Section 6: Gases

6.1 Introduction
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Section 6

GASES

6.1 Introduction

Gases included in this section:

Hydrogen, H_2	Noble gases
Deuterium, D_2	Helium, He
Nitrogen, N_2	Neon, Ne
Oxygen, O_2	Argon, Ar
Carbon monoxide, CO	Krypton, Kr
Carbon dioxide, CO_2	Xenon, Xe
Nitrous oxide, N_2O	
Nitric oxide, NO	
Methane, CH_4	
Ammonia, NH_3	

Composition of Air

Molecular weights and assumed fractional-volume composition of sea-level dry air:

Gas species	Molecular weight (kg/kmol)	Fractional volume (percent)
N_2	28.0134	0.78084
O_2	31.9988	0.209476
Ar	39.948	0.00934
CO_2	44.00995	0.000314
Ne	20.183	0.00001818
He	4.0026	0.00000524
Kr	83.80	0.00000114
Xe	131.30	0.000000087
CH_4	16.04303	0.000002
H_2	2.01594	0.0000005
N_2O	44.0129	0.0000005

From the "U.S. Standard Atmosphere, 1976," National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration and the United States Air Force, 1976. The U.S. Standard Atmosphere, 1976, is an idealized, steady-state representation of the earth's atmosphere from the surface to 1000 km, as it is assumed to exist in a period of moderate solar activity The air is assumed to be dry, and at heights sufficiently below 86 km, the atmosphere is assumed to be homogeneously mixed with a relative-volume composition leading to a mean molecular weight.

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Mean Free Path of Gases

Gas	Pressure 1 mm Hg (293 K)	Pressure 760 mm Hg (273 K)	Gas	Collision frequency (293 K)
Argon	4.73×10^{-5} m	6.30×10^{-8} m	Ammonia	9150×10^{6}
Helium	13.32	17.4	Argon	4000
Hydrogen	8.81	11.1	Carbon monoxide	5100
Krypton	3.63	4.8	Carbon dioxide	6120
Neon	9.4	12.4	Helium	4540
Nitrogen	4.5	5.9	Hydrogen	10060
Oxygen	4.82	6.3	Nitrogen	5070
Xenon	2.62	3.5	Oxygen	4430

6.2 Physical Properties of Selected Gases

Values of all properties in this section are for atmospheric pressure, P = 101.325 kPa.

Physical Properties

Gas	Specific gravity (kg/m^3)	Molecular mass	Mole fraction solubility* in H_2O ($\times 10^5$)
Noble gases			
He	0.17846	4.0026	0.6997
Ne	0.90035	20.180	0.8152
Ar	1.7839	39.948	2.519
Kr	3.745	83.80	4.512
Xe	5.8971	131.29	7.890
Other gases			
H_2	0.08988	2.01588	1.411
D_2	—	4.0282	1.460
O_2	1.42897	31.9988	2.293
CO	1.2504	28.0104	1.774
N_2	1.2506	28.0134	1.183
CO_2	1.97693	44.0098	6.1.5
CH_4	0.5547	16.0428	2.552
NO	1.3402	30.0061	3.477
N_2O	1.977	44.0129	43.67
NH_3	0.7710	17.031	—
air	1.205	28.966	—

* Mole fraction solubility is at 298 K.

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Physical Properties—*continued*

Gas	Ionization potential (eV)	Permittivity ε	Polarizability 10^{-24} cm^3	Dipole moment μ/D	Dielectic strength*
Noble gases					
He	24.5874	1.0000650	—	0	0.15[1]
Ne	21.5645	1.00013	0.3956	0	0.16,[2] 0.25[1]
Ar	15.7596	1.0005172	1.6411	0	0.18[2]
Kr	13.9996	1.00078	2.4844	0	—
Xe	12.1299	1.00126	4.044	0	—
Other gases					
H_2	15.4259	1.0002538	0.8042	0	0.50[1,2]
D_2	15.46	—	0.7954	0	—
O_2	12.07	1.0004947	1.5812	0	0.92[2]
N_2	15.581	1.0005480	1.7403	0	1.00
CO	14.014	1.00262	1.95	0.110	1.02,[1] 1.05[2]
CO_2	13.723	1.000922	2.911	0	0.82,[2] 0.88[1]
CH_4	12.71	1.00081	2.593	0	1.00,[1] 1.13[2]
NO	9.264	1.00060	1.70	0.159	
N_2O	12.886	1.00104	3.03	0.161	1.24[2]
NH_3	10.2	1.00622	2.81	—	—
air	—	1.0005364	—	—	0.97[3]
					3.0 kV/mm[4]
					~0.5 V/mm[5]
					1.4 kV/mm[6]

Values for the permittivity (dielectric constant) and the average electric dipole polarization for ground state molecules are for 293 K.

Debye unit: 1 D = 3.33564 x 10^{-30} C m.

* Relative to nitrogen. The dielectric strength (or breakdown voltage) of a material depends on the specimen thickness, the electrode shape, and the rate of the applied voltage increase. Values are given for standard conditions.

References:

CRC Handbook of Chemistry and Physics, 82nd edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 2001). Gas properties at other temperatures are also given in this reference.

1. Vijh, A. K., *IEEE Trans*. EI-12, 313 (1997).
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Physical Properties—*continued*

Gas	Thermal conductivity κ(W/m K)	Heat capacity at 288 K C_p(J/kg K)	Viscosity at 300 K (μPa)
Noble gases			
He	0.1567*	5192	20.0
Ne	0.0498*	1030	32.1
Ar	0.0179*	519.2	22.9
Kr	0.0095*	247.0	25.6
Xe	0.0055*	158.3	23.2
Other gases			
H_2	0.1869	14277	9.0
D_2		7250	12.6
O_2	0.0263	917	20.8
N_2	0.0260	1043	17.9
CO	0.0250*	1031	17.8
CO_2	0.0166	843.2	15.0
CH_4	0.0341	2226	11.2
NO	0.0259	—	19.2
N_2O	0.0174	—	15.0
NH_3	0.0244	2091	—
air	0.0262	1005	18.6

* Low pressure limiting value. In general values differ by less than 1% at atmosphere pressure.

Reference:
CRC Handbook of Chemistry and Physics, 75th edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 1994). Values of properties at other temperatures are also given in this reference.

Thermal Conductivity at Different Temperatures

Thermal Conductivity (mW/m K)

Gas	100 K	200 K	300 K	400 K	500 K	600 K	Ref.
Noble gases							
He*	75.5	119.3	156.7	190.6	222.3	252.4	1
Ne*	22.3	37.6	49.8	60.3	69.9	78.7	1
Ar*	6.2	12.4	17.9	22.6	26.8	30.6	1,2
Kr*	3.3	6.4	9.5	12.3	14.8	17.1	1
Xe*	2.0	3.6	5.5	7.3	8.9	10.4	1

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Thermal Conductivity (mW/m K)—*continued*

Gas	100 K	200 K	300 K	400 K	500 K	600 K	Ref.
Other gases							
H_2	68.6	131.7	186.9	230.4			3
O_2	9.3	18.4	26.3	33.7	41.0	48.1	4
CO*			25.0	32.3	39.2	45.7	5
N_2	9.8	18.7	26.0	32.3	38.3	44.0	6
CO_2		9.6	16.8	25.1	33.5	41.6	7
CH_4		22.5	34.1	49.1	66.5	84.1	8,9
NO		17.8	25.9	33.1	39.6	46.2	10
N_2O		9.8	17.4	26.0	34.1	41.8	10
air	9.4	18.4	26.2	33.3	39.7	45.7	11

* Low pressure limiting value. In general values differ by less than 1% at atmosphere pressure.

References:

1. Kestin, J. et al., Equilibrium and transport properties of the noble gases and their mixtures at low density, *J. Phys. Chem. Ref. Data* 13, 299 (1984).
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Viscosity

Gas	Viscosity in micropascal seconds (μPa s) 100 K	200 K	300 K	400 K	500 K	600 K	Ref.
Noble gases							
He*	9.7	15.3	20.0	24.4	28.4	32.3	1
Ne*	14.4	24.3	32.1	38.9	45.0	50.8	1
Ar*	8.0	15.9	22.9	28.8	34.2	39.0	1,2
Kr*	8.8	17.1	25.6	33.1	39.8	45.9	1
Xe*	8.3	15.4	23.2	30.7	37.6	44.0	1
Other gases							
H_2*	4.2	6.8	9.0	10.9	12.7	14.4	3
D_2*	5.9	9.6	12.6	15.4	17.9	20.3	4
O_2*	7.5	14.6	20.8	26.1	30.8	35.1	5
CO	6.7	12.9	17.8	22.1	25.8	29.1	6
N_2*		12.9	17.9	22.2	26.1	29.6	5
CO_2		10.0	15.0	19.7	24.0	28.0	7,8
CH_4		7.7	11.2	14.3	17.0	19.4	8
NO		13.8	19.2	23.8	28.0	31.9	6
N_2O		10.0	15.0	19.4	23.6	27.4	6
air		13.3	18.6	23.1	27.1	30.8	9

* Low pressure limiting value. In general values differ by less than 1% at atmosphere pressure.

References:

1. Kestin, J. et al., Equilibrium and transport properties of the noble gases and their mixtures at low density, *J. Phys. Chem. Ref. Data* 13, 299 (1984).
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6.3 Index of Refraction

Index of Refraction n of Helium, He

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
0.092		1.0000485	1
O.1000		1.0000453	1
0.1100		1.0000426	1
0.1200		1.0000407	1
0.1300		1.0000396	1
0.1400		1.0000389	1
0.1500		1.0000383	1
0.1600		1.0000378	1
0.1700		1.0000374	1
0.1800		1.0000373	1
0.1820		1.00003720	3
0.184949		1.00003718	3
0.194232		1.00003690	3
0.213923		1.00003634	3
0.228872		1.00003601	3
0.253728		1.00003549	3
	0.275278	1.00003573	3,4
	0.289360	1.00003562	3,4
	0.292541	1.00003559	3,4
	0.296728	1.00003557	3,4
	0.302150	1.00003553	3,4
	0.312566	1.00003547	3,4
	0.334148	1.00003536	3,4
	0.366328	1.00003523	3,4
	0.390641	1.00003516	3,4
	0.404656	1.00003512	3,4
	0.435835	1.00003505	3,4
	0.479992	1.00003498	5
	0.508582	1.00003494	5
	0.521007	1.00003493	3
0.546226	0.546074	1.00003490	3
0.577120	0.576959	1.00003486	3
0.579227	0.579065	1.00003486	3
0.644025	0.643847	1.00003481	3
	0.742511	1.00003477	5
	0.826452	1.00003474	5
	0.912296	1.00003472	5
	1.013979	1.00003470	5

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Index of Refraction n of Helium, He—*continued*

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
	1.371857	1.00003466	5
	1.529596	1.00003465	5
	2.058128	1.00003464	5

References:

1. Huber, M. C. E. and Tondello, G., Refractive index of He in the region 920 AA, *J. Opt. Soc. Am*. 64, 390 (1974).
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5. Mansfield, C. R. and Peck, E. R., Dispersion of helium, *J. Opt. Soc. Am.* 59, 199 (1969).

Dispersion formula [λ (μm) in vacuum at T = 273 K]	Range (μm)
$n = 1 + 0.01470091\lambda^2/423.98\lambda^2 - 1$	0.48–2.06

Reference: Mansfield, C. R. and Peck, E. R., Dispersion of helium, *J. Opt. Soc. Am.* 59, 199 (1969).

Index of Refraction n of Neon, Ne

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
0.1404		1.00007736	1
0.1525		1.00007520	1
0.1641		1.00007317	1
0.1702		1.00007280	1
0.180731		1.00007221	1
0.184949		1.00007190	1
0.194232		1.00007095	1
0.213923		1.00007017	1
0.228872		1.00006941	1
0.253728		1.00006872	1
	0.289360	1.00006860	2,3
	0.296728	1.00006850	2,3
	0.302150	1.00006843	2,3
	0.313183	1.00006831	2,3
	0.334148	1.00006812	2,3
	0.366328	1.00006788	2,3
	0.390641	1.00006773	2,3
	0.404656	1.00006766	2,3
	0.407781	1.00006765	2,3
	0.435835	1.00006753	2,3
	0.479992	1.00006739	2

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Index of Refraction n of Neon, Ne—*continued*

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
	0.491604	1.00006736	2,3
	0.508582	1.00006731	2
	0.521007	1.00006729	2
0.546226	0.546074	1.00006724	2
0.577120	0.576959	1.00006718	2
0.579227	0.579065	1.00006718	2
0.644025	0.643847	1.00006711	2

References:

1. Bideau-Mehu, A., Guern, R., Abjean, Y., and Johannin-Gilles, A., Measurement of refractive indexes of He, Ar, Kr, and Xe in the 253.7–140.4 nm wavelength range. Dispersion relation and estimated oscillator strength of the resonance lines, *J. Quant. Spectrosc. Radiat. Transfer* 25, 395 (1981).
2. Leonard, P. J., *Atomic Data and Nuclear Data Tables* 14, 21 (1974).
3. Cuthbertson, C. and Cuthbertson, M., *Proc. Roy. Soc. A* 135, 40 (1932).

Dispersion formula [λ (μm) in vacuum at T = 273 K]	Range (μm)
$n = 1 + 0.012055[0.1063\lambda^2/(184.661\lambda^2 - 1) + 182.90\lambda^2/(376.840\lambda^2 - 1)]$	0.14–0.66

Reference: Bideau-Mehu, A., Guern, R. Abjean, Y., and Johannin-Gilles, A., Measurement of refractive indexes of He, Ar, Kr, and Xe in the 253.7–140.4 nm wavelength range. Dispersion relation and estimated oscillator strength of the resonance lines, *J. Quant. Spectrosc. Radiat. Transfer* 25, 395 (1981).

Index of Refraction n of Argon, Ar (vacuum ultraviolet)

$\lambda_{vac}(\mu m)$	n (273 K)	Ref.	$\lambda_{vac}(\mu m)$	n (273 K)	Ref.
0.1110	1.0008025	1	0.1700	1.0003451	1
0.1140	1.0006435	1	0.1702	1.0003446	2
0.1160	1.0005878	1	0.1805	1.0003352	1
0.1180	1.0005492	1	0.180731	1.0003352	2
0.1200	1.0005200	1	0.184949	1.0003315	2
0.1210	1.0005080	1	0.1850	1.0003318	1
0.1216	1.0005016	1	0.1900	1.0003281	1
0.1250	1.0004707	1	0.194232	1.0003256	2
0.1300	1.0004394	1	0.2000	1.0003220	1
0.1350	1.0004166	1	0.2100	1.0003169	1
0.1400	1.0003966	1	0.213923	1.0003150	2
0.1404	1.0003964	2	0.2200	1.0003127	1
0.1500	1.0003749	1	0.228872	1.0003102	2
0.1525	1.0003685	2	0.2300	1.0003091	1
0.1600	1.0003577	1	0.253728	1.0003029	2
0.1641	1.0003514	2			

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Index of Refraction Index n of Argon, Ar (ultraviolet, visible, and near infrared)

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
	0.230209	1.00030922	3
	0.234555	1.00030786	3
	0.237999	1. 00030689	3
	0.244691	1.00030507	3
	0.246407	1.00030463	3
	0.257630	1.00030202	3
	0.267499	1.00030002	3
	0.275278	1.00029865	3
	0.275971	1.00029852	3
	0.289357	1.00029643	3
	0.292541	1.00029599	3
	0.334148	1.00029135	3
	0.380166	1.00028806	3
	0.410807	1.00028285	3
0.467947	0.467816	1.00028434	3,4
0.480126	0.479992	1.00028399	3
		1.00028398	3,4
	0.491604	1.00028368	3
0.508724	0.508582	1.00028325	3,4
		1.00028322	3
	0.521007	1.00028296	3
0.546226	0.546074	1.00028247	3
	0.567717	1.00028209	3
0.577120	0.576959	1.00028190	3
0.579227	0.579065	1.00028190	3
0.644025	0.643847	1.00028103	3
0.703435	0.703241	1.00028045	3,4
0.724716	0.724511	1.00028028	3,4
0.826679	0.826452	1.00027962	3,4
0.912547	0.912296	1.00027923	3,4
0.922703	0 922449	1.00027920	3,4
0.966043	0.965778	1.00027904	3,4
1.014257	1.013979	1.00027890	3,4
1.372233	1.371857	1.00027825	3,4
1.475650	1.475246	1.00027814	3,4
1.529354	1.528936	1.00027810	3,4
1.530015	1.529596	1.00027809	3,4
1.694521	1.694057	1.00027798	3,4
2.058691	2.058128	1.00027782	3,4

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2. Bideau-Mehu, A., Guern, R., Abjean, Y., and Johannin-Gilles, A., *J. Quant. Spectrosc. Radiat. Transfer* 25, 395 (1981).
3. Leonard, P. J., *Atomic Data and Nuclear Data Tables* 14, 21 (1974).
4. Peck, E. R. and Fisher, D. J., *J. Opt. Soc. Am.* 54, 1362 (1964).

Temperature variation of the index of refraction of argon at 293 K.

$dn/dT\ (K^{-1}) = -0.897 \times 10^{-6}$ at 546.1 nm

$dn/dT\ (K^{-1}) = -0.894 \times 10^{-6}$ at 632.8 nm

Dispersion formula [λ in vacuum (μm) at T = 273 K]	Range (μm)	Ref.
$n = 1 + 0.012055[0.2075\lambda^2/(91.012\ \lambda^2 - 1) + 0.0415\lambda^2/(87.892\lambda^2 - 1) + 4.3330\lambda^2/(214.02\lambda^2 - 1)]$	0.14–2.1	1
$n = 1 + [67.86711 + 30182.943\lambda^2/(144\lambda^2 - 1)] \times 10^{-6}$	0.47–2.06	2

References:

1. Bideau-Mehu, A., Guern, R., Abjean, Y., and Johannin-Gilles, A., Measurement of refractive indexes of He, Ar, Kr, and Xe in the 253.7–140.4 nm wavelength range. Dispersion relation and estimated oscillator strength of the resonance lines, *J. Quant. Spectrosc. Radiat. Transfer* 25, 395 (1981).
2. Peck, E. R. and Fisher, D. J., *J. Opt. Soc. Am.* 54, 1362-1364 (1964).

Index of Refraction n of Krypton, Kr

λ_{vac}(μm)	λ_{air}(μm)	n (273 K)	Ref.
0.1404		1.0007723	1
0.1525		1.0006548	1
0.1641		1.0005973	1
0.16846		1.0005829	2
0.16991		1.0005780	2
0.17015		1.0005773	2
0.1702		1.0005801	1
0.17044		1.0005767	2
0.17134		I .0005740	2
0.17224		1.0005718	2
0.18169		1.0005483	2
0.18365		1.0005442	2
0.1844		1.0005433	1
0.18455		1.0005425	2
0.18475		1.0005423	2
0.18507		1.0005416	2

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Index of Refraction n of Krypton, Kr—*continued*

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
0.19013		1.0005326	2
0.19832		1.0005197	2
0.19889		1.0005191	2
	0.202551	1.00051493	3,4
0.20588		1.0005101	2
0.2062		1.0005108	1
0.21248		1.0005028	2
0.213923		1.0005023	1
	0.214438	1 00050126	3,4
	0.219463	1.00049664	3,4
0.22116		1.0004950	2
0.22174		1.0004946	2
	0.226502	1.00049089	3,4
0.228872		1.0004890	1
	0.230209	1.00048845	3,5
	0.232928	1.00048617	3,4
	0.234555	1.00048542	3,5
	0.237999	1.00048318	3,5
0.24359		1.0004791	2
	0.244691	1.00047910	3,5
	0.246407	1.00047815	3,5
0.25073		1.0004751	2
0.25151		1.0004747	2
0.25169		1.0004746	2
0.25200		1.0004745	2
0.25249		1.0004742	2
0.25293		1.0004740	2
	0.257309	1.00047221	3,4
	0.257630	1.00047236	3,5
0.26321		1.0004691	2
	0.267499	1.00046804	3,5
	0.274858	1.00046489	3,4
	0.275278	1.00046499	3,5
	0.275971	1.00046471	3,5
	0.283691	1.00046181	3,4
	0.285697	1.00046138	3,5
0.28824		1.0004601	2
	0.289360	1.00046017	3,5
	0.292541	1.00045924	3,5
	0.298063	1.00045739	3,4
	0.334148	1.00044933	3,5

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Index of Refraction n of Krypton, Kr—*continued*

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
	0.340365	1.00044829	3,4
	0.380166	1.00044241	3,5
	0.410807	1.00043909	3,5
	0.441304	1.00043621	3,4
0.480126	0.479992	1.00043391	3,4
	0.491604	1.00043333	3,5
0.508724	0.508582	1.00043245	3,4
0.546226	0.546074	1.00043084	3
	0.567717	1.00043011	3,5
	0.607262	1.00042885	3,5
	0.612327	1.00042873	3,5
	0.623437	1.00042847	3,5

References:

1. Bideau-Mehu, A., Guern, R., Abjean, Y., and Johannin-Gilles, Measurement of refractive indexes of He, Ar, Kr, and Xe in the 253.7–140.4 nm wavelength range. Dispersion relation and estimated oscillator strength of the resonance lines, *J. Quant. Spectrosc. Radiat. Transfer* 25, 395 (1981).
2. Smith, P. L., Parkinson, W. H., and Huber, M. C. E., The refractive index of krypton for 168 nm to 288 nm, *Opt. Commun*. 14, 374 (1975).
3. Leonard, P. J., *Atomic Data and Nuclear Data Tables* 14, 21-37 (1974)..
4. Kronjager, W., *Z. Physik* 98, 17 (1936).
5. Koch, J., *Kungl. Fysiografiska Sällskapets i Lund Förhandlingar* 19, 173 (1949).

Dispersion formula [λ (μm) in vacuum at T = 273 K]	Range (μm)
$n = 1 + 0.012055[0.2104\lambda^2/(65.4742\lambda^2 - 1) + 0.2270\lambda^2/(73.698\lambda^2 - 1) + 5.14975\lambda^2/(181.08\lambda^2 - 1)]$	0.15–0.62

Reference: See reference 1 above.

Index of Refraction n of Xenon, Xe

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
0.1483		1.005091	1
0.1495		1.003210	1
0.1525		1.0020686	1
0.1550		1.0018107	2
0.1600		1.0014614	2
0.1641		1.0013192	1
0.1650		1.0012978	2
0.1700		1.0011934	2
0.1702		1.0011867	1
0.1750		1.0011213	2
0.1800		1.0010678	2
0.180731		1.0010630	1

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Index of Refraction n of Xenon, Xe—*continued*

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
0.184949		1.0010302	1
0.1850		1.0010226	2
0.1900		1.0009917	2
0.194232		1.0009713	1
0.1950		1.0009635	2
0.2000		1.0009398	2
0.2050		1.0009194	2
0.2100		1.0009018	2
0.213923		1.0008941	1
0.2150		1.0008862	2
0.2200		1.0008725	2
0.2250		1.0008603	2
0.228872		1.0008584	1
0.2300		1.0008494	2
	0.230209	1.00085519	3,4
	0.234555	1.00084664	3,4
	0.237999	1.00084025	3,4
	0.244691	1.00082907	3,4
	0.246407	1.00082640	3,4
0.253728		1.0008127	1
	0.257630	1.00081078	3,4
	0.267499	1.00079923	3,4
	0.275278	1.00079124	3,4
	0.275971	1.00079060	3,4
	0.285697	1.00078186	3,4
	0.289360	1.00077885	3,4
	0.292541	1.00077637	3,4
	0.334148	1.00075143	3,4
	0.380166	1.00073430	3,4
	0.410807	1.00072623	3,4
	0.491604	1.00071241	3,4
0.546226	0.546074	1.00070660	3
	0.567717	1.00070477	3,4
	0.607262	1.00070188	3,4
	0.612327	1.00070157	3,4
	0.623437	1.00070091	3,4

1. Bideau-Mehu, A., Guern, R., Abjean, Y., and Johannin-Gilles, A., *J. Quant. Spectrosc. Radiat. Transfer* 25, 395 (1981).
2. Chashchina, G. I. and Shreider, E. Ya., *Opt. Spektrosk.* 27, 161 (1969) English transl.: *Opt. Spectrosc. USSR* 27, 79-80 (1969).
3. Leonard, P. J., *Atomic Data and Nuclear Data Tables* 14, 21-37 (1974).
4. Kronjager, W., *Z. Physik* 98, 17 (1936).

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Dispersion formula [λ (μm) in vacuum at T = 273 K]	Range (μm)
$n = 1 + 0.012055[0.26783\lambda^2/(46.301\lambda^2 - 1) + 0.29481\lambda^2/(50.578\lambda^2 - 1) + 5.0333\lambda^2/(112.74\lambda^2 - 1)]$	0.15–0.62

Reference: Bideau-Mehu, A., Guern, R., Abjean, Y., and Johannin-Gilles, A., Measurement of refractive indexes of He, Ar, Kr, and Xe in the 253.7–140.4 nm wavelength range. Dispersion relation and estimated oscillator strength of the resonance lines, *J. Quant. Spectrosc. Radiat. Transfer* 25, 395 (1981).

Index of Refraction n of Hydrogen, H_2

λ_{air}(μm)	n (273 K)	λ_{air}(μm)	n (273 K)
0.230209	1.0001594	0.334148	1.0001461
0.237832	1.0001577	0.354308	1.0001450
0.244691	1.0001563	0.366328	1.0001443
0.246406	1.0001560	0.390641	1.0001432
0.253652	1.0001547	0.398400	1.0001430
0.257630	1.0001540	0.404656	1.0001427
0.267499	1.0001525	0.407781	1.0001426
0.275278	1.0001515	0.410807	1.0001426
0.275971	1.0001514	0.435835	1.0001418
0.285697	1.0001503	0.486133	1.0001406
0.289360	1.0001499	0.491604	1.0001405
0.292541	1.0001495	0.546074	1.0001397
0.296728	1.0001491	0.579065	1.0001393
0.312567	1.0001477	0.656279	1.0001387
0.313184	1.0001477	0.670784	1.0001385

Reference: Leonard, P. J., *Atomic Data and Nuclear Data Tables* 14, 21 (1974)

Index of Refraction n of Deuterium, D_2

λ_{air}(μm)	n (273 K)	λ_{air}(μm)	n (273 K)
0.230209	1.00015680	0.289357	1.00014756
0.234555	1.00015584	0.292541	1.00014725
0.237999	1.00015510	0.334148	1.00014395
0.244691	1.00015378	0.380166	1.00014160
0.246407	1.00015347	0.410807	1.00014048
0.257630	1.00015158	0.491604	1.00013850
0.267499	1.00015014	0.546074	1.00013766
0.275278	1.00014915	0.576959	1.00013731
0.275971	1.00014906	0.579065	1.00013727

Reference: Leonard, P. J., *Atomic Data and Nuclear Data Tables* 14, 21-37 (1974)

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Index of Refraction n of Nitrogen, N_2 (vacuum ultraviolet, ultraviolet, and visible)

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
0.1641		1.0003748	1
0.1702		1.0003656	1
0.180731		1.0003552	2
0.184949		1.0003495	2
0.194232		1.0003435	2
0.213923		1.0003349	2
0.228872		1.0003299	2
	0.237832	1.0003261	3
	0.244691	1.0003241	3
	0.246406	1.0003236	3
	0.253652	1.0003218	3
0.253728		1.0003217	2
	0.257630	1.0003208	3
	0.267499	1.0003187	3
	0.275278	1.0003172	3
	0.275971	1.0003171	3
	0.285697	1.0003154	3
	0.289360	1 0003148	3
	0.292541	1.0003143	3
	0.296728	1.0003137	3
	0 334148	1.0003094	3
	0.354308	1.0003076	3
	0.390641	1.0003051	3
	0.398400	1.0003047	3
	0.407781	1.0003042	3
	0.410807	1.0003041	3
	0.491604	1.0003011	3
	0.546074	1.0002977	3
0.546226		l.0002911	4

References:

1. Bideau-Mehu, A., Guern, Y., Abjean, R., and Johannin-Gilles, A., Measurement of refractive indexes of gases in the vacuum ultraviolet and revised values for krypton, *Opt. Commun*. 16, 186 (1976).
2. Abjean, R., Mehu, A., and Johannin-Gilles, A., Interferometric measurement of the refractive indices of neon and helium in the ultraviolet, *Comptes Rendus* 271, 411-414 (1970).
3. Leonard, P. J., *Atomic Data and Nuclear Data Tables* 14, 21-37 (1974).
4. Peck, E. R. and Hanna, B. N., *J. Opt. Soc. Am.* 56, 1059-1063 (1966).

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Index of Refraction n of Nitrogen, N_2 (vacuum ultraviolet, ultraviolet, and visible)

$\lambda_{vac}(\mu m)$	$\lambda_{air}(\mu m)$	n (273 K)	Ref.
0.1641		1.0003748	1
0.1702		1.0003656	1
0.180731		1.0003552	2
0.184949		1.0003495	2
0.194232		1.0003435	2
0.213923		1.0003349	2
0.228872		1.0003299	2
	0.237832	1.0003261	3
	0.244691	1.0003241	3
	0.246406	1.0003236	3
	0.253652	1.0003218	3
0.253728		1.0003217	2
	0.257630	1.0003208	3
	0.267499	1.0003187	3
	0.275278	1.0003172	3
	0.275971	1.0003171	3
	0.285697	1.0003154	3
	0.289360	1 0003148	3
	0.292541	1.0003143	3
	0.296728	1.0003137	3
	0.334148	1.0003094	3
	0.354308	1.0003076	3
	0.390641	1.0003051	3
	0.398400	1.0003047	3
	0.407781	1.0003042	3
	0.410807	1.0003041	3
	0.491604	1.0003011	3
	0.546074	1.0002977	3
0.546226		l.0002911	4

References:

1. Bideau-Mehu, A., Guern, Y., Abjean, R., and Johannin-Gilles, A., Measurement of refractive indexes of gases in the vacuum ultraviolet and revised values for krypton, *Opt. Commun*. 16, 186 (1976).
2. Abjean, R., Mehu, A., and Johannin-Gilles, A., Interferometric measurement of the refractive indices of neon and helium in the ultraviolet, *Comptes Rendus* 271, 411 (1970).
3. Leonard, P. J., *Atomic Data and Nuclear Data Tables* 14, 21 (1974).
4. Peck, E. R. and Hanna, B. N., *J. Opt. Soc. Am.* 56, 1059 (1966).

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Index of Refraction n of Nitrogen, N_2
(visible and near infrared)

$\lambda_{vac}(\mu m)$	n (288 K)	$\lambda_{vac}(\mu m)$	n (288 K)
0.467947	1.00028543	0.978719	1.00028000
0.480126	1.00028507	1.014257	1.00027989
0.508724	1.00028433	1.129050	1.00027961
0.546226	1.00028352	1.350788	1.00027926
0.703435	1.00028149	1.372233	1.00027923
0.724716	1.00028130	1.475650	1.00027912
0.826679	1.00028063	1.529354	1.00027907
0.912547	1.00028023	1.694521	1.00027896
0.922703	1.00028019	2.058691	1.00027879
0.966043	1.00028004		

Reference: Peck, E. R. and Hanna, B. N., *J. Opt. Soc. Am.* 56, 1059 (1966).

Temperature variation of index of refraction at 293 K:
dn/dT (K^{-1}) = -0.953×10^{-6} at 546.1 nm
dn/dT (K^{-1}) = -0.949×10^{-6} at 632.8 nm

Dispersion formula [λ (μm) in vacuum at T = 273 K]	Range (_m)
$n = 1 + [68.5520 + 32431.57\lambda^2/144\lambda^2 - 1)]x10^{-6}$	0.47–2.06

Reference: Peck, E. R. and Hanna, B. N., *J. Opt. Soc. Am.* 56, 1059 (1966).

Index of Refraction n of Oxygen, O_2

$\lambda_{air}(\mu m)$	n (273 K)
0.275278	1.0003242
0.289360	1.0002936
0.302150	1.0002912
0.318770	1.0002879
0.388865	1.0002797
0.447148	1.0002763
0.471250	1.0002751
0.501568	1.0002740
0.587562	1.0002718
0.667815	1.0002708

Reference: Abjean, R., Mehu, A., and Johannin-Gilles, A., *Comptes Rendus* 271, 411 (1970).

Temperature variation of the index of refraction of oxygen at 293 K:
dn/dT (K^{-1}) = -0.864×10^{-6} at 546.1 nm
dn/dT (K^{-1}) = $-0.858 \times 10^{--6}$ at 632.8 nm

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Index of Refraction n of Carbon Dioxide, CO_2

$\lambda_{vac}(\mu m)$	n (273 K)	Ref.	$\lambda_{vac}(\mu m)$	n (273 K)	Ref.
0.180731	1.0005513	1	0.410925	1.0004582	2
0.184949	1.0005441	1	0.480126	1.0004534	3
0.194232	1.0005333	1	0.491720	1.0004529	2
0.206230	1.0005207	1	0.508724	1.0004520	3
0.213923	1.0005142	1	0.546223	1.0004505	2
0.228872	1.0005034	1	0.724716	1.0004461	3
0.237910	1.0004973	2	0.744095	1.0004458	3
0.244764	1.0004937	2	0.826679	1.0004446	3
0.246482	1.0004929	2	0.877716	1.0004440	3
0.253728	1.0004895	1	0.893115	1.0004439	3
0.257708	1 0004878	2	0.912547	1.0004437	3
0.267577	1.0004840	2	0.922703	1.0004436	3
0.276058	1.0004811	2	0.966043	1.0004431	3
0.285780	1.0004781	2	1.014257	1.0004427	3
0.296813	1.0004752	2	1.296021	1.0004405	3
0.334242	1.0004674	2	1.372232	1.0004399	3
0.354469	1.0004644	2	1.475650	1.0004392	3
0.368104	1.0004625	2	1.529354	1.0004387	3
0.398507	1.0004593	2	1.694521	1.0004374	3

References:

1. Bideau-Mehu, A., Guern, Y., Abjean, R., and Johannin-Gilles, A., Interferometric determination of the refractive index of CO2 in the ultraviolet region, Opt. Commun. 9, 432 (1973).
2. Leonard, P. J., Atomic Data and Nuclear Data Tables 14, 21 (1974).
3. Old, J. G., Gentili, K. L., and Peck, E. R., Dispersion of carbon dioxide, J. Opt. Soc. Am. 61, 89 (1971).

Temperature variation of the index of refraction of carbon dioxide at 293 K:

$dn/dT\ (K^{-1}) = 1.432 \times 10^{-6}$ at 546.1 nm

$dn/dT\ (K^{-1}) = 1.424 \times 10^{-6}$ at 632.8 nm

Dispersion formula [λ (μm) in vacuum at T = 273 K]	Range (μm)
$n = 1 + 0.012055[0.579925\lambda^2/(166.175\lambda^2 - 1) + 0.12005\lambda^2\ (79.609\lambda^2 - 1)$ $+ 0.0053334\lambda^2/(56.3064\lambda^2 - 1) + 0.0043244\lambda^2/(46.0196\lambda^2 - 1)$ $+ 0.0001218145\lambda^2/(0.0584738\lambda^2 - 1)]$	0.18–1.7

Reference: Bideau-Mehu, A., Guern, Y., Abjean, R., and Johannin-Gilles, A., Interferometric determination of the refractive index of CO_2 in the ultraviolet region, *Opt. Commun.* 9, 432 (1973).

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Index of Refraction n of Methane, CH_4

$\lambda_{air}(\mu m)$	n (273 K)	Reference
0.5290	1.0004478	1
0.5718	1.0004454	1
0.5893	1.000444	2
0.5935	1.0004435	1
0.6375	1.0004411	1
0.6585	1.0004404	1

References:

1. *International Critical Tables of Numerical Data, Physics and Chemistry and Technology*, Vol. VII, Washburn, E. W., Ed., (McGraw-Hill, New York, 1930).
2. Kaye, G. W., and Laby, T. H., *Tables of Physical and Chemical Constants* (Longman Group, London, 1986).

Index of Refraction n of Ammonia, NH_3

$\lambda_{air}(\mu m)$	n (273 K)	Reference
0.47999	1.0003830	1
0.50858	1.0003808	1
0.52091	1.0003800	1
0.54607	1.0003786	1
0.57695	1.0003771	1
0.57905	1.0003770	1
0.5893	1.000376	2
0.64385	1.0003746	1
0.67078	1.0003738	1

References:

1. *International Critical Tables of Numerical Data, Physics and Chemistry and Technology*, Vol. VII, Washburn, E. W., Ed., (McGraw-Hill, New York, 1930).
2. Kaye, G. W., and Laby, T. H., *Tables of Physical and Chemical Constants* (Longman Group, London, 1986).

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Index of Refraction n of Air

λ_{air} (μm)	n (288 K)	$\lambda_{vac}-\lambda_{air}$ (μm)	λ_{air} (μm)	n (288 K)	$\lambda_{vac}-\lambda_{air}$ (μm)
0.200	1.0003256	0.0000651	0.560	1.0002769	0.0001551
0.210	1.0003188	0.0000670	0.570	1.0002768	0.0001578
0.220	1.0003132	0.0000689	0.580	1.0002766	0.0001604
0.230	1.0003086	0.0000710	0.590	1.0002765	0.0001631
0.240	1.0003047	0.0000731	0.600	1.0002763	0.0001658
0.250	1.0003014	0.0000754	0.610	1.0002762	0.0001685
0.260	1.0002986	0.0000776	0.620	1.0002761	0.0001712
0.270	1.0002962	0.0000800	0.630	1.0002760	0.0001739
0.280	1.0002941	0.0000824	0.640	1.0002759	0.0001766
0.290	1.0002923	0.0000848	0.650	1.0002758	0.0001792
0.300	1.0002907	0.0000872	0.660	1.0002757	0.0001819
0.310	1.0002893	0.0000897	0.670	1.0002756	0.0001846
0.320	1.0002880	0.0000922	0.680	1.0002755	0.0001873
0.330	1.0002869	0.0000947	0.690	1.0002754	0.0001900
0.340	1.0002859	0.0000972	0.700	1.0002753	0.0001927
0.350	1.0002850	0.0000998	0.710	1.0002752	0.0001954
0.360	1.0002842	0.0001023	0.720	1.0002751	0.0001981
0.370	1.0002835	0.0001049	0.730	1.0002751	0.0002008
0.380	1.0002829	0.0001075	0.740	1.0002750	0.0002035
0.390	1.0002823	0.0001101	0.750	1.0002749	0.0002062
0.400	1.0002817	0.0001127	0.760	1.0002749	0.0002089
0.410	1.0002812	0.0001153	0.770	1.0002748	0.0002116
0.420	1.0002808	0.0001179	0.780	1.0002748	0.0002143
0.430	1.0002803	0.0001205	0.790	1.0002747	0.0002170
0.440	1.0002799	0.0001232	0.800	1.0002746	0.0002197
0.450	1.0002796	0.0001258	0.810	1.0002746	0.0002224
0.460	1.0002792	0.0001284	0.825	1.0002745	0.0002265
0.470	1.0002789	0.0001311	0.850	1.0002744	0.0002332
0.480	1.0002786	0.0001338	0.875	1.0002743	0.0002400
0.490	1.0002784	0.0001364	0.900	1.0002742	0.0002468
0.500	1.0002781	0.0001391	0.925	1.0002741	0.0002536
0.510	1.0002779	0.0001417	0.950	1.0002740	00002604
0.520	1.0002777	0.0001444	0.975	1.0002740	0.0002671
0.530	1.0002775	0.0001471	1.000	1.0002739	0.0002739
0.540	1.0002773	0.0001497	1.050	1.0002738	0.0002875
0.550	1.0002771	0.0001524	1.100	1.0002737	0.0003011

Reference:

CRC Handbook of Chemistry and Physics, 75th edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 1994).

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6.4 Nonlinear Optical Properties

6.4.1 Nonlinear Refractive Index γ (300 K)

Gas	λ(nm)	γ (10^{-22} m^2/W)	Ref.
Noble gases			
He	694.3	0.014	1
Ne	694.3	0.006	2
Ar	248.4	0.29 ± 0.10	2
	694.3	0.25	1
Other gases			
H_2	694.3	0.21	3
D_2	694.3	0.21	1
O_2	248.4	3.0 ± 0.3	2
	694.3	0.21	1
N_2	248.4	0.76 ± 0.26	2
	694.3	0.21	1
CO_2	248.4	0.32	1
	694.3	1.1	2
CH_4	248.4	1.1 ± 0.4	2
	694.3	0.47	1

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6.4.2 Two-Photon Absorption

Two-Photon Absorption Coefficients

Gas	Excitation duration (ns)	Applied two-photon energy (eV)	Two-photon cross-section 10^{-50} cm^4 s/ phot. mol.	Ref.	Additional information
Anthracene	30	3.57	0.09	1	503 K, 1.7 Torr
Benzene	10	4.92	0.0126	2	30 Torr, Ar buffer
Benzene	10	8.43	0.0016	2	30 Torr, Ar buffer
Benzene	10	8.44	0.00075	2	30 Torr, Ar buffer
Benzene	10	8.53	0.00146	2	30 Torr, Ar buffer
Benzene	10	8.87	0.00001	2	30 Torr, Ar buffer
Perylene	30	3.57	1.2	1	583 K, 0.6 Torr
POPOP	30	3.57	0.05	1	603 K, 1.23 Torr

POPOP : 1,4-di[2-(5-phenyloxazolyl)] benzene.

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6.4.3 Third-Order Nonlinear Optical Coefficients

Gas	Nonlinear optical process	Coefficient C_{jn}^{mic} x 10^{20} m^2 V^{-2}	Wavelength (μm)
Noble gases			
Helium, He	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.00245$	0.6943
	$(-3\omega;\ \omega,\ \omega,\ -\omega)$	$C_{11} = 0.00122$	0.6943
	$(-2\omega;\ 0,\ \omega,\ \omega)$	$C_{22} = 0.0027$	0.6943
Neon, Ne	$(-2\omega;\ 0,\ \omega,\ \omega)$	$C_{22} = 0.00735 \pm 0.00024$	0.6943
	$(-3\omega;\ \omega,\ \omega,\ -\omega)$	$C_{11} = 0.00312 \pm 0.00053$	0.6943
Argon, Ar	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.0217 \pm 10\%$	0.6943
	$(-3\omega;\ \omega,\ \omega,\ -\omega)$	$C_{11} = 0.0875$	0.308
		$C_{11} = 0.0441 \pm 0.007$	0.6943
	$(-2\omega;\ 0,\ \omega,\ \omega)$	$C_{22} = 0.0833 \pm 0.0027$	0.6943
Krypton, Kr	$(-3\omega;\ \omega,\ \omega,\ -\omega)$	$C_{11} = 0.13516 \pm 0.0262$	0.6943
	$(-2\omega;\ 0,\ \omega,\ \omega)$	$C_{22} = 0.2037 \pm 0.0098$	0.6943
Xenon, Xe	$(-2\omega;\ 0,\ \omega,\ \omega)$	$C_{11} = 0.3426 \pm 0.0655$	0.6943
		$C_{22} = 0.5635 \pm 0.0392$	0.6943
Other gases			
Carbon dioxide, CO_2	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.028 \pm 10\%$	
	$(-3\omega;\ \omega,\ \omega,\ -\omega)$	$C_{11} = 0.054 \pm 0.008$	0.6943
Carbon monoxide, CO	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.0252 \pm 10\%$	0.6943
	$(-3\omega;\ \omega,\ \omega,\ -\omega)$	$C_{11} = 1.95$	9.33
Deuterium, D_2	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.0182 \pm 10\%$	0.6943
Ethane, C_2H_8	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.0868 \pm 10\%$	0.6943
Hydrogen, H_2	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.0294 \pm 10\%$	0.6943
	$(-3\omega;\ \omega,\ \omega,\ -\omega)$	$C_{11} = 0.028 \pm 0.0024$	0.6943
Methane, CH_4	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{jn}^{mic} = 0.1925 \pm 0.0161$	0.6943
	$(-2\omega;\ 0,\ \omega,\ \omega)$	$C_{jn}^{mic} = 0.1708 \pm 0.084$	0.6943
	$(-\omega;\ 0,\ 0,+\ \omega)$	$C_{22} = 0.1806 \pm 0.013$	0.6943
	$(-2\omega;\ \omega,\ \omega,0)$	$C_{11} = 0.0413 \pm 10\%$	0.6943
Nitric oxide, NO	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.0588 \pm 10\%$	0.6943
Nitrogen, N_2	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.0189 \pm 10\%$	0.6943
	$(-3\omega;\ \omega,\ \omega,\ -\omega)$	$C_{11} = 0.03745 \pm 0.006$	0.6943
Oxygen, O_2	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.0182 \pm 10\%$	0.6943
Sulfur hexafluoride, SF_6	$(-2\omega_1+\omega_2;\ \omega_1,\ \omega_1,\ -\omega_2)$	$C_{11} = 0.035 \pm 10\%$	0.6943
	$(-3\omega;\ \omega,\ \omega,\ -\omega)$	$C_{11} = 5862$	10.6

Data from a table of S. Singh, Nonlinear optical materials, *Handbook of Laser Science and Technology, Vol. III: Optical Materials, Part 1* (CRC Press, Boca Raton, FL., 1986), p. 60 ff.

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6.4.4 Stimulated Raman Scattering

Stimulated Raman Scattering Transitions in Gases

Substance	Raman frequency shift ν_o (cm^{-1})	Ref.
barium vapor,[a] Ba	IR[b]	11
cesium vapor,[a] Cs	IR[b]	12,13
hydrogen fluoride, HF	FIR[b]	14
potassium vapor,[a] K	IR[b]	13,15
rubidium vapor,[a] Rb	IR[b]	16
para-hydrogen, p-H_2	354	17,18
silane, SiH_4	2186	5
germane, GeH_4	2111	5
sulfur hexafluoride, SF_6	775	5
carbon tetrafluoride, CF_4	980	19
oxygen, O_2	1552	24
nitrogen, N_2	2331	20
potassium vapor, K	2721	21
methane, CH_4	2916	22
deuterium, D_2	2991	22
hydrogen deuteride, HD	3628	23
hydrogen, H_2	4155	22

[a] Stimulated electronic Raman scattering (SERS).

[b] Generally tunable transitions in the infrared (IR) and far infrared (FIR).

The above table is from Milanovich, F. P., Stimulated Raman scattering, *Handbook of Laser Science and Technology, Vol. III: Optical Materials* (CRC Press, Boca Raton, FL, 1986), p. 283.

Raman Gain Parameters of Selected Gases at 298 K

Gas	Mode	ν_o (cm^{-1})	$\Delta\nu_g$ (MHz)[a]	Ref.	gain (cm/GW)	ρ (amagat)	λ_l (nm)	Ref.
H_2	Q(1)	4155	$\frac{309}{\rho} + 52.2\rho$	1	2.5 ± 0.4	20	532	2
					2.64 ± 0.2	60	532	3
					3.5 ± 0.3	20	477	2
					5.7	High density	350	4
					6.6 ± 0.8	20	308	2
	Q(0)		$\frac{257}{\rho} + 76.6\rho$	1	7.00	>20	248	5
	S(1)	587	119ρ	4	1.2	High density	350	4
p-H_2 (81 K)	Q(0)	354	$\frac{76.6}{\rho} + 45.4\rho$	1				
(80 K)	S(1)				0.096 ± .009		10P(20)[b]	6
					0.102 ± .014		10R(20)[b]	6
					0.111 ± .012		9P(20)[b]	6
					0.123 ± .014		9R(20)[b]	6

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Raman Gain Parameters of Selected Gases at 298 K—*continued*

Gas	Mode	ν_o (cm^{-1})	$\Delta\nu_g$ (MHz)[a]	Ref.	gain (cm/GW)	ρ (amagat)	λ_l (nm)	Ref.
D_2	Q(2)	2987	$\frac{101}{\rho}+120\rho$	7,8	0.45 ± 0.05	60 atm	532	3
			66ρ	4	1.9	High density	350	4
					0.47	High density	350	4
D_2	S(2)	414	124ρ	4				4
HD	Q(1)	3628	693ρ	4				
					0.23	High density	350	4
	S(1)	443	760ρ	4	0.098	High density	350	4
CH_4	ν_1	2917	8220 + 384ρ	3	1.26	115	532	3
			9000 (1<ρ<10)	5	0.12ρ		248	5
					1.2			
					0.66			
N_2	Q branch	2327	22.5 (ρ<10)	5	0.3ρ		248	5
	S(6)	60	0.00285 (D)	9	0.0063	>1 torr	400	9
			3570ρ	10	0.0036	>.01	566	10
	S(8)	76	0.00363 (D)	9	0.0073	>1 torr	400	9
			3570ρ	10	0.0046	>.01	565.5	10
	S(10)	92	0.00441 (D)	9	0.0072	>1 torr	400	9
			3570ρ	10	0.0048	>.01	565	10
	S(12)	108	0.00516 (D)	9	0.0061	>1 torr	400	9
			3570ρ	10	0.0043	>.01	564.5	10
O_2	Q branch	1552	54	5	0.012ρ		248	5
SiH_4	Q branch	2186	15 (est)	5	0.19ρ		248	5
GeH_4	ν_1	2111	15 (est)	5	0.27ρ		248	5
CF_4	ν_1	980	21 (est)	5	0.008ρ		248	5
SF_6	ν_1	775	30 (est)	5	0.014ρ		248	5

a ρ is measured in amagats
b CO_2 laser lines.
(D) Doppler

The above table is from Reintjes, J. F., Stimulated Raman and Brillouin scattering, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 334.

Polarization Dependence of Relative Gain

	Pump polarization	Stokes polarization	Relative gain
Rotational scattering, linear molecules	linear	linear parallel	1.0
	linear	linear, perpendicular	0.75
	circular	circular, same sense	0.25
	circular	circular, opposite sense	1.5

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6.4.5 Brillouin Phase Conjugation

Gases Used for Brillouin Phase Conjugation

Gas	Wavelength λ (nm)	Refract. index n	Sound speed v_s (km/s)	Brillouin shift at λ (GHz)	Phonon lifetime τ_p (ns)	Line width $\Delta\nu_b$ (MHz)	Gain g (cm/GW)	Density ρ (g/cm^3)	Ref.
Argon, Ar	1064		0.34		3		4	50[a]	1
Chlorotrifluoromethane, $CClF_3$ (Freon 13)									2
Dichlorodifluoromethane, CCl_2F_2 (Freon 12)	248	1.001	0.15	1.2		960	0.19	1	3[c]
Hexafluoroethane, C_2F_6 (Freon 116)									2
Methane, CH_4	1064		0.46		3		8	150[a]	1
	694					32	18	50	4
	694					22	40		4
	694					20	72	75	4
	694					20	100	105	5,6
Nitrogen, N_2	694				10		5[b]	150[a]	7
	1064		0.36		15	15	4	135	1
	694		0.39				30		4
Sulfur hexafluoride, SF_6	1064		0.14		20		6	20	1
	694				6		8	10	2
	694		0.113			14	35	22	3[c]

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Gases Used for Brillouin Phase Conjugation—*continued*

Gas	Wavelength λ (nm)	Refract. index n	Sound speed v_S (km/s)	Brillouin shift at λ (GHz)	Phonon lifetime τ_p (ns)	Line width $\Delta\nu_b$ (MHz)	Gain g (cm/GW)	Density ρ (g/cm^3)	Ref.
Xenon	1064		0.18		35		47	40[a]	1
	694				6[d]		10	20[a]	2
	694				15		90	80[a]	2
	694		0.149			11	44	39	4
	1315				65			50	8

[a]Density in amagats rather than pressure in atmospheres; [b]This is the transient gain; the authors calculate steady-state gain as 30 cm/GW, and give a pressure dependence as well; [c]Some of the numbers in this row are theoretical calculations; the reference reports energy conversions; [d]Damzen et. al.[2] give the formula $t_B(\text{ns}) = 0.65 l_L^2 p$ (atm).

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

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6.5 Magnetooptic Properties

Verdet Constant V (degrees/Tesla meter) of Gases at 273 K

	Wavelength (nm)							
	363.5	**400**	**500**	**600**	**700**	**800**	**900**	**987.5**
Noble gases								
He	0.0209	0.0168	0.0106	0.0074	0.0054	0.0041	0.0034	
Ne	0.0388	0.0326	0.0204	0.0137	0.0090	0.0064	0.0052	0.0047
Ar	0.4106	0.3297	0.2055	0.1403	0.1004	0.0768	0.0610	0.0516
Kr	0.8637	0.6820	0.4232	0.2855	0.2040	0.1531	0.1203	0.1004
Xe	2.1112	1.64492	1.0055	0.6684	0.4766	0.3567	0.2812	0.2354
Other gases								
H_2	0.2882	0.2308	0.1425	0.0969	0.0690	0.0531	0.0422	0.0351
D_2	0.2815	0.2221	0.1375	0.0943	0.0679	0.0522	0.0413	0.0344
O_2	0.1948	0.1620	0.1144	0.0886	0.0725	0.0631	0.0568	0.0536
N_2	0.2820	0.2268	0.1407	0.0968	0.0698	0.0527	0.0421	0.0359
CO_2	0.4205	0.3391	0.2104	0.1445	0.1044	0.0789	0.0583	0.0536
CH_4	0.7875	0.6246	0.3861	0.2618	0.1881	0.1433	0.1140	0.0953

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6.6 Atomic Resonance Filters

Atomic resonance filters (ARFs) are a class of filter devices that have very narrow bandwidth (~0.001 nm) and a wide field of view (180°). A cell containing atomic vapor (e.g., Rb, Cs, etc.) is placed between two narrow bandpass filters. The input filter has a peak transmission wavelength corresponding to a strong electron transition in the vapor species. Incoming light is then strongly absorbed, yielding an excited state population which decays, emitting photons of a second wavelength. The bandpass of the output filter corresponds to the emitted wavelength. Use of both ground state (passive operation) and excited state (laser-pumped operation) transitions have been reported for a variety of atomic vapors operating at a variety of wavelengths. A detailed review of the physics of ARFs is given by Gelbwachs.[1]

Atomic Resonance Filters

Atomic	**Wavelength**		**Pump**	
species	**Input**	**Output**	**source**	**Ref.**
Na	1480 nm	489 nm	optical	2
	2340 nm	569 nm	optical	2
	3420 nm	616 nm	optical	2
K	~10.6 μm	497 nm	optical	3
Rb	20,487–776 nm	420 nm	diode laser	1
	459 nm	894 nm	none	4

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Atomic Resonance Filters—*continued*

Atomic species	Wavelength Input	Wavelength Output	Pump source	Ref.
Cs[a]	456 nm	852 nm	none	4
	534 nm	404 nm	diode laser	5
Tl	535 nm	378 nm	photochemical	6
Mg	518 nm	384 nm	Nd:YAG	7
Ca[a]	423 nm	272 nm	diode laser	8

[a] Not experimentally verified.

An alternative atomic resonance filter design is the Faraday anomalous dispersion optical filter (FADOF).[2,3] An atomic vapor cell is placed in a magnetic field between crossed polarizers. The resonant Faraday effect causes polarization rotation at frequencies corresponding to atomic transitions. At other frequencies rotation is negligible. Thus, by proper adjustment of atomic vapor concentration, cell length, and magnetic field strength, ultranarrow-linewidth bandpass filters may be produced. FADOFs do not shift the output wavelength, and no reponse delay occurs. In principle, transmission is near unity at the center of the filter bandpass for linearly polarized incident light.

Atomic Faraday Filter Data

Atomic species	Operating wavelength (nm)	Peak transmission (%)	Bandwidth (GHz)	Rejection ratio	Ref.
K	766, 770	71	1.6		9
Rb	780	63	1.0	10^5	9
Cs	852	82	0.6	10^5	10

The above table is from Cook, L. M., Filter materials, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 115 (with additions).

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