Material Properties 4

Introduction

Glass manufacturers provide hundreds of different glass types with differing optical transmissibility and mechanical strengths. CVI Melles Griot 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 help those in such situations.

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 be transmissive 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, at various wavelengths, 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 dispersions, 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

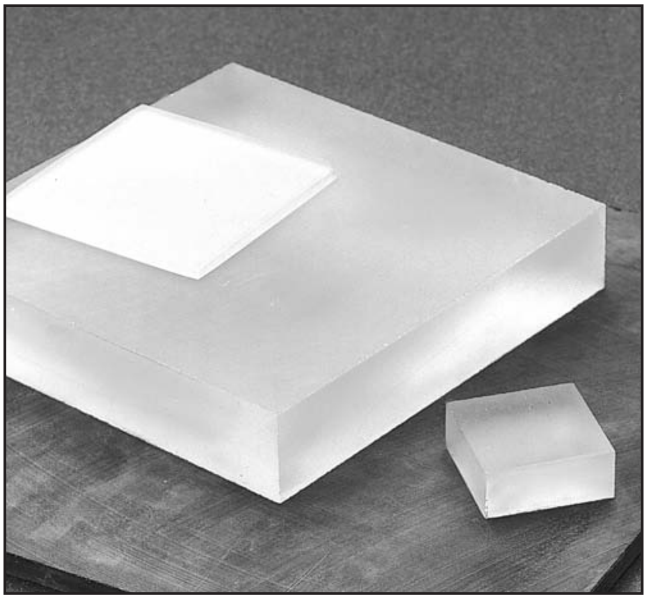
The mechanical characteristics of a material are significant in many areas. They can affect how easy it is to fabricate the material into shape, which affects product cost. Scratch resistance is important if the component will require frequent cleaning. Shock and vibration resistance are important for 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.



Raw and partially processed glass blanks

Optical Properties

The most important optical properties of a material are its internal and external transmittances, surface reflectances, and refractive indexes. 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). 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

$$T_e = t_1 t_2 T_i = t_1 t_2 e^{-\mu t_c} \tag{4.1}$$

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,

$$t_1 t_2 = 1 - 2r + r^2 \tag{4.2}$$

where

$$r = \left(\frac{n-1}{n+1} \right)^2 \tag{4.3}$$

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 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 μ must be found from these. Thus

$$\bar{\mu} = -\frac{1}{2}\left[\frac{\ln T_i(t_{c1})}{t_{c1}} + \frac{\ln T_i(t_{c2})}{t_{c2}} \right] \tag{4.4}$$

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

$$\mu = -\frac{1}{t_c} \ln T_i \ . \tag{4.5}$$

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

$$n^2 - 1 = \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3} \tag{4.6}$$

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 1×10^{-5} over the entire transmission range, and even better in the visible spectrum.

continued

OTHER OPTICAL CHARACTERISTICS

Refractive Index Homogeneity

The tolerance for the refractive index within melt for all Schott fine annealed glass used in CVI Melles Griot catalog components is $\pm 1 \times 10^{-4}$. Furthermore, the refractive index homogeneity, a measure of deviation within a single piece of glass, is better than $\pm 2 \times 10^{-5}$.

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 Melles Griot 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.

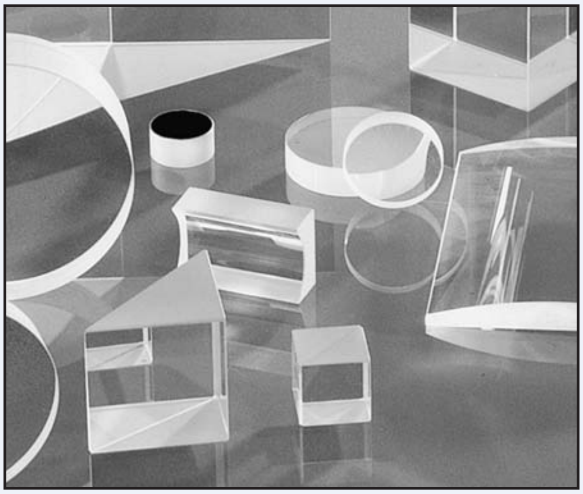
Stress Birefringence

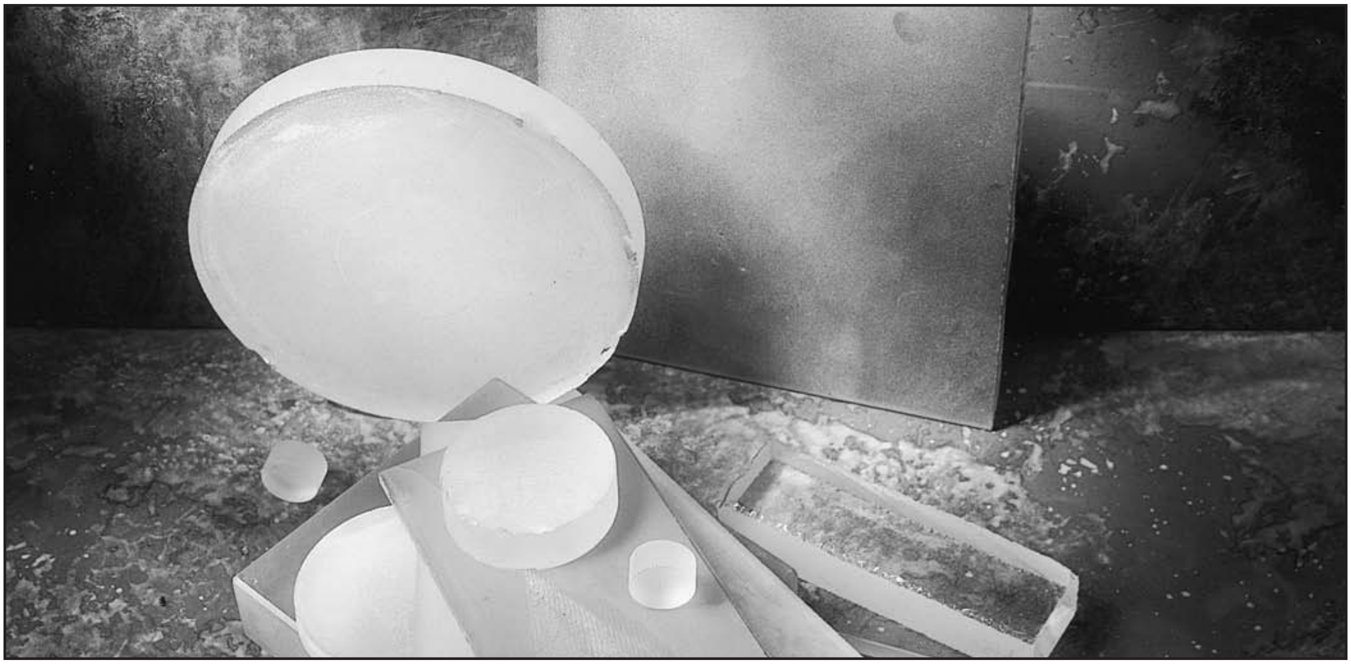
Mechanical stress in optical glass leads to birefringence (anisotropy in index of refraction) which can impair the optical performance of a finished component. Optical glass is annealed (heated and cooled) to remove any residual stress left over from the original manufacturing process. Schott Glass defines 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.





Unpolished glass substrates

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 Melles Griot lenses are made of synthetic fused silica, BK7 grade A fine annealed glass, and several other materials. The following table identifies the materials used in CVI Melles Griot 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 Melles Griot 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 Melles Griot 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.

BK7 OPTICAL GLASS

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

Lens Material Table

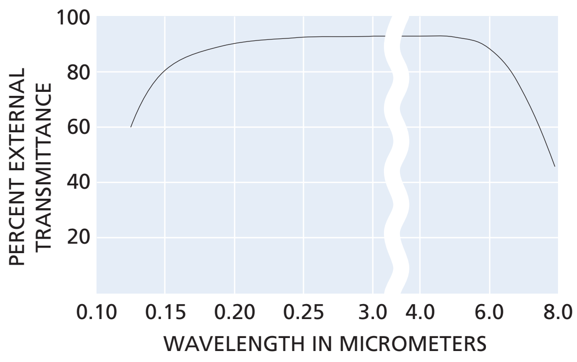
Material	Product Code	
Synthetic Fused Silica, UV Grade	LUP-UV	LUK-UV
	PLCX-UV	PLCC-UV
	LUD-UV	LUB-UV
	BICX-UV	BICC-UV
	RCX-UV	RCC-UV
	SCX-UV	SCC-UV
	CLCX-UV	CLCC-UV
	BFPL-UV	
Synthetic Fused Silica, Excimer Grade	PLCX-EUV	
BK7, Grade A Fine Annealed	LPX-C	LPK-C
	PLCX-C	PLCC-C
	LDX-C	LDK-C
	BICX-C	BICC-C
	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

**CVI Melles Griot offers a range of lead- and arsenic-free glasses which are manufactured under ISO 14001 requirements. Contact your local office for details.*

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

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.



External transmittance for 5-mm-thick uncoated magnesium fluoride

Magnesium Fluoride Constants

Density	3.177 g/cm^3
Young's Modulus	138.5 GPa
Poisson's Ratio	0.271
Knoop Hardness	415
Coefficient of Thermal Expansion	8.48 × 10^{-6}/°C (perpendicular to c axis) 13.70 × 10^{-6}/°C (parallel to c axis)
Melting Point	1585°C
Dispersion Constants (Ordinary Ray)	B_1=4.87551080 × 10^{-1} B_2=3.98750310 × 10^{-1} B_3=2.31203530 C_1=1.88217800 × 10^{-3} C_2=8.95188847 × 10^{-3} C_3=5.66135591 × 10^2
Dispersion Constants (Extraordinary Ray)	B_1=4.13440230 × 10^{-1} B_2=5.04974990 × 10^{-1} B_3=2.49048620 C_1=1.35737865 × 10^{-3} C_2=8.23767167 × 10^{-3} C_3=5.65107755 × 10^2

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

Fundamental Optics
Gaussian Beam Optics
Optical Specifications
Material Properties
Optical Coatings

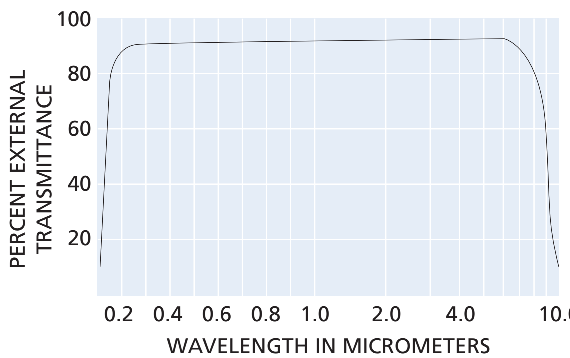
Calcium Fluoride

Calcium fluoride (CaF_2), a cubic single-crystal material, has widespread applications in the ultraviolet and infrared spectra. 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 μm. 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

Calcium Fluoride Constants

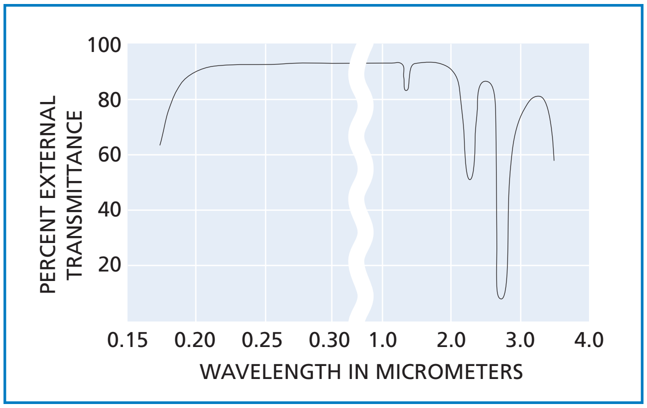
Density	3.18 g/cm^3 @ 25°C
Young's Modulus	1.75×10^7 psi
Poisson's Ratio	0.26
Knoop Hardness	158
Thermal Coefficient of Refraction	$dn/dT = -10.6 \times 10^{-6}$/°C
Coefficient of Thermal Expansion	18.9×10^{-6}/°C (20°–60°C)
Melting Point	1360°C
Dispersion Constants	$B_1 = 0.5675888$ $B_2 = 0.4710914$ $B_3 = 3.8484723$ $C_1 = 0.00252643$ $C_2 = 0.01007833$ $C_3 = 1200.5560$

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.



External transmittance for 10-mm-thick uncoated suprasil 1

Suprasil 1 Constants

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	$B_1 = 0.6961663$ $B_2 = 0.4079426$ $B_3 = 0.8974794$ $C_1 = 0.0046791$ $C_2 = 0.0135121$ $C_3 = 97.9340025$

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 $\pm 3 \times 10^{-5}$*

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 Melles Griot 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:

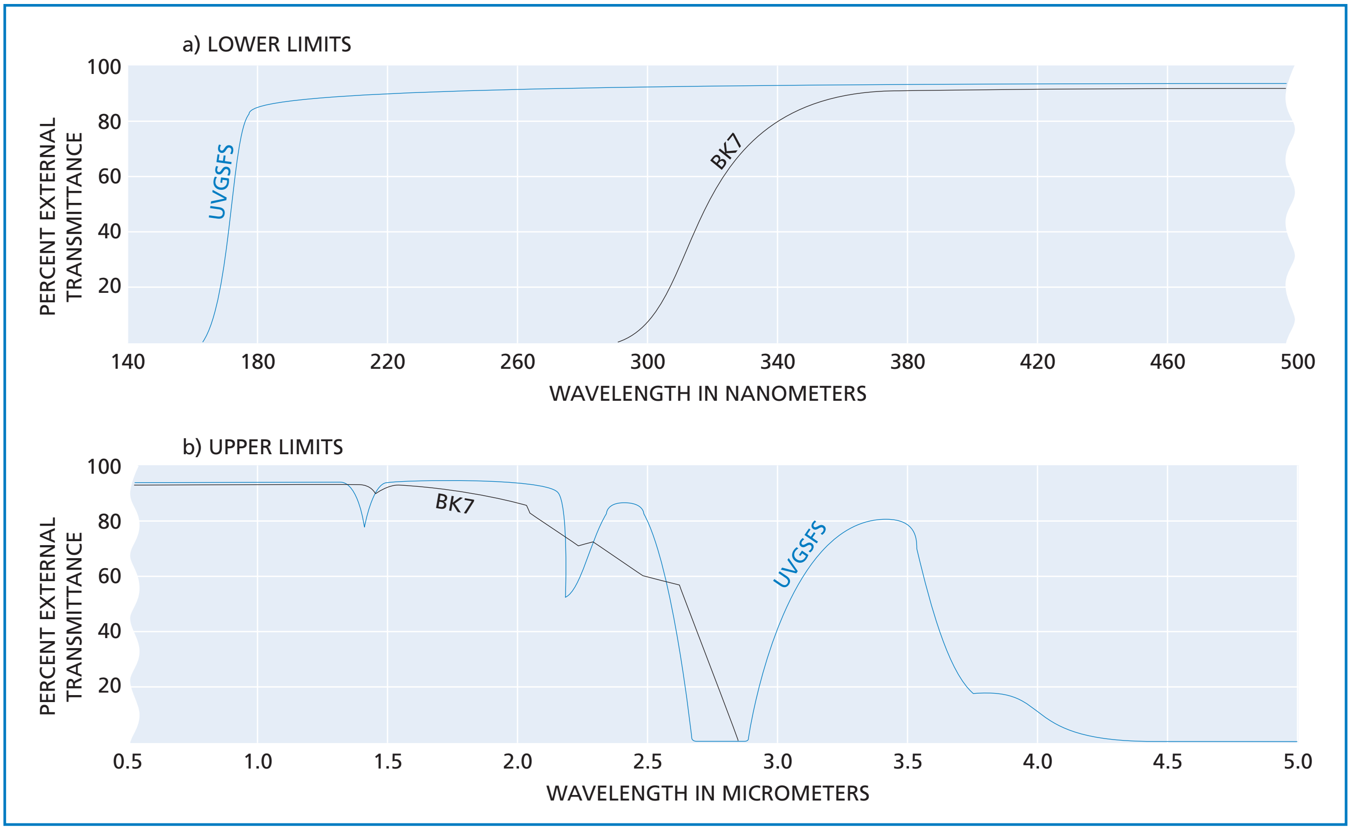
- Greater ultraviolet and infrared transmission
- Low coefficient of thermal expansion, which provides stability and resistance to thermal shock over large temperature excursions
- Wider thermal operating range
- Increased hardness and resistance to scratching
- Much higher resistance to radiation darkening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

Synthetic Fused Silica Constants

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	$B_1 = 0.6961663$ $B_2 = 0.4079426$ $B_3 = 0.8974794$ $C_1 = 0.0046791$ $C_2 = 0.0135121$ $C_3 = 97.9340025$



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

Refractive Index of UV-Grade Synthetic Fused Silica*

Wavelength (nm)	Index of Refraction	Wavelength (nm)	Index of Refraction	Wavelength (nm)	Index of Refraction	Wavelength (nm)	Index of Refraction
180.0	1.58529	330.3	1.48054	532.0	1.46071	1014.0	1.45024
190.0	1.56572	340.4	1.47858	546.1	1.46008	1064.0	1.44963
200.0	1.55051	351.1	1.47671	587.6	1.45846	1100.0	1.44920
213.9	1.53431	361.1	1.47513	589.3	1.45840	1200.0	1.44805
226.7	1.52275	365.0	1.47454	632.8	1.45702	1300.0	1.44692
230.2	1.52008	404.7	1.46962	643.8	1.45670	1400.0	1.44578
239.9	1.51337	435.8	1.46669	656.3	1.45637	1500.0	1.44462
248.3	1.50840	441.6	1.46622	694.3	1.45542	1550.0	1.44402
265.2	1.50003	457.9	1.46498	706.5	1.45515	1660.0	1.44267
275.3	1.49591	476.5	1.46372	786.0	1.45356	1700.0	1.44217
280.3	1.49404	486.1	1.46313	820.0	1.45298	1800.0	1.44087
289.4	1.49099	488.0	1.46301	830.0	1.45282	1900.0	1.43951
296.7	1.48873	496.5	1.46252	852.1	1.45247	2000.0	1.43809
302.2	1.48719	514.5	1.46156	904.0	1.45170	2100.0	1.43659

** Accuracy* $\pm 3 \times 10^{-5}$

Crystal Quartz

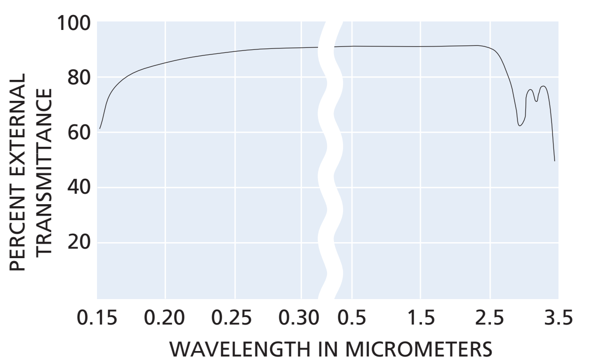
Crystal quartz is a positive uniaxial birefringent single crystal grown using a hydrothermal process. Crystal quartz from CVI Melles Griot is selected to minimize inclusions and refractive index variation. Crystal quartz is most commonly used for high-damage-threshold waveplates and solarization-resistant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

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

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

Crystal Quartz Constants

Transmission Range	0.170–2.8 μm
Melting Point	1463°C
Knoop Hardness	741
Density	2.64 g/cm^3
Young's Modulus	
Perpendicular	76.5 Gpa
Parallel	97.2 Gpa
Thermal Expansion Coefficient	
Perpendicular	13.2×10^{-6}/°C
Parallel	7.1×10^{-6}/°C
Dispersion Constants (Ordinary Ray)	A_0=2.35728
	$A_1 = -1.17000 \times 10^{-2}$
	$A_2 = 1.05400 \times 10^{-2}$
	$A_3 = 1.34143 \times 10^{-4}$
	$A_4 = -4.45368 \times 10^{-7}$
	$A_5 = 5.92362 \times 10^{-8}$
Dispersion Constants (Extraordinary Ray)	A_0=2.38490
	$A_1 = -1.25900 \times 10^{-2}$
	$A_2 = 1.07900 \times 10^{-2}$
	$A_3 = 1.65180 \times 10^{-4}$
	$A_4 = -1.94741 \times 10^{-7}$
	$A_5 = 9.36476 \times 10^{-8}$



External transmittance for 10-mm-thick uncoated crystal quartz

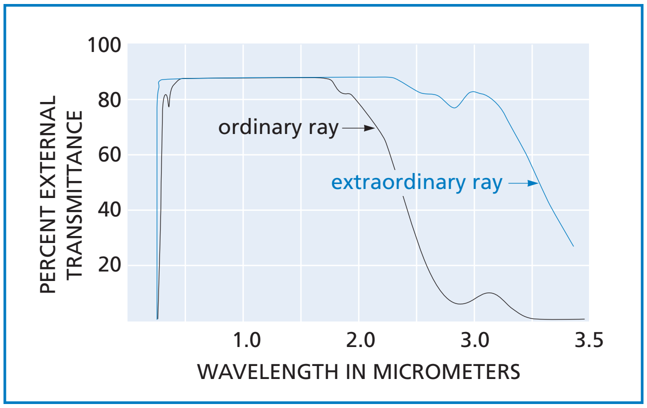
Refractive Index of Crystal Quartz

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
1064	1.53410	1.54282
1320	1.53068	1.53922
1550	1.52761	1.53596
2010	1.52073	1.52863

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

Calcite Constants

Density	2.71 g/cm^3
Mohs Hardness	3
Melting Point	1339 °C
Dispersion Constants (Ordinary Ray)	$B_1 = 1.56630$ $B_2 = 1.41096$ $B_3 = 0.28624$ $C_1 = 105.58893$ $C_2 = 0.01583669$ $C_3 = -0.01182893$
Dispersion Constants (Extraordinary Ray)	$B_1 = 8.418192 \times 10^{-5}$ $B_2 = 1.183488$ $B_3 = 0.03413054$ $C_1 = 0.3468576$ $C_2 = 7.741535 \times 10^{-3}$ $C_3 = 12.185616$

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

Five Schott Glass Types

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 Melles Griot 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 Five 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	$2.31792344 \times 104^{1}$	$3.11168974 \times 104^{1}$	$3.20435298 \times 104^{1}$	$3.09276848 \times 104^{1}$	$2.09073176 \times 104^{1}$
B_3	1.01046945	1.17490871	1.92900751	$8.81511957 \times 104^{1}$	$9.37357162 \times 104^{1}$
C_1	$6.00069867 \times 104^{3}$	$1.36068604 \times 104^{2}$	$1.18537266 \times 104^{2}$	$6.44742752 \times 104^{3}$	$9.97743871 \times 104^{3}$
C_2	$2.00179144 \times 104^{2}$	$6.15960463 \times 104^{2}$	$5.27381770 \times 104^{2}$	$2.22284402 \times 104^{2}$	$4.70450767 \times 104^{2}$
C_3	1.03560653×10^{2}	1.21922711×10^{2}	1.66256540×10^{2}	1.07297751×10^{2}	1.11886764×10^{2}
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	7.1×104^{6}	6.1×104^{6}	7.4×104^{6}	7.6×104^{6}	8.2×104^{6}
+20° to +300°C	8.3×104^{6}	6.8×104^{6}	8.4×104^{6}	8.6×104^{6}	9.2×104^{6}
Transition Temperature	557°C	505°C	703°C	592°C	438°C
Young's Modulus (dynes/mm^2)	8.20×10^{9}	6.60×10^{9}	1.09×10^{10}	7.30×10^{9}	5.70×10^{9}
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 Five Schott Glass Types

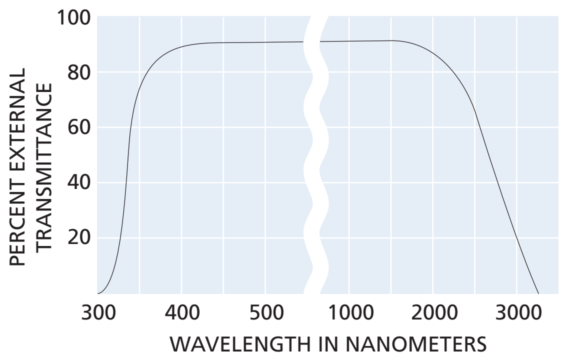
Wavelength λ (nm)	Refractive Index, n					Fraunhofer Designation	Source	Spectral Region
	BK7 (N-BK7)	SF11	LaSFN9	BaK1 (N-BaK1)	F2			
351.1	1.53894	—	—	1.60062	1.67359		Ar laser	UV
363.8	1.53649	—	—	1.59744	1.66682		Ar laser	UV
404.7	1.53024	1.84208	1.89844	1.58941	1.65064	h	Hg arc	Violet
435.8	1.52668	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 BK7. Optical crown glass is suitable for applications in which component tolerances are fairly loose and as a substrate material for mirrors.

Optical Crown Glass Constants

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	93.3×10^{-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

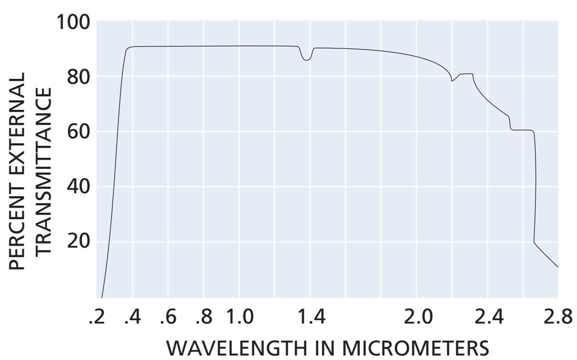
Note: Transmission in visible region (including reflection loss) = 91.7% (t = 2 mm)

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 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.

Low-Expansion Borosilicate Glass Constants

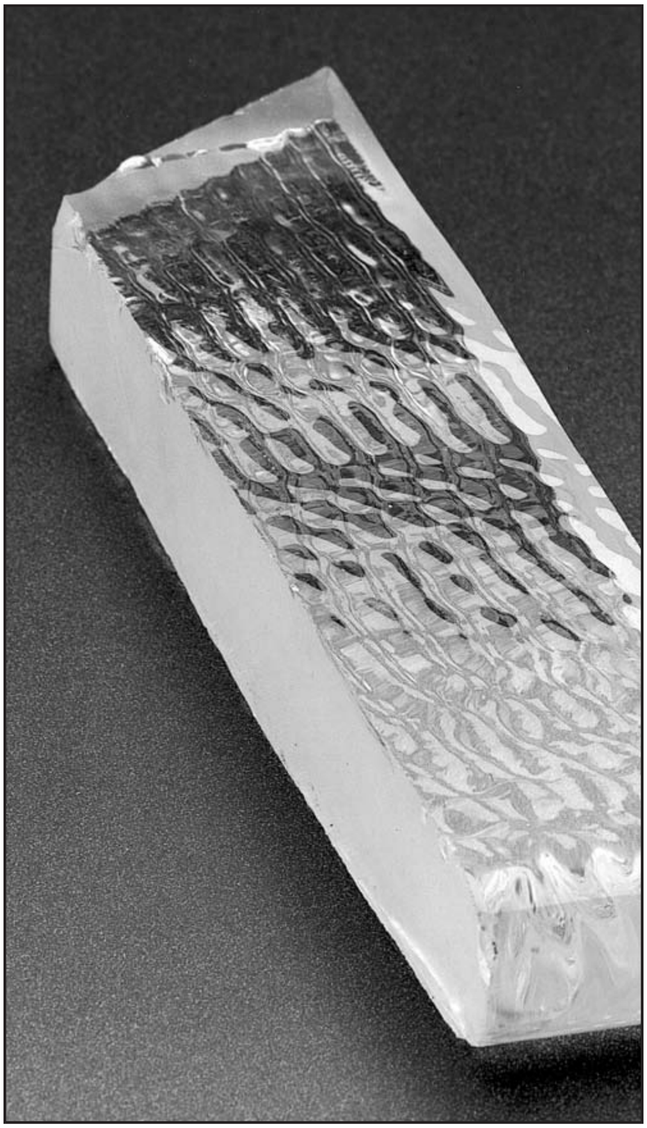
Abbé Constant	66
Knoop Hardness	480
Density	2.23 g/cm^3 @ 25°C
Young's Modulus	5.98×10^9 dynes/mm^2
Poisson's Ratio	0.20
Specific Heat	0.17 cal/g/°C @ 25°C
Coefficient of Thermal Expansion	3.25×10^{-6}/°C (0°–300°C)
Softening Point	820°C
Melting Point	1250°C



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

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



Partially processed borosilicate glass

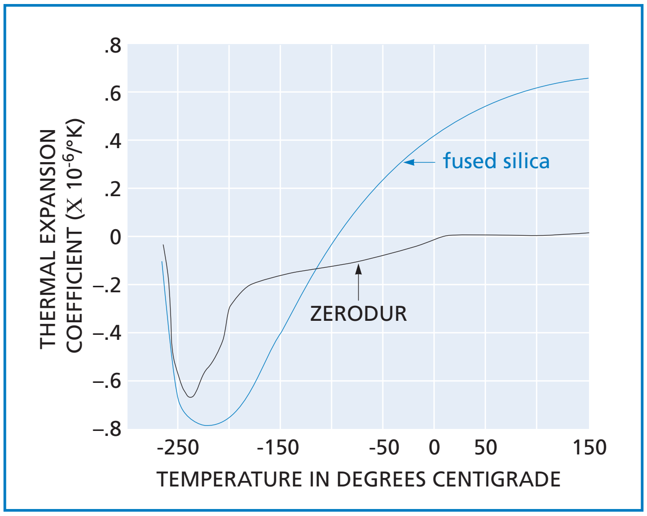
ZERODUR®

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 $\pm 0.15 \times 10^{-6}$/°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.



Comparison of thermal expansion coefficients of ZERODUR® and fused silica

ZERODUR® Constants

Abbé Constant	66
Dispersion	$(n_F - n_C) = 0.00967$
Knoop Hardness	620
Density	2.53 g/cm^3 @ 25°C
Young's Modulus	9.1×10^9 dynes/mm^2
Poisson's Ratio	0.24
Specific Heat	0.196 cal/g/°C
Coefficient of Thermal Expansion	$0.05 \pm 0.10 \times 10^{-6}$/°C (20°–300°C)
Maximum Temperature	600°C

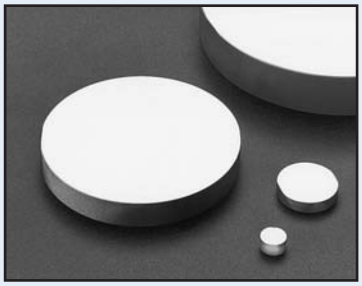
Refractive Index of ZERODUR®

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

Do you need . . .

Mirror Substrates

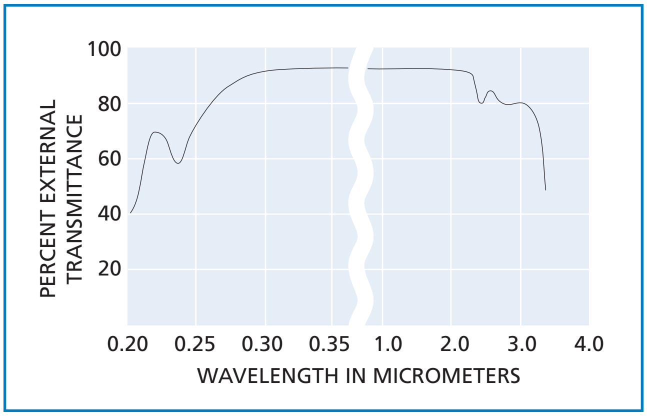
ZERODUR® is commonly used as a substrate for λ/20 mirrors with metallic coatings.



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

Infrasil 302 Constants

OH content	<8 ppm
Knoop Hardness	590
Thermal Expansion Coefficient	0.58×10^{-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 $\Delta n \leq 5 \times 10^{-6}$
Spectral Transmittance	Very weak absorption band occur at wavelengths arouns 1.39μm, 2.2μm, and 2.72μm 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

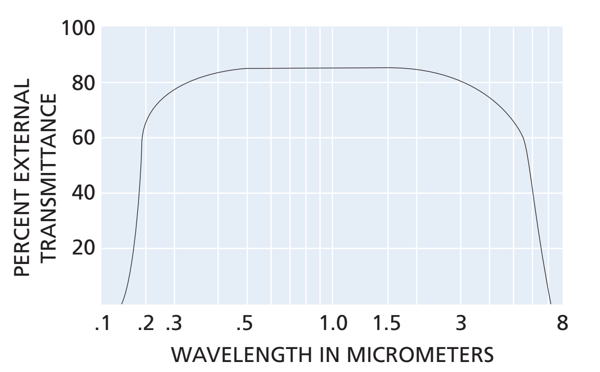
Fundamental Optics
Gaussian Beam Optics
Optical Specifications
Material Properties
Optical Coatings

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 (such as diamond or boron nitride) other than itself. 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 300ºC. Sapphire exhibits high internal transmittance all the way from 150 nm (vacuum ultraviolet) to 6 μm (middle 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.



External transmittance for 1-mm-thick uncoated sapphire

Sapphire Constants

Density	3.98 g/cm^3 @ 25ºC
Young's Modulus	3.7×10^{10} dynes/mm^2
Poisson's Ratio	-0.02
Mohs Hardness	9
Specific Heat	0.18 cal/g/ºC @ 25ºC
Coefficient of Thermal Expansion	7.7×10^{-6}/ºC (0º–500ºC)
Softening Point	1800ºC
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)	$B_1 = 1.5039759$
	$B_2 = 0.55069141$
	$B_3 = 6.5927379$
	$C_1 = 0.00548026$
	$C_2 = 0.01479943$
	$C_3 = 402.8951$

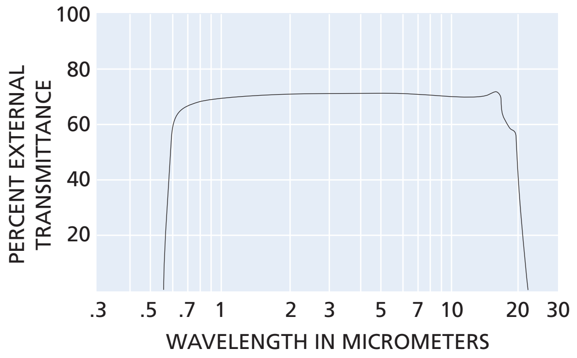
Refractive Index of Sapphire

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

** Sapphire is anisotropic and many of its properties require tensor description. These values are averages over many directions.*

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.



External transmittance for 10-mm-thick uncoated zinc selenide

Zinc Selenide Constants

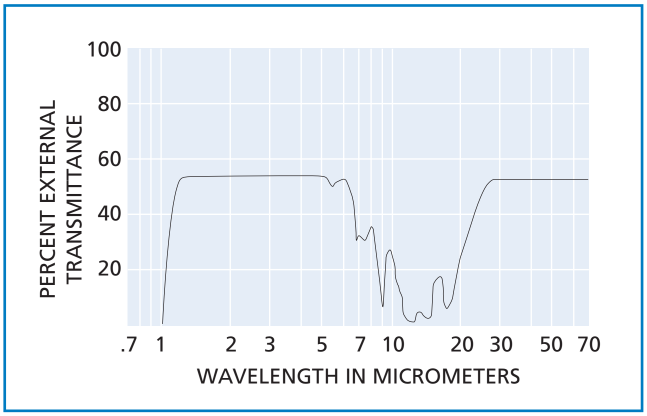
Transmission Range	0.5–22 μm
Refractive Index Inhomogeneity @ 633 nm	<3 × 10^{-6}
Temperature Coefficient of Refractive Index @ 10.6 μm	61 × 10^{-6}/°C
Bulk Absorption Coefficient @ 10 μm	0.0004/cm
Melting Point	1520°C
Knoop Hardness	112
Density	5.27 g/cm^3
Rupture Modulus	55.2 Mpa
Young's Modulus	67.2 Gpa
Fracture Toughness	0.5 Mpa/m
Thermal Expansion Coefficient	7.6 × 10^{-6}/°C

Refractive Index of Zinc Selenide

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



External transmittance for 5-mm-thick uncoated silicon

Silicon Constants

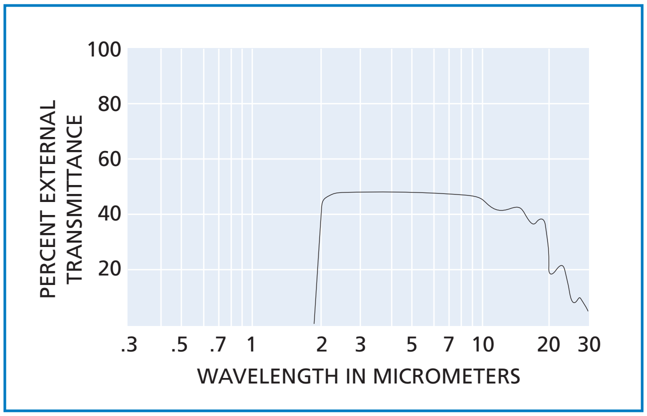
Transmission Range	1.5–7 μm
Temperature Coefficient of Refractive Index @ 10.6 μm	160×10^{-6}/°C
Melting Point	1417°C
Knoop Hardness	1100
Density	2.33 g/cm^3
Young's Modulus	131 Gpa
Thermal Expansion Coefficient	4.50×10^{-6}/°C

Refractive Index of Silicon

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



External transmittance for 10-mm-thick uncoated germanium

Germanium Constants

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

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

Wavelength (μm)	Index of Refraction
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	Usable Transmission Range	Index of Refraction	Features
Magnesium Fluoride	MAGNESIUM FLUORIDE	1.41 @ 0.27 µm	Tetragonal positive birefringent crystal material preferred for high vacuum UV applications for windows, polarizers, and lenses
Calcium Fluoride	CALCIUM FLUORIDE	1.399 @ 5 µm	This popular UV excimer laser material is used for windows, lenses, and mirror substrates
UV-Grade Synthetic Fused Silica (UVGSFS)	UVGSFS	1.46 @ 0.55 µm	Material provides excellent UV transmission and superior mechanical characteristics
Suprasil 1	SUPRASIL	1.50@ 0.27 µm	Type of fused silica with high purity, multiple axis homogeneity, and low fluorescence
Crystal Quartz	CRYSTAL QUARTZ	1.55@ 0.63 µm	Uniaxial birefringent single crystal used primarily on high damage threshold waveplates and Brewster windows
Infrasil 302	INFRASIL	1.46@ 0.63 µm	Low OH content fused quartz recommended for NIR high energy windows and lenses
Calcite	CALCITE	1.66@ 0.55 µm	Naturally occuring negative uniaxial crystal with pronounced birefringence makes this material suitable for polarizing prisms
Low-expansion borosilicate glass (LEBG)	LEBG	1.48 @ 0.55 µm	Excellent thermal stability, low cost, and homogeneity makes LEBG useful for high-temperature windows, mirror substrates, and condenser lenses
BK7 N-BK7	BK7	1.52 @ 0.55 µm	Excellent all-around lens material provides broad transmission with excellent mechanical characteristics
Optical Crown Glass	OPTICAL CROWN	1.52 @ 0.55 µm	This lower tolerance glass can be used as a mirror substrate or in non-critical applications
LaSFN9	LaSFN9	1.86 @ 0.55 µm	High-refractive-index flint glass provides more power with less curvature
ZERODUR®	ZERODUR®	1.55@ 0.55 µm	Highly homogeneous glass-ceramic with near-zero coefficient of thermal expansion is ideal for mirror substrates for stringent applications
SF11	SF11	1.79 @ 0.55 µm	High-refractive-index flint glass provides more power with less curvature
F2	F2	1.62 @ 0.55 µm	Material represents a good compromise between higher index and acceptable mechanical characteristics
BaK1 N-BaK1	BaK1	1.57 @ 0.55 µm	Excellent all-around lens material, but has weaker chemical characteristics than BK7
Sapphire	SAPPHIRE	1.77 @ 0.55 µm	Excellent mechanical and thermal characteristics make it a superior window material
Zinc Selenide	ZINC SELENIDE	2.40 @ 10.6 µm	Zinc selenide is most popular for transmissive IR optics; transmits visible and IR, and has low absorption in the red end of the spectrum
Silicon	SILICON	3.42@ 10.6 µm	Lighter weight than the other IR materials, Si is often used in lenses, mirrors, and filters
Germanium	GERMANIUM	4.00@ 10.6 µm	Higher refractive index than ZnSe provides more power with less curvature than ZnSe
	0.1 0.5 1.0 5.0 10.0 WAVELENGTHS IN µm		