Glass Materials

Glass materials used for optical systems are divided into three major types. Optical glass that transmits light such as prisms and half mirrors, substrate glass used for mirrors, and glass for a lens that is subdivided by refractive index and wavelength dispersion.

Optical Glass Materials

Typical optical glass materials are BK7 and synthetic fused silica. These materials have excellent internal quality, are chemically stable, and relatively easy to procure.

BK7

Optical glass material that is collectively called BK7, and has been used for lenses and prisms through the ages.
The model number differs among manufacturers such as BSC7 or BSL7, but since the composition ratio, optical property, physical property and chemical property are almost the same, "BK7" is used as a generic name.
This material has high permeability in the visible range and very low amounts of bubbles and inclusions, and striate and uneven refractive index that are problems in optical systems are reduced to the level where they practically do not have any influence.
In addition to the use in lenses and prisms, it is used in most optics such as substrates of mirrors and beamsplitters or substrates of various deposited filters.

Synthetic Fused Silica

Optical glass made of pure SiO_2 without inclusion of any other components.
The properties of this material include higher transmittance in the ultraviolet region and infrared region than BK7, and low thermal expansion.
Its refractive index is slightly smaller than BK7, but it provides internal quality equivalent to BK7, and is used in various optics as in the case of BK7.
Especially, this is often the material of choice for use with wavelengths other than the visible range.
Its low thermal expansion also makes it useful for substrates of high-precision mirrors or plane standards.

Synthetic Fused Silica for Excimer Laser

When you irradiate glass with ultraviolet light, the glass sometimes fluoresces.
Also, prolonged exposure to ultraviolet light causes a phenomenon called solarization, in which coloration to reddish brown occurs inside the glass.
Synthetic fused silica is glass resistant to fluorescence and solarization, but these phenomena sometimes occur when the wavelength of ultraviolet light is short. The causes are impurities inside the glass or molecular level flaws, and these causes can be reduced by improving purity of materials or devising a manufacturing method.
Synthetic fused silica manufactured in such a special manufacturing method is used for excimer lasers ArF (193nm) and KrF (248nm).
(Contact our International Sales Division when using with an ArF excimer laser.)

Water Free Synthetic Fused Silica

Synthetic fused silica exhibits characteristic absorption at the infrared wavelengths of 1.38μm, 2.22μm and 2.7μm.
This absorption is due to water (OH radical) attached to SiO_2 molecules.
Water free synthetic fused silica is manufactured in a special environment to prevent water from bonding with SiO_2, thus it can provide high transmittance up to 3.0μm infrared.
On the other hand, its transmittance in the ultraviolet region is not very high because impurities are added to dewater it forcibly.

Comparison Chart of Refractive Index and Transmittance between Synthetic Fused Silica and BK7 (Reference Data) Substrate thickness: 10mm

Wavelength [nm]	Synthetic Fused Silica		BK7		Note
	Refractive Index n	Transmittance T [%]	Refractive Index n	Transmittance T [%]	
165					
166		0			
167		20			
168		35			
169		46			
170		50			
173		75			
175		80			
180		84			
185.4		85			
190		86			
193.5	1.561	87			Ar*F laser
200	1.548	88			
210	1.540	90			
220	1.534	91			
230	1.523	91			
240	1.515	92			
248.4	1.510	92			Kr*F laser
266	1.499	92		0	YAG4ω laser
281.8	1.492	92		2	Xe*Br laser
308	1.485	92		51	Xe*Cl laser
325	1.483	92	1.545	79	He-Cd laser
337.1	1.480	93	1.541	86	N_2 Laser
355	1.476	93	1.539	90	YAG3ω laser
365	1.475	93	1.536	91	Hg i
404.7	1.470	93	1.530	92	Hg h
435.8	1.467	93	1.527	92	Hg g
441.6	1.466	93	1.526	92	He-Cd laser
457.9	1.465	93	1.525	92	Ar laser
480	1.464	93	1.523	92	Cd F′
486.1	1.463	93	1.522	92	H F
488	1.463	93	1.522	92	Ar laser
514.5	1.461	93	1.520	92	Ar laser
532	1.461	93	1.519	92	YAG2ω laser
546.1	1.460	93	1.519	92	Hg e
587.6	1.458	93	1.517	92	He d
589.3	1.458	93	1.517	92	Na D
632.8	1.457	94	1.515	92	He-Ne laser
643.9	1.457	94	1.515	92	Cd C′
650	1.457	94	1.514	92	Red LD
656.3	1.456	94	1.514	92	H C
670	1.456	94	1.514	92	Red LD
694.3	1.456	94	1.513	92	RUBY laser
780	1.454	94	1.512	92	Near Infrared LD

Wavelength [nm]	Synthetic Fused Silica		BK7		Note
	Refractive Index n	Transmittance T [%]	Refractive Index n	Transmittance T [%]	
830	1.452	94	1.510	92	Near Infrared LD
852.1	1.452	94	1.510	92	Cs s
904	1.452	94	1.509	92	Near Infrared LD
1014	1.450	94	1.508	92	Hg t
1064	1.449	94	1.507	92	YAG laser
1100	1.449	94	1.507	92	
1200	1.448	93	1.505	92	
1320	1.447	92	1.504	92	LD for communication
1400	1.446	87	1.503	91	
1500	1.445	93	1.501	91	
1550	1.444	93	1.500	91	LD for communication
1600	1.443	94	1.500	91	
1700	1.442	94	1.499	91	
1800	1.441	94	1.497	88	
1900	1.440	94	1.497	85	
2000	1.438	94	1.495	83	
2100	1.437	92	1.493	81	
2200	1.435	67	1.492	73	
2220	1.434	56	1.492	71	
2250	1.434	64	1.491	70	
2300	1.433	80	1.490	72	
2400	1.431	87	1.487	65	
2500	1.430	73	1.485	59	
2600	1.428	58	1.484	55	
2650	1.427	20	1.483	40	
2700	1.426	0	1.483	30	
2720	1.426	0	1.482	23	
2750	1.425	0	1.481	19	
2800	1.424	0		9	
2900	1.422	40		0	
3000	1.419	65			
3100	1.417	75			
3200	1.414	78			
3300	1.412	81			
3400	1.409	80			
3500	1.407	70			
3600		61			
3700		50			
3800		25			
3900		21			
4000		23			
4100		15			
4200		4			
4300		0			

	BK7	Synthetic Fused Silica
Abbe Number ν_d	64.1	67.8
Density [g/cm³]	2.52	2.20
Coefficient of Thermal Expansion [$\times 10^{-6}$/°C]	7.2	0.47
Thermal Conductivity [$Wm^{-1}K^{-1}$]	1.13	1.38

* Transmittance includes loss of the light volume by reflection on the front and back surfaces.

Application Systems
Optics & Optical Coatings
Opto-Mechanics
Bases
Manual Stages
Actuators & Adjusters
Motoeized Stages
Light Sources & Laser Safety
Index
Guide
Mirrors
Beamsplitters
Polarizers
Lenses
Multi-Element Optics
Filters
Prisms
Substrates/Windows
Optical Data
Maintenance

Glass Materials

Substrate Glass Materials

Usually a mirror uses a substrate made of BK7 or synthetic fused silica glass, polished to high precision. In cases where high surface flatness is not required or a thin substrate is used, however, a mirror is fabricated from glass called Pyrex®, which is used as a material of sheet glass, white glass or blue glass.
Some sheet glass achieves high flatness without polishing, and sometimes mirrors are fabricated by depositing coatings directly on this type of sheet glass.

Hard Glass (Pyrex®)

The generic name of glass used for dishes or heat-resistant containers, and Pyrex® is a typical product.
This material is resistant to scratches because it is chemically very stable, which makes it useful as glass substrates of mirrors.
Pyrex® is a registered trademark of Corning Incorporated.

Wavelength [nm]	Refractive Index
350	1.480
400	1.478
500	1.474
600	1.472
Density [g/cm^3]	2.23
Coefficient of Thermal Expansion [x10^{-6}/°C]	3.25 (20 – 300°C)
Thermal Conductivity [Wm^{-1}K^{-1}]	1.1
Transmission Range [μm]	0.38 – 2.3

B270®-Superwhite

This material is sheet glass generally called white sheet glass.
Since its optical properties are similar to BK7, it is sometimes used as an alternative to a BK7 glass substrate. However, the usage is limited because its internal quality is not guaranteed.
B270® is a registered trademark of SCHOTT AG.

Wavelength [nm]	Refractive Index
546	1.525
588	1.523
Density [g/cm^3]	2.55
Coefficient of Thermal Expansion [x10^{-6}/°C]	9.4 (20 – 300°C)
Thermal Conductivity [Wm^{-1}K^{-1}]	About 1
Transmission Range [μm]	0.35 – 2.5

Blue Sheet

This material is called soda-lime glass or blue sheet glass, relatively inexpensive and used for windowpanes.
Alkali components added for melting it at low temperature cause a slightly greenish color. This material is rarely used for optics unless for special cases.

Glass for Lens

Different glasses that vary in refractive index and wavelength dispersion (the Abbe number) are used for camera lenses and lenses for various lens devices.
A lens system created with only one type of glass will have greater chromatic aberration, and cannot provide high-performance properties.
When different glass is used for each lens, however, it is possible to create a functional and high-performance lens system.
This catalog lists only some of the glass for lenses because one type of glass is sufficient to achieve a purpose in case of a simple lens system for experiments such as for focusing or collimating laser light.
This catalog uses general names of glass materials, but eco materials that do not contain lead or hazardous substances are used for products to which RoHS applies.

Wavelength [nm]	Refractive Index		
	SK2	SF15	LaSF9
334.1	1.643	–	–
365.1	1.634	–	–
404.7	1.626	1.742	1.898
488.0	1.615	1.715	1.869
546.1	1.610	1.704	1.857
587.6	1.607	1.699	1.850
632.8	1.605	1.694	1.845
706.5	1.602	1.689	1.838
852.1	1.598	1.681	1.830
1064.0	1.595	1.675	1.823
1529.6	1.589	1.666	1.814
1970.1	1.584	1.659	1.807
2325.4	1.579	1.653	1.801
Abbe Number ν_d	56.8	30.1	32.3
Density [g/cm^3]	3.53	2.96	4.36
Coefficient of Thermal Expansion* [x10^{-6}/°C]	6.5	7.5	7.7
Thermal Conductivity [Wm^{-1}K^{-1}]	0.802	1.049	0.874
Transmission Range [μm]	0.36 – 2.2	0.42 – 2.4	0.46 – 2.2

* When between –30°C and 70°C

Crown Glasses and Flint Glasses

An achromatic lens reduces chromatic aberration by combining glass that has low wavelength dispersion of refractive index with glass that has high wavelength dispersion.
Glasses that have low wavelength dispersion (an Abbe number of 55 or over) are called crown glasses, and glasses that have high wavelength dispersion (an Abbe number of 50 or more) are called flint glasses.
The glasses for lens are mainly divided into these two categories.
Both crown glasses and flint glasses are subdivided by the properties of refractive index and wavelength dispersion, and named in a way using XX crown or XX flint such as crown glass K, borosilicate crown glass BK, flint glass F or dense flint glass SF. BK7 seems to be so named because it was developed as the 7th borosilicate crown glass.
Nowadays, these glasses are usually called by the abbreviated former model numbers used by SCHOTT, and complicated glass names are rarely used.

Incidentally, the glass was named crown because its viscosity is so high that when it is melted and a glass drop falls onto the liquid surface, the surface spreads in a crown shape. It was originally a jargon of glassworks artisans.
Regarding flint, it came from flint used as a raw material.

Glass Filters

Glass fabricated by adding absorbing substances such as metal ions to glass so that it will absorb a certain wavelength range.
Due to the fact that different glass materials are used for different transmission wavelengths, the optical, chemical and mechanical properties sometimes significantly differ. It is dangerous to consider that glasses with similar transmission wavelength characteristics have similar properties such as refractive index. Consult our International Sales Division for properties of glass filters.

Low Expansion Glass Materials

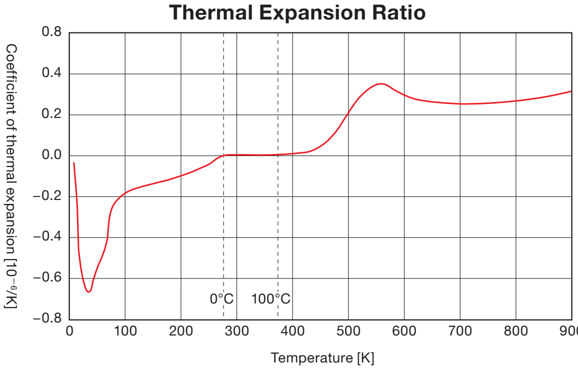
If a mirror with high surface accuracy is used in an environment subjected to drastic temperature fluctuation, the surface flatness of the mirror sometimes gets distorted.
The cause is the temperature distribution in the glass substrate of the mirror, because expansion varies among high temperature parts and low temperature parts. For this reason, substrates used for mirrors that require high precision are made of low expansion materials.
In general, silica glass is often used (coefficient of thermal expansion 5.5×10^{-7}/°C), but if higher precision is required, materials called low expansion glass or zero expansion glass are used.

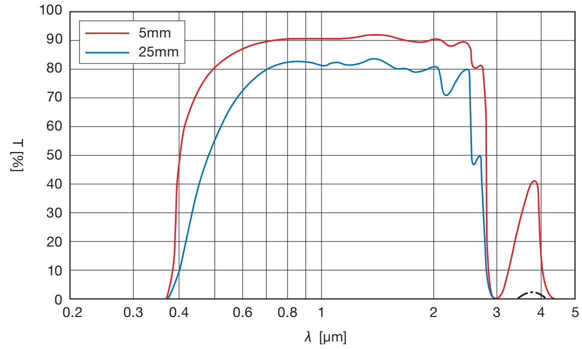
Zerodur®

This material is a glass ceramic containing a crystalline component that has a negative coefficient of expansion mixed in a low expansion vitreous component, and its coefficient of expansion is minimized to $\pm1\times10^{-7}$/°C in the temperature range between 0°C and 50°C.
Scattering by the crystals clouds the inside of the glass, and attenuation of light occurs inside the glass.
Since this material is relatively easy to process and polish, it is often used for large mirrors.
Zerodur® is a registered trademark of SCHOTT AG.

Wavelength [nm]	Refractive Index
486.1	1.5491
587.6	1.5424
656.3	1.5394
Transmitted Wavelength Range	0.4 – 2.5µm
Surface Reflectance	4.6% (587.6nm)
Density	2.53g/cm³

Thermal Expansion Ratio



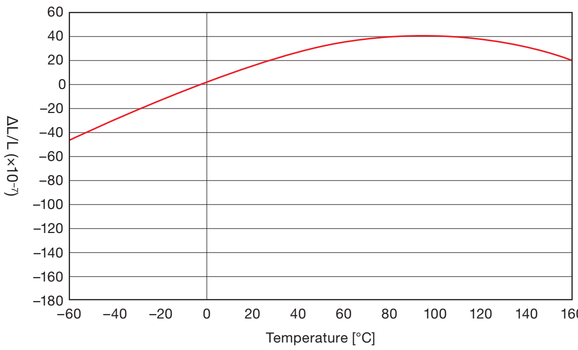


CLEARCERAM®-Z

This material is a zero-expansion glass ceramic fabricated by crystallizing crystal grains that have a negative coefficient of expansion inside glass.
Its coefficient of expansion is minimized to $\pm1\times10^{-7}$/°C in the temperature range between 0°C and 50°C.
The inside of the glass is transparent and transmits light. Its superior thermal, mechanical and chemical properties make it useful for laser mirrors or standard block gauges.
CLEARCERAM® is a registered trademark of OHARA INC.

Refractive Index	1.546 (587.6nm)
Transmitted Wavelength Range	0.4 – 2.5µm
Surface Reflectance	4.6% (587.6nm)
Density	2.55g/cm³

Thermal Expansion Ratio (temperature range: −60 – +160°C)



Application Systems
Optics & Optical Coatings
Opto-Mechanics
Bases
Manual Stages
Actuators & Adjusters
Motoeized Stages
Light Sources & Laser Safety
Index
Guide
Mirrors
Beamsplitters
Polarizers
Lenses
Multi-Element Optics
Filters
Prisms
Substrates/Windows
Optical Data
Maintenance

Optical Crystals

Some crystals exhibit excellent optical properties that glass materials cannot achieve.
On the other hand, crystals also have properties not desirable for optics such as deliquescent or birefringence properties.
Optics utilize useful crystals after comprehensive evaluation of these properties.

Optical Window Materials

Crystal Name	Calcium Fluoride	Sapphire	Zinc Selenide	Silicon	Germanium	Barium Fluoride	Lithium Fluoride	Magnesium Fluoride
Composition Formula	CaF_2	Al_2O_3	ZnSe	Si	Ge	BaF_2	LiF	MgF_2
Transmitted Wavelength [µm]	0.13 – 8	0.23 – 5	0.6 – 20	1.2 – 8	2 – 20	0.18 – 12	0.12 – 8	0.12 – 7
Surface Reflectance [%]	3.1 (1µm)	7.6 (0.9µm)	17 (3µm)	30 (3µm)	36 (5µm)	3.6(1µm)	2.7 (1µm)	2.5 (0.9µm)
Density [g/cm^3]	3.18	3.99	5.27	2.33	5.33	4.89	2.64	3.17
Thermal Conductivity [Wm^{-1}K^{-1}]	9.72 (36°C)	42 (25°C)	18.0 (23°C)	129.5 (40°C)	58.7 (20°C)	11.7	4	0.3
Coefficient of Thermal Expansion [×10^{-6}/°C]	24 (20 – 60°C)	6.9/7.6*	7.1 (0°C)	4.2 (25°C)	5.5 (25°C)	18	37	12.8 (parallel to the c-axis)
Solubility [g/100g of water]	1.51×10^{-3} (20°C)	–	–	–	–	0.17 (23°C)	0.27 (20°C)	7.6×10^{-3} (18°C)
Crystal Classification	Isotropic	Uniaxial	Isotropic	Isotropic	Isotropic	Isotropic	Isotropic	Uniaxial

* C-axis vertical/C-axis parallel, 200°C

Comparison Chart of Refractive Index of Crystal Materials (Reference Data)

Wavelength [nm]	Refractive Index					Note
	CaF_2	Al_2O_3	ZnSe	Si	Ge	
120.0	2.0500					
130.0	1.8300					
140.0	1.7400					
150.0	1.6600					
160.0	1.5800					
170.0	1.5340					
180.0	1.5180					
193.5	1.5015					Ar*F laser
200.0	1.4955					
210.0	1.4880	1.8340				
220.0	1.4811	1.8340				
230.0	1.4760	1.8340				
240.0	1.4712	1.8340				
248.4	1.4670	1.8340				Kr*F laser
266.0	1.4620	1.8340				YAG4ω laser
281.8	1.4580	1.8235				Xe*Br laser
308.0	1.4525	1.8115				Xe*Cl laser
325.0	1.4495	1.8040				He-Cd laser
337.1	1.4484	1.8010				N_2 Laser
355.0	1.4460	1.7960				YAG3ω laser
365.0	1.4450	1.7940				Hg i
404.7	1.4415	1.7860				Hg h
435.8	1.4395	1.7813				Hg g
441.6	1.4392	1.7808				He-Cd laser
457.9	1.4383	1.7787				Ar laser
480.0	1.4373	1.7764				Cd F′
486.1	1.4370	1.7757				H F
488.0	1.4369	1.7755				Ar laser
514.5	1.4360	1.7730				Ar laser
532.0	1.4354	1.7718				YAG2ω laser
546.1	1.4350	1.7710	2.6680			Hg e
587.6	1.4339	1.7685	2.6260			He d
589.3	1.4338	1.7684	2.6250			Na D
632.8	1.4329	1.7660	2.5940			He-Ne laser
643.9	1.4327	1.7655	2.5870			Cd C′
650.0	1.4326	1.7653	2.5840			Red LD
656.3	1.4325	1.7650	2.5795			H C
670.0	1.4322	1.7646	2.5720			Red LD
694.3	1.4319	1.7636	2.5600			RUBY laser
780.0	1.4307	1.7603	2.5295			Near Infrared LD
830.0	1.4302	1.7590	2.5170			Near Infrared LD
852.1	1.4300	1.7585	2.5120			Cs s
904.0	1.4296	1.7576	2.5023			Near Infrared LD

Wavelength [nm]	Refractive Index					Note
	CaF_2	Al_2O_3	ZnSe	Si	Ge	
1014	1.4288	1.7555	2.4892			Hg t
1064	1.4285	1.7545	2.4825	3.5510	4.4100	YAG laser
1100	1.4283	1.7537	2.4792	3.5400	4.4000	
1200	1.4277	1.7520	2.4715	3.5193	4.3500	
1320	1.4270	1.7500	2.4643	3.5030	4.3050	LD for communication
1400	1.4267	1.7485	2.4609	3.4940	4.2780	
1500	1.4262	1.7470	2.4573	3.4830	4.2450	
1550	1.4260	1.7460	2.4558	3.4770	4.2300	LD for communication
1600	1.4258	1.7450	2.4544	3.4730	4.2200	
1800	1.4248	1.7418	2.4496	3.4615	4.1630	
2000	1.4239	1.7380	2.4463	3.4540	4.1200	
2200	1.4228	1.7330	2.4440	3.4490	4.0950	
2400	1.4217	1.7280	2.4420	3.4445	4.0730	
2600	1.4205	1.7220	2.4400	3.4405	4.0600	
2800	1.4192	1.7165	2.4387	3.4370	4.0511	
3000	1.4179	1.7105	2.4376	3.4350	4.0443	
3400	1.4148	1.6990	2.4355	3.4325	4.0344	
3600	1.4132	1.6910	2.4345	3.4313	4.0307	
3800	1.4115	1.6840	2.4337	3.4305	4.0276	
4000	1.4096	1.6740	2.4331	3.4295	4.0250	
4500	1.4047	1.6495	2.4313	3.4280	4.0200	
5000	1.3990	1.6240	2.4295	3.4261	4.0162	
5500	1.3930		2.4277	3.4250	4.0135	
6000	1.3856		2.4258	3.4242	4.0115	
6500	1.3775		2.4239	3.4235	4.0100	
7000	1.3693		2.4218	3.4231	4.0086	
7500	1.3600		2.4196	3.4227	4.0075	
8000	1.3498		2.4173	3.4224	4.0067	
8500	1.3385		2.4148	3.4221	4.0060	
9000	1.3268		2.4122	3.4219	4.0054	
9400	1.3164		2.4100	3.4218	4.0049	CO_2 laser
10000			2.4065	3.4215	4.0038	
10600			2.4026		4.0035	CO_2 laser
12000			2.3929		4.0029	
13000			2.3849		4.0022	
14000			2.3761		4.0018	
15000			2.3663		4.0013	
16000			2.3555		4.0009	
17000			2.3435		4.0004	
18000			2.3303		4.0000	
19000					3.9996	
20000					3.9992	

Calcium Fluoride CaF_2

The natural mineral is called fluorite and although it is rare, some fluoresce when irradiated with ultraviolet light. Artificial calcium fluoride is used for high-grade camera lenses or beamsplitters of spectroscopes. It has optical properties such as high transmittance in a wide range from vacuum ultraviolet to infrared, and small dispersion of refractive index and different dispersion curve (abnormal partial dispersion) compared to average optical glass, making it very advantageous when designing achromatic lenses. Its isotropic crystal structure does not cause birefringence.
It is more generally used than lithium fluoride or magnesium fluoride due to its relative chemical stability and low deliquescence.

Zinc Selenide ZnSe

It is an amber color crystal, capable of transmitting up to long-wavelength infrared of 20μm. However, it does not transmit blue and green in the visible range.
Zinc selenide is often used as a lens material of CO_2 lasers. Red laser light is sometimes used as the guide light of a CO_2 laser, and zinc selenide can transmit this guide light together with the CO_2 laser light. It is legally classified as a poisonous and deleterious substance, and some products require a document of transfer of poisonous and deleterious substances. In addition, disposal of used zinc selenide products as general waste is prohibited. Zinc selenide products no longer used must be returned to the place of purchase. It is insoluble in water, but reacts with acids to form toxic hydrogen selenide. Transmission loss by surface reflectance is high due to its high refractive index, but it can achieve 99% or higher transmittance with the addition of anti-reflection coating.

Germanium Ge

This material has metallic luster and although it does not transmit light, it transmits a wide infrared range from 2 to 20μm. It is used as a material of thermography camera lenses.
Since it has a high refractive index of 4, its transmittance goes down to lower than 50% due to transmission loss by surface reflectance if used without an anti-reflection coating.

Sapphire Al_2O_3

Sapphire is a hard mineral second to diamond, and is a crystal difficult to scratch. It has long been popular for use in watches as crystals, shafts of gears or bearings. Sometimes called sapphire glass, but its structure is not vitreous but crystalline.
Sapphire is chemically very stable making it useful as an alternative to glass. Artificial sapphire is transparent and colorless, and has a wide transmission range from ultraviolet to infrared. Since sapphire is a single crystal, birefringence occurs depending on the orientation of the crystal. While it has good insulation properties, its thermal conductivity is relatively high.
It is used as titanium-sapphire (Ti: sapphire) for an excitable medium of ultrashort pulse lasers or substrates that grow purple LED.

Silicon Si

It is single crystal silicon used in semiconductors, has metallic luster and although it does not transmit light, it transmits infrared light from wavelengths of 2 to 6μm. It can also be used as a filter for infrared detectors.
Its excellent thermal conductivity also makes it useful as substrates of gold coating mirrors used for high-output CO_2 lasers.

Attention

- ▶Infrared-transparent materials need to consider the influence of the radiation spectrum due to temperature in addition to transmission and reflection.
- ▶When observing infrared of wavelength 10μm or higher, or using in an environment where an optical system is 30°C or higher, all substances emit infrared radiant light making it impossible to observe the infrared spectrum of an analyte.

Birefringence Materials

There are isotropic and anisotropic crystals, and birefringence is found in anisotropic crystals.
Especially single crystals among anisotropic crystals are utilized as polarization optics such as waveplates or polarizers.

Quartz Crystal SiO_2

This material is a single crystal quartz without impurities (trigonal) and exhibits small birefringence.
Artificial crystals are mass produced as materials for low pass filters of crystal oscillators or CCD imaging devices.
Production of waveplates utilizes small refractive index difference between ordinary beam (n_o) and extraordinary beam (n_e).

Wavelength [nm]	Refractive Index	
	Ordinary Beam (n_o)	Extraordinary Beam (n_e)
404.7	1.5572	1.5667
546.1	1.5462	1.5553
589.3	1.5443	1.5534
656.3	1.5419	1.5509
Transmitted Wavelength Range [μm]		0.2 – 2
Density [g/cm^3]		2.65
Thermal Conductivity [$Wm^{-1}K^{-1}$] (70°C)		9.3/5.4
Coefficient of Thermal Expansion [$\times10^{-6}$/°C] (20°C)		6.8/12.2

Excerpt from Chronological Scientific Tables

Calcite $CaCO_3$

Calcite is transparent and colorless, and abundant in nature.
It is a single crystal (trigonal) and exhibits large birefringence.
Its refractive index difference between ordinary beam (n_o) and extraordinary beam (n_e) is utilized in Glan-Thompson polarizers with high extinction ratio performance.
Calcite is a soft crystal and easily scratched.
* Since it is a natural mineral, the transmittance property differs by individual crystal.

Wavelength [nm]	Refractive Index	
	Ordinary Beam (n_o)	Extraordinary Beam (n_e)
404.7	1.6813	1.4969
546.1	1.6616	1.4879
589.3	1.6584	1.4864
656.3	1.6544	1.4846
Transmitted Wavelength Range [μm]		0.35 – 2.3*
Density [g/cm^3]		2.71
Thermal Conductivity [$Wm^{-1}K^{-1}$] (0°C)		5.39/4.51
Coefficient of Thermal Expansion [$\times10^{-6}$/°C] (0 – 80°C)		26.3/5.44

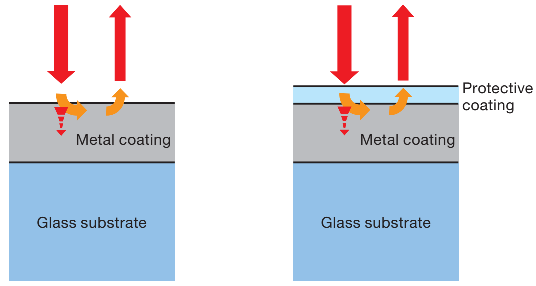
Excerpt from Chronological Scientific Tables

Optical Coatings

Optical experiments use various optics with coatings.
In many cases, a coating is deposited on a polished glass surface, and this coating provides most of the properties of light required for optical experiments such as reflectance, wavelength characteristic, and polarization property. For this reason, mirrors and the like are used by directly irradiating their coating side with light to make full use of their performances.
Coatings are mainly divided into two types, metal deposition coating and transparent film (dielectric coating) deposition coating.
Both of them are used as mirrors for optical experiments, but their usage, properties and various other points are different due to their completely different reflection mechanisms.

Metal Coating

You can obtain mirrors of high reflectance by coating polished glass substrates with metals such as aluminum (Al) and gold (Au). In addition, metals such as silver (Ag), platinum (Pt) and Chrome (Cr) are sometimes used for mirrors.
Metal coatings reflect a very wide wavelength range, and have small dependency on incident angle.
Since metals absorb light that was not reflected, if you make the metal coating a little thicker, light does not transmit through to the glass substrate side.



Metal film coated | Metal film coated with a protective film

Aluminum Coating

Aluminum offers high reflectance throughout ultraviolet to infrared, but is prone to oxidation and cannot provide stable performance especially in the ultraviolet region. It is also easily scratched, which disenables wiping of dirt on the surface.
That is why mirrors fabricated with aluminum have a protective coating to protect the metal coating from oxidation or scratches.
Protective coatings have the effect of maintaining reflectance in a certain wavelength range, but may lower reflectance in other wavelength ranges.
On the contrary, some special protective coatings increase the reflectance only in a certain wavelength range.

Gold Coating

It exhibits the wavelength characteristic of yellow in the visible range (absorbs blue), but in infrared, it offers high reflectance in a very wide range.
Since gold alone cannot adhere firmly to glass and easily comes off, a chrome coating is generally used as a base coating.
A gold coating is soft and easily scratched. A gold coating with protective coating is used for a specific wavelength range, but a gold coating without protective coating is often used for use with the entire infrared range.
You must not wipe a gold coating with paper or cloth. If it once gets scratches, then it cannot be restored.

Chrome Coating

Chrome and other alloys (inconel) are used as partial reflection coatings.
Chrome has lower reflectance compared to aluminum or gold, and absorbs light strongly, making it unsuitable for mirrors, but its small fluctuation in reflectance and absorptance in a wide wavelength range makes it useful as reflective ND filters or beamsplitters.

Comparison of Reflectance of Metal Coatings (Reference Data)

Wavelength [nm]	Reflectance (45 degrees incidence) [%]				
	$Al+MgF_2$	Al+SiO	UV Enhanced Al	Al	Au
200	54	–	91	75	24
250	76	43	93	89	28
300	89	87	90	90	31
350	84	87	87	91	34
400	88	82	85	91	37
450	90	87	85	91	41
500	92	90	85	90	52
550	91	91	85	90	81
600	91	91	85	90	91
650	89	90	85	89	95
700	88	88	83	88	96
750	84	85	82	87	97
800	81	83	81	86	97
850	82	82	81	86	97
900	86	84	84	89	98
950	88	86	88	91	98
1000	90	87	89	93	98
1050	91	89	90	94	98
1100	92	89	91	94	98
1150	93	90	91	95	98
1200	93	91	92	95	98

Wavelength [nm]	Reflectance (45 degrees incidence) [%]		
	Al+SiO	Al	Au
1250	91	95	98
1300	92	96	98
1350	92	96	98
1400	93	96	99
1450	93	96	99
1500	94	96	99
1550	94	96	99
1600	94	96	99
1650	94	96	99
1700	95	96	99
1750	95	96	99
1800	95	96	99
1850	95	96	99
1900	95	96	99
1950	95	97	99
2000	95	97	99
2100	96	97	99
2200	96	96	99
2300	96	97	99
2400	97	96	99
2500	97	97	99

Wavelength [nm]	Reflectance [%]
	Au
3000	99
4000	99
5000	99
10000	99

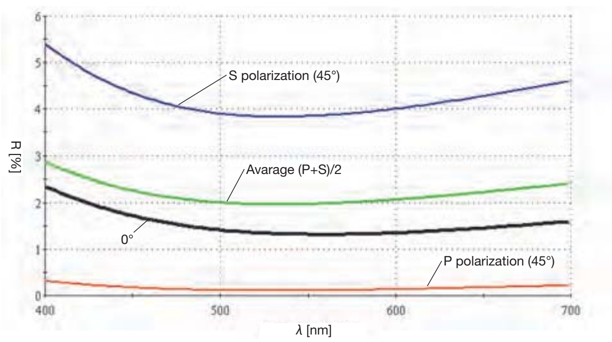
Dielectric Coating

Dielectric materials are transparent and colorless, having no large reflection or absorption like metals.
On the other hand, however, proper selection of materials and coating thickness can cause interference of light at the interface between a glass substrate, coating and air, creating special transmittance and reflectance wavelength characteristics.

Single-layer Anti-reflection Coating

When light enters a glass substrate, about 4% of reflection occurs and results in transmittance loss. However, you can change the reflectance of the glass substrate by coating the glass substrate with a dielectric material that has a lower refractive index than glass.
When the thickness of dielectric coating is adjusted so that the optical path length (refractive index n × coating thickness d) is $\lambda/4$, the reflectance is minimized because reflections at the interface between the glass substrate and the dielectric coating, and between the dielectric coating and air cancel each other.
Note that it is impossible to achieve a reflectance of complete zero because the refractive index is limited by coating materials. Since the refractive index of glass substrate also has influence, the coating cannot provide an anti-reflection effect to all glass substrates.

Reflectance Wavelength Characteristic of Single-layer Anti-reflection Coating (SLAR)



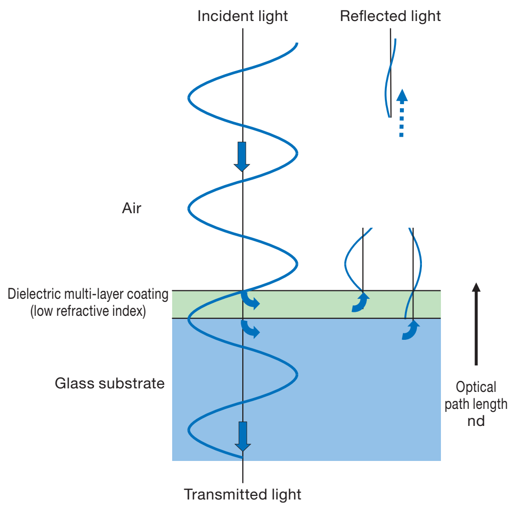
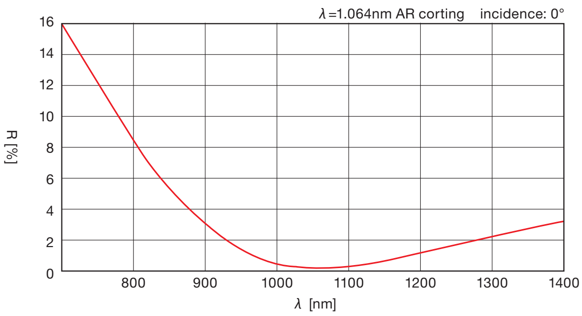


Image of single-layer die electric Anti-reflection coating structure

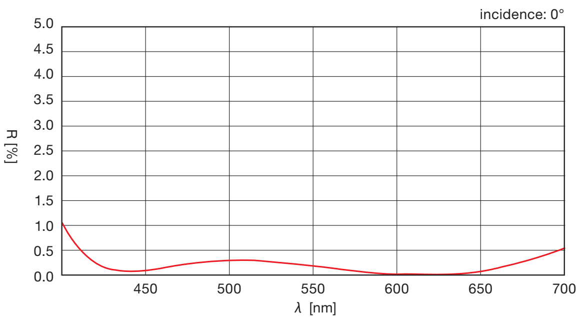
Multi-layer Anti-reflection Coating

Due to the small selection of coating materials for single-layer coating, reflection of a glass substrate remains to a certain extent. To deal with the limited coating materials, you can layer coatings to gain optimal anti-reflection effect.
In addition, it is possible to fabricate narrowband multi-layer anti-reflection coating (NMAR) that reduces reflectance in a specific wavelength, or multi-layer (broadband) anti-reflection coating (MLAR) that reduces reflectance in a broad wavelength range.

Reflectance Wavelength Characteristic of Narrowband Multi-layer Anti-reflection Coating (NMAR)



Reflectance Wavelength Characteristic of Broadband Multi-layer Anti-reflection Coating (BMAR)



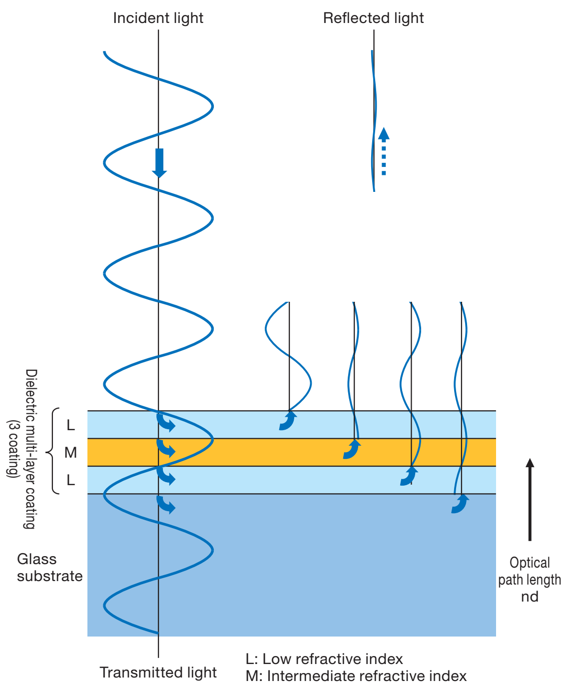


Image of multi-layer die electric Anti-reflection coating structure

Application Systems
Optics & Optical Coatings
Opto-Mechanics
Bases
Manual Stages
Actuators & Adjusters
Motoeized Stages
Light Sources & Laser Safety
Index
Guide
Mirrors
Beamsplitters
Polarizers
Lenses
Multi-Element Optics
Filters
Prisms
Substrates/Windows
Optical Data
Maintenance

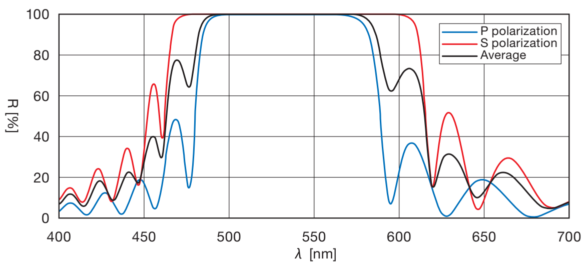
Application Systems
Optics & Optical Coatings
Opto-Mechanics
Bases
Manual Stages
Actuators & Adjusters
Motoeized Stages
Light Sources & Laser Safety
Index
Guide
Mirrors
Beamsplitters
Polarizers
Lenses
Multi-Element Optics
Filters
Prisms
Substrates/Windows
Optical Data
Maintenance

Optical Coatings

Multi-layer Reflection Coating

You can fabricate a reflection coating with very high reflectance by layering a dielectric coating of high refractive index and that of low refractive index alternately on top of a glass substrate.
Small reflection occurs at the interface between high refractive index and low refractive index.
The thickness of dielectric coating of all layers is adjusted to the optical path length of $\lambda/4$ (refractive index n × thickness of coating d), thus the light reflected by each layer has a matched phase causing the combined amplitude to increase. On the contrary, the multiple reflected lights that proceed in the direction of transmission cancel each other to zero.
If there is a sufficient number of layers of dielectric coating, incident light is attenuated and practically not transmitted.
Attenuated light all shifts to reflected light. Since dielectric coatings do not absorb light, 100% of incident light becomes reflected light without any loss.

Reflectance Wavelength Characteristic of Dielectric Multi-layer Coating (DML)



You can add a special effect to a multi-layer coating by changing its coating structure.
For example, you can design a coating according to various requirements such as broaden the wavelength band or on the contrary, narrow the transmission band extremely, prevent passage of different wavelength ranges or set the reflectance to an arbitrary value.

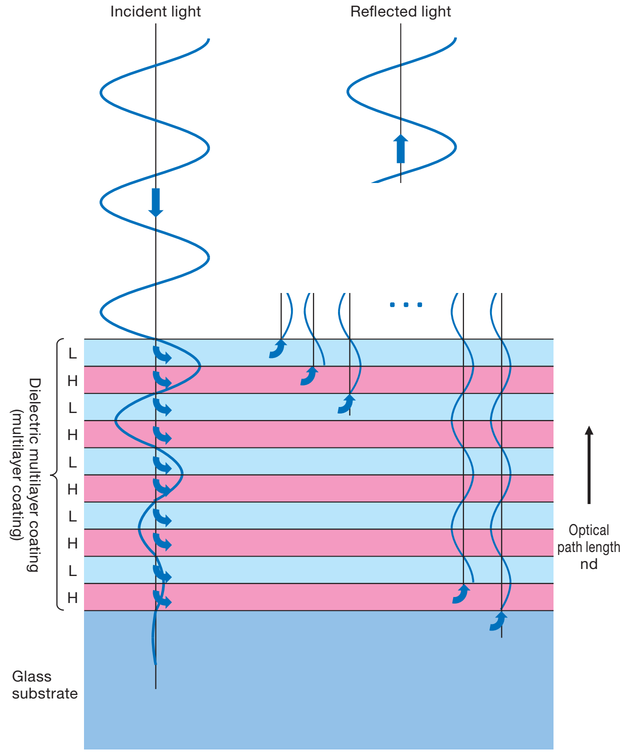


Image of multi-layer die electric high Anti-Reflection coating structure

Special Coatings

Dielectric multi-layer coatings can offer various wavelength characteristics, and are used for various optical devices.
Meanwhile, leading edge research requires higher performance, and a dielectric multi-layer coating sometimes takes a very special structure consisting of 100 layers or more.

Ultra Broadband Mirror

A dielectric multi-layer coating having a few dozen layers is sufficient to reflect the visible range, but if you need to handle a wavelength range including from ultraviolet to infrared range, then you need to combine three or more multi-layer coatings for the ultraviolet range, visible range, and infrared range.
Consequently, the number of coating layers increases extremely, and its fabrication requires very high technology.

Low Dispersion Coating for Femtosecond Laser

When you irradiate a broadband dielectric multi-layer coating with a femtosecond laser, wavelength dispersion occurs because the transmission path within the coating differs depending on the wavelength.
A low dispersion coating for femtosecond laser is designed so that the path length within the coating will not change depending on the wavelength to minimize the wavelength dispersion. In addition to that, its coating structure can withstand high power.

Coating for High Power Laser

If you irradiate a dielectric multi-layer coating with high power pulse laser, the laser power on the interface of the coating becomes extremely large so that it breaks the coating.
To prevent this, the coating structure and materials have been reviewed and special multi-layer coatings have been developed to avoid laser damage.

Hybrid Coating

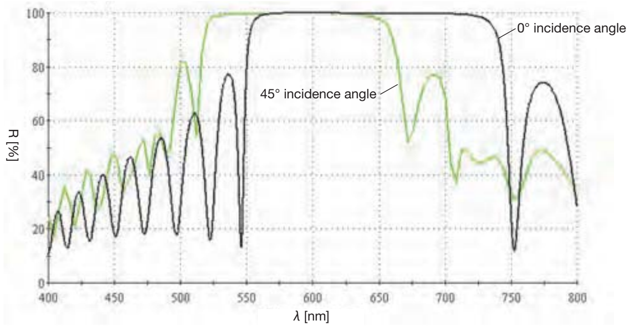
By inserting a metal coating inside a dielectric multi-layer coating, you can create an optic with properties that have been impossible to achieve before. This type of coating is called hybrid coating because it is a combination of dielectric multi-layer coating and metal coating.
In practice, it is used for broadband non-polarizing beamsplitters and bandpass filters. Unfortunately, this coating causes a little intensity loss due to absorption by metal.

Properties of Multi-layer Coating

While multi-layer coatings can achieve any reflectance and transmittance wavelength characteristics, they have various limitations.

Incident Angle Dependence

When you change the incident angle of light against a multi-layer coating, the wavelength characteristics of transmittance and reflectance change.
If the incident angle of light is oblique against the thickness of each layer of a multi-layer coating, then the optical path length the light goes through within the coating becomes long. This is the reason why the transmittance and reflectance wavelength characteristics are of the longest wavelength at the incident angle of zero degree (perpendicular), and shifts to those of shorter wavelength.
This phenomenon is called a blueshift.



Temperature Dependence

The thickness of dielectric coating or the refractive index of coating material change due to temperature, which also causes changes in the transmittance and reflectance wavelength characteristics of the multi-layer coating. Since this temperature dependency differs according to the manufacturing method and materials of coating, consideration needs to be given in the design stage of coating.
Consult us about the use environment and temperature fluctuation range in advance.

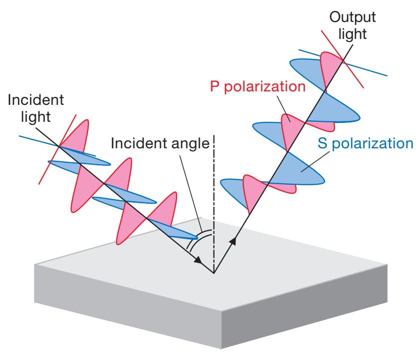
Weatherability

Dielectric multi-layer coating may change with time depending on the use environment.
Although it differs depending on the manufacturing method and coating composition, a coating might swell and its wavelength characteristic may change a little when the coating is placed in a high temperature high humidity environment for a long time.
Special care is required for products of which transmittance and reflectance versus wavelength change significantly such as dichroic mirrors or band-pass filters.
Maintain laboratories and inside devices where optics are used at ordinary temperature and low humidity, and when optics are not in use, keep them in a dry storage such as Dry-Cabi®.

Polarization Properties

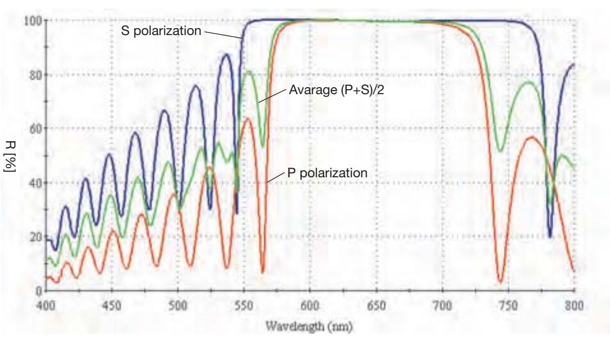
Optics have polarization properties when used other than at the incident angle of zero degrees (perpendicular incidence).
There are two types of polarization properties, one is the property that transmittance and reflectance change between P polarization and S polarization, and the other is that phase difference changes between P polarization and S polarization.
The property of phase difference is difficult to control, and the coating products listed in this catalog do not guarantee the property. For example, if a linear polarized beam enters a coating product at a 45 degrees angle, the polarization of the output beam will not be a linear polarized beam at 45 degrees, but will become an elliptic polarized beam. However, the intensity of the output light becomes the average value of the P polarized component and the S polarized component, thus it will not affect the property of transmittance and reflectance when considering P polarization and S polarization separately.

If irradiating a glass substrate without coating with light at 45 degrees incidence, the reflectance of P polarization differs from that of S polarization.
Similarly the reflectance of P polarization and that of S polarization change at the interface between each layer of coating, and in a multi-layer coating, fluctuation occurs in the wavelength characteristic in addition to significant fluctuation in the transmittance and reflectance between P polarization and S polarization.
For this reason, this catalog shows a P polarization and S polarization graph for transmittance and reflectance wavelength characteristics.
Coated optics have polarization properties even if a graph of P polarization and S polarization is not shown, and a graph of the average of P polarization and S polarization is listed for them.
Since most light sources other than laser light are unpolarized light, a graph of the average value of the P polarization and S polarization is sufficient, but in case of laser light which is a linear polarized beam, whether it takes the value of P polarization, S polarization or a value between them changes depending on the polarization direction.
Especially for coated optics that characteristically have the transmission band and reflection band switch in a narrow wavelength range such as a dichroic mirror, the wavelength where transmission switches to reflection differs depending on whether to use S polarization or P polarization.

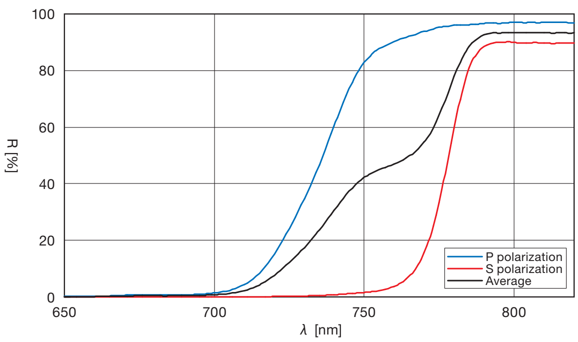


The definition of S polarization and P polarization

Reflectance Wavelength Characteristic of Dielectric Multi-layer Mirror



Reflectance Wavelength Characteristic of Dichroic Mirror



Application Systems
Optics & Optical Coatings
Opto-Mechanics
Bases
Manual Stages
Actuators & Adjusters
Motoeized Stages
Light Sources & Laser Safety
Index
Guide
Mirrors
Beamsplitters
Polarizers
Lenses
Multi-Element Optics
Filters
Prisms
Substrates/Windows
Optical Data
Maintenance

Optical Coatings

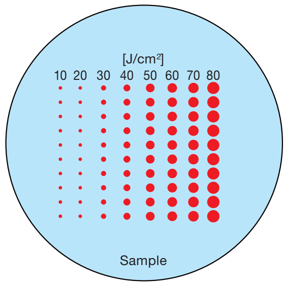
Laser Damage Threshold

The optics used in laser oscillator or in laser processing system must have a high resistance to high power laser source incident over time without damaging the coated surface. The resistance is determined by a numerical information called Laser damage threshold. This term is frequently applied in optics selection for use in high power laser processing system and optical system design.
The laser damage threshold evaluation method is regulated by the S-on-1 test method according to the international ISO 21254 standard.

S-on-1 test

Using a pulse laser with variable power in a system for irradiating a target substrate surface with appropriate density.
Place the target onto a XY translation stage for enabling the irradiation position to change after the end of each irradiation cycle. Oscillate repeatedly the laser onto the target substrate S times on a same position. Repeating 10 times the same irradiation with the same power onto the next position.
Change the laser power for the next repeatedly 10 times irradiation operation, then repeat the operation within the limitation of the laser power.
Inspect the tested target with a 150× magnification microscope evaluate the presence of damaging spot.
Plot the damage occurrence ratio vs the power density data onto a graph. The result is the power density and the occurrence ratio curb to the maximum occurrence level. (The occurrence ratio is 0% and 0% up to maximum level). This number is the laser damage threshold.
* Sigma Koki's method is 1 irradiation=200 pulses, it is egal 200 on 1 test method.

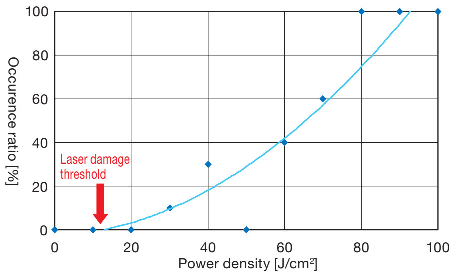
The relation in between the irradiation cylcle time and the power density



Important point about Laser damage threshold

- The result may change depending on the wavelenght, the pulse width and the repetition frequency of the laser used for the test. The set up test condition must be consistent.
- Pulse laser exist in single mode laser (TEM_{00}) and multi-mode laser. The TEM_{00} laser was used for the laser damage threshold test. The multi-mode laser has a particularity of having high local density energy, which is also called spike shape. It happens that even by applying a low laser damage threshold multi-mode laser with spike shape, the optics can be damaged. If a multi-mode laser with a frequent optics damage problem occurs, the multi-mode laser optics adjustment may be a problem. In this case, please check the mode pattern of the laser or contact the laser maker.
- The optics can be damaged easily even with a low power laser if the optics surface is dirty with dust or oil mark. Make sure that the optics are clean with no dust before applying to high power laser.
- The laser damage threshold value must be evalued under the similar test condition for a correct comparaison. Every makers may test their optics with different test condition, it is not possible to judge the optics's superiority by refering to the laser damage threshold value mentioned in the catalog. Sigma Koki provides to its customer a safety range of usage with strict test conditon. But even using a below range laser damage threshold, the deterioration change with time is inevitable.

The occurence ratio of the laser damage by power density

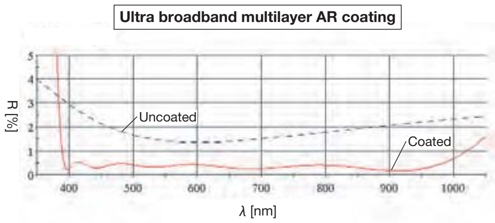


Custom Coating

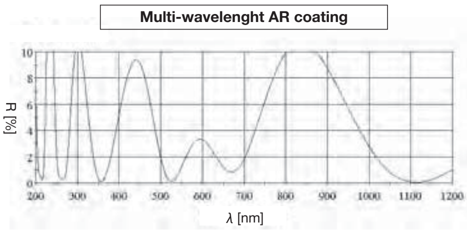
We support all types specifications of custom optics design and coating design which may not be found in our catalog.
We are open to all kind of inquiries, ranging from project development to mass production optics.
Again, we accept to do customized coating on our standard no-coated optics, as well as a completed customized optics, also on supplied optics. Please do not hesistate to contact our Intenational sales division for all your inquiries.
Please fill out the inquiry form with your specifications required for us to support you smoothly.
For custom coating we may require a longer lead time, please contact our International Sales Division for details.

Sample of custom coating T: Transmission R: Reflectance

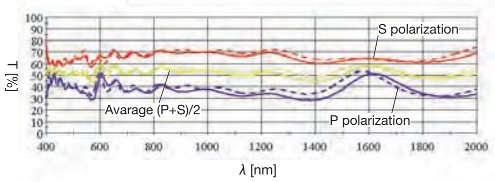
Ultra broadband multilayer AR coating



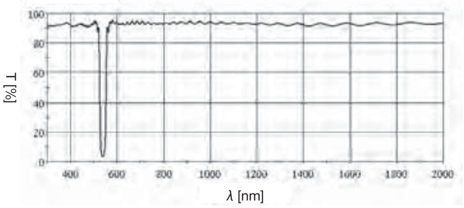
Multi-wavelenght AR coating



Ultra broadband half-mirror



Notch filter



Thin Film Design Software (Essential Macleod) | EMS

This software will enable you to design thin film coatings by only inputting the transmittance values and the reflectance values of your requirements. It can also handle optical characteristics simulation when coating experiment value change. The Essential Macleod is a professional optical coatings design software but it also is suitable for a beginner user because of its intuitive operation.

- The Essential Macleod is a Windows®-based optical thin film design software developed by Angus Macleod, who is renowned for monographs on optical thin films such as Thin-film optical filters.
- The software contains a range of functions needed for sophisticated coating design, including simulations of optical thin film characteristics, automatic calculations, and building of coating material databases.

Attention

- ▶May be incompatible with other windows programs. Installation on a dedicated PC is recommended.
- ▶The price is subject to change depending on exchange rate fluctuations, the addition of features or other factors. Contact us for more information.

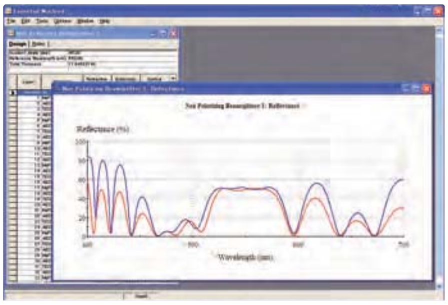
Specifications

Part Number	**EMS-1**

<Developer>
Thin Film Center Inc.
2745 East Via Rotonda, Tucson, AZ 85716-5227
TEL: +1-520-322-6171 FAX: +1-520-325-8721

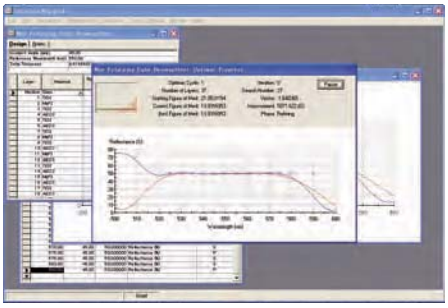
* The logo of Thin Film Center Inc. and Essential Macleod are registered trademarks of Thin Film Center Inc.
* Windows® is a registered trademark of Microsoft Corporation in the United States and other countries.

Simulations of Optical Thin Film Characteristics



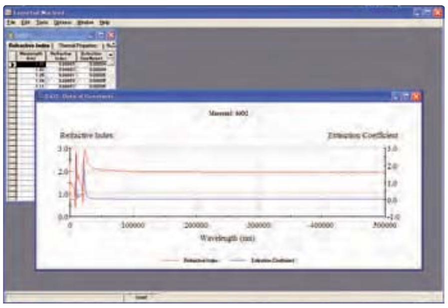
- Simulation of transmittance and reflectance of a thin film
- Simulation of phase change in transmitting light and reflecting light
- Simulation of influence of error in film thickness
- Simulation of group velocity dispersion, etc.

Optimization by Automatic Calculation



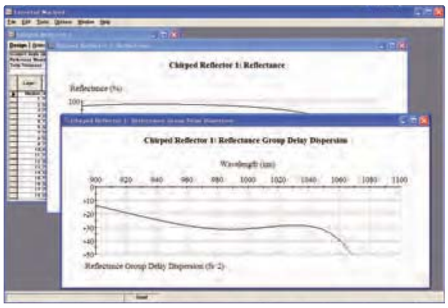
- Transmittance and reflectance
- Phase change in S and P polarization
- Phase change in transmitting light and reflecting light

Database of Coating Materials



- Database of optical constants (n, k) of major coating materials
- Database management based on multiple information items
- Calculation of optical constants from measured values of spectral characteristics
- Creation of variance data of coating materials

Other Functions



- Calculation of group velocity dispersion
- Analysis of thin film electric field distribution
- Calculation of transmittance of thin film combined with glass substrate

Hardware Requirements

- IBM-PC and its compatible devices
- MS-Windows® operating system
- 20MB or more of free space on hard disk

Support

- Free support and upgrades for one year after purchase. After one year, free support and upgrades are available with a membership contract.

Optional

- Additional license (Allows the software to run on one additional PC.)
- Membership contract (Offers free support for another year when one year passed after purchase.)

Optical Design

Lens system that is used in optical products of Sigma Koki is originally designed. Utilizing this design capability, to meet the needs of our customers, Sigma Koki provide lens design service. We will meet with a wide range of customer needs from design of a single lens to the optical system to be used in the satellite. Not limited to the lens design, we are operating an integrated in-house production systems covering broad range of fabrication processes such as lens polishing, coating, housing, optical adjustment, electronic circuits, drive mechanism, and software.

- We will offer a flexible service of custom lens design, from prototypes to a single test unit, and the mass-production item.
- However, assuming that customer will be ordering for manufacture of optical lens or equipment, we will refuse the request of the lens design only.
- To request a custom lens design, please use the “Contact sheet for Lens Design”.

Typical Product with Custom Lens Design

Achromatic Lenses

It is a cemented doublet lens to be used as the telescope and the laser collimator.
Optimal lens is designed from the parameters such as wavelength, focal length and clear aperture.
We can also design the achromat for dual-band wavelength or the range other than the visible.

Focusing Lenses

In a focusing lens for laser processing, performance close to the theoretical limit is required. To meet this requirement, doublet or triplet lens should be designed to eliminate the spherical aberration.
Optimal lens design is achieved from the parameters like laser wavelength, focal length and spot size. We custom-design various focusing lenses in the ultra-violet region that requires a special glass, and achromatic design optimized to both invisible laser and guiding light.

Objective Lenses

By eliminating the use of adhesive, and also preventing laser intensity to be high on lens surface, the objective lens can be used for normal microscope, but also designed to be used for high power laser processing.
Since observation of laser processing image is required, The objective lens is generally designed achromatic for both laser wavelength and visible. It is also an important factor to take a long working distance as much as possible. In addition, a special design is needed for the objective lens used for laser processing through a thin glass substrate or multiple wavelengths.

fθ Lenses

A specially designed lens to be used for galvanometer scanners, and the laser patterning.
Has the effect of suppressing the distortion of the drawing pattern, or change of the line width between rim and center of the scanning range.
The design of the fθ lens changes by specifications of the galvanometer mirror, the scanning range, and the shape of the workpiece (the presence of irregularities or steps).

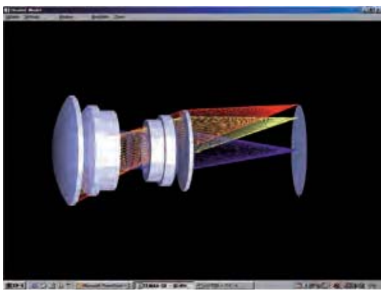
Laser Beam Expanders

An optical component that expand the narrow laser beam to a large diameter collimated beam.
The design of the beam expander, which is commonly used in the experiment are standardized. For a collimated beam of multi-wavelength laser or specially large diameter, the custom lens design is needed.

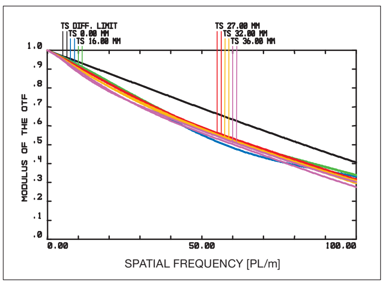
Others

We have been designing various optical system like an illumination system, high precision camera lens for the imaging sensor, and zoom microscopes.

Optical simulation and evaluation

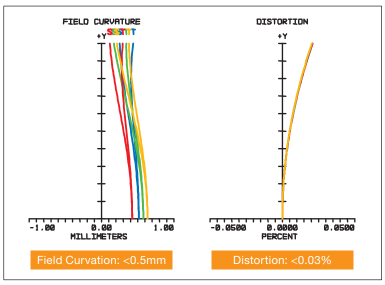


MTF simulation



Black: Diffraction theory limit Blue: Image height 0mm
Green: Image height 16mm Red: Image height 27mm
Orange: Image height 32mm Pink: Image height 36mm

Field curvature and distortion



Green: 546nm (base Wavelength)
Blue: 405nm Red: 436nm Yellow: 579nm

Traceability

All products produced by Sigma Koki are inspected with valid metrology instruments that have supporting traceability. Instruments and supporting equipment in our metrology department are calibrated by their respective manufacturers or certified laboratories. Our maintenance program ensures that the level of accuracy is always at optimum levels. It is possible to request for a Calibration Inspection Certificate for the metrology instrument used against any of our products inspected. (Please note that that will be a small fee for this request)

Nspecting Machine	Manufacture	Inspecting Item
Interferometer	ZYGO CORPORATION	Reflecting Wavefront Accuracy, Transmitting Wavefront Accuracy (Up to ϕ150mm)
Auto-collimator	NIKON CORP.	Parallelism (within 30arcmin)
Spectrophotometer	HITACHI LTD	Transmittance

Traceability System of Interferometer

NIST (National Institude of Standards and Technology)

Calibration Number
821/253170-94

ZYGO CORPORATION

Calibration of reference plate
by Zygo Corporation

Canon Marketing Japan Inc.

Calibration of interfercomer
by Canon Marketing Japan Inc.

Traceability of Interferometer at Sigma Koki

Traceability System of Auto-collimator

NIKON CORPORATION

Calibration of reference flat, "standard mirror and auto-collimator by Nikon Corporation"

Traceability of Auto-Collimator at Sigma Koki

Traceability System of Spectrophotometer

Japan Quality Assurance Organization (JQA)

Calibration of optical filter is done by spectrophotometer that callibrated with a linearity calibrator (technology transterred from National Institute of Industrial Science and Technorogy) and discharge lamp (authorized as international standard wavelength).

HITACHI INSTRUMENT SERVICE CO.,LTD.

Calibration of spectrophotometer is done with standard optical filter calibrated by JQA.

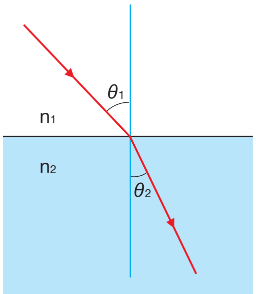
Traceability of Spectrophotometer at Sigma Koki

(Our guarantee is in the range of 400nm – 700nm.)

Optical Formula

Snell's law

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$



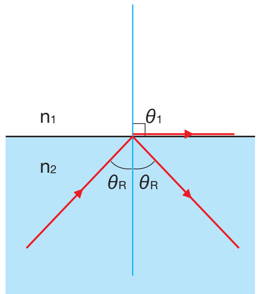
Critical angle $\theta_R = \theta_2$

$\theta_1 = 90°\quad n_1 = 1$

$$\sin\theta_R = \frac{1}{n_2}$$

Conditions for total internal reflection

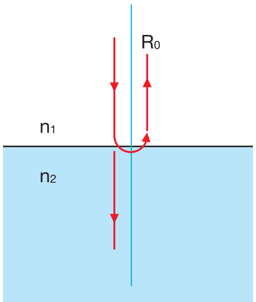
$$\theta_R < \theta_2$$



Reflectance (Normal incidence) R_0

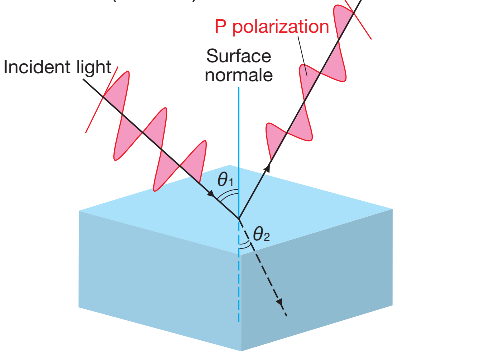
$\theta_1 = \theta_2 = 0\quad n_1 = 1$

$$R_0 = \left[\frac{n_2 - 1}{n_2 + 1}\right]^2$$



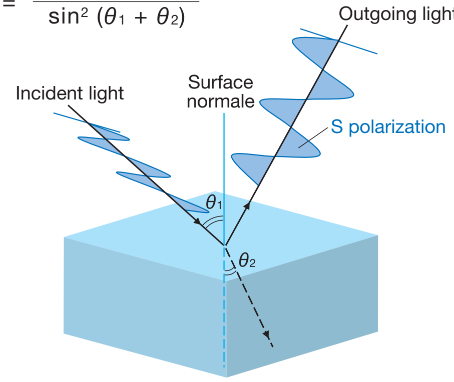
Reflectance (P polarization) R_P

$$R_P = \frac{\tan^2(\theta_1 - \theta_2)}{\tan^2(\theta_1 + \theta_2)}$$



Reflectance (S polarization) R_S

$$R_S = \frac{\sin^2(\theta_1 - \theta_2)}{\sin^2(\theta_1 + \theta_2)}$$



Brewster angle $\theta_B = \theta_1$

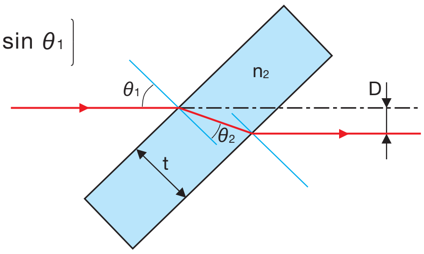
$R_P = 0$

$$\tan\theta_B = n_2$$

Translation of beam for Optical Parallel D

$$D = t\cos\theta_1(\tan\theta_1 - \tan\theta_2)$$

$$\theta_2 = \sin^{-1}\left[\frac{1}{n_2}\sin\theta_1\right]$$

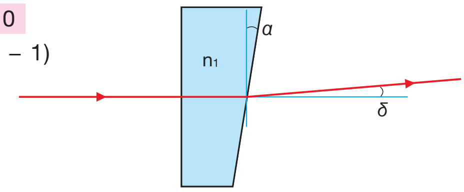


Deviation angle of beam by wedge plate δ

$$\sin(\alpha+\delta) = n_1 \sin\alpha$$

$\alpha \fallingdotseq 0$

$$\delta \fallingdotseq \alpha(n_1 - 1)$$



Optical Density OD

$$OD = \log\left[\frac{I_1}{I_2}\right] = -\log(T)$$

Transmittance: T
Intensity of incident light: I_1
Intensity of outgoing light: I_2

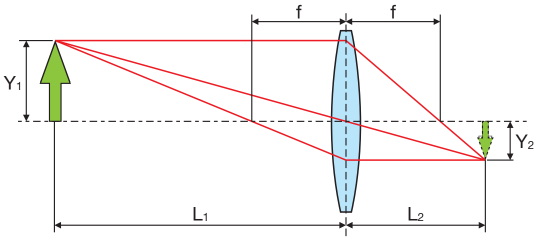
Lens formula

$$\frac{1}{f} = \frac{1}{L_1} + \frac{1}{L_2}$$

Focal length: f

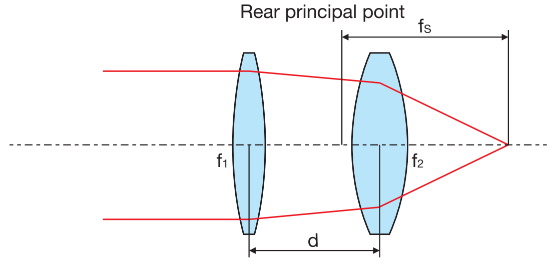
Magnification of the image

$$B = \frac{Y_2}{Y_1} = \frac{L_2}{L_1}$$

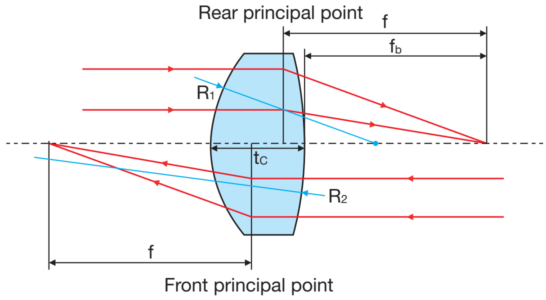


Focal length of Lens combinations

$$f_S = \frac{f_1 \cdot f_2}{f_1 + f_2 - d}$$



Focal length of a lens



Focal length of thick lens

Condition of biconvex lens $R_1 > 0$ $R_2 < 0$

$$\frac{1}{f} = (n-1)\left\{\frac{1}{R_1} - \frac{1}{R_2} + \frac{t_C(n-1)}{R_1 R_2 n}\right\}$$

$$f_b = f\left\{1 - \frac{t_C(n-1)}{nR_1}\right\}$$

Focal length of biconvex lens

Condition of symmetric convex lens $R_1 = -R_2 = R$

$$f = \frac{nR^2}{(n-1)\{2nR - t_C(n-1)\}}$$

$$f_b = f\left\{1 - \frac{t_C(n-1)}{nR}\right\}$$

Focal length of glass sphere

Condition of glass sphere $2R = t_C$

$$f = \frac{nR}{2(n-1)}$$

$$f_b = f - R$$

Focal length of plano convex lens

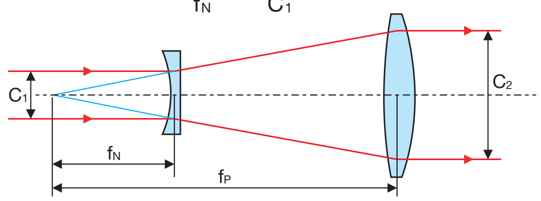
Condition of plano convex lens $R_1 > 0$ $R_2 = \infty$

$$f = \frac{R_1}{n-1}$$

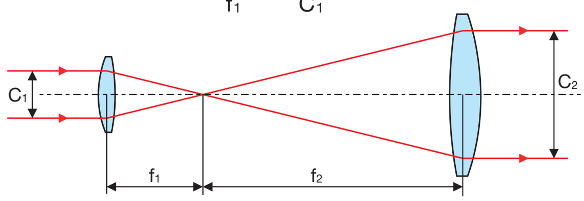
$$f_b = f - \frac{t_C}{n}$$

Magnification of Beam Expander B

Galilean type $B = \dfrac{f_P}{f_N} = \dfrac{C_2}{C_1}$

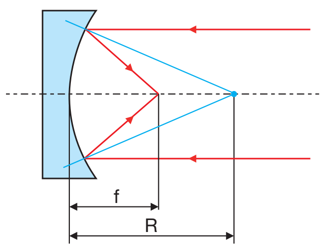


Keplerian type $B = \dfrac{f_2}{f_1} = \dfrac{C_2}{C_1}$



Focal length of Concave Mirrors

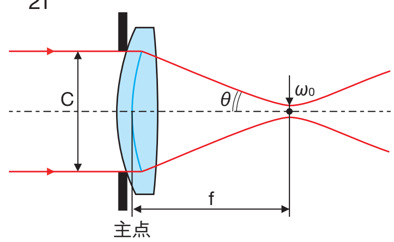
$$f = \frac{1}{2}R$$



Formula of concentrated beam

$$NA = \sin\theta = {}^{C}\!/_{2f}$$

$$F_{NO} = \frac{f}{C}$$



Beam waist $1/e^2$

$$\omega_0 = \frac{\lambda}{\pi \cdot NA}$$

Resolution of light microscope

$$\delta = \frac{0.61\lambda}{NA}$$

Application Systems
Optics & Optical Coatings
Opto-Mechanics
Bases
Manual Stages
Actuators & Adjusters
Motoeized Stages
Light Sources & Laser Safety
Index
Guide
Mirrors
Beamsplitters
Polarizers
Lenses
Multi-Element Optics
Filters
Prisms
Substrates/Windows
Optical Data
Maintenance

Outer Dimension Tolerance and Standard Chamfer (Company Standard)

Application Systems
Optics & Optical Coatings
Opto-Mechanics
Bases
Manual Stages
Actuators & Adjusters
Motoeized Stages
Light Sources & Laser Safety
Index
Guide
Mirrors
Beamsplitters
Polarizers
Lenses
Multi-Element Optics
Filters
Prisms
Substrates/Windows
Optical Data
Maintenance

Optical Flats
Optical Parallels
Wedged Substrates
Concave Mirror and Substrates
(Applies to Other Standard Coated Optics Also)

Outer Dimension Tolerance (mm)

Round Shaped	Dimension Tolerance	Thickness Tolerance
ϕ≦50	0 to −0.1	±0.1 (Concave mirror and its substrate is +/−0.2)
ϕ51 to 150	0 to −0.2	±0.2
ϕ151 to 200	0 to −0.3	±0.3
ϕ201 to 300	0 to −0.5	±0.5

* Tolerance of center thickness for standard Concave mirror and its substrate is +/−0.2

Square or Rectangular Shaped	Dimension Tolerance	Thickness Tolerance
≦50	0 to −0.1	±0.1 (Concave mirror and its substrate is +/−0.2)
51 to 150	0 to −0.2	±0.2
151 to 200	0 to −0.3	±0.3
201 to 300	0 to −0.5	±0.5

* Outside tolerance of 50×60 size is 0 to −0.2

Standard Chamfer (mm)

Thickness	Dimension	Standard Chamfer
1.0 to 3.0	Specify	≦0.3×45°
3.1 to 5.0	≦40	≦0.3×45°
	41 to 70	≦0.4×45°
	71 to 100	≦0.5×45°
	101 to 150	0.2 to 0.6×45°
	151 to 200	0.3 to 0.7×45°
	201 to 300	0.4 to 0.8×45°
≦5.1 to	≦40	≦0.3×45°
	41 to 70	≦0.4×45°
	71 to 100	≦0.5×45°
	101 to 150	0.3 to 0.7×45°
	151 to 200	0.4 to 0.8×45°
	201 to 300	0.5 to 1×45°

Caution1: Chamfer of concave mirror is identical to Spherical Lens.
Caution2: Chamfer finish is for protection to suffer from chipping, and the amount of chamfer may vary.

Spherical Lens
Cylindrical Lens

Outer Dimension Tolerance (mm)

Size	Dimension Tolerance
≦60	0 to −0.1
61 to 80	0 to −0.15
81 to 100	0 to −0.2
101 to 200	0 to −0.25
201 to 300	0 to −0.3

Standard Chamfer (mm)

	Diameter	Standard Chamfer
Convex-side	≦50	≦0.3×45°
	51 to 100	≦0.4×45°
	101 to 150	≦0.5×45°
	151 to 200	0.3 to 0.6×45°
	201 to 300	0.4 to 0.7×45°
Concave-side, Flat-side	≦50	≦0.3×45°
	51 to 100	≦0.5×45°
	101 to 150	0.3 to 0.6×45°
	151 to 200	0.4 to 0.8×45°
	201 to 300	0.6 to 1×45°

* Some standard parts has other tolerance than above data.

Prism

About Outer Dimension Tolerance

Prisms have sharp edges because of its function and therefore usually needs protective bevels.
Outer dimensions of prisms are noted by length without bevels.