Optical Glass

There are a multitude of optical grade glasses available from various manufacturers worldwide. They have a wide variety of optical characteristics which allows aberrations to be corrected to the level required for very demanding imaging applications. Optical glasses are predominantly used from 350nm–2500nm - in fact within this spectral region there is usually no need to consider any other material. Two of the most important optical characteristics of an optical glass are the refractive index and the dispersion. The dispersion is the index difference between the extreme ends of the spectral region of interest. Another figure sometimes more convenient in discussing the properties of an optical material is the Abbe number, which is related to, and calculated from the dispersion. Although these quantities can be defined using any arbitrary wavelengths, a particular choice which has become the de facto standard in the industry is the use of the three wavelengths d,C,F (587.6, 656.3, 486.1nm respectively). In this case the Abbe number V_d is defined as

$$V_d = \frac{n_d - 1}{n_F - n_c}$$

Sometimes the refractive index and Abbe number are combined into a six figure glass code, which allows substitute glasses from alternative suppliers to be located with greater ease. This code is formed by using the first three significant figures after the decimal point in the value of n_d followed by the three most significant digits in the value of V_d.

Irrespective of the glass manufacturer, it is very common for the Schott designation to be given in the catalog listing of material properties. Most manufacturers produce glasses which are, for practical purposes, identical to many of the more popular glasses in the Schott range, in addition to specialty glasses of their own.

For historical reasons the range of glasses is divided into two subgroups:– The crown glasses with $n_d < 1.6$ and $V_d > 55$ or $n_d > 1.6$ and $V_d > 50$; with the remaining glasses known as the flint glasses.

The ideal glass prescription would be a glass with a high value of both n_d and V_d, as this would enable components of high refracting power to be constructed from components with shallow curves. In addition the color aberrations and some of the monochromatic aberrations would be greatly reduced. Unfortunately, (in order to increase the refractive index), oxides of heavier elements have to be added to the basic SiO_2 matrix upon which most optical glasses are made. This generally results in a loss of transmission at the blue end of the spectrum and an increase in the optical dispersion. Glasses with high values of n_d tend to be flints, and as a general rule an increase in n_d and V_d both lead to an increase in material cost (in some cases by an order of magnitude).

By far the most popular optical glass is BK7(517642). It exhibits excellent transmission from 350nm to 2000nm. The transmission tails away slowly in the infrared with a complete extinction beyond 2.7 microns. At the UV end of the spectrum the material is not really usable at wavelengths lower than 300nm.

BK7 is a low index crown glass. It exhibits a good resistance to atmospheric attack, acid and alkali conditions and to staining - all of these features being desirable both in the final component and during the manufacturing processes that are required. The popularity of the material is such that all the major glass manufacturers produce a functionally identical equivalent, ensuring ready availability. In addition especially large pieces with improved levels of homogeneity and freedom from internal defects can be produced, at additional cost.

The majority of the components for the visible region in the Ealing Catalog are manufactured from BK7, except where special optical or physical properties are required.

Examples of this are in the use of F2(620364) and SF10(728284) glass to give a high spectral separation in some of the dispersing prisms, and LaSFN9(850322) in the micro lenses.

Also a wide variety of crown and flint combinations are used to correct the aberrations in compound lenses, such as the cemented achromatic doublets.

The nominal refractive indices of the four glasses BK7, LaSFN9, F2 and SF10 at any wavelength in the region 0.365 to 1.060 microns can be computed using the following expression:

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

where λ is the wavelength in microns and the coefficients for each glass are as shown below.

Glass Type Coefficient	BK7	LaSFN9	F2	SF10
A_0	2.2718929	3.2994326	2.5554063	2.8784725
A_1	$-1.0108077\mathrm{x}10^{-2}$	$-1.1680436\mathrm{x}10^{-2}$	$-8.8746150\mathrm{x}10^{-3}$	$-1.0565453\mathrm{x}10^{-2}$
A_2	$1.0592509\mathrm{x}10^{-2}$	$4.0133103\mathrm{x}10^{-2}$	$2.2494787\mathrm{x}10^{-2}$	$3.3279420\mathrm{x}10^{-2}$
A_3	$2.0816965\mathrm{x}10^{-4}$	$1.3263988\mathrm{x}10^{-3}$	$8.6924972\mathrm{x}10^{-4}$	$2.0551378\mathrm{x}10^{-3}$
A_4	$-7.6472538\mathrm{x}10^{-6}$	$4.7438783\mathrm{x}10^{-6}$	$-2.4011704\mathrm{x}10^{-5}$	$-1.1396226\mathrm{x}10^{-4}$
A_5	$4.9240991\mathrm{x}10^{-7}$	$7.8507188\mathrm{x}10^{-6}$	$4.5365169\mathrm{x}10^{-6}$	$1.6340021\mathrm{x}10^{-5}$

Further data and transmission curves are shown on the next Page.

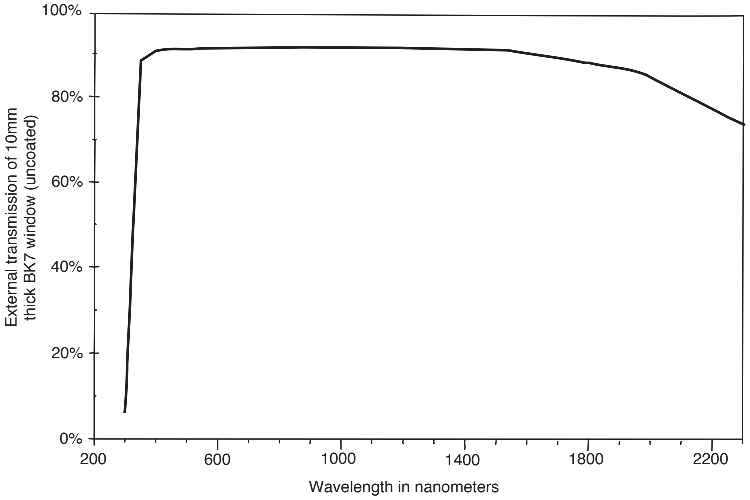
OPTICAL GLASS

Other important data and the transmission curves for these materials are given below.

Material	BK7 (517642)	LaSFN9 (850322)	F2(620364)	SF10(728284)
Abbe Number V_d	64.17	32.17	36.37	28.41
Density (g/cm^3)	2.51	4.44	3.61	4.28
Coefficient of Expansion ($10^{-6}/K$) (Room Temperature)	7.1	7.4	8.2	7.5
Specific Heat (J/g/K)	0.858	–	0.557	0.465
Thermal Conductivity (W/m/K)	1.114	–	0.780	0.741
Youngs Modulus ($10^3 N/mm^2$)	81	109	58	64
Poissons Ratio	0.208	0.286	0.225	0.232
Knoop Hardness	520	510	370	370

Refractive index versus λ

λ (nm)	Material			
	BK7	LaSFN9	F2	SF10
365.0	1.53626	–	1.66621	–
404.7	1.53024	1.89844	1.65063	1.77578
435.8	1.52669	1.88467	1.64202	1.76197
486.1	1.52238	1.86899	1.63208	1.74648
546.1	1.51872	1.85651	1.62408	1.73430
587.6	1.51680	1.85026	1.62004	1.72825
632.8	1.51509	1.84489	1.61656	1.72309
656.3	1.51432	1.84526	1.61503	1.72085
852.1	1.50981	1.82997	1.60672	1.70889
1060.0	1.50669	1.82293	1.60191	1.70229



Fused Silica and Fused Quartz

Both of these materials exhibit transmission characteristics which bear some similarity to the optical glasses with which they are closely related. However, their simpler chemical composition, in particular the absence of some of the heavier metal oxides, leads them to have improved transmission in the Ultraviolet region of the spectrum. Special grades of material may be specified which are pre–treated to reduce the water content. This eliminates characteristic O–H absorption lines in the near Infrared region of the spectrum although at the expense of transmission in the Ultraviolet. The spectral transmission curves are given below.

The physical properties of Fused Quartz and Fused Silica are similar, and in applications where the materials are chosen for their strength, chemical inertness or their resistance to elevated temperature or shock, the less expensive Fused Quartz may be the preferred option.

The fundamental difference between Fused Quartz and Fused Silica is in the method of manufacture. Most Fused Quartz is produced by the melting and re–fusing of silica sand and natural quartz. This means that trace impurities in the raw materials used can be carried across into the final material matrix. The presence of heavy metallic ions is in part responsible for absorption at Ultraviolet wavelengths or for unacceptable levels of absorption in high power visible lasers.

By comparison Fused Silica is produced by the flame hydrolysis of a silica halide. The resultant material is hence much purer, and free from the sites which could cause absorption in the Ultraviolet or problems with internal absorption in the use of high power lasers.

Either of these materials is the most suitable choice for use in high power lamp sources. As they are far more resistant to thermal shock than optical glass, the final choice would be dependent on the spectral range required.

The refractive index of Fused Silica and Fused Quartz at various wavelengths may be calculated using the following Sellmeier type formula with the coefficients due to Malitson. (J.Opt.Soc.Am. 55 p1205 (1965))

$$n^2 = 1 + \frac{A_0\lambda^2}{\lambda^2 - B_0} + \frac{A_1\lambda^2}{\lambda^2 - B_1} + \frac{A_2\lambda^2}{\lambda^2 - B_2}$$

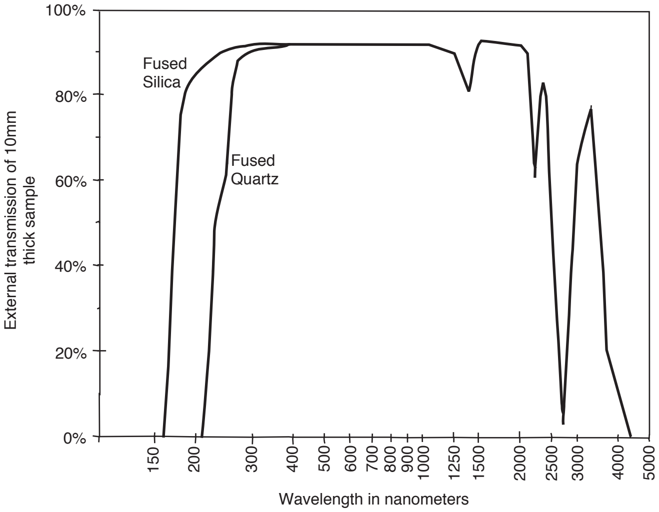
where $A_0 = 0.6961663$
$B_0 = 0.004679148$
$A_1 = 0.4079426$
$B_1 = 0.01351206$
$A_2 = 0.8974794$
$B_2 = 97.934003$

and λ is the wavelength in microns.

Abbe Number V_d:	67.8
Density:	2.203 g/cm^3
Softening Point:	1730°C
Annealing Point:	1180°C
Specific Heat:	0.76 J/g/K at 20°C
Thermal Conductivity:	1.39 W/m/K
Thermal Expansion:	0.55x10^{-6} /°C
Youngs Modulus:	72.8 x 10^3 N/mm^2
Hardness (Mohs):	5–7

Refractive index versus λ

λ (nm)	Index
214.4	1.53372
248.3	1.50840
265.2	1.50000
302.2	1.48719
334.1	1.47976
365.0	1.47454
404.7	1.47962
435.8	1.46669
486.1	1.46313
546.1	1.46008
587.6	1.45846
656.3	1.45637
852.1	1.45247
1014.0	1.45024
1530.0	1.44427
1970.0	1.43852
2325.4	1.43293



CALCIUM FLUORIDE

Calcium Fluoride

Calcium Fluoride (CaF_2) has a useful transmission over the spectral range from 0.2–8.0 microns. The low refractive index (1.35–1.51) means that it may be used without recourse to an anti–reflection coating.

It may be used as an alternative to Fused Silica in the Ultraviolet region, especially as a crown type material for assemblies which require reduced levels of chromatic aberration. In addition, the high Abbe number in the visible region, and the anomalous dispersion characteristics, render it useful for correcting visible systems for secondary color aberration (for example, apochromatic microscope objectives).

It is the least expensive material, with visible transmission, that also covers the complete 3–5 micron band.

Calcium Fluoride is slightly soluble in water, although the surfaces should be expected to withstand several years exposure to normal atmospheric conditions. Calcium Fluoride is also susceptible to thermal shock, reducing its usefulness somewhat with high radiance sources.

The refractive index of Calcium Fluoride at various wavelengths may be calculated using the following Sellmeier type formula with the coefficients due to Malitson. (Appl.Opt. 2,p1103(1963)).

$$n^2 = 1 + \frac{A_0\lambda^2}{\lambda^2 - B_0} + \frac{A_1\lambda^2}{\lambda^2 - B_1} + \frac{A_2\lambda^2}{\lambda^2 - B_2}$$

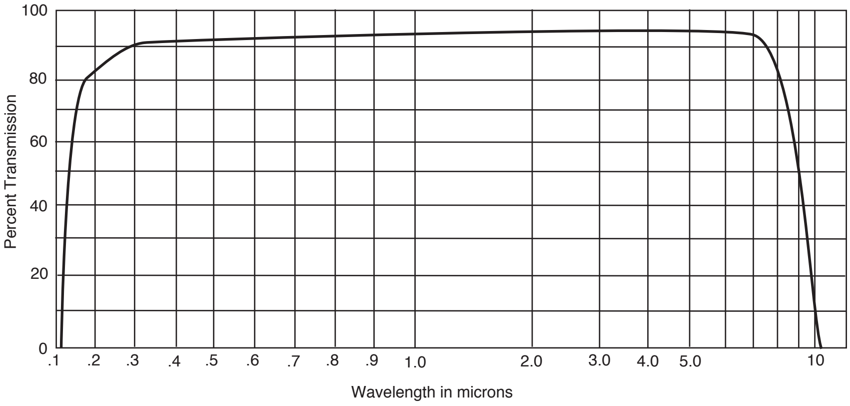
where $A_0 = 0.5675888$
$B_0 = 0.00252643$
$A_1 = 0.4710914$
$B_1 = 0.01007833$
$A_2 = 3.8484723$
$B_2 = 1200.5560$

and λ is the wavelength in microns

Abbe Number V_d:	94.9
V_{3-5}:	21.7
Density:	3.179 g/cm^3
Melting Point:	1360°C
Specific Heat:	0.857 J/g/K at 0°C
Thermal Conductivity:	1.037W/m/K at 0°C
Thermal Expansion:	18.9x10^{-6}/K at 20°C
Youngs Modulus:	76x10^{3}N/mm^2
Solubility:	0.00177 g/100 g H_2O (at 26°C)

Refractive index versus λ

λ(nm)	Index
248.3	1.46793
265.2	1.46233
334.1	1.44852
365.0	1.44490
404.7	1.44451
435.8	1.43949
486.1	1.43703
546.1	1.43494
587.6	1.43388
656.3	1.43246
852.1	1.43002
1014.0	1.42879
1530.0	1.42642
1970.0	1.42401
2325.4	1.42212
3507.0	1.41398
5018.8	1.39873
7464.4	1.36070



Germanium

Germanium is a semiconductor material, which has high internal transmittance for radiation in the wavelength range from 1.8–12 microns. It is particularly favored for use in the 3–5 and 8–12 micron regions, for which the atmosphere is transparent. In addition the lower cost of the raw material compared to the possible alternatives is a strong factor in its favor.

Its high refractive index (approx 4.0) allows components of high refractive power to be constructed without excessive thickness or extreme curvatures. This keeps material usage down and reduces the processing time in quantity production.

The high index also ensures an exceptional single wavelength performance for a “best form” singlet constructed from Germanium. The extremely high Abbe number in the 8–12 micron band, and the relatively high value in the 3–5 micron band, means that in most cases special achromatizing measures are not required.

A drawback of the high refractive index is the high uncoated surface reflection losses of 36% per surface, giving an uncoated component an external transmittance of 40% . This makes the application of an AR coating essential in virtually all practical situations. Fortunately the high refractive index can actually simplify the coating design in some cases, and a range of coatings is available to meet the majority of requirements.

The optimum form of material for use in most optical applications is n–type doped material with a resistivity in the range of 5–40Ωcm. This material, which is doped with a controlled amount of Antimony(Sb), exhibits a lower absorption loss than other forms of the material, provided the temperature of the material is kept below 50°C.

For high power applications, especially those which involve CW lasers or lasers with high energy pulses and a fast repetition rate, it is preferable to use Zinc Selenide. The problem with Germanium in these applications is its susceptibility to thermal runaway. If energy is absorbed in the component the local temperature near the beam may increase because the thermal conductivity of Germanium is too low for the heat to be dissipated. If this happens then the local value of the absorption coefficient will also rise. There is the possibility of a continual and uncontrolled rise in temperature leading to component failure. Even where water cooling is used, the thermal gradient required to allow the heat away may only reach a steady state condition at a point where thermal distortion of the beam has upset the system performance.

The refractive index of Germanium at various wavelengths can be calculated using the following formula due to Salzberg and Villa:– (J.Opt.Soc.Am. 43 p 579 (1953))

$$n = A+BL+CL^2+D\lambda^2+E\lambda^4$$

where
A = 3.99931
B = 0.391707
C = 0.163492
D =–0.0000060
E = 0.000000053

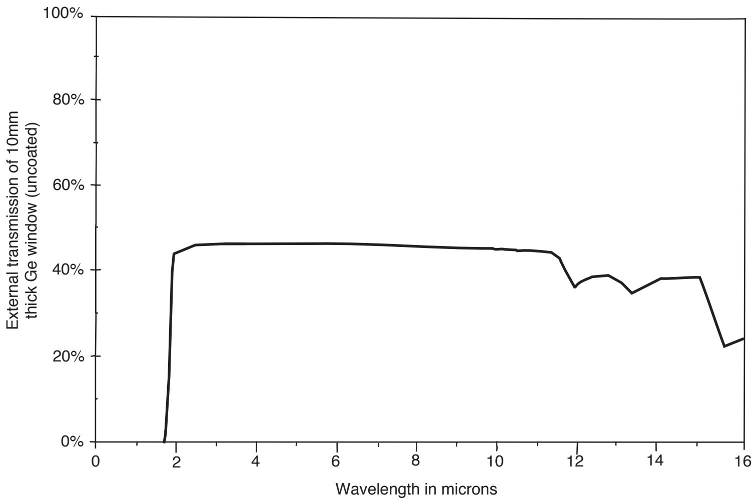
$$L = \frac{1}{(\lambda^2-0.028)}$$

and λ is the wavelength in microns

Abbe Number V_{3-5}:	101.5
V_{8-12}:	988
Density:	5.327 g/cm^3
Melting Point:	936°C
Specific Heat:	0.32J/g/K at 0°C
Thermal Conductivity:	59.9W/m/K at 20°C
Thermal Expansion:	5.75x10^{-6}/K at 20°C
Youngs Modulus:	103x10^{3}Nmm^{-2}

Refractive index versus λ

λ (microns)	Index
2.0	4.10827
2.5	4.06645
3.0	4.04495
3.5	4.03239
4.0	4.02439
4.5	4.01898
5.0	4.01514
5.5	4.01232
6.0	4.01018
6.5	4.00852
7.0	4.00721
7.5	4.00616
8.0	4.00531
8.5	4.00461
9.0	4.00403
9.5	4.00356
10.0	4.00317
10.5	4.00286
11.0	4.00261
12.0	4.00227
13.0	4.00213
14.0	4.00217



ZINC SELENIDE

Zinc Selenide

Zinc Selenide is a transparent polycrystalline material with a transmission range from 0.5–15 microns. The material is produced by a CVD (Chemical Vapor Deposition) process, which ensures that the extrinsic impurity levels are kept low. The purity of the material minimizes the bulk absorption loss figures.

Although the material is more expensive than Germanium, the ability to use visual alignment aids (such as a He–Ne laser), can reduce the costs incurred by the end user. This is especially so if many optical components are used in sequence.

The absorption losses are not only lower than Germanium, they are also far more stable with temperature. This ensures that the risk of thermal runaway leading to component failure is reduced, and this material should always be considered in any high power laser application. In addition the possible dangers of having an unpredictable path through misaligned optics is far less because of the visual checks which can be carried out prior to firing up the laser.

The average refractive index value of approximately 2.4 gives uncoated reflection losses of 17% per surface, and an external transmittance of 69% in the principal beam. Usually the main issue is not the loss of radiation so much as the unwanted stray light problem. Some form of AR coating is recommended on ZnSe components and coatings are available to meet both narrow band and wide band requirements.

The refractive index of Zinc Selenide at various wavelengths may be calculated using the following Sellmeier type formula with the coefficients due to Feldman, Horowitz, Waxler and Dodge. "Optical Materials Characterization Final Report February 1, 1978 – September 30, 1978", NBS Technical Note 993.

$$n^2 = 1 + \frac{A_0\lambda^2}{\lambda^2 - B_0} + \frac{A_1\lambda^2}{\lambda^2 - B_1} + \frac{A_2\lambda^2}{\lambda^2 - B_2}$$

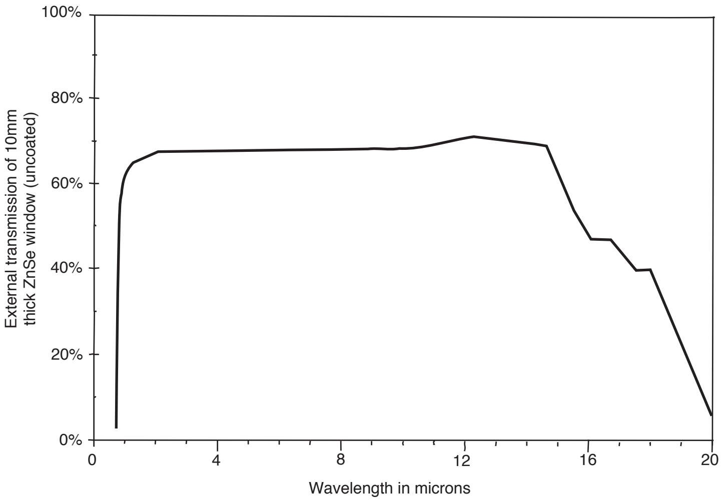
where $A_0 = 4.2980149$
$B_0 = 0.036888196$
$A_1 = 0.62776557$
$B_1 = 0.14347626$
$A_2 = 2.8955633$
$B_2 = 2208.4920$

and λ is the wavelength in microns.

Abbe Number V_{3-5}: 178
V_{8-12}: 57.5
Density: 5.27g/cm^3
Specific Heat: 0.34 J/g/K at 25°C
Thermal Conductivity: 18 W/m/K at 25°C
Thermal Expansion: 7.1x10^{-6}/K at 0°C
Youngs Modulus: 67x10^{3}N/Kmm^{-2}

Refractive index versus λ

λ (microns)	Index
1.0	2.48882
1.5	2.45708
2.0	2.44620
2.5	2.44087
3.0	2.43758
3.5	2.43517
4.0	2.43316
4.5	2.43132
5.0	2.42953
5.5	2.42772
6.0	2.42584
6.5	2.42388
7.0	2.42181
7.5	2.41961
8.0	2.41728
8.5	2.41481
9.0	2.41218
9.5	2.40939
10.0	2.40644
10.5	2.40331
11.0	2.40000
12.0	2.39281
13.0	2.38481
14.0	2.37593



Sapphire

This material has excellent mechanical and optical properties. It is extremely hard (9 on the mohs scale) and has a strength which is retained even at elevated temperatures. In addition it is resistant to virtually all forms of chemical attack. It has a transmission band which extends from the UV at around 0.18nm, throughout the visible and near IR regions to 5.5 microns.

The high cost of this versatile material naturally tends to limit its use to the following areas:–

1) As a durable single lens in detector applications which do not require multi–component correction.

2) As a protective window to shield more delicate optics from harsh environments such as debris from laser cutting processes. The window can frequently be kept extremely thin, saving on material cost and lowering any possible internal absorption. Vigorous cleaning methods can also be used with less danger of scratching the window and causing losses due to surface scatter.

3) It has also been used more recently in the form of spherical balls in fiber coupling applications.

Depending on the wavelength at which it is used the Fresnel reflection losses vary from 5% – 20% per surface. However at the wavelengths where these losses are highest the refractive index of 1.7–1.8 is almost ideal for the application of a single layer coating of MgF_2.

The internal structure of the material is anisotropic, which means that certain properties have a dependence on the direction in which they are measured in the bulk material. The most significant of these properties is the birefringence introduced, which could be a problem in a particularly demanding application. Fortunately the thinness of the substrates used is usually a sufficient protection against this source of image degradation.

The refractive index of Sapphire at various wavelengths may be calculated using the following Sellmeier type formula with the coefficients due to Malitson. (J.Opt.Soc.Am. 52 p 1377 (1962))

$$n^2 = 1 + \frac{A_0\lambda^2}{\lambda^2 - B_0} + \frac{A_1\lambda^2}{\lambda^2 - B_1} + \frac{A_2\lambda^2}{\lambda^2 - B_2}$$

where $A_0=1.023798$
$B_0=0.00377588$
$A_1=1.058264$
$B_1=0.0122544$
$A_2=5.280792$
$B_2=321.3616$

and λ is the wavelength in microns

Abbe Number V_d:	72.2
Density:	3.98 g/cm^3
Melting Point:	2055°C
Specific Heat:	756 J/kg/°C at 18°C
Thermal Conductivity:	24 W/m/K
Thermal Expansion:	6.5x10^{-6}/K
Youngs Modulus:	345x10^{3}N/mm^2

(Properties are dependent on orientation)

Refractive index versus λ

λ(nm)	Index
265.2	1.83365
334.1	1.80181
365.0	1.79358
404.7	1.78582
435.8	1.78120
486.1	1.77558
546.1	1.77077
587.6	1.76823
656.3	1.76494
852.1	1.75887
1014.0	1.75546
1530.0	1.74659
1970.0	1.73835
2325.4	1.73055
3507.0	1.69501
5145.6	1.61510