda^2/(376.840\lambda^2 - 1)]$	0.14–0.66

Reference: Bideau-Mehu, A., Guern, R. Abjean, Y., and Johannin-Gilles, A., Measurement of refractive indexes of He, Ar, Kr, and Xe in the 253.7–140.4 nm wavelength range. Dispersion relation and estimated oscillator strength of the resonance lines, *J. Quant. Spectrosc. Radiat. Transfer* 25, 395 (1981).

Index of Refraction n of Argon, Ar (vacuum ultraviolet)

$\lambda_{vac}(\mu m)$	n (273 K)	Ref.	$\lambda_{vac}(\mu m)$	n (273 K)	Ref.
0.1110	1.0008025	1	0.1700	1.0003451	1
0.1140	1.0006435	1	0.1702	1.0003446	2
0.1160	1.0005878	1	0.1805	1.0003352	1
0.1180	1.0005492	1	0.180731	1.0003352	2
0.1200	1.0005200	1	0.184949	1.0003315	2
0.1210	1.0005080	1	0.1850	1.0003318	1
0.1216	1.0005016	1	0.1900	1.0003281	1
0.1250	1.0004707	1	0.194232	1.0003256	2
0.1300	1.0004394	1	0.2000	1.0003220	1
0.1350	1.0004166	1	0.2100	1.0003169	1
0.1400	1.0003966	1	0.213923	1.0003150	2
0.1404	1.0003964	2	0.2200	1.0003127	1
0.1500	1.0003749	1	0.228872	1.0003102	2
0.1525	1.0003685	2	0.2300	1.0003091	1
0.1600	1.0003577	1	0.253728	1.0003029	2
0.1641	1.0003514	2			

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Index of Refraction Index n of Argon, Ar (ultraviolet, visible, and near infrared)

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
	0.230209	1.00030922	3
	0.234555	1.00030786	3
	0.237999	1. 00030689	3
	0.244691	1.00030507	3
	0.246407	1.00030463	3
	0.257630	1.00030202	3
	0.267499	1.00030002	3
	0.275278	1.00029865	3
	0.275971	1.00029852	3
	0.289357	1.00029643	3
	0.292541	1.00029599	3
	0.334148	1.00029135	3
	0.380166	1.00028806	3
	0.410807	1.00028285	3
0.467947	0.467816	1.00028434	3,4
0.480126	0.479992	1.00028399	3
		1.00028398	3,4
	0.491604	1.00028368	3
0.508724	0.508582	1.00028325	3,4
		1.00028322	3
	0.521007	1.00028296	3
0.546226	0.546074	1.00028247	3
	0.567717	1.00028209	3
0.577120	0.576959	1.00028190	3
0.579227	0.579065	1.00028190	3
0.644025	0.643847	1.00028103	3
0.703435	0.703241	1.00028045	3,4
0.724716	0.724511	1.00028028	3,4
0.826679	0.826452	1.00027962	3,4
0.912547	0.912296	1.00027923	3,4
0.922703	0 922449	1.00027920	3,4
0.966043	0.965778	1.00027904	3,4
1.014257	1.013979	1.00027890	3,4
1.372233	1.371857	1.00027825	3,4
1.475650	1.475246	1.00027814	3,4
1.529354	1.528936	1.00027810	3,4
1.530015	1.529596	1.00027809	3,4
1.694521	1.694057	1.00027798	3,4
2.058691	2.058128	1.00027782	3,4

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3. Leonard, P. J., *Atomic Data and Nuclear Data Tables* 14, 21 (1974).
4. Peck, E. R. and Fisher, D. J., *J. Opt. Soc. Am.* 54, 1362 (1964).

Temperature variation of the index of refraction of argon at 293 K.

$dn/dT\ (K^{-1}) = -0.897 \times 10^{-6}$ at 546.1 nm

$dn/dT\ (K^{-1}) = -0.894 \times 10^{-6}$ at 632.8 nm

Dispersion formula [λ in vacuum (μm) at T = 273 K]	Range (μm)	Ref.
$n = 1 + 0.012055[0.2075\lambda^2/(91.012\ \lambda^2 - 1) + 0.0415\lambda^2/(87.892\lambda^2 - 1) + 4.3330\lambda^2/(214.02\lambda^2 - 1)]$	0.14–2.1	1
$n = 1 + [67.86711 + 30182.943\lambda^2/(144\lambda^2 - 1)] \times 10^{-6}$	0.47–2.06	2

References:

1. Bideau-Mehu, A., Guern, R., Abjean, Y., and Johannin-Gilles, A., Measurement of refractive indexes of He, Ar, Kr, and Xe in the 253.7–140.4 nm wavelength range. Dispersion relation and estimated oscillator strength of the resonance lines, *J. Quant. Spectrosc. Radiat. Transfer* 25, 395 (1981).
2. Peck, E. R. and Fisher, D. J., *J. Opt. Soc. Am.* 54, 1362-1364 (1964).

Index of Refraction n of Krypton, Kr

λ_{vac}(μm)	λ_{air}(μm)	n (273 K)	Ref.
0.1404		1.0007723	1
0.1525		1.0006548	1
0.1641		1.0005973	1
0.16846		1.0005829	2
0.16991		1.0005780	2
0.17015		1.0005773	2
0.1702		1.0005801	1
0.17044		1.0005767	2
0.17134		I .0005740	2
0.17224		1.0005718	2
0.18169		1.0005483	2
0.18365		1.0005442	2
0.1844		1.0005433	1
0.18455		1.0005425	2
0.18475		1.0005423	2
0.18507		1.0005416	2

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Index of Refraction n of Krypton, Kr—*continued*

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
0.19013		1.0005326	2
0.19832		1.0005197	2
0.19889		1.0005191	2
	0.202551	1.00051493	3,4
0.20588		1.0005101	2
0.2062		1.0005108	1
0.21248		1.0005028	2
0.213923		1.0005023	1
	0.214438	1 00050126	3,4
	0.219463	1.00049664	3,4
0.22116		1.0004950	2
0.22174		1.0004946	2
	0.226502	1.00049089	3,4
0.228872		1.0004890	1
	0.230209	1.00048845	3,5
	0.232928	1.00048617	3,4
	0.234555	1.00048542	3,5
	0.237999	1.00048318	3,5
0.24359		1.0004791	2
	0.244691	1.00047910	3,5
	0.246407	1.00047815	3,5
0.25073		1.0004751	2
0.25151		1.0004747	2
0.25169		1.0004746	2
0.25200		1.0004745	2
0.25249		1.0004742	2
0.25293		1.0004740	2
	0.257309	1.00047221	3,4
	0.257630	1.00047236	3,5
0.26321		1.0004691	2
	0.267499	1.00046804	3,5
	0.274858	1.00046489	3,4
	0.275278	1.00046499	3,5
	0.275971	1.00046471	3,5
	0.283691	1.00046181	3,4
	0.285697	1.00046138	3,5
0.28824		1.0004601	2
	0.289360	1.00046017	3,5
	0.292541	1.00045924	3,5
	0.298063	1.00045739	3,4
	0.334148	1.00044933	3,5

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Index of Refraction n of Krypton, Kr—*continued*

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
	0.340365	1.00044829	3,4
	0.380166	1.00044241	3,5
	0.410807	1.00043909	3,5
	0.441304	1.00043621	3,4
0.480126	0.479992	1.00043391	3,4
	0.491604	1.00043333	3,5
0.508724	0.508582	1.00043245	3,4
0.546226	0.546074	1.00043084	3
	0.567717	1.00043011	3,5
	0.607262	1.00042885	3,5
	0.612327	1.00042873	3,5
	0.623437	1.00042847	3,5

References:

1. Bideau-Mehu, A., Guern, R., Abjean, Y., and Johannin-Gilles, Measurement of refractive indexes of He, Ar, Kr, and Xe in the 253.7–140.4 nm wavelength range. Dispersion relation and estimated oscillator strength of the resonance lines, *J. Quant. Spectrosc. Radiat. Transfer* 25, 395 (1981).
2. Smith, P. L., Parkinson, W. H., and Huber, M. C. E., The refractive index of krypton for 168 nm to 288 nm, *Opt. Commun*. 14, 374 (1975).
3. Leonard, P. J., *Atomic Data and Nuclear Data Tables* 14, 21-37 (1974)..
4. Kronjager, W., *Z. Physik* 98, 17 (1936).
5. Koch, J., *Kungl. Fysiografiska Sällskapets i Lund Förhandlingar* 19, 173 (1949).

Dispersion formula [λ (μm) in vacuum at T = 273 K]	Range (μm)
$n = 1 + 0.012055[0.2104\lambda^2/(65.4742\lambda^2 - 1) + 0.2270\lambda^2/(73.698\lambda^2 - 1) + 5.14975\lambda^2/(181.08\lambda^2 - 1)]$	0.15–0.62

Reference: See reference 1 above.

Index of Refraction n of Xenon, Xe

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
0.1483		1.005091	1
0.1495		1.003210	1
0.1525		1.0020686	1
0.1550		1.0018107	2
0.1600		1.0014614	2
0.1641		1.0013192	1
0.1650		1.0012978	2
0.1700		1.0011934	2
0.1702		1.0011867	1
0.1750		1.0011213	2
0.1800		1.0010678	2
0.180731		1.0010630	1

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Index of Refraction n of Xenon, Xe—*continued*

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
0.184949		1.0010302	1
0.1850		1.0010226	2
0.1900		1.0009917	2
0.194232		1.0009713	1
0.1950		1.0009635	2
0.2000		1.0009398	2
0.2050		1.0009194	2
0.2100		1.0009018	2
0.213923		1.0008941	1
0.2150		1.0008862	2
0.2200		1.0008725	2
0.2250		1.0008603	2
0.228872		1.0008584	1
0.2300		1.0008494	2
	0.230209	1.00085519	3,4
	0.234555	1.00084664	3,4
	0.237999	1.00084025	3,4
	0.244691	1.00082907	3,4
	0.246407	1.00082640	3,4
0.253728		1.0008127	1
	0.257630	1.00081078	3,4
	0.267499	1.00079923	3,4
	0.275278	1.00079124	3,4
	0.275971	1.00079060	3,4
	0.285697	1.00078186	3,4
	0.289360	1.00077885	3,4
	0.292541	1.00077637	3,4
	0.334148	1.00075143	3,4
	0.380166	1.00073430	3,4
	0.410807	1.00072623	3,4
	0.491604	1.00071241	3,4
0.546226	0.546074	1.00070660	3
	0.567717	1.00070477	3,4
	0.607262	1.00070188	3,4
	0.612327	1.00070157	3,4
	0.623437	1.00070091	3,4

1. Bideau-Mehu, A., Guern, R., Abjean, Y., and Johannin-Gilles, A., *J. Quant. Spectrosc. Radiat. Transfer* 25, 395 (1981).
2. Chashchina, G. I. and Shreider, E. Ya., *Opt. Spektrosk.* 27, 161 (1969) English transl.: *Opt. Spectrosc. USSR* 27, 79-80 (1969).
3. Leonard, P. J., *Atomic Data and Nuclear Data Tables* 14, 21-37 (1974).
4. Kronjager, W., *Z. Physik* 98, 17 (1936).

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Dispersion formula [λ (μm) in vacuum at T = 273 K]	Range (μm)
$n = 1 + 0.012055[0.26783\lambda^2/(46.301\lambda^2 - 1) + 0.29481\lambda^2/(50.578\lambda^2 - 1) + 5.0333\lambda^2/(112.74\lambda^2 - 1)]$	0.15–0.62

Reference: Bideau-Mehu, A., Guern, R., Abjean, Y., and Johannin-Gilles, A., Measurement of refractive indexes of He, Ar, Kr, and Xe in the 253.7–140.4 nm wavelength range. Dispersion relation and estimated oscillator strength of the resonance lines, *J. Quant. Spectrosc. Radiat. Transfer* 25, 395 (1981).

Index of Refraction n of Hydrogen, H_2

λ_{air}(μm)	n (273 K)	λ_{air}(μm)	n (273 K)
0.230209	1.0001594	0.334148	1.0001461
0.237832	1.0001577	0.354308	1.0001450
0.244691	1.0001563	0.366328	1.0001443
0.246406	1.0001560	0.390641	1.0001432
0.253652	1.0001547	0.398400	1.0001430
0.257630	1.0001540	0.404656	1.0001427
0.267499	1.0001525	0.407781	1.0001426
0.275278	1.0001515	0.410807	1.0001426
0.275971	1.0001514	0.435835	1.0001418
0.285697	1.0001503	0.486133	1.0001406
0.289360	1.0001499	0.491604	1.0001405
0.292541	1.0001495	0.546074	1.0001397
0.296728	1.0001491	0.579065	1.0001393
0.312567	1.0001477	0.656279	1.0001387
0.313184	1.0001477	0.670784	1.0001385

Reference: Leonard, P. J., *Atomic Data and Nuclear Data Tables* 14, 21 (1974)

Index of Refraction n of Deuterium, D_2

λ_{air}(μm)	n (273 K)	λ_{air}(μm)	n (273 K)
0.230209	1.00015680	0.289357	1.00014756
0.234555	1.00015584	0.292541	1.00014725
0.237999	1.00015510	0.334148	1.00014395
0.244691	1.00015378	0.380166	1.00014160
0.246407	1.00015347	0.410807	1.00014048
0.257630	1.00015158	0.491604	1.00013850
0.267499	1.00015014	0.546074	1.00013766
0.275278	1.00014915	0.576959	1.00013731
0.275971	1.00014906	0.579065	1.00013727

Reference: Leonard, P. J., *Atomic Data and Nuclear Data Tables* 14, 21-37 (1974)

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Index of Refraction n of Nitrogen, N_2 (vacuum ultraviolet, ultraviolet, and visible)

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
0.1641		1.0003748	1
0.1702		1.0003656	1
0.180731		1.0003552	2
0.184949		1.0003495	2
0.194232		1.0003435	2
0.213923		1.0003349	2
0.228872		1.0003299	2
	0.237832	1.0003261	3
	0.244691	1.0003241	3
	0.246406	1.0003236	3
	0.253652	1.0003218	3
0.253728		1.0003217	2
	0.257630	1.0003208	3
	0.267499	1.0003187	3
	0.275278	1.0003172	3
	0.275971	1.0003171	3
	0.285697	1.0003154	3
	0.289360	1 0003148	3
	0.292541	1.0003143	3
	0.296728	1.0003137	3
	0 334148	1.0003094	3
	0.354308	1.0003076	3
	0.390641	1.0003051	3
	0.398400	1.0003047	3
	0.407781	1.0003042	3
	0.410807	1.0003041	3
	0.491604	1.0003011	3
	0.546074	1.0002977	3
0.546226		l.0002911	4

References:

1. Bideau-Mehu, A., Guern, Y., Abjean, R., and Johannin-Gilles, A., Measurement of refractive indexes of gases in the vacuum ultraviolet and revised values for krypton, *Opt. Commun*. 16, 186 (1976).
2. Abjean, R., Mehu, A., and Johannin-Gilles, A., Interferometric measurement of the refractive indices of neon and helium in the ultraviolet, *Comptes Rendus* 271, 411-414 (1970).
3. Leonard, P. J., *Atomic Data and Nuclear Data Tables* 14, 21-37 (1974).
4. Peck, E. R. and Hanna, B. N., *J. Opt. Soc. Am.* 56, 1059-1063 (1966).

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Index of Refraction n of Nitrogen, N_2 (vacuum ultraviolet, ultraviolet, and visible)

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
0.1641		1.0003748	1
0.1702		1.0003656	1
0.180731		1.0003552	2
0.184949		1.0003495	2
0.194232		1.0003435	2
0.213923		1.0003349	2
0.228872		1.0003299	2
	0.237832	1.0003261	3
	0.244691	1.0003241	3
	0.246406	1.0003236	3
	0.253652	1.0003218	3
0.253728		1.0003217	2
	0.257630	1.0003208	3
	0.267499	1.0003187	3
	0.275278	1.0003172	3
	0.275971	1.0003171	3
	0.285697	1.0003154	3
	0.289360	1 0003148	3
	0.292541	1.0003143	3
	0.296728	1.0003137	3
	0.334148	1.0003094	3
	0.354308	1.0003076	3
	0.390641	1.0003051	3
	0.398400	1.0003047	3
	0.407781	1.0003042	3
	0.410807	1.0003041	3
	0.491604	1.0003011	3
	0.546074	1.0002977	3
0.546226		l.0002911	4

References:

1. Bideau-Mehu, A., Guern, Y., Abjean, R., and Johannin-Gilles, A., Measurement of refractive indexes of gases in the vacuum ultraviolet and revised values for krypton, *Opt. Commun*. 16, 186 (1976).
2. Abjean, R., Mehu, A., and Johannin-Gilles, A., Interferometric measurement of the refractive indices of neon and helium in the ultraviolet, *Comptes Rendus* 271, 411 (1970).
3. Leonard, P. J., *Atomic Data and Nuclear Data Tables* 14, 21 (1974).
4. Peck, E. R. and Hanna, B. N., *J. Opt. Soc. Am.* 56, 1059 (1966).

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Index of Refraction n of Nitrogen, N_2
(visible and near infrared)

$\lambda_{vac}(\mu m)$	n (288 K)	$\lambda_{vac}(\mu m)$	n (288 K)
0.467947	1.00028543	0.978719	1.00028000
0.480126	1.00028507	1.014257	1.00027989
0.508724	1.00028433	1.129050	1.00027961
0.546226	1.00028352	1.350788	1.00027926
0.703435	1.00028149	1.372233	1.00027923
0.724716	1.00028130	1.475650	1.00027912
0.826679	1.00028063	1.529354	1.00027907
0.912547	1.00028023	1.694521	1.00027896
0.922703	1.00028019	2.058691	1.00027879
0.966043	1.00028004		

Reference: Peck, E. R. and Hanna, B. N., *J. Opt. Soc. Am.* 56, 1059 (1966).

Temperature variation of index of refraction at 293 K:
dn/dT (K^{-1}) = -0.953×10^{-6} at 546.1 nm
dn/dT (K^{-1}) = -0.949×10^{-6} at 632.8 nm

Dispersion formula [λ (μm) in vacuum at T = 273 K]	Range (_m)
$n = 1 + [68.5520 + 32431.57\lambda^2/144\lambda^2 - 1)]x10^{-6}$	0.47–2.06

Reference: Peck, E. R. and Hanna, B. N., *J. Opt. Soc. Am.* 56, 1059 (1966).

Index of Refraction n of Oxygen, O_2

$\lambda_{air}(\mu m)$	n (273 K)
0.275278	1.0003242
0.289360	1.0002936
0.302150	1.0002912
0.318770	1.0002879
0.388865	1.0002797
0.447148	1.0002763
0.471250	1.0002751
0.501568	1.0002740
0.587562	1.0002718
0.667815	1.0002708

Reference: Abjean, R., Mehu, A., and Johannin-Gilles, A., *Comptes Rendus* 271, 411 (1970).

Temperature variation of the index of refraction of oxygen at 293 K:
dn/dT (K^{-1}) = -0.864×10^{-6} at 546.1 nm
dn/dT (K^{-1}) = $-0.858 \times 10^{--6}$ at 632.8 nm

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Index of Refraction n of Carbon Dioxide, CO_2

$\lambda_{vac}(\mu m)$	n (273 K)	Ref.	$\lambda_{vac}(\mu m)$	n (273 K)	Ref.
0.180731	1.0005513	1	0.410925	1.0004582	2
0.184949	1.0005441	1	0.480126	1.0004534	3
0.194232	1.0005333	1	0.491720	1.0004529	2
0.206230	1.0005207	1	0.508724	1.0004520	3
0.213923	1.0005142	1	0.546223	1.0004505	2
0.228872	1.0005034	1	0.724716	1.0004461	3
0.237910	1.0004973	2	0.744095	1.0004458	3
0.244764	1.0004937	2	0.826679	1.0004446	3
0.246482	1.0004929	2	0.877716	1.0004440	3
0.253728	1.0004895	1	0.893115	1.0004439	3
0.257708	1 0004878	2	0.912547	1.0004437	3
0.267577	1.0004840	2	0.922703	1.0004436	3
0.276058	1.0004811	2	0.966043	1.0004431	3
0.285780	1.0004781	2	1.014257	1.0004427	3
0.296813	1.0004752	2	1.296021	1.0004405	3
0.334242	1.0004674	2	1.372232	1.0004399	3
0.354469	1.0004644	2	1.475650	1.0004392	3
0.368104	1.0004625	2	1.529354	1.0004387	3
0.398507	1.0004593	2	1.694521	1.0004374	3

References:

1. Bideau-Mehu, A., Guern, Y., Abjean, R., and Johannin-Gilles, A., Interferometric determination of the refractive index of CO2 in the ultraviolet region, Opt. Commun. 9, 432 (1973).
2. Leonard, P. J., Atomic Data and Nuclear Data Tables 14, 21 (1974).
3. Old, J. G., Gentili, K. L., and Peck, E. R., Dispersion of carbon dioxide, J. Opt. Soc. Am. 61, 89 (1971).

Temperature variation of the index of refraction of carbon dioxide at 293 K:

$dn/dT\ (K^{-1}) = 1.432 \times 10^{-6}$ at 546.1 nm

$dn/dT\ (K^{-1}) = 1.424 \times 10^{-6}$ at 632.8 nm

Dispersion formula [λ (μm) in vacuum at T = 273 K]	Range (μm)
$n = 1 + 0.012055[0.579925\lambda^2/(166.175\lambda^2 - 1) + 0.12005\lambda^2\ (79.609\lambda^2 - 1)$ $+ 0.0053334\lambda^2/(56.3064\lambda^2 - 1) + 0.0043244\lambda^2/(46.0196\lambda^2 - 1)$ $+ 0.0001218145\lambda^2/(0.0584738\lambda^2 - 1)]$	0.18–1.7

Reference: Bideau-Mehu, A., Guern, Y., Abjean, R., and Johannin-Gilles, A., Interferometric determination of the refractive index of CO_2 in the ultraviolet region, *Opt. Commun.* 9, 432 (1973).

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Index of Refraction n of Methane, CH_4

$\lambda_{air}(\mu m)$	n (273 K)	Reference
0.5290	1.0004478	1
0.5718	1.0004454	1
0.5893	1.000444	2
0.5935	1.0004435	1
0.6375	1.0004411	1
0.6585	1.0004404	1

References:

1. *International Critical Tables of Numerical Data, Physics and Chemistry and Technology*, Vol. VII, Washburn, E. W., Ed., (McGraw-Hill, New York, 1930).
2. Kaye, G. W., and Laby, T. H., *Tables of Physical and Chemical Constants* (Longman Group, London, 1986).

Index of Refraction n of Ammonia, NH_3

$\lambda_{air}(\mu m)$	n (273 K)	Reference
0.47999	1.0003830	1
0.50858	1.0003808	1
0.52091	1.0003800	1
0.54607	1.0003786	1
0.57695	1.0003771	1
0.57905	1.0003770	1
0.5893	1.000376	2
0.64385	1.0003746	1
0.67078	1.0003738	1

References:

1. *International Critical Tables of Numerical Data, Physics and Chemistry and Technology*, Vol. VII, Washburn, E. W., Ed., (McGraw-Hill, New York, 1930).
2. Kaye, G. W., and Laby, T. H., *Tables of Physical and Chemical Constants* (Longman Group, London, 1986).

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Index of Refraction n of Air

λ_{air} (μm)	n (288 K)	$\lambda_{vac}-\lambda_{air}$ (μm)	λ_{air} (μm)	n (288 K)	$\lambda_{vac}-\lambda_{air}$ (μm)
0.200	1.0003256	0.0000651	0.560	1.0002769	0.0001551
0.210	1.0003188	0.0000670	0.570	1.0002768	0.0001578
0.220	1.0003132	0.0000689	0.580	1.0002766	0.0001604
0.230	1.0003086	0.0000710	0.590	1.0002765	0.0001631
0.240	1.0003047	0.0000731	0.600	1.0002763	0.0001658
0.250	1.0003014	0.0000754	0.610	1.0002762	0.0001685
0.260	1.0002986	0.0000776	0.620	1.0002761	0.0001712
0.270	1.0002962	0.0000800	0.630	1.0002760	0.0001739
0.280	1.0002941	0.0000824	0.640	1.0002759	0.0001766
0.290	1.0002923	0.0000848	0.650	1.0002758	0.0001792
0.300	1.0002907	0.0000872	0.660	1.0002757	0.0001819
0.310	1.0002893	0.0000897	0.670	1.0002756	0.0001846
0.320	1.0002880	0.0000922	0.680	1.0002755	0.0001873
0.330	1.0002869	0.0000947	0.690	1.0002754	0.0001900
0.340	1.0002859	0.0000972	0.700	1.0002753	0.0001927
0.350	1.0002850	0.0000998	0.710	1.0002752	0.0001954
0.360	1.0002842	0.0001023	0.720	1.0002751	0.0001981
0.370	1.0002835	0.0001049	0.730	1.0002751	0.0002008
0.380	1.0002829	0.0001075	0.740	1.0002750	0.0002035
0.390	1.0002823	0.0001101	0.750	1.0002749	0.0002062
0.400	1.0002817	0.0001127	0.760	1.0002749	0.0002089
0.410	1.0002812	0.0001153	0.770	1.0002748	0.0002116
0.420	1.0002808	0.0001179	0.780	1.0002748	0.0002143
0.430	1.0002803	0.0001205	0.790	1.0002747	0.0002170
0.440	1.0002799	0.0001232	0.800	1.0002746	0.0002197
0.450	1.0002796	0.0001258	0.810	1.0002746	0.0002224
0.460	1.0002792	0.0001284	0.825	1.0002745	0.0002265
0.470	1.0002789	0.0001311	0.850	1.0002744	0.0002332
0.480	1.0002786	0.0001338	0.875	1.0002743	0.0002400
0.490	1.0002784	0.0001364	0.900	1.0002742	0.0002468
0.500	1.0002781	0.0001391	0.925	1.0002741	0.0002536
0.510	1.0002779	0.0001417	0.950	1.0002740	00002604
0.520	1.0002777	0.0001444	0.975	1.0002740	0.0002671
0.530	1.0002775	0.0001471	1.000	1.0002739	0.0002739
0.540	1.0002773	0.0001497	1.050	1.0002738	0.0002875
0.550	1.0002771	0.0001524	1.100	1.0002737	0.0003011

Reference:

CRC Handbook of Chemistry and Physics, 75th edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 1994).

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6.4 Nonlinear Optical Properties

6.4.1 Nonlinear Refractive Index γ (300 K)

Gas	λ(nm)	γ (10^{-22} m^2/W)	Ref.
Noble gases			
He	694.3	0.014	1
Ne	694.3	0.006	2
Ar	248.4	0.29 ± 0.10	2
	694.3	0.25	1
Other gases			
H_2	694.3	0.21	3
D_2	694.3	0.21	1
O_2	248.4	3.0 ± 0.3	2
	694.3	0.21	1
N_2	248.4	0.76 ± 0.26	2
	694.3	0.21	1
CO_2	248.4	0.32	1
	694.3	1.1	2
CH_4	248.4	1.1 ± 0.4	2
	694.3	0.47	1

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6.4.2 Two-Photon Absorption

Two-Photon Absorption Coefficients

Gas	Excitation duration (ns)	Applied two-photon energy (eV)	Two-photon cross-section 10^{-50} cm^4 s/ phot. mol.	Ref.	Additional information
Anthracene	30	3.57	0.09	1	503 K, 1.7 Torr
Benzene	10	4.92	0.0126	2	30 Torr, Ar buffer
Benzene	10	8.43	0.0016	2	30 Torr, Ar buffer
Benzene	10	8.44	0.00075	2	30 Torr, Ar buffer
Benzene	10	8.53	0.00146	2	30 Torr, Ar buffer
Benzene	10	8.87	0.00001	2	30 Torr, Ar buffer
Perylene	30	3.57	1.2	1	583 K, 0.6 Torr
POPOP	30	3.57	0.05	1	603 K, 1.23 Torr

POPOP : 1,4-di[2-(5-phenyloxazolyl)] benzene.

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6.4.3 Third-Order Nonlinear Optical Coefficients

Gas	Nonlinear optical process	Coefficient C_{jn}^{mic} x 10^{20} m^2 V^{-2}	Wavelength (μm)
Noble gases			
Helium, He	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.00245$	0.6943
	$(-3\omega;\ \omega,\ \omega,\ -\omega)$	$C_{11} = 0.00122$	0.6943
	$(-2\omega;\ 0,\ \omega,\ \omega)$	$C_{22} = 0.0027$	0.6943
Neon, Ne	$(-2\omega;\ 0,\ \omega,\ \omega)$	$C_{22} = 0.00735 \pm 0.00024$	0.6943
	$(-3\omega;\ \omega,\ \omega,\ -\omega)$	$C_{11} = 0.00312 \pm 0.00053$	0.6943
Argon, Ar	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.0217 \pm 10\%$	0.6943
	$(-3\omega;\ \omega,\ \omega,\ -\omega)$	$C_{11} = 0.0875$	0.308
		$C_{11} = 0.0441 \pm 0.007$	0.6943
	$(-2\omega;\ 0,\ \omega,\ \omega)$	$C_{22} = 0.0833 \pm 0.0027$	0.6943
Krypton, Kr	$(-3\omega;\ \omega,\ \omega,\ -\omega)$	$C_{11} = 0.13516 \pm 0.0262$	0.6943
	$(-2\omega;\ 0,\ \omega,\ \omega)$	$C_{22} = 0.2037 \pm 0.0098$	0.6943
Xenon, Xe	$(-2\omega;\ 0,\ \omega,\ \omega)$	$C_{11} = 0.3426 \pm 0.0655$	0.6943
		$C_{22} = 0.5635 \pm 0.0392$	0.6943
Other gases			
Carbon dioxide, CO_2	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.028 \pm 10\%$	
	$(-3\omega;\ \omega,\ \omega,\ -\omega)$	$C_{11} = 0.054 \pm 0.008$	0.6943
Carbon monoxide, CO	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.0252 \pm 10\%$	0.6943
	$(-3\omega;\ \omega,\ \omega,\ -\omega)$	$C_{11} = 1.95$	9.33
Deuterium, D_2	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.0182 \pm 10\%$	0.6943
Ethane, C_2H_8	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.0868 \pm 10\%$	0.6943
Hydrogen, H_2	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.0294 \pm 10\%$	0.6943
	$(-3\omega;\ \omega,\ \omega,\ -\omega)$	$C_{11} = 0.028 \pm 0.0024$	0.6943
Methane, CH_4	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{jn}^{mic} = 0.1925 \pm 0.0161$	0.6943
	$(-2\omega;\ 0,\ \omega,\ \omega)$	$C_{jn}^{mic} = 0.1708 \pm 0.084$	0.6943
	$(-\omega;\ 0,\ 0,+\ \omega)$	$C_{22} = 0.1806 \pm 0.013$	0.6943
	$(-2\omega;\ \omega,\ \omega,0)$	$C_{11} = 0.0413 \pm 10\%$	0.6943
Nitric oxide, NO	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.0588 \pm 10\%$	0.6943
Nitrogen, N_2	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.0189 \pm 10\%$	0.6943
	$(-3\omega;\ \omega,\ \omega,\ -\omega)$	$C_{11} = 0.03745 \pm 0.006$	0.6943
Oxygen, O_2	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.0182 \pm 10\%$	0.6943
Sulfur hexafluoride, SF_6	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.035 \pm 10\%$	0.6943
	$(-3\omega;\ \omega,\ \omega,\ -\omega)$	$C_{11} = 5862$	10.6

Data from a table of S. Singh, Nonlinear optical materials, *Handbook of Laser Science and Technology, Vol. III: Optical Materials, Part 1* (CRC Press, Boca Raton, FL., 1986), p. 60 ff.

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6.4.4 Stimulated Raman Scattering

Stimulated Raman Scattering Transitions in Gases

Substance	Raman frequency shift ν_o (cm^{-1})	Ref.
barium vapor,[a] Ba	IR[b]	11
cesium vapor,[a] Cs	IR[b]	12,13
hydrogen fluoride, HF	FIR[b]	14
potassium vapor,[a] K	IR[b]	13,15
rubidium vapor,[a] Rb	IR[b]	16
para-hydrogen, p-H_2	354	17,18
silane, SiH_4	2186	5
germane, GeH_4	2111	5
sulfur hexafluoride, SF_6	775	5
carbon tetrafluoride, CF_4	980	19
oxygen, O_2	1552	24
nitrogen, N_2	2331	20
potassium vapor, K	2721	21
methane, CH_4	2916	22
deuterium, D_2	2991	22
hydrogen deuteride, HD	3628	23
hydrogen, H_2	4155	22

[a] Stimulated electronic Raman scattering (SERS).

[b] Generally tunable transitions in the infrared (IR) and far infrared (FIR).

The above table is from Milanovich, F. P., Stimulated Raman scattering, *Handbook of Laser Science and Technology, Vol. III: Optical Materials* (CRC Press, Boca Raton, FL, 1986), p. 283.

Raman Gain Parameters of Selected Gases at 298 K

Gas	Mode	ν_o (cm^{-1})	$\Delta\nu_g$ (MHz)[a]	Ref.	gain (cm/GW)	ρ (amagat)	λ_l (nm)	Ref.
H_2	Q(1)	4155	$\frac{309}{\rho} + 52.2\rho$	1	2.5 ± 0.4	20	532	2
					2.64 ± 0.2	60	532	3
					3.5 ± 0.3	20	477	2
					5.7	High density	350	4
					6.6 ± 0.8	20	308	2
	Q(0)		$\frac{257}{\rho} + 76.6\rho$	1	7.00	>20	248	5
	S(1)	587	119ρ	4	1.2	High density	350	4
p-H_2 (81 K)	Q(0)	354	$\frac{76.6}{\rho} + 45.4\rho$	1				
(80 K)	S(1)				0.096 ± .009		10P(20)[b]	6
					0.102 ± .014		10R(20)[b]	6
					0.111 ± .012		9P(20)[b]	6
					0.123 ± .014		9R(20)[b]	6

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Raman Gain Parameters of Selected Gases at 298 K—*continued*

Gas	Mode	ν_o (cm^{-1})	$\Delta\nu_g$ (MHz)[a]	Ref.	gain (cm/GW)	ρ (amagat)	λ_l (nm)	Ref.
D_2	Q(2)	2987	$\frac{101}{\rho}+120\rho$	7,8	0.45 ± 0.05	60 atm	532	3
			66ρ	4	1.9	High density	350	4
					0.47	High density	350	4
D_2	S(2)	414	124ρ	4				4
HD	Q(1)	3628	693ρ	4				
					0.23	High density	350	4
	S(1)	443	760ρ	4	0.098	High density	350	4
CH_4	ν_1	2917	8220 + 384ρ	3	1.26	115	532	3
			9000 (1<ρ<10)	5	0.12ρ		248	5
					1.2			
					0.66			
N_2	Q branch	2327	22.5 (ρ<10)	5	0.3ρ		248	5
	S(6)	60	0.00285 (D)	9	0.0063	>1 torr	400	9
			3570ρ	10	0.0036	>.01	566	10
	S(8)	76	0.00363 (D)	9	0.0073	>1 torr	400	9
			3570ρ	10	0.0046	>.01	565.5	10
	S(10)	92	0.00441 (D)	9	0.0072	>1 torr	400	9
			3570ρ	10	0.0048	>.01	565	10
	S(12)	108	0.00516 (D)	9	0.0061	>1 torr	400	9
			3570ρ	10	0.0043	>.01	564.5	10
O_2	Q branch	1552	54	5	0.012ρ		248	5
SiH_4	Q branch	2186	15 (est)	5	0.19ρ		248	5
GeH_4	ν_1	2111	15 (est)	5	0.27ρ		248	5
CF_4	ν_1	980	21 (est)	5	0.008ρ		248	5
SF_6	ν_1	775	30 (est)	5	0.014ρ		248	5

a ρ is measured in amagats
b CO_2 laser lines.
(D) Doppler

The above table is from Reintjes, J. F., Stimulated Raman and Brillouin scattering, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 334.

Polarization Dependence of Relative Gain

	Pump polarization	Stokes polarization	Relative gain
Rotational scattering, linear molecules	linear	linear parallel	1.0
	linear	linear, perpendicular	0.75
	circular	circular, same sense	0.25
	circular	circular, opposite sense	1.5

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6.4.5 Brillouin Phase Conjugation

Gases Used for Brillouin Phase Conjugation

Gas	Wavelength λ (nm)	Refract. index n	Sound speed v_s (km/s)	Brillouin shift at λ (GHz)	Phonon lifetime τ_p (ns)	Line width $\Delta\nu_b$ (MHz)	Gain g (cm/GW)	Density ρ (g/cm^3)	Ref.
Argon, Ar	1064		0.34		3		4	50[a]	1
Chlorotrifluoromethane, $CClF_3$ (Freon 13)									2
Dichlorodifluoromethane, CCl_2F_2 (Freon 12)	248	1.001	0.15	1.2		960	0.19	1	3[c]
Hexafluoroethane, C_2F_6 (Freon 116)									2
Methane, CH_4	1064		0.46		3		8	150[a]	1
	694					32	18	50	4
	694					22	40		4
	694					20	72	75	4
	694					20	100	105	5,6
Nitrogen, N_2	694				10		5[b]	150[a]	7
	1064		0.36		15	15	4	135	1
	694		0.39				30		4
Sulfur hexafluoride, SF_6	1064		0.14		20		6	20	1
	694				6		8	10	2
	694		0.113			14	35	22	3[c]

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Gases Used for Brillouin Phase Conjugation—*continued*

Gas	Wavelength λ (nm)	Refract. index n	Sound speed v_S (km/s)	Brillouin shift at λ (GHz)	Phonon lifetime τ_p (ns)	Line width $\Delta\nu_b$ (MHz)	Gain g (cm/GW)	Density ρ (g/cm^3)	Ref.
Xenon	1064		0.18		35		47	40[a]	1
	694				6[d]		10	20[a]	2
	694				15		90	80[a]	2
	694		0.149			11	44	39	4
	1315				65			50	8

[a]Density in amagats rather than pressure in atmospheres; [b]This is the transient gain; the authors calculate steady-state gain as 30 cm/GW, and give a pressure dependence as well; [c]Some of the numbers in this row are theoretical calculations; the reference reports energy conversions; [d]Damzen et. al.[2] give the formula $t_B(\text{ns}) = 0.65 l_L^2 p$ (atm).

Table from Pepper, D. M., Minden, M. L., Bruesselbach, H. W., and Klein, M. B., Nonlinear optical phase conjugation materials, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 467.

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6.5 Magnetooptic Properties

Verdet Constant V (degrees/Tesla meter) of Gases at 273 K

	Wavelength (nm)							
	363.5	**400**	**500**	**600**	**700**	**800**	**900**	**987.5**
Noble gases								
He	0.0209	0.0168	0.0106	0.0074	0.0054	0.0041	0.0034	
Ne	0.0388	0.0326	0.0204	0.0137	0.0090	0.0064	0.0052	0.0047
Ar	0.4106	0.3297	0.2055	0.1403	0.1004	0.0768	0.0610	0.0516
Kr	0.8637	0.6820	0.4232	0.2855	0.2040	0.1531	0.1203	0.1004
Xe	2.1112	1.64492	1.0055	0.6684	0.4766	0.3567	0.2812	0.2354
Other gases								
H_2	0.2882	0.2308	0.1425	0.0969	0.0690	0.0531	0.0422	0.0351
D_2	0.2815	0.2221	0.1375	0.0943	0.0679	0.0522	0.0413	0.0344
O_2	0.1948	0.1620	0.1144	0.0886	0.0725	0.0631	0.0568	0.0536
N_2	0.2820	0.2268	0.1407	0.0968	0.0698	0.0527	0.0421	0.0359
CO_2	0.4205	0.3391	0.2104	0.1445	0.1044	0.0789	0.0583	0.0536
CH_4	0.7875	0.6246	0.3861	0.2618	0.1881	0.1433	0.1140	0.0953

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6.6 Atomic Resonance Filters

Atomic resonance filters (ARFs) are a class of filter devices that have very narrow bandwidth (~0.001 nm) and a wide field of view (180°). A cell containing atomic vapor (e.g., Rb, Cs, etc.) is placed between two narrow bandpass filters. The input filter has a peak transmission wavelength corresponding to a strong electron transition in the vapor species. Incoming light is then strongly absorbed, yielding an excited state population which decays, emitting photons of a second wavelength. The bandpass of the output filter corresponds to the emitted wavelength. Use of both ground state (passive operation) and excited state (laser-pumped operation) transitions have been reported for a variety of atomic vapors operating at a variety of wavelengths. A detailed review of the physics of ARFs is given by Gelbwachs.[1]

Atomic Resonance Filters

Atomic	**Wavelength**		**Pump**	
species	**Input**	**Output**	**source**	**Ref.**
Na	1480 nm	489 nm	optical	2
	2340 nm	569 nm	optical	2
	3420 nm	616 nm	optical	2
K	~10.6 μm	497 nm	optical	3
Rb	20,487–776 nm	420 nm	diode laser	1
	459 nm	894 nm	none	4

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Atomic Resonance Filters—*continued*

Atomic species	Wavelength Input	Wavelength Output	Pump source	Ref.
Cs[a]	456 nm	852 nm	none	4
	534 nm	404 nm	diode laser	5
Tl	535 nm	378 nm	photochemical	6
Mg	518 nm	384 nm	Nd:YAG	7
Ca[a]	423 nm	272 nm	diode laser	8

[a] Not experimentally verified.

An alternative atomic resonance filter design is the Faraday anomalous dispersion optical filter (FADOF).[2,3] An atomic vapor cell is placed in a magnetic field between crossed polarizers. The resonant Faraday effect causes polarization rotation at frequencies corresponding to atomic transitions. At other frequencies rotation is negligible. Thus, by proper adjustment of atomic vapor concentration, cell length, and magnetic field strength, ultranarrow-linewidth bandpass filters may be produced. FADOFs do not shift the output wavelength, and no reponse delay occurs. In principle, transmission is near unity at the center of the filter bandpass for linearly polarized incident light.

Atomic Faraday Filter Data

Atomic species	Operating wavelength (nm)	Peak transmission (%)	Bandwidth (GHz)	Rejection ratio	Ref.
K	766, 770	71	1.6		9
Rb	780	63	1.0	10^5	9
Cs	852	82	0.6	10^5	10

The above table is from Cook, L. M., Filter materials, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 115 (with additions).

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Appendices

Appendix I Safe Handling of Optical Materials

Appendix II Abbreviations, Acronyms, Initialisms, and Mineralogical or Common Names of Optical Materials

Appendix III Abbreviations for Methods of Preparing Optical Materials and Thin Films

Appendix IV Fundamental Physical Constants

Appendix V Units and Conversion Factors

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APPENDIX I

Safe Handling of Optical Materials

When using any optical material—solid, liquid, or gas—it is always advisable to consult the Material Safety Data Sheet (MSDS). These informative documents prepared by the manufacturer or importer of a hazardous substance describe the physical and chemical properties of the product, are helpful in understanding potential health and physical hazards, and describe how to respond effectively to exposure situations. They include information such as hazardous ingredients, physical data of the material, fire and explosion hazard data, health hazard data, reactivity data, spill or leak procedures, special protection information, and emergency and first aid procedures.

Hazards associated with optical materials depend on how the material is used. This is particularly important in the case of liquids where properties such as viscosity, toxicity, and system compatibility may need to be considered. Within the refractive index range of 1.45 to 1.55 there are so many possible liquids that one can easily choose one with low toxicity. Outside this range of indices the choices of liquid are fewer, thus some degree of toxicity may be unavoidable and the use of ventilation, fume hoods, protective gloves, eye protection, and other protective devices may be mandatory. When working with optical liquids, it is always a good idea to wear appropriate gloves and eye protection and to work where ventilation is sufficient.

The following tables present information about the suitability of various common glove materials for handling liquids and about the flammability of selected liquids.

Resistance to Liquids of Common Glove Materials

Liquid	Natural rubber	Neoprene	Nitrile	Vinyl
acetic acid, $C_2H_4O_2$	excellent	excellent	excellent	excellent
acetone, C_3H_6O	good	good	good	fair
benzene,[a] C_6H_6	poor	fair	good	fair
carbon disulfide, CS_2	poor	poor	good	fair
carbon tetrachloride,[a] CCl_4	poor	fair	good	fair
cyclohexane, C_6H_{12}	fair	excellent	—	poor
diethyl ether, CH_2Cl_2	fair	good	excellent	poor
dimethylsulfoxide,[b] C_2H_6OS	—	—	—	—
ethylene glycol, $C_2H_6O_2$	good	good	excellent	excellent
glycerine (glycerol), $C_3H_8O_3$	good	good	excellent	excellent
hexane, C_6H_{14}	poor	excellent	—	poor
toluene, C_7H_8	poor	fair	good	fair

a Aromatic and halogenated hydrocarbons will attack all types of natural and synthetic glove materials.

b No data are available on the resistance to methylsulfoxide of natural rubber, neoprene, nitrile rubber, or vinyl materials; the manufacturer recommends the use of butyl rubber gloves.

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Flammability of Selected Liquids

Properties listed in the table below:

Boiling point: at a pressure of 101.325 kPa.

Flash point: minimum temperature at which the vapor pressure of the liquid is sufficient to form an ignitable mixture with air near the surface of the liquid.

Ignition temperature (also called autoignition temperature): minimum temperature required for self-sustained combustion in the absence of an external ignition source.

Both the flash point and the ignition temperature are not intrinsic properties but depend on the test conditions. Observed values may differ by several degrees and large uncertainties should be assumed.

Flammability

Liquid	Boiling point (°C)	Flash point (°C)	Ignition temperature (°C)
acetic acid, $C_2H_4O_2$	117.9	39	463
acetone, C_3H_6O	56	-20	465
benzene, C_6H_6	80.0	-11	498
carbon disulfide, CS_2	46	-30	90
cyclohexane, C_6H_{12}	80.7	-20	245
1,2-dichloroethane, $C_2H_4Cl_2$	83.5	13	413
dicloromethane, CH_2Cl_2	40	—	556
diethyl ether, $C_4H_{10}O$	34.5	-45	180
dimethylsulfoxide, C_2H_6OS	189	95	215
1,4-dioxane, $C_4H_8O_2$	101.5	12	180
ethanol, C_2H_6O	78.2	13	363
ethylene glycol, $C_2H_6O_2$	197.3	111	398
glycerine (glycerol), $C_3H_8O_3$	290	199	370
heptane, C_7H_{16}	98.5	—	204
hexane, C_6H_{14}	68.7	-22	225
methanol, CH_4O	64.6	11	464
methylcyclohexane, C_7H_{14}	100.9		250
nitrobenzene, $C_6H_5NO_2$	210.8	88	482
toluene, C_7H_8	110.6	4	480

Data for the above tables are from the *CRC Handbook of Chemistry and Physics*, 82nd ed., Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 2001), p. 16–13 and 16–16. This reference contains extensive data on the flammability of many additional chemical substances.

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The internet site *www.MSDS-Search.com* provides links to all major online MSDS databases.

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Prudent Practices for Handling Hazardous Chemicals in Laboratories, National Academy Press, Washington, DC (1981).

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APPENDIX II

Abbreviations, Acronyms, Initialisms, and Mineralogical or Common Names of Optical Materials

α-quartz	silicon dioxide (crystal)	SiO_2
αβ-YAG	alphabet YAG	$Y_3Al_5O_{12}:Ho^{3+},Er^{3+},Tm^{3+}$
AANP	2-adamantylamino-5-nitropyridine	
AB5	ammonium pentaborate	$NH_4B_5O_8•4H_2O$
ABS	acrylonitrile, butadiene, styrene terpolymer	$[CH_2CH(CN)]_x$-$[CH_2CHCHCH_2]_y$-$[CH_2CH(C_6H_5)]_z$
acrylic	polymethyl methacrylate	$[CH_2C(CH_3)(COOCH_3)]_n$
ADA	ammonium dihydrogen arsenate	$NH_4H_2AsO_4$
AD*A[a]	deuterated ammonium dihydrogen arsenate	$NH_4(H,D)_2AsO_4$
ADC	allyl diglycol carbonate	$O(CH_2CH_2OCOOCH_2CHCH_2)_2$
ADP	ammonium dihydrogen phosphate	$NH_4H_2PO_4$
AD*P	deuterated ammonium dihydrogen phosphate	$NH_4(H,D)_2PO_4$
AGS	silver gallium silicate	$AgGaS_2$
AGSe	silver gallium sellenide	$AgGaSe_2$
AHC	alkali halide crystal	
alexandrite	Cr-doped chrysoberyl	$BeAl_2O_4:Cr$
ALON	aluminum oxynitride	$5AlN\text{-}9Al_2O_3$
altaite	lead selenide	PbSe
alumina	aluminum oxide	Al_2O_3
AMTIR	amorphous GeAsSe (glass)	GeAsSe
AN	acrylonitrile	$[CH_2CH(CN)]_n$
anatase	titanium dioxide	TiO_2
andalusite	aluminum silicate	Al_2SiO_5
anglesite	lead sulfate	$PbSO_4$
AODCST	alkyl-oxydicyanostyrene	
apatite	calcium phosphate plus fluorine or chlorine	$Ca_5(PO_4)_3(F,OH,Cl)$
APDA	8-(4'-acetylphenyl)-1,4-dioxa-8-azaspiro[4,5]decane	
APO	amorphous polyolefin	$[CH_2CRR']_n$
aragonite	calcium carbonate	$CaCO_3$
ASN	strontium magnesium aluminate	$SrMgAl_{11}O_{19}$
ATCC	allythiourea cadmium chloride	
AZF	alumino-zirco-fluoride (glass)	variable compositions
β"-alumina	beta double-prime alumina	$Na_{1+x}Mg_xAl_{11-x}O_{17}$
BANANAS	barium sodium niobate	$Ba_2NaNb_5O_{15}$

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barite	barium sulfate	$BaSO_4$
BBB	beta barium borate	β-BaB_2O_4
BBcP	2,5-bis(benzylidene) cycloheptanone	
BBO	barium metaborate	BaB_2O_4
BCBF	barium calcium fluoroborate	$BaCaBO_3F$
BCT	barium calcium titanate	$Ba_{0.77}Ca_{0.23}TiO_3$
BEL	lanthanum beryllate	$La_2Be_2O_5$
berlinite	aluminum phosphate	$AlPO_4$
beryl	beryllium aluminum silicate	$Be_3Al_2(SiO_3)_6$
BFAP	barium fluoroapatite	$Ba_5(PO_4)_3F$
BGO	bismuth germanate	$Bi_{12}GeO_{20}$
BGO	bismuth germanium oxide	$Bi_4Ge_3O_{12}$
BIBO	bismuth metaborate	BiB_3O_6
BIG	bismuth substituted iron garnet	$Bi_{3x}Y_{3(1-x)}Fe_5O_{12}$
BIGGSe	barium-indium-gallium-germanium selenide glass	variable compositions
BluB	barium lanthanium borate	$Ba_3La(BO_3)_3$
BMAG	barium magnesium germinate	$Ba_2MgGe_2O_7$
BNB	m-bromonitrobenzene	$Br(C_6H_4NO_2)$
BOV	barium vanadate	$Ba_5(VO_4)_3$
bromellite	beryllium oxide	BeO
bromyrite	silver bromide	AgBr
brookite	titanium dioxide	TiO_2
BSG	borosilicate glass	variable compositions
BSKNN	barium strontium potassium sodium niobate	$Ba_{2-x}Sr_xK_{1-y}Na_yNb_5O_{15}$
BSO	bismuth silicate	$Bi_{12}SiO_{20}$
BST	barium strontium titanate	$Ba_{1-x}Sr_xTiO_3$
BSTN	barium strontium titanium niobate	$Ba_4Sr_2Ti_2Nb_8O_{30}$
BT	barium titanate	$BaTiO_3$
BTO	bismuth titanate	$Bi_{12}TiO_{20}$
BYF	barium yttrium fluoride	BaY_2F_8
BZMA	benzyl methacrylate	$[CH_2C(CH_3)(COOCH_2C_6H_5)]_n$
CAAP	calcium fluoroarsenite	$Ca_{5(}AsO_4)_3F$
CAB	cellulose acetate butyrate	$(C_6H_7O_2)(C_2H_3O_2)_x(C_4H_7O_2)_{y-}(OH)_z$
CaGB	calcium gadolinium borate	$Ca_3Gd_2(BO_3)_4$
calcite	calcium carbonate	$CaCO_3$

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Abbreviations, Acronyms, Initialisms, and Mineralogical or Common Names of Optical Materials—*continued*

CALO	cerium aluminate	$CeAlO_3$
calomel	mercurous chloride	HgCl
CAMGAR	calcium magnesium garnet	$CaY_2Mg_2Ge_3O_{12}$
CAS	calcium aluminum silicate	$Ca_2Al_2SiO_7$
cassiterite	tin oxide	SnO_2
CAT	cadmium triallyd thiource	
CAZGAR	calcium zinc garnet	$CaZn_2Y_2Ge_3O_{12}$
CBN	cubic boron nitride	BN
CBO	cesium triborate	CsB_3O_5
CBS	carbon black suspension	C + liquid
CDA	cesium dihydrogen arsenate	CsH_2AsO_4
CD*A	deuterated cesium dihydrogen arsenate	$Cs(H,D)_2AsO_4$
cerargyrite	silver chloride	AgCl
cerussite	lead carbonate	$PbCO_3$
CGA	cadmium germanium arsenate	$CdGeAs_2$
CGS	calcium gallium silicate	$Ca_2Ga_2SiO_7$
ChG	chalcogendie glass	variable compositions
chrysoberyl	beryllium aluminate	$BeAl_2O_4$
cinnabar	mercury sulfide	HgS
CIS	copper indium diselenide	$CuInSe_2$
CIGS	copper indium gallium diselenide	$CuIn_{1-x}Ga_xSe_2$
CLBO	cesium lithium triborate	$CsLi(BO_3)_3O$
CMP-M	2-cyano-3-(2-methyl phenyl)-propenoic acid methyl ester	
CMT	cadmium mercury telluride	$Cd_{1-x}Hg_xTe$
CNGG	calcium niobate gallium garnet	$Ca_3(NbLiGa)_5O_{12}$
COANP	2-cyclo-octylamino-5-nitropyridine	
colquiriite	lithium calcium aluminum fluoride	$LiCaAlF_6$
corundum	aluminum oxide, alumina	Al_2O_3
cotunnite	lead chloride	$PbCl_2$
CPAP	calcium fluoroapatite	$Ca_5(PO_4)_3F$
CPF	calcium fluoroapatite	$Ca_5(PO_4)_3F$
CR 39	allyl diglycol carbonate	$[O(CH_2CH_2OCOOCH_2CHCH_2)_2]_n$
cristobalite	silica (allotropic form)	SiO_2
cryolite	sodium fluoroaluminate	Na_3AlF_6
CS-FAP	calcium-strontium fluoroapatite	$(Ca,Sr)_5(PO_4)_3F$
CTA	cesium titanyl arsenate	$CsTiOAsO_4$

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Abbreviations, Acronyms, Initialisms, and Mineralogical or Common Names of Optical Materials—*continued*

CTH:YAG	chromium-thulium-holmium doped YAG	$Y_3Al_5O_{12}$:Cr,Tm,Ho
CTP	cesium titano phosphnate	$CsTiOPO_4$
cunyite	calcium germanate	Ca_2GeO_4
CVAP	calcium fluorovandate	$Ca_{5(}VO_4)_3F$
CWO	cadmium tungstate	$CdWO_4$
CYB	calcium yttrium borate	$Ca_3Y_2(BO_3)_4$
CYS	calcium yttrium silicate oxyapatite	$CaY_4(SiO_4)_3O$
CZ	cubic zirconia	ZrO_2
CZT	cadnium zinc telluride	(Cd,Zn)Te
DAN	4-(*N,N*-dimethylamino)-3-nitroacetanilide	
DANS	4-di-methylamino-4'-nitrostilbene	
DAST	dimethylamino-*N*-methyl-4-stilbazolium-tosylate	
DBNMNA	2,6-dibromo-*N*-methyl-4-nitroailne	
DCANP	2-docosylamino-5-nitropyridine	
D-CDA	deuterated cesium dihydrogen arsenate	$Cs(H,D)_2AsO_4$
DCM	4-dicyanomethylene-2-methyl-6-dimethylamino-4'-nitrostyrene	
DCMNA	2-docosyl-2-methyl-4-nitroaniline	
DEANS`	4-di-ethylamino-4'-nitrostilbene	
DEANST	4-(*N,N*-diethylamino)-*b*-nitrostyrene	
diamond	carbon	C
diopside	calcium magnesium silicate	$CaMgSi_2O_6$
D-KB5	deuterated potassium pentaborate	$KB_5O_8•4D_2O$
D-KDA	deuterated potassium dihydrogen arsenate	$K(H,D)_2AsO_4$
D-KDP	deuterated potassium dihydrogen phosphate	$K(H,D)_2PO_4$
D-LAP	deuterated L-arginine phosphate	$[C_6H_{7+x}D_{8-x}N_4O_2]^+•H_2PO_4.H_2O$
DMC	7-dimethylamino-4-methylcoumarin	$C_{14}H_{17}NO_2$
DMNP	3,5-dimethyl-1-(4 nitrophenylpyrzole	
DMSM	trans-4'-dimethylamino-*N*-methyl-4-stilbazolium methyl sulfate	
dolomite	calcium magnesium carbonate	$CaMg(CO_3)_2$
D-RDA	deuterated rubidium dihydrogen arsenate	$Rb(H,D)_2AsO_4$
DTGS	deuterated triglycine sulfate	$[N(H,D)_2CH_2COOH)_3•H_2SO_4$
ECOB	erbium calcium oxyborate	$ErCa_4(BO_3)_3O$
EDDT	ethylene diamine dextrotartrate	$C_6H_{14}N_2O_6$
elpasolite	potassium sodium aluminum fluoride	K_2NaAlF_6

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Abbreviations, Acronyms, Initialisms, and Mineralogical or Common Names of Optical Materials—*continued*

emerald	Cr-doped beryl	$Be_3Al_2Si_6O_{18}$:Cr
eulytite	bismuth silicate	$Bi_4Si_3O_{12}$
EVA	ethylene-vinyl acetate	$[CH_2CH_2]_x$-$[CH_2CH(OCOCH_3)]_v$
EYAB	erbium yttrium aluminum borate	$YAl_3(BO_3)_4$:Er
FAG	fluoroaluminate glass	variable compositions
FAP	calcium fluoroapatite	$Ca_5(PO_4)_3F$
FEP	perfluorinated ethylene propylene	
fluorapatite	calcium phosphate fluoride	$Ca_5(PO_4)_3(F,Cl,OH)$
fluorite	calcium fluoride	CaF_2
forsterite	magnesium silicate	Mg_2SiO_4
fused quartz	silicon dioxide (amorphous)[(b)]	SiO_2
fused silica	silicon dioxide (amorphous)	SiO_2
GAB	gadolinium aluminate borate	$GdAl_3(BO_3)_4$
gahnite	zinc aluminate	$ZnAl_2O_4$
galena	lead sulfide	PbS
garnet	complex family of mineral compositions	$A_3B_2C_3O_{12}$
GASH	quanidinium aluminate sulfate hexahydrate	$(CN_3H_6)Al(SO_4)_2 \cdot 6H_2O$
g-C	graphite	C
gelenite	calcium aluminium silicate	$Ca_2Al_2SiO_7$
GFG	gallium fluoride garnet	$Na_3Ga_2Li_3F_{12}$
GGG	gadolinium gallium garnet	$Gd_3Ga_5O_{12}$
GIGG	gadolinium indium gallium garnet	$Gd_3In_2Ga_3O_{12}$
GLF	gadolinium lithium tetrafluoride	$GdLiF_4$
GLS	generating luminescence stekla (Russian)	laser glass
GLS	gallium lanthanum sulfide (glass)	$\sim 70GaS–30La_2O_3$
GOS	gadolinium oxysulfide	Gd_2O_2S
greenockite	cadmium sulfide	CdS
grossularite	calcium aluminum silicate garnet	$Ca_3Al_2Si_3O_{12}$
GSAG	gadolinium scandium aluminum garnet	$Gd_3Sc_2Al_3O_{12}$
GSGG	gadolinium scandium gallium garnet	$Gd_3(Sc,Ga)_2Ga_3O_{12}$
GSO	gadolinium orthosilicate	Gd_2SiO_5
GVO	gadolimium vanadate	$GdVO_4$
GYAG	gadolimium-yttrium luminum garnet	$(Gd,Y)_3Al_5O_{12}$
halite	sodium chloride	NaCl
HAP	high-average-power (laser) glass	variable compositions
hematite	ferric oxide	Fe_2O_3
HMF	heavy metal fluoride (glass)	variable compositions

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Abbreviations, Acronyms, Initialisms, and Mineralogical or Common Names of Optical Materials—*continued*

HMO	heavy metal oxde (glass)	variable compositions
HPP glass	high-peak-power (laser) glass	variable compositions
hydroxy-apatite	calcium phosphate hydroxide	$Ca_5(PO_4)_3OH$
ilmenite	iron titanate	$FeTiO_3$
iodyrite	silver iodide	β-AgI
Irtran 1	magnesium fluoride (polycrystalline)	MgF_2
Irtran 2	zinc sulfide (polycrystalline)	ZnS
Irtran 3	calcium fluoride (polyscrystalline)	CaF_2
Irtran 4	zinc selenide (polycrystalline)	ZnSe
Irtran 5	magnesium oxide (polycrystalline)	MgO
Irtran 6	cadmium tellurite (polycrystalline)	CdTe
ITO	indium tin oxide	$\sim 0.9In_2O_3–0.1SnO_2$
KABO	potassium aluminum borate	$K_2Al_2B_2O_7$
KAP	potassium acid phthalate	$C_8H_5O_4K$
KB5	potassium pentaborate	$KB_5O_8•4H_2O$
KBBF	potassium beryllium borate fluoride	$KBeBO_3F_2$
KCND	potassium cerium nitrate dihydrate	$K_2Ce(NO_3)_5.H_2O$
KDA	potassium dihydrogen arsenate	KH_2AsO_4
KD*A[a]	deuterated potassium dihydrogen arsenate	$K(H,D)_2AsO_4$
KDP	potassium dihydrogen phosphate	KH_2PO_4
KD*P[a]	deuterated potassium dihydrogen phosphate	$K(H,D)_2PO_4$
KGW	potassium gadolinium tungstate	$KGd(WO_4)_2$
KLGF	potassium lithium gadolinium fluoride	$KLiGdF_5$
KLN	potassium lithium nitrate	$K_3Li_2\text{-}xNb_{5+x}O_{15+2x}$
KLND	potassium lanthanum nitrate dihydrate	$K_2La(NO_3)_5.2H_2O$
KLTN	potassium lithium tantalate niobate	$K_{1-y}Li_yTa_{1-x}Nb_xO_3$
KLYF	potassium lithium yttrium fluoride	$KLiYF_4$
KN	potassium niobate	$KNbO_3$
KNB	potassium niobium borate	$KNbB_2O_6$
KNLF	potassium neodymium lithium fluoride	$K_5NdLi_2F_{10}$
KNSBN	potassium sodium strontium barium niobate	$(K_xNa_{1-x})_{0.4}(Sr_yBa_{1-y})_{0.8}Nb_2O_6$
KRS-5	thallium bromoiodide	$Tl(Br_{1-x},I_x)$
KRS-6	thallium chlorobromide	$Tl(Cl_{1-x},Br_x)$
KRTA	potassium-rubidium titanyl arsenate	$(K,Rb)TiOAsO_4$
KSAG	lutetium scadium aluminum garnet	$Lu_3Cs_2Al_5O_{12}$
KTA	potassium titanyl arsenate	$KTiOAsO_4$

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KTN	potassium tantalate niobate	$KTa_{1-x}Nb_xO_3$
KTP	potassium titanyl phosphate	$KTiOPO_4$
KTP-GTR	potassium titanyl phosphate-greytrack resistant	$KTiOPO_4$
kyanite	aluminum silicate	Al_2SiO_5
KYF	potassium yttrium fluoride	KYF_4
LABO	lanthanum metaborate	LaB_3O_6
LAP	L-arginine phosphate	$[C_6H_{15}N_4O_2]^+ \cdot H_2PO_4^- \cdot H_2O$
LB	Langmuir–Blodgett (film)	various compositions
LBG	lanthanium boron germanium oxide	$LaBGeO_5$
LBO	lithium triborate	LiB_3O_5
LC	liquid crystal	various compositions
Lexan	polycarbonate plastic	$[OCOOC_6H_4C(CH_3)_2C_6H_4]_n$
LFM	lithium formate monohydrate	$LiHCO_2 \cdot H_2O$
LGO	lithium germanate	Li_2GeO_5
LGS	lanthanum gallium silicate	$La_3Ga_5SiO_{14}$
LI	lithium iodate	$LiIO_3$
LiBAF	lithium barium aluminum fluoride	$LiBaAlF_6$
LiCAF	lithium calcium aluminum fluoride	$LiCaAlF_6$
LiChrom	lithium strontium chromium fluoride	$LiSrCrF_6$
LiSAF	lithium strontium aluminum fluoride	$LiSrAlF_6$
LiSGaF	lithium strontium gallium fluoride	$LiSrGaF_6$
litharge	lead oxide	PbO
LLF	Lutetium lithium fluoride	$LuLiF_4$
LLGG	lanthanum lutetium gallium garnet	$(La,Lu)_3(Lu,Ga)_2Ga_3O_{12}$
LMA	lanthanum magnesium hexaluminate	$LaMgAl_{11}O_{19}$
LN	lithium niobate	$LiNbO_3$
LNA	lanthanum neodymium hexaluminate	$LaMgAl_{11}O_{19}$:Nd
LNP	lithium neodymium tetraphosphate	$LiNdP_4O_{12}$
LNPP	lanthum neodymium pentaphosphate	$La_{1-x}Nd_xP_5O_{14}$
LOP	lutetium orthophosphate	$LuPO_4$
LSB	lanthanium scandium borate	$LaSc_3(BO_3)_4$
LSO	lutetium silicon oxide (orthosilicate)	Lu_2SiO_5
LT	lithium tantalate	$LiTaO_3$
LuAG	lutetium aluminum garnet	$Lu_3Al_5O_{12}$
Lucalox	alumina (polycrystalline)	Al_2O_3
magnesite	magnesium carbonate	$MgCO_3$

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magnetite	iron oxide	Fe_3O_4
MAP	methyl-(2,4-dinitrophenyl)-aminopropanoate	$C_{10}H_{12}N_3O_6$
massicot	lead oxide	PbO
MBANP	2-(a-methyl benzylamino)-5-nitropyridine	
MBBF	alkali metal beryllium borate fluoride	$(Na,K)BeBO_3F_2$
MCT	mercury cadmium telluride	HgCdTe
MEH-PPV	poly(2-methoxy-5-(2'-ethyl-hexyloxy)-1,4-phenylene vinylene	
Mg:LN	MgO-doped lithium niobate	$Mg:LiNbO_3$
Mg:SLN	MgO-doped stoichiometric lithium niobate	$Mg:LiNbO_3$
mica	potassium aluminosilicate	$KAl_3Si_3O_{10}.(OH)_2$
MMA	methylmethacrylate	$CH_2C(CH_3)(COOCH_3)$
MMONS	3-methyl-4-methoxy-4'-nitrostilbene	
MNA	2 methyl-4-nitro-aniline	$CH_3NH_2NO_2C_6H_4$
MND	4-methoxy-4'-nitro-diphenyl-diacetylene-	
MNMA	2-methyl-4-nitro-*N*-methylaniline	
MNT	4-methyl-4'-nitrolan	
monazite	rare earth phosphate	$(rare\ earth)PO_4$
MPMMA	modified polymethylmethacrylate	
MSO	magnesium silicate	Mg_2SiO_4
MTTNPH	5-methylthio-thiophenecarboxaldehyde-4-nitrophenyl-hydrazone	
mullite	aluminum silicate	$Al_6Si_2O_{13}$
NAB	neodymium aluminum borate	$NdAl_3(BO_3)_4$
nantokite	copper chloride	CuCl
NAS	methyl methacrylate styrene copolymer	$[CH_2C(CH_3)(COOCH_3)]_x$-$[CH_2CH(C_6H_5)]_y$
NBD-Cl	7-chloro-4'-nitrobenzo-2-oxa-1,3-diazole	
NdPP	neodymium pentaphosphate	NdP_5O_{14}
NGAB	neodymium gadolinium aluminum borate	$Nd_xGd_{1-x}Al_3(BO_3)_4$
NMBA	4-nitro-4'-methyl-benzylidene aniline	
NPP	*N*-4-nitrophenyl-(L,S)-prolinol	
NPP	neodymium pentaphosphate	NdP_5O_{14}
NPPA	*N*-(4-nitro-2-pyridinyl)-phenylalaninol	
NYAB	neodymium yttrium aluminum borate	$Nd_xY_{1-x}Al_3(BO_3)_4$
olivine	magnesium iron silicate	$(Mg,Fe)_2SiO_4$
ORMOSIL	organic modified silicate	SiO_2

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orpiment	arsenic trisulfide	As_2S_3
PAMS	poly(alpha-methylstyrene)	
paratelluride	tellurium oxide	TeO_2
PBDG	poly(g-benzl-D-glutamate)	
PBLG	poly(g-benzl-L-glutamate)	
PBN	lead barium niobate	$Pb_{1-x}Ba_xNb_2O_6$
PBSP	photonic band-gap structure	variable compositions
PBT	polybenzothiazole	$[C_6H_3NSC]_n$
PBZT	poly(p-phenylene benzo bis thiozole)	
PCS	plastic clad silica	
PDA	polydiacetylene	$[C(R)CCC(R)]_n$
PDBT	poly(3,4-dibutoxythiophene	
PDHG	poly(di-*n*-hexylgermane)	
PDHS	poly(di-*n*-hexylsilane)	
PDLC	polymer dispersed liquid crystal	variable compositions
periclase	magnesium oxide	MgO
perovskite	calcium titanate	$CaTiO_3$
PET	pentaery-thritol	$[OCH_2CH_2OOCC_6H_4CO]_n$
PGO	lean germanium oxide	$Pb_5Ge_3O_{11}$
plattnerite	lead oxide	PbO
PLZT	lead lanthanum zirconium titanate	$PbLa(Zr,Ti)O_3$
PMMA	polymethylmethacrylate	
PMPS	poly(methyl phenyl silane)	
PNP	2-(*N*-prolinol)-5-nitropyridine	
POF	plastic optical fiber	variable compositions
poly-4BCMU	polydiacetylene poly-[5,7-dodecadiyn-2,12-diol-bis(*n*-butoxycarbonyl-methyl-urethane]	
POM	3-methyl-4-nitropyridine-1-oxide	NO_2• $CH_3NOC_5H_4$
POMT	poly(3-octyloxy,4-methyl thiophene)	
PSC	porous silicon carbide	SiC
powellite	calcium molybdate	$CaMoO_4$
PPKTP	periodically poled potassium titanyl phosphate	$KTiOPO_4$
PPLN	periodically poled lithium niobate	$LiNbO_3$
PPLT	periodically poled lithium tantalate	$LiTaO_3$
PPNA	poly-*p*-nitroaniline	
PPRTA	periodically poled rubidium titanyl arsenate	$RbTiOAsO_4$
PPV	poly(*p*-phenylene vinylene)	

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Abbreviations, Acronyms, Initialisms, and Mineralogical or Common Names of Optical Materials—*continued*

proustite	silver arsenic sulfide	Ag_3AsS_3
PrPP	praseodymium pentaphosphate	PrP_5O_{14}
PS	polystyrene	$[CH_2CH(C_6H_5)]_n$
PSG	porous silica glass	SiO_2
PSZ	partially stabilized zirconia	ZrO_2: (Mg,Ca,Y)
PT	polythiophene	
PTB	lead tetraborate	PbB_4O_7
PTG	poly(3-hexylthiophene	
PTOPT	poly-[3-(4-octylphenyl)]-2,2'-bithiophene	
PTS	poly-bis-(*p*-toluene sulfonate)-2,4-hexazine -1,6-diole	
PTV	poly(2,5-thienyl vinylene)	
PU	polyurethane	$[OCONHRNHCOOR']_n$
pucherite	bismuth vanadate	$BiVO_4$
PV	polyvinylxylene	$[CH_2CH(CH_2C_6H_4CH_3)]_n$
PVA	polyvinyl alcohol	
PVF_2	polyvinylidene fluoride	
PVP	polyvinyl-pyrrolidimone	
pyrite	iron sulfide	FeS_2
PZT	lead zirconium titanate	$Pb(Zr,Ti)O_3$
QC	quantum crystallite (quantum dot)	
quartz	silicon dioxide (crystal)	SiO_2
RAP	rubidium acid phthalate	$C_8H_5O_4Rb$
RB5	rubidium pentaborate	$RbB_5O_8 \cdot 4H_2O$
RbAP	rubidim acid phthalate	$CO_2HC_6H_4CO_2Rb$
RDA	rubidium dihydrogen arsenate	RbH_2ASO_4
RD*A	deuterated rubidium dihydrogen arsenate	$Rb(H,D)_2AsO_4$
RDP	rubidium dihydrogen phosphate	RbH_2PO_4
RD*P	deuterated rubidium dihydrogen phosphate	$Rb(H,D)_2PO_4$
RGB	rubidium gadolinium bromide	$RbGd_2Br_7$
rochelle salt	sodium potassium tartrate	$NaKC_4H_4O_6 \cdot 4H_2O$
rocksalt	sodium chloride	NaCl
RTA	rubidium titanyl arsenate	$RbTiOAsO_4$
RTP	rubidium titanyl phosphate	$RbTiOPO_4$
ruby	Cr-doped corundum (sapphire)	Al_2O_3:Cr
rutile	titanium dioxide	TiO_2
SAN	styrene acrylonitrile copolymer	$[CH_2CH(C_6H_5)]_x$-$[CH_2CH(CN)]_v$

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Abbreviations, Acronyms, Initialisms, and Mineralogical or Common Names of Optical Materials—*continued*

sapphire	aluminum oxide	Al_2O_3
sapphire	aluminum oxide (gemstone)	Al_2O_3:Ti,Fe
SBA	sodium-β" alumina	$Na_{1+x}Mg_xAl_{11-x}O_{17}$
SBBO	strontium beryllium borate	$Sr_2Be_2B_2O_7$
SBN	strontium barium niobate	$Sr_{1-x}Ba_xNb_2O_6$
SCAB	scandium aluminum beryllate	$ScAlBeO_4$
scheelite	calcium tungstate	$CaWO_4$
SDG	semiconductor-doped glass	variable compositions
sellaite	magnesium fluoride	MGF_2
S–FAP	strontium fluoroapatite	$Sr_5(PO_4)_3F$
SGGM	strontium gadolinium gallium melilite	$SrGdGaO_7$
silica	silicon dioxide	SiO_2
SIMOX	separation by implanation of oxygen (silicon-on-insulator material)	
SLG	strontium lanthanum gallate	$SrLaGa_3O_7$
SMA	polystyrene co-maleic anhydride	$[CH_2CH(C_6H_5)CH(COOCO)CH]_n$
SMMA	polystyrene co-methyl methacrylate	$[CH_2C(CH_3)(COOCH_3)]_x$-$[CH_2CH(C_6H_5)]_y$
SNA	strontium aluminate	$SrAl_{12}O_{19}$
SOAP	calcium silico-oxyapatite	$CaY_4(SiO_4)_3O$
SOI	silicon-on-insulator (material)	
SOS	silicon (Si) epitaxial film on sapphire substrate	Si/Al_2O_3
SPAP	strontium fluoroapatite	$Sr_5(PO_4)_3F$
SPF	strontium fluoroapatite	$Sr_5(PO_4)_3F$
spodumene	lithium aluminum silicate	$LiAlSi_2O_6$
sphalerite	zinc sulfide (cubic)	ZnS
STRAP	strontium fluoroapatite	$Sr_5(PO_4)_3F$
sphalerite	zinc sulfide	ZnS
spinel	magnesium aluminate	$MgAl_2O_4$
spodumene	lithium aluminum silicate	$LiAlSi_2O_6$
SrYBO	strontium yttrium borate	$Sr_3Y(BO_3)_3$
styrene	polystyrene	
STZO	strontium titanate zironate	$\sim 0.8SrTiO_3–0.2ZrO_2$
S-VAP	strontium vanadium fluoroapatite	$Sr_5(VO_4)_3F$
sylvite	potassium chloride	KCl
SYS	strontium yttrium silicate oxyapatite	$SrY_4(SiO_4)_3O$
T-12	barium fluoride-calcium fluoride	BaF_2-CaF_2

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TAS	thallium arsenic selenide	Tl_3AsSe_3
TBPc	tetrakis (tert-butyl) phthalocyanine	
TCDMA	tricyclodecyl co-methacrylate	$[CH_2C(CH_3)(COOC_{10}H_{15})]_n$
TCO	transparent conductive oxide	e.g., ITO
TCNQ	7,7,8,8-tetracyanoquinodimethane	
TEOS	tetraethyl orthosilicate	$(C_2H_5O)_4Si$
TeX	tellurium halide glass	variable composition
TGG	terbium gallium garnet	$Tb_3Ga_5O_{12}$
TGS	triglycine sulfate	$(NH_2CH_2COOH)_3 \cdot H_2SO_4$
TGSe	triglycine selenate	
THAM-P	tris-hydroxylmethylaminomethane-phosphate	
THAM-S	tris-hydroxylmethylaminomethane-sulfate	
TiOPc	titanyl pthalocyanine	
Ti:S	Ti-doped corundum/alumina	Al_2O_3:Ti
Ti sapphire	Ti-doped corundum/alumina	Al_2O_3:Ti
TlAP	thallium acid phthalate	$C_8H_5O_4Tl$
TMOS	tetramethyloxysilane	$Si(OCH_3)_4$
TOC	transparent optical ceramic	various compositions
topaz	aluminum silicate fluoride hydroxide	$Al_2SiO_4(F,OH)_2$
tourmaline	sodiun aluminum borosilicate	$Na_3Al_6Si_6O_{18}(BO_3)_2(OH,F)_4$
TPX	methyl pentene polymer	
tridymite	silicon dioxide	SiO_2
TSCCC	thiosemicarbazide cadmium chloride monohydrate	
tysonite	lanthanum trifluoride	LaF_3
urea	urea crystal	CH_4N_2O
VAC	vinyl acetate	$[CH_2CH(OCOCH_3)]_n$
VB	vinyl benzoate	
villiaumite	sodium fluoride	NaF
VOPc	vanadyl phthalocyanine	
VPAC	vinyl phenyl acetate	$[CH_2CH(OCOC_6H_5)]_n$
VTE LN	vapor-transport-equilibrated lithium niobate	$LiNbO_3$
weberite	sodium magnesium aluminum fluoride	$NaMgAlF_7$
willemite	zinc silicate	$ZnSiO_4$
wollastonite	calcium silicate	$CaSiO_3$
wulfenite	lead molybdate	$PbMoO_4$
wurtzite	zinc sulfide (hexagonal)	ZnS

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Abbreviations, Acronyms, Initialisms, and Mineralogical or Common Names of Optical Materials—*continued*

xenotime	yttrium phosphate	YPO_4
YAB	yttrium aluminum borate	$YAl_3(BO_3)_4$
YAG	yttrium aluminum garnet[c]	$Y_3Al_5O_{12}$
YAlG	yttrium aluminum garnet	$Y_3Al_5O_{12}$
valliaumite	sodium fluoride	NaF
yablonovite	photonic bandgap crystal	variant of the diamond structure
YAlO	yttrium orthoaluminate	$YAlO_3$
YAP	yttrium aluminum perovskite	$YAlO_3$
YAM	yttrium aluminum monoclinic	$Y_4Al_2O_9$
YBF	yttrium barium fluoride	Y_2BaF_8
YGG	yttrium gallium garnet	$Y_3Ga_5O_{12}$
YGO	yttrium gadolinium oxide	$(Y,Gd)_2O_3$
YGOB	yttrium gadolinium borate	$CaY_4(BO_3)_3O$
YIG	yttrium iron garnet	$Y_3Fe_5O_{12}$
YIGG	yttrium indium gallium gadolinium garnet	$Y_3(In,Ga)_2Gd_3O_{12}$
YLF	yttrium lithium fluoride	$YLiF_4$ ($LiYF_4$)
YOP	yttrium orthophosphate	YPO_4
YOS	yttrium orthosilicate	Y_2SiO_5
YSAG	yttrium scandium aluminum garnet	$Y_3Sc_2Al_3O_{12}$
YSB	yttrium scandium borate	$YSc_3(BO_3)_4$
YSGG	yttrium scandium gallium garnet	$Y_3Sc_2Ga_3O_{12}$
YSO	yttrium silicon oxide (orthosilicate)	Y_2SiO_5
YSZ	yttria stabilized zirconia	ZrO_2:Y_2O_3
yttralox	yttrium oxide (polycrystalline)	Y_2O_3
Zerodur	glass ceramic	SiO_2–Al_2O_3+ . . .
zinc blende	zinc sulfide (cubic)	ZnS
zincite	zinc oxide	ZnO
ZTS	zinc tris(thiourea) sulfate	$Zn[CS(NH_2)_2]_3SO_4$
zircon	zirconium silicate	$ZrSiO_4$
zirconia	zirconium dioxide	ZrO_2

(a) When crystals are grown in heavy water (D_2O) solution, hydrogen is replaced in part or totally by deuterium. Such crystals are designated by a prefix d- or D-, or by an asterisk, e.g., d-CDA and CD*A.

(b) Produced from natural quartz.

(c) Nd-doped YAG lasers are frequently simply called YAG lasers.

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APPENDIX III

Abbreviations for Methods of Preparing Optical Materials and Thin Films

ACR	—	accelerated crucible rotation (flux growth)
ACRT	—	accelerated crucible rotation technique
ALE	—	atomic layer epitaxy
ALL MBE	—	atomic layer-by-layer molecular beam epitaxy
APCVD	—	accelerated plasma chemical vapor deposition
APD	—	accelerated plasma deposition
APE	—	annealed proton exchange
ARE	—	activated reactive evaporation
BARE	—	biased activated reactive evaporation
BE	—	bond and etch (waveguide structure)
Br	—	Bridgman (growth)
CAIBE	—	chemically-assisted ion beam epitaxy
CAMBE	—	chemically-assisted molecular beam epitaxy
CBE	—	chemical beam epitaxy
CLD	—	chemical liquid deposition
CVD	—	chemical vapor deposition
CVT	—	chemical vapor transport
Cz	—	Czochralski (growth)
DIBD	—	dual ion beam deposition
DIBS	—	dual ion beam sputtering
DMILC	—	double-metal-induced lateral crystallization
DWB	—	direct wafer bonding (waveguide structure)
ED	—	electrodeposition
EDFF	—	edge-defined film-fed (growth)
EFG	—	edge-defined film-fed growth
FHD	—	flame hydrolysis deposition
FIB	—	focused ion beam (sputtering)
FICZ	—	flat interface Czochralski (growth)
FZ	—	float zone
GD	—	glow discharge
GILD	—	gas immersion laser doping
GS-MBE	—	gas-source molecular beam epitaxy
HBr	—	horizontal Bridgman (growth)
HCD	—	hollow cathode discharge deposition
HEM	—	heat exchange method
HGF	—	horizontal gradient freeze
HIP	—	hot isostatic pressing
HPBr	—	high-pressure Bridgman (growth)
HPVB	—	high-pressure vertical Bridgman

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Abbreviations for Methods of Preparing Optical Materials and Thin Films—*continued*

HTS	—	high temperature solution
HTSG	—	high temperature solution growth
HVPE		hydride vapor-phase epitaxy
IAD	—	ion assisted deposition
IAD	—	ion beam assisted deposition
IBD	—	ion beam deposition
IBE	—	ion beam etching
IBED	—	ion beam enhanced deposition
IBS	—	ion beam sputtering
ICB	—	ion cluster beam
ICBD	—	ionized cluster beam deposition
ISZ-THM	—	increasing solution zone travelling heater method
IVD	—	inside vapor deposition
IVDO	—	inside vapor deposition oxidation
JVD	—	jet vapor deposition
LAD	—	laser aerosol deposition
LAD	—	laser-assisted deposition
LB	—	Langmuir-Blodgett (film technique)
LBD	—	Langmuir-Blodgett deposition
LCVD	—	laser-induced chemical vapor deposition
LEC	—	liquid-encapsulated Czochralski (growth)
LECVD	—	liquid-encapsulated chemical vapor deposition
LEVGF	—	liquid-encapsulated vertical gradient freeze
LHPG	—	laser heated pedestal growth
LPCVD	—	liquid-phase chemical vapor deposition
LPCVD	—	low-pressure chemical vapor deposition
LPE	—	liquid phase epitaxy
LP-MOVPE	—	low-pressure metal-organic vapor-phase epitaxy
LTE	—	local thermal equilibrium
LTGCz	—	low-thermal gradient Czochralski (growth)
LT-MBE	—	low-temperature molecular beam epitaxy
LVRIP	—	low-voltage reactive ion plating
MBD	—	molecular beam deposition
MBE	—	molecular beam epitaxy
MCVD	—	modified chemical vapor deposition
MIC	—	metal-induced crystallization
MILC	—	metal-induced lateral crystallization
MOCVD	—	metal-organic chemical vapor deposition
MOMBE	—	metal-organic molecular beam epitaxy
MOVD	—	modified vapor deposition
MOVPE	—	metal-organic vapor-phase epitaxy

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Abbreviations for Methods of Preparing Optical Materials and Thin Films—*continued*

MPD	—	microwave plasma deposition
NSP	—	neutral solution processing
OMCVD	—	organometallic chemical vapor deposition
OMMBE	—	organometallic molecular beam epitaxy
OMVPE	—	organometallic vapor-phase epitaxy
OVD	—	outside vapor deposition
OVPO	—	outside vapor phase
PCVD	—	plasma chemical vapor deposition
PACVD	—	plasma-assisted chemical vapor deposition
PAE	—	plasma assisted epitaxy
PCVD	—	plasma chemical vapor deposition
PE	—	plasma etching
PECVD	—	plasma-enhanced chemical vapor deposition
PIBD	—	primary ion beam deposition
PICVD	—	plasma ionization chemical vapor deposition
PLD	—	physical liquid deposition
PLD	—	pulsed laser deposition
PVD	—	physical vapor deposition
PVT	—	physical vapor transport
RAP	—	reactive atmosphere processing
RE	—	reactive evaporation
RIBE	—	reactive ion beam etching
RICBD	—	reactive ionized cluster beam deposition
RIE	—	reactive ion etching
RS	—	reactive sputtering
SAM	—	self-assembled monolayer
SIBD	—	secondary ion beam deposition
SOL GEL	—	solution gelation (processing)
SPCVD	—	surface-plasma chemical vapor deposition
SPE	—	solid phase epitaxy
SPVT	—	seeded physical vapor transport
SSE	—	solid-state epitaxy
SSMOCVD	—	solid source metal-organic chemical vapor deposition
SSVG	—	self-selected vapor growth
St	—	Stockbarger (growth)
TGZM	—	temperature-gradient zone melting
THM	—	travelling heater method
TNFC	—	top nucleated floating crstal (growth)
TSFZ	—	travelling solvent float zone
TSM	—	travelling solvent method
TSSG	—	top-seeded solution growth

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Abbreviations for Methods of Preparing Optical Materials and Thin Films—*continued*

UHV-CVD	—	ultra-high-vacuum chemical vapor deposition
VAD	—	vapor-phase axial deposition
VBr	—	vertical Bridgman (growth)
VD	—	vacuum deposition
VGD	—	vapor gel deposition
VGF	—	vertical gradient freeze
VLPC	—	very-low-pressure chemical
VD	—	vapor deposition
VLS	—	vapor-liquid-solid
VMS	—	vapor melt solid
VPE	—	vapor-phase epitaxy
VPG	—	vapor-phase growth
VPO	—	vapor-phase oxidation
VT	—	vapor transport
VTE	—	vapor transport equilibrated
ZM	—	zone rnelted
ZMR	—	zone melting recrystallization

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APPENDIX IV

Fundamental Physical Constants

Quantity	Symbol	Value
speed of light in vacuum	c	299 792 458 m/s
permeability of vacuum, $4\pi \times 10^{-7}$	μ_0	$1.256\ 637\ 061\ 4 \times 10^{-6}$ N/A^2
permittivity of vacuum, $1/\mu_0 c^2$	ε_0	$8.854\ 187\ 817 \times 10^{-12}$ F/m
Planck constant	h	$6.626\ 075\ 5 \times 10^{-34}$ J s
elementary charge	e	$1.602\ 177\ 33 \times 10^{-19}$ C
magnetic flux quantum, $h/2e$	Φ_0	$2.067\ 834\ 61 \times 10^{-15}$ Wb
electron mass	m_e	$9.109\ 389\ 7 \times 10^{-31}$ kg
proton mass	m_p	$1.672\ 623\ 1 \times 10^{-27}$ kg
fine structure constant, $\mu_0 c e^2/2h$	α	$7.297\ 353\ 08 \times 10^{-3}$
inverse fine-structure constant	$1/\alpha$	137.035 989 5
Rydberg constant, $m_e c\alpha^2/2h$	R_y, R_∞	10 973 731.534 m^{-1}
Bohr radius, $\alpha/4\pi R_\infty$	a_0	$0.529\ 177\ 249 \times 10^{-10}$ m
Hartree energy, $e^2/4\pi\varepsilon_0 a_0 = 2R_\infty hc$	E_h	$4.359\ 748\ 2 \times 10^{-18}$ J
in eV, E_h/e		27.211 396 1 eV
Compton wavelength, $h/m_e c$	λ_C	$2.426\ 310\ 58 \times 10^{-12}$ m
classical electron radius, $\alpha^2 a_0$	r_e	$2.817\ 940\ 92 \times 10^{-15}$ m
Bohr magneton, $eh/4\pi m_e$	μ_B	$9.274\ 015\ 4 \times 10^{-24}$ J/T
nuclear magneton, $eh/4\pi m_p$	μ_N	$5.050\ 786\ 6 \times 10^{-27}$ J/T
electron magnetic moment	μ_e	$9.284\ 770\ 1 \times 10^{-24}$ J/T
magnetic moment anomaly, $\mu_e/\mu_B - 1$	a_e	$1.159\ 653\ 193 \times 10^{-3}$
electron g factor, $2(1 + a_e)$	g_e	2.002 319 304 386
proton gyromagnetic ratio	γ_p	$2.675\ 221\ 28 \times 10^{8}$ s^{-1}T^{-1}
Avogadro constant	N_A	$6.022\ 136\ 7 \times 10^{23}$ mol^{-1}
Boltzmann constant, R/N_A	k	$1.380\ 658 \times 10^{-23}$ J/K
Faraday constant, $N_A e$	F	96 485.309 C/mol
molar gas constant	R	8.314 510 J/mol K
Stefan-Boltzmann constant	s	$5.670\ 51 \times 10^{-8}$ W/m^2 K^4

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Cohen, E. R., and Taylor, B. N., The 1986 adjustment of the fundamental physical constants, *Rev. Mod. Phys.* 59, 1121 (1987).

Taylor, B. N., and Cohen, E. R., Recommended values of the fundamental physical constants: a status report, *J. Res. Natl. Inst. Stand. Technol.* 95, 497 (1990).

For updated values see NIST Web site: physics.nist.gov/constants.

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APPENDIX V

Units and Conversion Factors

Energy E(eV)

Multiply E(eV) by 1.6022×10^{-19} to convert to E(J)
Multiply E(eV) by 8065.5 to convert to E(cm^{-1})

Photon energy (eV) = $1.2398/\lambda_{vacuum}(\mu m)$

Linear absorption coefficient α (cm^{-1}) = $(4\pi n \times 10^4/\lambda)k$, where n is the index of refraction of the material, the wavelength λ is in microns (μm), and k is the complex index of refraction.

Two-photon absorption coefficient β (m/W)

β (m/W) = $(N/E)\sigma^2$, where N is the number density of molecules per cm^3, E is the photon energy (J), σ^2 is the two-photon absorption cross section (cm^4 s/molecule).
Multiply β (m/W) by 10^{-9} to convert to the CGS system (cal/cm s/erg)

Nonlinear index of refraction γ (m^2/W)

Multiply γ (m^2/W) by $2.386 \times 10^6 n$ to convert to the esu system, where n is the index of refraction of the material.
n_2[cm^3/erg] = $238.7n\ \gamma$[cm^2/W]

Linear electrooptic coefficient r (m/V)

Multiply r (m/V) by 2.9979×10^4 to convert to the CGS system (cm/statvolt)

Kerr constant B (10^{-16}m V^2)

Multiply B (10^{-16}m V^2) by 8.988×10^6 to convert to the CGS system ($cm/statvolt^2$)

Verdet constant V (rad/T m)

Multiply V (rad/T m) by 3.438×10^{-3} to convert to the CGS system (min/Oe cm)

Temperature T(K)

Temperature T(˚C) = T(K) – 273.15

Specific heat capacity c_p (J/kg K)

Multiply c_p (J/kg K) by 2.388×10^{-4} to convert to the CGS system (cal/g K)

Thermal conductivity κ (W/m K)

Multiply κ (W/m K) by 2.388×10^{-3} to convert to the CGS system (cal/cm s K)

Hardness (Knoop or Vickers)

1 kgf/mm^2 = 9.8066 N/mm^2

Pressure, mechanical stress (Pa)

1 Pa = 1 N/m^2 = 1 kg/m s^2
10^5 Pa = 1 bar
1 psi = 6.9 x 10^3 Pa

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