Section 2: Glasses

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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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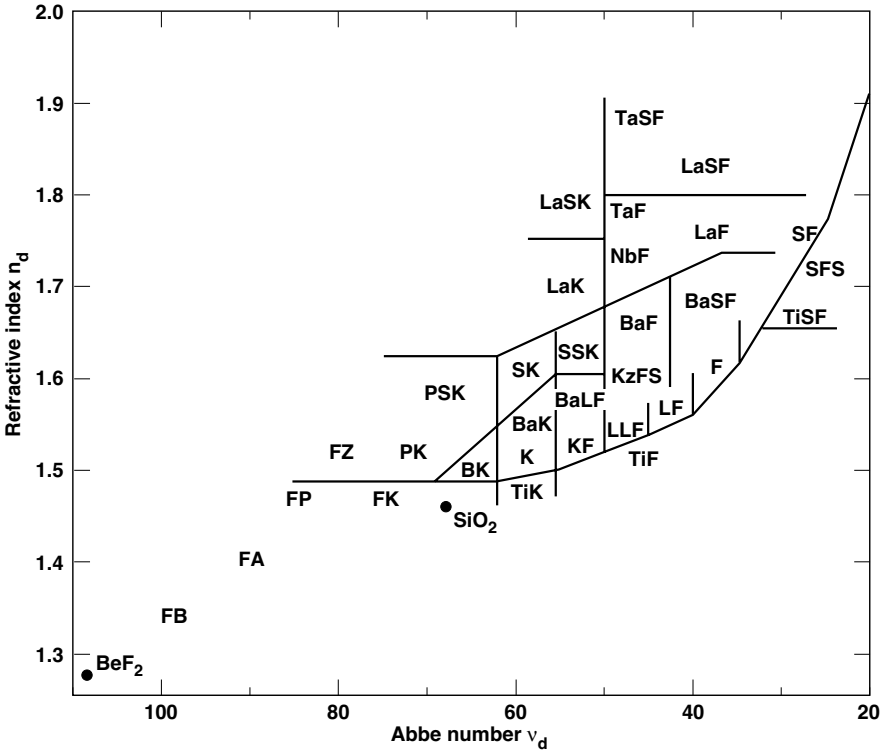

Figure 2.1.1 Glass map of the optical glass compositions in Table 2.1.1.

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.

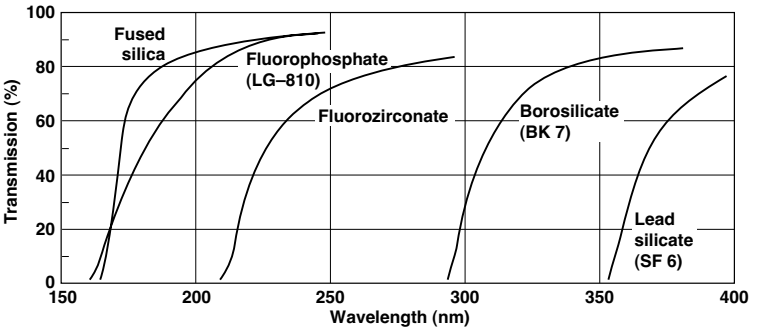

Figure 2.1.2. Ultraviolet absorption edge of representative optical glasses. Sample thicknesses: 5 mm except for SiO_2 and LG 810 which are 2 mm.

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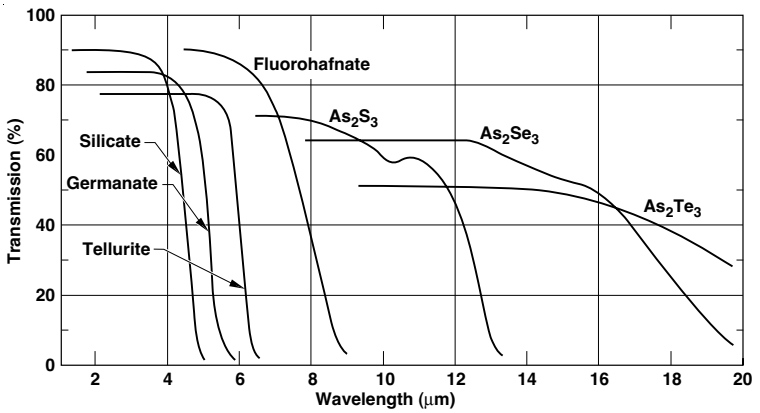

Figure 2.1.3. Infrared absorption edge of representative optical glasses. Sample thicknesses: 2 mm.

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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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

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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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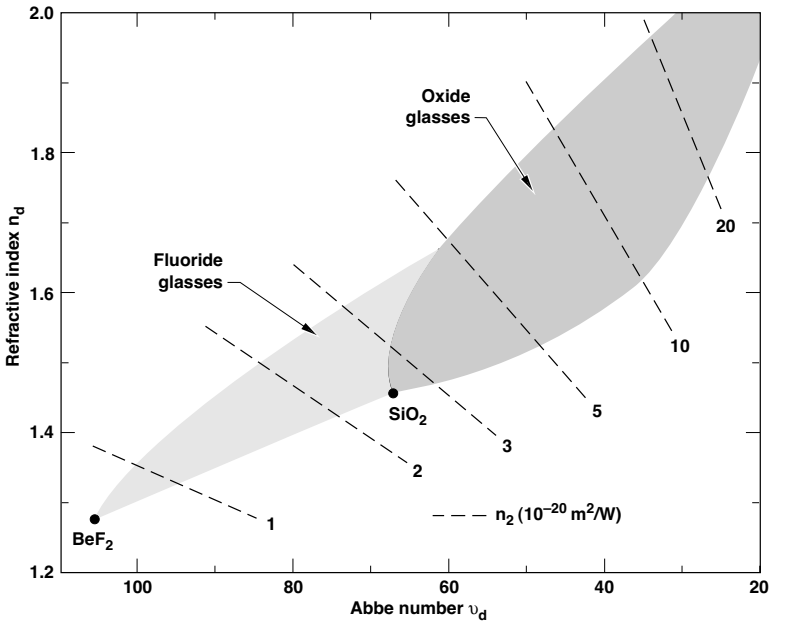
Techniques for Measuring the Nonlinear Refractive Index

	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

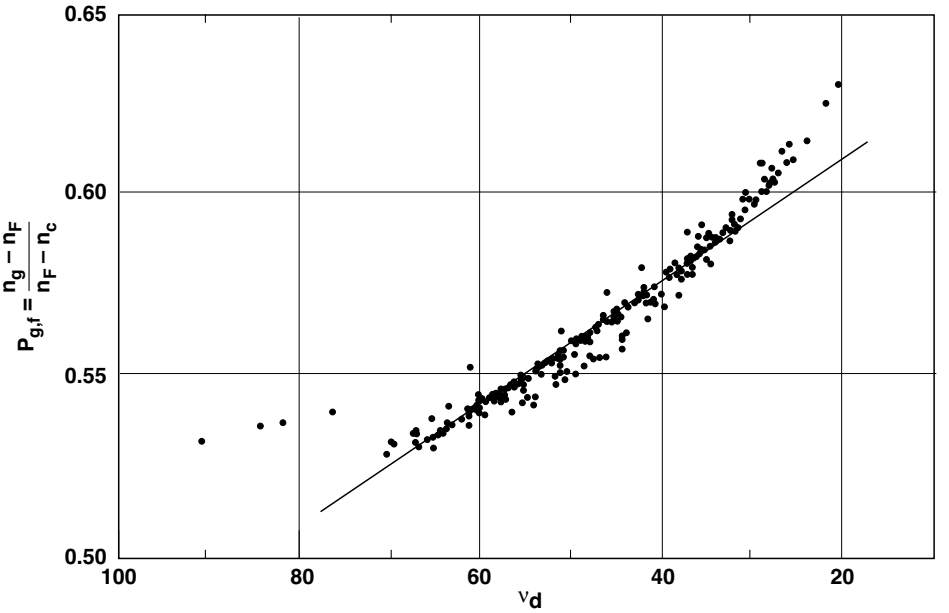
$$P_{x,y} = (n_x - n_y)/(n_F - n_C)$$

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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