LEARNING – UNDERSTANDING – INTRODUCING – APPLYING

Optical Theory Simplified: 9 Fundamentals To Becoming An Optical Genius

APPLICATION NOTES

- Optics Application Examples
- Understanding Optical Specifications
- All About Aspheric Lenses
- Optical Filters
- Why Use An Achromatic Lens
- Introduction To Prisms
- Optical Cage System Design Examples
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OPTICS APPLICATION EXAMPLES

APPLICATION 1: DETECTOR SYSTEMS

Every optical system requires some sort of preliminary design. Getting started with the design is often the most intimidating step, but identifying several important specifications of the system will help establish an initial plan. The following questions will illustrate the process of designing a simple detector or emitter system.

GOAL: WHERE WILL THE LIGHT GO?

Although simple lenses are often used in imaging applications, in many cases their goal is to project light from one point to another within a system. Nearly all emitters, detectors, lasers, and fiber optics require a lens for this type of light manipulation. Before determining which type of system to design, an important question to answer is "Where will the light go?" If the goal of the design is to get all incident light to fill a detector, with as few aberrations as possible, then a simple singlet lens, such as a plano-convex (PCX) lens or double-convex (DCX) lens, can be used.

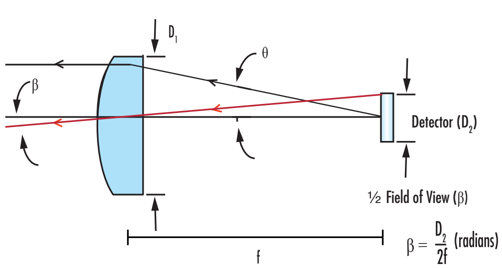


Figure 1:
PCX Lens as FOV Limit in Detector Application

Figure 1 shows a PCX lens, along with several important specifications: Diameter of the lens (D_1) and Focal Length (f). Figure 1 also illustrates how the diameter of the detector limits the Field of View (FOV) of the system, as shown by the approximation for Full Field of View (FFOV):

(1.1)

$$FFOV = \frac{D_2}{f}$$

or, by the exact equation:

(1.2)

$$FFOV = 2\tan^{-1}\left(\frac{D_2}{2f}\right)$$

For detectors used in scanning systems, the important measure is the Instantaneous Field of View (IFOV), which is the angle subtended by the detector at any instant during scanning.

(1.3)

$$IFOV = \frac{Pixel\ Size}{f}$$

Continue

GOAL: WHERE WILL THE LIGHT GO? (CONT.)

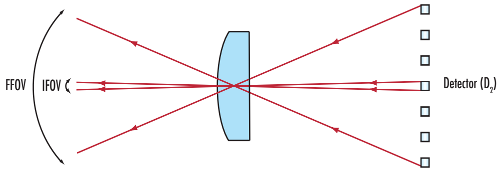


Figure 2:
Instantaneous FOV

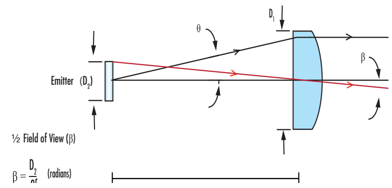


Figure 3:
PCX Lens as FOV Limit in Emitter Application

Considered in reverse, Figure 1 can also represent an emitting system (Figure 3), with the lens used to collimate the light. This setup will be the premise of the application example.

LIGHT TRANSMISSION: HOW MUCH LIGHT EXISTS INITIALLY?

Knowing where the light will go is only the first step in designing a light-projecting system; it is just as important to know how much light is transmitted from the object, or the source. The efficiency is based on how much light is received by the detector, thereby answering the question "How much light exists initially?" The Numerical Aperture (NA) and F-number (F/#) of a lens measure the amount of light it can collect based on f, D, index of refraction (n), and Acceptance Angle (θ). Figure 4 illustrates the relationship between F/# and NA.

(1.4)

$$F/\# = \left(\frac{f}{D}\right)$$

(1.5)

$$NA = \left(\frac{1}{2(F/\#)}\right)$$

(1.6)

$$NA = n\sin\theta$$
$$\approx n\theta$$

Correspondingly, this relationship can be mathematically expressed according to Equation 1.5. It is important to note that the larger the Diameter, the smaller the F/#; this allows more light to enter the system. To create the most efficient system, it is best to match the emitted cone of light from the source to the acceptance cone of the lens, as this avoids over or under filling the lens area.

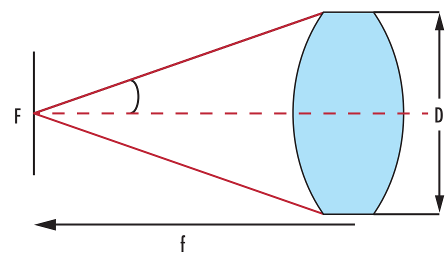


Figure 4:
DCX Lens Showing F/# and NA

OPTICAL THROUGHPUT: HOW MUCH LIGHT GETS THROUGH THE SYSTEM?

When using a lens as a tool to transfer light from an emitter to a detector, it is important to consider Throughput (TP), a quantitative measurement of transmitted light energy. In other words, answering the question "How much light gets through the system?" dictates the geometry of the lens used and the configuration of the system. Because emitters and detectors are areas of light and not point sources, the diameter of a lens affects TP even when the ratio between Diameter and Focal Length (specified by F/#) remains constant.

(1.7)

$$TP = n^2 A\Omega$$

Figure 5 shows the basic definition of throughput (TP) as expressed in Equation 1.7, where A is the Area of the object, (light source), Ω is the Solid Angle, and z is the Object Distance (with their conjugates in image space as A', Ω', and z').

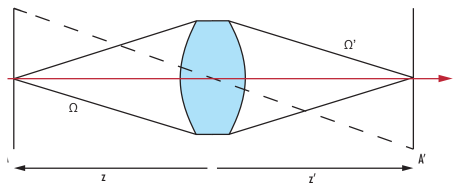


Figure 5:
DCX Lens Illustrating Throughput

OPTICAL THROUGHPUT: HOW MUCH LIGHT GETS THROUGH THE SYSTEM?

Solid angle is defined as $\Omega = A/r^2$, with the area of the lens surface and the radius (r) being the distance from the lens to the object (z) or image plane (z'), for Ω or Ω', respectively.

The amount of light reaching the detector can be reduced by vignetting, which is the result of light being physically blocked within the system due to lens aperture limitations. However, some systems benefit from intentional vignetting, as it can eliminate stray light that would negatively affect the quality of the image. It is important to note that properly aligning the system reduces stray light and unintentional vignetting.

ABERRATIONS: HOW DOES THE IMAGE LOOK?

Determining how much light passes through the system is important, but aberrations within the system also play a major role. Answering "How does the image look?" can lead to improving the system's design in order to reduce aberrations and improve image quality. Aberrations are errors inherent with any optical system, regardless of fabrication or alignment. Since every optical system contains aberrations, balancing performance with cost is an important decision for any designer. Several basic aberrations, such as coma (variation in magnification or image size with aperture), spherical (light rays focusing in front of or behind paraxial focus), and astigmatism (having one focus point for horizontal rays and another for vertical) can be reduced by a large F/#, as shown in the following relations.

(1.8)

$$Spherical \propto \frac{1}{(F/\#)^3}$$

(1.9)

$$Coma \propto \frac{1}{(F/\#)^2}$$

(1.10)

$$Astigmatism \propto \frac{1}{(F/\#)}$$

APPLICATION EXAMPLE: DETECTOR SYSTEM

As an example, consider a system in which light is emitted from a 1/4" diameter fiber optic light guide, as shown in Figure 3.

- **Initial Parameters**

NA of Light Guide = 0.55
Diameter of Source (Emitter) = 6.35mm
Index of Refraction of Air = 1

A PCX lens of F/1, meaning the F/# is 1, would be ideal to place in front of the light guide in order to collimate as much light as possible. According to Equation 1.4, if the F/# is 1, then the diameter and focal length of a lens are equal. In other words, if we consider a lens with a diameter of 12mm, then the focal length is also 12mm.

- **Calculated Parameters**

F- Number (F/#)

(1.11)

$$NA = \frac{1}{2(F/\#)}$$

$$0.55 = \frac{1}{2(F/\#)}$$

$$F/\# = 0.9$$

Continue

APPLICATION EXAMPLE: DETECTOR SYSTEM

Full Field of View (FFOV)

(1.12)

$$FFOV = \frac{D_2}{f} = \frac{D_{source}}{F_{lens}} = = \frac{6.35mm}{12mm} = 0.529 \text{ radians}$$

Throughput (TP)

(1.13)

$$A_{source} = \pi r^2 = \pi \left(\frac{6.35mm}{2}\right)^2 = 31.669mm^2$$

(1.14)

$$A_{lens} = \pi r^2 = \pi \left(\frac{12mm}{2}\right)^2 = 113.097mm^2$$

(1.15)

$$\Omega = \frac{Area_{lens}}{Radius^2} = \frac{113.097mm^2}{(12mm)^2} = 0.7854 \text{ steradians}$$

Steradians correspond to a 2-dimensional angle in 3-dimensional space, as the angle from the edge to edge of the lens is in two dimensions. A higher value in steradians is given by a shorter distance from emitter to lens, or a larger diameter of the lens. The largest value a solid angle can have is 4π, or about 12.57, as this would be equivalent to the solid angle of all space.

In order to calculate Throughput (TP) of this system, we need to first calculate the Area of the Source (Equation 1.11), the Area of the Lens (Equation 1.12) and the Solid Angle (Equation 1.13). As a rule of thumb for collimating light from a divergent source (i.e. the light guide in this example), place the lens a distance equal to one focal length away from the source.

(1.16)

$$TP = n^2 A\Omega = (1)(31.669mm^2)(0.7854 steradians) = 24.873mm^2 steradians$$

Since the system is in free space, where n is approximated as 1, n^2 does not factor into the final calculation.

APPLICATION 2: SELECTING THE RIGHT LENS

High image quality is synonymous with low aberrations. As a result, designers often utilize two or more lens elements in order to obtain higher image quality compared to a single lens solution. Many factors contribute to selecting the right lens for an application: type of source, space constraints, cost, etc.

Figures 6a - 6e compare a variety of lens systems for a relay lens, or 1:1 imaging, application. In this specific example, outlined in the following series of comparisons, it is easy to see how image quality is affected by the inherent geometry and optical properties of the lenses chosen.

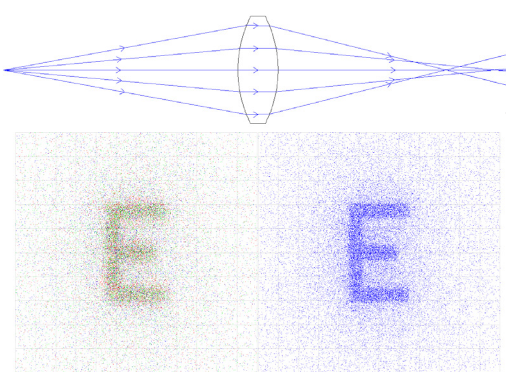


Figure 6a: DCX Lens Relay System: 25mm EFL x 20mm Entrance Pupil Diameter (Left is Color and Right is Monochromatic)

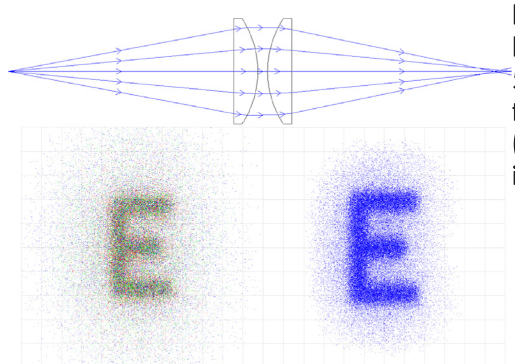


Figure 6b: PCX Lens Relay System: 50mm EFL x 20mm Entrance Pupil Diameter (Left is Color and Right is Monochromatic)

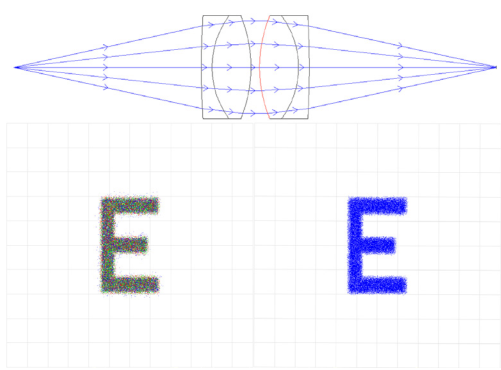


Figure 6c:
Achromatic Lens Relay System: 50mm EFL x 20mm Entrance Pupil Diameter (Left is Color and Right is Monochromatic)

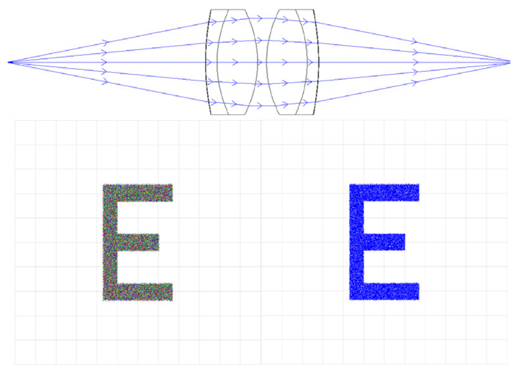


Figure 6d:
Aspherized Achromatic Lens Relay System: 50mm EFL x 50mm Entrance Pupil Diameter (Left is Color and Right is Monochromatic)

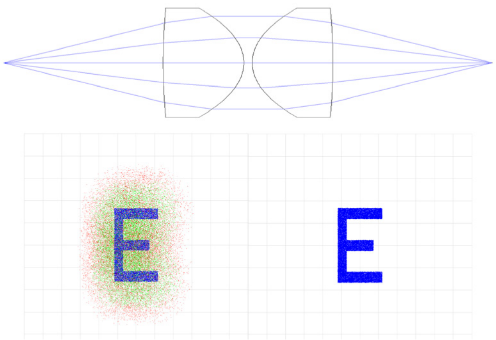


Figure 6e:
Aspheric Lens Relay System: 50mm EFL x 40mm Entrance Pupil Diameter (Left is Color and Right is Monochromatic)

APPLICATION EXAMPLE: SINGLE ELEMENT LENS SYSTEM

A double-convex (DCX) lens is regarded as the best single element for 1:1 imaging because of its symmetrical shape, as both sides of the lens have equal power, instead of one side bending rays more than the other, such as a plano-convex (PCX) lens. Since the lens system is made of just one lens, the aperture stop is essentially the lens, which allows for the reduction of many aberrations. For these reasons, a DCX lens is preferable to a single PCX lens for 1:1 imaging. However, it is important to keep in mind that at a low F/#, there is still significant spherical aberration and coma. These aberrations are caused by the Shape Factor (S) of the single lens:
where R1 and R2 are the radii of each surface of the lens.

(2.1)
$$S = \frac{R_1+R_2}{R_2-R_1}$$

For applications that only need one lens, with the object or source at infinity, a better shape factor can be found, to reduce whichever aberration is most detrimental to the system. For example, to reduce spherical aberration, the ideal shape factor can be calculated by:

(2.2)
$$S = -\frac{2(n^2-1)}{n+2}p$$

(2.3)
$$S = \frac{R_1+R_2}{R_2-R_1}$$

(2.4)
$$p = \frac{z' + z}{z' - z}$$

Continue

APPLICATION EXAMPLE: SINGLE ELEMENT LENS SYSTEM (CONT.)

Where n is the Index of Refraction of the Glass Substrate, p is the Position Factor, z is Object Distance (measured to be a negative value), and z' is Image Distance (measured to be a positive value).

To reduce coma for an object at infinity, the Shape Factor can be calculated by:

(2.5)

$$S = -\frac{(2n^2 - n - 1)}{n + 1}p$$

For glass that has an index of 1.5 (N-BK7 is 1.517), with an object at infinity, a Shape Factor of about 0.8 will balance the corrections of both coma and spherical aberrations.

APPLICATION EXAMPLE: DOUBLE ELEMENT LENS SYSTEM

In order to improve the system, a single DCX lens could be replaced with two equal PCX lenses each with a focal length twice that of the DCX, with an aperture stop in the center. Doing so splits the power of each surface of the lenses, as the focal length is inversely proportional to power. Since each lens has less power, there is less spherical aberration created in the system. By using two lenses, the powers of each surface add, which allows for the same overall focal length, but less spherical aberration. Since the diameter also has remained the same, the F/# did not change between using a single DCX or two PCX lenses, but the spherical aberration is decreased, even if the F/# is large.

The convex surfaces are nearly in contact, with the aperture stop located between them. Better image quality is achieved by orienting the convex surfaces towards the longest conjugate distance

APPLICATION EXAMPLE: ACHROMATIC LENS SYSTEM

Another option is to use two achromatic lenses, or achromats. An achromatic lens consists of two optical components cemented together, usually a positive low-index (crown) element and a negative high-index (flint) element. Using achromats improves polychromatic (white light, multiple wavelength) imaging as well as reduces spherical aberration and coma. If both lenses are achromats with convex surfaces facing each other, a far superior imaging system is obtained, as many aberrations are significantly reduced compared to the same system with single lenses (either DCX or two PCXs). While spherical aberration is negligible at large apertures or high F/#s, chromatic aberration is greatly reduced with the use of achromats. Many relay lens systems on the market utilize this type of four element configuration.

APPLICATION EXAMPLE: ASPHERIC LENS SYSTEM

Unlike PCX, DCX and achromatic lenses, which are made from portions of a sphere, an aspheric lens is one that has a curvature other than that of a sphere or cylinder, usually made from portions of a hyperbola or parabola. The key concept of aspheric lenses, or aspheres, is that the radius of curvature varies radially from the optical axis of the lens. As a result, aspheric lenses easily correct spherical aberration, and are great for correcting off-axis aberrations.

Aspheric lenses are used in many systems, as one aspheric lens can replace two or more spherical lenses, thereby reducing space and costs within a system.

Continue

APPLICATION EXAMPLE: ASPHERIC LENS SYSTEM (CONT)

Type of Lens System	Spherical Aberration	Chromatic Aberration
DCX Singlet	*High*	*High*
2 PCX	*Medium*	*High*
w Achromats	*Low*	*Negligible*
2 Aspherized Achromats	*Negligible*	*Negligible*

APPLICATION 3: BUILDING A PROJECTION SYSTEM

Designing a custom projector system can often be time-consuming and expensive. Nevertheless, there are some simple steps to follow to make the process easy and cost-effective. These same basic steps can be applied to many system design applications.

Custom Design Steps:

1) Divide the System into Parts – Optical applications are many and varied, from simple magnifiers to laser beam conditioning. Most applications, however, can be broken down into smaller modules that can be developed almost independently.

2) Design Each Part Separately – By taking each module and designing it for optimum individual performance, the system as a whole can benefit. This is true as long as the optimization of one module doesn't adversely affect the design of another module, so it is important to keep the overall system in mind as you design the separate parts.

3) Computer Optimize – After computing the initial dimensions, putting the design into lens design software, such as ZEMAX or Code V, is the best way to optimize the modules independently, as well as the overall design. Optimizing each system module will give the best case scenarios for which appropriate mounting components can be chosen. This also works as a double check to make sure the calculations yield reasonable data.

4) Assemble the System – After each module is designed, the entire system must be constructed. Prior to putting the modules together, it is necessary to check them individually to guarantee they work properly before adding them to the system. After the system is constructed, it is best to run the entire system through lens design software as well, in order to make sure the modules work together correctly within the system.

5) Select Parts – Most lens design software packages include a library of stock lens prescriptions and a "closest-match" algorithm, which helps one pick real lenses and items in place of custom parts. Lens design software will optimize to a glass number that may not exist, but the closest-match will yield a very similar glass type that can be purchased. Beyond selecting the right glasses, finding mechanics to fit the system is an important step. Size, weight, and appearance must be considered before choosing lens holders and system mounting.

Custom Design Steps

Most projectors, like the old-fashioned slide projector, employ two main modules: a condenser lens system and a projector lens system. The condenser lens system evenly illuminates a slide; the projector lens system projects an image of the slide onto a screen. Each module can be created with simple components and methods. 25mm diameter optics will be used in this example because of their large aperture and wide variety of focal lengths available.

PART 1: THE PROJECTION LENS SYSTEM

The projection lens system is limited by the desired magnification and throw distance of the reticle image. Since most projection systems utilize white light, using achromatic lenses will yield the best image. To determine which achromats to use, decide how far from the projected image the projection lens system will be (I) and the desired magnification (M). Magnification can be calculated by the focal lengths of the lenses (Equation 3.1) or by the image to object distance (Equation 3.2).

(3.1) $$M = \frac{F_2}{F_1}$$

(3.2) $$M = \frac{I}{O}$$

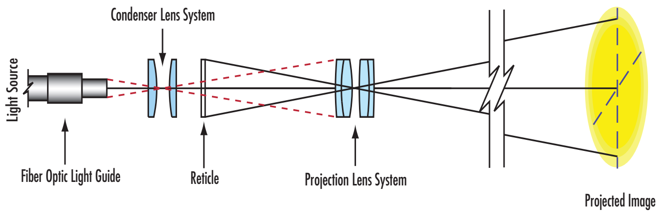


Figure 7: Basic Projection System

PART 2: THE CONDENSER LENS SYSTEM

The condenser lens systems collects light from divergent illumination sources, then redirects and condenses the light to flood the projector lens system. The classical condenser lens system consists of two PCX lenses mounted with their convex sides facing each other, as shown in Figure 7. The first lens collects the divergent light cone from the illuminator (object or projector) and the second lens outputs the light as a convergent cone (image), which will illuminate the reticle.

Implicitly, the projection lens solution defines part of the condenser lens system, which is why designing the projection lens system first is crucial. The distance of the condenser lens system to the projector lens system is at least as great as the distance from the reticle to the projector lens system.

APPLICATION EXAMPLE: DESIGNING A PROJECTION SYSTEM

- **Initial Parameters**

Diameter of Lens = 25mm
Image Distance = Throw Distance = 250mm
Magnification = 2.5X

- **Calculated Parameters**

Object Distance, or Distance to the Reticle

(3.3)
$$M = \frac{F_2}{F_1} \qquad 2.5 = \frac{250mm}{F_1} \qquad F_1 = \frac{250mm}{2.5} = 100mm$$

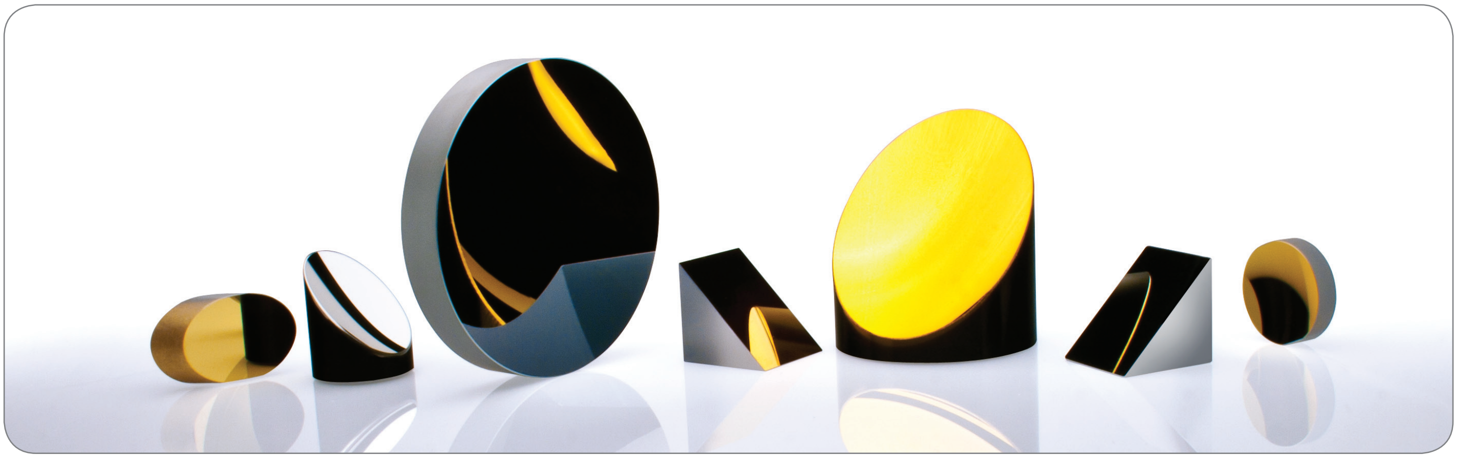
Two 100mm focal length achromatic lenses with a 25mm diameter would be ideal for creating the projection lens system. 25mm diameter lenses are great for their large apertures and compatibility with mechanical components, as well as their variety of coatings and focal lengths.

Focal Length of PCX Condenser Lens

(3.4)
$$M = \frac{F_2}{F_1} \qquad F2 = = MF1 = (2.5X)(100mm) = 250mm$$

Two 250mm focal length PCX lenses with a 25mm diameter are needed to complete the projection system.

UNDERSTANDING OPTICAL SPECIFICATIONS



Optical specifications are utilized throughout the design and manufacturing of a component or system to characterize how well it meets certain performance requirements. They are useful for two reasons: first, they specify the acceptable limits of key parameters that govern system performance; second, they specify the amount of resources (i.e. time and cost) that should be spent on manufacturing.

An optical system can suffer from either under-specification or over-specification, both of which can result in unnecessary expenditure of resources. Under-specification occurs when not all of the necessary parameters are properly defined, resulting in inadequate performance. Over-specification occurs when a system is defined too tightly without any consideration for changes in optical or mechanical requirements, resulting in higher cost and increased manufacturing difficulty.

In order to understand optical specifications, it is important to first review what they mean. To simplify the ever-growing number, consider the most common manufacturing, surface, and material specifications for lenses, mirrors, and windows. Filters, polarizers, prisms, beamsplitters, gratings, and fiber optics also share many of these optical specifications, so understanding the most common provides a great baseline for understanding those for nearly all optical products.

MANUFACTURING SPECIFICATIONS

DIAMETER TOLERANCE

The diameter tolerance of a circular optical component provides the acceptable range of values for the diameter. This manufacturing specification can vary based on the skill and capabilities of the particular optical shop that is fabricating the optic. Although diameter tolerance does not have any effect on the optical performance of the optic itself, it is a very important mechanical tolerance that must be considered if the optic is going to be mounted in any type of holder. For instance, if the diameter of an optical lens deviates from its nominal value it is possible that the mechanical axis can be displaced from the optical axis in a mounted assembly, thus causing decenter (Figure 1). Typical manufacturing tolerances for diameter are: +0.00/-0.10 mm for typical quality, +0.00/-0.050 mm for precision quality, and +0.000/-0.010 mm for high quality.

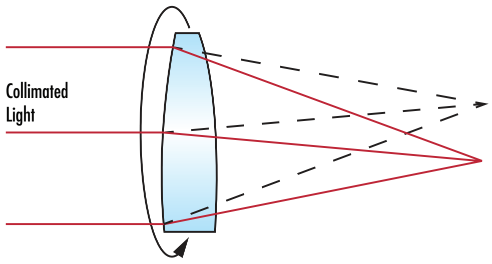


Figure 1: Decentering of Collimated Light

Continue

CENTER THICKNESS TOLERANCE

The center thickness of an optical component, most notably a lens, is the material thickness of the component measured at the center. Center thickness is measured across the mechanical axis of the lens, defined as the axis exactly between its outer edges. Variation of the center thickness of a lens can affect the optical performance because center thickness, along with radius of curvature, determines the optical path length of rays passing through the lens. Typical manufacturing tolerances for center thickness are: +/-0.20 mm for typical quality, +/-0.050 mm for precision quality, and +/-0.010 mm for high quality.

RADIUS OF CURVATURE

The radius of curvature is defined as the distance between an optical component's vertex and the center of curvature. It can be positive, zero, or negative depending on whether the surface is convex, plano, or concave, respectfully. Knowing the value of the radius of curvature allows one to determine the optical path length of rays passing through the lens or mirror, but it also plays a large role in determining the power of the surface. Manufacturing tolerances for radius of curvature are typically +/-0.5, but can be as low as +/-0.1% in precision applications or +/-0.01% for extremely high quality needs.

CENTERING

Centering, also known by centration or decenter, of a lens is specified in terms of beam deviation δ (Equation 1). Once beam deviation is known, wedge angle W can be calculated by a simple relation (Equation 2). The amount of decenter in a lens is the physical displacement of the mechanical axis from the optical axis. The mechanical axis of a lens is simply the geometric axis of the lens and is defined by its outer cylinder. The optical axis of a lens is defined by the optical surfaces and is the line that connects the centers of curvature of the surfaces. To test for centration, a lens is placed into a cup upon which pressure is applied. The pressure applied to the lens automatically situates the center of curvature of the first surface in the center of the cup, which is also aligned with the axis of rotation (Figure 2). Collimated light directed along this axis of rotation is sent through the lens and comes to a focus at the rear focal plane. As the lens is rotated by rotating the cup, any decenter in the lens will cause the focusing beam to diverge and trace out a circle of radius Δ at the rear focal plane (Figure 1).

(1)

$$\delta = \left(\frac{\Delta}{f}\right)$$

(2)

$$W = \left(\frac{\delta}{n - 1}\right)$$

where W is the wedge angle, often reported as arcminutes, and n is the index of refraction.

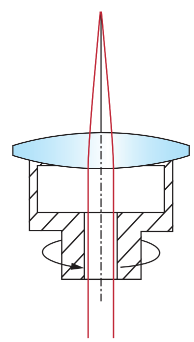


Figure 2:
Test for Centration

PARALLELISM

Parallelism describes how parallel two surfaces are with respect to each other. It is useful in specifying components such as windows and polarizers where parallel surfaces are ideal for system performance because they minimize distortion that can otherwise degrade image or light quality. Typical tolerances range from 5 arcminutes down to a few arcseconds.

ANGLE TOLERANCE

In components such as prisms and beamsplitters, the angles between surfaces are critical to the performance of the optic. This angle tolerance is typically measured using an autocollimator assembly, whose light source system emits collimated light. The autocollimator is rotated about the surface of the optic until the resultant Fresnel reflection back into it produces a spot on top of the surface under inspection. This verifies that the collimated beam is hitting the surface at exactly normal incidence. The entire autocollimator assembly is then rotated around the optic to the next optical surface and the same procedure is repeated. Figure 3 shows a typical autocollimator setup measuring angle tolerance. The difference in angle between the two measured positions is used to calculate the tolerance between the two optical surfaces. Angle tolerance can be held to tolerances of a few arcminutes all the way down to a few arcseconds.

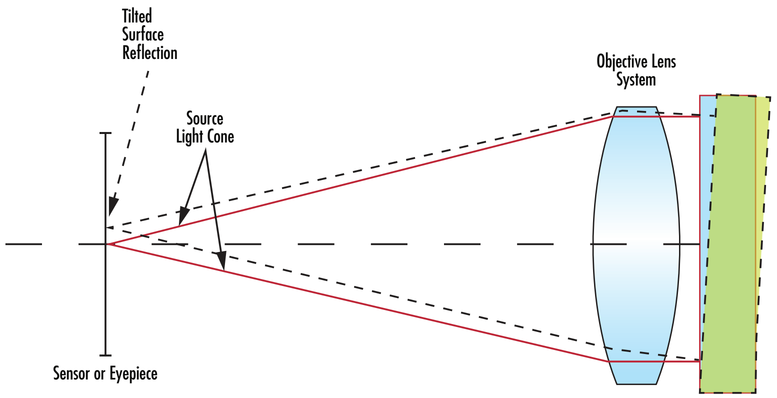


Figure 3: Autocollimator Setup Measuring Angle Tolerance

BEVEL

Glass corners can be very fragile, therefore, it is important to protect them when handling or mounting a component. The most common way of protecting these corners is to bevel the edges. Bevels serve as protective chamfers and prevent edge chips. They are defined by their face width and angle (Figure 4).

Bevels are most commonly cut at 45° and the face width is determined by the diameter of the optic. Optics with diameters less than 3.00mm, such as micro-lenses or micro-prisms, are typically not beveled due to the likelihood of creating edge chips in the process. It is important to note that for small radii of curvature, for example, lenses where the diameter is ≥ 0.85 x radius of curvature, no bevel is needed due to the large angle between the surface and edge of the lens. For all other diameters, the maximum face widths are provided in Table 1.

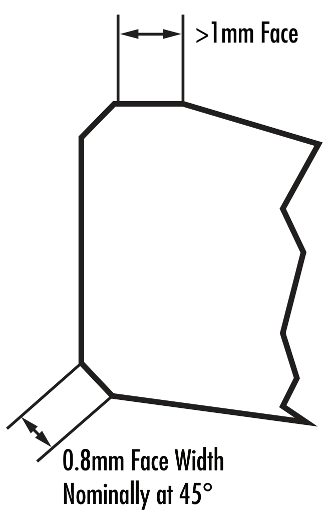


Figure 4: Bevel on an Optical Lens

Table 1: Bevel Tolerances

Diameter	Maximum Face Width of Bevel
3.00mm-5.00mm	0.1mm
5.01mm - 25.40mm	0.25mm
25.41mm - 50.00mm	0.3mm
50.01mm - 75.00mm	0.4mm

Continue

CLEAR APERTURE

Clear aperture is defined as the diameter or size of an optical component that must meet specifications. Outside of it, manufacturers do not guarantee the optic will adhere to the stated specifications. Due to manufacturing constraints, it is virtually impossible to produce a clear aperture exactly equal to the diameter, or the length by width, of an optic. Typical clear apertures for lenses are show in Table 2.

Table 2: Clear Aperture Tolerances

Diameter	Clear Aperture
3.00mm - 10.00mm	*90% of Diameter*
10.01mm - 50.00mm	*Diameter - 1mm*
≥50.01mm	*Diameter - 1.5mm*

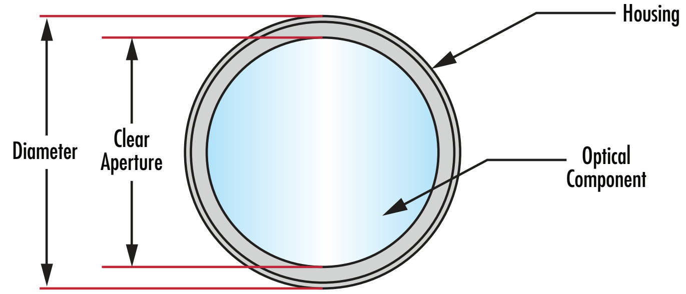


Figure 5: Graphic Indicating Clear Aperture and Diameter of a Filter

SURFACE SPECIFICATIONS

SURFACE QUALITY

The surface quality of an optical surface describes its cosmetic appearance and includes such defects as scratches and pits, or digs. In most cases, these surface defects are purely cosmetic and do not significantly affect system performance, though, they can cause a small loss in system throughput and a small increase in scattered light. Certain surfaces, however, are more sensitive to these effects such as: (1) surfaces at image planes because these defects are in focus and (2) surfaces that see high power levels because these defects can cause increased absorption of energy and damage the optic. The most common specification used for surface quality is the scratch-dig specification described by MIL-O-13830A. The scratch designation is determined by comparing the scratches on a surface to a set of standard scratches under controlled lighting conditions. Therefore the scratch designation does not describe the actual scratch itself, but rather compares it to a standardized scratch according to the MIL-Spec. The dig designation, however, does directly relate to the dig, or small pit in the surface. The dig designation is calculated at the diameter of the dig in microns divided by 10. Scratch-dig specifications of 80-50 are typically considered standard quality, 60-40 precision quality, and 20-10 high precision quality.

SURFACE FLATNESS

Surface flatness is a type of surface accuracy specification that measures the deviation of a flat surface such as that of a mirror, window, prism, or plano-lens. This deviation can be measured using an optical flat, which is a high quality, highly precise flat reference surface used to compare the flatness of a test piece. When the flat surface of the test optic is placed against the optical flat, fringes appear whose shape dictates the surface flatness of the optic under inspection. If the fringes are evenly spaced, straight, and parallel, then the optical surface under test is at least as flat as the reference optical flat. If the fringes are curved, the number of fringes between two imaginary lines, one tangent to the center of a fringe and one through the ends of that same fringe, indicate the flatness error. The deviations in flatness are often measured in values of waves (λ), which are multiples of the wavelength of the testing source. One fringe corresponds to ½ of a wave. 1λ flatness is considered typical grade, ¼λ flatness is considered to be precision grade, and 1/20λ is considered high precision grade.

Continue

POWER

Power, a type of surface accuracy specification, applies to curved optical surfaces, or surfaces with power. It is tested in a fashion similar to flatness, in that a curved surface is compared against a reference surface with a highly calibrated radius of curvature. Using the same principle of interference caused by the air gaps between the two surfaces, the interferences pattern of fringes is used to describe the deviation of the test surface from the reference surface. A deviation from the reference piece will create a series of rings, known as Newton's Rings. The more rings that are present, the larger the deviation. The number of dark or light rings, not the sum of both light and dark, corresponds to twice the number of waves of error.

IRREGULARITY

Irregularity, a type of surface accuracy specification, describes how the shape of a surface deviates from the shape of a reference surface. It is obtained from the same measurement as power. Regularity refers to the sphericity of the circular fringes that are formed from the comparison of the test surface to the reference surface. When the power of a surface is more than 5 fringes, it is difficult to detect small irregularities of less than 1 fringe. Therefore it is common practice to specify surfaces with a ratio of power to irregularity of approximately 5:1.

SURFACE FINISH

Surface finish, also known as surface roughness, measures small scale irregularities on a surface. They are usually an unfortunate by-product of the polishing process. Rough surfaces tend to wear faster than smooth surfaces and may not be suitable for some applications, especially those with lasers or intense heat, due to possible nucleation sites that can appear in small cracks or imperfections. Manufacturing tolerances for surface finish range from 50Å RMS for typical quality, 20Å RMS for precision quality, and 5Å RMS for high quality.

MATERIAL SPECIFICATIONS

INDEX OF REFRACTION

The index of refraction of a medium is the ratio of the speed of light in vacuum to the speed of light in the medium. Typical indices of refraction for glass range from 1.4 - 4.0; visible glasses have lower ranges than those optimized for the infrared. For example, N-BK7 (a popular visible glass) has an index of 1.517, whereas, germanium (a popular IR glass) has an index of 4.003. The index of refraction of an optical glass is an important property because the power of an optical surface is derived from both the radius of curvature of the surface and the difference in the index of refraction of the media on either side of the surface. Inhomogeneity, specified by the glass manufacturer, describes the variation of index of refraction in a glass.

It is specified according to different classes, where class and inhomogeneity are inversely related – as class increases, inhomogeneity decreases (Table 3).

Table 3: Inhomogeneity Specifications

Inhomogeneity Class	Maximum Permissible Variation of Index of Refraction
0	$\pm 50 \times 10^{-6}$
1	$\pm 20 \times 10^{-6}$
2	$\pm 5 \times 10^{-6}$
3	$\pm 2 \times 10^{-6}$
4	$\pm 1 \times 10^{-6}$
5	$\pm 0.5 \times 10^{-6}$

ABBE NUMBER

Another material property of glasses is the Abbe number, which quantifies the amount of dispersion that a glass exhibits. It is a function of the refractive index of a material at the f (486.1nm), d (587.6nm), and c (656.3nm) wavelengths (Equation 3),

(3)

$$v_d = \frac{n_d - 1}{n_f - n_c}$$

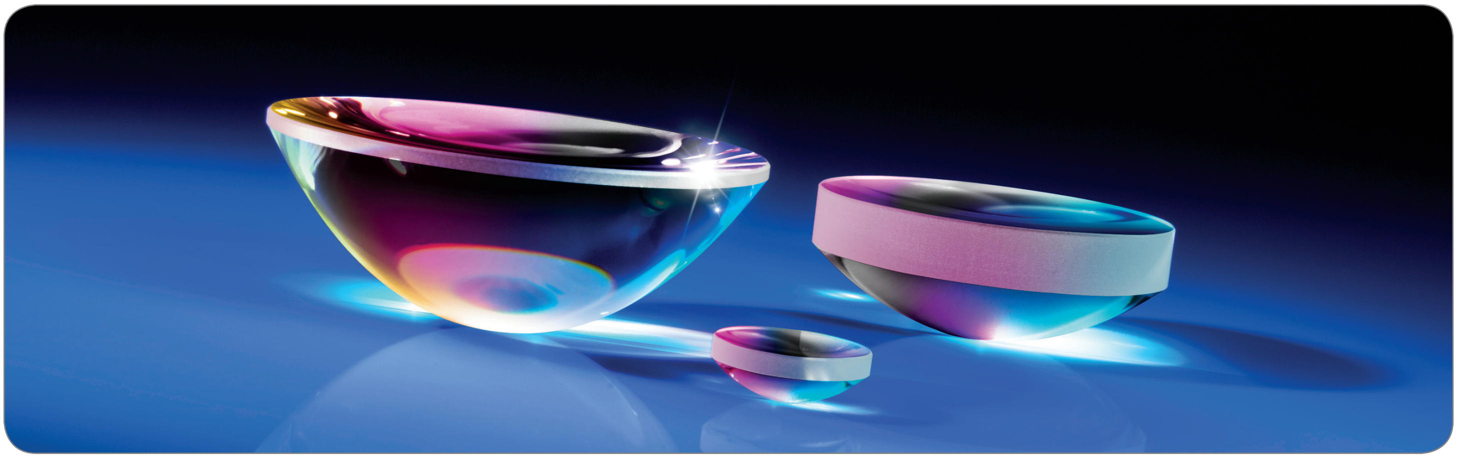
Typical values of Abbe number range from 25 – 65. Glasses with an Abbe number greater than 55 (less dispersive) are considered crown glasses and those with an Abbe number less than 50 (more dispersive) are considered flint glasses. Due to dispersion, the index of refraction of a glass varies with wavelength. The most notable consequence of this is the fact that a system will have slightly different focal lengths for different wavelengths of light.

LASER DAMAGE THRESHOLD

Laser damage threshold indicates the maximum amount of laser power per area that a surface can withstand before it is damaged. Values are provided for pulsed lasers and continuous wave (CW) lasers. Laser damage threshold is a very important material specification for mirrors since they are used in conjunction with laser products more than any other optic; however, any laser-grade optic will provide a threshold. For example, consider a Ti: Sapphire Laser Mirror with damage threshold ratings of 0.5 J/cm^2 @ 150 femtosecond pulses and 100kW/cm^2 CW. This means that the mirror can withstand energy densities of 0.5J per square centimeter from a high repetition femtosecond pulsed laser or 100kW per square centimeter from a high power CW laser. If the laser is concentrated on a smaller region, then the proper consideration must be taken to ensure the overall threshold does not exceed the specified values.

Though a host of additional manufacturing, surface, and material specifications exist, understanding the most common optical specifications can greatly alleviate confusion. Lenses, mirrors, windows, filters, polarizers, prisms, beamsplitters, gratings, and fiber optics share a variety of attributes, therefore, knowledge of how they relate to each other and can affect overall system performance helps to choose the best components for integration into optics, imaging, or photonics applications.

ALL ABOUT ASPHERIC LENSES



ANATOMY OF AN ASPHERIC LENS

An aspheric lens, also referred to as an asphere, is a rotationally symmetric optic whose radius of curvature varies radially from its center. It improves image quality, reduces the number of required elements, and lowers costs in optical designs. From digital cameras and CD players to high-end microscope objectives and fluorescence microscopes, aspheric lenses are growing into every facet of the optics, imaging, and photonics industries due to the distinct advantages that they offer compared to traditional spherical optics.

Aspheric lenses have been traditionally defined with the sur profile (sag) given by Equation 1:

(1)

$$Z(s)=\frac{Cs^2}{1+\sqrt{1-(1+k)C^2s^2}}+A_4s^4+A_6s^6+A_8s^8+\ldots$$

Where
Z = sag of surface parallel to the optical axis
s = radial distance from the optical axis
C = curvature, inverse of radius
k = conic constant
A_4, A_6, A_8 = 4th, 6th, 8th… order aspheric terms

As they have increased in popularity, there is now a more technically accurate way of describing the surface:

(2)

$$Z(\rho)=\frac{C_{bfs}\rho^2}{1+\sqrt{1-C_{bfs2}\rho^2}}+u^4\sum_{m=0}^{m}a_m Q_m^{con}(u^2)$$

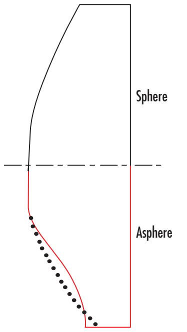
Where
C_{bfs} = curvature of best fit sphere
ρ = radial distance from the optical axis
u = ρ/ρmax
Q_m^{con} = orthonormal basis of asphere coefficients
a_m = normalization term
When the aspheric coefficients are equal to zero, the resulting aspheric surface is considered to be a conic. The following table shows how the actual conic surface generated depends on the magnitude and sign of the conic constant k.

Conic Constant	Conic Surface
k = 0	Sphere
k > -1	Ellipse
k = -1	Parabola
k < -1	Hyperbola

ANATOMY OF AN ASPHERIC LENS (CONT.)

The most unique geometric feature of aspheric lenses is that the radius of curvature changes with distance from the optical axis, unlike a sphere, which has a constant radius (Figure 1). This distinctive shape allows aspheric lenses to deliver improved optical performance compared to standard spherical surfaces.

Figure 1:
Comparison of Spherical and Aspheric Surface Profiles



BENEFITS OF AN ASPHERIC LENS

SPHERICAL ABERRATION CORRECTION

The most notable benefit of aspheric lenses is their ability to correct for spherical aberration. Spherical aberration results from using a spherical surface to focus or collimate light. In other words, all spherical surfaces suffer from spherical aberration independent of alignment or manufacturing errors; therefore, a non-spherical, or aspheric surface, is needed to correct for it. By adjusting the conic constant and aspheric coefficients, an aspheric lens can be optimized for maximum cancellation of aberrations. For example, consider Figure 2 which shows a spherical lens with significant spherical aberration compared to an aspheric lens with practically no spherical aberration. In a spherical lens, spherical aberration causes incident light rays to focus at different points, creating a blur; in an aspheric lens, light focuses to a point, creating comparatively no blur and improving image quality.

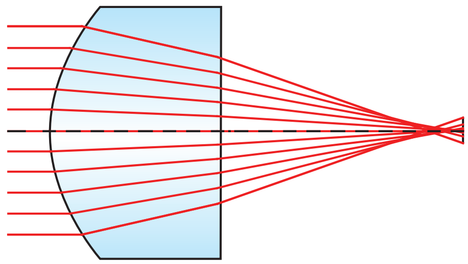
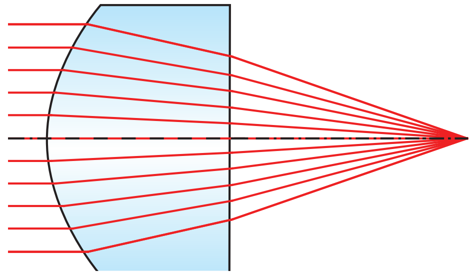


Figure 2: Spherical Aberration (above) in a Spherical Lens Compared to No Aberration in an Aspheric Lens (below)



To get a better idea of the difference in focusing performance between an aspheric lens and a spherical lens, consider a quantitative example of two comparable lenses with 25mm diameters and 25mm focal lengths (F/1 lenses). The following table compares the spot size, or blur size, of on-axis (0° object angle) and off-axis (0.5° and 1.0° object angles) collimated, monochromatic light rays of 587.6nm. Since a smaller spot size indicates better performance, it is clear to see that the aspheric lens produces much better image quality by two orders of magnitude compared to an identical spherical lens.

Object Angle (°)	Spherical Spot Size (μm)	Aspheric Spot Size (μm)
0.0	710.01	1.43
0.5	710.96	3.91
1.0	713.84	8.11

Continue

ADDITIONAL PERFORMANCE BENEFITS

Although various techniques exist to correct aberrations caused by spherical surfaces, none match the imaging performance and flexibility that aspheric lenses provide. Another technique used includes increasing the F/# by "stopping down" the lens. Although this can increase image quality, it also reduces the amount of light throughput in the system, thereby leading to a tradeoff between the two.

On the other hand, when using aspheric lenses, additional aberration correction makes it possible to design high throughput (low F/#, high numerical aperture) systems while simultaneously maintaining good image quality. The image degradation from a higher throughput design can be sustained because a slight tradeoff in image quality can still outperform a spherical system. Consider an 81.5mm focal length, F/2 triplet lens (Figure 3) consisting of all spherical surfaces versus the same triplet with an aspheric first surface where both designs use the same glass types, effective focal length, field of view, F/#, and total system length. The following table quantitatively compares modulation transfer function (MTF) @ 20% contrast of on-axis and off-axis collimated, polychromatic light rays at 486.1nm, 587.6nm, and 656.3nm. The triplet lens with the aspheric surface shows increased imaging performance at all field angles, indicated by high tangential and sagittal resolution values, by factors as high as four compared to the triplet with only spherical surfaces.

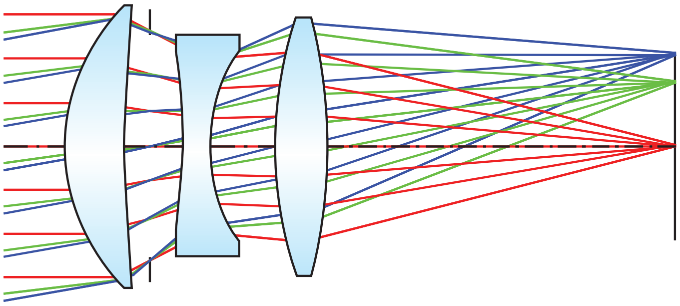


Figure 3:
Polychromatic Light Through A Triplet Lens

Object Angle (°)	All Spherical Surfaces		Aspherical First Surface	
	Tangential (lp/mm)	Sagittal (lp/mm)	Tangential (lp/mm)	Sagittal (lp/mm)
0.0	13.3	13.3	61.9	61.9
7.0	14.9	13.1	31.1	40.9
10.0	17.3	14.8	36.3	41.5

SYSTEM ADVANTAGES

Aspheric lenses allow optical designers to correct aberrations using fewer elements than conventional spherical optics because the former gives them more aberration correction than multiple surfaces of the latter. For example, in zoom lenses where ten or more lens elements are typically used, one or two aspheric lenses can be substituted for a handful of spherical lenses in order to achieve similar or better optical results, minimize the overall cost of production, as well as reduce system size.

An optical system with more elements can negatively affect both optical and mechanical parameters, contributing to higher priced mechanical tolerances, additional alignment procedures, and increased anti-reflection coating requirements. All of these may ultimately decrease total system utility because of the necessity for increased support components. As a result, incorporating aspheric lenses (though higher priced than similar F/# singlet and doublet lenses) can actually reduce overall system design costs.

PRECISION GLASS MOLDING

Precision glass molding is a type of manufacturing technique where optical glass cores are heated to high temperatures until the surface becomes malleable enough to be pressed into an aspheric mold (Figure 4). After several hours of cooling the cores to room temperature, they maintain the shape of the mold. Until recently, the technology was not available for lenses greater than 10mm in diameter, but new tools, optical glass, and metrology processes have all aided in the advancement of precision glass molding. Creating the mold has high initial startup costs because it has to be precisely made from very durable material that can maintain a smooth surface and take into account any shrinkage of the glass cores in order to yield the desired aspheric shape. However, once the mold is finished, the incremental cost for each lens is lower than that of standard manufacturing techniques, making it a great option for high volume production.

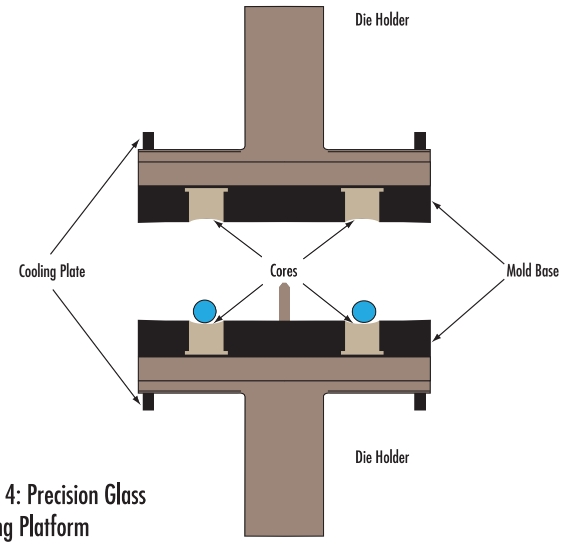
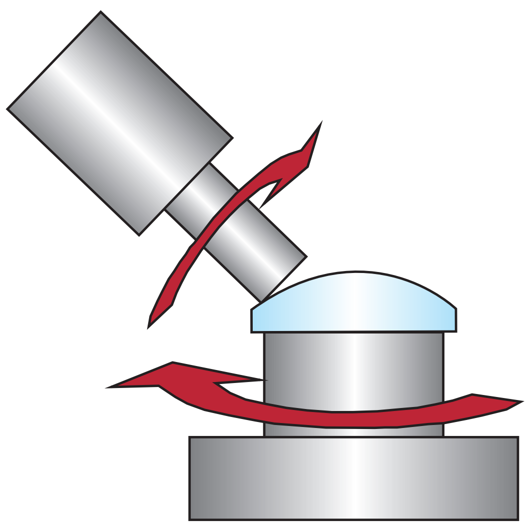


Figure 4: Precision Glass Molding Platform

PRECISION POLISHING

Grinding and polishing one aspheric lens at a time has been the standard manufacturing technique, but continually increasing technological advances now allow for previously unattainable levels of accuracy. Most notably, computer controlled precision polishing (Figure 5) automatically adjusts the tool dwell parameters to polish away high spots where more polishing is needed. If higher quality polishing is required, magneto-rheological finishing (MRF) is used to finalize the surface (Figure 6). MRF technology provides high performance finishing in less time than standard polishing techniques because of its precise control of the removal location and high removal rate. While more specialized manufacturing techniques require specialized molds, polishing utilizes standard tooling which makes it the primary option for prototyping and low volume production.



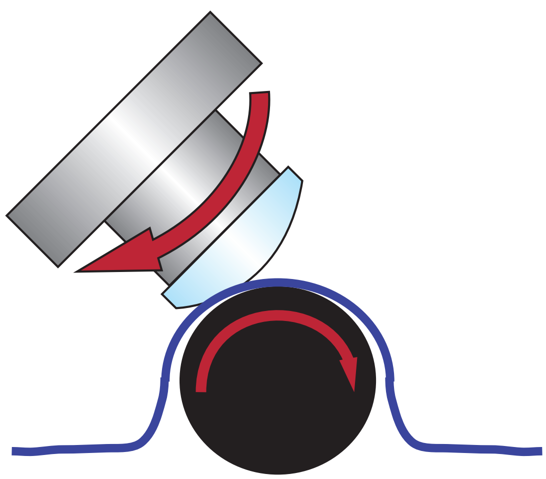


Figure 6:
Magneto-Rheological Finishing (MRF)

Continue

HYBRID MOLDING

Hybrid molding begins with a standard spherical surface, such as an achromatic lens, which is then pressed onto a thin layer of photopolymer in an aspheric mold to give the net result of an aspheric surface. The technique uses a diamond ground aspheric mold and a glass achromatic lens (though other types of singlet or doublet lenses can be used). A photopolymer injection is introduced into the aspheric mold, against which the achromatic lens is pressed. The two surfaces are compressed and UV cured at room temperature to yield an aspherized achromatic lens that combines the optical properties of the constituent parts: chromatic and spherical aberration correction. Figure 7 overviews the process of creating a hybrid lens. Hybrid molding is useful for high volume precision applications where additional performance is required and the quantity can justify the initial tooling costs.

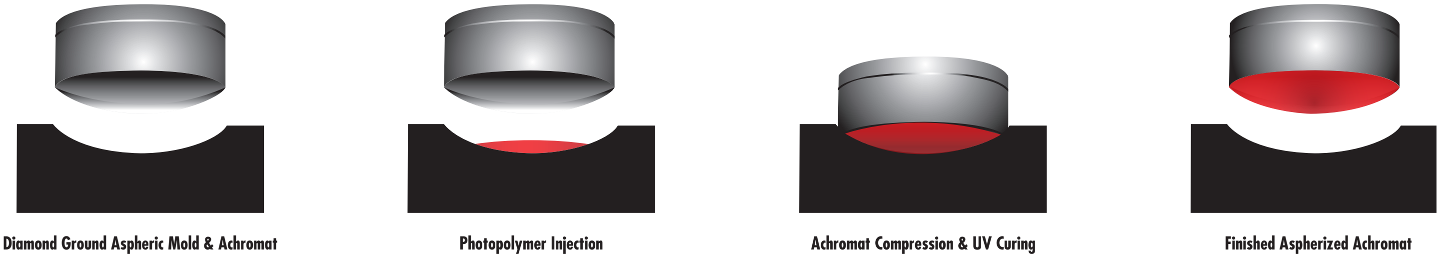


Figure 7: Hybrid Molding Technique

PLASTIC MOLDING

In addition to the aforementioned manufacturing techniques for glass, there exists one unique technique for plastic. Plastic molding involves injecting molten plastic into an aspheric mold. Since plastic is not as thermally stable and resistant to pressure as glass, it has to be treated specially in order to create a comparable aspheric lens. Nevertheless, plastic is advantageous because it is light-weight, easily molded, and can be integrated with a mount to create a single piece. While the selection of optical quality plastic is limited, the cost and weight benefits sometimes drive designs toward plastic aspheric lenses.

SELECTING THE APPROPRIATE ASPHERIC LENS

Since all applications do not use the same lenses, selecting the appropriate aspheric lenses is an important decision. The main driving factors to consider are volume and cost. Once those two are decided upon, it is easy to pick which aspheric product is the right one.

While stock aspheric components are available for immediate delivery or with short lead times for any application budget, they are only available in certain sizes, focal lengths and coating options. If off-the-shelf products are not sufficient, consider custom aspheric manufacturing for prototype, pre-production or large volume applications.

Type	Benefit
Precision Glass Molded	Ideal for high volume production requirements because of rapid production of many lenses and low tooling upkeep costs.
Precision Polished	Ideal for prototype or low volume requirements because of short lead time, minim special tooling and setup.
Hybrid Molded	Ideal for multi-spectral applications because of correction for both spherical and chromatic aberration.
Plastic Molded	Ideal for volume production as a weight-sensitive, low-cost alternative to glass aspheric lenses.

OPTICAL FILTERS

Optical filters can be used to attenuate or enhance an image, transmit or reflect specific wavelengths, and/or split an image into two identical images with controlled brightness levels relative to each other. To understand the importance of choosing the correct optical filter for any application, consider key terminology, fabrication techniques, and the various types of filters available today.

KEY OPTICAL FILTER TERMINOLOGY

Before delving into fabrication techniques and the types of optical filters available in the industry today, it is first important to review key terminology associated with them. Since all filters, independent of how they are manufactured, pass, absorb, and/or reflect some portion of incident light, they share common optical parameters.

CENTRAL WAVELENGTH

Center Wavelength (CWL) is the midpoint between the wavelengths where transmittance is 50% of the specified minimum transmission, referred to as the Full Width at Half Maximum (FWHM). For interference filters, the peak is typically not at the midpoint wavelength. Refer to Figure 1 for an illustration of CWL and FWHM.

BANDWIDTH + BLOCKING RANGE

Bandwidth is a wavelength range used to denote a specific part of the spectrum that passes incident energy through a filter. Bandwidth is also referred to as FWHM (Figure 1).

Blocking Range is a wavelength interval used to denote a spectral region of energy that is attenuated by the filter (Figure 2). The degree of its blocking is typically specified in terms of optical density.

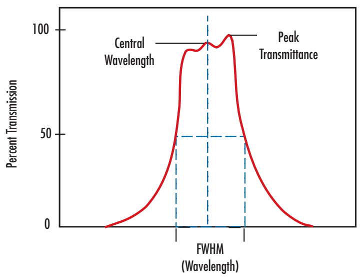


Figure 1: Illustration of Center Wavelength and Full Width at Half Maximum

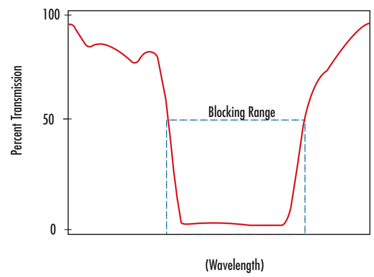


Figure 2: Illustration of Blocking Range

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OPTICAL DENSITY

Optical Density (OD) describes the blocking specification of a filter and is related to the amount of energy transmitted through it (Equations 1 – 2). A high optical density value indicates very low transmission, and low optical density indicates high transmission. Figure 3 depicts three different optical densities: OD 1.0, OD 1.3 and OD 1.5 that show the higher the OD value, the lower the transmission.

(1)

$$T\ (Percent\ Transmission) = 10^{-OD} x100$$

(2)

$$OD = -log\left(\frac{T\%}{100}\right)$$

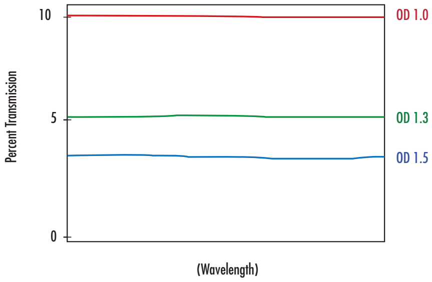


Figure 3: Illustration of Optical Density

DICHROIC FILTER

A Dichroic Filter is a type of filter used to transmit or reflect light, depending on the wavelength; light of a specific wavelength range is transmitted, while light of a different range is reflected or absorbed (Figure 4). Dichroic filters are commonly used for longpass and shortpass applications.

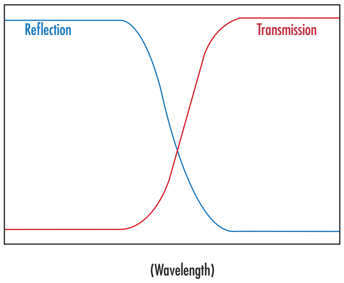


Figure 4: Illustration of a Dichroic Filter Coating

CUT-ON AND CUT-OFF WAVELENGTH

Cut-On Wavelength is a term used to denote the wavelength at which the transmission increases to 50% throughput in a longpass filter. Cut-on wavelength is indicated by λ_{cut-on} in Figure 5.

Cut-Off Wavelength is a term used to denote the wavelength at which the transmission decreases to 50% throughput in a shortpass filter. Cut-off wavelength is indicated by $\lambda_{cut-off}$ in Figure 6.

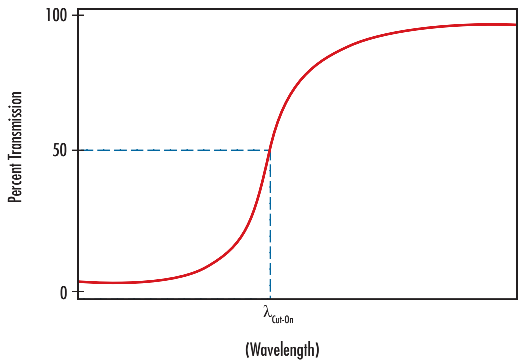


Figure 5: Illustration of Cut-On Wavelength

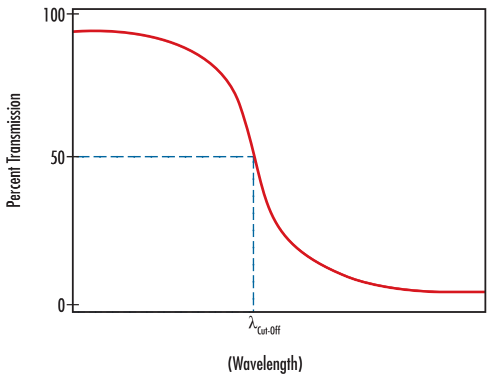


Figure 6: Illustration of Cut-Off Wavelength

Continue

ABSORPTIVE AND DICHROIC FILTERS

The wide range of optical filters can be broken into two main categories: absorptive and dichroic. The difference between the two does not lie in what they filter, but how they filter. In an absorptive filter, light is blocked based on the absorption properties of the glass substrate used. In other words, light that is blocked does not reflect off the filter; rather, it is absorbed and contained within the filter. In applications where noise in a system from unwanted light is an issue, an absorptive filter is ideal. Absorptive filters also have the added bonus of not being very angle sensitive; light can be incident upon the filter from a wide range of angles and the filter will maintain its transmission and absorption properties.

Conversely, a dichroic filter works by reflecting unwanted wavelengths, while transmitting the desired portion of the spectrum. In some applications, this is a desirable effect because light can be separated by wavelength into two sources. This is achieved by adding a layer, or multiple layers, of material of varying indexes of refraction to exploit the interference nature of light waves. In interference filters, light traveling from a lower index material will reflect off a higher index material; only light of a certain angle and wavelength will constructively interfere with the incoming beam and pass through the material, while all other light will destructively interfere and reflect off the material (Figure 7).

Unlike absorptive filters, dichroic filters are extremely angle sensitive. When used for any angle(s) outside of their intended design, dichroic filters cannot meet the transmission and wavelength specifications originally indicated. As a rule of thumb, increasing the angle of incidence through a dichroic filter will shift it towards shorter wavelengths (i.e. towards bluer wavelengths); and decreasing the angle will shift it towards longer wavelengths (i.e. towards redder wavelengths).

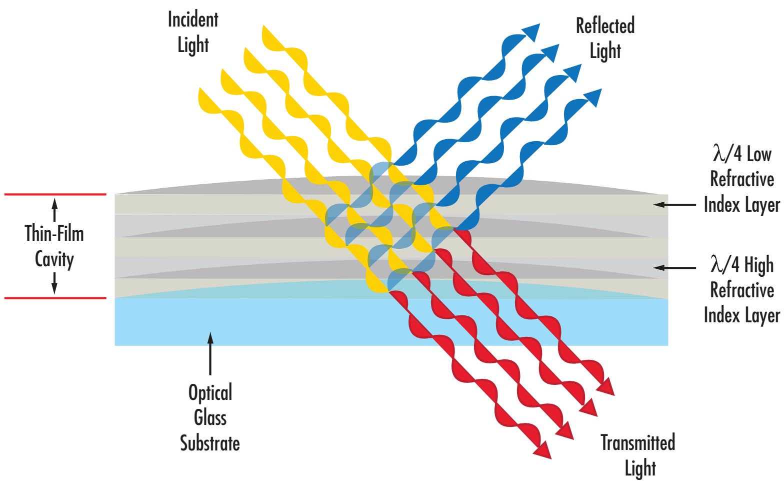


Figure 7: Deposition of Multiple Layers of Alternating High and Low Index Materials onto a Glass Substrate

EXPLORING DICHROIC BANDPASS FILTERS

Bandpass filters are used in a wide range of industries and can be either dichroic or color substrate. Dichroic bandpass filters are manufactured by two different techniques: traditional and hard sputtered, or hard coated. Both techniques achieve their unique transmission and reflection properties by a deposition of numerous layers of alternating high and low index of fraction materials onto glass substrates. In fact, depending upon the application, there can be more than 100 layers of material deposited per face of a given substrate.

The difference between traditional-coated filters and hard-sputtered filters is the number of substrate layers. In traditional-coated bandpass filters, layers of varying index materials are deposited onto multiple substrates which are then sandwiched together. For example, imagine the illustration in Figure 7 repeated up to and even more than 100 times. This technique leads to a thick filter with reduced transmission. This reduction in transmission is caused by incident light traveling through and being absorbed and/or reflected by numerous substrate layers. Conversely, in hard-sputtered bandpass filters, materials of varying indices are deposited onto only a single substrate (Figure 8). This technique leads to thin filters with high transmission.

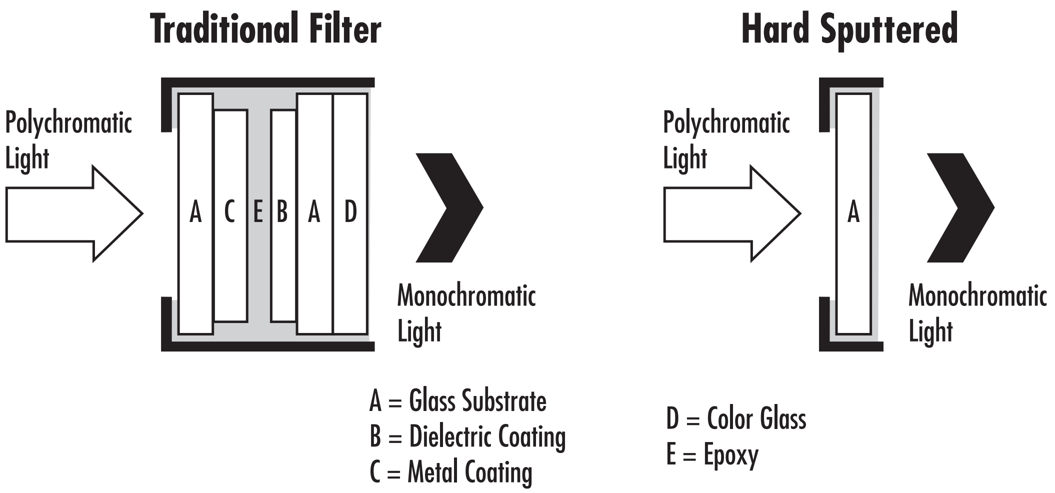
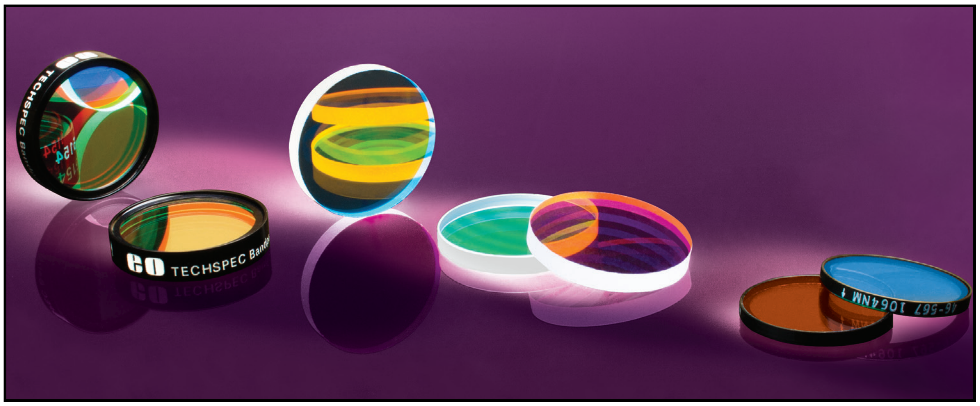


Figure 8: Traditional Filter (Left) and Hard-Sputtered Filter (Right)

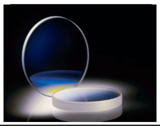
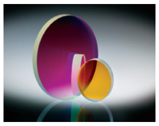
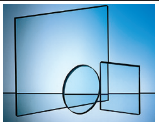
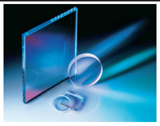
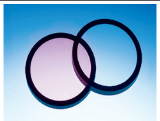
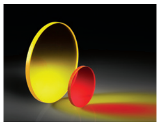
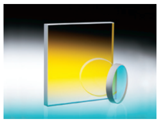
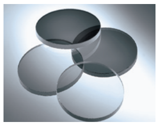
TYPES OF OPTICAL FILTERS

To aid in understanding the similarities and differences between the large variety of optical filters available today, consider ten of the most popular types. The following selection guide contains a brief description, as well as sample product images and performance curves for easy comparison.



Continue

TYPES OF OPTICAL FILTERS

Optical Filter Selection Guide	
Sample Image	Optical Filter Type
	**Bandpass Filters** Bandoass filters have extremely narrow band (<2nm to 10nm) or broadband (50nm and 80nm) transmittance across the substrate. They are particularly angle sensitive, so care should be taken when mounting and placing them within an optical setup. Hard sputtered filters should be chosen to maximize the transmission of selected wavelengths.
	**Longpass Filters** Longpass filters transmit all wavelengths longer than the specified cut on wavelength. Longpass filters include cold mirrors, colored glass filters, and Thermoset ADS (optical cast plastic) filters.
	**Shortpass Filters** Shortpass filters transmit all wavelengths shorter than the specified cut off wavelength. Shortpass filters include IR cutoff filters, hot mirrors, and head absorbing glass.
	**Heat Absorbing Glasses** Heat absorbing glasses will transmit visable light and absorb infrared radiation. The absorbed energy is then dissipates as heat into the air around the glass. Forced air cooling is typically recommended to remove teh excess head. Heat absorbing glass can also be used as shortpass filters.
	**Cold Mirrors** Cold mirrors are specific types of dichroic filters designed to have high reflectivity in the visible spectrum while maintaining high transmission in the infrared. Cold mirrors are designed for use in any application where heat build-up can cause damage or adverse effects.
	**Hot Mirrors** Hot mirrors are specific types of dichroic filters designed to have high reflectivity in the infrared spectrum and high transmission in the visable. Hot mirrors are used primarily in projection and illumination systems.
	**Notch Filters** Notch filters are designed to block a pre-selected bandwidth while transmitting all other wavelengths withiing the design range of the filter. Notch filters are used to remove a single laser wavelength, or narrow band, from an optical system.
	**Color Substrate Filters** Color substrate filters are manufactured from substrated with inherently different absorption and transmission properties across a specific spectral region. Color substrate filters are often used as longpass and bandpass filters. The boundry between transmission and blocking is less sharp compared to some coating based filters.
	**Dichroic Filters** Dichroic filters are coated with thin-films to achieve a desired transmission and reflection percentage across a given spectrum. They are often used as color filters (both additive and subtractive). Dichroic filters are slightly angle sensitive but are much moreforgiving than intereference filters.
	**Neutral Density (ND) Filters** Neutral density (ND) filters are designed to reduce transmission evenly across a portion of a certain spectrum, ultraviolet and visible, visable, or infrared. There are two types of ND filters: absorptive and reflective. The absorptive type absorbs light that is not transmitted through the filter, while the reflective type reflects it back toward the direction from which it was incident. Special care should be taken when using the former type in order too ensure that any reflected light does not interefere with the appplication setup. ND Filters are often used to prevent blooming or overexposure of cameras and other detectors.

2950 Unique Filters!

www.edmundoptics.com/filters

EXAMPLE 1: COLOR MATCH IMAGING

Monochrome cameras cannot inherently differentiate different colors. However, the addition of a color filter greatly increases the contrast between objects. A good rule of thumb is that a given color filter will lighten objects of the same color, while darkening objects of opposing colors. Consider an example where two red and two green pills are imaged with a monochrome camera. Figures 9a - 9d show actual images of a sample under inspection and various images using color filters. It is clear to see that with no filter (Figure 9b), the monochrome camera cannot distinguish between red and green. It would be impossible to inspect these pills on a factory floor. On the other hand, when a red filter is used (Figure 9c), objects of its opposing color (i.e. the green pills) appear gray due to increased image contrast and can be easily discerned from the red pills. Conversely, when a green filter is used (Figure 9d), the red pills appear gray.

SAMPLE UNDER INSPECTION

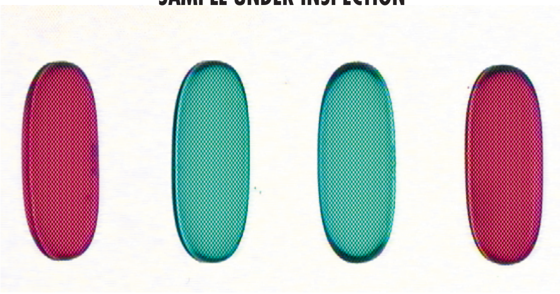


Figure 9a: Contrast Enhancement: Sample under Inspection

NO FIILTER

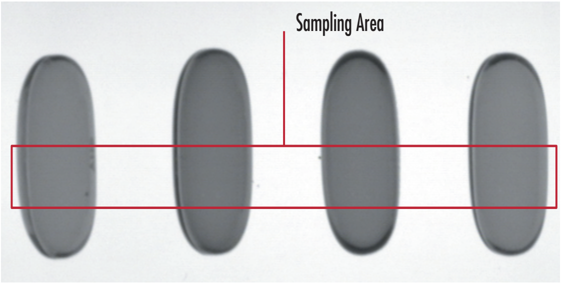


Figure 9b: Contrast Enhancement: No Filter

RED FILTER

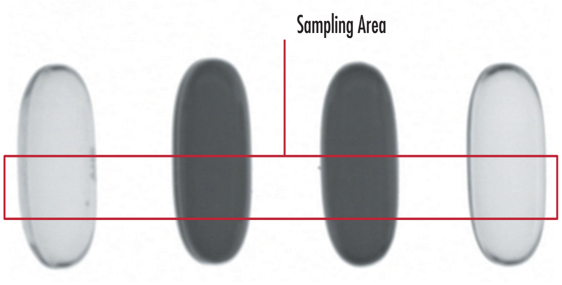


Figure 9c: Contrast Enhancement: Red Filter

GREEN FILTER

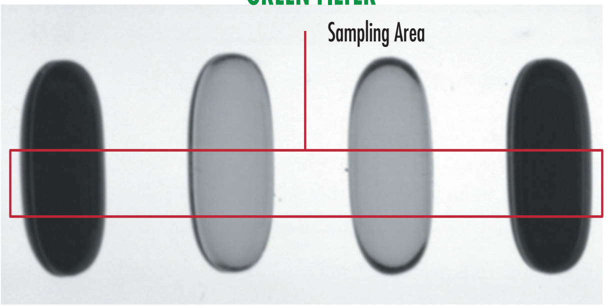
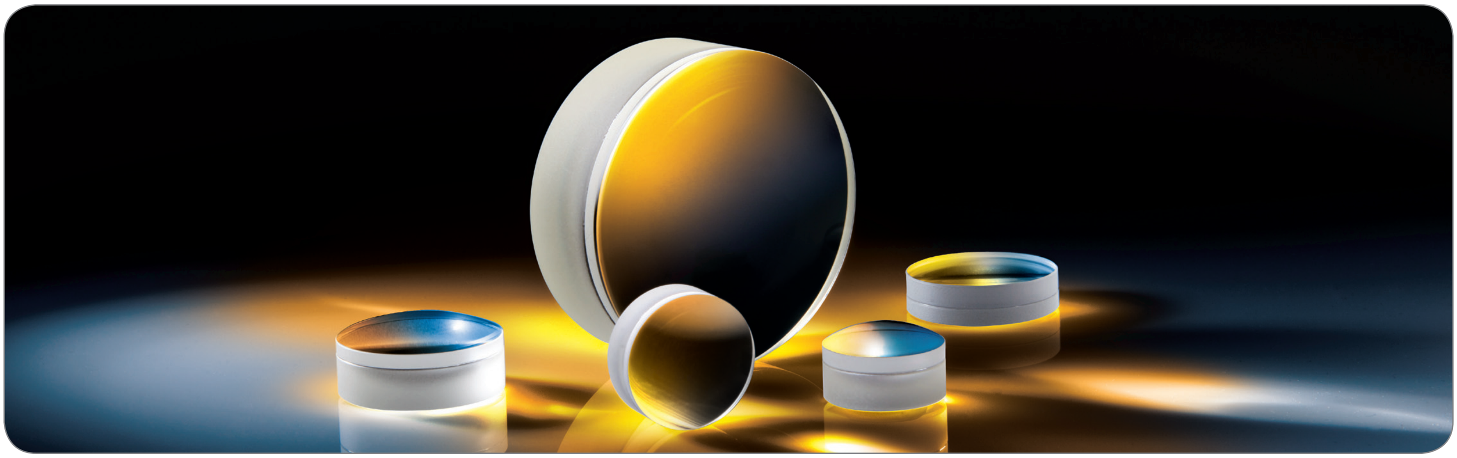


Figure 9d: Contrast Enhancement: Green Filter

Continue

WHY USE AN ACHROMATIC LENS?



An achromatic lens, also referred to as an achromat, typically consists of two optical components cemented together, usually a positive low-index (crown) element and a negative high-index (flint) element. In comparison to a singlet lens, or singlet for short, which only consists of a single piece of glass, the additional design freedom provided by using a doublet design allows for further optimization of performance. Therefore, an achromatic lens will have noticeable advantages over a comparable diameter and focal length singlet.

An achromatic lens comes in a variety of configurations, most notably, positive, negative, triplet, and aspherized. It is important to note that it can be a doublet (two elements) or triplet (three elements); the number of elements is not related to the number of rays for which it corrects. In other words, an achromatic lens corrects for red and blue, independent of it being a doublet or triplet configuration. Refer to Figures 1 — 4 for illustrations of each type.

Legend for Configurations	
Dia.	Diameter
R	Radius of Curvature
ET	Edge Thickness
EFL	Effective Focal Length
CT	Center Thickness
P	Principle Point
BFL	Back Focal Length

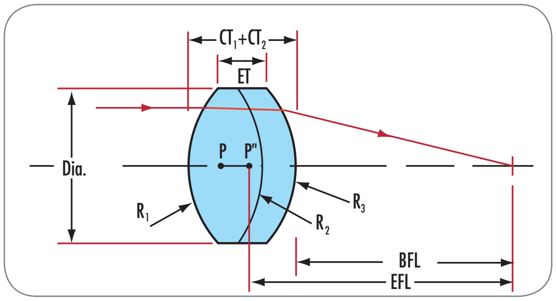


Figure 1: Positive

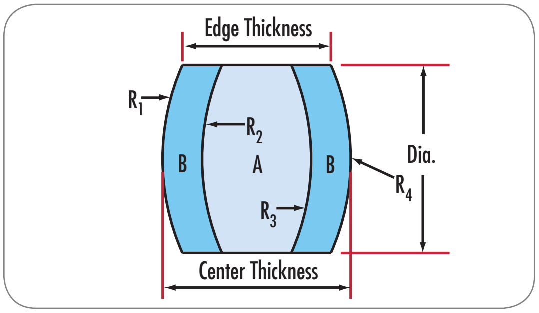


Figure 3:Triplet

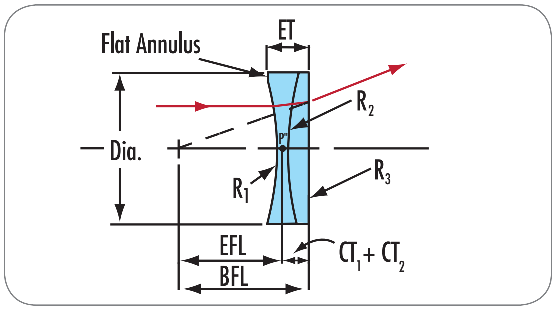


Figure 2: Negative

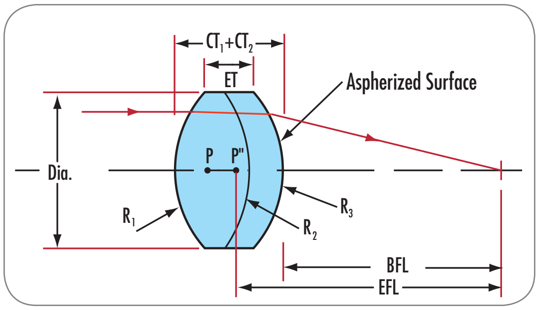


Figure 4: Aspherized

Continue

EXPLORING AN ASPHERIZED ACHROMATIC LENS

A new technology linking the superior image quality of an aspheric lens with the precision color correction in an achromatic lens is here. An aspherized achromatic lens is cost-effective featuring excellent correction for both chromatic and spherical aberrations, creating an economical way to meet the stringent imaging demands of today's optical and visual systems. Relays, condensing systems, high numerical aperture imaging systems, and beam expanders are a few examples of lens designs that could improve with the aid of an aspherized achromatic lens. Figures 5 and 6 compare an achromatic lens to an aspherized achromatic lens. Figure 5 shows a modulation transfer function (MTF) and transverse ray fan aberration plot for #45-209 12.5mm Diameter 14mm Focal Length TECHSPEC® Achromatic Lens, whereas Figure 6 shows the same for #49-658 12.5mm Diameter 14mm Focal Length TECHSPEC® Aspherized Achromatic Lens. It is easy to see that resolution performance is much better in the aspherized achromatic design.

An aspherized achromatic lens is composed of glass optical lens elements bonded with a photosensitive polymer. The polymer is applied only on one face of the doublet and is easy to replicate in a short amount of time while providing the flexibility associated with typical multi-element components. Unlike a glass element however, an aspherized achromatic lens has a smaller operating temperature range, -20°C to 80°C. This temperature range also limits the possibility of Anti-Reflection (AR) Coatings on the aspherized achromat surface. The aspherized achromatic lens material blocks Deep-UV (DUV) transmission, making it unsuitable for some applications. Though not scratch resistant, the lens is cost-effective and simple to replace. The benefits of the technology remain substantial. Figure 7 overviews the manufacturing process.

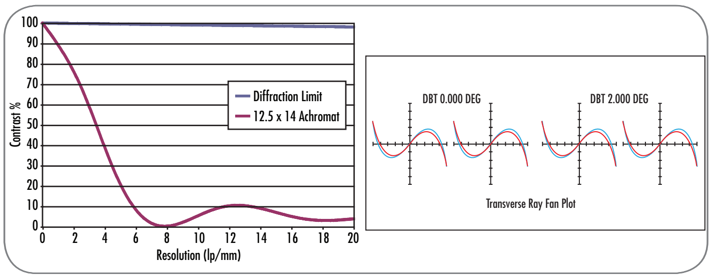


Figure 5: MTF and Transverse Ray Fan Aberration Plots for Achromatic Lens

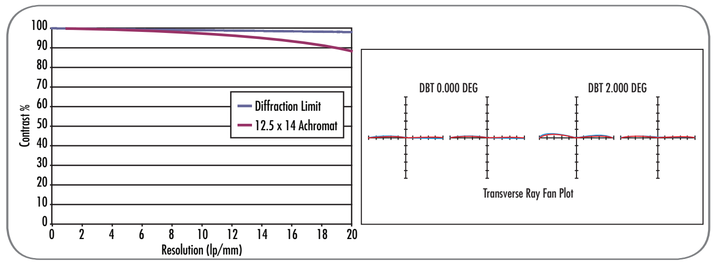


Figure 6: MTF and Transverse Ray Fan Aberration Plots for Aspherized Achromatic Lens

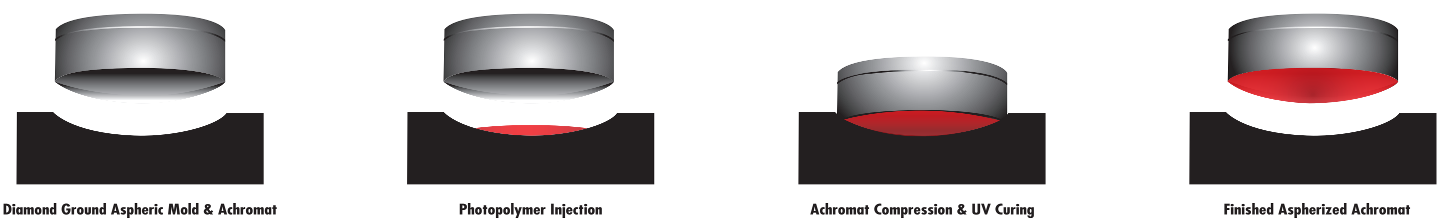


Figure 7: Aspherized Achromatic Lens Manufacturing

IMPROVED POLYCHROMATIC IMAGING

At the critical angle, the angle of refraction is equal to 90°. Referencing Figure 3, notice that TIR occurs only if θ exceeds the critical angle. If the angle is below the critical angle, then transmission will occur along with reflection as given by Snell's Law. If a prism face does not meet TIR specifications for the desired angle(s), then a reflective coating must be used. This is why some applications require coated versions of a prism that would otherwise work well uncoated in another application.

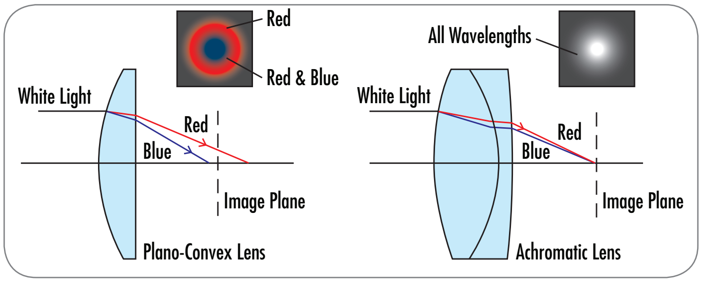


Figure 8: Polychromatic Imaging using a Plano-Convex Lens versus an Achromatic Lens

CORRECTION OF SPHERICAL ABERRATION AND ON-AXIS COMA

Freedom from spherical aberration and coma implies better on-axis performance at larger apertures. Unlike a simple lens, an achromatic lens provides consistently smaller spot sizes and superior images without decreasing the clear aperture. Figure 9 shows how an achromatic lens corrects for longitudinal color and spherical aberration for an axial object; Figure 10 a double-convex lens breaking up white light similar to a prism, blue rays focus closer than red; Figure 11 how a double-convex lens is spherically under-corrected. Spherical Aberration (SA) varies with f/# and is less for a small aperture.

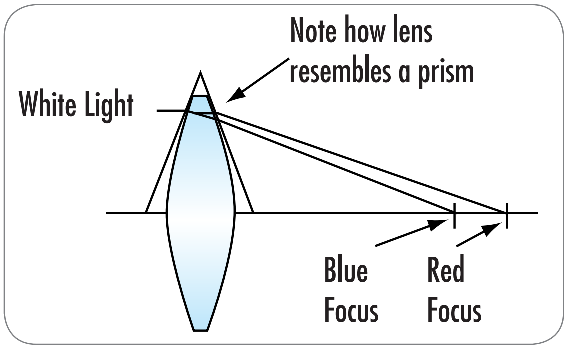


Figure 10: Spherical Aberration

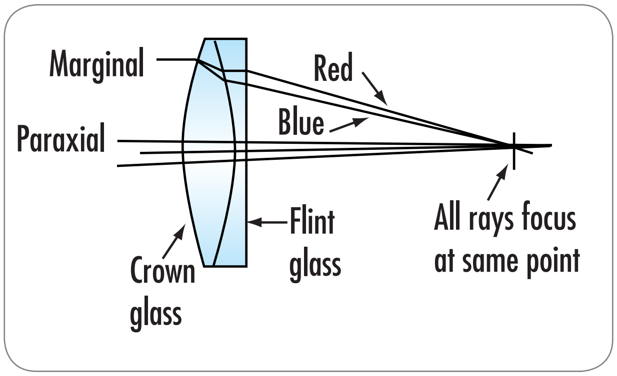


Figure 9: Achromatic Lens

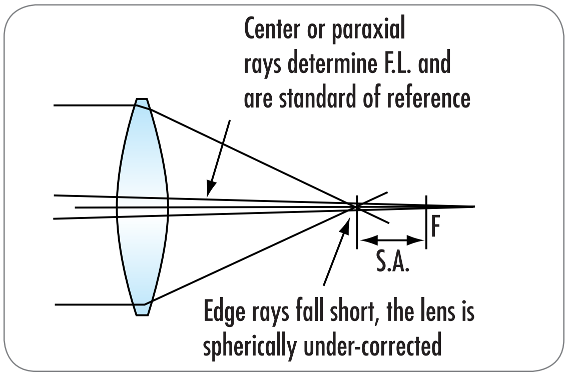
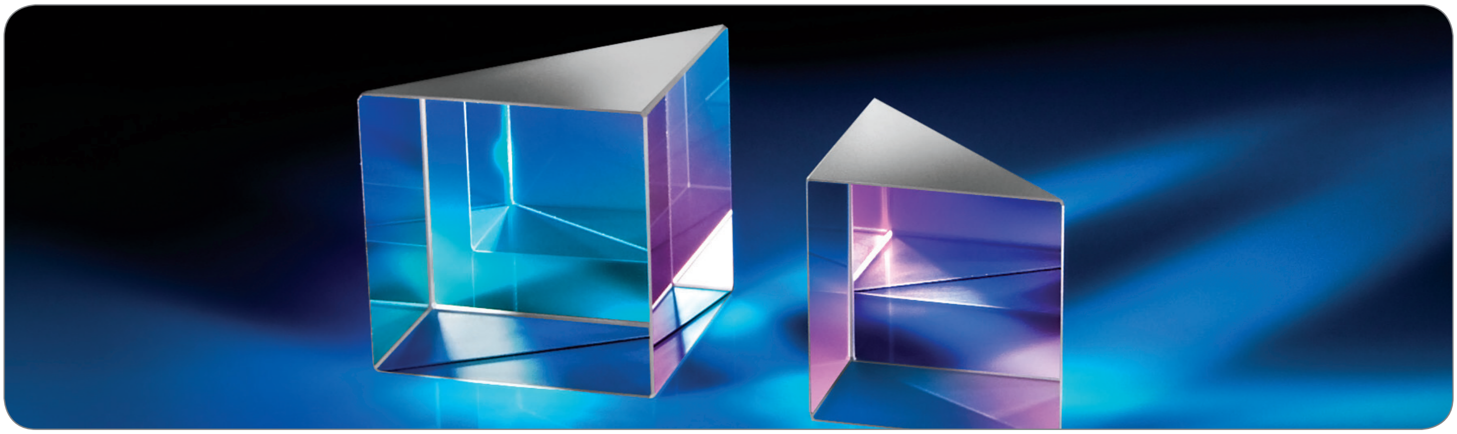


Figure 10: Longitudinal Color

BRIGHTER IMAGES AND BETTER ENERGY THROUGHPUT

Because on-axis performance of an achromatic lens will not deteriorate with larger clear apertures, "stopping down" the optical system becomes unnecessary. "Stopping down" the aperture refers to reducing its size, for example via a pinhole or iris diaphragm, in order to improve overall performance. With the entire clear aperture utilized, an achromatic lens and achromatic lens systems are faster, more efficient, and more powerful than equivalent systems using singlet lenses.

INTRODUCTION TO PRISMS



Prisms are solid glass optics that are ground and polished into geometrical and optically significant shapes. The angle, position, and number of surfaces help define the type and function. One of the most recognizable uses of prisms, as demonstrated by Sir Isaac Newton, consists of dispersing a beam of white light into its component colors (Figure 1). This application is utilized by refractometer and spectrographic components. Since this initial discovery, prisms have been used in "bending" light within a system, "folding" the system into a smaller space, changing the orientation (also known as handedness or parity) of an image, as well as combining or splitting optical beams with partial reflecting surfaces. These uses are common in applications with telescopes, binoculars, surveying equipment, and a host of others.

A notable characteristic of prisms is their ability to be modeled as a system of plane mirrors in order to simulate the reflection of light within the prism medium. Replacing mirror assemblies is perhaps the most useful application of prisms, since they both bend or fold light and change image parity. Often, multiple mirrors are needed to achieve results similar to a single prism. Therefore, the substitution of one prism in lieu of several mirrors reduces potential alignment errors, increasing accuracy and minimizing the size and complexity of a system.

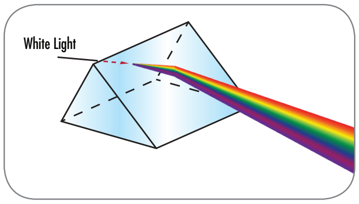


Figure 1:
Dispersion through a Prism

PRISM MANUFACTURING

Before delving into the theory behind prisms, consider their manufacturing process. In order to be used successfully in most applications, prisms must be manufactured with very strict tolerances and accuracies. Due to the variability in shape, size, and, most importantly, the number of surfaces, a large-scale automated process for prism manufacturing is quite infeasible. In addition, most high precision prisms tend to be made in low quantities, meaning an automated process would be unnecessary.

First, a block of glass (known as a "blank") of a specified grade and glass type is obtained. This block is then ground, or generated, by a metal diamond bonded wheel into a near-finished product. A majority of the glass is removed quickly in this stage resulting in flat, but still coarse surfaces (Figure 2a). At this point, the dimensions of the prism-to-be are very close to the desired specifications. Next is a fine grinding process that removes subsurface breaks from the surface; this stage is known as smoothening.

Scratches left from the first stage are removed in the second stage (Figure 2b). After smoothening, the glass surfaces should appear cloudy and opaque. In both the first two stages, the prism surface must be wet in order to expedite glass removal and prevent overheating of the glass itself.

Continue

The third stage involves polishing the prism to the correctly specified surface accuracy. In this stage, the glass is rubbed against a polyurethane polisher wet with "slurry," an optical polishing compound typically comprised of water mixed with pumice or cerium oxide (Figure 2c). The exact duration of the polishing stage is highly dependent on the surface specifications required. Once polishing is completed, chamfering can begin. In this fourth stage, the edges of the prism are subjected to a spinning diamond plate in order to slightly dull the sharp edges it obtains throughout the aforementioned steps (Figure 2d). After chamfering, the finished prism is cleaned, inspected (via both manual and automated means), and coated with anti-reflection (AR) and/or metallic mirror coatings, if necessary, to further aid in overall transmission and/or reflection. Though the process is much more involved and may require more iterations or operations due to the number of surfaces on a prism, the Generating, Smoothening, Polishing and Chamfering Stages are roughly outlined in Figures 2a - 2d.

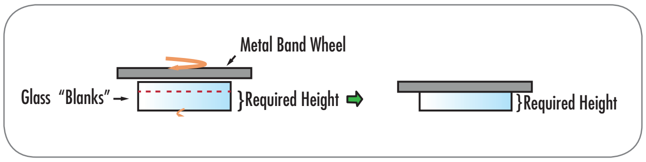


Figure 2a:
Prism Manufacturing Process:
Generating Stage

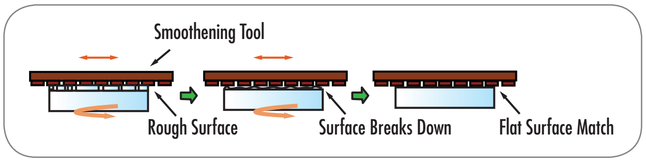


Figure 2b:
Prism Manufacturing Process:
Smoothening Stage

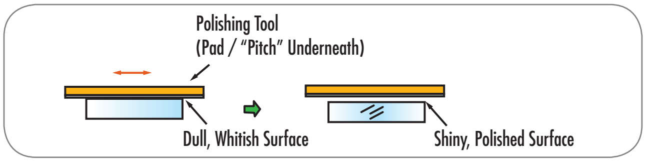


Figure 2c:
Prism Manufacturing Process:
Polishing Stage

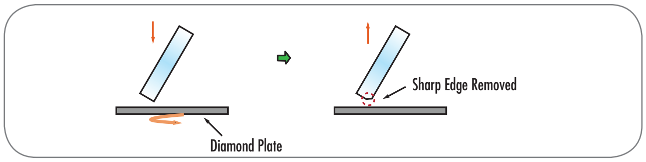


Figure 2d:
Prism Manufacturing Process:
Chamfering Stage

Throughout the manufacturing of a prism, it is necessary to continually adjust and secure each surface being worked on. Securing a prism in place involves one of two methods: blocking and contacting. Blocking entails arranging the prism in a metal tool with hot wax. Contacting, on the other hand, is an optical bonding process done at room temperature where two clean glass surfaces are fastened together simply through their Van Der Waals interaction. Contacting is utilized if high precision tolerances are required because it does not require additional adjustments to be made during the Generating, Smoothening, or Polishing Stages to account for the wax thickness between the prism surface and the contact block.

During every stage of the prism manufacturing process, from generating to blocking and contacting, a skilled optician is required to manually inspect and adjust the prism surfaces being worked on. As a result, it is extremely labor intensive and requires experience and skill in order to complete. The entire process often requires a significant amount of time, work, and concentration.

Continue

THEORY: LIGHT AND REFRACTION

Understanding how a prism works is key to deciding which type of prism fits best for a specific application. In order to do so, it is important to first understand how light interacts with an optical surface. This interaction is described by Snell's Law of Refraction:

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

Where n_1 is the index of the incident medium, θ_1 is the angle of the incident ray, n_2 is the index of the refracted/reflected medium, and θ_2 is the angle of the refracted/reflected ray. Snell's Law describes the relationship between the angles of incidence and transmission when a ray travels between multiple media (Figure 3).

A prism is notable for its ability to reflect the ray path without the need for a special coating, such as that required when using a mirror. This is achieved through a phenomenon known as total internal reflection (TIR). TIR occurs when the incident angle (angle of the incident ray measured from normal) is higher than the critical angle θ_c:

$$\sin(\theta_c) = \frac{n_1}{n_2}$$

Where n_1 is the index of refraction for the medium where the ray originates, and n_2 is the index of refraction for the medium where the ray exits. It is important to note that TIR only occurs when light travels from a high index medium to a low index medium.

At the critical angle, the angle of refraction is equal to 90°. Referencing Figure 3, notice that TIR occurs only if θ exceeds the critical angle. If the angle is below the critical angle, then transmission will occur along with reflection as given by Snell's Law. If a prism face does not meet TIR specifications for the desired angle(s), then a reflective coating must be used. This is why some applications require coated versions of a prism that would otherwise work well uncoated in another application.

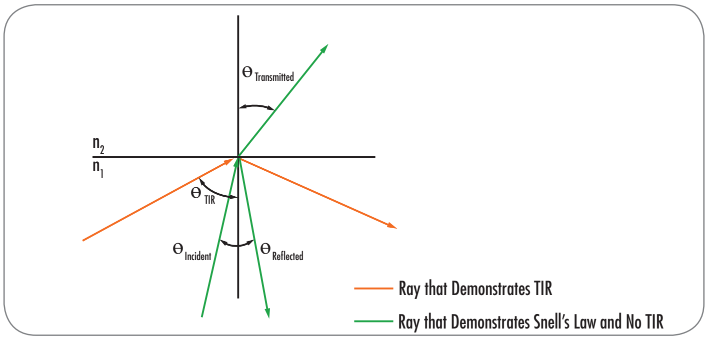


Figure 3: Snell's Law and Total Internal Reflection

THEORY: IMAGE HANDEDNESS/PARITY

A significant aspect of imaging through a prism is image handedness (parity), otherwise referred to as the orientation of the image. This is introduced every time the ray path hits a plane mirror, any flat reflective surface, or a prism surface at an angle that produces TIR. There are two types of handedness: right and left. Right handedness (Figure 4) describes the case where an image undergoes an even number of reflections, resulting in the ability to read it clearly (assuming the image is text) in at least one position. Left handedness (Figure 5) describes the case where the image undergoes an odd number of reflections, leading to an irregularity in the position of the image that is comparable to what one sees in a mirror.

In addition to parity, there are three types of image change (Figure 6). An inversion is an image-flip over a horizontal axis, whereas a reversion is an image-flip over a vertical axis. When both are done at the same time, an image rotation of 180° occurs and there is no change in parity. Another way to think of parity is defining it as being determined by looking back against the propagation direction towards either the object or image in its optical space (Figure 7).

Figure 4: Right Handedness or Even Parity

Figure 5: Left Handedness or Odd Parity

THEORY: IMAGE HANDEDNESS/PARITY (CONT.)

When using a prism, consider the following four points:

1. Image Handedness Changes Every Time an Image is Reflected.
2. Any Point along the Plane of the Reflecting Surface is Equidistant from the Object and Its Image.
3. Snell's Law Can Be Applied to All Surfaces.
4. When Testing for Image Handedness/Parity, It is Best to Use a Non-Symmetrical Letter Such as R, F, or Q. Avoid Using Letters Like X, O, A, etc.

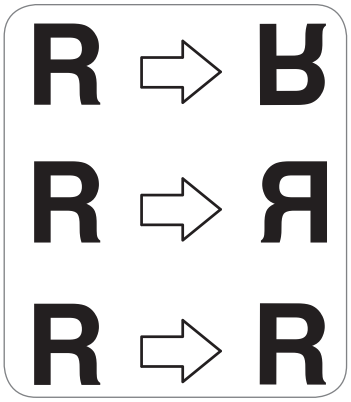


Figure 6: Inversion (Top), Reversion (Middle), Rotation (Bottom)

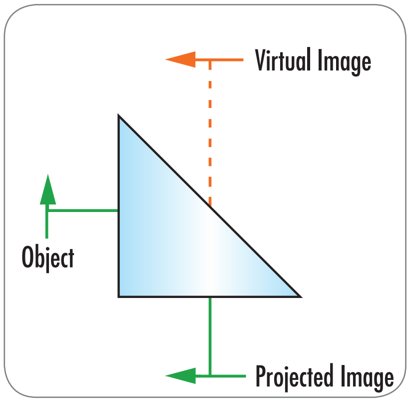


Figure 7: How Parity is Determined

TYPES OF PRISMS

There are four main types of prisms: dispersion prisms, deviation, or reflection prisms, rotation prisms, and displacement prisms. Deviation, displacement, and rotation prisms are common in imaging applications; dispersion prisms are strictly made for dispersing light, therefore not suitable for any application requiring quality images.

Dispersion Prisms

Prism dispersion is dependent upon the geometry of the prism and its index dispersion curve, based on the wavelength and index of refraction of the prism substrate. The angle of minimum deviation dictates the smallest angle between the incident ray and the transmitted rays (Figure 8). The green wavelength of light is deviated more than red, and blue more than both red and green; red is commonly defined as 656.3nm, green as 587.6nm, and blue as 486.1nm.

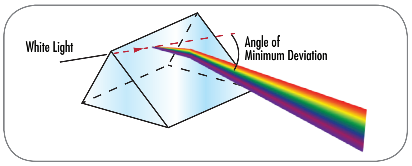


Figure 8: Dispersion through a Prism

Deviation, Rotation, and Displacement Prisms

Prisms that deviate the ray path, rotate the image, or simply displace the image from its original axis are helpful in many imaging systems. Ray deviations are usually done at angles of 45°, 60°, 90°, and 180°. This helps to condense system size or adjust the ray path without affecting the rest of the system setup. Rotation prisms, such as dove prisms, are used to rotate an image after it is inverted. Displacement prisms maintain the direction of the ray path, yet adjust its relation to the normal.

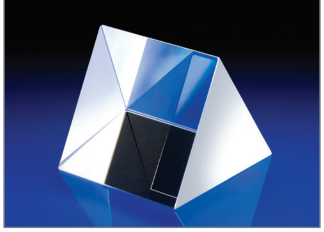
Prism Selection Guide

To aid in selecting the best prisms for specific applications, consider the following selection guide of the most commonly used in the optics, imaging, and photonics industries.

Continue

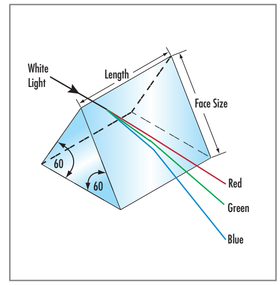
PRISM SELECTION GUIDE

Equilateral Prisms



Function
- Disperse White Light into Its Component Colors

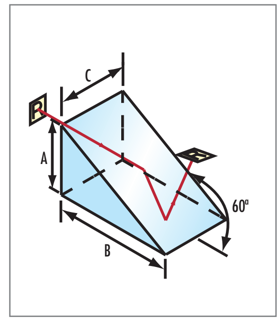
Application
- Spectroscopy
- Telecommunications
- Wavelength Separation



Littrow Prisms

Function
- Uncoated: Disperse White Light into Its Component Colors
- Coated: Deviate the Ray Path by 60°
- Image is Right-Handed

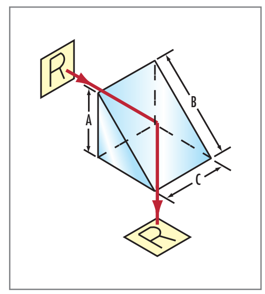
Application
- Spectroscopy (Uncoated)
- Multi-Spectral Laser System Tuning (Coated)



Right Angle Prisms

Function
- Deviate the Ray Path by 90°
- Image is Left-Handed
- Used in Combination for Image/Beam Displacement

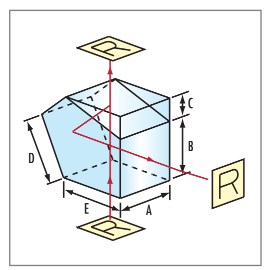
Application
- Spectroscopy (Uncoated)
- Multi-Spectral Laser System Tuning (Coated)



Penta Prisms

Function
- Deviate the Ray Path by 90°
- Image is Right-Handed

Application
- Visual Targeting
- Projection
- Measurement
- Display Systems

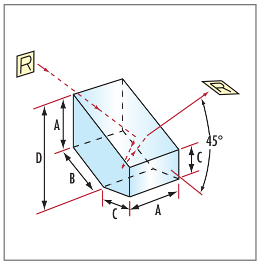


PRISM SELECTION GUIDE

Half-Penta Prisms

Function
- Deviate the Ray Path by 45°
- Image is Right-Handed

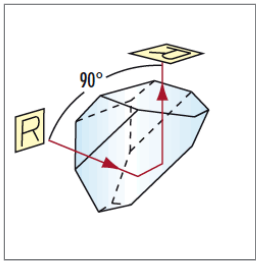
Application
- Pechan Erector Assemblies



Amici Roof Prisms

Function
- Deviate the Ray Path by 90°
- Image is Right-Handed

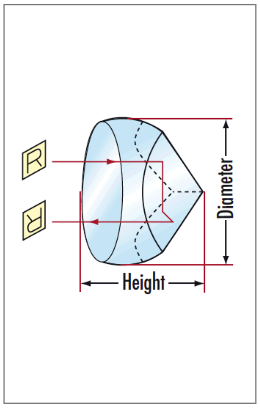
Application
- Microscopes
- Telescope Eyepieces



Retroreflectors

Function
- Deviate the Ray Path by 180°
- Image is Left-Handed
- Reflects Any Beam Entering the Prism Face, Regardless of the Orientation of the Prism, Back onto Itself

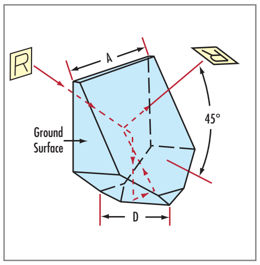
Application
- Interferometry
- Laser Tracking
- Boresighting
- Precision Alignment
- Rangefinding



Schmidt Prisms

Function
- Deviate the Ray Path by 45°
- Image is Right-Handed

Application
- Stereo Microscopes
- Pechan Erector Assemblies

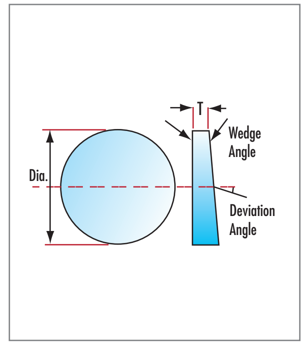


PRISM SELECTION GUIDE

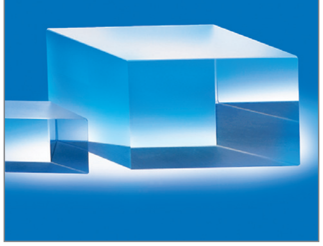
Wedge Prisms

Function
- Used Individually to Deviate a Laser Beam a Set Angle
- Combine Two to Create An Anamorphic Pair for Beam Shaping

Application
- Beam Steering
- Tunable Lasers
- Anamorphic Imaging
- Forestry

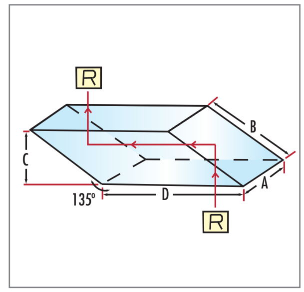


Rhomboid Prisms



Function
- Displace Optical Axis without Changing Handedness
- Direction Remains the Same (No Ray Deviation Occurs)

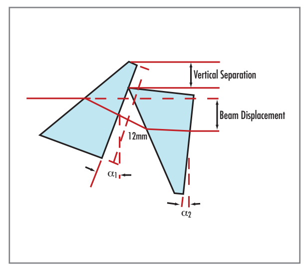
Application
- Binoculars
- Rangefinders
- Laser Instrumentation



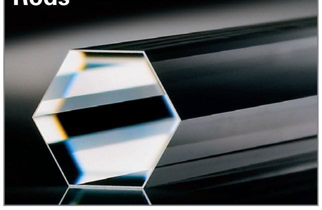
Anamorphic Prism Pairs

Function
- Expand Incident Beam Diameter in One Dimension
- Ideal for Making Elliptical Beams Circular

Application
- Laser Diode Beam Expanders
- HD Imaging Lenses

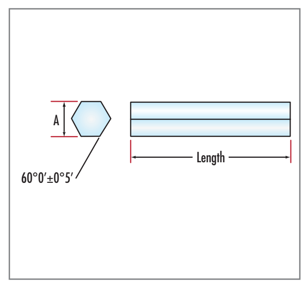


Light Pipe Homogenizing Rods

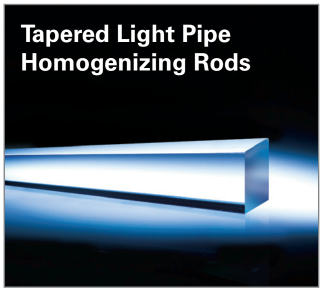


Function
- Homogenize Non-Uniform Light Sources

Application
- LED Illuminators
- Micro-Projectors
- Laser Speckle Reducers
- OEM Illumination

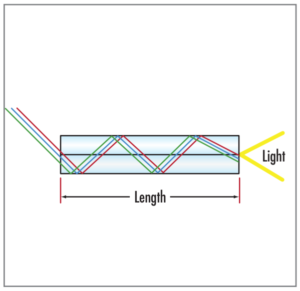


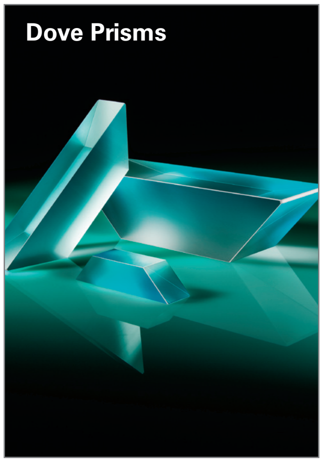
PRISM SELECTION GUIDE



Function
- Homogenize Non-Uniform Light Sources While Reducing Output Numerical Aperture (NA)

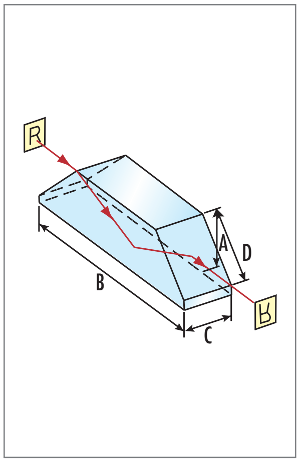
Application
- Projectors
- Micro-Display Relay Systems

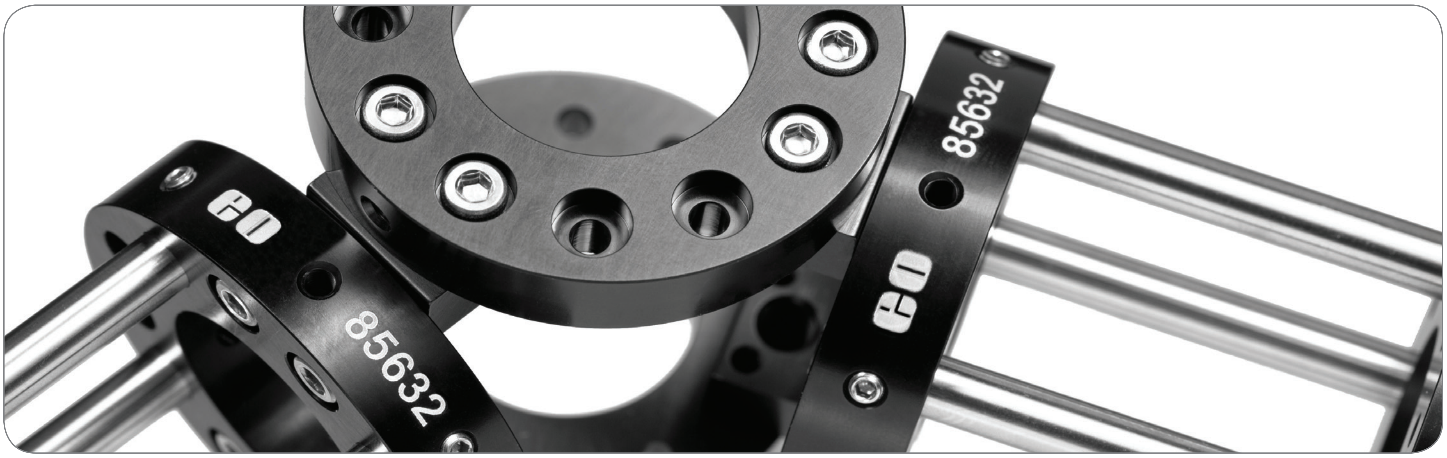




Function
- Uncoated: Rotate an Image by Twice the Prism Rotation Angle
- Uncoated: Image is Left-Handed
- Coated: Reflect Any Beam Entering the Prism Face Back onto Itself
- Coated: Image is Right-Handed

Application
- Interferometry
- Astronomy
- Pattern Recognition
- Imaging Behind Detectors or Around Corners





Designed for modularity and flexibility, optical cage systems are high precision alternatives to complex optical alignment systems. These systems are constructed of rods and plates, allowing the user to continuously modify the system's design by adding additional components, such as optical mounts and angular brackets.

For an introduction to what can be done with optical cage systems, consider eight unique design examples. Each design can be applied toward larger systems, and provide familiarity to the cage system. For example, Figure 1 illustrates a sample system comprised of four stock numbers: #85-632 25mm Standard Cage Plate, #85-664 Cage Plate Angle Bracket, #85-488 6mm Diameter x 100mm Length Cage Support Rod, and #85-543 25mm Cage 20mm Diameter Lens Mount. Note: These stock numbers are only one sample setup; components can be replaced with those of different sizes.

Figure 1: Sample Optical Cage System Components with #85-632, #85-664, #85-488, and #85-543

OPTICAL CAGE SYSTEM DESIGN EXAMPLES INCLUDE

- **Cube**
- **Angle Bracket Joints**
- **Skeletal Rails**
- **Swivel Joint**
- **Bent Elbow Telescope**
- **Spectroscope**
- **Interchangeable Optical Mount**
- **Retaining Ring Pair**

DESIGN EXAMPLE 1: OPTICAL CAGE SYSTEM CUBE

The optical cage system cube is a fundamental design that enables the addition or intersection of beam paths, or bends the system in 90°. While a TECHSPEC® Cage System Sphere is superior in rigidity, the cube system offers increased flexibility, and can be designed using Cage System Plates and Cage System Plate Angle Brackets. By using plates of different inner diameters, the cube system can be customized to best fit the application. For example, Figure 2 shows a cube system consisting of six #85-632 25mm Standard Cage Plates and eight #85-664 Cage Plate Angle Brackets. Note: Do not tighten adjustment screws fully until all cage system components are attached.

Figure 2: Optical Cage System Cube

Continue

DESIGN EXAMPLE 2: OPTICAL CAGE SYSTEM ANGLE BRACKET JOINTS

Similar to the build of the cube system in Design Example 1, it is possible to create joints angled at 30°, 60°, and 90°. Due to their diverse use in many setups, angle brackets are crucial components in a variety of cage system setups. All 30°, 60°, and 90° angles can be created with two Cage System Plates (such as #85-632), two #85-617 25mm Fixed Angle Mounting Plates, and four #85-664 Cage Plate Angle Brackets.

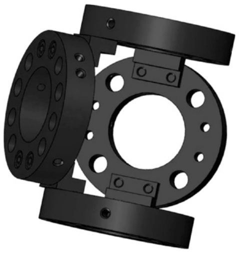


Figure 3: Optical Cage System Angle Bracket Joints

DESIGN EXAMPLE 3: OPTICAL CAGE SYSTEM SKELETAL RAILS

Building from Design Example 2, skeletal rails can be added to connect the cube system or angle bracket joints. When joining numerous joints and components together, use TECHSPEC® 6mm Cage System Support Rods to hold the optical axis in place. A cage system can be built with either two or four rods. A four rod system adds additional stability for long systems, while two rods simplify assembly and allow easy access to the optical components within the cage.

When connecting 6mm Cage System Support Rods to Cage System Plates, it is best to lay each plate on a flat surface such as a laboratory table and connect each support rod into the appropriate sized holes. Then, use a set screw to secure the support rods in place.

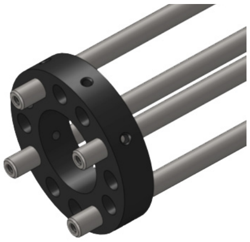


Figure 4: Illustration of Optical Cage System Plate with Four 6mm Support Rods

DESIGN EXAMPLE 4: OPTICAL CAGE SYSTEM SWIVEL JOINT

TECHSPEC® Cage System Angle Adjustment Plates are used to construct fixed 30°, 60°, and 90° bends in a cage system's optical path. For applications requiring customized angular positions, swivel joints are an ideal alternative to angle adjustment plates. For example, a pair of #85-670 Swivel Adapter Plates can be used with a single #85-692 Post Mount Adapter to enable 180° of continuous angular adjustment. Each swivel adapter plate features three M3 set screws which allow the angle to be locked into place. For this design example, the swivel joint consists of two #85-632 Cage System Plates, four #85-670 Swivel Adapter Plates, two #85-692 Post Mount Adapters, eight #85-488 6mm Diameter x 100mm Length Support Rods, and two #85-664 Cage Plate Angle Brackets.

Figure 5: Optical Cage System Swivel Joint

DESIGN EXAMPLE 5: OPTICAL CAGE SYSTEM BENT ELBOW TELESCOPE

Optical cage system components can be used to build a bent elbow telescope. To construct this design example, first start with an angle bracket joint positioned at 90° (refer to Design Example 2 for construction details). The design also needs eight 6mm Cage System Support Rods (for this example #85-486; make sure the total optical path length matches the focal lengths necessary for the afocal system), two Cage System Plates, two #85-543 25mm Cage 20mm Diameter Lens Mount, one #85-696 45° Tip/Tilt Mount, lenses for the lens mount, and a mirror for the tip/tilt mount.

To construct the arms of the bent elbow telescope, attach four rods to two plates; the arms should create a 90° angle. At the end of one arm, mount a plate and secure it in place. Repeat the step for the other arm. Then, slide the lens mount, with lens mounted within, into the inner diameter of the mounting plate. Secure the lens in place with a set screw. Slide the tip/tilt mount into the inner diameter of one of the plates. Make sure the 45° tilt from the mirror mount faces the plate with the 6mm support rods arms. Once the mirror mount is in place, secure it by tightening the set screw.

Figure 6: Illustration of Optical Cage System Bent Elbow Telescope

DESIGN EXAMPLE 6: OPTICAL CAGE SYSTEM SPECTROSCOPE

Another practical use of an optical cage system is to build a spectroscope from the structure outlined in Design Example 4. In addition to a swivel joint, the spectroscope also needs two Cage System Optical Mounts (such as #85-543), one more lens mount to hold #58-544 100µm x 3mm Mounted Precision Air Slit (such as #85-543), and one prism.

To accurately see the spectra produced by the prism, secure the two lenses onto the arm. For a Keplerian-design spectroscope, keep in mind that the Cage System Plates are the focal length of lens 1 and 2 combined. Secure the plates into place along the rails by a set screw. Using a retaining ring, mount the lenses into the lens mounts. Then, connect the mounts in their respective plate inner diameter, and secure with set screws.

The second arm contains two Cage System Plates that are used to direct a light source through the prism. The outermost plate holds a fiber adapter piece that secures a fiber optic. The second plate holds a 100µm x 3mm Precision Air Slit, which uses a lens mount to secure the slit. This lens mount then slides into place and secures with a set screw. The swivel joint is ideal because the arm containing the spectroscope can be positioned at different angles, ensuring access to the prism's full spectrum without any clipping.

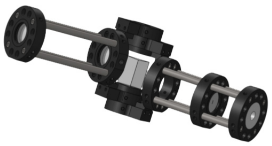


Figure 7: Illustration of Optical Cage System Spectroscope

DESIGN EXAMPLE 7: OPTICAL CAGE SYSTEM INTERCHANGEABLE OPTICAL MOUNT

Connecting #85-717 25mm Interchangeable Optic Mount with #85-641 30mm Side Access Mounting Plate simplifies adding or removing optical components within a cage system. The 60° cutout in the mounting plate enables the optic mount to easily slide in and out of place, avoiding disassembly and reassembly of the entire cage system. Use set screws to secure the mounting plate in the optic mount to create flexibility without loss of precision. This two-component assembly can be used with a variety of cage system setups.

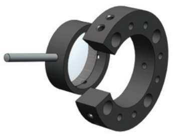


Figure 8: Illustration of Optical Cage System Interchangeable Optical Mount

DESIGN EXAMPLE 8: OPTICAL CAGE SYSTEM RETAINING RING PAIR

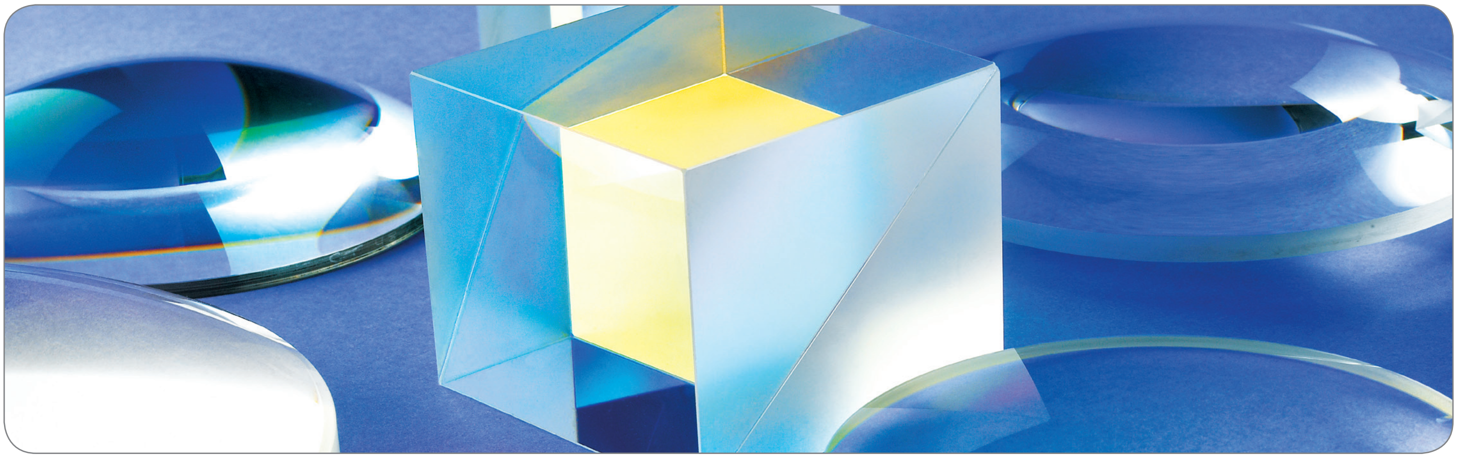
To mount an optical component such as a lens or filter into a Cage System Tube, use a pair of retaining rings. For example, use a tube with a 30mm outer diameter and length of 10mm (such as #85-589) as the outer tubing; then, match the retaining ring to the respective optic diameter. If the application uses a 25mm diameter optic, #85-597 retaining ring with a clear aperture of 23mm is the ideal choice.

To connect the components together, thread one retaining ring into the extension tube until the ring is in the desired position. Gently place the optic onto the retaining ring so that the face of the optic is in contact with the face of the retaining ring. Thread in the second retaining ring until it makes contact with the optic and holds it firmly in place. Note: To avoid damage to the optic, do not over tighten the retaining ring. Similar to Design Example 7, the Optical Cage System Retaining Ring Pair is a crucial component to a variety of cage system applications.

Figure 9: Illustration of Optical Cage System Retaining Ring Pair

The preceding eight design examples are just a few of the almost limitless number of structures that can be created with a TECHSPEC® Optical Cage System. No matter the application or complexity of setup, the cage system offers a wide range of components.

OPTICAL GLASS



OPTICAL GLASS SPECIFICATIONS

Selecting a glass material is important since different glass types have different characteristics. Edmund Optics® offers a wide variety of glass types which can be selected on the basis of the following characteristics.

The index of refraction and Abbe number of a glass are typically used by designers as degrees of freedom when designing systems. The index of refraction refers to the ratio of the speed of light in a vacuum to the speed of light through a given material at a given wavelength, while the Abbe number of a material quantifies the amount of dispersion (variations in index) for a specific spectral range. For instance, a higher index of refraction generally bends light more efficiently so there is less of a need of curvature in the lens. Spherical aberration is less present in lenses with higher indices of refraction, while light travels faster through materials with lower indices of refraction. A high Abbe number generally gives less color dispersion and reduces color aberration. Also, certain glass types have different transmission wavelength regions.

The density of a glass helps determine the weight of the optical assembly and, along with lens diameter, becomes critical for weight sensitive applications. Density also generally denotes the ability to work with the glass and is somewhat proportional to the cost of the material. When dealing with applications involving extreme temperatures and quick temperature differentials, a glass' coefficient of expansion becomes a key factor. Opto-mechanical designers need to keep this in mind when designing optical assemblies.

Many glass manufacturers offer the same material characteristics under different trade names and most have modified their products and processes to be ECO-friendly (free of lead and arsenic).

Continue

OPTICAL GLASS SPECIFICATIONS (CONT.)

Table 1: Essential Values for Many Types of Glass					
Glass Name	Index of Refraction (n_d)	Abbe Number (v_d)	Density (g/cm^3)	Coefficient of Linear Expansion*	Max Operating Temp (°C)
CaF_2	1.434	95.10	3.18	18.85	800
Fused Silica	1.458	67.70	2.20	0.55	1000
Schott BOROFLOAT™	1.472	65.70	2.20	3.25	450
Corning Pyrex 7740®	1.474†	65.40†	2.23	3.20	490
S-FSL5	1.487	70.20	2.46	9.00	457
N-BK7	1.517	64.20	2.46	7.10	557
N-K5	1.522	59.50	2.59	8.20	546
B270/S1	1.523	58.50	2.55	8.20	533
Schott Zerodur®	1.562	56.20	2.53	0.05	600
N-SK11	1.564	60.80	3.08	6.50	604
N-BaK4	1.569	56.10	3.10	7.00	555
N-BaK1	1.573	57.55	3.19	7.60	592
L-BAL35	1.589	61.15	2.82	6.60	489
N-SK14	1.603	60.60	3.44	7.30	649
N-SSK8	1.618	49.80	3.33	7.10	598
N-F2	1.620	36.40	3.61	8.20	432
BaSF1	1.626	38.96	3.66	8.50	493
N-SF2	1.648	33.90	3.86	8.40	441
N-Lak22	1.651	55.89	3.73	6.60	689
S-BaH11	1.667	48.30	3.76	6.80	575
N-BaF10	1.670	47.20	3.76	6.80	580
N-SF5	1.673	32.30	4.07	8.20	425
N-SF8	1.689	31.20	4.22	8.20	422
N-LaK14	1.697	55.41	3.63	5.50	661
N-SF15	1.699	30.20	2.92	8.04	580
N-BaSF64	1.704	39.38	3.20	9.28	582
N-LaK8	1.713	53.83	3.75	5.60	643
N-SF18	1.722	29.30	4.49	8.10	422
N-SF10	1.728	28.40	4.28	7.50	454
S-TIH13	1.741	27.80	3.10	8.30	573
N-SF14	1.762	26.50	4.54	6.60	478
Sapphire**	1.768	72.20	3.97	5.30	2000
N-SF11	1.785	25.80	5.41	6.20	503
N-SF56	1.785	26.10	3.28	8.70	592
N-LaSF44	1.803	46.40	4.46	6.20	666
N-SF6	1.805	25.39	3.37	9.00	605
N-SF57	1.847	23.80	5.51	8.30	414
N-LaSF9	1.850	32.20	4.44	7.40	698
N-SF66	1.923	20.88	4.00	5.90	710
S-LAH79	2.003	28.30	5.23	6.00	699
ZnSe	2.403	N/A	5.27	7.10	250
Silicon	3.422	N/A	2.33	2.55	1500
Germanium	4.003	N/A	5.33	6.10	100

*microns/m°C (-30 to 70°C)

**Sapphire is a birefringent material. All specifications correspond to parallel to C-Axis.

†Pyrex 7740® nd and vd specified at 589.3nm

OPTICAL GLASS PROPERTIES

Today, the quality and integrity of optical glass is a fundamental assumption made by optical designers. Until recently, however, that was not the case. Nearly 125 years ago, Otto Schott began a revolution by systematicallyresearching and developing glass compositions. His development work on composition and the production process took glass manufacturing from the realm of trial and error to its state today as a truly technical material. Now optical glass properties are predictable, reproducible and homogeneous - the essential prerequisites of a technical material. The fundamental properties that characterize optical glass are refractive index, dispersion, and transmission.

REFRACTIVE INDEX

Refractive Index is the ratio of the speed of light in a vacuum to the speed of light in the specified material - a description of how light slows down as it passes through an optical material. The refractive index for optical glasses, n_d, is specified at a wavelength of 587.6nm (Helium d-line). Materials with a low index of refraction are commonly referred to as “crowns” whereas materials with a high index of refraction are referred to as “flints.” Note: The typical index of refraction tolerance for optical components manufactured by Edmund Optics is ±0.0005.

DISPERSION

Dispersion is a description of the variation of the refractive index with wavelength. It is specified using the Abbe number, vd, defined as $(n_d - 1)/(n_F - n_C)$ where n_F and n_C are the refractive indices at 486.1nm (Hydrogen F-line) and 656.3nm (Hydrogen C-line). A low Abbe number indicates high dispersion. Crown glasses tend to have lower dispersion than flints. Note: The typical Abbe tolerance for optical components manufactured by Edmund Optics is ±0.8%.

TRANSMISSION

Standard optical glasses offer high transmission throughout the entire visible spectrum and beyond in the near ultraviolet and near infrared ranges (Figure 1). Crown glasses tend to have better transmission in the NUV than do flint glasses. Flint glasses, because of their high index, feature higher Fresnel reflection loss and thus should always be specified with an anti-reflection (AR) coating.

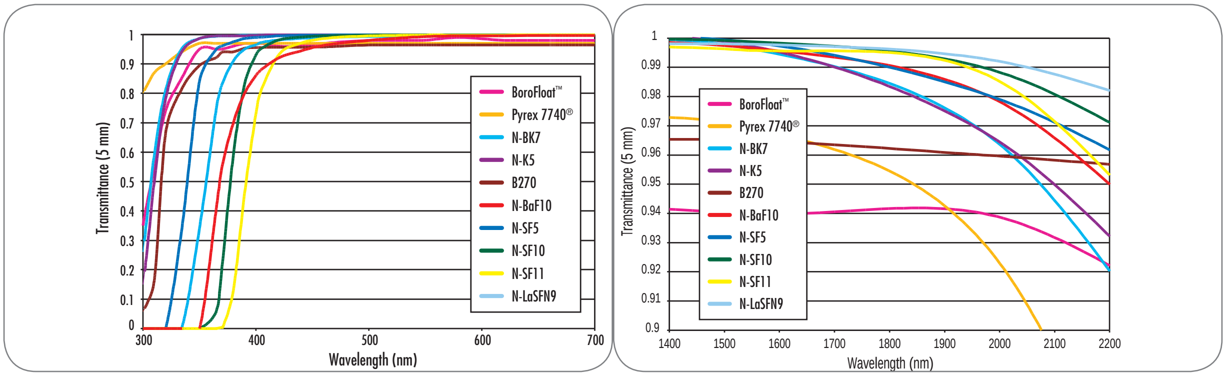


Figure 1: Sample Optical Glass Transmittance Curves

ADDITIONAL PROPERTIES

When designing an optic that will be used in an extreme environment it is important to realize that each optical glass will have slightly different chemical, thermal, and mechanical properties. These properties can be found on the glass datasheet.

Continue

OPTICAL GLASS SELECTION

Optical systems have to be optimized for a total set of functional characteristics. Geometrical and color induced aberrations can be compensated only by the use of more than one glass type. In most cases three or more glass types are used. The requirements on optical systems for different applications cover a range so wide that they cannot be met with just a small set of glass types. So a wide range of glass types has been developed. Traditionally they are shown in the refractive index versus dispersion diagram - the Abbe diagram.

The Abbe diagram, first introduced by SCHOTT in 1923, is a long established survey of the optical glass program. Glass types are given in a two-dimensional coordinate system with the Abbe number (vd) as x-axis and the refractive index (nd) as y-axis. The x-axis is in reversed direction with numbers increasing to the left side (Figure 2).

In the Abbe diagram, glass materials are divided into type denominations like BK, SK, F, SF, etc. These “glass families” correspond to the regions in the Abbe diagram defined by the blue lines. There is a major line that separates crown glass types (last letter “K” from German “Kron” for crown) from flint glass types (last letter “F”). This line starts upwards from the bottom at Abbe number 55, steps aside at refractive index 1.60 to Abbe number 50, and continues upwards to the top.

The leading letters in the glass name characterize an important chemical element used in the glass type: F - Fluorine, P – Phosphorus, B – Boron, BA – Barium, LA – Lanthanum. Deviating from this rule are the glass types from the crown - flint series, which progresses from K (“Kron”) to KF (“Kronflint” – crownflint) to flints of increasing lead content and hence density: LLF (“Very light flint”), LF (“Light flint”), F (“flint”), and SF (“Schwerflint” – heavy flint). Another deviation is the SK and SSK glass types: SK (“heavy crown”) and SSK (“heaviest crown”). LAK, LAF and LASF mean Lanthanum crown, flint and dense flint glass types, respectively.

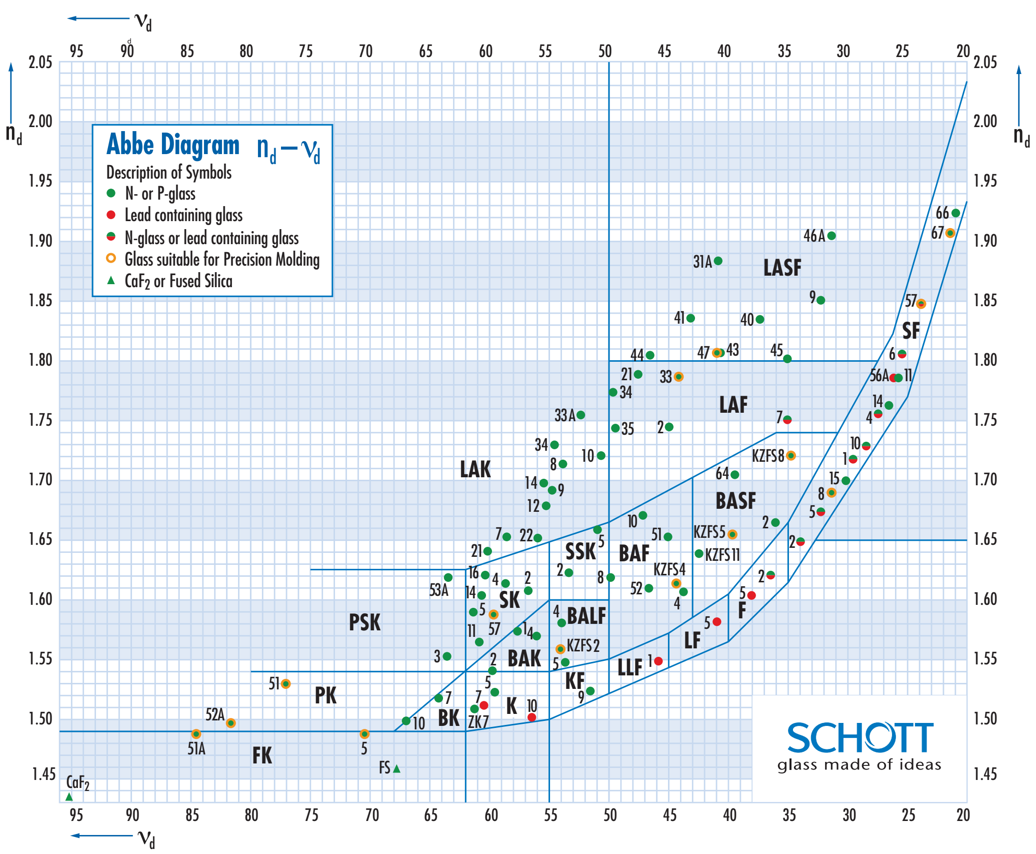
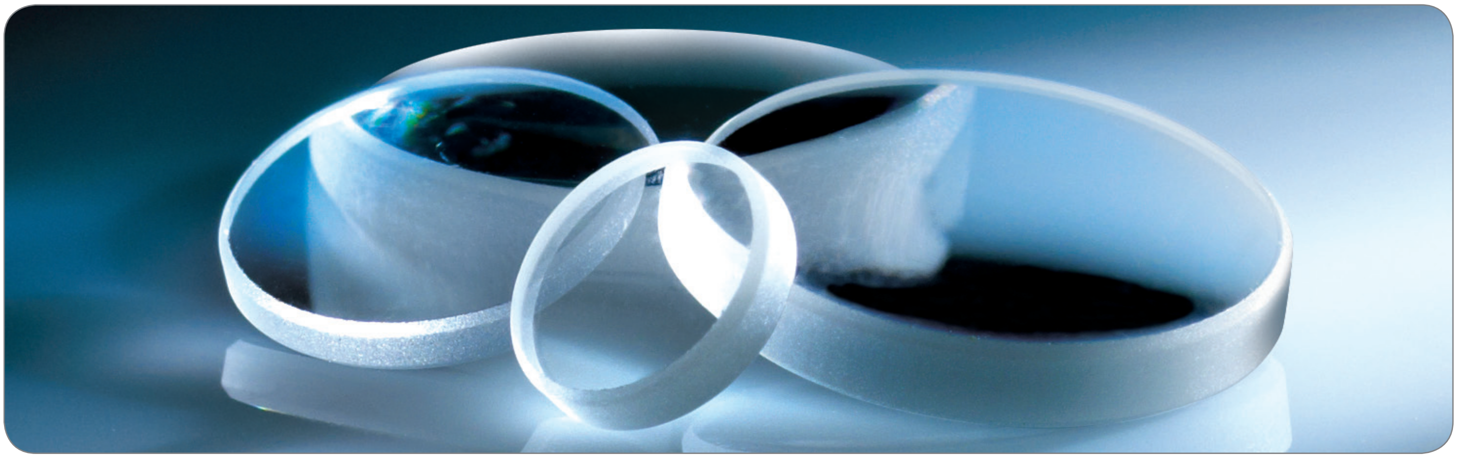


Figure 2: Schott Abbe Diagram

AN INTRODUCTION TO OPTICAL COATINGS



An optical coating is composed of a combination of thin film layers that create interference effects used to enhance transmission or reflection properties within an optical system. The performance of an optical coating is dependent upon the number of layers, the thickness of the individual layers and the refractive index difference at the layer interfaces. The most common types of coatings used on precision optics are: Anti-Reflection (AR) Coatings, High Reflective (Mirror) Coatings, Beamsplitter coatings, and Filter coatings. Anti-reflection coatings are included on most refractive optics and are used to maximize throughput and reduce ghosting. High Reflective coatings are designed to maximize reflectance at either a single wavelength or across a broad range of wavelengths. Beamsplitter coatings are used to divide incident light into known transmitted and reflected light outputs. Filters are found in a large number of industry applications and are used to transmit, reflect, absorb, or attenuate light at specific wavelengths. Edmund Optics can also offer a variety of Custom Coatings to meet any application need.

Optical Coatings are designed for a specific incident angle of light and for a specific polarization of light such as S-polarized, P-polarized, or random polarization. If a coating is designed for light at a 0° angle of incidence, but is used with light at a 45° angle of incidence, the coating will not perform at the stated transmission/reflection specifications. Similarly, coatings are generally designed for randomly polarized light so using S-polarized or P-polarized light with a coating designed for randomly polarized light will again fail to produce the stated specifications.

Optical Coatings are created by depositing dielectric and metallic materials such Ta_2O_5 and/or Al_2O_3 in thin layers that are typically quarter-wave optical thickness (QWOT) or halfwave optical thickness (HWOT) the wavelength of the light used in the application. These thin films alternate between layers of high index of refraction, and low index of refraction, thereby inducing the interference effects needed. Refer to Figure 1 for a sample illustration of a broadband anti-reflection coating design.

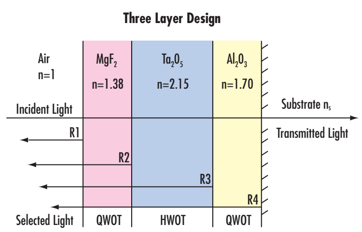


Figure 1: Sample Three Layer BBAR Coating Design

COATING THEORY

Coatings control the reflection and transmission of light through the mechanism of optical interference. When two beams propagate along coincident paths and their phases match, the spatial location of the wave peaks also match and will combine to create a larger total amplitude. When the beams are out of phase (180° shift), their overlay will result in a subtractive effect at all the peaks causing the combined amplitude to decrease. These effects are known as constructive and destructive interference respectively.

The relations that dictate the total reflectance of a multi-layer thin film structure are given in Equations 1 - 4:

Continue

(1)

$$\begin{bmatrix} B \\ C \end{bmatrix} = \left\{ \prod_{p=1}^{q} \begin{bmatrix} \cos\delta_p & i\sin\delta_p/\eta_p \\ i\eta_p\sin\delta_p & \cos\delta_p \end{bmatrix} \right\} \begin{bmatrix} 1 \\ \eta_\eta \end{bmatrix}$$

(2)

$$\delta_p = \frac{2\pi N_p d_p \cos\theta_p}{\lambda}$$

q = Number of Layers
δ = Phase Term
η = Optical Admittance of the Layers
N_p = Complex Refractive Index
t_p = Physical Thickness of the Layer

(3)

$$Y = \frac{C}{B}$$

(4)

$$R = \left(\frac{\eta_0 - Y}{\eta_0 + Y}\right)\left(\frac{\eta_0 - Y}{\eta_0 + Y}\right)$$

λ = Wavelength
θ_p = Angle of Incidence
Y = The Optical Admittance of the Stack
R = Reflectance of the Stack

While the wavelength of light and angle of incidence are usually specified, the index of refraction and thickness of layers can be varied to optimize performance. Changes in any of these will have an effect on the path length of the light rays within the coating which, in turn, will alter the phase values as the light travels. This effect can most simply be explained through the example of a single-layer anti-reflection coating. As light propagates through the system, reflections will occur at the two interfaces of index change on either side of the coating. In order to minimize reflection, we would like to have 180° phase shift between these two reflected portions when they recombine at the first interface. This phase difference directly corresponds to a λ/2 shift of the sinusoid wave, which can best be accomplished by setting the optical thickness of the layer to λ/4. Refer to Figure 2 for an illustration of this concept.

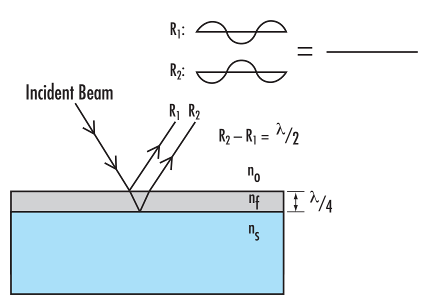


Figure 2: 180° Phase Shift between Two Reflected Beams

Index of refraction not only influences optical path length (and thus, phase), but also the reflection characteristics at each interface. The reflection is defined through Fresnel's Equation (Equation 5), which provides the amount of reflection that will occur from the refractive index change at an interface at normal incidence.

(5)

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

The final parameter that must be taken into account is the incident angle of the light the coating is to be designed for. If the incident angle of the light is altered, the internal angles and optical path lengths within each layer will be affected which, in turn, will influence the amount of phase change in the reflected beams. When a non-normal incidence is used, S-polarized and P-polarized light will reflect differently from one another at each interface which will cause different optical performances at the two polarizations. It is this phenomenon that allows for the design of polarizing beamsplitters.

COATING MANUFACTURING

The manufacturing process involved for optical coatings is both labor-intensive and time-consuming. The factors that influence the cost of a coating are the number of optics being coated, type of optic, the number of layers in the coating, and number of coated surfaces on the optic. The deposition process used to apply the coating also plays a huge factor in coating cost. Furthermore, a great deal of prep work is necessary to ensure the highest level of quality in every coated optic.

Cleaning and preparation of optics prior to coating is a vital part of the process. An optical element being coated must have a clean surface for the coating to adhere. Also, any stains on the substrate that are not removed can often be enhanced by the coating. For this reason, Edmund Optics® runs all of its optical elements being coated through our Automated Ultrasonic Cleaning System, ensuring a consistent, high quality final product.

Edmund Optics® also implements two different coating deposition techniques. The first, which applies to most standard coatings, is Ion-Assisted Electron Beam Deposition. This process involves an electron beam melting the surface of the layer material at temperatures up to 3000°C within a vacuum chamber. The Evaporated material is then energized by an ion beam that provides improved adhesion onto the substrate which creates a denser final coating. The second process is Advanced Plasma Reactive Sputtering (APRS). APRS is a state of the art approach to sputtering in which a magnetron is used to energetically remove atomic particulate off the surface of the target material. This technique results in a high level of control in rate and energy of the deposition process, as well as enhanced structural characteristics in the coating itself. With this level of control, the APRS system is capable of producing precision optical coatings with over 200 layers.

COATING TECHNOLOGY

HARD IBS (ION-BEAM SPUTTER)

Conventional narrowband interference filters are fabricated in two steps – one to determine the center wavelength and bandwidth of the filter, and a second step to determine its blocking capabilities. The first step is created by depositing up to 50 layers of quarter-wave optical thickness (QWOT) and halfwave optical thickness (HWOT) dielectric materials of alternating high and low refractive indices. The bandwidth of the filter is determined by the ratio of high and low index materials, the number of layers, and the number of “cavities” created by HWOT layers and adjacent stacks. On an alternate substrate, metallic film layers are deposited for broad-spectrum blocking. Finally, these two sections are scribed, laminated, cut, and mounted. Additional colored glass materials may be inserted between the two layers for further blocking.

This conventional method leads to three fundamental problems. First, the colored glass and metallic film blocking layers reduce transmission at all wavelengths, including the design passband wavelengths, limiting the overall signal through the filter. Typical transmissions range from 25 - 50%, depending on center wavelength. Second, the construction of the filters (several layers of glass, several layers of epoxy, and dielectric materials) is quite complicated, making it difficult to use these filters in imaging applications. With so many layers of different materials, accurate ray-tracing through the filter is impossible, and repeatable construction of the filters is difficult and costly. Loose tolerancing on the overall thickness and on the center wavelength is commonplace. Finally, because the epoxy and often the coating materials themselves have poor mechanical and optical durability and are prone to humidity-induced swelling and degradation, the overall reliability of the filters is limited.

Continue

HARD IBS (ION-BEAM SPUTTER) (CONT.)

"Hard" ion-beam sputtered (IBS) coating has solved these three fundamental problems. Dielectric films of arbitrary thickness are deposited on a single substrate, eliminating the need for complex cavity designs and epoxy layers. With arbitrary film thicknesses and capabilities to deposit up to 200 layers, excellent transmission and broad spectrum blocking can be achieved entirely by the dielectric coatings applied to the substrate. Transmissions typically exceed 90% at the design wavelength, with much steeper edges and deeper blocking. The combination of improved signal transmission and ambient illumination rejection simultaneously yields brighter images and darker backgrounds, greatly improving system signal-to-noise ratio. While initial cost of purchase may be somewhat higher than with conventional interference filters, long-term cost of ownership is significantly reduced.

A typical thin film production sequence using Hard IBS coating is outlined by the following steps:

1. Prepare tooling to mount optics in chamber.
2. Clean optics and load them into tooling.
3. Clean chamber and refill with source material needed to produce coating evaporates. Prepare monitoring system.
4. Load tooling containing optical components into chamber.
5. Reduce chamber pressure to <2 x 10^{-5} Torr and heat chamber to 200 - 300°C.
6. Deposit coating layers as per coating design.
7. Cool and vent coating chamber.
8. Remove optics from chamber and test optics for coating performance.
9. Inspect and wrap optics.

Total Cycle time is over 3 hours not including cleaning and inspection. Note that all steps must be completed regardless of the number of optics being coated. For this reason, low-volume coating runs have a higher per-unit cost.

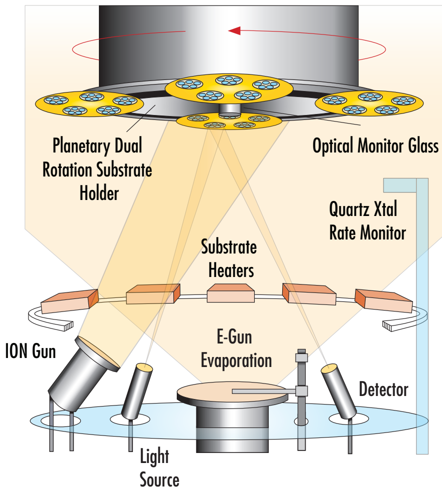


Figure 3: Ion-Assisted E-Beam Deposition Process

ADVANCED PLASMA REACTIVE SPUTTERING (APRS)

With the recent addition of the Advanced Plasma Reactive Sputtering (APRS) platform, even the most difficult of coating designs can be accurately produced with minimal lead time. The APRS platform offers the ability to deposit over 200 highly accurate, shift-free layers in a single coating run. The process itself is high energy, allowing for a very stable and controlled deposition in comparison to most other methods. The final coating is free of impurities and highly resistant to environmental damage. Because of its ability to create coatings that operate over an extremely large region of the spectrum, the APRS platform is ideal for deposition of custom filters of the most complex and demanding designs. Furthermore, its load-locked, high capacity structure results in very high throughput which increases the total number of coated elements per run and lowers the price per coated component.

The custom coatings designed and applied by Edmund Optics® include: Broadband AR, V-Coat AR, Polarizing, Non-Polarizing, Beamsplitter, Laser Mirror, Metallic, Bandpass and up to 200+ layers of custom design. With the addition of the APRS platform, our custom coating capabilities now also extend into the entire range of filter designs, including Biomedical and Notch Filters. These coatings are available for both large manufacturing needs and in prototype volumes.