Optical Materials

Section 17

Materials

Index of Refraction

Some common indices:

vacuum		1.0
helium		1.000036
hydrogen		1.000132
air		1.000293
water		1.33
fused silica		1.46
plastics		1.48-1.6
borosilicate crown glass		1.51
crown glass		1.52
light flint glass		1.57
dense barium crown		1.62
dense flint		1.72
diamond		2.4
ZnSe	@ 0.5 µm	2.8
	@ 5 µm	2.2
ZnS	@ 1 µm	2.5
	@ 10 µm	2.4
Silicon	@ 10 µm	3.4
Germanium	@ 13 µm	4.0

The index of refraction is usually quoted relative to air instead of vacuum.

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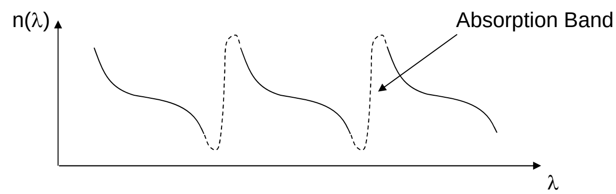
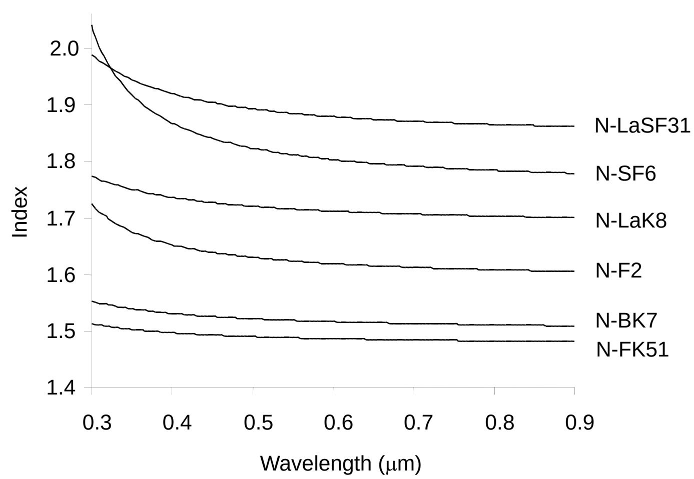
Dispersion

The refractive index is a function of wavelength. The index increases at the absorption bands. This is anomalous dispersion. Between the absorption bands the index decreases with wavelength.



Optical materials – Generally one of the absorption bands occurs in the ultraviolet and one occurs in the infrared. The normal part of the curve is used in the visible. The index for blue wavelengths is higher than the index for red wavelengths.

Different Materials



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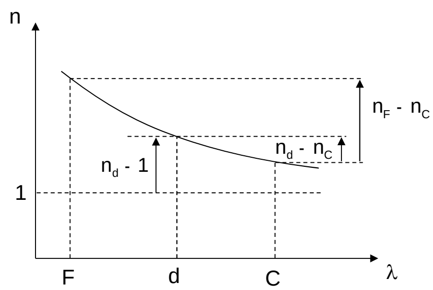
Dispersion Curves

Index of refraction is commonly measured and reported at the specific wavelengths of elemental spectral lines. Over the visible spectrum, the dispersion of the index of refraction for optical glass is about 0.5% (low dispersion) to 1.5% (high dispersion) of the mean value of the index.



F	(H)	486.1 nm
d	(He)	587.6 nm
C	(H)	656.3 nm
I	(Hg)	365.0 nm
h	(Hg)	404.7 nm
F'	(Cd)	480.0 nm
g	(Hg)	435.8 nm
e	(Hg)	546.1 nm
D	(Na)	589.3 nm
C'	(Cd)	643.8 nm
r	(He)	706.5 nm
t	(Hg)	1014.0 nm

Refractivity: $n_d - 1$

Principal Dispersion: $n_F - n_C$

Partial Dispersion $n_d - n_C$

Dispersion: $\frac{dn}{d\lambda} < 0$

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Abbe Number

Abbe number (or reciprocal relative dispersion) is the single number used to characterize the dispersion of the index of an optical material:

$$\nu = V = \frac{n_d - 1}{n_F - n_C} \qquad \frac{Refractivity}{Principal\ dispersion}$$

Typical values of the Abbe number for optical glass range from 25 to 65. Low ν-values indicate high dispersion.

Relative partial dispersion ratio or P-value gives the fraction of the total index change that occurs between the d and C wavelengths n_d -n_C.

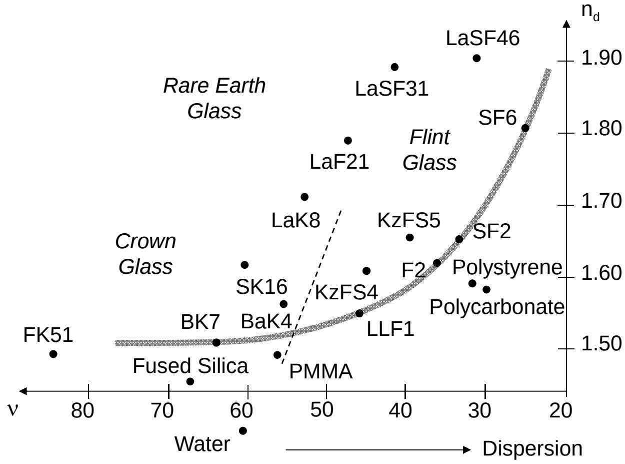
$$P = P_{d,C} = \frac{n_d - n_C}{n_F - n_C}$$

Due to the flattening of the dispersion curve, $P_{d,C} < 0.5$. P-values can also be defined for other sets of wavelengths:

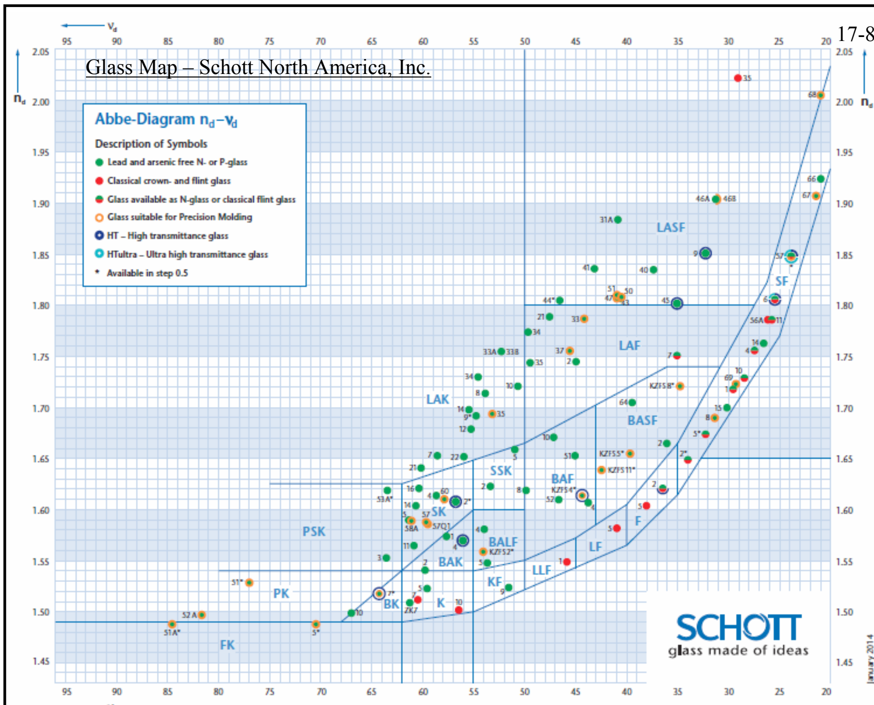
$$P_{X,Y} = \frac{n_X - n_Y}{n_F - n_C}$$

Glass Map

The glass map plots index of refraction versus Abbe number. By tradition, the Abbe number increases to the left, so that dispersion increases to the right. The glass line is the locus of ordinary optical glasses based on silicon dioxide.



Glass Map – Schott North America, Inc.



Glass Map - Continued

The line at $\nu \approx 50\text{-}60$ separates the glasses into the two primary classifications: crown glass (low dispersion) and flint glass (high dispersion).

The addition of lead oxide increases the dispersion and the index and moves the glass up the glass line. To increase the index without changing the dispersion, barium oxide is added. The rare earth glasses are lanthanum oxide based (instead of silicon dioxide) and provide high index and low dispersion.

Glasses away from the glass line are softer and more difficult to polish. They are also susceptible to staining. They can be very expensive just for the raw material .

Low index glasses are less dense and generally have better blue transmission.

Glasses have been recently reformulated to eliminate lead and arsenic. Lead is replaced with other elements, especially titanium. The new or environmentally safe glasses usually carry an N, S or E prefix (depending on the manufacturer).

Glass Code

The six-digit glass code specifies the index and the Abbe number:

$abcdef \qquad n_d = 1.abc \qquad \nu = de.f$

For example BK7 (the single most common optical glass):

$517642 \qquad n_d = 1.517 \qquad \nu = 64.2$

The enhanced glass code also encodes the density of the glass in g/cm^3:

For BK7: 517642.251

The glass density is 2.51 g/cm^3

Glass Data

* Schott Glass Technologies Inc. designation. Equivalent glasses can also be obtained from Ohara Corp. and Hoya Corp.

Material	Code	n_d	n_F	n_C	ν	P	Rel $
N-FK51*	487845	1.48656	1.49056	1.48480	84.5	0.306	35
N-BK7	517642	1.51680	1.52238	1.51432	64.2	0.308	1.0
LLF1	548458	1.54814	1.55655	1.54457	45.8	0.298	5
N-BaK4	569560	1.56883	1.57591	1.56575	56.0	0.303	2.5
N-KzFS4	613445	1.61336	1.62300	1.60922	44.5	0.301	23
N-F2	620364	1.62005	1.63208	1.61506	36.4	0.294	3.5
N-SK16	620603	1.62041	1.62756	1.61727	60.3	0.305	3.5
N-SF2	648338	1.64769	1.66125	1.64210	33.8	0.292	3.5
N-KzFS5	654397	1.65412	1.66570	1.64922	39.7	0.297	10
N-LaK8	713538	1.71300	1.72222	1.70897	53.8	0.304	8
N-LaF21	788475	1.78800	1.79960	1.78301	47.5	0.301	15
N-SF6	805254	1.80518	1.82783	1.79608	25.4	0.287	9
N-LaSF31A	883408	1.88300	1.89822	1.87656	40.8	0.297	35
N-LaSF46A	904313	1.90366	1.92411	1.89526	31.3	0.291	15
Fused Silica	458678	1.45847	1.46313	1.45637	67.8	0.311	
PMMA	492574	1.492	1.498	1.489	≈55	≈0.33	
Polycarbonate	585299	1.585	1.600	1.580	≈30	≈0.25	
Polystyrene	590311	1.590	1.604	1.585	≈31	≈0.26	
Water	333560	1.333	1.337	1.331	≈60	≈0.33	

The properties of an individual sample, especially for the plastic materials and water, can vary from these catalog values. For precision systems, the measured indices of the actual glass should be used in final designs. The listed indices are measured relative to air ($n \approx 1.0003$), and the indices should be corrected for use in vacuum.

Other Glass Properties

In addition to index data at various wavelengths, the glass catalog lists other materials properties important for a design such as coefficients of thermal expansion, temperature coefficients of refractive index, internal transmission as a function of wavelength, several mechanical properties, and chemical resistance values.

Chemical properties (low is good):

- CR – Climate resistance, water vapor (Scale 1-4)
- FR – Stain resistance (Scale 0-5)
- SR – Resistance to acids (Scale 1-4 plus 51-53)
- AR – Alkali resistance (Scale 1-4)
- PR – Phosphate resistance (Scale 1-4)

α = Temperature coefficient of expansion
T_g = Glass transition temperature
C_p = Specific heat
λ = Thermal conductivity
ρ = Density
HK = Knoop Hardness
τ_i = Internal transmission (5 mm and 25 mm thick)

dn/dt = Temperature coefficient of refractive index
Coefficients of the dispersion formula

Approx. Glass Cost (2014):

N-BK7	$11/lb
N-LaK8	$85/lb
N-FK51	$280/lb
N-LaSF31	$380/lb

Glass Properties– Schott North America, Inc.

Refractive indices
The refractive indices n are listed for a maximum of 23 wavelengths in the range between 248.2 nm and 2325.4 nm.

Constants of the dispersion formula
From the Sellmeier dispersion formula

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

the refractive indices for any wavelength within the range from the near UV to 2.3 µm can be calculated with the help of the constants B_1, B_2, B_3, and C_1, C_2, C_3.

Constants of the formula dn/dT
The temperature dependence of the refractive index can be calculated using the following formula:

$$\frac{dn_{abs}(\lambda, T)}{dT} = \frac{n^2(\lambda, T_0) - 1}{2\,n(\lambda, T_0)} \left(D_0 + 2\,D_1\,\Delta T + 3\,D_2\,\Delta T^2 + \frac{E_0 + 2\,E_1\,\Delta T}{\lambda^2 - \lambda^2_{TK}} \right)$$

The constants are valid for a temperature range from -100°C to +140°C and a wavelength range from 0.365 µm to 1.014 µm. The temperature coefficients in the data sheets are guideline values.

Temperature coefficient of refraction
$\Delta n_{rel} / \Delta T$ referring to air at normal pressure 1013.3 mbar
$\Delta n_{abs} / \Delta T$ referring to vacuum

Internal transmittance τ_i
The internal transmittance in the wavelength range between 250 nm and 2500 nm is listed for thickness of 10 and 25 mm. The internal transmittance and color code listed in the data sheet represent median values from several melts of one glass type. For HT and HTultra grade, the internal transmittance in the visible spectrum includes guaranteed minimum values.

Color code
The color code lists the wavelength λ_{80} and λ_5 at which the transmittance is 0.80 and 0.05 at 10 mm thickness. The values are rounded off to 10 nm and denoted by eliminating the first digit. For high index glass types with nd>1.83, the data of the color codes (marked by *) refers to the transmittance values 0.70 and 0.05 (λ_{70} and λ_5).

Relative partial dispersion
The relative partial dispersions P_{xy} and P'_{xy} for the wavelengths x and y are derived from the equations.

$$P_{xy} = \frac{n_x - n_y}{n_F - n_C} \text{ und } P'_{xy} = \frac{n_x - n_y}{n_{F'} - n_{C'}}$$

Deviation of the relative partial dispersion from the "normal line" ΔP
The term ΔP_{xy} quantitatively describes a deviation relation of the dispersion from the "normal glasses".

Glass Properties – Schott North America, Inc.

Other characteristics

$\alpha_{-30/+70}$	=	The coefficient of thermal expansion in the temperature range between – 30°C und + 70°C in 10^{-6}/K
$\alpha_{20/300}$	=	The coefficient of linear thermal expansion in the temperature range between + 20°C und + 300°C in 10^{-6}/K
Tg	=	Transformation temperature in °C
$T_{10^{13.0}}$	=	Temperature of the glass in °C at a viscosity of 10^{13} dPa·s
$T_{10^{7.6}}$	=	Temperature of the glass in °C at a viscosity of $10^{7.6}$ dPa·s
c_p	=	average specific heat capacity in J/(g·K)
λ	=	Thermal conductivity in W/(m·K)
AT*	=	Yield point/sag temperature in °C
ρ	=	Density in g/cm³
E	=	Elasticity modulus in 10^3 N/mm²
µ	=	Poisson's ratio
K	=	Stress optical coefficient in 10^{-6} mm²/N
HK	=	Knoop hardness
HG	=	Grindability class (ISO 12844)
Abrasion Aa*	=	Grindability according to JOGIS**
CR	=	Climatic resistance Resistance to moisture in the air expressed in CR classes 1 (high) to 4 (low).
FR	=	Stain resistance Resistance to stain formation expressed in FR classes 0 (high) to 5 (low).
SR	=	Acid resistance Resistance to acid solutions expressed in SR classes 1 (high) to 4 (low) and 51 to 53 (very low).
AR	=	Alkali resistance Resistance to alkaline solutions expressed in AR classes 1 (high) to 4 (low).
PR	=	Phosphate resistance Resistance to alkaline phosphate containing solutions expressed in PR classes 1 (high) to 4 (low).

SCHOTT N-BK 7®
517642.251

n_d = 1.51680	ν_d = 64.17	$n_F - n_C$ = 0.008054
n_e = 1.51872	ν_e = 63.96	$n_{F'} - n_{C'}$ = 0.008110

Refractive Indices

	λ [nm]	
$n_{2325.4}$	2325.4	1.48921
$n_{1970.1}$	1970.1	1.49495
$n_{1529.6}$	1529.6	1.50091
$n_{1060.0}$	1060.0	1.50669
n_t	1014.0	1.50731
n_s	852.1	1.50980
n_r	706.5	1.51289
n_C	656.3	1.51432
$n_{C'}$	643.8	1.51472
$n_{632.8}$	632.8	1.51509
n_D	589.3	1.51673
n_d	587.6	1.51680
n_e	546.1	1.51872
n_F	486.1	1.52238
$n_{F'}$	480.0	1.52283
n_g	435.8	1.52668
n_h	404.7	1.53024
n_i	365.0	1.53627
$n_{334.1}$	334.1	1.54272
$n_{312.6}$	312.6	1.54862
$n_{296.7}$	296.7	
$n_{280.4}$	280.4	
$n_{248.3}$	248.3	

Internal Transmittance τ_i

λ [nm]	τ_i (10mm)	τ_i (25mm)
2500	0.665	0.360
2325	0.793	0.560
1970	0.933	0.840
1530	0.992	0.980
1060	0.999	0.997
700	0.998	0.996
660	0.998	0.994
620	0.998	0.994
580	0.998	0.996
546	0.998	0.996
500	0.998	0.994
460	0.997	0.993
436	0.997	0.992
420	0.997	0.993
405	0.997	0.993
400	0.997	0.992
390	0.996	0.989
380	0.993	0.983
370	0.991	0.977
365	0.988	0.971
350	0.967	0.920
334	0.905	0.780
320	0.770	0.520
310	0.574	0.250
300	0.292	0.050
290	0.063	
280		
270		
260		
250		

Relative Partial Dispersion

$P_{s,t}$	0.3098
$P_{C,s}$	0.5612
$P_{d,C}$	0.3076
$P_{e,d}$	0.2386
$P_{g,F}$	0.5349
$P_{i,h}$	0.7483
$P'_{s,t}$	0.3076
$P'_{C',s}$	0.6062
$P'_{d,C'}$	0.2566
$P'_{e,d}$	0.2370
$P'_{g,F'}$	0.4754
$P'_{i,h}$	0.7432

Deviation of Relative Partial Dispersions ΔP from the "Normal Line"

$\Delta P_{C,t}$	0.0216
$\Delta P_{C,s}$	0.0087
$\Delta P_{F,e}$	-0.0009
$\Delta P_{g,F}$	-0.0009
$\Delta P_{i,g}$	0.0035

Other Properties

$\alpha_{-30/+70°C}$ [10^{-6}/K]	7.1
$\alpha_{+20/+300°C}$ [10^{-6}/K]	8.3
T_g [°C]	557
$T_{10}^{13.0}$ [°C]	557
$T_{10}^{7.6}$ [°C]	719
c_p [J/(g·K)]	0.858
λ [W/(m·K)]	1.114
ρ [g/cm³]	2.51
E [10^3 N/mm²]	82
μ	0.206
K [10^{-6} mm²/N]	2.77
$HK_{0.1/20}$	610
HG	3
CR	1
FR	0
SR	1
AR	2.3
PR	2.3

Constants of Dispersion Formula

B_1	1.03961212
B_2	0.231792344
B_3	1.01046945
C_1	0.00600069867
C_2	0.0200179144
C_3	103.560653

Constants of Dispersion dn/dT

D_0	$1.86 \cdot 10^{-6}$
D_1	$1.31 \cdot 10^{-8}$
D_2	$-1.37 \cdot 10^{-11}$
E_0	$4.34 \cdot 10^{-7}$
E_1	$6.27 \cdot 10^{-10}$
λ_{TK} [μm]	0.17

Color Code

λ_{80}/λ_5	33/29
(*= λ_{70}/λ_5)	

Remarks

step 0.5 available

Temperature Coefficients of Refractive Index

	$\Delta n_{rel}/\Delta T$ [10^{-6}/K]			$\Delta n_{abs}/\Delta T$ [10^{-6}/K]		
[°C]	1060.0	e	g	1060.0	e	g
-40/-20	2.4	2.9	3.3	0.3	0.8	1.2
+20/+40	2.4	3.0	3.5	1.1	1.6	2.1
+60/+80	2.5	3.1	3.7	1.5	2.1	2.7

N-BK7– Schott North America, Inc.

N-LAK8
713538.375

n_d = 1.71300	ν_d = 53.83	$n_F - n_C$ = 0.013245
n_e = 1.71616	ν_e = 53.61	$n_{F'} - n_{C'}$ = 0.013359

Refractive Indices

	λ [nm]	
$n_{2325.4}$	2325.4	1.67294
$n_{1970.1}$	1970.1	1.68075
$n_{1529.6}$	1529.6	1.68890
$n_{1060.0}$	1060.0	1.69710
n_t	1014.0	1.69802
n_s	852.1	1.70181
n_r	706.5	1.70668
n_C	656.3	1.70897
$n_{C'}$	643.8	1.70962
$n_{632.8}$	632.8	1.71022
n_D	589.3	1.71289
n_d	587.6	1.71300
n_e	546.1	1.71616
n_F	486.1	1.72222
$n_{F'}$	480.0	1.72297
n_g	435.8	1.72944
n_h	404.7	1.73545
n_i	365.0	1.74573
$n_{334.1}$	334.1	1.75687
$n_{312.6}$	312.6	
$n_{296.7}$	296.7	
$n_{280.4}$	280.4	
$n_{248.3}$	248.3	

Internal Transmittance τ_i

λ [nm]	τ_i (10mm)	τ_i (25mm)
2500	0.398	0.100
2325	0.707	0.420
1970	0.950	0.880
1530	0.992	0.979
1060	0.998	0.994
700	0.998	0.996
660	0.998	0.995
620	0.998	0.994
580	0.998	0.994
546	0.998	0.995
500	0.998	0.994
460	0.995	0.987
436	0.992	0.979
420	0.988	0.970
405	0.981	0.952
400	0.977	0.943
390	0.965	0.915
380	0.946	0.870
370	0.905	0.780
365	0.877	0.720
350	0.739	0.470
334	0.509	0.185
320	0.276	0.040
310	0.137	0.010
300	0.044	
290	0.010	
280		
270		
260		
250		

Relative Partial Dispersion

$P_{s,t}$	0.2661
$P_{C,s}$	0.5408
$P_{d,C}$	0.3042
$P_{e,d}$	0.2383
$P_{g,F}$	0.5450
$P_{i,h}$	0.7764
$P'_{s,t}$	0.2636
$P'_{C',s}$	0.5843
$P'_{d,C'}$	0.2536
$P'_{e,d}$	0.2363
$P'_{g,F'}$	0.4638
$P'_{i,h}$	0.7698

Deviation of Relative Partial Dispersions ΔP from the "Normal Line"

$\Delta P_{C,t}$	0.0266
$\Delta P_{C,s}$	0.0124
$\Delta P_{F,e}$	-0.0026
$\Delta P_{g,F}$	-0.0083
$\Delta P_{i,g}$	-0.0428

Other Properties

$\alpha_{-30/+70°C}$ [10^{-6}/K]	5.6
$\alpha_{+20/+300°C}$ [10^{-6}/K]	6.7
T_g [°C]	643
$T_{10}^{13.0}$ [°C]	635
$T_{10}^{7.6}$ [°C]	717
c_p [J/(g·K)]	0.620
λ [W/(m·K)]	0.840
ρ [g/cm³]	3.75
E [10^3 N/mm²]	115
μ	0.289
K [10^{-6} mm²/N]	1.81
$HK_{0.1/20}$	740
HG	2
CR	3
FR	2
SR	52.3
AR	1
PR	3.3

Constants of Dispersion Formula

B_1	1.33183167
B_2	0.546623206
B_3	1.19084015
C_1	0.00620023871
C_2	0.0216465439
C_3	82.5827736

Constants of Dispersion dn/dT

D_0	$4.10 \cdot 10^{-6}$
D_1	$1.25 \cdot 10^{-8}$
D_2	$-1.60 \cdot 10^{-11}$
E_0	$4.30 \cdot 10^{-7}$
E_1	$6.29 \cdot 10^{-10}$
λ_{TK} [μm]	0.213

Color Code

λ_{80}/λ_5	37/30
(*= λ_{70}/λ_5)	

Remarks

Temperature Coefficients of Refractive Index

	$\Delta n_{rel}/\Delta T$ [10^{-6}/K]			$\Delta n_{abs}/\Delta T$ [10^{-6}/K]		
[°C]	1060.0	e	g	1060.0	e	g
-40/-20	4.0	4.7	5.4	1.7	2.4	3.0
+20/+40	4.1	5.0	5.8	2.6	3.5	4.3
+60/+80	4.3	5.2	6.2	3.1	4.1	5.0

N-BK7– Schott North America, Inc.

Other Optical Materials

Fused Silica or Fused Quartz:

- Pure SiO_2; not crystalline (amorphous)
- Good UV transmission to about 200 nm (depends on purity)
- Used for microlithography lenses
- Low thermal expansion:

BK7	$\alpha = 7.1 \times 10^{-6}/°C$
Fused Silica	$\alpha = 5.5 \times 10^{-7}/°C$

Note: Fused silica has an extremely high change of index with temperature even though it is dimensionally very stable. May not be a good choice for thick windows.

Low Expansion Materials:

- Partially crystallized glasses – glass ceramics
  - CER-VIT
  - ULE
  - Zerodur

$\alpha = 0 \pm 1 \times 10^{-7}/°C$

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More Optical Materials

Crystalline Materials:

- Some are birefringent.
- Others are polycrystalline – prone to scattering.
- Often the only way to obtain transmission in the IR.
- Examples:

Si	$n \approx 3.4$	1.2-7.0 μm and 25-300 μm	
Ge	$n \approx 4$	2-14 μm	
ZnS	$n \approx 2.2$	3-12 μm	
ZnSe	$n \approx 2.4$	.6-16 μm	
CaF_2	$n \approx 1.4$	.13-7 μm	(Fluorite)
NaCl	$n \approx 1.5$	.2-20 μm	
LiF	$n \approx 1.35$	.12-5 μm	
CsBr	$n \approx 1.6$	.22-55 μm	
CsI	$n \approx 1.7$	.25-55 μm	

- A high index implies high Fresnel reflections (36% for Ge) – require AR coating.
- Some of the materials are sensitive to water vapor.
- Some provide excellent transmission in the UV and the IR.
- Some are very soft and fragile – hard to polish.
- For IR applications, some of the materials may be single-point diamond turned.

Plastics:

- Usually molded; can also be cast.
- Index changes with water absorption.
- Most common:
  - Acrylic (PMMA) (Plexiglas)
  - Polystyrene
  - Polycarbonate