MATERIAL PROPERTIES

INTRODUCTION

Glass manufacturers provide hundreds of different glass types with differing optical transmission and mechanical strengths. CVI Laser Optics has simplified the task of selecting the right material for an optical component by offering each of our standard components in a single material, or in a small range of materials best suited to typical applications.

There are, however, two instances in which one might need to know more about optical materials: one might need to determine the performance of a catalog component in a particular application, or one might need specific information to select a material for a custom component. The information given in this chapter is intended to assist in that process.

The most important material properties to consider in regard to an optical element are as follows:

- Transmission versus wavelength
- Index of refraction
- Thermal characteristics
- Mechanical characteristics
- Chemical characteristics
- Cost

TRANSMISSION VERSUS WAVELENGTH

A material must transmit efficiently at the wavelength of interest if it is to be used for a transmissive component. A transmission curve allows the optical designer to estimate the attenuation of light as a function of wavelength caused by internal material properties. For mirror substrates, the attenuation may be of no consequence.

INDEX OF REFRACTION

The index of refraction, as well as the rate of change of index with wavelength (dispersion), might require consideration. High-index materials allow the designer to achieve a given power with less surface curvature, typically resulting in lower aberrations. On the other hand, most high-index flint glasses have higher dispersion, resulting in more chromatic aberration in polychromatic applications. They also typically have poorer chemical characteristics than lower-index crown glasses.

THERMAL CHARACTERISTICS

The thermal expansion coefficient can be particularly important in applications in which the part is subjected to high temperatures, such as high-intensity projection systems. This is also of concern when components must undergo large temperature cycles, such as in optical systems used outdoors.

MECHANICAL CHARACTERISTICS

The mechanical characteristics of a material are significant in many areas. They can affect how easy it is to fabricate the material into shape, which affects product cost. Scratch resistance is important if the component will require frequent cleaning. Shock and vibration resistance are important for military, aerospace, or certain industrial applications. Ability to withstand high pressure differentials is important for windows used in vacuum chambers.

CHEMICAL CHARACTERISTICS

The chemical characteristics of a material, such as acid or stain resistance, can also affect fabrication and durability. As with mechanical characteristics, chemical characteristics should be taken into account for optics used outdoors or in harsh conditions.

COST

Cost is almost always a factor to consider when specifying materials. Furthermore, the cost of some materials, such as UV-grade synthetic fused silica, increases sharply with larger diameters because of the difficulty in obtaining large pieces of the material.

OPTICAL PROPERTIES

The most important optical properties of a material are its internal and external transmittances, surface reflectance, and refractive indexe. The formulas that connect these variables in the on-axis case are presented below.

TRANSMISSION

External transmittance is the single-pass irradiance transmittance of an optical element. Internal transmittance is the single-pass irradiance transmittance in the absence of any surface reflection losses (i.e., transmittance of the material itself). External transmittance is of paramount importance when selecting optics for an image-forming lens system because external transmittance neglects multiple reflections between lens surfaces. Transmittance measured with an integrating sphere will be slightly higher. If T_e denotes the desired external irradiance transmittance, T_i the corresponding internal transmittance, t_1 the single-pass transmittance of the first surface, and t_2 the single-pass transmittance of the second surface, then

$$T_e = t_1 t_2 T_i = t_1 t_2 e^{-\mu t_c} \quad (2.1)$$

where e is the base of the natural system of logarithms, μ is the absorption coefficient of the lens material, and t_c is the lens center thickness. This allows for the possibility that the lens surfaces might have unequal transmittances (for example, one is coated and the other is not). Assuming that both surfaces are uncoated,

$$t_1 t_2 = 1 - 2r + r^2 \quad (2.2)$$

where

$$r = \left(\frac{n-1}{n+1}\right)^2 \quad (2.3)$$

is the single-surface single-pass irradiance reflectance at normal incidence as given by the Fresnel formula. The refractive index n must be known or calculated from the material dispersion formula found in the next section. These results are applicable to monochromatic. Both μ and n are functions of wavelength.

To calculate either T_i or the T_e for a lens at any wavelength of interest, first find the value of absorption coefficient μ. Typically, internal transmittance T_i is tabulated as a function of wavelength for two distinct thicknesses t_{c1} and t_{c2}, and m must be found from these.

Thus where the bar denotes averaging. In portions of the spectrum where absorption is strong, a value for T_i is typically given only for the lesser thickness. Then

$$\mu = -\frac{1}{t_c} \ln T_i \ . \quad (2.5)$$

When it is necessary to find transmittance at wavelengths other than those for which T_i is tabulated, use linear interpolation.

The on-axis T_e value is normally the most useful, but some applications require that transmittance be known along other ray paths, or that it be averaged over the entire lens surface. The method outlined above is easily extended to encompass such cases. Values of t_1 and t_2 must be found from complete Fresnel formulas for arbitrary angles of incidence. The angles of incidence will be different at the two surfaces; therefore, t_1 and t_2 will generally be unequal. Distance t_c, which becomes the surface-to-surface distance along a particular ray, must be determined by ray tracing. It is necessary to account separately for the *s*- and *p*-planes of polarization, and it is usually sufficient to average results for both planes at the end of the calculation.

REFRACTIVE INDEX AND DISPERSION

The Schott Optical Glass catalog offers nearly 300 different optical glasses. For lens designers, the most important difference among these glasses is the index of refraction and dispersion (rate of change of index with wavelength). Typically, an optical glass is specified by its index of refraction at a wavelength in the middle of the visible spectrum, usually 587.56 nm (the helium d-line), and by the Abbé v-value, defined to be

$v_d = (n_d-1)/(n_F-n_C)$. The designations F and C stand for 486.1 nm and 656.3 nm, respectively. Here, v_d shows how the index of refraction varies with wavelength. The smaller v_d is, the faster the rate of change is. Glasses are roughly divided into two categories: crowns and flints. Crown glasses are those with $n_d < 1.60$ and $v_d > 55$, or $n_d > 1.60$ and $v_d > 50$. The others are flint glasses.

The refractive index of glass from 365 to 2300 nm can be calculated by using the formula

$$n^2 - 1 = \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3} \quad (2.6)$$

Here λ, the wavelength, must be in micrometers, and the constants B_1 through C_3 are given by the glass manufacturer. Values for other glasses can be obtained from the manufacturer's literature. This equation yields an index value that is accurate to better than $1\text{x}10^{-5}$ over the entire transmission range, and even better in the visible spectrum.

OTHER OPTICAL CHARACTERISTICS

REFRACTIVE INDEX HOMOGENEITY

The tolerance for the refractive index within melt for all Schott fine annealed glass used in CVI Laser Optics catalog components is $\pm1\text{x}10^{-4}$. Furthermore, the refractive index homogeneity, a measure of deviation within a single piece of glass, is better than $\pm2\text{x}10^{-5}$.

STRIAE GRADE

Striae are thread-like structures representing subtle but visible differences in refractive index within an optical glass. Striae classes are specified in ISO 10110. All CVI Laser Optics catalog components that utilize Schott optical glass are specified to have striae that conform to ISO 10110 class 5 indicating that no visible striae, streaks, or cords are present in the glass.

STRESS BIREFRINGENCE

Mechanical stress in optical glass leads to birefringence (anisotropy in index of refraction) which can impair the optical performance of a finished component. Optical glass is annealed (heated and cooled) to remove any residual stress left over from the original manufacturing process. Schott Glass defines fine annealed glass to have a stress birefringence of less than or equal to 10 nm/cm for diameters less than 300 mm and for thicknesses less than or equal to 60 mm. For diameters between 300 and 600 mm and for thicknesses between 60 and 80 mm, stress birefringence would be less than or equal to 12 nm/cm.

APPLICATION NOTE

Fused-Silica Optics

Synthetic fused silica is an ideal optical material for many laser applications. It is transparent from as low as 180 nm to over 2.0 μm, has low coefficient of thermal expansion, and is resistant to scratching and thermal shock.

MECHANICAL AND CHEMICAL PROPERTIES

Mechanical and chemical properties of glass are important to lens manufacturers. These properties can also be significant to the user, especially when the component will be used in a harsh environment. Different polishing techniques and special handling may be needed depending on whether the glass is hard or soft, or whether it is extremely sensitive to acid or alkali.

To quantify the chemical properties of glasses, glass manufacturers rate each glass according to four categories: climatic resistance, stain resistance, acid resistance, and alkali and phosphate resistance.

CLIMATIC RESISTANCE

Humidity can cause a cloudy film to appear on the surface of some optical glass. Climatic resistance expresses the susceptibility of a glass to high humidity and high temperatures. In this test, glass is placed in a water vapor-saturated environment and subjected to a temperature cycle which alternately causes condensation and evaporation. The glass is given a rating from 1 to 4 depending on the amount of surface scattering induced by the test. A rating of 1 indicates little or no change after 30 hours of climatic change; a rating of 4 means a significant change occurred in less than 30 hours.

STAIN RESISTANCE

Stain resistance expresses resistance to mildly acidic water solutions, such as fingerprints or perspiration. In this test, a few drops of a mild acid are placed on the glass. A colored stain, caused by interference, will appear if the glass starts to decompose. A rating from 0 to 5 is given to each glass, depending on how much time elapses before stains occur. A rating of 0 indicates no observed stain in 100 hours of exposure; a rating of 5 means that staining occurred in less than 0.2 hours.

ACID RESISTANCE

Acid resistance quantifies the resistance of a glass to stronger acidic solutions. Acid resistance can be particularly important to lens manufacturers because acidic solutions are typically used to strip coatings from glass or to separate cemented elements. A rating from 1 to 4 indicates progressively less resistance to a pH 0.3 acid solution, and values from 51 to 53 are used for glass with too little resistance to be tested with such a strong solution.

ALKALI AND PHOSPHATE RESISTANCE

Alkali resistance is also important to the lens manufacturer since the polishing process usually takes place in an alkaline solution. Phosphate resistance is becoming more significant as users move away from cleaning methods that involve chlorofluorocarbons (CFCs) to those that may be based on traditional phosphate-containing detergents. In each case, a two-digit number is used to designate alkali or phosphate resistance. The first number, from 1 to 4, indicates the length of time that elapses before any surface change occurs in the glass, and the second digit reveals the extent of the change.

MICROHARDNESS

The most important mechanical property of glass is microhardness. A precisely specified diamond scribe is placed on the glass surface under a known force. The indentation is then measured. The Knoop and the Vickers microhardness tests are used to measure the hardness of a polished surface and a freshly fractured surface, respectively.

Knoop Hardness Values for Standard Optical Materials

Material	Knoop Hardness
Magnesium Fluoride	415
Calcium Fluoride	158
Fused Silica	522
BK7 (N-BK7)	610
Optical Crown Glass	542
Borosilicate Glass	480
Zerodur	620
Zinc Selenide	112
Silicon	1100
Germanium	780

APPLICATION NOTE

Glass Manufacturers

The catalogs of optical glass manufacturers contain products covering a very wide range of optical characteristics. However, it should be kept in mind that the glass types that exhibit the most desirable properties in terms of index of refraction and dispersion often have the least practical chemical and mechanical characteristics. Furthermore, poor chemical and mechanical attributes translate directly into increased component costs because working these sensitive materials increases fabrication time and lowers yield. Please contact us before specifying an exotic glass in an optical design so that we can advise you of the impact that that choice will have on part fabrication.

LENS MATERIALS

CVI Laser Optics lenses are made of synthetic fused silica, N-BK7 grade A fine annealed glass, and several other materials. The following table identifies the materials used in CVI Laser Optics lenses. Some of these materials are also used in prisms, mirror substrates, and other products.

Glass type designations and physical constants are the same as those published by Schott Glass. CVI Laser Optics occasionally uses corresponding glasses made by other glass manufacturers but only when this does not result in a significant change in optical properties.

The performance of optical lenses and prisms depends on the quality of the material used. No amount of skill during manufacture can eradicate striae, bubbles, inclusions, or variations in index. CVI Laser Optics takes considerable care in its material selection, using only first-class optical materials from reputable glass manufacturers. The result is reliable, repeatable, consistent performance.

The following physical constant values are reasonable averages based on historical experience. Individual material specimens may deviate from these means. Materials having tolerances more restrictive than those published in the rest of this chapter, or materials traceable to specific manufacturers, are available only on special request.

N-BK7 OPTICAL GLASS

A borosilicate crown glass, N-BK7, is the material used in many CVI Laser Optics products. N-BK7 performs well in chemical tests so that special treatment during polishing is not necessary. N-BK7, a relatively hard glass, does not scratch easily and can be handled without special precautions. The bubble and inclusion content of N-BK7 is very low, with a cross-section total less than 0.029 mm^2 per 100 cm^3. Another important characteristic of N-BK7 is its excellent transmittance, at wavelengths as low as 350 nm. Because of these properties, N-BK7 is used widely throughout the optics industry. A variant of N-BK7, designated UBK7, has transmission at wavelengths as low as 300 nm. This special glass is useful in applications requiring a high index of refraction, the desirable chemical properties of N-BK7, and transmission deeper into the ultraviolet range. N-BK7 refers to the lead and arsenic-free version of BK7, with most optical properties identical between the two.

CVI Laser Optics reserves the right, without prior notice, to make material changes or substitution on any optical component.

Lens Material Table

Material	Product Code	
Synthetic Fused Silica UV Grade	LUP-UV	LUK-UV
	PLCX-UV	PLCC-UV
	LUD-UV	LUB-UV
	BICX-UV	BICC-UV
	RCX-UV	RCC-UV
	SCX-UV	SCC-UV
	CLCX-UV	CLCC-UV
	BFPL-UV	
Synthetic Fused Silica Excimer Grade	PLCX-EUV	
N-BK7 Grade A Fine Annealed	LPX-C	LPK-C
	PLCX-C	PLCC-C
	LDX-C	LDK-C
	BICX-C	BICC-C
	LCP-C	LCN-C
	RCX-C	RCC-C
	SCX-C	SCC-C
	CLCC-C	CLCX-C
	MENP-C	MENN-C
	BFPL-C	
LaSFN9 Grade A Fine Annealed	**LMS** and selected **LPX** series	
SK11 and SF5 Grade A Fine Annealed	LAI	
BaK1 Grade A Fine Annealed	selected **LPX** series	
SF11 Grade-A Fine Annealed	PLCX-SF11	PLCC-SF11
	LAP	LAN
Optical Crown Glass	LAG	
Low-Expansion Borosilicate Glass (LEBG)	selected **CMP** series	
Sapphire	PXS	
Calcium Fluoride	PLCX-CFUV	PLCX-CFIR
	RCX-CFUV	RCC-CFUV
Magnesium Fluoride	BICX-MF	PLCX-MF
Zinc Selenide	PLCX-ZnSe	MENP-ZnSe
Various Glass Combinations (including lead- and arsenic-free glasses)	LAO	LAL
	AAP	FAP
	HAP	HAN
	YAP	YAN
	LBM	LSL
	GLC	OAS

MAGNESIUM FLUORIDE

Magnesium Fluoride (MgF_2) is a tetragonal positive birefringent crystal grown using the vacuum Stockbarger technique. MgF_2 is a rugged material resistant to chemical etching as well as mechanical and thermal shock. High-vacuum UV transmission and resistance to laser damage make MgF_2 a popular choice for VUV and excimer laser windows, polarizers, and lenses.

Specifications

Density: 3.177 g/cm^3

Young's Modulus: 138.5 GPa

Poisson's Ratio: 0.271

Knoop Hardness: 415

Coefficient of Thermal Expansion:
8.48x10^{-6}/°C (perpendicular to c axis)
13.70x10^{-6}/°C (parallel to c axis)

Melting Point: 1585°C

Dispersion Constants (Ordinary Ray):
B_1=4.87551080x10^{-1}
B_2=3.98750310x10^{-1}
B_3=2.31203530
C_1=1.88217800x10^{-3}
C_2=8.95188847x10^{-3}
C_3=5.66135591x10^{2}

Dispersion Constants (Extraordinary Ray):
B_1=4.13440230x10^{-1}
B_2=5.04974990x10^{-1}
B_3=2.49048620
C_1=1.35737865x10^{-3}
C_2=8.23767167x10^{-3}
C_3=5.65107755x10^{2}

Refractive Index of Magnesium Fluoride

Wavelength (nm)	Index of Refraction Ordinary Ray (n_O)	Index of Refraction Extraordinary Ray (n_E)
193	1.42767	1.44127
213	1.41606	1.42933
222	1.41208	1.42522
226	1.41049	1.42358
244	1.40447	1.41735
248	1.40334	1.41618
257	1.40102	1.41377
266	1.39896	1.41164
280	1.39620	1.40877
308	1.39188	1.40429
325	1.38983	1.40216
337	1.38859	1.40086
351	1.38730	1.39952
355	1.38696	1.39917

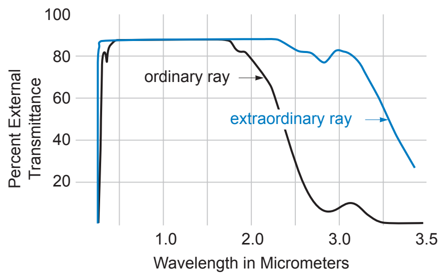
CALCIUM FLUORIDE

Calcium fluoride (CaF_2), a cubic single-crystal material, has widespread applications in the ultraviolet and infrared spectrum. CaF_2 is an ideal material for use with excimer lasers. It can be manufactured into windows, lenses, prisms, and mirror substrates.

CaF_2 transmits over the spectral range of about 130 nm to 10 mm. Traditionally, it has been used primarily in the infrared, rather than in the ultraviolet. CaF_2 occurs naturally and can be mined. It is also produced synthetically using the time- and energy-consuming Stockbarger method. Unfortunately, achieving acceptable deep ultraviolet transmission and damage resistance in CaF_2 requires much greater material purity than in the infrared, and it completely eliminates the possibility of using mined material.

To meet the need for improved component lifetime and transmission at 193 nm and below, manufacturers have introduced a variety of inspection and processing methods to identify and remove various impurities at all stages of the production process. The needs for improved material homogeneity and stress birefringence have also caused producers to make alterations to the traditional Stockbarger approach. These changes allow tighter temperature control during crystal growth, as well as better regulation of vacuum and annealing process parameters.

Excimer-grade CaF_2 provides the combination of deep ultraviolet transmission (down to 157 nm), high damage threshold, resistance to color-center formation, low fluorescence, high homogeneity, and low stress-birefringence characteristics required for the most demanding deep ultraviolet applications.



External transmittance for 5 mm thick uncoated calcium fluoride

Specifications

Density: 3.18 g/cm³ @ 25°C

Young's Modulus: 1.75x107 psi

Poisson's Ratio: 0.26

Knoop Hardness: 158

Thermal Coefficient of Refraction: dn/dT =–10.6x10⁻⁶/°C

Coefficient of Thermal Expansion: 18.9x10⁻⁶/°C (20°–60°C)

Melting Point: 1360°C

Dispersion Constants:
B1 = 0.5675888
B2 = 0.4710914
B3 = 3.8484723
C1 = 0.00252643
C2 = 0.01007833
C3 = 1200.5560

Refractive Index of Calcium Fluoride

Wavelength (μm)	Index of Refraction
0.193	1.501
0.248	1.468
0.257	1.465
0.266	1.462
0.308	1.453
0.355	1.446
0.486	1.437
0.587	1.433
0.65	1.432
0.7	1.431
1.0	1.428
1.5	1.426
2.0	1.423
2.5	1.421
3.0	1.417
4.0	1.409
5.0	1.398
6.0	1.385
7.0	1.369
8.0	1.349

SUPRASIL 1

Suprasil 1 is a type of fused silica with high chemical purity and excellent multiple axis homogeneity. With a metallic content less than 8 ppm, Suprasil 1 has superior UV transmission and minimal fluorescence. Suprasil 1 is primarily used for low fluorescence UV windows, lenses and prisms where multiple axis homogeneity is required.

Specifications

Abbé Constant: 67.8±0.5

Change of Refractive Index with Temperature (0° to 700°C): 1.28×10^{-5}/°C

Homogeneity (maximum index variation over 10-cm aperture): 2×10^{-5}

Knoop Hardness: 590

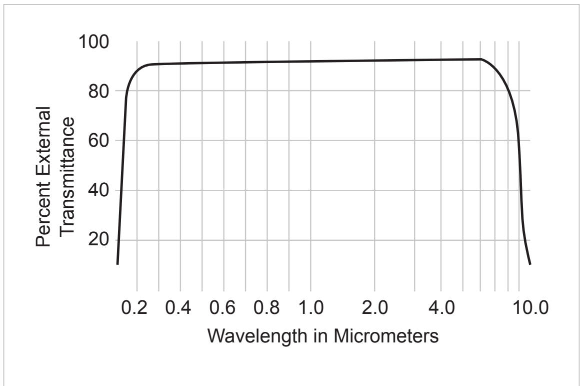
Density: 2.20 g/cm^3 @ 25°C

Continuous Operating Temperature: 900°C maximum

Coefficient of Thermal Expansion: 5.5×10^{-7}/°C

Specific Heat: 0.177 cal/g/°C @ 25°C

Dispersion Constants:
B_1 = 0.6961663
B_2 = 0.4079426
B_3 = 0.8974794
C_1 = 0.0046791
C_2 = 0.0135121
C_3 = 97.9340025



External transmittance for 5 mm thick uncoated calcium fluoride

Refractive Index of Suprasil 1*

Wavelength (nm)	Index of Refraction
193.4	1.56013
248.4	1.50833
266.0	1.49968
308.0	1.48564
325.0	1.48164
337.0	1.47921
365.5	1.47447
404.7	1.46962
435.8	1.46669
441.6	1.46622
447.1	1.46578
486.1	1.46313
488.0	1.46301
514.5	1.46156
532.0	1.46071
546.1	1.46008
587.6	1.45846
632.8	1.45702
656.3	1.45637
694.3	1.45542
752.5	1.45419
905.0	1.45168
1064.0	1.44963
1153.0	1.44859
1319.0	1.44670

* Accuracy ±3 x 10^{-5}

UV-GRADE SYNTHETIC FUSED SILICA

Synthetic fused silica (amorphous silicon dioxide), by chemical combination of silicon and oxygen, is an ideal optical material for many applications. It is transparent over a wide spectral range, has a low coefficient of thermal expansion, and is resistant to scratching and thermal shock.

The synthetic fused silica materials used by CVI Laser Optics are manufactured by flame hydrolysis to extremely high standards. The resultant material is colorless and non-crystalline, and it has an impurity content of only about one part per million.

Synthetic fused silica lenses offer a number of advantages over glass or fused quartz:

- Greater ultraviolet and infrared transmission
- Low coefficient of thermal expansion, which provides stability and resistance to thermal shock over large temperature excursions
- Wider thermal operating range
- Increased hardness and resistance to scratching
- Much higher resistance to radiation darkening from ultraviolet, x-rays, gamma rays, and neutrons.

UV-grade synthetic fused silica (UVGSFS or Suprasil 1) is selected to provide the highest transmission (especially in the deep ultraviolet) and very low fluorescence levels (approximately 0.1% that of fused natural quartz excited at 254 nm). UV-grade synthetic fused silica does not fluoresce in response to wavelengths longer than 290 nm. In deep ultraviolet applications, UV-grade synthetic fused silica is an ideal choice. Its tight index tolerance ensures highly predictable lens specifications.

The batch-to-batch internal transmittance of synthetic fused silica may fluctuate significantly in the near infrared between 900 nm and 2.5 μm due to resonance absorption by OH chemical bonds. If the optic is to be used in this region, Infrasil 302 may be a better choice.

Specifications

Abbé Constant: 67.8±0.5

Change of Refractive Index with Temperature (0° to 700°C): 1.28×10^{-5}/°C

Homogeneity (maximum index variation over 10-cm aperture): 2×10^{-5}

Density: 2.20 g/cm^3 @ 25°C

Knoop Hardness: 522

Continuous Operating Temperature: 900°C maximum

Coefficient of Thermal Expansion: 5.5×10^{-7}/°C

Specific Heat: 0.177 cal/g/°C @ 25°C

Dispersion Constants:
B_1 = 0.6961663
B_2 = 0.4079426
B_3 = 0.8974794
C_1 = 0.0046791
C_2 = 0.0135121
C_3 = 97.9340025

Refractive Index of UV-Grade Synthetic Fused Silica*

Wavelength (nm)	Index of Refraction
180.0	1.58529
190.0	1.56572
200.0	1.55051
213.9	1.53431
226.7	1.52275
230.2	1.52008
239.9	1.51337
248.3	1.50840
265.2	1.50003
275.3	1.49591
280.3	1.49404
289.4	1.49099
296.7	1.48873
302.2	1.48719
330.3	1.48054
340.4	1.47858
351.1	1.47671
361.1	1.47513
365.0	1.47454
404.7	1.46962
435.8	1.46669

* Accuracy ±3 x 10^{-5}

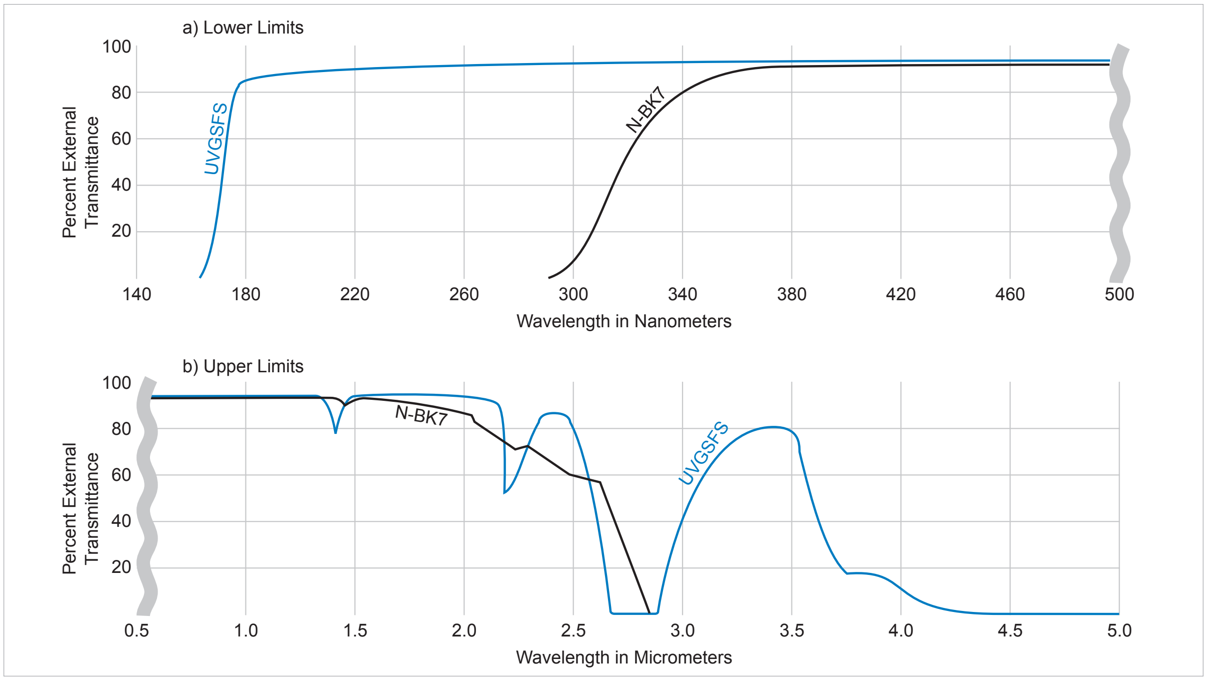
Refractive Index of UV-Grade Synthetic Fused Silica*

Wavelength (nm)	Index of Refraction
441.6	1.46622
457.9	1.46498
476.5	1.46372
486.1	1.46313
488.0	1.46301
496.5	1.46252
514.5	1.46156
532.0	1.46071
546.1	1.46008
587.6	1.45846
589.3	1.45840
632.8	1.45702
643.8	1.45670
656.3	1.45637
694.3	1.45542
706.5	1.45515
786.0	1.45356
820.0	1.45298

Refractive Index of UV-Grade Synthetic Fused Silica*

Wavelength (nm)	Index of Refraction
830.0	1.45282
852.1	1.45247
904.0	1.45170
1014.0	1.45024
1064.0	1.44963
1100.0	1.44920
1200.0	1.44805
1300.0	1.44692
1400.0	1.44578
1500.0	1.44462
1550.0	1.44402
1660.0	1.44267
1700.0	1.44217
1800.0	1.44087
1900.0	1.43951
2000.0	1.43809
2100.0	1.43659

* Accuracy ±3 x 10^{-5}



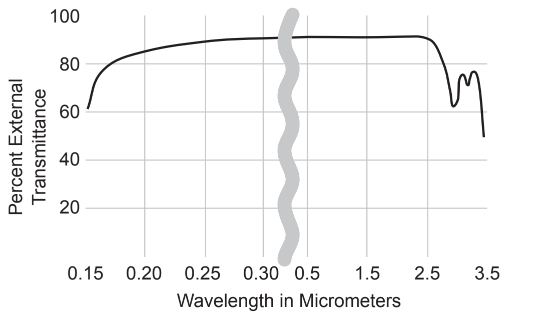
Comparison of uncoated external transmittances for UVGSFS and N-BK7, all 10 mm in thickness

CRYSTAL QUARTZ

Crystal quartz is a positive uniaxial birefringent single crystal grown using a hydrothermal process. Crystal quartz from CVI Laser Optics is selected to minimize inclusions and refractive index variation. Crystal quartz is most commonly used for high-damage-threshold waveplates and solarization-resistant Brewster windows for argon lasers.

The dispersion for the index of refraction is given by the Laurent series shown below.

$$\eta^2 = A_0 + A_1\lambda^2 + \frac{A_2}{\lambda^2} + \frac{A_3}{\lambda^4} + \frac{A_4}{\lambda^6} + \frac{A_5}{\lambda^8}$$



External transmittance for 10 mm thick uncoated crystal quartz

Specifications

Transmission Range: 0.170–2.8 μm

Melting Point: 1463°C

Knoop Hardness: 741

Density: 2.64 g/cm³

Young's Modulus, Perpendicular: 76.5 GPa

Young's Modulus, Parallel: 97.2 GPa

Thermal Expansion Coefficient, Perpendicular: 13.2×10^{-6}/°C

Thermal Expansion Coefficient, Parallel: 7.1×10^{-6}/°C

Dispersion Constants (Ordinary Ray):
$A_0=2.35728$
$A_1=41.17000 \times 10^{-2}$
$A_2=1.05400 \times 10^{-2}$
$A_3=1.34143 \times 10^{-4}$
$A_4=44.45368 \times 10^{-7}$
$A_5=5.92362 \times 10^{-8}$

Dispersion Constants (Extraordinary Ray):
$A_0=2.38490$
$A_1=41.25900 \times 10^{-2}$
$A_2=1.07900 \times 10^{-2}$
$A_3=1.65180 \times 10^{-4}$
$A_4=41.94741 \times 10^{-7}$
$A_5=9.36476 \times 10^{-8}$

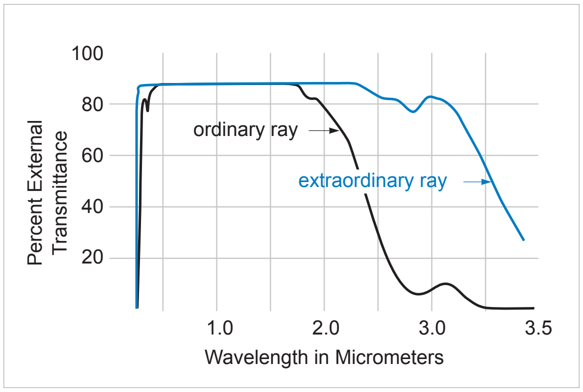
Refractive Index of Crystal Quartz

Wavelength (nm)	Index of Refraction Ordinary Ray (n_O)	Index of Refraction Extraordinary Ray (n_E)
193	1.66091	1.67455
213	1.63224	1.64452
222	1.62238	1.63427
226	1.61859	1.63033
244	1.60439	1.61562
248	1.60175	1.61289
257	1.59620	1.60714
266	1.59164	1.60242
280	1.58533	1.59589
308	1.57556	1.58577
325	1.57097	1.58102
337	1.56817	1.57812
351	1.56533	1.57518
355	1.56463	1.57446
400	1.55772	1.56730
442	1.55324	1.56266
458	1.55181	1.56119
488	1.54955	1.55885
515	1.54787	1.55711
532	1.54690	1.55610
590	1.54421	1.55333
633	1.54264	1.55171
670	1.54148	1.55051
694	1.54080	1.54981
755	1.53932	1.54827
780	1.53878	1.54771
800	1.53837	1.54729
820	1.53798	1.54688
860	1.53724	1.54612
980	1.53531	1.54409

CALCITE

Calcite ($CaCO_3$) is a naturally occurring negative uniaxial crystal which exhibits pronounced birefringence. Strong birefringence and a wide transmission range have made this mineral popular for making polarizing prisms for over 100 years. Although it can now be grown artificially in small quantities, most optical calcite is mined in Mexico, Africa, and Siberia. Finding optical grade crystals remains a time-consuming task requiring special skills. Cutting and polishing calcite is also challenging due to the softness of the mineral and its tendency to cleave easily. These factors explain why, even many years after the techniques were developed, calcite prisms remain expensive when compared to other types of polarizers.

Since calcite is a natural crystal, the transmission will vary from piece to piece. In general, a 10 mm thick sample will fall within the following ranges: 350 nm, 40 – 45%; 400 nm, 70 – 75%; 500 – 2300 nm, 86 – 88%.



Typical external transmittance for 10 mm thick calcite

Specifications

Density: 2.71 g/cm^3

Mohs Hardness: 3

Melting Point: 1339 °C

Dispersion Constants (Ordinary Ray):

B_1 = 1.56630
B_2 = 1.41096
B_3 = 0.28624
C_1 = 105.58893
C_2 = 0.01583669
C_3 =40.01182893

Dispersion Constants (Extraordinary Ray):

B_1 = 8.418192x10^{-5}
B_2 = 1.183488
B_3 = 0.03413054
C_1 = 0.3468576
C_2 = 7.741535x10^{-3}
C_3 = 12.185616

Refractive Index of Calcite

Wavelength (nm)	Index of Refraction Ordinary Ray (n_O)	Index of Refraction Extraordinary Ray (n_E)
250	1.76906	1.53336
350	1.69695	1.50392
450	1.67276	1.49307
550	1.66132	1.48775
650	1.65467	1.48473
750	1.65041	1.48289
850	1.64724	1.48157
950	1.64470	1.48056
1050	1.64260	1.47980
1150	1.64068	1.47916
1250	1.63889	1.47792
1350	1.63715	1.47803
1450	1.63541	1.47765
1550	1.63365	1.47722
1650	1.63186	1.47681
1750	1.62995	1.47638
1850	1.62798	1.47597
1950	1.62594	1.47555
2050	1.62379	1.47513
2150	1.62149	1.47486
2250	1.61921	1.47482
2350	1.61698	1.47528

SCHOTT GLASS

The following tables list the most important optical and physical constants for Schott optical glass types BK7, SF11, LaSFN9, BaK1, and F2, with N-BK7 and N-BaK1 denoting the lead and arsenic-free versions of BK7 and BaK1. These types are used in most CVI Laser Optics simple lens products and prisms. Index of refraction as well as the most commonly required chemical characteristics and mechanical constants, are listed. Further numerical data and a more detailed discussion of the various testing processes can be found in the Schott Optical Glass catalog.

Physical Constants of Schott Glasses

	Glass Type				
	BK7 (N-BK7)	SF11	LaSFN9	BaK1 (N-BaK1)	F2
Melt-to-Melt Mean Index Tolerance	±0.0005	±0.0005	±0.0005	±0.0005	±0.0005
Stress Birefringence nm/cm Yellow Light	10	10	10	10	10
Abbé Factor (v_d)	64.17	25.76	32.17	57.55	36.37
Constants of Dispersion Formula:					
B_1	1.03961212	1.73848403	1.97888194	1.12365662	1.34533359
B_2	2.31792344x10^{-1}	3.11168974x10^{-1}	3.20435298x10^{-1}	3.09276848x10^{-1}	2.09073176x10^{-1}
B_3	1.01046945	1.17490871	1.92900751	8.81511957x10^{-1}	9.37357162x10^{-1}
C_1	6.00069867x10^{-3}	1.36068604x10^{-4}	1.18537266x10^{-2}	6.44742752x10^{-3}	9.97743871x10^{-3}
C_2	2.00179144x10^{-2}	6.15960463x10^{-2}	5.27381770x10^{-2}	2.22284402x10^{-2}	4.70450767x10^{-2}
C_3	1.03560653x102	1.21922711x102	1.66256540x102	1.07297751x102	1.11886764x102
Density (g/cm^3)	2.51	4.74	4.44	3.19	3.61
Coefficient of Linear Thermal Expansion (cm/°C):					
–30° to +70°C	7.1x104^{6}	6.1x104^{6}	7.4x104^{6}	7.6x104^{6}	8.2x104^{6}
+20° to +300°C	8.3x104^{6}	6.8x104^{6}	8.4x104^{6}	8.6x104^{6}	9.2x104^{6}
Transition Temperature	557°C	505°C	703°C	592°C	438°C
Young's Modulus (dynes/mm^2)	8.20x10^{9}	6.60x10^{9}	1.09x10^{10}	7.30x10^{9}	5.70x109
Climate Resistance	2	1	2	2	1
Stain Resistance	0	0	0	1	0
Acid Resistance	1.0	1.0	2.0	3.3	1.0
Alkali Resistance	2.0	1.2	1.0	1.2	2.3
Phosphate Resistance	2.3	1.0	1.0	2.0	1.3
Knoop Hardness	610	450	630	530	420
Poisson's Ratio	0.206	0.235	0.286	0.252	0.220

Refractive Index of Schott Glass

Wavelength λ (nm)	Refractive Index, *n*					Fraunhofer Designation	Source	Spectral Region
	BK7 (N-BK7)	SF11	LaSFN9	BaK1 (N-BaK1)	F2			
351.1	1.53894	—	—	1.60062	1.67359		Ar laser	UV
363.8	1.53649	—	—	1.59744	1.66682		Ar laser	UV
404.7	1.53024	1.84208	1.89844	1.58941	1.65064	h	Hg arc	Violet
435.8	1.52668	1.82518	1.88467	1.58488	1.64202	g	Hg arc	Blue
441.6	1.52611	1.82259	1.88253	1.58415	1.64067		HeCd laser	Blue
457.9	1.52461	1.81596	1.87700	1.58226	1.63718		Ar laser	Blue
465.8	1.52395	1.81307	1.87458	1.58141	1.63564		Ar laser	Blue
472.7	1.52339	1.81070	1.87259	1.58071	1.63437		Ar laser	Blue
476.5	1.52309	1.80946	1.87153	1.58034	1.63370		Ar laser	Blue
480.0	1.52283	1.80834	1.87059	1.58000	1.63310	F′	Cd arc	Blue
486.1	1.52238	1.80645	1.86899	1.57943	1.63208	F	H_2 arc	Blue
488.0	1.52224	1.80590	1.86852	1.57927	1.63178		Ar laser	Blue
496.5	1.52165	1.80347	1.86645	1.57852	1.63046		Ar laser	Green
501.7	1.52130	1.80205	1.86524	1.57809	1.62969		Ar laser	Green
514.5	1.52049	1.79880	1.86245	1.57707	1.62790		Ar laser	Green
532.0	1.51947	1.79479	1.85901	1.57580	1.62569		Nd laser	Green
546.1	1.51872	1.79190	1.85651	1.57487	1.62408	e	Hg arc	Green
587.6	1.51680	1.78472	1.85025	1.57250	1.62004	d	He arc	Yellow
589.3	1.51673	1.78446	1.85002	1.57241	1.61989	D	Na arc	Yellow
632.8	1.51509	1.77862	1.84489	1.57041	1.61656		HeNe laser	Red
643.8	1.51472	1.77734	1.84376	1.56997	1.61582	C′	Cd arc	Red
656.3	1.51432	1.77599	1.84256	1.56949	1.61503	C	H_2 arc	Red
694.3	1.51322	1.77231	1.83928	1.56816	1.61288		Ruby laser	Red
786.0	1.51106	1.76558	1.83323	1.56564	1.60889			IR
821.0	1.51037	1.76359	1.83142	1.56485	1.60768			IR
830.0	1.51020	1.76311	1.83098	1.56466	1.60739		GaAlAs	laser IR
852.1	1.50980	1.76200	1.82997	1.56421	1.60671	s	Ce arc	IR
904.0	1.50893	1.75970	1.82785	1.56325	1.60528		GaAs laser	IR
1014.0	1.50731	1.75579	1.82420	1.56152	1.60279	t	Hg arc	IR
1060.0	1.50669	1.75445	1.82293	1.56088	1.60190		Nd laser	IR
1300.0	1.50370	1.74901	1.81764	1.55796	1.59813		InGaAsP laser	IR
1500.0	1.50127	1.74554	1.81412	1.55575	1.59550			IR
1550.0	1.50065	1.74474	1.81329	1.55520	1.59487			IR
1970.1	1.49495	1.73843	1.80657	1.55032	1.58958		Hg arc	IR
2325.4	1.48921	1.73294	1.80055	1.54556	1.58465		Hg arc	IR

OPTICAL CROWN GLASS

In optical crown glass, a low-index commercial-grade glass, the index of refraction, transmittance, and homogeneity are not controlled as carefully as they are in optical-grade glasses such as N-BK7. Optical crown glass is suitable for applications in which component tolerances are fairly loose, and as a substrate material for mirrors.

Specifications

Glass Type Designation: B270

Abbé Constant: 58.5

Dispersion: $(n_F - n_C) = 0.0089$

Knoop Hardness: 542

Density: 2.55 g/cm^3 @ 23°C

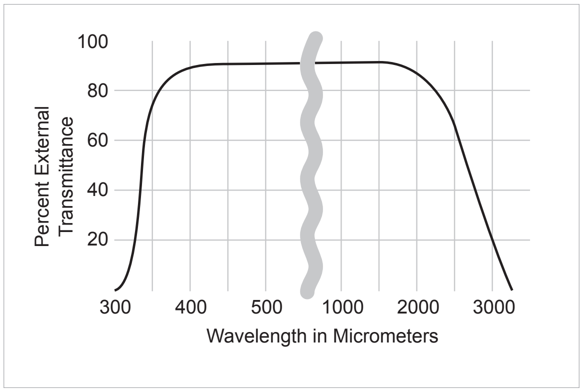
Young's Modulus: 71.5 kN/mm^2

Specific Heat: 0.184 cal/g/°C (20°C to 100°C)

Coefficient of Thermal Expansion: 93.3x10^{-7}/°C (20°C to 300°C)

Transformation Temperature: 521°C

Softening Point: 708°C



External transmittance for 10 mm thick uncoated optical crown glass

Refractive Index of Optical Crown Glass

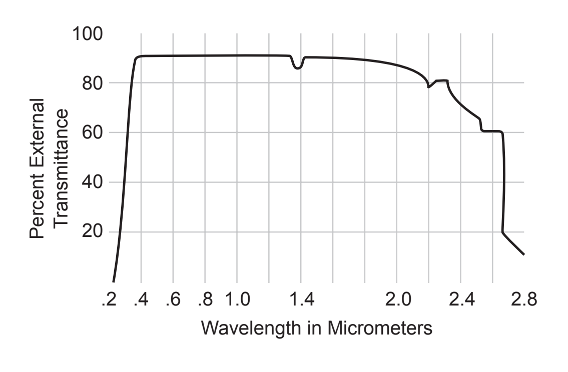
Wavelength (nm)	Index of Refraction	Fraunhofer Designation	Source	Spectral Region
435.8	1.53394	g	Hg arc	Blue
480.0	1.52960	F′	Cd arc	Blue
486.1	1.52908	F	H_2 arc	Blue
546.1	1.52501	e	Hg arc	Green
587.6	1.52288	d	He arc	Yellow
589.0	1.52280	D	Na arc	Yellow
643.8	1.52059	C′	Cd arc	Red
656.3	1.52015	C	H_2 arc	Red

Transmission Values for 6 mm thick Sample

Wavelength (nm)	Transmission (%)
300.0	0.3
310.0	7.5
320.0	30.7
330.0	56.6
340.0	73.6
350.0	83.1
360.0	87.2
380.0	88.8
400.0	90.6
450.0	90.9
500.0	91.4
600.0	91.5

LOW-EXPANSION BOROSILICATE GLASS

The most well-known low-expansion borosilicate glass (LEBG) is Pyrex® made by Corning. It is well suited for applications in which high temperature, thermal shock, or resistance to chemical attack are primary considerations. On the other hand, LEBG is typically less homogeneous and contains more striae and bubbles than optical glasses such as N-BK7. This material is ideally suited to such tasks as mirror substrates, condenser lenses for high-power illumination systems, or windows in high-temperature environments. Because of its low cost and excellent thermal stability, it is the standard material used in test plates and optical flats. The transmission of LEBG extends into the ultraviolet and well into the infrared. The index of refraction in this material varies considerably from batch to batch. Typical values are shown in the accompanying table.



External transmittance for 8 mm thick uncoated low-expansion borosilicate glass

Specifications

Abbé Constant: 66

Knoop Hardness: 480

Density: 2.23 g/cm^3 @ 25°C

Young's Modulus: 5.98x109 dynes/mm^2

Poisson's Ratio: 0.20

Specific Heat: 0.17 cal/g/°C @ 25°C

Coefficient of Thermal Expansion: 3.25x10^{-6}/°C (0°–300°C)

Softening Point: 820°C

Melting Point: 1250°C

Low-Expansion Borosilicate Glass

Wavelength (nm)	Index of Refraction	Fraunhofer Designation	Source	Spectral Region
486.1	1.479	F	H_2 arc	Blue
514.5	1.477		Ar laser	Green
546.1	1.476	e	Hg arc	Green
587.6	1.474	d	Na arc	Yellow
643.8	1.472	C′	Cd arc	Red

ZERODUR®

Many optical applications require a substrate material with a near-zero coefficient of thermal expansion and/or excellent thermal shock resistance. ZERODUR® with its very small coefficient of thermal expansion at room temperature is such a material.

ZERODUR, which belongs to the glass-ceramic composite class of materials, has both an amorphous (vitreous) component and a crystalline component. This Schott glass is subjected to special thermal cycling during manufacture so that approximately 75% of the vitreous material is converted to the crystalline quartz form. The crystals are typically only 50 nm in diameter, and ZERODUR appears reasonably transparent to the eye because the refractive indices of the two phases are almost identical.

Typical of amorphous substances, the vitreous phase has a positive coefficient of thermal expansion. The crystalline phase has a negative coefficient of expansion at room temperature. The overall linear thermal expansion coefficient of the combination is almost zero at useful temperatures.

The figure below shows the variation of expansion coefficient with temperature for a typical sample. The actual performance varies very slightly, batch to batch, with the room temperature expansion coefficient in the range of ±0.15x10^{-6}/°C. By design, this material exhibits a change in the sign of the coefficient near room temperature. A comparison of the thermal expansion coefficients of ZERODUR and fused silica is shown in the figure. ZERODUR is markedly superior over a large temperature range, and consequently, makes ideal mirror substrates for such stringent applications as multiple-exposure holography, holographic and general interferometry, manipulation of moderately powerful laser beams, and space-borne imaging systems.

Specifications

Abbé Constant: 66

Dispersion: $(n_F - n_C)$ = 0.00967

Knoop Hardness: 620

Density: 2.53 g/cm^3 @ 25°C

Young's Modulus: 9.1x109 dynes/mm^2

Poisson's Ratio: 0.24

Specific Heat: 0.196 cal/g/°C

Coefficient of Thermal Expansion:
0.0580.10x10^{-6}/° (20°–300°C)

Maximum Temperature: 600°C

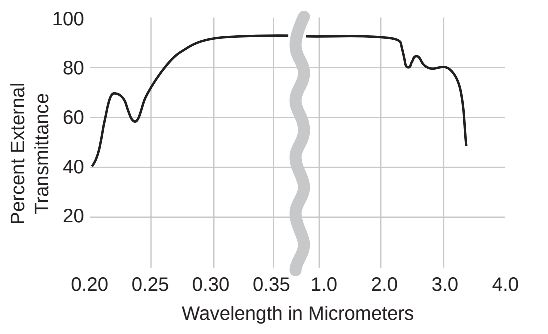
Refractive Index of ZERODUR®

Wavelength (nm)	Index of Refraction	Fraunhofer Designation
435.8	1.5544	g
480.0	1.5497	F′
486.1	1.5491	F
546.1	1.5447	e
587.6	1.5424	d
643.8	1.5399	C′
656.3	1.5394	C

INFRASIL 302

Infrasil 302 is an optical-quality quartz glass made by fusing natural quartz crystals in an electric oven. It combines excellent physical properties with excellent optical characteristics, especially in the near infrared region (1 to 3 μm) because it does not exhibit the strong OH absorption bands typical of synthetic fused silica.

Infrasil 302 is homogeneous in the primary functional direction. Weak striations, if any, are parallel to the major faces and do not affect optical performance.



External transmittance for 10 mm thick uncoated Infrasil 302

Specifications

OH content: <8 ppm

Knoop Hardness: 590

Thermal Expansion Coefficient: $0.58x10^{-6}$/°C (0°C to 200°C)

Bubble class: 0

Maximum bubble diameter: ≤0.15 mm typical

Optical Homogeneity:

Granular Structure: None

Striations: In all three dimensions free of striations

Index Homogeneity: In all three dimensions guaranteed total $\Delta n \leq 5x10^{-6}$

Spectral Transmittance: Very weak absorption band occur at wavelengths arouns 1.39 mm, 2.2 mm, and 2.72 μm according to an OH content of ≤8 ppm (weight).

Refractive Index of Infrasil 302

Wavelength (nm)	Index of Refraction
435.8	1.46681
486.1	1.46324
587.6	1.45856
656.3	1.45646

SAPPHIRE

Sapphire is a superior window material in many ways. Because of its extreme surface hardness, sapphire can be scratched by only a few substances other than itself (such as diamond or boron nitride). Chemically inert and insoluble in almost everything except at highly elevated temperatures, sapphire can be cleaned with impunity. For example, even hydrogen fluoride fails to attack sapphire at temperatures below 300°C. Sapphire exhibits high internal transmittance all the way from 150 nm (vacuum ultraviolet) to 6 µm (mid-infrared). Because of its great strength, sapphire windows can safely be made much thinner than windows of other glass types, and therefore are useful even at wavelengths that are very close to their transmission limits. Because of the exceptionally high thermal conductivity of sapphire, thin windows can be very effectively cooled by forced air or other methods. Conversely, sapphire windows can easily be heated to prevent condensation.

Sapphire is single-crystal aluminum oxide (Al_2O_3). Because of its hexagonal crystalline structure, sapphire exhibits anisotropy in many optical and physical properties. The exact characteristics of an optical component made from sapphire depend on the orientation of the optic axis or c-axis relative to the element surface. Sapphire exhibits birefringence, a difference in index of refraction in orthogonal directions. The difference in index is 0.008 between light traveling along the optic axis and light traveling perpendicular to it.

The transmission of sapphire is limited primarily by losses caused by surface reflections. The high index of sapphire makes magnesium fluoride almost an ideal single-layer antireflection coating. When a single layer of magnesium fluoride is deposited on sapphire and optimized for 550 nm, total transmission of a sapphire component can be kept above 98% throughout the entire visible spectrum.

Specifications

Density: 3.98 g/cm^3 @ 25°C

Young's Modulus: 3.7x1010 dynes/mm^2

Poisson's Ratio: –0.02

Mohs Hardness: 9

Specific Heat: 0.18 cal/g/°C @ 25°C

Coefficient of Thermal Expansion: 7.7x10 /°C (0°–500°C)

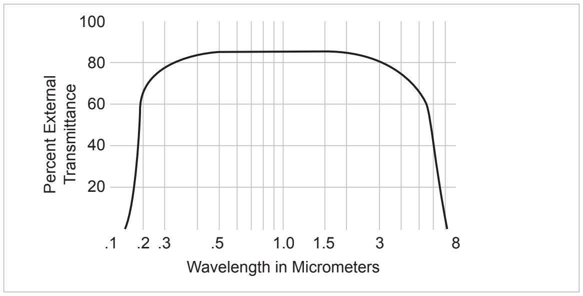
Softening Point: 1800°C

Dispersion Constants (Ordinary Ray):
B_1 = 1.4313493
B_2 = 0.65054713
B_3 = 5.3414021
C_1 = 0.00527993
C_2 = 0.01423827
C_3 = 325.0178

Dispersion Constants (Extraordinary Ray):
B_1 = 1.5039759
B_2 = 0.55069141
B_3 = 6.5927379
C_1 = 0.00548026
C_2 = 0.01479943
C_3 = 402.8951

Refractive Index of Sapphire

Wavelength (nm)	Index of Refraction Ordinary Ray (n_O)	Index of Refraction Extraordinary Ray (n_E)
265.2	1.83359	1.82411
351.1	1.79691	1.78823
404.7	1.78573	1.77729
488.0	1.77533	1.76711
514.5	1.77304	1.76486
532.0	1.77170	1.76355
546.1	1.77071	1.76258
632.8	1.76590	1.75787
1550.0	1.74618	1.73838
2000.0	1.73769	1.72993



External transmittance for 1 mm thick uncoated sapphire

ZINC SELENIDE

ZnSe is produced as microcrystalline sheets by synthesis from H_2Se gas and zinc vapor. It has a remarkably wide transmission range and is used extensively in CO_2 laser optics.

Specifications

Transmission Range: 0.5–22 μm

Refractive Index Inhomogeneity @ 633 nm: <3x10^{-6}

Temperature Coefficient of Refractive Index @ 10.6 μm: 61x10^{-6}/°C

Bulk Absorption Coefficient @ 10 μm: 0.0004/cm

Melting Point: 1520°C

Knoop Hardness: 112

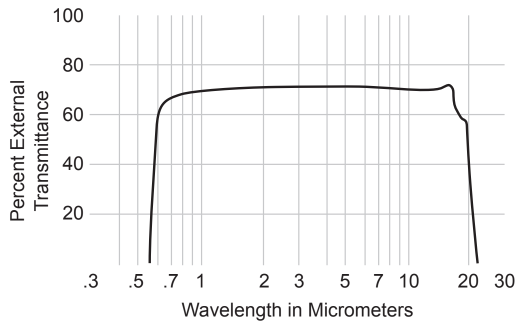
Density: 5.27 g/cm^3

Rupture Modulus: 55.2 MPa

Young's Modulus: 67.2 GPa

Fracture Toughness: 0.5 MPa/m

Thermal Expansion: Coefficient 7.6x10^{-6}/°C



External transmittance for 10 mm thick uncoated zinc selenide

Refractive Index of Zinc Selenide

Wavelength (μm)	Index of Refraction
0.63	2.590
1.40	2.461
1.50	2.458
1.66	2.454
1.82	2.449
2.05	2.446
2.06	2.446
2.15	2.444
2.44	2.442
2.50	2.441
2.58	2.440
2.75	2.439
3.00	2.438
3.42	2.436
3.50	2.435
4.36	2.432
5.00	2.430
6.00	2.426
6.24	2.425
7.50	2.420
8.66	2.414
9.50	2.410
9.72	2.409
10.60	2.400
11.00	2.400
11.04	2.400
12.50	2.390
13.02	2.385
13.50	2.380
15.00	2.370
16.00	2.360
16.90	2.350
17.80	2.340
18.60	2.330
19.30	2.320
20.00	2.310

SILICON

Silicon is commonly used as substrate material for infrared reflectors and windows in the 1.5–8 µm region. The strong absorption band at 9 µm makes it unsuitable for CO_2 laser transmission applications, but it is frequently used for laser mirrors because of its high thermal conductivity and low density.

Specifications

Transmission Range: 1.5–7 µm

Temperature Coefficient of Refractive Index @ 10.6 µm: 160x10^{-6}/°C

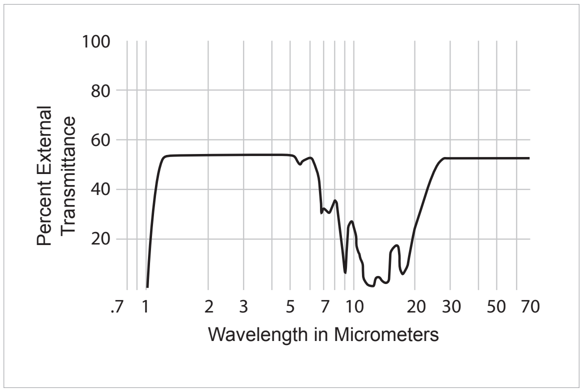
Melting Point: 1417°C

Knoop Hardness: 1100

Density: 2.33 g/cm^3

Young's Modulus: 131 GPa

Thermal Expansion Coefficient: 4.50x10^{-6}/°C



External transmittance for 5 mm thick uncoated silicon

Refractive Index of Silicon

Wavelength (µm)	Index of Refraction
0.63	3.920
1.40	3.490
1.50	3.480
1.66	3.470
1.82	3.460
2.05	3.450
2.06	3.490
2.15	3.470
2.44	3.470
2.50	3.440
2.58	3.436
2.75	3.434
3.00	3.431
3.42	3.428
3.50	3.427
4.36	3.422
5.00	3.420
6.00	3.419
6.24	3.419
7.50	3.417
8.66	3.416
9.50	3.416
9.72	3.416
10.60	3.416
11.00	3.416
11.04	3.416
12.50	3.416
13.02	3.416
13.50	3.416
15.00	3.416
16.00	3.416
16.90	3.416
17.80	3.416
18.60	3.416
19.30	3.416
20.00	3.416

GERMANIUM

Germanium is commonly used in imaging systems working in the 2 to 12 µm wavelength region. It is an ideal substrate material for lenses, windows and mirrors in low-power cw and CO_2 laser applications.

Specifications

Transmission Range: 2–23 µm

Temperature Coefficient of Refractive Index @ 10.6 µm: 277×10^{-6}/°C

Bulk Absorption Coefficient @ 10 µm: 0.035/cm

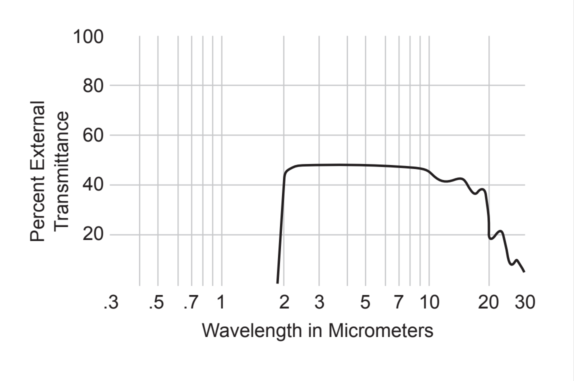
Melting Point: 973°C

Knoop Hardness: 692

Density: 5.323 g/cm^3

Young's Modulus 102.6: GPa

Thermal Expansion Coefficient: 5.7×10^{-6}/°C



External transmittance for 10 mm thick uncoated germanium

Refractive Index of Germanium

Wavelength (µm)	Index of Refraction
0.63	5.390
1.40	4.340
1.50	4.350
1.66	4.330
1.82	4.290
2.05	4.250
2.06	4.240
2.15	4.240
2.44	4.070
2.50	4.220
2.58	4.060
2.75	4.053
3.00	4.054
3.42	4.037
3.50	4.036
4.36	4.023
5.00	4.018
6.00	4.014
6.24	4.010
7.50	4.010
8.66	4.007
9.50	4.006
9.72	4.006
10.60	4.006
11.00	4.006
11.04	4.006
12.50	4.000
13.02	4.000
13.50	4.000
15.00	4.000
16.00	4.000
16.90	4.000
17.80	4.000
18.60	4.000
19.30	4.000
20.00	4.000

MATERIAL PROPERTIES OVERVIEW

Material	Transmission Range (Wavelength (μm))	Index of Refraction	Typical Scratch/Dig	Surface Figure	Laser Damage Threshold	CTE (/°C)	Knoop Hardness
MgF_2	0.13 - 8.0	1.41 @ 0.27 μm	40-20	l/20	High	8.04E-06/ 1.30E-05	415
CaF_2	0.15 - 8.0	1.501 @ 0.193 μm	40-20	l/20	High	1.89E-05	158
UV Fused Silica	0.18 - 2.0	1.46 @ 0.55 μm	10-5	l/20	High	5.50E-07	522
Suprasil 1	0.2 - 2.0	1.51 @ 0.248 μm	10-5	l/20	High	5.50E-07	590
Crystal Quartz	0.2 - 2.0	1.55 @ 0.63 μm	10-5	l/20	High	7.64E-06/ 1.4E-05	820
Optical Crown	0.2 - 2.0	1.52 @ 0.55 μm	20-10	l/20	Low	5.0E-06	610
Infrasil 301	0.25 - 2.0	1.46 @ 0.63 μm	10-5	l/20	High	5.80E-07	590
N-BK7	0.35 - 2.0	1.52 @ 0.55 μm	10-5	l/20	Medium	7.10E-06	610
N-BAK1	0.25 - 2.2	1.57 @ 0.63 μm	10-5	l/20	Medium	7.60E-06	530
N-SF10 (SF10)	0.4 - 2.4	1.73 @ 0.55 μm	10-5	l/20	Medium	9.40E-06	540
Calcite	0.4 - 2.5	1.66 @ 0.55 μm	40-20	l/20	Low	4.6E-06/ 8.3E-05	75
N-LaK21	0.37 - 2.0	1.64 @ 0.55 μm	10-5	l/20	Medium	6.80E-06	600
N-SF2 (SF2)	0.37 - 2.3	1.65 @ 0.55 μm	10-5	l/20	Medium	6.70E-06	539
N-SF11	0.5 - 2.5	1.79 @ 0.55 μm	10-5	l/20	Medium	6.10E-06	450
N-F2 (F2)	0.4 - 2.0	1.62 @ 0.55 μm	10-5	l/20	Medium	8.20E-06	420
Zerodur	0.5 - 2.5	1.55 @ 0.55 μm	10-5	l/20	High	5.00E-09	620
Sapphire	0.3 - 5.0	1.77 @ 0.55 μm	40-20	l/20	High	7.70E-06	1370
Silicon	1.0 - 10	3.42 @ 10.6 μm	20-10	l/20	High	4.50E-06	1100
ZnS	8 - 12	2.20 @ 10.6 μm	20-10	l/20	Medium	6.50E-06	1780
ZnS (MS)	0.4 - 12	2.20 @ 10.6 μm	40-20	l/20	Medium	6.50E-06	160
AMTIR	0.8 - 14	2.50 @ 10.6 μm	40-20	l/20	Medium	1.2E-05	170
GaAs	1.5 - 15	3.29 @ 0.55 μm	40-20	l/20	Medium	5.40E-06	7500
ZnSe	0.5 - 20	2.40 @ 10.6 μm	40-20	l/20	High	7.60E-06	112
Germanium	2.0 - 20	4.00 @ 10.6 μm	20-10	l/20	Medium	5.70E-06	692

0.1 0.4 0.7 1.0 3.0 6.0 10 20
Wavelength (μm)