# Material Properties

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# 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

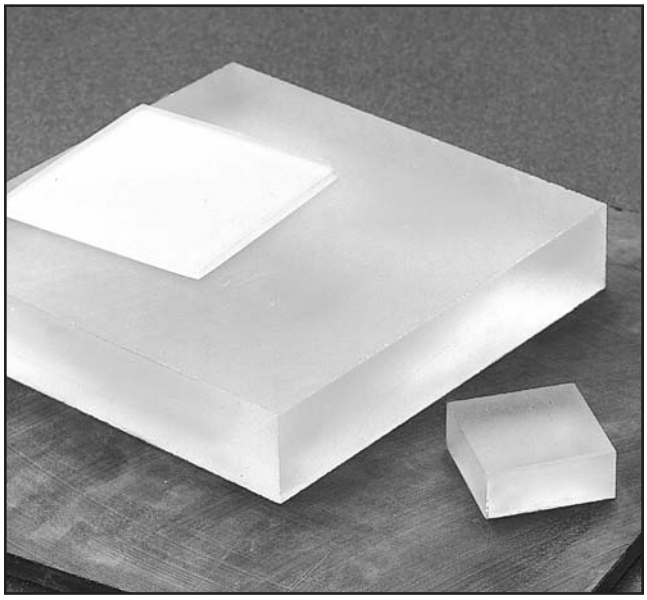
The mechanical characteristics of a material are significant in many areas. They can affect how easy it is to fabricate the material into shape, which affects product cost. Scratch resistance is important if the component will require frequent cleaning. Shock and vibration resistance are important for 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, $\mu$ 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 $\mu$ 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 $\mu$. Typically, internal transmittance $T_i$ is tabulated as a function of wavelength for two distinct thicknesses $t_{c1}$ and $t_{c2}$, and $\mu$ 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 $\lambda$, 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 $1 \times 10^{-5}$ 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.

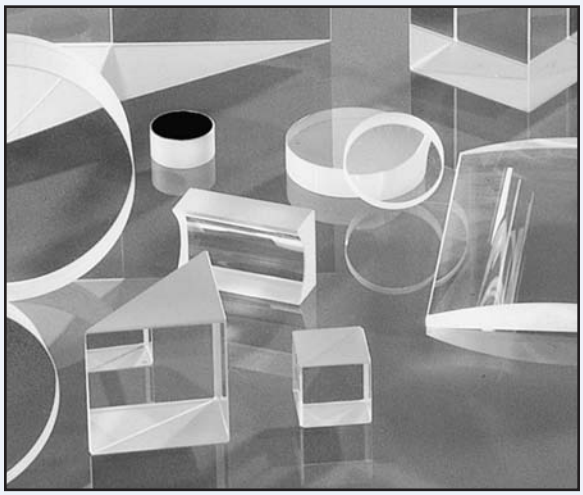
### Stress Birefringence

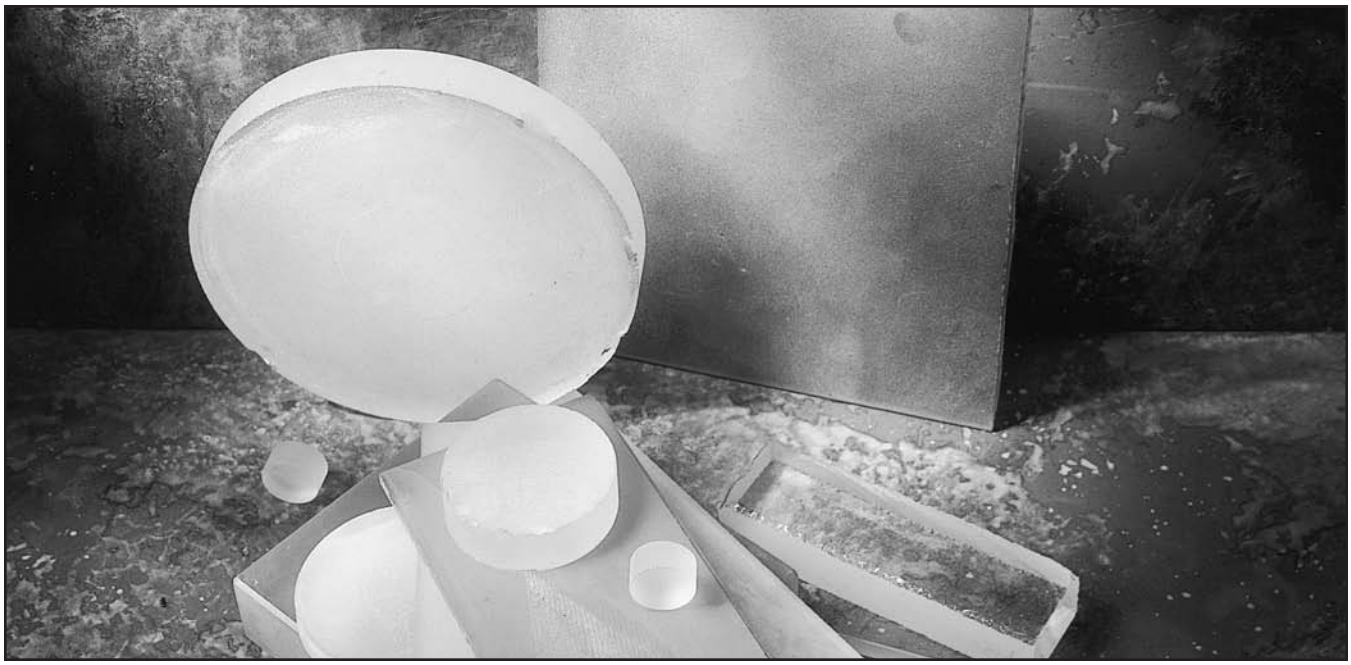
Mechanical stress in optical glass leads to birefringence (anisotropy in index of refraction) which can impair the optical performance of a finished component. Optical glass is annealed (heated and cooled) to remove any residual stress left over from the original manufacturing process. Schott Glass defines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

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

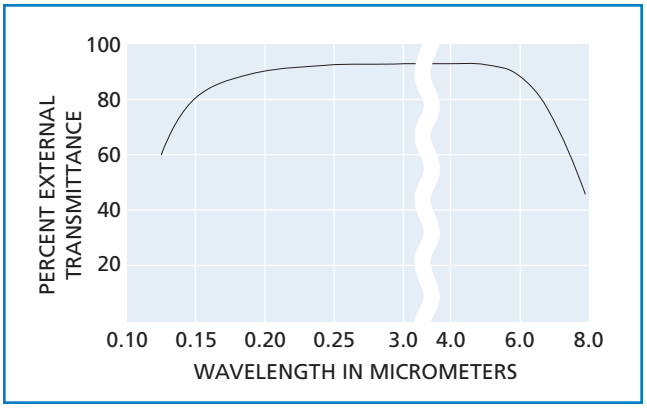
### Lens Material Table

| 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 | |
| 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.*

# 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** | $8.48 \times 10^{-6}$/°C (perpendicular to c axis)<br>$13.70 \times 10^{-6}$/°C (parallel to c axis) |
| **Melting Point** | 1585°C |
| **Dispersion Constants (Ordinary Ray)** | $B_1$=4.87551080 × $10^{-1}$<br>$B_2$=3.98750310 × $10^{-1}$<br>$B_3$=2.31203530<br>$C_1$=1.88217800 × $10^{-3}$<br>$C_2$=8.95188847 × $10^{-3}$<br>$C_3$=5.66135591 × $10^2$ |
| **Dispersion Constants (Extraordinary Ray)** | $B_1$=4.13440230 × $10^{-1}$<br>$B_2$=5.04974990 × $10^{-1}$<br>$B_3$=2.49048620<br>$C_1$=1.35737865 × $10^{-3}$<br>$C_2$=8.23767167 × $10^{-3}$<br>$C_3$=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 |

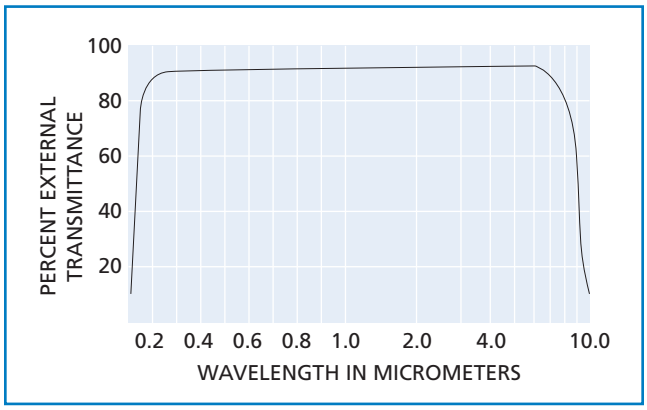
# Calcium Fluoride

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 $\mu$m. 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

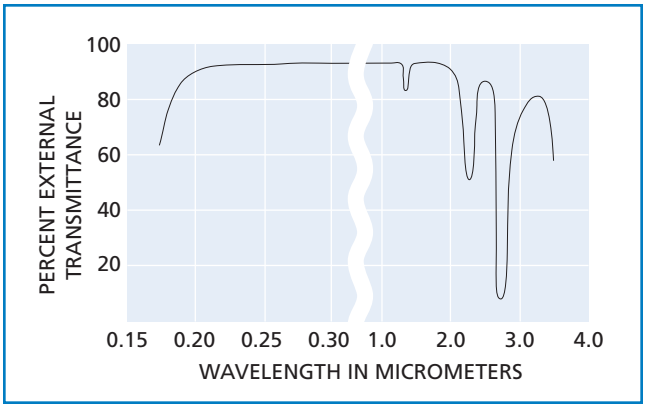
| | |
|---|---|
| **Density** | 3.18 g/cm$^3$ @ 25°C |
| **Young's Modulus** | $1.75 \times 10^7$ psi |
| **Poisson's Ratio** | 0.26 |
| **Knoop Hardness** | 158 |
| **Thermal Coefficient of Refraction** | $dn/dT = -10.6 \times 10^{-6}$/°C |
| **Coefficient of Thermal Expansion** | $18.9 \times 10^{-6}$/°C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

### Refractive Index of Calcium Fluoride

| Wavelength ($\mu$m) | 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** | $67.8 \pm 0.5$ |
| **Change of Refractive Index with Temperature (0° to 700°C)** | $1.28 \times 10^{-5}$/°C |
| **Homogeneity (maximum index variation over 10-cm aperture)** | $2 \times 10^{-5}$ |
| **Knoop Hardness** | 590 |
| **Density** | 2.20 g/cm$^3$ @ 25°C |
| **Continuous Operating Temperature** | 900°C maximum |
| **Coefficient of Thermal Expansion** | $5.5 \times 10^{-7}$/°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:

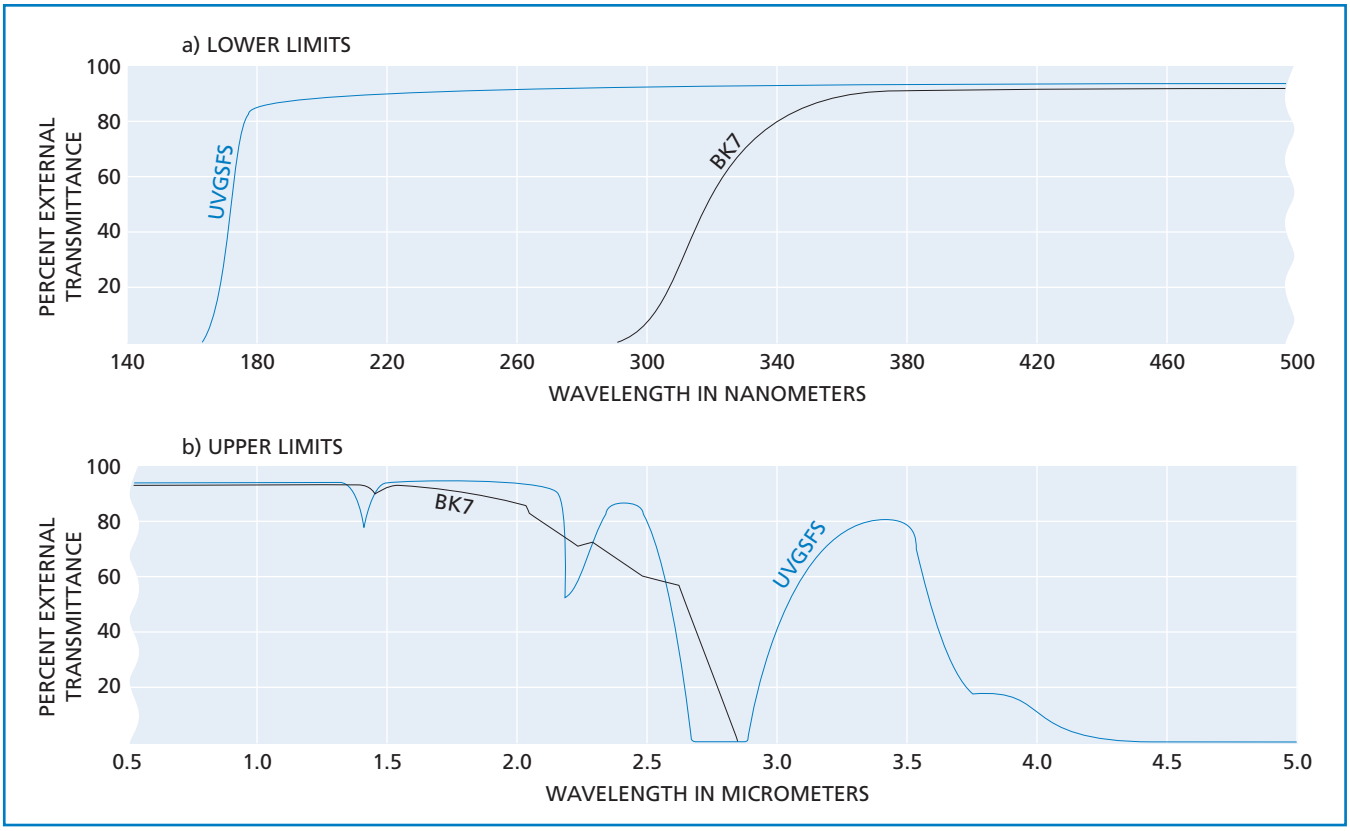
- Greater ultraviolet and infrared transmission
- Low coefficient of thermal expansion, which provides stability and resistance to thermal shock over large temperature excursions
- Wider thermal operating range
- Increased hardness and resistance to scratching
- Much higher resistance to radiation darkening 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 $\mu$m 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** | $67.8 \pm 0.5$ |
| **Change of Refractive Index with Temperature (0° to 700°C)** | $1.28 \times 10^{-5}$/°C |
| **Homogeneity (maximum index variation over 10-cm aperture)** | $2 \times 10^{-5}$ |
| **Density** | 2.20 g/cm$^3$ @ 25°C |
| **Knoop Hardness** | 522 |
| **Continuous Operating Temperature** | 900°C maximum |
| **Coefficient of Thermal Expansion** | $5.5 \times 10^{-7}$/°C |
| **Specific Heat** | 0.177 cal/g/°C @ 25°C |
| **Dispersion Constants** | $B_1 = 0.6961663$<br>$B_2 = 0.4079426$<br>$B_3 = 0.8974794$<br>$C_1 = 0.0046791$<br>$C_2 = 0.0135121$<br>$C_3 = 97.9340025$ |




**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

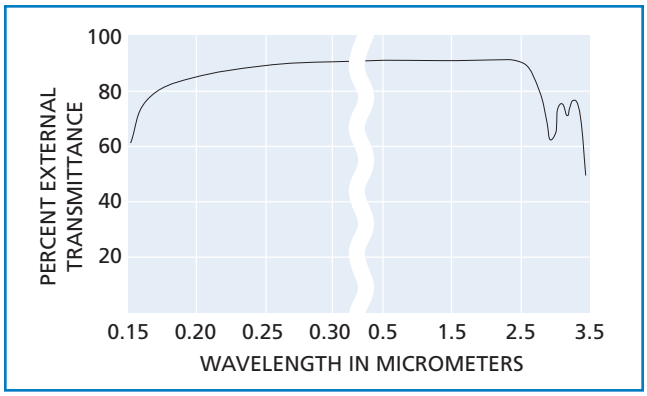
Crystal quartz is a positive uniaxial birefringent single crystal grown using a hydrothermal process. Crystal quartz from CVI Melles Griot is selected to minimize inclusions and refractive index variation. Crystal quartz is most commonly used for high-damage-threshold waveplates and solarization-resistant 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 $\mu$m |
| **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 | $13.2 \times 10^{-6}$/°C |
| Parallel | $7.1 \times 10^{-6}$/°C |
| **Dispersion Constants (Ordinary Ray)** | $A_0$=2.35728 |
| | $A_1 = -1.17000 \times 10^{-2}$ |
| | $A_2$=1.05400 × $10^{-2}$ |
| | $A_3$=1.34143 × $10^{-4}$ |
| | $A_4 = -4.45368 \times 10^{-7}$ |
| | $A_5$=5.92362 × $10^{-8}$ |
| **Dispersion Constants (Extraordinary Ray)** | $A_0$=2.38490 |
| | $A_1 = -1.25900 \times 10^{-2}$ |
| | $A_2$=1.07900 × $10^{-2}$ |
| | $A_3$=1.65180 × $10^{-4}$ |
| | $A_4 = -1.94741 \times 10^{-7}$ |
| | $A_5$=9.36476 × $10^{-8}$ |




**External transmittance for 10-mm-thick uncoated crystal quartz**

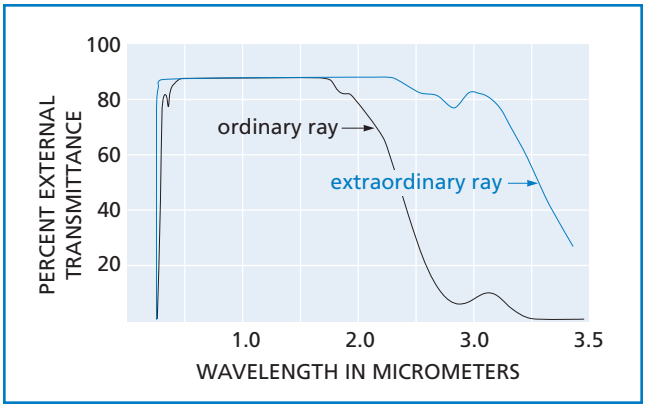
### Refractive Index of Crystal Quartz

| 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 |
| $B_2$ | $2.31792344 \times 10^{-1}$ | $3.11168974 \times 10^{-1}$ | $3.20435298 \times 10^{-1}$ | $3.09276848 \times 10^{-1}$ | $2.09073176 \times 10^{-1}$ |
| $B_3$ | 1.01046945 | 1.17490871 | 1.92900751 | $8.81511957 \times 10^{-1}$ | $9.37357162 \times 10^{-1}$ |
| $C_1$ | $6.00069867 \times 10^{-3}$ | $1.36068604 \times 10^{-2}$ | $1.18537266 \times 10^{-2}$ | $6.44742752 \times 10^{-3}$ | $9.97743871 \times 10^{-3}$ |
| $C_2$ | $2.00179144 \times 10^{-2}$ | $6.15960463 \times 10^{-2}$ | $5.27381770 \times 10^{-2}$ | $2.22284402 \times 10^{-2}$ | $4.70450767 \times 10^{-2}$ |
| $C_3$ | $1.03560653 \times 10^{2}$ | $1.21922711 \times 10^{2}$ | $1.66256540 \times 10^{2}$ | $1.07297751 \times 10^{2}$ | $1.11886764 \times 10^{2}$ |
| 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 | $7.1 \times 10^{-6}$ | $6.1 \times 10^{-6}$ | $7.4 \times 10^{-6}$ | $7.6 \times 10^{-6}$ | $8.2 \times 10^{-6}$ |
| +20° to +300°C | $8.3 \times 10^{-6}$ | $6.8 \times 10^{-6}$ | $8.4 \times 10^{-6}$ | $8.6 \times 10^{-6}$ | $9.2 \times 10^{-6}$ |
| Transition Temperature | 557°C | 505°C | 703°C | 592°C | 438°C |
| Young's Modulus (dynes/mm$^2$) | $8.20 \times 10^{9}$ | $6.60 \times 10^{9}$ | $1.09 \times 10^{10}$ | $7.30 \times 10^{9}$ | $5.70 \times 10^{9}$ |
| 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

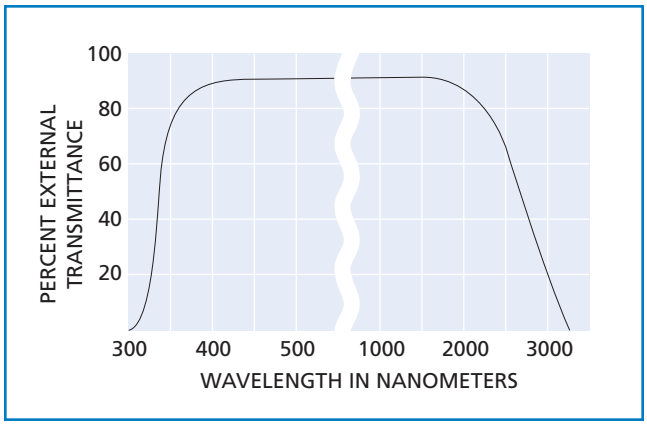
| Wavelength λ (nm) | Refractive Index, $n$ BK7 (N-BK7) | SF11 | LaSFN9 | BaK1 (N-BaK1) | F2 | Fraunhofer Designation | Source | Spectral Region |
|---|---|---|---|---|---|---|---|---|
| 351.1 | 1.53894 | — | — | 1.60062 | 1.67359 | | Ar laser | UV |
| 363.8 | 1.53649 | — | — | 1.59744 | 1.66682 | | 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

| | |
|---|---|
| **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** | $93.3 \times 10^{-7}$/°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 |

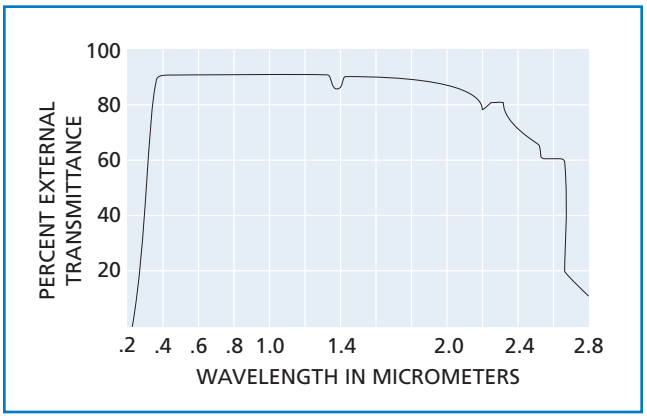
*Note: Transmission in visible region (including reflection loss) = 91.7% (t = 2 mm)*

## 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**

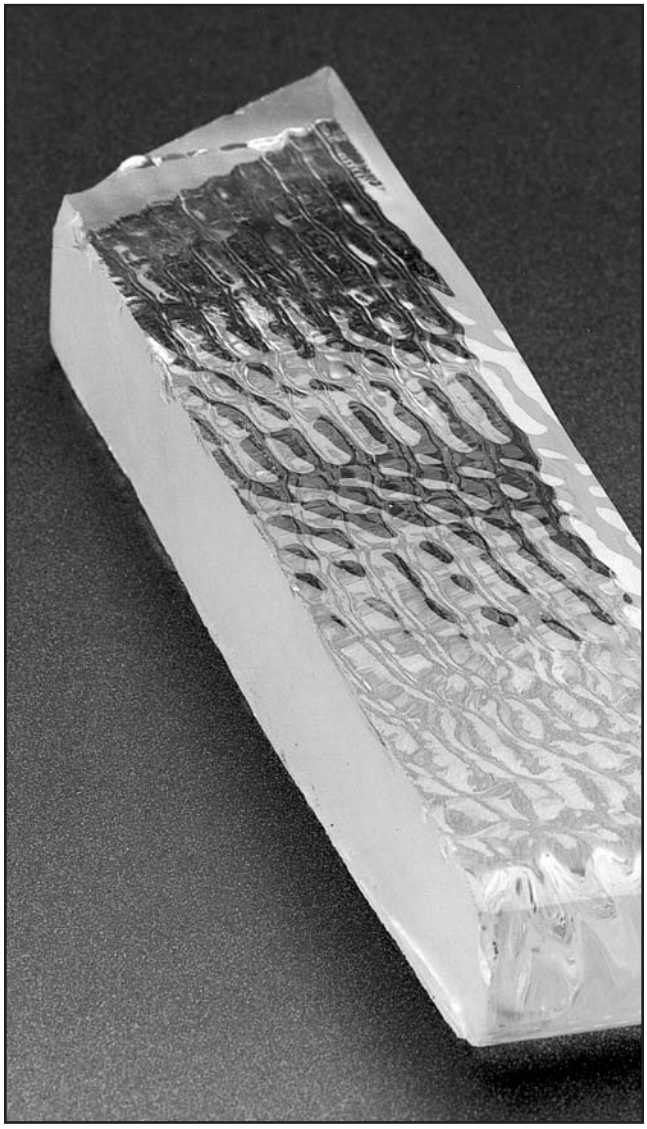
| | |
|---|---|
| **Abbé Constant** | 66 |
| **Knoop Hardness** | 480 |
| **Density** | 2.23 g/cm$^3$ @ 25°C |
| **Young's Modulus** | $5.98 \times 10^9$ dynes/mm$^2$ |
| **Poisson's Ratio** | 0.20 |
| **Specific Heat** | 0.17 cal/g/°C @ 25°C |
| **Coefficient of Thermal Expansion** | $3.25 \times 10^{-6}$/°C (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**

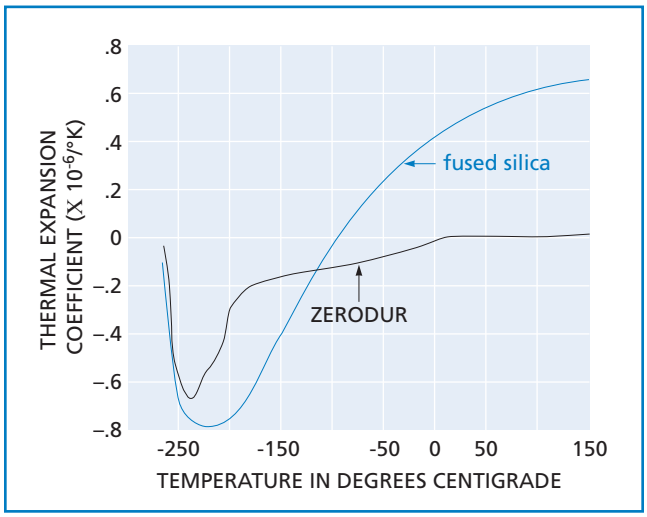
# ZERODUR®

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** | $9.1 \times 10^9$ 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 |

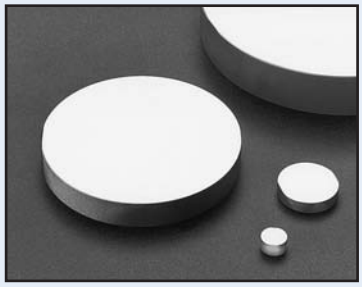
### Refractive Index of ZERODUR®

| 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.

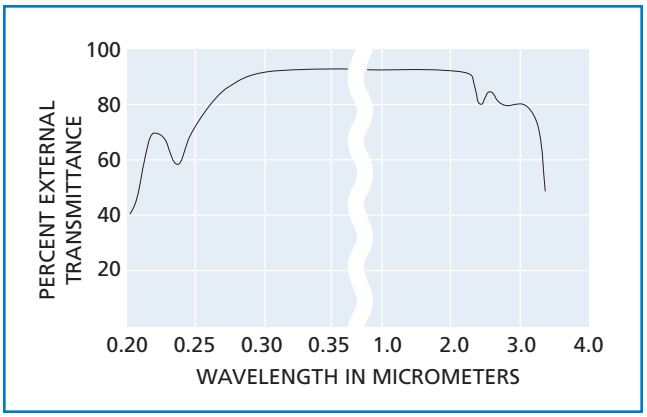


*ZERODUR® is a registered trademark of Schott Glass Technologies, Inc.*

# 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 $\mu$m) 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** | $0.58 \times 10^{-6}$/°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 1.39$\mu$m, 2.2$\mu$m, and 2.72$\mu$m according to an OH content of ≤8 ppm (weight). |

### Refractive Index of Infrasil 302

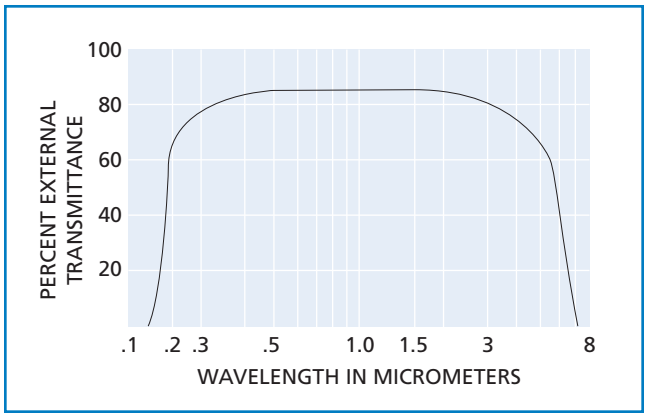
| Wavelength (nm) | Index of Refraction |
|---|---|
| 435.8 | 1.46681 |
| 486.1 | 1.46324 |
| 587.6 | 1.45856 |
| 656.3 | 1.45646 |

# 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 (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 300°C. Sapphire exhibits high internal transmittance all the way from 150 nm (vacuum ultraviolet) to 6 $\mu$m (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$^3$ @ 25°C |
| **Young's Modulus** | $3.7 \times 10^{10}$ dynes/mm$^2$ |
| **Poisson's Ratio** | $-0.02$ |
| **Mohs Hardness** | 9 |
| **Specific Heat** | 0.18 cal/g/°C @ 25°C |
| **Coefficient of Thermal Expansion** | $7.7 \times 10^{-6}$/°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)** | $B_1 = 1.5039759$ |
| | $B_2 = 0.55069141$ |
| | $B_3 = 6.5927379$ |
| | $C_1 = 0.00548026$ |
| | $C_2 = 0.01479943$ |
| | $C_3 = 402.8951$ |

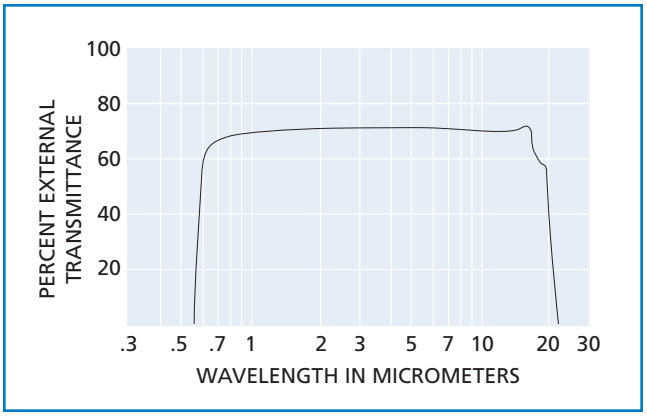
### Refractive Index of Sapphire

| 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 |

** 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

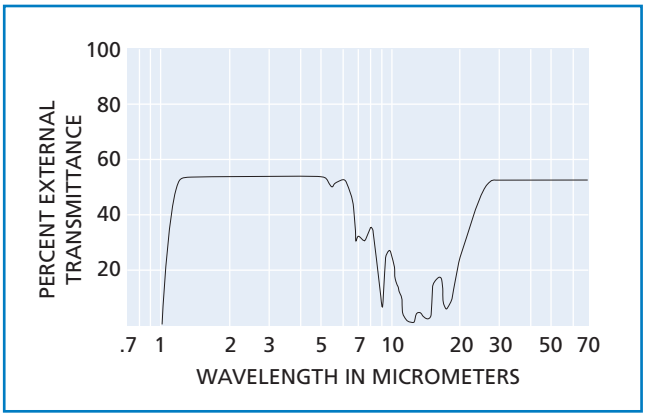
| | |
|---|---|
| **Transmission Range** | 0.5–22 $\mu$m |
| **Refractive Index Inhomogeneity @ 633 nm** | $<3 \times 10^{-6}$ |
| **Temperature Coefficient of Refractive Index @ 10.6 $\mu$m** | $61 \times 10^{-6}$/°C |
| **Bulk Absorption Coefficient @ 10 $\mu$m** | 0.0004/cm |
| **Melting Point** | 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** | $7.6 \times 10^{-6}$/°C |

## Refractive Index of Zinc Selenide

| Wavelength ($\mu$m) | Index of Refraction | Wavelength ($\mu$m) | 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 $\mu$m region. The strong absorption band at 9 $\mu$m 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

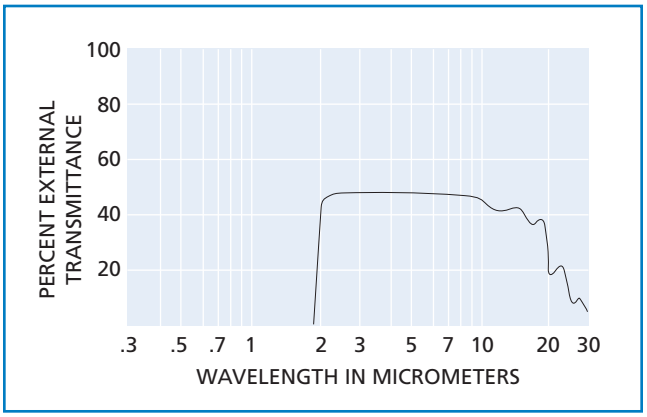
| | |
|---|---|
| **Transmission Range** | 1.5–7 $\mu$m |
| **Temperature Coefficient of Refractive Index @ 10.6 $\mu$m** | $160 \times 10^{-6}$/°C |
| **Melting Point** | 1417°C |
| **Knoop Hardness** | 1100 |
| **Density** | 2.33 g/cm$^3$ |
| **Young's Modulus** | 131 Gpa |
| **Thermal Expansion Coefficient**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

### Refractive Index of Silicon

| Wavelength ($\mu$m) | Index of Refraction | Wavelength ($\mu$m) | 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 $\mu$m wavelength region. It is an ideal substrate material for lenses, windows and mirrors in low-power cw and $CO_2$ laser applications.



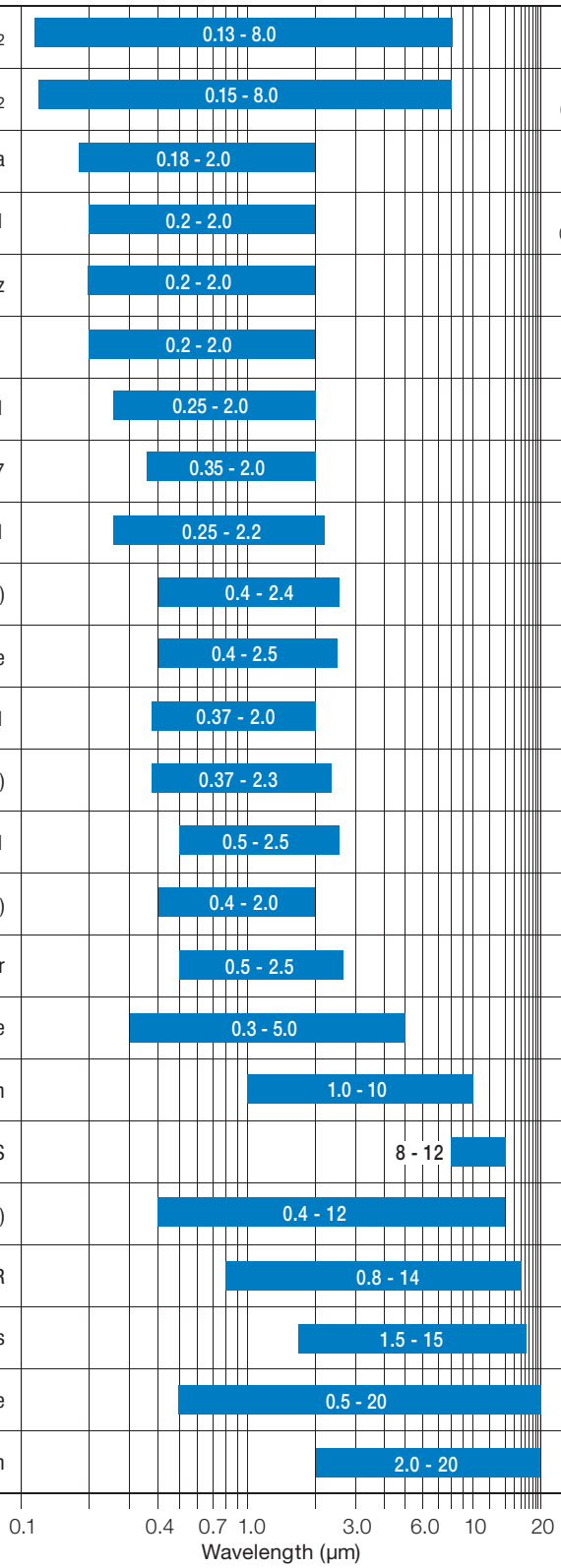

**External transmittance for 10-mm-thick uncoated germanium**

### Germanium Constants

| | |
|---|---|
| **Transmission Range** | 2–23 $\mu$m |
| **Temperature Coefficient of Refractive Index @ 10.6 $\mu$m** | $277 \times 10^{-6}$/°C |
| **Bulk Absorption Coefficient @ 10 $\mu$m** | 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** | $5.7 \times 10^{-6}$/°C |

### Refractive Index of Germanium

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

# Material Properties Overview

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