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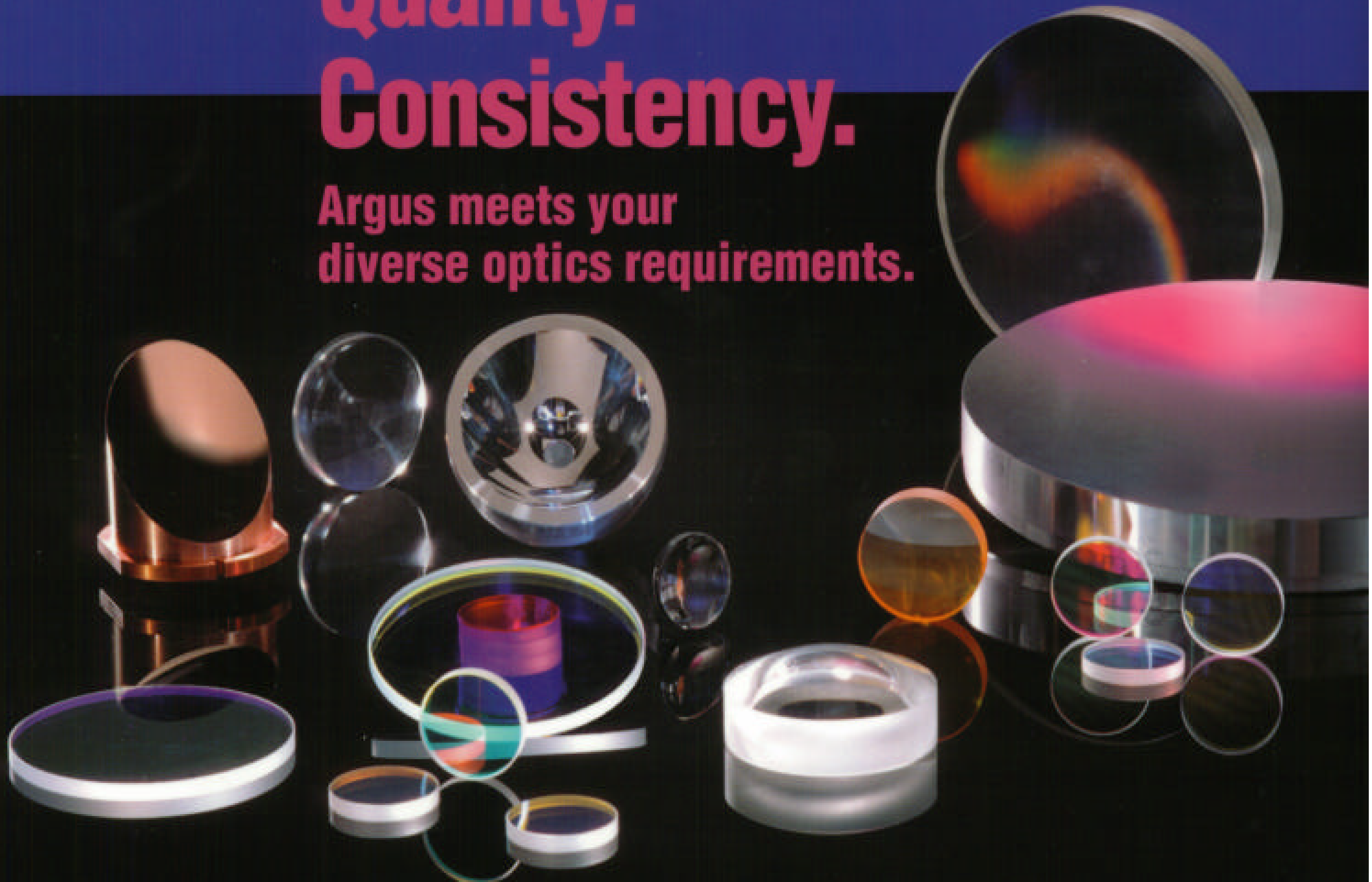

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CATALOG CONTENTS

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Fundamental Optics

INTRODUCTION

With hundreds of different optical components listed in this catalog, the task of choosing the right elements for your particular optical system can seem daunting. However, for many applications a few simple calculations will enable you to select the appropriate optics, or at very least, yield a narrow list of choices. How to perform these basic optical engineering calculations is the subject of this chapter.

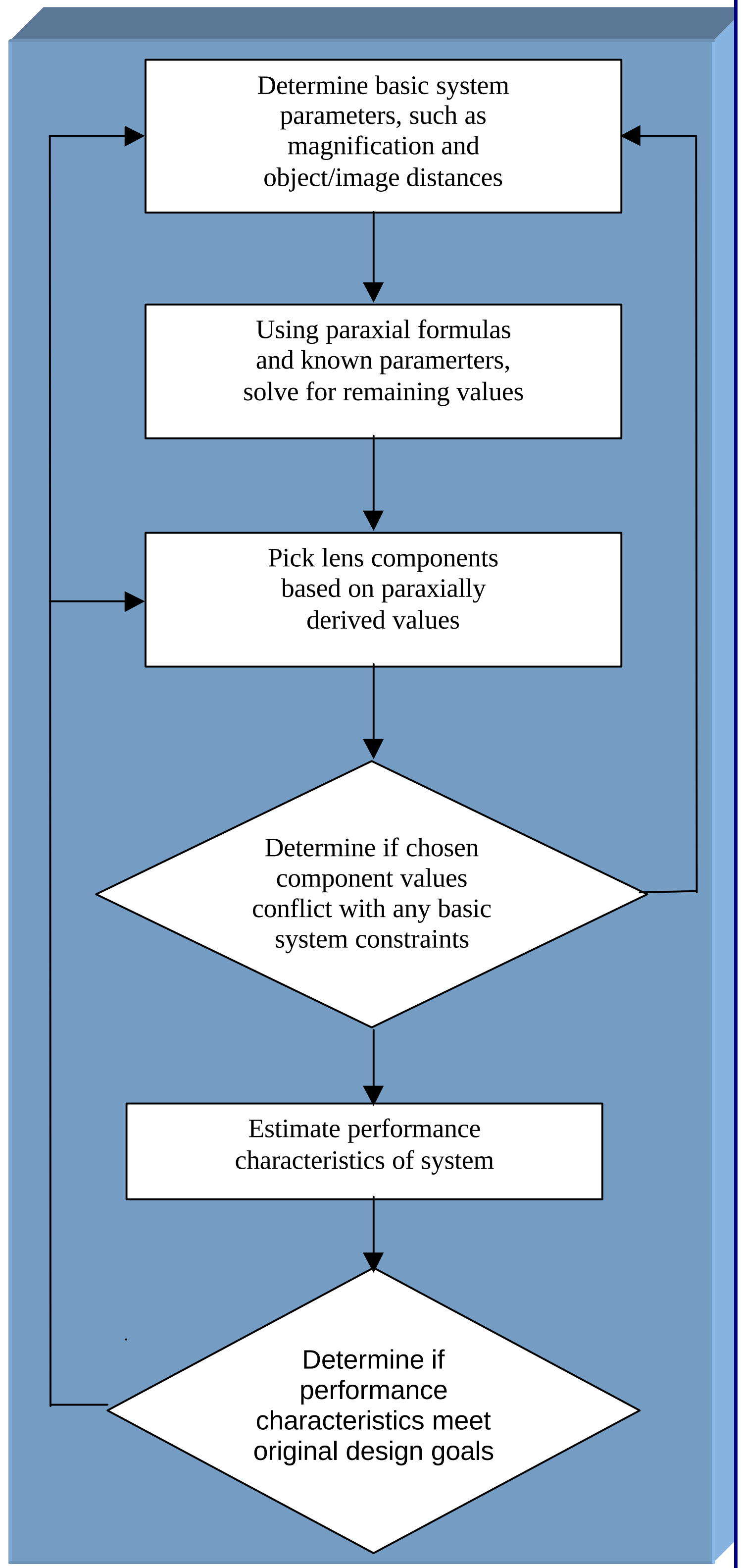
The process of solving virtually any optical engineering problem can be broken down into two main steps. In the first step, paraxial, or first order, calculations are made to determine critical quantities such as magnification, focal length(s), clear aperture (diameter), and object and image position. These paraxial calculations are covered in the first section of this chapter.

The next part of optical problem solving involves choosing actual components based on these paraxial values, and then evaluating their real world performance, particularly the effects of aberrations. Now, a truly rigorous performance analysis for all but the simplest optical systems generally requires computer ray tracing, but, again, there are several simple rules and general guidelines, which can be used. This is especially true when the lens selection process is constrained to the use of a limited range of component shapes. The second part of this chapter explores the main factors, which affect real world performance, and gives guidelines for selecting the most appropriate catalog component for a particular task.

In practice, the performance evaluation stage may reveal conflicts with design constraints, such as component size, cost, and product availability. In this case, system parameters may then have to be modified, meaning a return to step one. Fortunately, a couple of iterations through this process will suffice for most applications.

Some of the terms used in this chapter will not be familiar to all readers. For this reason, the last part of this chapter consists of a complete glossary defining all the terminology used in these optical engineering calculations.

Finally, it should also be noted that the discussion in this chapter relates only to systems with uniform illumination; optical systems for gaussian beams will be covered in the next chapter.



Paraxial Formulas

Typically, the first step in optical problem solving is to select system focal length based on other system constraints such as magnification or conjugate distances (object and image distance). The relationship between focal length, object position and image position is given by:

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{s''}$$

This formula referenced to the accompanying drawing and sign convention.

By definition, magnification is the ratio of image size to object size or:

$$f = \frac{s''}{s} = \frac{h''}{h}$$

Using this relationship, we can recast the first formula in the following forms:

$$f = m\left(\frac{s + s''}{m + 1}\right)$$

Where (s + s”) is the approximate object-to-image distance.

$$f = \frac{sm}{m + 1}$$

$$f = \frac{s + s''}{m + 2 + 1}$$

$$s\,(m + 1) = s + s''$$

These are just different versions of the same formula; the form used to solve a particular problem will depend upon which variables are known, and which are to be solved for.

Notice that in a real lens of finite thickness, image distance, object distance, and focal length are all referenced to the principal points, not the physical center of the lens. By neglecting the distance between the lens’ principal points, known as the hiatus, s + s” becomes the object to image distance. This simplification, called the *thin lens approximation*, can speed calculation when dealing with simple optical systems.

Examples:

#1: A 1-mm-high object is place on the optical axis, 200 mm left of the left principal point of a 01 **LDX** 103 (50mm fl). Where is the image formed, and what is the magnification?

$$\frac{1}{s''} = \frac{1}{f} - \frac{1}{s}$$

$$\frac{1}{s''} = \frac{1}{50} - \frac{1}{20}$$

s” = 66.7 mm

$$m = \frac{s''}{s} = \frac{66.7}{200} = 0.33$$

(or real mage is 0.33 mm high and inverted)

SIGN CONVENTION

The validity of the paraxial lens formulas given is dependent of adherence to the sign convention shown here:

For lenses:

s is + for object to left of H (the first principal point)

s is – for object to right of H

s” is + for image to right of H” (the second principal point)

s” is – for image to left of H”

m is + for an inverted image

m is – for an upright image

For mirrors:

f is + for convex (converging) mirrors

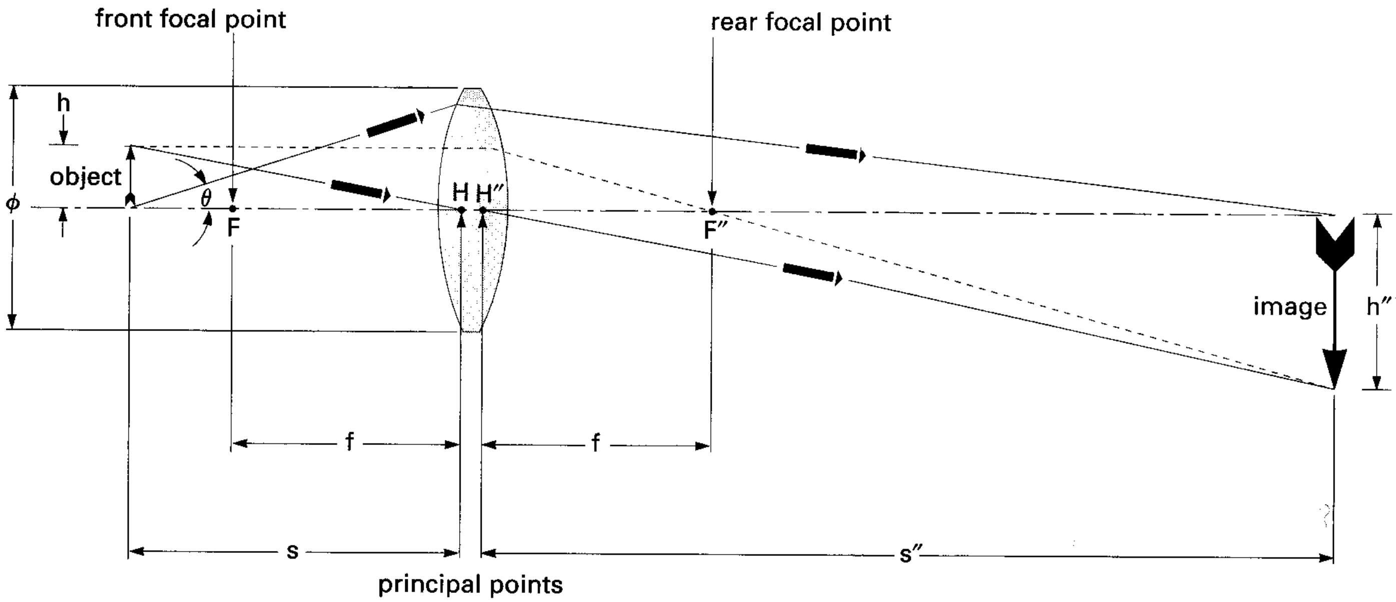
f is – for concave (diverging) mirrors

s is + for object to right of H

s” is – for image to left of H”

m is + for inverted image

m is – for an upright image



Note location of object and image relative to front and rear focal points.

ι = Lens diameter

m = s"/s = h"/h = magnification or conjugate ratio, said to be infinite if either s" or s is infinite

σ = arcsin (ι/2s)

h = object height

h" = image height

s = Object distance, positive for object (whether real or virtual) to the left of principal point H

s" = Image distance (s and s" are collectively called conjugate distances, with object and mage in conjugate planes), positive for image (whether real or virtual) to the right of the principal point H"

f = effective focal length (EFL), may be positive (as shown or negative. f represents both FH and H"F", assuming lens to be surrounded by medium of index 1.0

#2: the same object is paced 30 mm left of the left principal point of the same lens. Where is the image formed, and what is the magnification?

$$\frac{1}{s''} = \frac{1}{50} - \frac{1}{30}$$

s" = - 75 mm

$$m = \frac{s''}{s} = \frac{-75}{50} = -1.5$$

(or virtual image is 1.5 mm high and upright)

In this second case, the lens is being used as a magnifier, and the image could only be viewed back through the lens.

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#3 A 1mm high object is pace on the optical axis, 50mm left of the first principal point of an 01 LDK 019 (- 50mm fl). Where is the image formed, and what is the magnification?

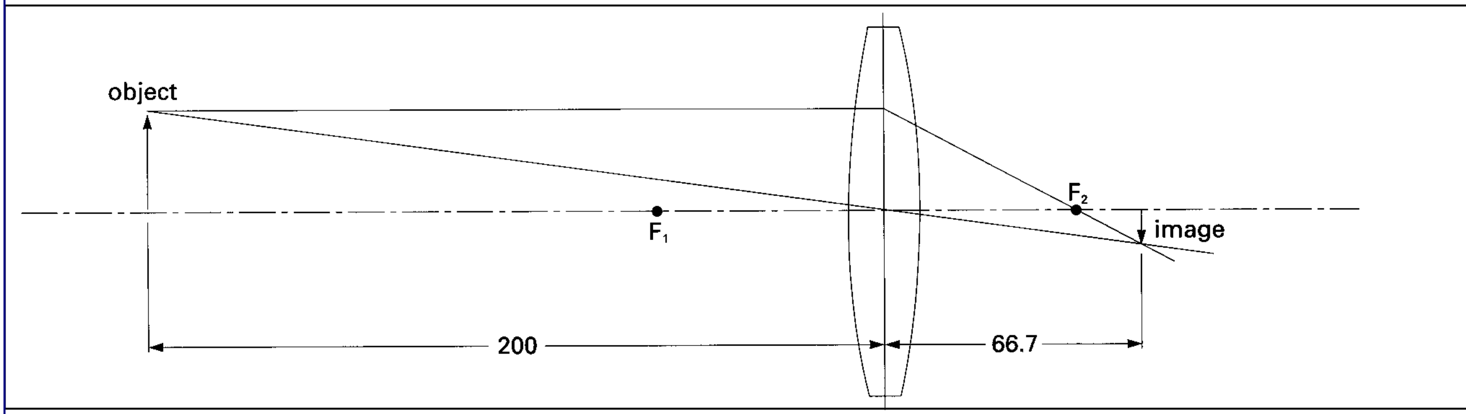
$$\frac{1}{s''} = \frac{1}{-50} - \frac{1}{50}$$

$$s'' = -25 \text{ mm}$$

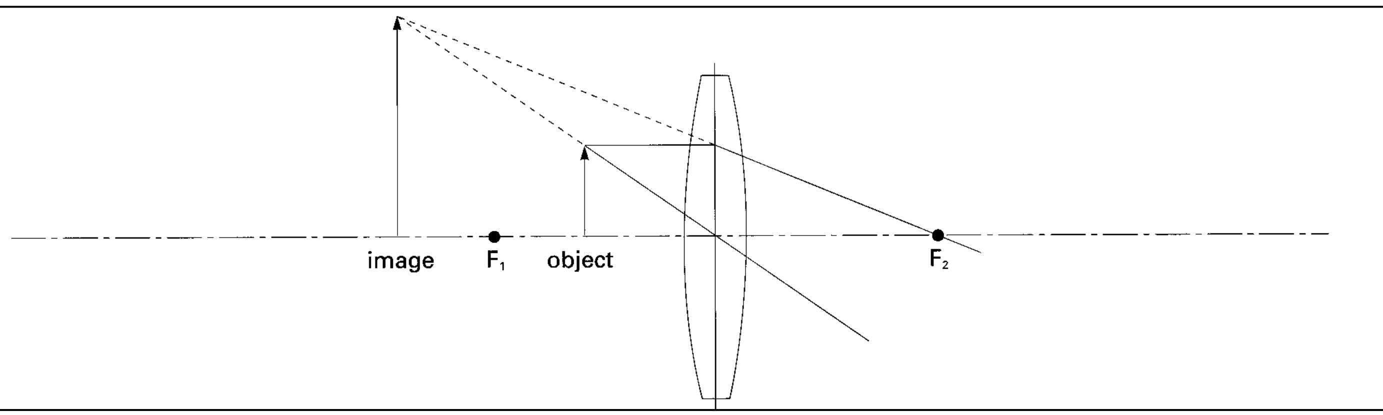
$$m = \frac{s''}{s} = \frac{-25}{50} = -0.5$$

(or virtual image is 0.5 mm high and upright)

A simple graphical method can also be used to determine paraxial image location and magnification. This graphical approach relies on two simple properties of an optical system. First, a ray which enters the system parallel to the optical axis crosses the optical axis at the focal point. Second, a ray which enters the first principal point of the system exits the system from the second principal point parallel to its original direction (that is, its exit angle with the optical axis is the same as its entrance angle). This method has been applied to the three previous examples in the figure. Note that using the thin lens approximation, this second property reduces to the statement that a ray that passes through the center of the lens is undeviated.



EXAMPLE #1. (f = 50 mm, s = 200 mm, s" = 66.7 mm)



EXAMPLE #2. (f = 50 mm, s = 30 mm, s" = - 75 mm)

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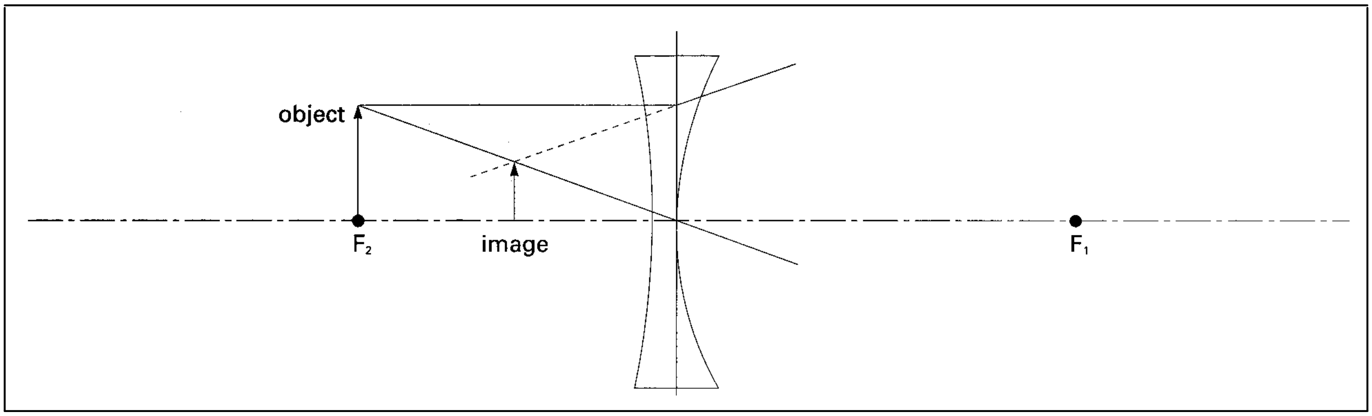


EXAMPLE #3. (f = **-** 50mm, s = 50 mm, s: = **-** 25 mm)

F-NUMBER AND NUMERICAL APERTURE

Besides focal length, the other important lens parameter which must be determined is diameter, or clear aperture. Too large a lens may represent unnecessary size and cost, too small a lens may provide inadequate throughput.

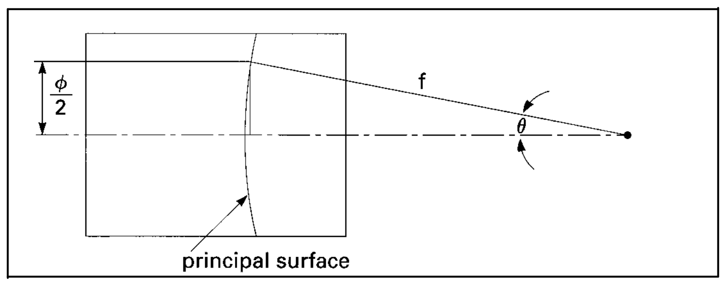
The paraxial calculations used to determine necessary element diameter are based on the concepts of focal ratio (f-number or fib) and numerical aperture (N.A.). F-number is the ratio of the lens' focal length to its clear aperture (effective diameter).

$$f - \text{number} = \frac{f}{\sigma}$$

To visualize f-number, consider a lens with positive focal length illuminated uniformly with collimated light. F-number defines the angle of the cone of light leaving the lens which ultimately forms the image. Obviously, this is an important concept when the throughput or light gathering power of an optical system is critical, such as when focusing light into a monochromator or in high power projection optics.

The other commonly used term to define this cone angle is numerical aperture (N.A.). Numerical aperture is, by definition, the sine of the angle the marginal ray makes with the optical axis; referring to the figure and using simple trigonometry, it can be seen that

$$\text{N.A.} = \sin\sigma = \frac{\sigma}{2f}$$



or

$$\text{N.A.} = \frac{1}{2\left(\text{f - number}\right)}$$

Note that ray f-numbers can also be defined for any arbitrary ray, knowing its conjugate distance, and the diameter at which it intersects the principal surface of the optical system.

The sign convention given previously is not used universally in all optics texts; hence, the reader may notice differences in the paraxial formulas from text to text. However, results will be correct as long as a consistent set of formulas and sign convention are used.

Imaging Properties of Lens Systems

THE OPTICAL INVARIANT

To understand the importance of N.A. let us see how it relates to magnification. Referring to the drawing:

$$\text{N.A. (object side)} = \sin\iota = \frac{\sigma}{2s}$$

$$\text{N.A.'' (image side)} = \sin\iota = \frac{\sigma}{2s''}$$

which can be rearranged to show

$$\iota = 2s \sin\sigma \text{ and}$$

$$\iota = 2s'' \sin\sigma''$$

leading to

$$\frac{s''}{s} = \frac{\sin\sigma}{\sin\sigma''} = \frac{\text{N.A.}}{\text{N.A.''}}$$

Since $\frac{s''}{s}$ is simply the magnifacation of the system, we arrive at:

$$m = \frac{\text{N.A.}}{\text{N.A.''}}$$

The magnification of the system is therefore equal to the ratio of the numerical apertures on the object and image sides of the system. This is a very powerful and useful result which is completely general; it is independent of the specifics of the optical system.

So how can we use this relationship to select a lens diameter? When using a lens or optical system to create an image of a source, it is natural to assume that increasing the diameter (σ) of the lens will enable us to collect more light and thereby produce a brighter image. However, because of the relationship between magnification and numerical apertures, there is sometimes a theoretical limit to this. Increasing N.A. beyond a certain value in some situations has no further effect on light collection efficiency; there is a maximum image brightness.

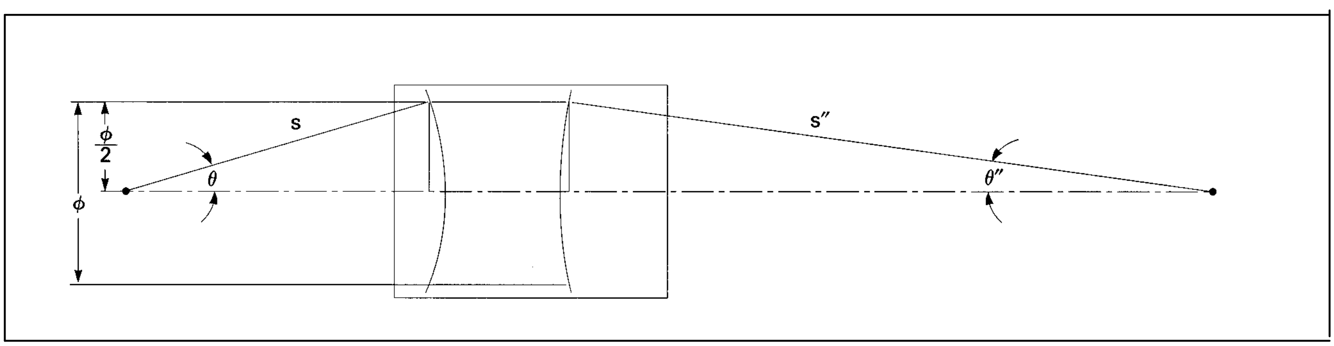
Now, since ray N.A. is given by σ/2s, once a focal length and magnification have been selected, the value of N.A. sets the value of σ. Thus, if we are dealing with a system in which N.A. is constrained on either the object or image side, increasing lens diameter beyond this value will increase system size and cost with no performance gain (throughput or image brightness). This concept is sometimes referred to the optical invariant.

SAMPLE CALCULATION

To understand how to use this relationship between magnification and N.A., let's work through an example to select a real lens diameter:

Receiving N.A. Fixed

Two very common applications of simple optics involve coupling light into an optical fiber or the entrance slit of a monochromator.



Although these may appear as quite different problems, they have the same limitation, namely, the N.A. of the receiver. Both the fiber and monochromator have a fixed N.A.; they cannot accept light from outside a finite cone. For monochromators, this limit is usually expressed as f-number. In addition they have an entrance pupil (image size) of fixed size.

Suppose it is necessary to couple the output of an incandescent bulb with a filament of 1 mm diameter into an optical fiber which has a core diameter of 100 ,um and a numerical aperture of 0.25. Assume that your design requires that the total distance from source to fiber be 110 mm. By definition, the magnification must be 0.1 x . Letting s + s" total 110 mm (using the thin lens approximation), we can use

$$f = m\frac{(s + s'')}{(m + 1)^2}$$

to determine the focal length, which comes out to be 9.1 mm. To determine the conjugate distances, s and s", we utilize the formula

$$s\,(m + 1) = s + s''$$

which yields s = 100 mm and s” = 10 mm

Now we can use the relationship N.A. = ¢/2s or N.A." = ol2s" to derive ¢, the optimum clear aperture (effective diameter) of the lens.

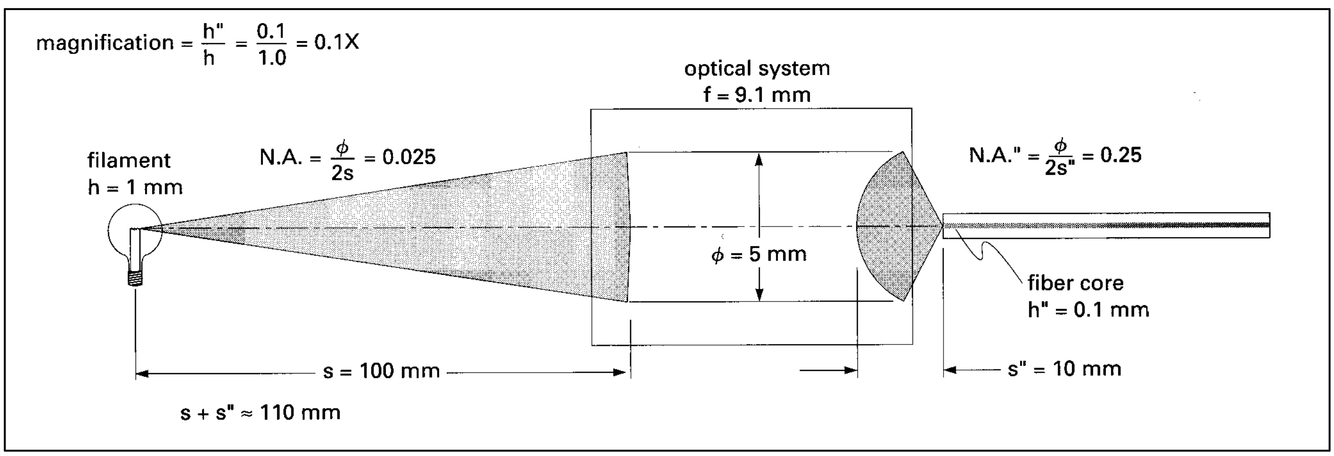
With an image N.A.” of O.25 and an image distance (s”) of 10 mm,

$$0.25 = \frac{\sigma}{20}$$

$$\iota = 5\ \text{mm}$$

Accomplishing this imaging task with a single lens would therefore require an optic with a 9.1mm focal length, and a 5mm diameter. Using a larger diameter lens would not result in any greater system throughput, due to the limited input N.A. of the optical fiber. If a singlet lens is to be used for this application, potential choices would be piano-convex lens 01 LPX 003 or bi-convex lenses 01 LDX 003 and 01 LDX 005.

So, with some very simple calculations, we have reduced our choice of lenses to just three. In the next chapter we will see how to make a final choice of lenses based on performance criteria.



GEOMETRY OF THE OPTICAL SYSTEM for focusing the output of an incandescent bulb into an optical fiber. The magnification of the system, which is determined by the ratio of image height to object height, is also the ratio between the numerical aperture on the collection side to that on the imaging side of the system. In systems such as this, with a predetermined numerical aperture on the imaging side, the numerical aperture on the collecting side is thus set as soon as the system magnification is determined. A constraint on the overall object to image distance (throw) will then yield the required system focal length and diameter. All that is left is to determine the necessary lens shape(s) to provide optimum performance.

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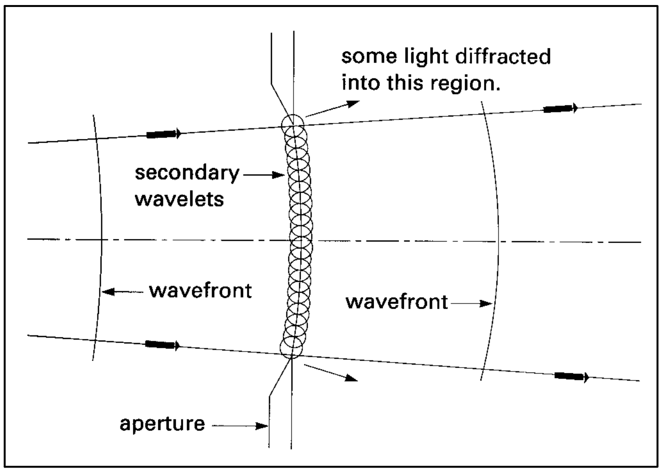
Diffraction Effects

In all light beams, some energy is spread outside the region which would be expected from considerations of rectilinear propagation. This effect is known as diffraction and is a fundamental and inescapable physical phenomenon.

Diffraction can be understood by considering the wave nature of light. Huygen's Principle states that each point on a propagating wavefront is an emitter of secondary wavelets. The combined locus of these expanding wavelets forms the propagating wave. Interference between the secondary wavelets gives rise to a fringe pattern which rapidly decreases in intensity with increasing angle from the initial direction of propagation. Huygen's Principle nicely describes diffraction, but rigorous explanation demands a detailed study of wave theory.



HUYGEN'S PRINCIPLE states that each point on a propagating wavefront is an emitter of secondary wavelets.

Diffraction effects are traditionally classified into either Fresnel or Fraunhofer types. Fresnel diffraction is primarily concerned with what happens to light in the immediate neighborhood of a diffracting object or aperture. It is thus only a concern when the illumination source is close to this aperture, and/or the light is being sensed close to the aperture. Consequently, Fresnel diffraction is rarely important in most optical setups.

Fraunhofer diffraction, on the other hand, is often very important. This is the light spreading effect of an aperture when the aperture (or object) is illuminated with an infinite source (plane wave illumination) and the light is sensed at an infinite distance (far field) from this aperture.

From these overly simple definitions one might naively assume that Fraunhofer diffraction is important only in optical systems with infinite conjugate, whereas Fresnel diffraction equations should be considered at finite conjugate ratios. Not so. A lens or lens system of finite positive focal length with plane wave input maps the far-field diffraction pattern of its aperture onto the focal plane, and so it is Fraunhofer diffraction which determines the limiting performance of optical systems. More generally, at any conjugate ratio, it is the far field angles that are transformed into spatial displacements in the image plane.

CIRCULAR APERTURE

Fraunhofer diffraction at a circular aperture is of considerable importance in that it dictates the fundamental limits of performance for circular lenses. The following notes give a mathematical treatment of this effect. If you do not wish to work through this derivation, the important result to remember is that the spot size. due to diffraction, of a circular lens is:

$$d = 2.44 \quad f/\#$$

where d is the diameter of the focused spot produced from plane wave illumination and X is the wavelength of light being focused. Notice that it is the f-number of the lens. not its absolute diameter, that determines this limiting spot size.

RAYLEIGH CRITERION

In imaging application, spatial resolution is ultimately limited by defecation. Calculating the maximum possible spatial resolution of an optical system requires an arbitrary definition on what is meant by resolving two features. In the Rayleigh Criterion, it is assumed that two point sources can be resolved as being separate when the center of the Airy Disc from one overlaps the first dark ring in the diffraction pattern of the second, In this case, the smallest resolvable distance, d, is given by:

$$d = \frac{0.61}{N.A.} = 1.22 \quad f/\#$$

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In reality, the diffraction pattern resulting from a uniformly illuminated circular aperture actually consists of a central bright region, known as the Airy Disc, surrounded by a number of much fainter rings. Each ring is separated by a circle of zero intensity. The irradiance distribution in this pattern can be described by

$$I_x = I_0 \left[\frac{2J_1\,x}{x}\right]^2,$$

Where I_0 = peak irradiance in image.

$$J_1(x) = x\varphi\,(-1)^{n+1}\frac{x^{n-2}}{n-1\ \ !n!2^{2n-1}},$$

$J_1(x)$ =Bessel function of the first kind of order unity.

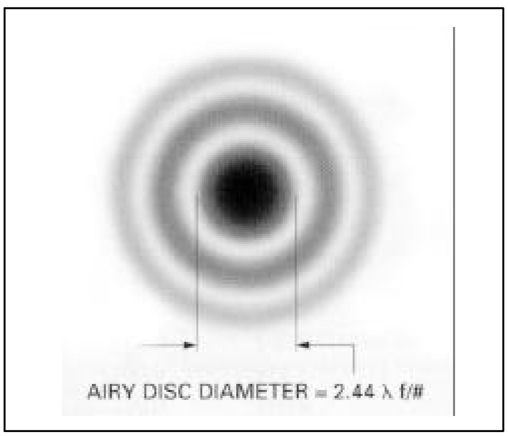
$$X = \frac{\pi D}{\ }\ \sin\sigma, \text{ where}$$

= wavelength

D = aperture diameter, and

σ = angular radius from pattern maximum

this useful formula shows the far-field irradiance distribution from a uniformly illuminated circular aperture of diameter, D.



CENTER OF A TYPICAL DIFFRACTION PATTERN for a circular aperture.

SLIT APERTURE

A slit aperture is mathematically simpler and is useful in relation to cylindrical optical elements. The irradiance distribution in the diffraction pattern of a uniformly illuminated slit aperture is described by

$$I_x = I_0 \left[\frac{\sin x}{x}\right]^2$$

where,

I_0 = peak irradiance in image,

$$x = \frac{\pi\, w \sin\sigma}{\ },$$

= wavelength

w = slit width, and

σ = angular deviation from pattern maximum.

ENERGY DISTRIBUTION TABLE

Following is a table showing the major features of the pure (unaberrated) Fraunhofer diffraction patterns of circular and slit apertures. The table shows the location, relative intensity, and percentage of total pattern energy corresponding to each ring or band in the patterns. It is especially convenient to characterize positions in either pattern with the same variable x. This variable is related to field angle in the circular aperture case by

$$\sin\sigma = \frac{x}{\pi D},$$

where D is the aperture diameter. For a slit aperture this relationship is given by

$$\sin\sigma = \frac{x}{\pi w},$$

where w is the slit width, π has its usual meaning, and we presume that D, w, and are all in the same units (preferably mm). Linear instead of angular field positions are simply found from

$$r = s'' \tan(\sigma),$$

where s" in the secondary conjugate distance. This last result is often seen in a different form which we now derive for circular aperture case.

Let U" denote the angular radius of the lens clear aperture as viewed from the secondary conjugate point, and suppose that the secondary principal surface is a sphere centered on the secondary conjugate point, a situation of which the Abbe sine condition is a special case. Then D, s", and U" are related by

$$\frac{D/2}{s''} = \sin U''$$

Solving for s" and substituting above we find

$$r = \frac{D}{2 \sin U''} \tan \sigma$$

In the present situation,

$$\sin \sigma = \frac{x}{\pi n'' D}.$$

where n" is the image space refractive index. From consideration of a right triangle of unit hypotenuse it follows that

$$\tan \sigma = \frac{\left(\frac{x}{\pi n'' D}\right)}{\sqrt{1 - \left(\frac{x}{\pi n'' D}\right)^2}}$$

In the small angle approximation the denominator is unity (the tangent equals the sine). Substituting in the last formula for r above, we find

$$r = \frac{D}{2 \sin U''} \times \frac{x}{\pi n'' D}$$

$$= \frac{x}{2\pi n'' \sin U''}$$

$$= \frac{x}{(2\pi)(N.A.)},$$

where (N.A.) denotes the numerical aperture. This result depends on the generalized Abbe sine condition and the small angle approximation. From the table, we can see that the edge of the central spot of light in the diffraction pattern occurs at an x value of 1.221r. Plugging this value into the preceding equation, gives us a beam radius for this central spot of

$$r = \frac{(1.22\pi)}{(2\pi)(N.A.)}$$

When expressed as a spot diameter, and in terms of f-number, rather than IDA., we get the formula stated at the outset of this section:

$$d = 2.44 \quad f/\#$$

This value represents the smallest spot size which can be achieved by an optical system with a circular aperture of a given f-number.

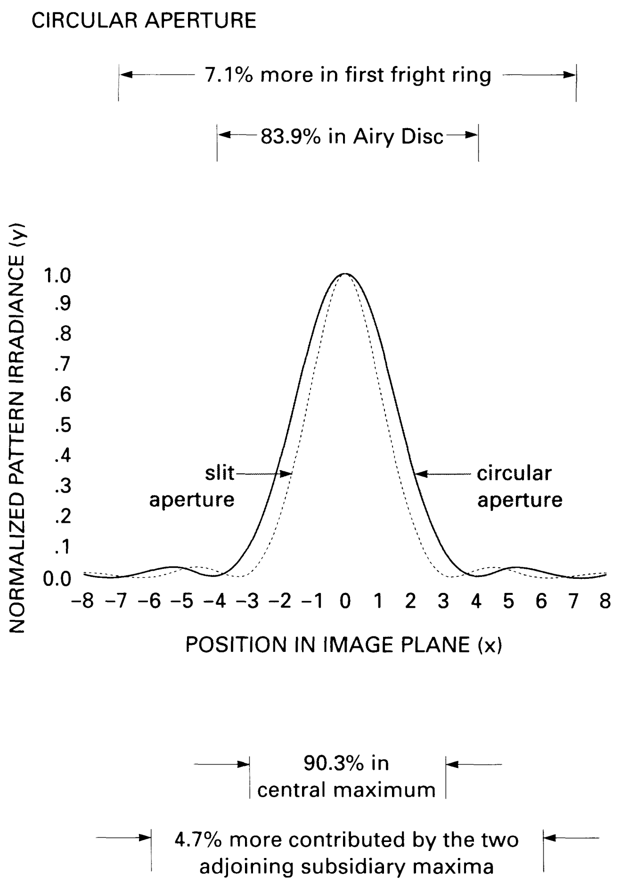
Energy Distribution in the Diffraction Pattern of a Circular or Slit Aperture:

Ring or Band	Circular Aperture Position (x)	Circular Aperture Relative Intensity (I_x/I_0)	Circular Aperture Energy in Ring (%)	Slit Aperture Position (x)	Slit Aperture Relative Intensity (I_x/I_0)	Slit Aperture Energy in Band (%)
Central Maximum	0.0	1.0	83.8	0.0	1.0	90.3
First Dark	1.22π	0.0		1.00π	0.0	
First Bright	1.64π	0.0175	7.2	1.43π	0.0472	4.7
Second Dark	2.23π	0.0		2.00π	0.0	
Second Bright	2.68π	0.0042	2.8	2.46π	0.0165	1.7
Third Dark	3.24π	0.0		3.00π	0.0	
Third Bright	3.70π	0.0016	1.5	3.47π	0.0083	0.8
Fourth Dark	4.24π	0.0		4.00π	0.0	
Fourth Bright	4.71π	0.0008	1.0	4.48π	0.0050	0.5
Fifth Dark	5.24π	0.0		5.00π	0.0	

The graph below shows the form of both circular and slit aperture diffraction patterns when plotted on the same normalized scale. Aperture diameter has been set equal to slit width so that for both patterns the correspondence between x-values and angular deviations in the far-field is the same.

GAUSSIAN BEAMS

Apodization, or nonuniformity of aperture irradiance, alters diffraction patterns. If your pupil irradiance is nonuniform, the formulas and results given previously do not apply. This is important to remember because most laser based optical systems do not have uniform pupil irradiance. The output beam of a laser operating in the TEM_{00} mode has a smooth Gaussian irradiance profile. Formulas to determine the focused spot size from such a beam are discussed in Chapter 2 under Gaussian Beam Theory. Furthermore, when dealing with Gaussian beams, the location of the focused spot also departs from that predicted by the paraxial equations.



$$y_c = \left(\frac{2J_1(x)}{x}\right)^2,$$

$$\text{where } J_1(x) = x\sum_{n=1}^{\infty}(-1)^{n+1}\frac{x^{2n-2}}{(n-1)!n!2^{2n-1}}$$

Note: $J_1(x)$ is the Bessel function of the first kind of order unity.

$$x = \frac{\pi}{\lambda} D \sin\theta$$

λ = Wavelength

D = Aperture diameter

θ = Angular radius from pattern maximum

$$y_s = \left(\frac{\sin x}{x}\right)^2, \text{ where } x = \frac{\pi}{\lambda} w \sin\theta$$

λ = Wavelength

w = Slit width

θ = Angular deviation direction of pattern maximum

Fraunhofer Diffraction Pattern of singlet slit superimposed on the Fraunhofer Diffraction Pattern of a circular aperture.

Lens Selection

We've now examined the most important factors which affect a lens' or lens system's performance. Let's turn now to the practical matter of selecting the optimum catalog components for a particular task.

Some of the most useful relationships to keep in mind through the selection process are:

Diffraction limited spot size = 2.44 f/#

Approximate on-axis spot size of a plano-convex lens at infinite conjugated due to spherical aberration = $\frac{0.067f}{f/\#^3}$

Optical invariant: m = $\frac{N.A.}{N.A."}$

Let's see how these are applied in some common situations:

Example #1:

Produce a collimated beam from a quartz halogen bulb having a filament with dimensions of approximately 1 mm square. Collect the maximum amount of light possible and produce a beam with the lowest possible divergence angle.

This problem involves the typical tradeoff between light collection efficiency and resolution (where a beam is being collimated rather than focused, resolution is defined by beam divergence). To collect more light, we need to work at a low f-number, but higher resolution (lower divergence angle) will be achieved by working at a higher f-number due to aberrations, at least for a system composed of catalog components.

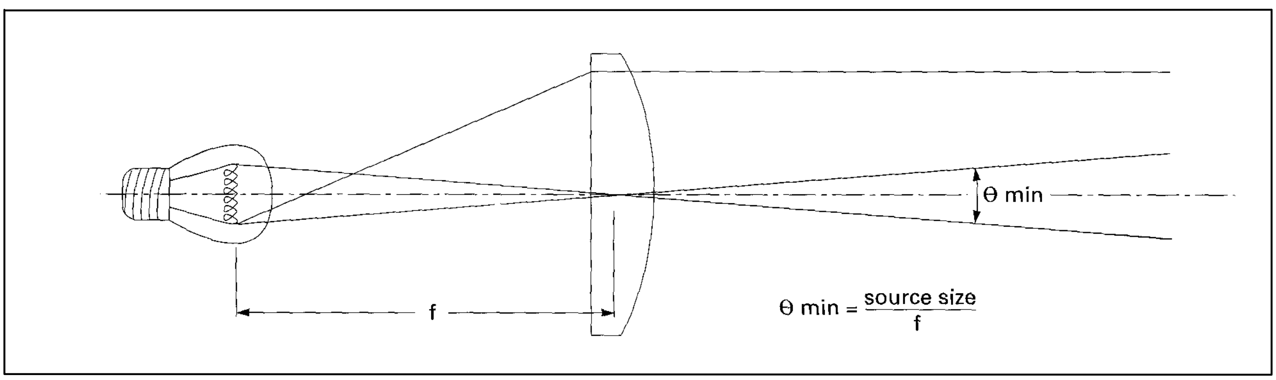
In terms of resolution, the first thing to realize here is that the minimum divergence angle (in radians) that can be achieved using any lens system is the source size divided by the system focal length. This is just a restatement of the fact that an off axis ray (from the edge of the source) which enters the first principal point of the system exits the second principal point at the same angle. Therefore, as we increase system focal length, we improve this limiting divergence since the source appears smaller.

Thus, we only need an optic which would produce a spot size of I mm when focusing a perfectly collimated beam. There's no point in striving for better resolution, since we're inherently limited by the source size. This level of resolution can easily be achieved with a piano-convex lens.

Now, while the angular divergence decreases with increasing focal length, the spherical aberration of a piano-convex lens increases with increasing focal length. In order to determine the appropriate focal length, let's simply set the spherical aberration formula for a piano-convex lens equal to our source (spot) size. This will guarantee that we pick a lens that meets the minimum performance we need.

$$\frac{0.067\ f}{f\#^3} = 1\ \text{mm}$$

We're going to have to make an arbitrary choice here about f-number in order to finally select a focal length. As we can see from the relationship, as we lower the f-number (increase collection



EXAMPLE 1. Collimating an incandescent source.

efficiency we're going to decrease the focal length, which will worsen the resultant divergence angle (minimum divergence = 1 mm/f).

Let's say we can live with f/2 collection efficiency. Plugging this in gives us a focal length of about 120 mm. For f/2 operation we would need a minimum diameter of 60 mm. Beam divergence would be about 8 mrad.

Finally, we need to verify that we aren't operating below the theoretical diffraction limit, even though the numbers (1 mm spot size) here make it fairly obvious that we're not.

diffraction limited spot size = 2.44 x .5 ,um x 2 = 2.44 Em

As suspected, were not even close to worrying about the diffraction limit here.

Example #2:

We discussed a system in which the output of an incandescent bulb with a filament of 1 mm diameter was to be coupled into an optical fiber which has a core diameter of 100 Em and a numerical aperture of 0.25. From the optical invariant and other constraints given in the problem we determined that system focal length was to be 9.1 mm, diameter = 5 mm, s = 100 mm, s" = 10 mm, N.A." = 0.25 and N.A. = 0.025 (or f/2 and f/20)..

We can immediately reject the biconvex lenses here, based on the discussion of spherical aberration give. We can estimate the performance of the focusing side using our spherical aberration formula (ignoring, for the moment, that we're not working at infinite conjugate).

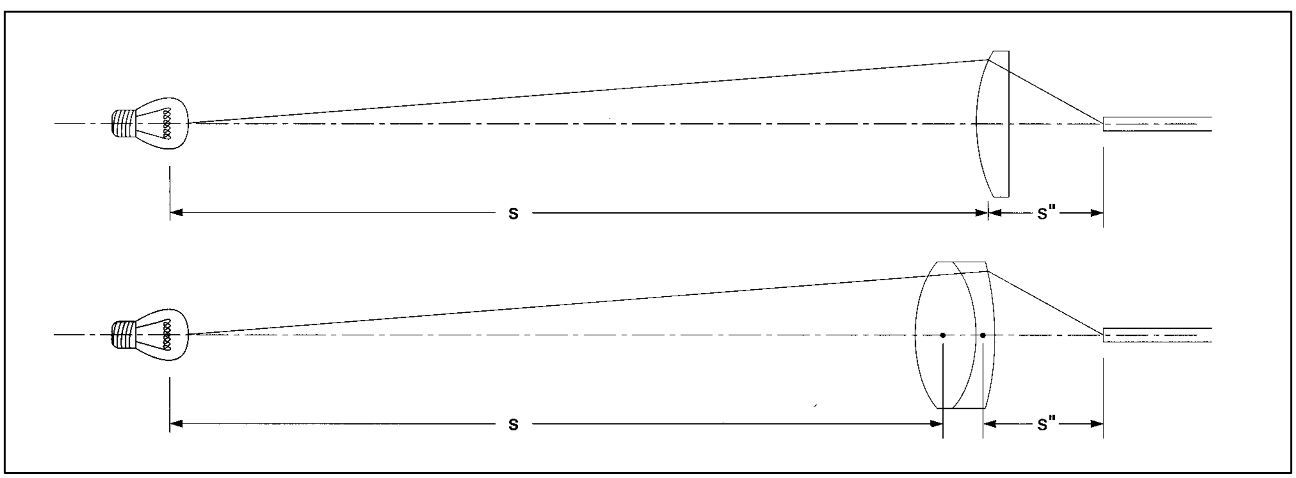
$$\text{Spot size} = \frac{0.067\,(10)}{2^3} = 84\ \text{um}$$

This is slightly smaller than the 100,um spot size we're trying to achieve. However, since we're not working at infinite conjugate, the spot size will be larger than given by our simple calculation. This lens is therefore likely to be marginal in this situation, especially if we take into account chromatic aberration. A better choice here is the achromat. While we would need a computer raytraee to determine it's exact performance here, it is virtually certain to provide the necessary performance, both in terms of spherical and chromatic aberration.

Example #3:

Couple an optical fiber with a 8 um core and a 0.15 N.A. into another fiber with the same characteristics. Assume a wavelength of 0.5 um.

This is essentially a 1:1 imaging situation; we want to collect and focus at an N.A. of 0.15 or f/3.3, and we need a lens which has an 8 Em spot size at this f-number.



EXAMPLE 2. Two solutions for coupling an incandescent source into a fiber.

Based on the discussion on page 1-22, our most likely setup is either a pair of identical piano-convex lenses or achromats, faced front-to-front. To determine the necessary focal length for a piano convex lens, we again use the spherical aberration estimate formula:

$$\frac{0.067\ f}{3.3^3} = 0.008 \text{ mm}$$

This yields a focal length of 4.3 mm and a minimum diameter of 1.3 mm. The biggest problem with utilizing these tiny, short focal length lenses is the practical considerations of handling, mounting, and positioning them. Since using a pair of longer focal length singlets would result in unacceptable performance, the next step might be to use a pair of the slightly longer focal length, larger achromats. The performance data, given, shows that this lens does provide the required 8 Em spot diameter.

Since we're dealing with fairly small spot sizes here, let's check to make sure we're not asking the system to work below the diffraction limit.

2.44×0.5 um $\times 3.3 = 4$ um

This is half our spot size due to aberrations, so we can safely assume that diffraction will not play a significant role here.

Example #4:

Determine at what f-number a piano convex lens being used at an infinite conjugate ratio with 0.5 um wavelength light becomes diffraction limited, i.e., the effects of diffraction exceed those due to aberration.
To solve this, we set the equations for diffraction limited spot size and third order spherical aberration equal to each other:

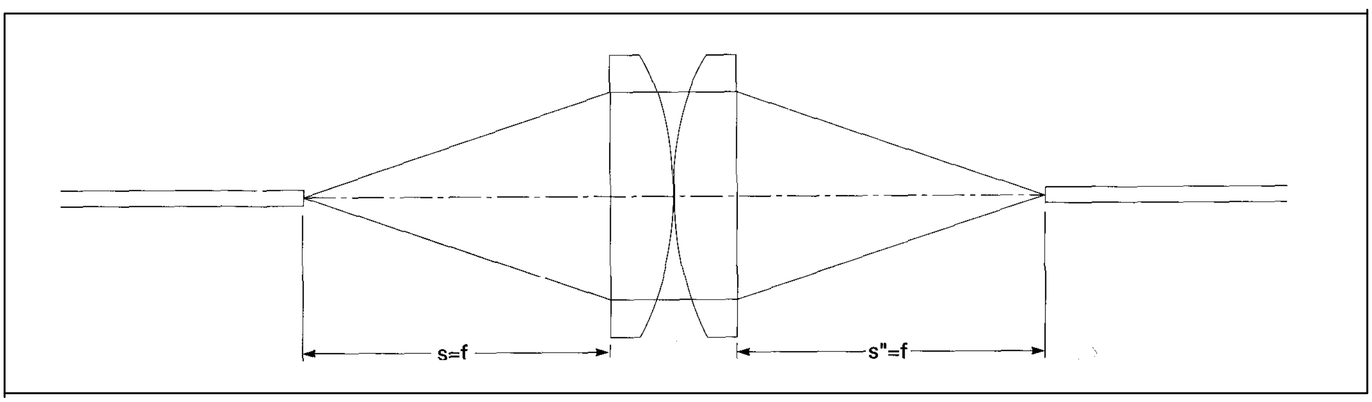
$$2.44 \times 0.5 \text{ um} \times f/\# = \frac{0.067 \times f}{f/\#^3}$$

or

$$f/\# = (54.9 \times f)^{1/4}$$

Thus, the result depends upon focal length, which is no surprise, since aberrations scale with focal length, while diffraction is solely dependent upon f-number. Substituting some common focal lengths into this formula, we get f/8.6 at f = 100 mm, V7.2 at f = 50 mm and f/4.8 at f = lO mm.

What this means is that when working with these focal lengths (and under the conditions stated at the outset), we can assume essentially diffraction limited performance above these f-numbers. Keep in mind, however, that this treatment does not take into account manufacturing tolerances or chromatic aberration, which will be present in polychromatic applications.



EXAMPLE 3. Symmetric Fiber-to-fiber coupling

Wavefront Distortion

Sometimes the best specification for an optical component is its effect on the emergent wavefront. This is particularly true for windows and retroreflectors.

Wavefront is the total, peak-to-peak, deformation (in the direction of propagation) of the emergent wavefront from its intended shape. Specifications are normally given in fractions of a wavelength.

Consider a perfectly plane monochromatic wavefront, incident in a direction normal to the face of a window. Deviations from perfect flatness in both surfaces of the window and, more importantly, inhomogeneities of the refractive index of the window, will all cause a deformation of that incident wavefront during transmission through the window. Likewise in a retroreflector each of the faces plus the material will affect the emergent wavefront. Also collimating lenses whose prime purpose is to produce a plane wavefront are best specified in terms of the maximum error in the emergent wavefront.

INTERFEROMETER MEASUREMENTS

Measurements of wavefront distortion are made using a laser interferometer. In the interferometers we use, the wavefront from a helium neon laser (= 632.8 nm) is expanded and then divided into a reference wavefront and a test wavefront by using a partially transmitting reference surface. The reference wavefront is reflected back to the interferometer and the test wavefront is transmitted through the surface to the test element. The reference surface is a known flat or spherical surface whose surface error is on the order of /20.

The test wavefront is reflected back to the interferometer either from the surface being tested or from another /20 reference surface, in this case passing twice through the element under test. The reference and test wavefronts are recombined at the interferometer where constructive and destructive interference takes place between the two wavefronts. A difference in optical paths of the two wavefronts is caused by any error present in the test element and any tilt of one wavefront relative to the other. The fringe pattern so produced is projected to a viewing screen or a camera system if a permanent record of the pattern is needed.

A slight tilt of the test wavefront to the reference wavefront produces a set of fringes whose parallelism and straightness depend on the amount that the test wavefront is altered by the element under test. The distance between successive fringes (usually measured dark band to dark band) represents one wavelength difference in optical path traveled by the two wavefronts. In both surface testing and transmitted wavefront testing, the test wavefront travels through the error in the test piece twice. Therefore one fringe spacing represents one half wavelength of surface or transmission error of the test element.

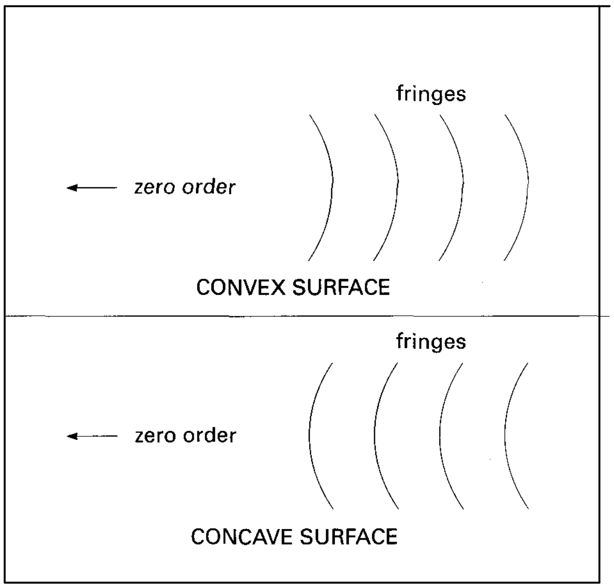
Determination of convexity or concavity of the test element error can be made if the zero order direction of the interference cavity, the space between the reference and test surfaces, is known. The zero order direction is the direction of the center of tilt between the reference and test wavefronts.

Fringes which curve around the center of tilt (zero order) are convex, caused by a high area on the test surface. Conversely, fringes which curve away from the center of tilt (zero order) are concave, caused by a low area on the test surface.

A fringe pattern in which a tilt of the reference wavefront with respect to the test wavefront is introduced, and the zero order direction is known, contains information as to the amount of error in the test element and the direction of the error, concave or convex. Normally about six fringes are introduced; increasing the angle between wavefronts decreases the spacing between interference fringes.

Wavefront distortion testing is used for the testing of achromats, windows, filters, beamsplitters, prisms, retroreflectors, and many other transmitting elements. This testing method is most nearly consistent with the way these optical elements or assemblies are used.

A flat, partially transmitting reference surface is used for most Forefront testing together with a flat or concave spherical reference mirror to reflect the test wavefront after it is transmitted by the test element.



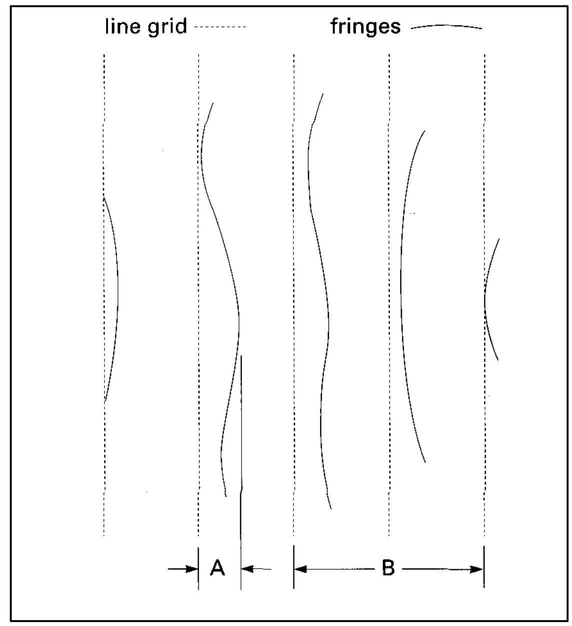
CONVEXITY OR CONCAVITY is determined by the direction of the zero order fringe in relation to the curvatures of the fringes.

NTERFEROGRAM INTERPRETATION

A straight, equally spaced line grid is the fringe pattern produced by a perfect reference surface and a perfect wavefront with a tilt introduced between the two. The deviation of a fringe from this straight line grid is a measure of the wavefront error of the element under test.

Test elements whose surface accuracy or wavefront distortion specification is 110 or worse can be evaluated by observing the fringe pattern at the interferometer. Since one fringe separation is equal to /2, an error of 0.2 fringe corresponds to an error of /10. This can easily be estimated by eye. If there is any doubt or if the specification is better than /10, the fringe pattern is photographed and an accurate evaluation is made from the interferogram.

To evaluate the interferogram a straight, equally spaced line grid with adjustable spacing is fitted to the fringe pattern on the photograph so that all the fringe error is to one side of the grid lines. The maximum deviation of the fringe pattern from the grid is measured and divided by two times the average spacing to give the number of wavelengths of error. The average fringe spacing is the same as the line grid spacing.



EVALUATION OF AN ITERFEROGRAM by comparison with a line grid. A represents the maximum deviation of the fringe pattern. B represents one wavelength. Thus the wavefront error = A/B wavelengths

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Modulation Transfer Function

Modulation Transfer Function (MTF) is a quantitative measure of image quality. It is the best such measure yet devised, and is far superior to any of the classical resolution criteria. From MTF the information content of an image can be deduced. MTF describes the ability of a lens or system, as a function of spatial frequency, to transfer object contrast to the image. MTF curves can be associated with the subsystems which make up a complete electro-optical or photographic system. With MTF data available, it can be seen whether overall system expectations are feasible.

Bar chart resolution testing of lens systems is deceptive, because almost 20% of the energy arriving at a lens system from a bar chart is modulated at 3rd harmonic and higher harmonic frequencies of the bar chart fundamental frequency. Consider instead a sine wave chart, in the form of a positive transparency on which transmittance varies one dimensionally in a precisely sinusoidal fashion. Such charts are difficult to make, but electronic methods exist by which experimental results duplicating those possible with a truly perfect sine wave chart can be achieved. Assume that the transparency is viewed against a uniformly illuminated background. The maximum and minimum transmittances are T_{max} and T_{min}, respectively. A lens system under test forms a real image of the sine wave chart, and the spatial frequency of the image is u cycles per millimeter. Corresponding to the transmittances T_{max} and T_{min} are the image irradiances I_{max} and I_{min}. By analogy with Michelson's definition of visibility of interference fringes, the contrast or modulation of the chart and image are respectively defined as

$$M_c = \frac{T_{max} - T_{min}}{T_{max} + T_{min}}$$

and

$$M_I = \frac{I_{max} - I_{min}}{I_{max} - I_{min}}$$

The modulation transfer function of the optical system at spatial frequency u is then defined to be

$$MTF = MTF(u) = M_I / M_c.$$

The graph of MTF versus u is a modulation transfer function curve. MTF is defined only for lenses or systems having positive focal length and forming real images.

MTF can be measured by a variety of methods, and instruments are commercially available which automatically measure MTF curves. MTF curves change as field angle positions are varied.

They also change with conjugate ratio. In a system with astigmatism or coma, different MTF curves are obtained corresponding to various azimuths in the image plane through a single image point. For cylindrical lenses only one azimuth is meaningful. MTF curves can be either polychromatic or monochromatic.

Polychromatic curves show the effect of any chromatic aberration that may be present. For a well-corrected achromatic system, polychromatic MTF can be computed by weighted averaging of monochromatic MTFs at a single image surface. Most instruments measure polychromatic MTF directly.

PERFECT CIRCULAR LENS

In diffraction limited performance, the monochromatic MTF of a circular aperture (perfect aberration free spherical lens) at arbitrary conjugate ratio is given by the formula

$$MDMTF(x) = \frac{2}{\pi}\left[\arccos(x) - x\sqrt{1 - x^2}\right].$$

where radian mode is intended for the arc cosine function, and x is the normalized spatial frequency

$$x = \frac{u}{u_{ic}}.$$

where u is the absolute spatial frequency, and u_{ic} is the incoherent diffraction cutoff spatial frequency. There are several formulas for u_{ic} including

$$u_{ic} = \frac{1.22}{r_d}$$

$$= \frac{n'' D \sqrt{1 - \left(\frac{1.22}{n'' D}\right)^2}}{s''}$$

$$= \frac{2n''\sin(u'') \sqrt{1 - \left(\frac{1.22}{n'' D}\right)^2}}{}$$

$$= \frac{2n''\sin[u'']}{} \qquad = \frac{n''D}{s''}.$$

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where rd is the linear spot radius in the case of pure diffraction (Airy Disc radius), D is the diameter of the lens clear aperture (or of a stop in near-contact), X is the wavelength, s" is the secondary conjugate distance, u" is the largest angle between any ray and the optical axis at the secondary conjugate point, the product n" sin(u") is by definition the image space numerical aperture, and n" is the image space refractive index. It is essential that D, X, and s" have consistent units (usually mm, in which case u and uic will be in cycles per millimeter). The relationship

$$\sin(u") = \frac{D}{2s"}$$

implies that the secondary principal surface is a sphere centered upon the secondary conjugate point. This means that the lens is completely free of spherical aberration and coma, and in the special case of infinite conjugate ratio (s" = f") this leads to the familiar textbook result that

$$u_{ic} = n" \frac{D}{f}.$$

Also, the Abbe sine condition is satisfied at infinite conjugate ratio. This is a mathematically definable condition, discovered by Abbe, in which the magnification for each part of the field is the same as for paraxial rays. This condition must be satisfied for a lens system to be free of coma and spherical aberration.

PERFECT RECTANGULAR LENS

In diffraction limited performance, the monochromatic MTF of a rectangular aperture (perfect aberration-less cylindrical lens) at arbitrary conjugate ratio is given by the formula

$$MDMTF(x) = (1 - x),$$

where x is again the normalized spatial frequency u/u_{jc}, where in the present cylindrical case

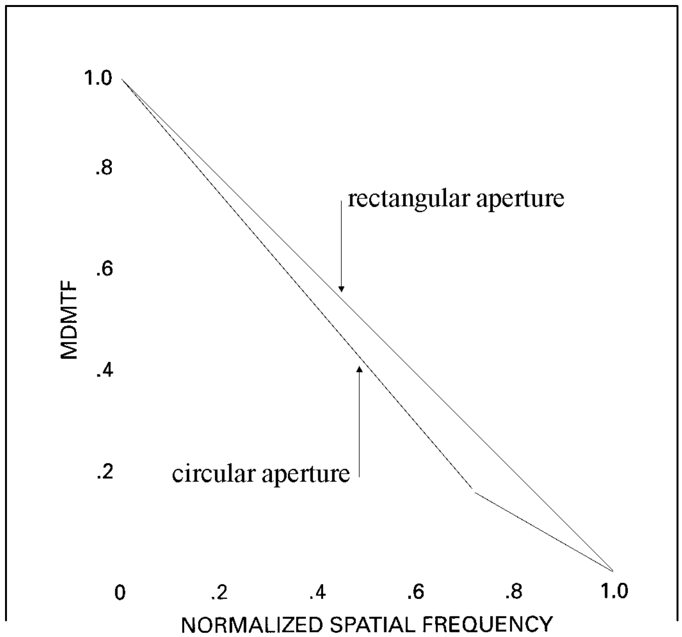
$$u_{ic} = \frac{1}{r_d},$$

and r_d must be interpreted as one-half the full width of the central stripe of the diffraction pattern measured from first maximum to f rst minimum. Notice how this formula differs (by a factor 1.22) from the corresponding formula in the circular aperture case. For both the circular and rectangular apertures, the following result applies:

$$u_{ic} = \frac{2n" \sin(u")}{}$$

The remaining three expressions for UjC in the circular aperture case can be applied to the present rectangular aperture case provided that two substitutions are made. Everywhere the constant 1.22 formerly appeared, it must be replaced by 1.00. Also the aperture diameter D must now be replaced by the aperture width w. The relationship sin(u") = w/2s" means that the secondary principal surface is a circular cylinder centered upon the secondary conjugate line. In the special case of infinite conjugate ratio this gives the result that for cylindrical lenses the incoherent cutoff frequency is

$$u_{ic} = n" \frac{w}{f}.$$



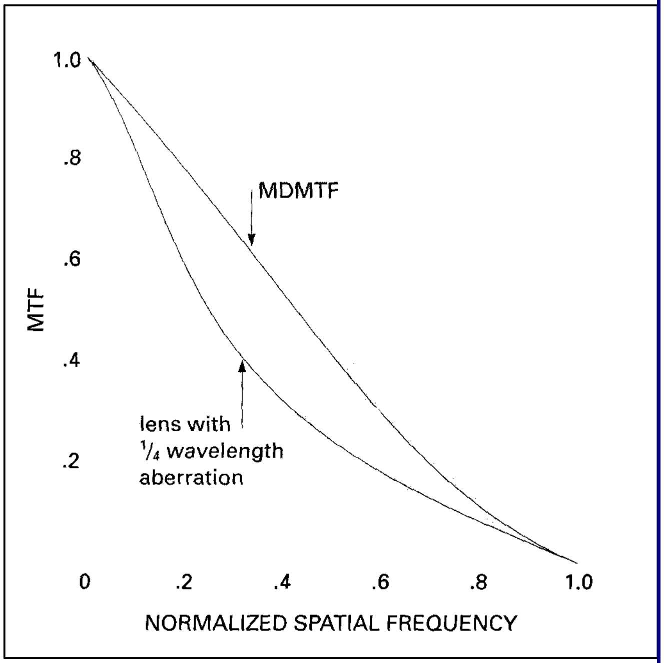
MDMTF(x) vs x. These curves (and the formulas they represent) precisely quantify an important and fundamental property common to all electromagnetic, de Broglie, and acoustic waves. All objects become more difficult, and ultimately impossible, to image as their dimensions diminish toward the radiation wavelength.

IDEAL PERFORMANCE AND REAL LENSES

For both formulas on the previous page, the x-intercept and MDMTF-intercept are at unity (1.0). MDMTF(x) for the rectangular case is a straight line between these intercepts. For the circular case MDMTF(x) is a curve which dips slightly below the straight line.

All real cylindrical monochromatic MTF curves fall on or below the straight MDMTF(x) line. Similarly all real spherical and monochromatic MTF curves fall on or below the circular MDMTF(x) curve. Thus the two MDMTF(x) curves represent the ultimate in optical performance. Optical element or system quality is measured by how closely the real MTF curve approaches the corresponding MDMTF(x) curve from below, and it is possible for real MTF curves to approach the MDMTF(x) curves very closely.

MTF is an extremely sensitive measure of image degradation. To illustrate this consider a lens having a quarter wavelength of spherical aberration. This aberration, barely discernible by eye, would reduce the MTF by as much as 0.2 at the midpoint of the spatial frequency range.



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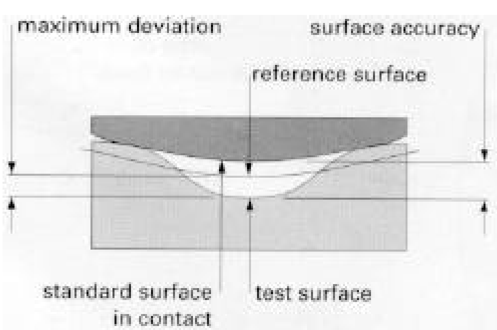
Surface Accuracy

When attempting to specify how closely an optical surface conforms to its intended shape, a measure of surface accuracy is needed. Common optical industry practice in the US, is to combine coarse and fine form errors stating one value for surface accuracy. The combination of form errors cannot exceed this value. Surface asymmetry and local deviations are both taken into account. Surface accuracy is a peakto-peak value, as is wavefront distortion, which has been discussed earlier.

Surface accuracy is defined as twice the maximum deviation of the surface under test from its ideal mathematical reference surface. Deviation has its customary statistical meaning here. The reference surface is defined by the ideal equation with coefficients which best approximate the surface under test. It is permitted to take up a position, embedded in the surface, so as to minimize the deviation. Specifications are normally given in fractions of a wavelength for either the mercury green line (546.1 nary), or the helium neon laser line (632.8 nary).



DEFINITION OF SURFACE ACCURACY.

SURFACE FLATNESS

Surface flatness is simply surface accuracy with respect to a plane reference surface. It is used extensively in mirror specifications.

POWER AND IRREGULARITY

During manufacture, a precision component is frequently compared with a test plate having an accurate polished surface which is the inverse of the surface under test. The two surfaces are brought together and viewed in near monochromatic light. Newton's rings (interference fringes caused by the near contact of the surfaces) are seen. The number of rings indicates the difference in radius between the surfaces. This is known as power, or sometimes figure. It is measured in rings which are equivalent to half wavelengths.

Beyond their number the rings may exhibit crookedness indicating non-uniform shape differences. The crookedness may be local to one small area of the surface or may be in the form of noncircular fringes over the whole aperture. All such non-uniformities are known collectively as irregularity.

Cosmetic Surface Quality
U.S. Military Specifications

Cosmetic surface quality describes the level of defects which can be visually noted on the surface of an optical component. Specifically, it defines the state of polish, freedom from scratches and digs, and the edge treatment of components. These factors are important, not merely to enhance the appearance of the component, but because they can have a serious adverse effect on performance due to light scattering. Scattering can be particularly important in laser applications due to the intensity of the incident illumination. Unwanted diffraction patterns caused by scratches can lead to degraded system performance, and scattering of high energy laser radiation can even cause component damage. Overspecifying cosmetic surface quality, on the other hand, can be costly. Components are specified at appropriate levels of cosmetic surface quality according to their intended application.

The most common and widely accepted convention for specifying surface quality is the U.S. Military Surface Quality Specification, MIL-0-13830A. The surface quality is defined according to this specification. In Europe there is an alternative specification, the DIN (Deutsche Industrie Norm) specification, DIN 3140, Sheet 7.

SPECIFICATION STANDARDS

As stated above, all the optics in this guide are referenced to the MIL Spec standards (MIL-0-13830A). These standards include those for scratches, digs, grayness, edge chips and cemented interfaces.

It is important to note that inspection of polished optical surfaces for scratches is accomplished by a purely visual comparison to scratch standards. Thus, it is not the actual width of the scratch which is ascertained, rather it is the appearance of the scratch as compared to these standards. A part is rejected if there are any scratches present which are more visible than the specified maximum. Digs, on the other hand, are specified by actual defect size, and can be measured quantitatively.

Due to the subjective nature of this examination, optics are compared by experienced QC personnel with scratch and dig standards which were manufactured according to the U.S. military drawing C7641866 Rev L; our inspection areas are equipped with lighting which meets the specific requirements of MIL-0-13830A.

The scratch and dig designation for a component or assembly is specified by two numbers; the first defining the allowable maximum scratch visibility, and the second referring to the allowable maximum dig diameter, separated by a hyphen.

For example:

80-50 represents a commonly acceptable cosmetic standard.

60 40 represents an acceptable standard for most scientific research applications.

10-5 represents a precise standard for very demanding laser applications.

SCRATCHES

A scratch is defined as any marking or tearing of a polished optical surface. In principle, the scratch number refers to the width of the reference scratch in ten thousandths of a millimeter; thus, an 80 scratch is equivalent to an 8 um standard scratch. However, keep in mind that this equivalence is determined purely by visual comparison, and the appearance of a scratch can depend upon the component material and presence of any coatings. Therefore, a scratch on the test optic which appears equivalent to the 80 standard scratch is not necessarily 8 um in width.

If maximum visibility scratches are present (e.g., several 60 scratches on a 60 40 lens), their combined lengths cannot exceed a quarter of the part diameter. Even with some maximum visibility scratches present, the MIL Spec still allows many combinations of smaller scratch sizes and lengths on the polished surface.

DIGS

A dig is defined as a pit or small crater on the polished optical surface.

Digs are defined by their diameters. The dig number represents the actual size of the dig in hundredths of a millimeter. The diameter of an irregularly shaped dig is 1/2 x (length plus width).

50 dig = 0.5 mm diameter

40 dig = 0.4 mm diameter

30 dig = 0.3 mm diameter

20 dig = 0.2 mm diameter

10 dig = 0.1 mm diameter

Smaller diameter digs are allowed with maximum diameter digs as shown below:

1. Clear aperture diameter 0 20 mm, 1 maximum dig allowed, and the maximum sum of dig diameters is 2 times the maximum dig diameter.

2. Clear aperture diameter 20 40 mm, 2 maximum digs allowed, and the maximum sum of dig diameters is 4 times the maximum dig diameter.

3. Clear aperture diameter 40 60 mm, 3 maximum digs allowed, and the maximum sum of dig diameter is 6 times the maximum dig diameter.

Digs of a specified maximum size of 10, or 0.1 mm diameter, must be separated edge to edge by at least 1 mm.

EDGE CHIPS

Lens edge chips are only allowed outside the clear aperture of the lens. The clear aperture is 90% of the lens diameter unless otherwise specified. Chips smaller than 0.5 mm are ignored and those larger than 0.5 mm are stoned or ground so that there is no shine to the chip. The sum of the widths of chips larger than 0.5 mm cannot exceed 10% of the lens perimeter.

Prism edge chips outside the clear aperture of the prism are allowed. If the prism leg dimension is 25.4 mm or less, chips may extend inward 1.0 mm from the edge. If the prism leg dimension is larger than 25.4 mm, chips may extend inward 2.0 mm from the edge. Chips smaller than 0.5 mm are ignored, and those larger than 0.5 mm must be stoned, or ground, leaving no shine to the chip. The sum of the widths of chips larger than 0.5 mm cannot exceed 10% of the length of the edge on which they occur.

CEMENTED INTERFACES

A cemented interface is considered a lens surface and specified surface quality standards apply. Edge separation at a cemented interface cannot extend into the element more than half the distance to the element clear aperture up to a maximum of 1.0 mm. The sum of edge separations deeper than 0.5 mm cannot exceed 10% of the element perimeter.

BEVELS

Although bevels are not specified in MIL-0-13830A, our standard shop practice specifies that element edges be beveled to a width of 0.25 to 0.5 mm at an angle of 45° ∀ 15°. Edges meeting at angles of 135° or larger are not beveled.

COATING DEFECTS

Defects caused by the coating of an optical element, such as coating scratches, voids or pinholes and dust or stain under the coating, are considered with the scratch and dig specification for that element. Coating defects are allowed if their size is within the stated scratch and dig tolerance.

Definition of Terms

FOCAL LENGTH

There are two distinct types of focal lengths associated with every lens or lens system. Most important of these is the Effective Focal Length (EFL) or Equivalent Focal Length (denoted f on the drawings which follow), which determines magnification and hence the image size. You will notice that f appears frequently in the lens formulas, in addition to being the quantity listed as focal length in the tables of standard lenses. Unfortunately, f is measured with reference to points (the principal points) which are usually inside the lens, and so the meaning of f is not immediately apparent when a lens is visually inspected.

The second type of focal length relates the focal plane positions directly to landmarks on the lens surfaces (namely the vertices) which are immediately recognizable. It is not simply related to image size, but is especially convenient for use when one is concerned about correct lens positioning or mechanical clearances. Examples of this second type of focal length are the Front Focal Length (FFL, denoted f_f on the drawing that follows) and the Back Focal Length (BFL, denoted f_b on the drawing that follows).

The convention in all of the drawings (with the exception of a single deliberately reversed ray in the following drawing) is that light travels from left to right.

FOCAL POINT (F OR F")

Rays which pass through or originate at either focal point must be, on the opposite side of the lens, parallel to the optical axis. This fact is the basis for locating both focal points.

PRIMARY PRINCIPAL SURFACE

Let us imagine that rays originating at the front focal point F (and therefore parallel to the optical axis after emergence from the opposite side of the lens) are singly refracted at some imaginary surface, instead of twice refracted (once at each lens surface) as actually happens. There is a unique imaginary surface, called the principal surface, at which this can happen.

To locate this unique surface, consider a single ray traced from the air on one side of the lens, through the lens and into the air on the other side. The ray is broken into three segments by the lens. Two of these are external (in the air), and the third is internal (in the glass). The external segments can be extended to a common point of intersection (certainly near, and usually within, the lens). The principal surface is the locus of all such points of intersection of extended external ray segments. The principal surface of a perfectly corrected optical system is a sphere centered on the focal point.

Near the optical axis, the principal surface is nearly flat, and for this reason, it is sometimes referred to as the Principal Plane.

SECONDARY PRINCIPAL SURFACE

Defined analogously to the primary principal surface, but for a collimated beam incident from the left and focused to the rear focal point F " on the right. Rays in that part of the beam nearest the axis can be thought of as once refracted at the secondary principal surface, instead of being refracted by both lens surfaces.

PRIMARY PRINCIPAL POINT IH) OR FIRST NODAL POINT

The intersection of the primary principal surface with optical axis.

SECONDARY PRINCIPAL POINT (H")
OR SECONDARY NODAL POINT

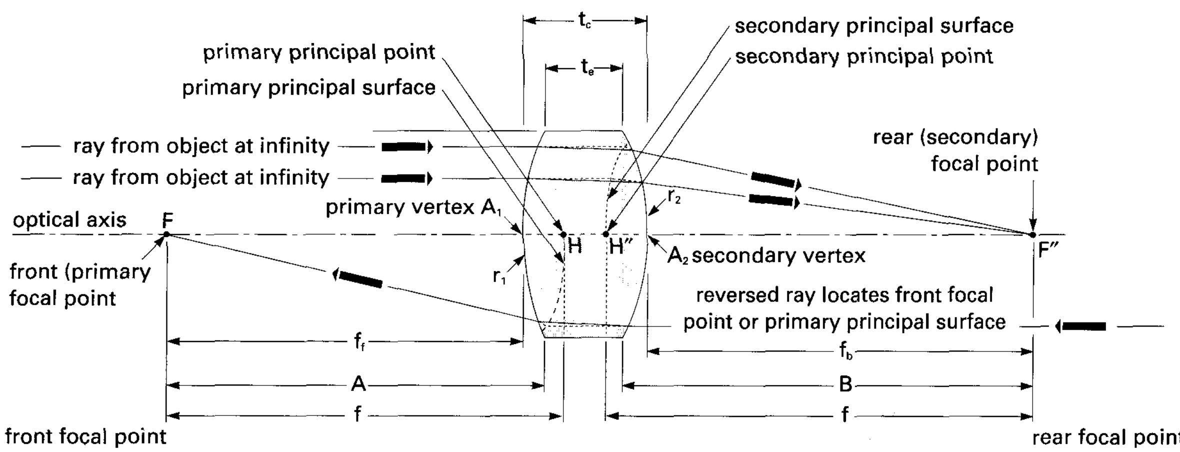
The intersection of the secondary principal surface with the optical axis.

CONJUGATE DISTANCES (S AND S")

The conjugate distances are the object distance, s, and image distance, s". Specifically, s is the distance from the object to H. and s" is the distance from H" to the image location. The term infinite conjugate ratio refers to the situation where a lens is either focusing incoming collimated light, or being used to collimate a source (therefore either s or s" is infinity).

PRIMARY VERTEX (A_1)

The intersection of the primary lens surface with the optical axis.



A	=	Front focus to front edge distance	f	=	Effective focal length (EFL), may be positive (as shown) or negative	t_e	=	Edge thickness	r_1	=	Radius of curvature of 1st surface (positive if center of curvature is to right)
B	=	Rear edge to rear focus distance	f_f	=	Front focal length (FFL)	t_c	=	Center thickness	r_2	=	Radius of curvature of 2nd surface (negative if center of curvature is to left)
			f_b	=	Back focal length (BFL)						

SECONDARY VERTEX (A_2)

The intersection of the secondary lens surface with the optical axis.

EFFECTIVE FOCAL LENGTH (f)

Assuming that the lens is surrounded by air or vacuum (refractive index 1.0), this is both the distance from the front focal point (F) to the primary principal point (H) and the distance from the secondary principal point (H") to the rear focal point (F"). Later we use (f) to designate the paraxial effective focal length for the design wavelength ($_0$).

FRONT FOCAL LENGTH (f_f)

The distance from the front focal point (F) to the primary vertex(A_1).

BACK FOCAL LENGTH (f_b)

The distance from the secondary vertex (A2) to the rear focal point (F").

EDGE-TO-FOCUS DISTANCES (A AND B)

A is the distance from the front focal point to the front edge of the lens. B is the distance from the rear edge of the lens to the rear focal point. Both distances are presumed to be always positive.

REAL IMAGE

A real image is one in which the light rays actually converge; if a screen were placed at the point of focus, an image would be formed on it.

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VIRTUAL IMAGE

A virtual image does not represent an actual convergence of light rays. A virtual image can only be viewed by looking back through the optical system at it, such as in the case of a magnifying glass.

F-NUMBER (FOCAL RATIO, RELATIVE APERTURE OR SPEED)

F-number of a lens system is defined to be the effective focal length divided by system clear aperture. Ray f-number is the conjugate distance for that ray divided by the height at which it intercepts the principal surface.

$$F/\# = \frac{f}{\iota}$$

NUMERICAL APERTURE (N.A.)

Numerical aperture of a lens system is defined to be the sine of the angle, 0~ that the marginal ray (the ray which exits the lens system at its outer edge) makes with the optical axis times the index of refraction, n of the medium. Numerical aperture can be defined for any ray as the sine of the angle which that ray makes with the optical axis times the index of refraction.

$$N.A. = \sin \sigma$$

MAGNIFICATION POWER

Often, we see positive lenses intended for use as simple magnifiers rated with a single magnification, such as 4 x . To create a virtual image for viewing with the human eye, in principle, any positive lens can be used at an infinite number of possible magnifications. However, there is usually a narrow range of magnifications which the viewer will find comfortable. It is typically found that when the viewer adjusts the object distance so that the image appears to be essentially at infinity (which is a comfortable viewing distance for most individuals), the following relationship gives magnification:

$$\text{Magnification} = \frac{250 \text{ mm}}{f}$$

Thus, a 25 mm focal length positive lens would be a 10x magnifier.

DIOPTERS

Diopters is a way of expressing focal length, or more exactly, the reciprocal of the focal length, commonly used in ophthalmic lenses. The inverse focal length of a lens expressed in diopters is

$$\text{Diopters} = \frac{1000}{f}$$

where f is in millimeters. Thus, the smaller the focal length, the larger the power in diopters.

DEPTH OF FIELD AND DEPTH OF FOCUS

In an imaging system, depth of field refers to the distance in object space over which the system delivers an acceptably sharp image. The criteria for what is acceptably sharp is arbitrarily chosen by the user; depth of field increases with increasing f-number.

For an imaging system, depth of focus is the range in image space over which the system delivers an acceptably sharp image. In other words, this is the amount that the image surface (such as a screen or piece of photographic film) could be moved and while maintaining acceptable focus. Again, the criteria for acceptability is defined arbitrarily.

In non-imaging applications, such as laser focusing, depth of focus refers to the range in image space over which the focused spot diameter remains below an arbitrary limit.

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Barium Fluoride (BaF_2)

MATERIAL: Barium Fluoride (BaF_2)
APPLICATIONS: Spectroscopic components extending into the IR slightly further than CaF_2. High density scintillator material with fast timing application.

PROPERTY	VALUE	REF. No
-OPTICAL-		
Transmission Range	0.15 to 12.5 microns	
Refractive Index	1.4626 at 2.6 microns	
Reflection Loss	6.8% at 2.6 microns (2 surfaces)	
Restrahlen Peak	47 microns	
dN/dT	-15.2×10^{-6}/°C	139
-PHYSICAL-		
Density	4.89 gm/cc	3, 6, 16, 26
Melting Point	1280°C	6
Thermal Conductivity	11.72 Wm^{-1} °K^{-1} at 13°C	3
Thermal Expansion	18.1×10^{-6}/°C at −100 to +120°C	30
Hardness	*Knoop 82 with 500gm indenter*	10, 12, 22, 31
Specific Heat Capacity	410 J Kgm^{-1} K^{-1} at 27°C	32
Dielectric Constant	7.33 at 2MHz	3
Young's Modulus (E)	53.07 GPa	32
Shear Modulus (G)	25.4 GPa	32
Bulk Modulus (K)	56.4 GPa	Calculated
Elastic Coefficients	C_{11}=89.2 C_{12}=40.0 C_{44}=25.4	32
Apparent Elastic Limit	26.89 MPa	31
Poisson Ratio	0.343	Calculated
-CHEMICAL-		
Solubility	0.17gm/100gm water at 23°C	6
Molecular Weight	175.36	
Class/Structure	Cubic CaF_2 (111) cleavage	

NOTES

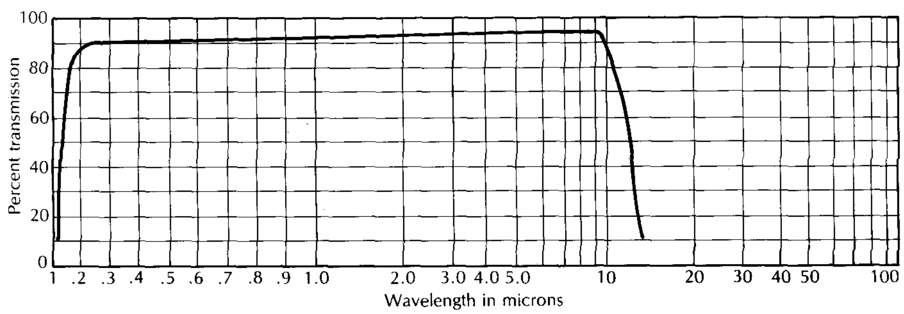
Barium fluoride is grown by vacuum Stockbarger technique in diameters up to 240mm. Polishing is quicker than calcium fluoride using diamond pastes but is less easy to obtain free of sleeks and is sensitive to temperature, and the material is susceptible to thermal shock.

Barium Fluoride scintillator grade material has typical absorbance of 0.2 at 190nm (transmissivity of 0.013mm^{-1}) through a 60mm path length, and 0.08 at 300nm (transmissivity of 0.015mm^{-1}).

For some detector applications, an intrinsic low radium count is required. Crystals can be supplied with a radium content <0.3 pgm/gm on request.

Materials Data

Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index
0.2652	1.51217	1.12866	1.46779
0.28035	1.50668	1.36728	1.46673
0.28936	1.50390	1.52952	1.46613
0.296728	1.50186	1.681	1.46561
0.30215	1.50044	1.7012	1.46554
0.3130	1.49782	1.97009	1.46472
0.32546	1.49521	2.1526	1.46440
0.334448	1.49363	2.32542	1.46356
0.340365	1.49257	2.5766	1.46262
0.34662	1.49158	2.6738	1.46234
0.361051	1.48939	3.2434	1.46018
0.366328	1.48869	3.422	1.45940
0.404656	1.48438	5.138	1.45012
0.465835	1.48173	5.3034	1.44904
0.486433	1.47855	5.343	1.44878
0.546074	1.47586	5.549	1.44732
0.589262	1.47443	6.238	1.44216
0.643847	1.47302	6.6331	1.43899
0.656279	1.47274	6.8559	1.43694
0.706519	1.47177	7.0442	1.43529
0.85211	1.46984	7.268	1.43314
0.89435	1.46942	9.724	1.40514
1.01398	1.46847	10.346	1.39636



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Calcium Fluoride (CaF_2)

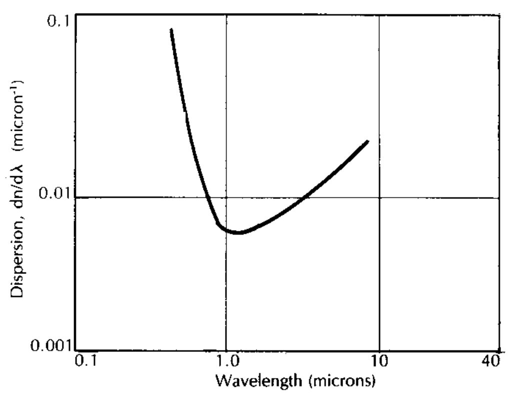
MATERIAL: Calcium Fluoride (CaF_2)
APPLICATIONS: Widespread IR application as spectroscopic accessories, prisms and lenses. Useful application in the UV as Eximer laser windows. Available doped with europium as a gamma ray scintillator.

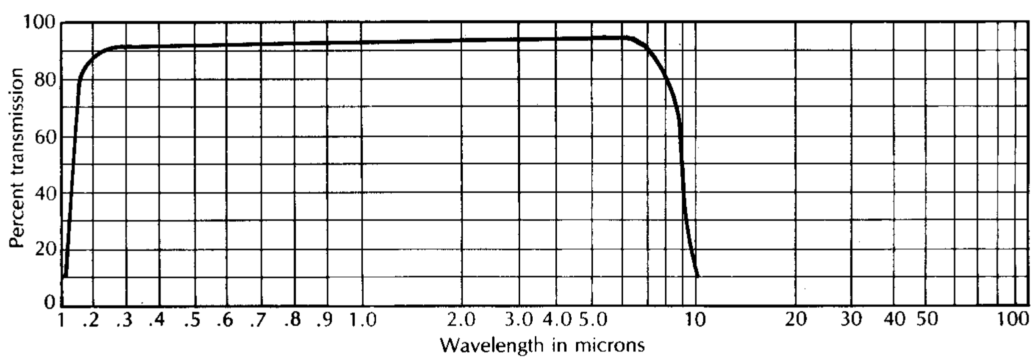
PROPERTY	VALUE	REF. No
-OPTICAL-		
Transmission Range	0.13 to 10 microns	
Refractive Index	1.39908 at 5 microns	
Reflection Loss	5.4% at 5 microns (2 surfaces)	
Restrahlen Peak	35 microns	120, 121
dN/dT	-10.6×10^{-6}/°C	139
-PHYSICAL-		
Density	3.18 gm/cc	24
Melting Point	1360°C	6
Thermal Conductivity	9.71 Wm^{-1} $°K^{-1}$	17
Thermal Expansion	18.85×10^{-6}/°C	19
Hardness	Knoop 158.3 (100)	11, 12, 20
Specific Heat Capacity	854 J Kgm^{-1} $°K^{-1}$	5, 6
Dielectric Constant	6.76 at 1MHz	3, 20, 26
Young's Modulus (E)	75.8 GPa	5, 20
Shear Modulus (G)	33.77 GPa	5, 20
Bulk Modulus (K)	82.71 GPa	5, 20
Elastic Coefficients	$C_{11}=164$ $C_{12}=53$ $C_{44}=33.7$	5
Apparent Elastic Limit	36.54 MPa	28
Poisson Ratio	0.26	21
-CHEMICAL-		
Solubility	0.0017gm/100gm water at 20°C	6
Molecular Weight	78.08	
Class/Structure	Cubic (111) cleavage	

NOTES
Calcium fluoride is grown by vacuum Stockbarger technique in diameters up to 35cm. Material for IR use is grown using naturally mined fluorite, in large quantities at relatively low cost. Optipur: CaF_2 is recommended for UV applications and is manufactured from chemically pure powder.

Materials Data

Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index
0.1495	1.580	1.4733	1.42642	2.800	1.41923
0.1612	1.549	1.5715	1.42596	2.880	1.41890
0.1950	1.500	1.650	1.42558	2.9466	1.41823
0.2	1.495	1.7680	1.42502	3.0500	1.41750
0.3	1.454	1.8400	1.42468	3.0980	1.41714
0.4	1.4419	1.8688	1.42454	3.2413	1.41610
0.48615	1.43704	1.900	1.42439	3.400	1.41487
0.58758	1.43388	1.9153	1.42431	3.5359	1.41376
0.58932	1.43384	1.9644	1.42407	3.8306	1.41119
0.65630	1.43249	2.0582	1.42360	4.000	1.40963
0.68671	1.43200	2.0626	1.42357	4.1252	1.40847
0.72818	1.43143	2.1608	1.42306	4.2500	1.40722
0.76653	1.4276	2.250	1.42258	4.4000	1.40568
0.88400	1.42980	2.3573	1.42198	4.6000	1.40357
1.0140	1.42884	2.450	1.42143	4.7146	1.40233
1.08304	1.42843	2.5537	1.42080	4.8000	1.40130
1.1000	1.42834	2.6519	1.42018	5.000	1.39908
1.1786	1.42789	2.700	1.41988	5.3036	1.39522
1.250	1.42752	2.750	1.41956	5.8932	1.38712
1.3756	1.42689			6.4825	1.37824
				7.0718	1.36805
				7.6612	1.35675
				8.2505	1.34440
				8.8398	1.33075
				9.4291	1.31605





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Germanium (Ge)

MATERIAL: Germanium (Ge)
APPLICATIONS: IR Optics in the 4-6 and 8-14 micron bands, particularly thermal imaging.

PROPERTY	VALUE	REF. No
-OPTICAL-		
Transmission Range	1.8 to 23 microns	27
Refractive Index	4.0034 at 9.72 microns	38, 78
Reflection Loss	52.9% at 10 microns (2 surfaces)	28
Restrahlen Peak		
dN/dT	396×10^{-6}/°C	78
-PHYSICAL-		
Density	5.327 gm/cc	
Melting Point	936°C	2, 39
Thermal Conductivity	58.61 Wm^{-1} $°K^{-1}$ at 20°C	
Thermal Expansion	5.5 to 6.1×10^{-6}/°C	39, 42
Hardness	Knoop 780	43, 44
Specific Heat Capacity	310 J Kgm^{-1} $°K^{-1}$ 0 to 100°C	39
Dielectric Constant	16.6 at 9.37GHz	45
Young's Modulus (E)	102.7 GPa (100), 155.3 GPa (111)	42, 46, 47
Shear Modulus (G)	67 GPa (100)	42, 47
Bulk Modulus (K)	77.2 GPa	42, 47
Elastic Coefficients	$C_{11}=129$ $C_{12}=48.3$ $C_{44}=67.1$	47
Apparent Elastic Limit		
Poisson Ratio	0.28	42
-CHEMICAL-		
Solubility	Soluble in hot H_2SO_4 and aqua-regia	6
Molecular Weight	72.59	
Class/Structure	Cubic, diamond structure. $E_g=0.67$ev	

NOTES

We do not manufacture germanium, but hold stock of Czochralski grown material of various diameters. It can be used polycrystalline or as single crystal. The purity should correspond to an electrical resistivity of at least 20 to 30 ohm cm, either p or n-type to avoid absorption bands.

Germanium polishes easily using pitch laps and alumina, and it can also be diamond machined readily into aspheric components. The high refractive index makes anti-reflection coating essential and recently the technique of hard diamond like coatings have been developed.

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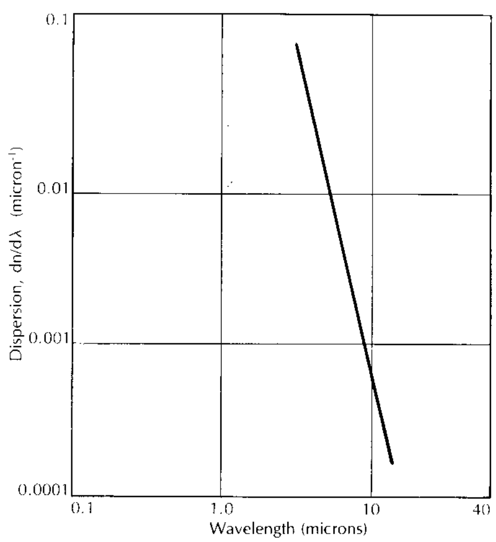
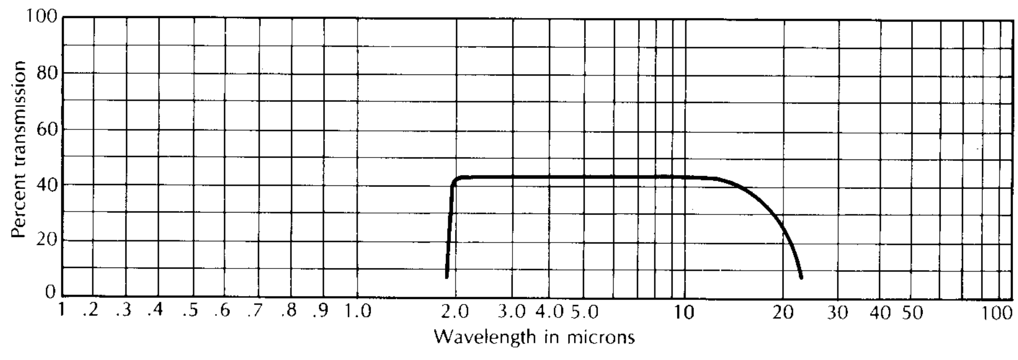
Materials Data

Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index
2.0581	4.1016	2.998	4.0452	8.66	4.0043
2.1526	4.0919	3.3033	4.0369	9.72	4.0034
2.3126	4.0786	3.4188	4.0334	11.04	4.0026
2.4374	4.0708	4.258	4.0216	12.0	4.0023
2.577	4.0609	4.866	4.0170	13.02	4.0021
2.7144	4.0552	6.238	4.0094		





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Lithium Fluoride (LiF)

MATERIAL: Lithium Fluoride (LiF)
APPLICATIONS: UV and Vacuum UV optics. X-ray monochromator plates.

PROPERTY	VALUE	REF. No
-OPTICAL-		
Transmission Range	0.12 to 8.5 microns	58
Refractive Index	1.3943 at 0.5 microns	146
Reflection Loss	5.3% at 0.5 microns (2 surfaces)	
Restrahlen Peak	25 microns	95
dN/dT	-12.7×10^{-6}/°C at 0.6 microns	
-PHYSICAL-		
Density	2.63905 gm/cc	135
Melting Point	870°C	6
Thermal Conductivity	4.01 Wm^{-1} $°K^{-1}$ at 41°C	11
Thermal Expansion	37×10^{-6}/°C	11
Hardness	Knoop 102 to 113 with 600gm indenter	11
Specific Heat Capacity	1562 J Kgm^{-1} $°K^{-1}$ at 10°C	6
Dielectric Constant	9.1 at 25°C	7
Young's Modulus (E)	64.79 GPa	11
Shear Modulus (G)	55.14 GPa	11
Bulk Modulus (K)	62.03 GPa	11
Elastic Coefficients	$C_{11}=97.4$ $C_{12}=40.4$ $C_{44}=55.4$	74
Apparent Elastic Limit	11.2 MPa	31
Poisson Ratio	0.326	Calculated
-CHEMICAL-		
Solubility	0.27gm/100gm water at 20°C	6
Molecular Weight	25.94	
Class/Structure	FCC, NaCl structure. Cleavage (100)	

NOTES

Lithium fluoride is grown by vacuum Stockbarger technique in diameters of 115mm for VUV quality, transmission of 40% at Lyman alpha (0.1216 microns) through 2mm is guaranteed. Although the optical characteristics are good the structure is not perfect and cleavage is difficult. For good structure LiF is less commonly grown by the Kyropoulos method (air-grown) specifically for monochromator plates. Cleavage is (100) and less commonly (110). LiF is slightly plastic and can be bent into radius plates.

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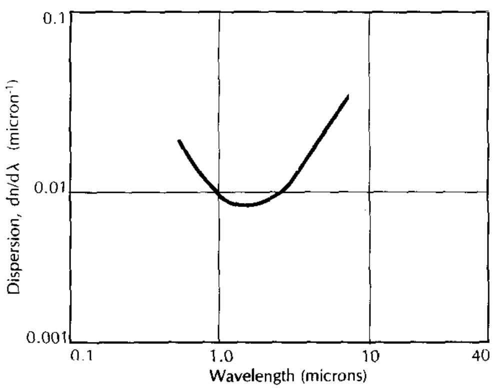
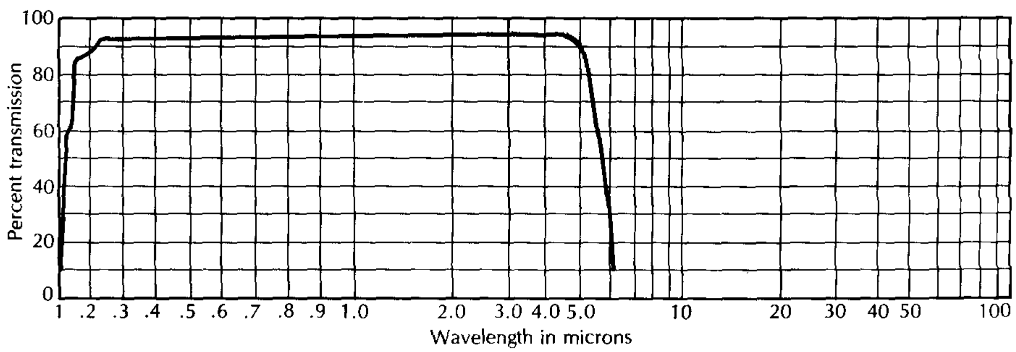
Materials Data

Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index
0.106	1.913	1.9	1.37971	3.9	1.35138
0.108	1.833	2.0	1.37875	4.0	1.34942
0.11	1.777	2.1	1.37774	4.1	1.34740
0.121	1.624	2.2	1.37669	4.2	1.34533
0.16	1.482	2.3	1.37560	4.3	1.34319
0.2	1.442	2.4	1.37446	4.4	1.34100
0.5	1.39430	2.5	1.37327	4.5	1.33875
0.6	1.39181	2.6	1.37203	4.6	1.33645
0.7	1.39017	2.7	1.37075	4.7	1.33408
0.8	1.38896	2.8	1.36942	4.8	1.33165
0.9	1.38797	2.9	1.36804	4.9	1.32916
1.0	1.38711	3.0	1.36660	5.0	1.32661
1.1	1.38631	3.1	1.36512	5.1	1.32399
1.2	1.38554	3.2	1.36359	5.2	1.32131
1.3	1.38477	3.3	1.36201	5.3	1.31856
1.4	1.38400	3.4	1.36037	5.4	1.31575
1.5	1.38320	3.5	1.35868	5.5	1.31287
1.6	1.38238	3.6	1.35693	5.6	1.30993
1.7	1.38153	3.7	1.35514	5.7	1.30692
1.8	1.38064	3.8	1.35329	5.8	1.30384





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Magnesium Fluoride (MgF2)

MATERIAL: Magnesium Fluoride (MgF_2)
APPLICATIONS: UV and Vacuum UV windows, lenses, polarisers.

PROPERTY	VALUE	REF. No
-OPTICAL-		
Transmission Range	0.11 to 7.5 microns	101
Refractive Index	No=1.3836 Ne=1.3957 at 0.405 microns	146
Reflection Loss	*11.2% at 0.12 microns (2 surfaces)*	*101*
Restrahlen Peak	20 microns	101
dN/dT and dN./dT	+2.3 and $+1.7\times10^{-6}$/°C at 0.4 microns	101
-PHYSICAL-		
Density	3.177 gm/cc	
Melting Point	1255°C	
Thermal Conductivity	0.3 Wm^{-1} °K^{-1} at 27°C	102
Thermal Expansion	13.7 and 8.48×10^{-6}/°C	101
Hardness	Knoop 415	16
Specific Heat Capacity		
Dielectric Constant	4.87 parallel and 5.45 perpendicular	101
Young's Modulus (E)	138.5 GPa	104
Shear Modulus (G)	54.66 GPa	104
Bulk Modulus (K)	101.32 GPa	104
Elastic Coefficients	C_{11}=140.2 C_{12}=89.5 C_{44}=56.8 C_{33}=204.7 C_{13}=62.9 C_{66}=95.7	104
Apparent Elastic Limit	49.64 MPa	108
Poisson Ratio	0.276	104
-CHEMICAL-		
Solubility	<0.0002 gm/100gm water at 0°C	6
Molecular Weight	62.32	
Class/Structure	Tetragonal, can cleave on C-axis	

NOTES

Magnesium fluoride is a positive birefringent crystal grown normally to 135mm diameter by vacuum Stockbarger technique, seeding along the C-axis. The main application is in the Vacuum UV region and so particular care is taken with the raw material and each ingot is sampled and tested to achieve a minimum transmission of 40% at Lyman-alpha (0.1216 micron) through a 2mm window, and all ingots are tested with a deuterium lamp for the weak fluorescence which can occur. Magnesium fluoride is a proven window material for Eximer lasers and resistance to laser damage is good, nevertheless permanent colour centre formation does occur.

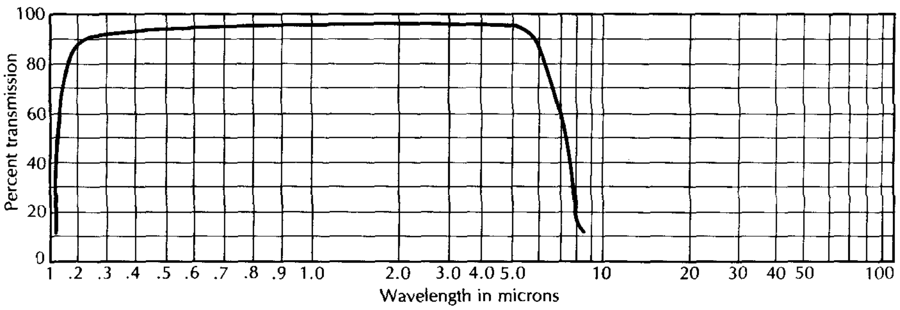
Magnesium fluoride is a rugged, hard material which is resistant to thermal and mechanical shock. Considerable mechanical shock is needed to cause cleavage which is near perfect when it occurs.

The natural form of MgF_2 is known as Sellaite. A hot pressed polycrystalline form of MgF_2 was developed by the Eastman Kodak company and known as Irtran-1.

Magnesium fluoride doped with cobalt is under investigation for laser systems.

Materials Data

Wave-length(μ)	Refractive Index No	Ne
0.114	1.7805	
0.115	1.742	1.7215
0.118	1.6800	
0.121	1.62	1.632
0.130	1.556	1.568
0.140	1.509	1.523
0.150	1.480	1.494
0.160	1.461	1.475
0.170	1.447	1.462
0.180	1.439	1.453
0.190	1.431	1.444
0.200	1.422	1.436
0.3	1.40	1.41
0.4	1.383	1.395
0.7	1.376	1.387



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Potassium Bromide (KBr)

MATERIAL: Potassium Bromide (KBr)
APPLICATIONS: IR Spectroscopic components, beamsplitters, CO_2 lasers

PROPERTY	VALUE	REF. No
-OPTICAL-		
Transmission Range	0.23 to 25 microns	
Refractive Index	1.52695 at 9.724 microns	73
Reflection Loss	8.4% at 10 microns (2 surfaces)	
Restrahlen Peak	77.6 microns	
dN/dT	-40.83×10^{-6}/°C	73
-PHYSICAL-		
Density	2.7533 gm/cc	136
Melting Point	730°C	
Thermal Conductivity	4.816 Wm^{-1} $°K^{-1}$ at 46°C	17
Thermal Expansion	43×10^{-6}/°C	11
Hardness	Knoop 5.9 (110) 7.0 (100) 200gm load	11
Specific Heat Capacity	435 J Kgm^{-1} $°K^{-1}$ 0°C	6
Dielectric Constant	4.9	7
Young's Modulus (E)	26.8 GPa	11
Shear Modulus (G)	5.08 GPa	11
Bulk Modulus (K)	15.03 GPa	11
Elastic Coefficients	C_{11}=34.5 C_{12}=5.4 C_{44}=5.08	74
Apparent Elastic Limit	1.1 MPa	11
Poisson Ratio	0.203	Calculated
-CHEMICAL-		
Solubility	53.48gm/100gm water at 0°C	
Molecular Weight	119.01	
Class/Structure	FCC NaCl structure. (100) cleavage	

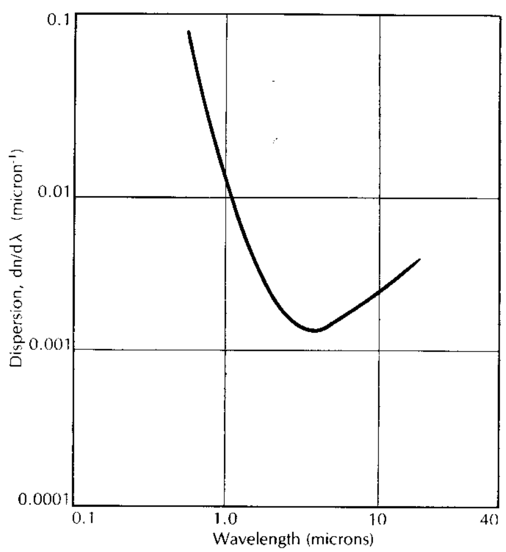
NOTES

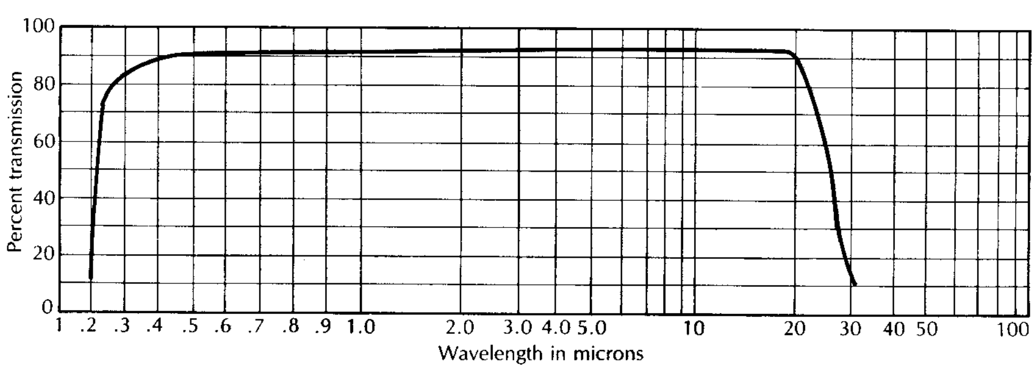
Potassium bromide is grown by Kyropoulos technique in diameters up to 300mm.

Potassium bromide can be hot forged using polished dies giving polycrystalline material of increased strength. Windows and lenses with an adequate IR surface quality can be fabricated directly and cost effectively by this method.

Materials Data

Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index
0.404656	1.589752	1.7012	1.53901	14.29	1.51505
0.435835	1.581479	2.44	1.53733	14.98	1.51280
0.486133	1.571791	2.73	1.53693	17.40	1.50390
0.508582	1.568475	3.419	1.53612	18.16	1.50076
0.546074	1.563928	4.258	1.53523	19.01	1.49703
0.587562	1.559965	6.238	1.53288	19.91	1.49288
0.643847	1.555858	6.692	1.53225	21.18	1.48655
0.706520	1.552447	8.662	1.52903	21.83	1.48311
1.01398	1.54408	9.724	1.52695	23.86	1.47140
1.12866	1.54258	11.035	1.52404	25.14	1.46324
1.36728	1.54061	11.862	1.52200		





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Sapphire (AI_2O_3)

MATERIAL: Sapphire (Al_2O_3)
APPLICATIONS: High temperature and severe environment windows, watch glasses.

PROPERTY	VALUE	REF. No
-OPTICAL-		
Transmission Range	0.15 to 5.5 microns	
Refractive Index	1.755 at 1.0139 microns	139, 140
Reflection Loss	14% at 1 micron (2 surfaces)	
Restrahlen Peak	13.5 microns	
dN/dT	$+13\times10^{-6}$/°C	
-PHYSICAL-		
Density	3.97 gm/cc	
Melting Point	2040°C	
Thermal Conductivity	22.21 Wm^{-1} $°K^{-1}$ at 46°C	141
Thermal Expansion	8.4×10^{-6}/°C	141
Hardness	Knoop 2000	
Specific Heat Capacity	419 J Kgm^{-1} $°K^{-1}$ 0°C	141
Dielectric Constant	11.5 parallel C-axis; 9.4 perpendicular	141
Young's Modulus (E)	335 GPa	141
Shear Modulus (G)	148 GPa	141
Bulk Modulus (K)	240 GPa	141
Elastic Coefficients	$C_{11}=496$ $C_{12}=164$ $C_{44}=148$ $C_{33}=498$	5
Apparent Elastic Limit	448 MPa to 689 MPa	141
Poisson Ratio	0.25	141
-CHEMICAL-		
Solubility	98×10^{-6} gm/100gm water	
Molecular Weight	101.96	
Class/Structure	Hexagonal-Rhombohedral R3c	

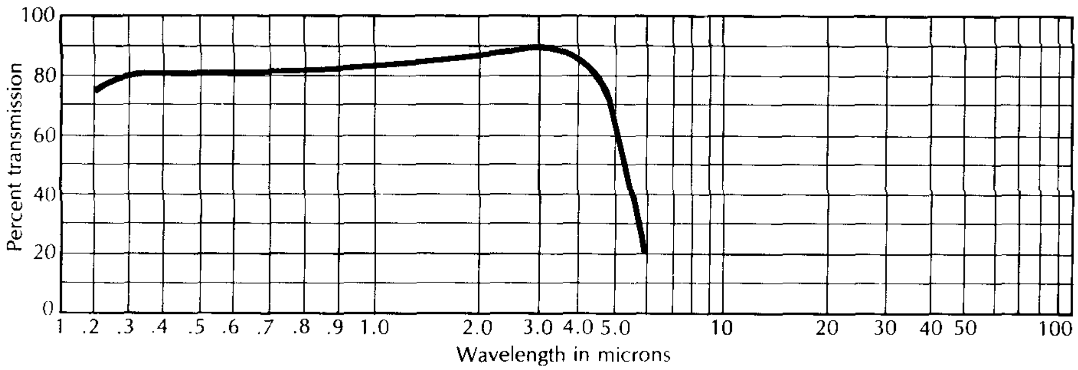
NOTES

Sapphire is an excellent material for severe environments, having high strength, hardness and chemical stability. The IR cut-off at 5.5 microns limits the ultimate usefulness of the material.

Sapphire is very slightly negative birefringent. Refractive indexes for the e-ray are approximately 0.008 less than the figures for the o-ray quoted.

Materials Data

Wave-l length(μ)	Refractive Index	Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index
0.265	1.833	0.4046	1.785	1.1286	1.753
0.280	1.824	0.5460	1.770	1.6932	1.743
0.2967	1.815	0.5790	1.765	2.2492	1.732
0.3130	1.809	0.7065	1.763	3.3026	1.702
0.3466	1.798	0.8944	1.757	4.2553	1.663
0.3650	1.793	1.0139	1.755	5.777	1.586



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Silicon (Si)

MATERIAL: Silicon (Si)
APPLICATIONS: IR windows in the 3-5 micron band

PROPERTY	VALUE	REF. No
-OPTICAL-		
Transmission Range	1.2 to 10 microns	
Refractive Index	3.4223 at 5 microns	76 to 79
Reflection Loss	46.1% at 5 microns (2 surfaces)	
Restrahlen Peak		
dN/dT	$+160\times10^{-6}$/°C	78
-PHYSICAL-		
Density	2.3291 gm/cc	
Melting Point	1420°C	
Thermal Conductivity	163.32 Wm^{-1} $°K^{-1}$ at 0°C	2, 41, 80
Thermal Expansion	4.15×10^{-6}/°C	39, 41, 81
Hardness	Knoop 1150	5, 75, 82
Specific Heat Capacity	703 J Kgm^{-1} $°K^{-1}$ at 25°C	3, 39, 41
Dielectric Constant	13.0 at 10GHz	45
Young's Modulus (E)	131 GPa	39, 83, 84
Shear Modulus (G)	79.9 GPa	39, 84
Bulk Modulus (K)	102.0 GPa	39
Elastic Coefficients	$C_{11}=167$ $C_{12}=65$ $C_{44}=80$	84
Apparent Elastic Limit		
Poisson Ratio	0.266	84
-CHEMICAL-		
Solubility	Insoluble in water	
Molecular Weight	28.09	
Class/Structure	Cubic, Diamond structure. $E_g=1.12$ eV	

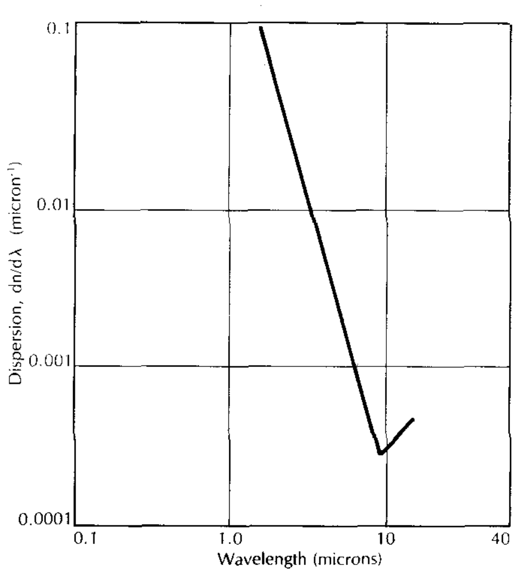
NOTES

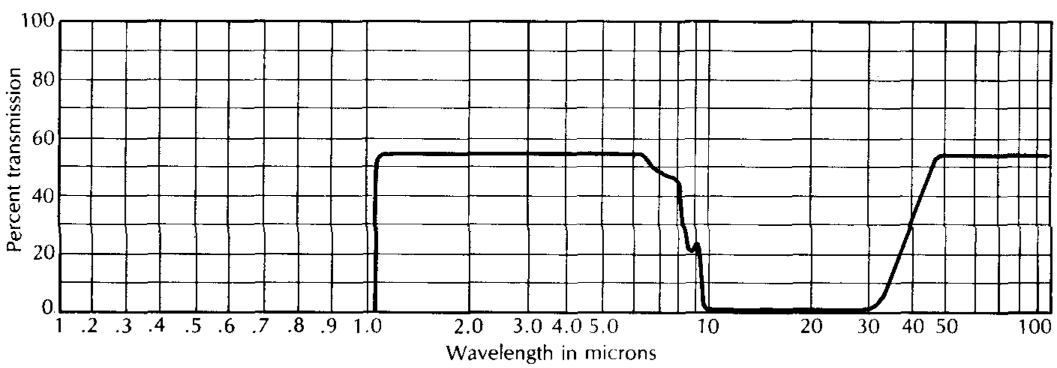
We do not manufacture silicon but hold stock of optical grade Czochralski grown ingot of various diameters.

Silicon can be polished in many ways but proprietary chemical-mechanical polishes as used in the semiconductor industry are most effective. The high refractive index means that silicon must be anti-reflection coated with SiO_2 or ZnS.

Materials Data

Wave-l length(μ)	Refractive Index	Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index
1.3570	3.4975	2.4373	3.4408	5.50	3.4213
1.3673	3.4962	2.7144	3.4358	6.00	3.4202
1.3951	3.4929	3.00	3.4320	6.50	3.4195
1.5295	3.4795	3.3033	3.4297	7.00	3.4189
1.6606	3.4696	3.4188	3.4286	7.50	3.4186
1.7092	3.4664	3.50	3.4284	8.00	3.4184
1.8131	3.4608	4.00	3.4255	8.50	3.4182
1.9701	3.4537	4.258	3.4242	10.00	3.4179
2.1526	3.4476	4.50	3.4236	10.50	3.4178
2.3254	3.4430	5.00	3.4223	11.04	3.4176





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Sodium Chloride (NaCI)

MATERIAL: Sodium Chloride (NaCl)
APPLICATIONS: Spectroscopic accessories, CO_2 lasers.

PROPERTY	VALUE	REF. No
-OPTICAL-		
Transmission Range	0.2 to 20 microns	1
Refractive Index	1.4998 at 9.5 microns	4
Reflection Loss	7.5% at 10 microns (2 surfaces)	
Restrahlen Peak	50.1 microns	
dN/dT	-36×10^{-6}/°C at 0.7 microns	5
-PHYSICAL-		
Density	2.165 gm/cc	5
Melting Point	801°C	2
Thermal Conductivity	1.15 Wm^{-1} $°K^{-1}$ at 0°C	3, 5
Thermal Expansion	44×10^{-6}/°C	5
Hardness	Knoop 18.2 (100)	11, 12
Specific Heat Capacity	854 J Kgm^{-1} $°K^{-1}$ at 0°C	5, 6
Dielectric Constant	5.9	7
Young's Modulus (E)	39.98 GPa	5
Shear Modulus (G)	12.61 GPa	5
Bulk Modulus (K)	24.42 GPa	5
Elastic Coefficients	C_{11}=48.5 C_{12}=12.3 C_{44}=12.61	5
Apparent Elastic Limit	2.41 MPa	5
Poisson Ratio	0.252	8
-CHEMICAL-		
Solubility	35.7gm/100gm water at 0°C	
Molecular Weight	58.45	
Class/Structure	FCC, NaCl structure, (100) cleavage	

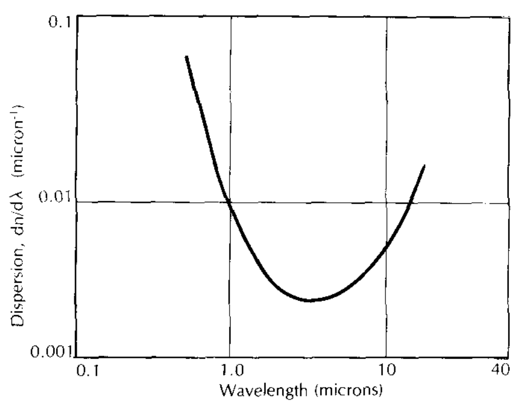
NOTES

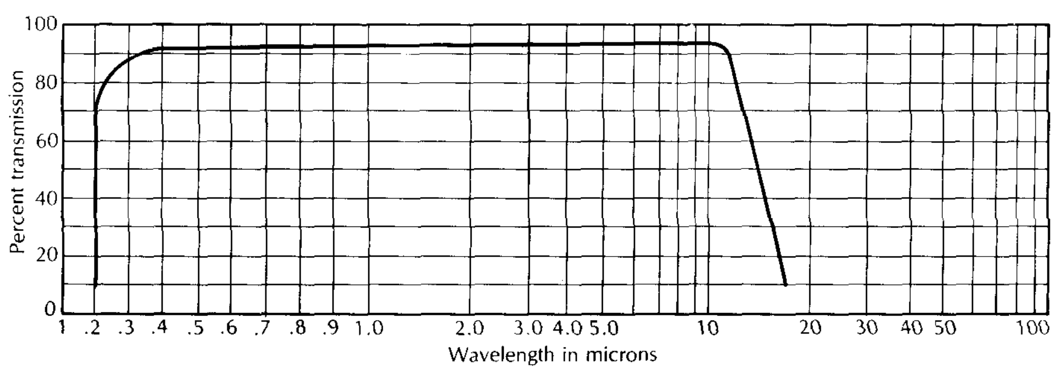
Sodium Chloride crystals are grown in large diameter ingots by the Kyropoulos process.

Sodium Chloride can be hot forged using polished dies giving polycrystalline material of increased strength. Windows and lenses with an adequate IR surface quality can be fabricated directly and cost effectively by this method.

Materials Data

Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index
0.589	1.54427	1.6848	1.52764	7.22	1.51020
0.6400	1.54141	1.7670	1.52736	7.59	1.50850
0.6874	1.53930	2.0736	1.52649	7.6611	1.50822
0.7604	1.53682	2.1824	1.52621	7.9558	1.50665
0.7858	1.53607	2.2464	1.52606	8.04	1.5064
0.8835	1.53395	2.3560	1.52579	8.8398	1.50192
0.9033	1.53361	2.6505	1.52512	9.00	1.50100
0.9724	1.53253	2.9466	1.52466	9.50	1.49980
1.0084	1.53206	3.2736	1.52371	10.0184	1.49462
1.0540	1.53153	3.5359	1.52312	11.7864	1.48171
1.0810	1.53123	3.6288	1.52286	12.50	1.47568
1.1058	1.53098	3.8192	1.52238	12.9650	1.47160
1.1420	1.53063	4.1230	1.52156	13.50	1.4666
1.1786	1.53031	4.7120	1.51979	14.1436	1.46044
1.2016	1.53014	5.0092	1.51883	14.7330	1.45427
1.2604	1.52971	5.3009	1.51790	15.3223	1.44743
1.3126	1.52937	5.8932	1.51593	15.9116	1.44090
1.4874	1.52845	6.4825	1.51347	17.93	1.4149
1.5552	1.52815	6.80	1.51200	20.57	1.3735
1.6368	1.52781	7.0718	1.51093	22.3	1.3403





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Sodium Fluoride (NaF)

MATERIAL: Sodium Fluoride (NaF)
APPLICATIONS: Cherenkov counters

PROPERTY	VALUE	REF. No
-OPTICAL-		
Transmission Range	0.15 to 14 microns	28
Refractive Index	1.327 at 0.5 microns	33 146
Reflection Loss	3.8% at 0.5 microns (2 surfaces)	
Restrahlen Peak	35.8 microns	
dN/dT		
-PHYSICAL-		
Density	2.726 gm/cc	133
Melting Point	980°C	6
Thermal Conductivity	3.746 Wm^{-1} $°K^{-1}$ at 0°C	16
Thermal Expansion	36×10^{-6}/°C	34
Hardness	Knoop 60	16
Specific Heat Capacity	1088 J Kgm^{-1} $°K^{-1}$ at 0°C	35
Dielectric Constant	6.0	3
Young's Modulus (E)	*79.01 GPa*	5
Shear Modulus (G)	12.7 GPa	5
Bulk Modulus (K)	47.9 GPa	5
Elastic Coefficients	$C_{11}=90.9$ $C_{12}=26.4$ $C_{44}=12.7$	5
Apparent Elastic Limit		
Poisson Ratio	0.326	Calculated
-CHEMICAL-		
Solubility	4.22gm/100gm water at 18°C	
Molecular Weight	42.0	
Class/Structure	Cubic, NaCl structure. (100) cleavage	

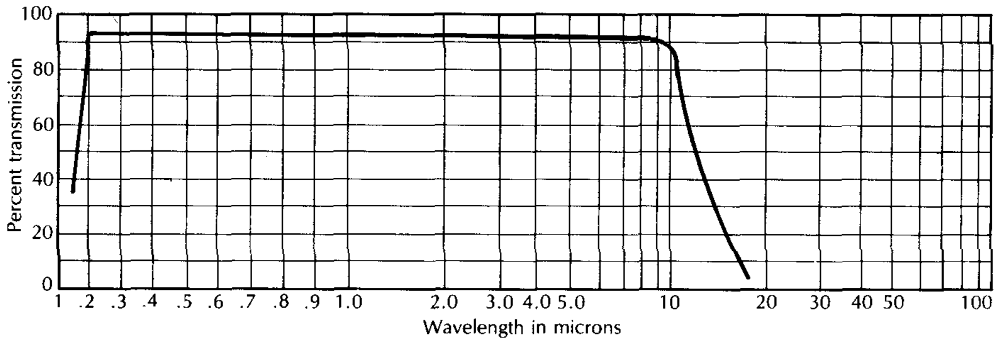
NOTES

Sodium Fluoride is grown by vacuum Stockbarger technique, normally in ingots of 120mm diameter. It is little used for its optical characteristics, these being inferior to CaF_2 or LiF, but sodium fluoride has one of the lowest refractive indexes of all materials in the UV, and is generating considerable interest as a detector material in High energy physics RICH (Ring Imaging Cherenkov) counters.

Sodium Fluoride may also be used as an a/r coating material.

Materials Data

Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index
0.145	1.499	0.546	1.32640	7.1	1.281
0.149	1.476	0.589	1.32549	8.1	1.269
0.161	1.438	0.707	1.32372	9.1	1.262
0.165	1.429	0.811	1.32272	10.3	1.233
0.175	1.410	0.912	1.32198	11.3	1.209
0.186	1.3930	1.014	1.32150	12.5	1.180
0.199	1.3805	2.0	1.317	13.8	1.142
0.203	1.3772	3.1	1.313	15.1	1.093
0.302	1.34232	4.1	1.308	16.7	1.034
0.405	1.33194	5.1	1.301	17.3	1.000
0.486	1.32818	6.1	1.292		



Thallium Bromide (TIBr)

MATERIAL: Thallium Bromide (TlBr)
APPLICATIONS: IR windows

PROPERTY	VALUE	REF. No
-OPTICAL-		
Transmission Range	0.44 to 40 microns	48
Refractive Index	2.338 at 10 microns	33, 49
Reflection Loss	27% at 10 microns (2 surfaces)	
Restrahlen Peak	173 microns	
dN/dT		
-PHYSICAL-		
Density	7.453 gm/cc	
Melting Point	460°C	6
Thermal Conductivity	0.586 $Wm^{-1}\,°K^{-1}$ at 46°C	50
Thermal Expansion	51×10^{-6}/°C	51
Hardness	Knoop 11.9	11
Specific Heat Capacity	188 J $Kgm^{-1}\,°K^{-1}$ at 20°C	53
Dielectric Constant	30.3 at 1MHz	7
Young's Modulus (E)	29.5 GPa	52
Shear Modulus (G)	7.58 GPa	52
Bulk Modulus (K)	22.47 GPa	52
Elastic Coefficients	$C_{11}=37.8$ $C_{12}=14.8$ $C_{44}=7.56$	52
Apparent Elastic Limit		
Poisson Ratio	0.281	Calculated
-CHEMICAL-		
Solubility	0.05gm/100gm water at 25°C	6
Molecular Weight	284.31	
Class/Structure	Cubic, CsCl structure. No cleavage.	

NOTES

Thallium bromide is grown in diameters of 100mm by sealed ampoule Stockbarger. The material is malleable and can be cut without chipping.

CAUTION: Thallium salts are considered toxic and should be handled with care.

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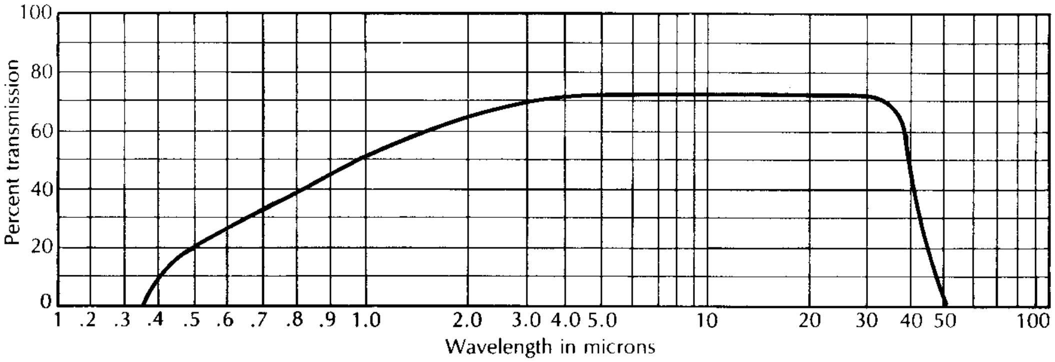
Materials Data

Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index
0.438	2.652	0.578	2.424	0.650	2.384
0.546	2.452	0.589	2.418	0.750	2.350



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Thallium Bromide-Chloride (KRS-6)

MATERIAL: KRS-6 (TlBr-TlCl)
APPLICATIONS: IR windows

PROPERTY	VALUE	REF. No
-OPTICAL-		
Transmission Range	0.4 to 32 microns	48
Refractive Index	2.1767 at 10 microns	56
Reflection Loss	24.2% at 10 microns (2 surfaces)	
Restrahlen Peak	91.5 microns	
dN/dT		
-PHYSICAL-		
Density	7.182 gm/cc	
Melting Point	423.5°C	33
Thermal Conductivity	0.7 Wm^{-1} $°K^{-1}$ at 56°C	17
Thermal Expansion	50×10^{-6}/°C	11
Hardness	Knoop 29.9	11
Specific Heat Capacity	188 J Kgm^{-1} $°K^{-1}$ at 0°C	28
Dielectric Constant	32 at 1MHz	7
Young's Modulus (E)	20.68 GPa	11
Shear Modulus (G)	8.48 GPa	11
Bulk Modulus (K)	22.81 GPa	11
Elastic Coefficients	$C_{11}=38.5$ $C_{12}=14.9$ $C_{44}=7.37$	52
Apparent Elastic Limit	21.0 MPa	5
Poisson Ratio	0.219	Calculated
-CHEMICAL-		
Solubility	0.3gm/100gm water at 20°C	
Molecular Weight	40 mole% TlBr:60 mole% TlCl	58
Class/Structure	Cubic, CsCl structure. No cleavage.	

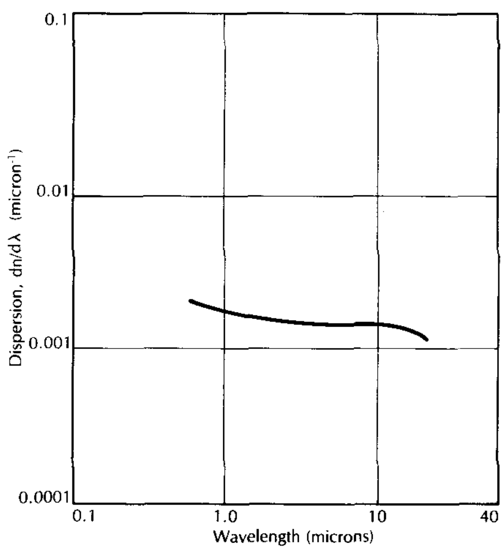
NOTES

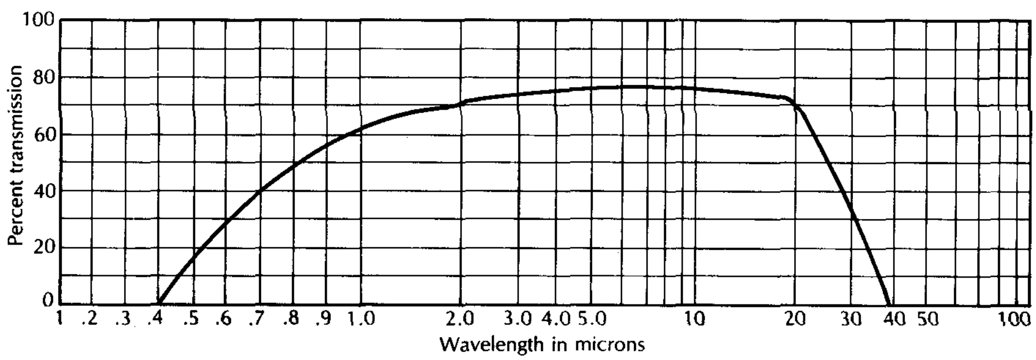
KRS6 is grown in diameters of 100mm by sealed ampoule Stockbarger technique. The uses are limited, KRS5 is preferred for most applications.

CAUTION: Thallium salts are considered toxic and should be handled with care.

Materials Data

Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index
0.5	2.3367	2.0	2.2059	11.0	2.1723
0.6	2.3294	2.2	2.2039	12.0	2.1674
0.7	2.2982	2.4	2.2024	13.0	2.1620
0.8	2.2660	2.6	2.2011	14.0	2.1563
0.9	2.2510	2.8	2.2001	15.0	2.1504
1.0	2.2404	3.0	2.1990	16.0	2.1442
1.1	2.2321	3.5	2.1972	17.0	2.1377
1.2	2.2255	4.0	2.1956	18.0	2.1309
1.3	2.2212	4.5	2.1942	19.0	2.1236
1.4	2.2176	5.0	2.1928	20.0	2.1154
1.5	2.2148	6.0	2.1900	21.0	2.1067
1.6	2.2124	7.0	2.1870	22.0	2.0976
1.7	2.2103	8.0	2.1839	23.0	2.0869
1.8	2.2086	9.0	2.1805	24.0	2.0752
1.9	2.2071	10.0	2.1767		





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Thallium Bromide-Iodide (KRS-5)

MATERIAL: KRS-5 (TlBr-TlI)
APPLICATIONS: Attenuated total reflection prisms, IR windows and lenses.

PROPERTY	VALUE	REF. No
-OPTICAL-		
Transmission Range	0.6 to 40 microns	58
Refractive Index	2.37069 at 10 microns	59, 60
Reflection Loss	28.4% at 10 microns (2 surfaces)	28
Restrahlen Peak	135 microns	28
dN/dT	-235×10^{-6}/°C	
-PHYSICAL-		
Density	7.371 gm/cc	
Melting Point	414.5°C	5
Thermal Conductivity	0.544 Wm^{-1} $°K^{-1}$ at 20°C	3
Thermal Expansion	58×10^{-6}/°C	11
Hardness	Knoop 40.2	11
Specific Heat Capacity	200 J Kgm^{-1} $°K^{-1}$ at 0°C	
Dielectric Constant	32.5	7
Young's Modulus (E)	15.85 GPa	11, 31
Shear Modulus (G)	5.79 GPa	11
Bulk Modulus (K)	19.78 GPa	11
Elastic Coefficients	$C_{11}=33.1$ $C_{12}=13.2$ $C_{44}=5.79$	52
Apparent Elastic Limit	26.2 MPa	11
Poisson Ratio	0.369	Calculated
-CHEMICAL-		
Solubility	0.05gm/100gm water at 20°C	61
Molecular Weight	42 mole% TlBr: 58 mole% TlI	
Class/Structure	Cubic, CsCl structure. No cleavage.	

NOTES

KRS-5 crystals are grown in diameters of 100mm by sealed ampoule Stockbarger technique. Starting materials of the very highest purity are employed to ensure that there are no anionic absorption bands between 2 and 16 microns and all crystals are checked for quality by using a pathlength of 120mm. Crystals of the highest quality are reserved as ATR (Attenuated Total Reflection) grade. The low solubility, high refractive index and low absorption makes KRS-5 ideal for this application.

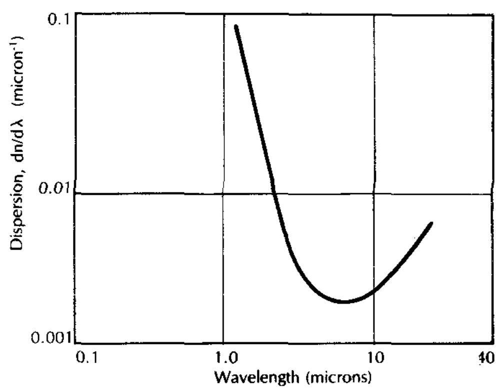
The refractive index of KRS-5 can vary due to small compositional changes and can sometimes be seen as a gradient across the material. If the composition corresponds to the minimum freezing temperature of the system (45.7%: 54.3%) this variance should be reduced to 1 part in 10^4.

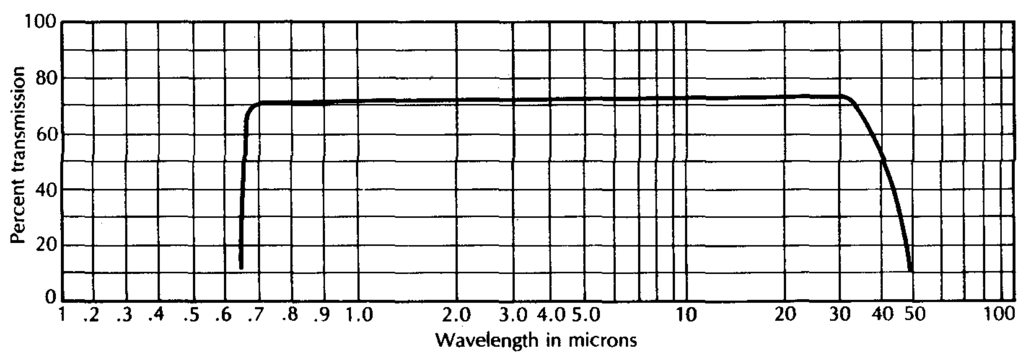
KRS-5 can be hot forged using polished dies giving polycrystalline material of increased strength. Windows and small lenses with an adequate IR surface quality can be fabricated directly and cost effectively by this method. Hot forging of single crystal is also performed as a means eliminating subtle variations in polishing characteristics due to small variations in orientation. Hot forged blanks being polycrystalline in structure give material with a greater hardness as well as tending to average out these variations and allow the polishing process to be refined.

Materials Data

CAUTION: Thallium salts are considered TOXIC and should be handled with care.

Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index
0.540	2.68059	13.0	2.36371	27.0	2.30676
1.00	2.44620	14.0	2.36101	28.0	2.30098
1.50	2.40774	15.0	2.35812	29.0	2.29495
2.00	2.39498	16.0	2.35502	30.0	2.28867
3.00	2.38574	17.0	2.35173	31.0	2.28212
4.00	2.38204	18.0	2.34822	32.0	2.27531
5.00	2.37979	19.0	2.34451	33.0	2.26823
6.00	2.37797	20.0	2.34058	34.0	2.26087
7.00	2.37627	21.0	2.33643	35.0	2.25322
8.00	2.37452	22.0	2.33206	36.0	2.24528
9.00	2.37267	23.0	2.32746	37.0	2.23705
10.0	2.37069	24.0	2.32264	38.0	2.22850
11.0	2.36854	25.0	2.31758	39.0	2.21965
12.0	2.36622	26.0	2.31229	40.0	2.21047





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ARGUS INTERNATIONAL, LTD.

Thallium Chloride (TICI)

MATERIAL: Thallium Chloride (TlCl)
APPLICATIONS: IR windows

PROPERTY	VALUE	REF. No
-OPTICAL-		
Transmission Range	0.44 to 30 microns	48
Refractive Index	2.193 at 10 microns	33, 49
Reflection Loss	24.5% at 10 microns (2 surfaces)	
Restrahlen Peak	131 microns	
dN/dT		
-PHYSICAL-		
Density	7.018 gm/cc	
Melting Point	430°C	6
Thermal Conductivity	0.75 Wm^{-1} $°K^{-1}$ at 38°C	50
Thermal Expansion	53×10^{-6}/°C	5
Hardness	Knoop 12.8	11
Specific Heat Capacity	218 J Kgm^{-1} $°K^{-1}$ at 0°C	6
Dielectric Constant	31.9 at 1MHz	3
Young's Modulus (E)	31.71 GPa	52
Shear Modulus (G)	7.58 GPa	52
Bulk Modulus (K)	23.57 GPa	52
Elastic Coefficients	$C_{11}=40.1$ $C_{12}=15.3$ $C_{44}=7.6$	52
Apparent Elastic Limit		
Poisson Ratio	0.276	
-CHEMICAL-		
Solubility	0.32gm/100gm water at 20°C	6
Molecular Weight	239.85	
Class/Structure	Cubic, CsCl structure. No cleavage.	

NOTES
Thallium chloride crystals are grown in diameters of 100mm by sealed ampoule Stockbarger technique.

Thallium chloride can be hot forged in a similar manner to KRS-5.

CAUTION: Thallium salts are considered toxic and should be handled with care.

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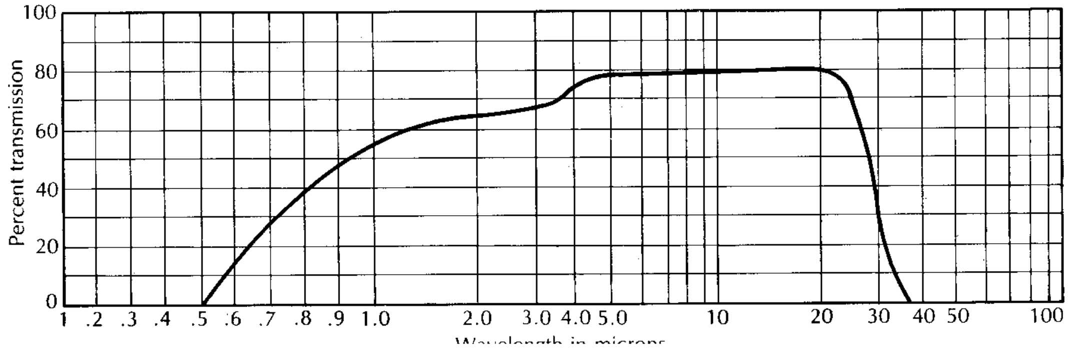
Materials Data

Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index
0.436	2.400	0.578	2.253	0.650	2.223
0.546	2.720	0.589	2.247	0.750	2.198



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ARGUS INTERNATIONAL, LTD.

Zinc Selenide (ZnSe)

MATERIAL: Zinc Selenide (ZnSe)
APPLICATIONS: Visible, IR, Laser windows, FLIR (Forward looking IR) systems.

PROPERTY	VALUE	REF. No
-OPTICAL-		
Transmission Range	0.5 to 22 microns for >10% uncoated 6mm	142
Refractive Index	2.4028 at 10.6 microns	142
Reflection Loss	29% at 10.6 microns (2 surfaces)	
Restrahlen Peak		
dN/dT	61×10^{-6}/°K at 10.6 microns 298°K	142
-PHYSICAL-		
Density	5.27 gm/cc	
Melting Point	1525°C	
Thermal Conductivity	18 Wm^{-1} $°K^{-1}$ at 25°C	
Thermal Expansion	7.8×10^{-6}/°K	142
Hardness	Knoop 120 50gm indenter	142
Specific Heat Capacity	339.1 J Kgm^{-1} $°K^{-1}$ at 25°C	142
Dielectric Constant		
Young's Modulus (E)	67.22 GPa	142
Shear Modulus (G)		
Bulk Modulus (K)		
Elastic Coefficients		
Apparent Elastic Limit	~55 MPa using 4-point test	142
Poisson Ratio	*0.28*	
-CHEMICAL-		
Solubility	Insoluble	
Molecular Weight	144.33	
Class/Structure	Polycrystalline cubic	142

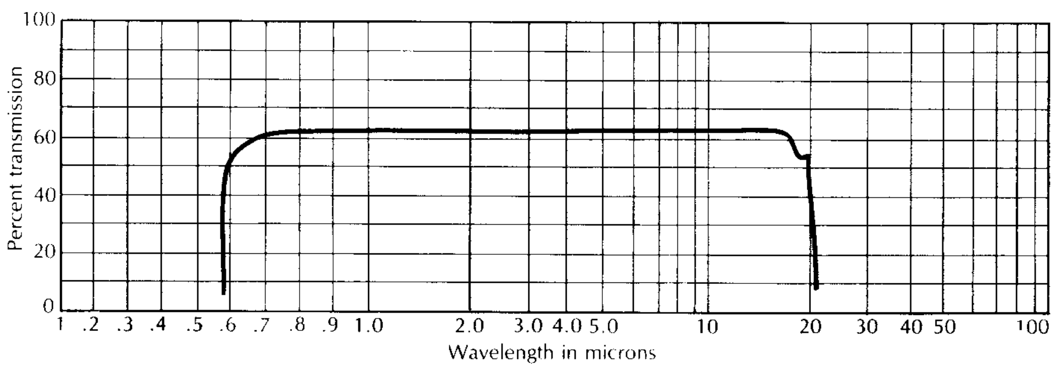
NOTES
BDH generally sources its basic stock of zinc selenide from CVD Inc., most data reproduced here is by courtesy of CVD Inc. but more detailed design data should be obtained directly.

This material is polycrystalline with a grain size of 50 to 70 microns

ARGUS INTERNATIONAL, LTD.

Materials Data

Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index
0.54	2.6754	3.80	2.4339	11.40	2.3974
0.58	2.6312	4.20	2.4324	11.80	2.3945
0.62	2.5994	4.60	2.4309	12.20	2.3915
0.66	2.5755	5.00	2.4295	12.60	2.3883
0.70	2.5568	5.40	2.4281	13.00	1.3850
0.74	2.5418	5.80	2.4266	13.40	1.3816
0.78	2.5295	6.20	2.4251	13.80	2.3781
0.82	2.5193	6.60	2.4235	14.20	2.3744
0.86	2.5107	7.00	2.4218	14.60	2.3705
0.90	2.5034	7.40	2.4201	15.00	2.3665
0.94	2.4971	7.80	2.4183	15.40	2.3623
0.98	2.4916	8.20	2.4163	15.80	2.3579
1.00	2.4892	8.60	2.4143	16.20	2.3534
1.40	2.4609	9.00	2.4122	16.60	2.3487
1.80	2.4496	9.40	2.4100	17.00	2.3438
2.20	2.4437	9.80	2.4077	17.40	2.3387
2.60	2.4401	10.20	2.4053	17.80	2.3333
3.00	2.4376	10.60	2.4028	18.20	2.3278
3.40	2.4356	11.00	2.4001		



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ARGUS INTERNATIONAL, LTD.

Zinc Sulphide (ZnS)

MATERIAL: Zinc Sulphide Cleartran™ (A Trademark of CVD Inc)
APPLICATIONS: IR, Laser windows, Lenses, FLIR systems.

PROPERTY	VALUE	REF. No
-OPTICAL-		
Transmission Range	0.37 to 14 microns for >10% uncoated 6mm	142
Refractive Index	2.188 at 10.6 microns	142
Reflection Loss	24% at 10.6 microns (2 surfaces)	
Restrahlen Peak		
dN/dT	38.7×10^{-6}/°K at 3.39 microns	142
-PHYSICAL-		
Density	4.09 gm/cc	
Melting Point		
Thermal Conductivity	27.21 Wm^{-1} $°K^{-1}$ at 25°C	142
Thermal Expansion	6.5×10^{-6}/°K	142
Hardness	Knoop 160 50gm indenter	142
Specific Heat Capacity	515 J Kgm^{-1} $°K^{-1}$ at 0°C	142
Dielectric Constant		
Young's Modulus (E)	74.46 GPa	142
Shear Modulus (G)		
Bulk Modulus (K)		
Elastic Coefficients		
Apparent Elastic Limit	~59 MPa using 4-point test	142
Poisson Ratio	0.28	
-CHEMICAL-		
Solubility	65×10^{-6} gm/100gm water	
Molecular Weight	97.43	
Class/Structure	Polycrystalline cubic	

NOTES

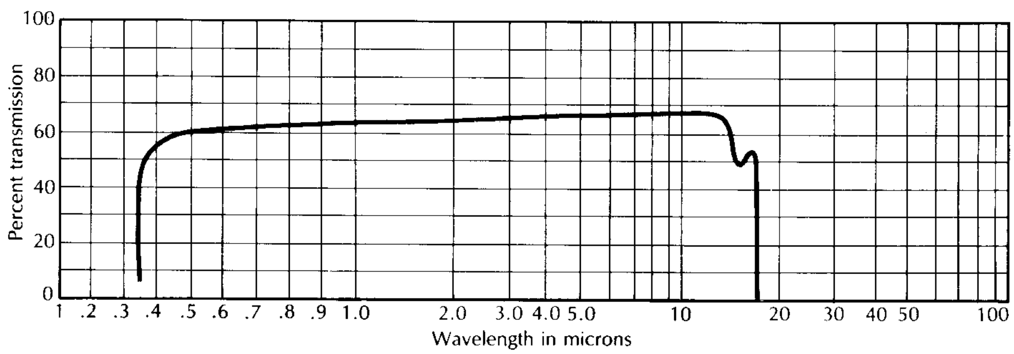
BDH generally sources its basic stock of zinc sulphide from Cleartran™ ZnS manufactured by CVD Inc. Most data reproduced here is by courtesy of CVD Inc. and *refers to Cleartran™ ZnS. More detailed design data should be obtained directly.* Cleartran™ ZnS is a water-clear form of zinc sulphide with the same chemical composition. Other visibly-opaque and lower cost forms of zinc sulphide are available from CVD Inc. and from other manufacturers. The characteristics, refractive index, are slightly different from the data reproduced here.

Cleartran™ is a trademark of CVD Inc. Woburn. MA 01801. USA.

ARGUS INTERNATIONAL, LTD.

Materials Data

Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index	Wave-length(μ)	Refractive Index
.35	2.727	.98	2.273	7.80	2.221
.36	2.670	1.00	2.270	8.20	2.221
.38	2.577	1.40	2.268	8.60	2.217
.40	2.523	1.80	2.263	9.00	2.212
.42	2.451	2.20	2.259	9.40	2.208
.46	2.408	2.60	2.256	9.80	2.203
.50	2.370	3.00	2.254	10.20	2.198
.54	2.349	3.40	2.252	10.60	2.188
.58	2.336	3.80	2.249	11.00	2.186
.62	2.320	4.20	2.244	11.40	2.176
.66	2.311	4.60	2.244	11.80	2.173
.70	2.301	5.00	2.243	12.20	2.167
.74	2.293	5.40	2.241	12.60	2.159
.78	2.286	5.80	2.241	13.00	2.152
.82	2.284	6.20	2.238	13.40	2.139
.86	2.281	6.60	2.231	13.80	2.135
.90	2.280	7.00	2.225	14.20	2.126
.94	2.276	7.40	2.224		



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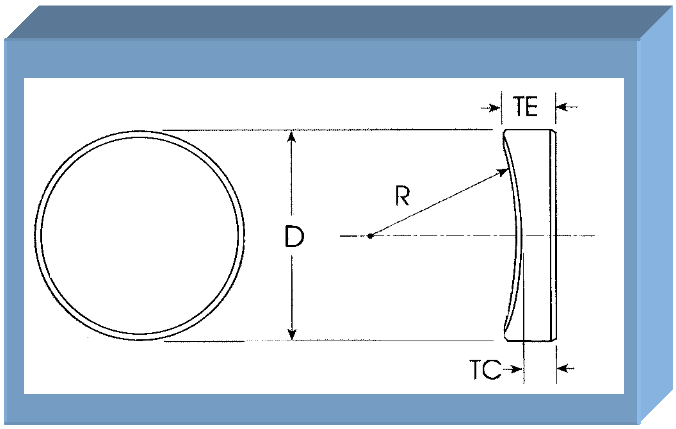
ARGUS INTERNATIONAL, LTD.

AIL-1-1001-Through -AIL-1-1006

Cylindrical BK7
Plano-Concave Lenses, Round



Specifications

Material:	BK7 glass
Surface Figure:	λ /4 at 633 nm
Surface Quality:	Both surfaces 20-10
Diameter Tolerance:	+ 0.00mm, - 0.25mm
Thickness Tolerance:	± 0.25 mm
Chamfer:	0.35 mm at 45° typical
Clear Aperture:	Central 85% of dimension
Concentricity:	≤ 0.2 mm
Focal Length Tolerance:	± 0.5%

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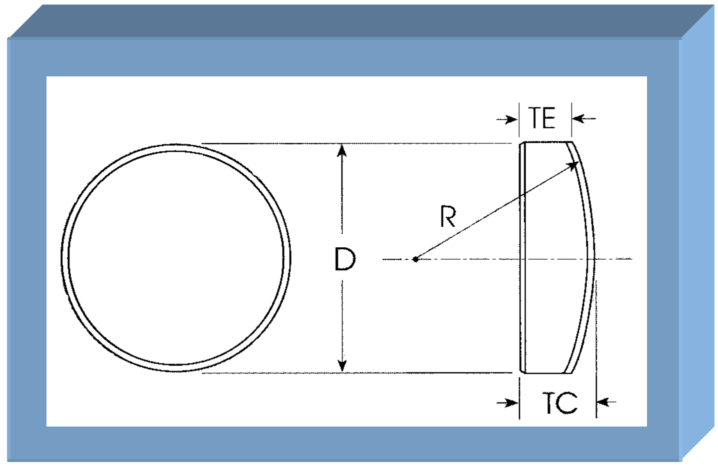
Cylindrical BK7 Plano-Concave Lenses, Round

Part Number	Nominal	488 nm f	532 nm f	800nm f	1300 nm f	Diameter	Radius
AIL-1-1001	-25.0	-24.3	-24.4	-24.9	-25.2	15.0	12.7
AIL-1-1002	-25.0	-24.3	-24.4	-24.9	-25.2	25.4	12.7
AIL-1-1003	-50.0	-48.6	-48.9	-49.7	-50.4	25.4	25.4
AIL-1-1004	-75.0	-73.0	-73.3	-74.6	-75.6	25.4	38.1
AIL-1-1005	-100.0	-97.5	-98.0	-99.7	-101.0	25.4	50.9
AIL-1-1006	-150.0	-146.1	-146.9	-149.4	-151.5	25.4	76.3

ARGUS INTERNATIONAL, LTD.

AIL-1-1007-Through AIL-1-1012

Cylindrical Fused Silica Plano-Convex Lenses, Round



Specifications

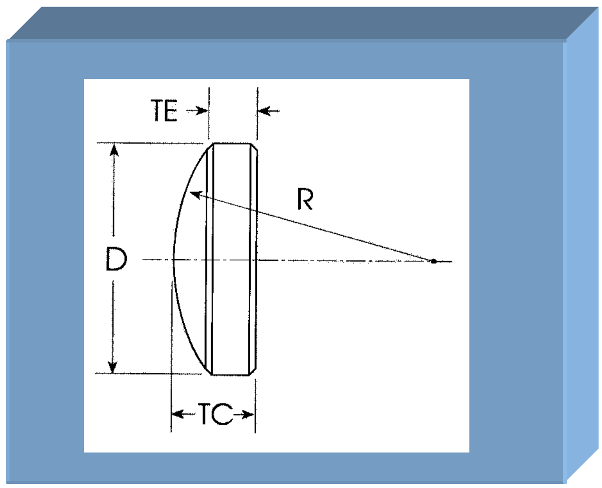
Material:	UV grade fused silica
Surface Figure:	λ /4 at 633 nm
Surface Quality:	Both surfaces 20-10
Diameter Tolerance:	+ 0.00mm, - 0.25 mm
Thickness Tolerance:	± 0.25 mm
Chamfer:	0.35 mm at 45° typical
Clear Aperture:	Central 85% of dimension
Concentricity:	≤ 0.2 mm
Focal Length Tolerance:	± 0.5%

Part Number	Nominal	193 nm f	248 nm f	308 nm f	355 nm f	Diameter	Radius
AIL-1-1007	25.0	22.6	25.0	26.2	26.7	15.0	12.7
AIL-1-1008	25.0	22.6	25.0	26.2	26.7	25.4	12.7
AIL-1-1009	50.0	45.3	49.9	52.3	53.3	25.4	25.4
AIL-1-1010	75.0	67.9	74.9	78.5	80.0	25.4	38.1
AIL-1-1011	100.0	90.8	100.1	104.8	106.9	25.4	50.9
AIL-1-1012	150.0	136.1	150.0	157.1	160.3	25.4	76.3

ARGUS INTERNATIONAL, LTD.

AIL-2-2001 Through AIL-2-2019

BK7 Singlet Lenses
Spherical Plano-Convex



Specifications

Material:	BK7 glass
Surface Figure:	Both surfaces λ /10 at 633 nm
Surface Quality:	Both surfaces 10-5 research grade Laser polish
Diameter Tolerance:	+ 0.00 mm, -0.25mm
Thickness Tolerance:	± 0.25mm
Chamfer:	0.35 mm at 45° typical
Clear Aperture:	Central 85% of diameter
Concentricity:	≤ 0.2 mm
Focal Length Tolerance:	± 0.5%

ARGUS INTERNATIONAL, LTD.

BK7 Singlet Lenses
Spherical Plano-Convex

Part Number	Nominal f	Diameter D	488 nm f	532 nm f	633 nm f	1064 nm f	Radius R	TC	TE
AIL-2-2001	3.5	3.6	3.4	3.5	3.5	3.6	1.8	2.0	0.2
AIL-2-2002	6.0	4.0	5.9	6.0	6.0	6.1	3.1	1.5	0.8
AIL-2-2003	10.0	5.0	10.0	10.0	10.1	10.3	5.2	3.9	3.3
AIL-2-2004	10.0	8.0	10.0	10.0	10.1	10.3	5.2	3.9	2.0
AIL-2-2005	12.0	7.5	12.3	12.3	12.4	12.6	6.4	2.2	1.0
AIL-2-2006	15.0	8.0	14.7	14.8	14.9	15.2	7.7	3.1	2.0
AIL-2-2007	15.0	10.0	14.7	14.8	14.9	15.2	7.7	3.8	2.0
AIL-2-2008	17.0	13.3	16.9	16.9	17.1	17.4	8.8	3.7	0.7
AIL-2-2009	18.0	8.0	17.8	17.9	18.1	18.4	9.3	2.9	2.0
AIL-2-2010	18.0	15.0	17.8	17.9	18.1	18.4	9.3	5.7	1.9
AIL-2-2011	20.0	10.0	19.7	19.8	20.0	20.3	10.3	3.9	2.6
AIL-2-2012	20.0	12.0	19.7	19.8	20.0	20.3	10.3	3.9	2.0
AIL-2-2013	22.0	18.0	21.6	21.8	21.9	22.3	11.3	6.0	1.5
AIL-2-2014	25.0	6.3	25.1	25.2	25.4	25.9	13.1	2.9	2.5
AIL-2-2015	25.0	8.0	24.7	24.8	25.0	25.5	12.9	4.0	3.4
AIL-2-2016	25.0	10.0	24.7	24.8	25.0	25.5	12.9	4.0	3.0
AIL-2-2017	25.0	12.7	24.7	24.8	25.0	25.5	12.9	4.0	2.3
AIL-2-2018	25.0	15.0	24.7	24.8	25.0	25.5	12.9	4.9	2.5
AIL-2-2019	25.0	25.4	24.7	24.8	25.0	25.5	12.9	12.7	2.1

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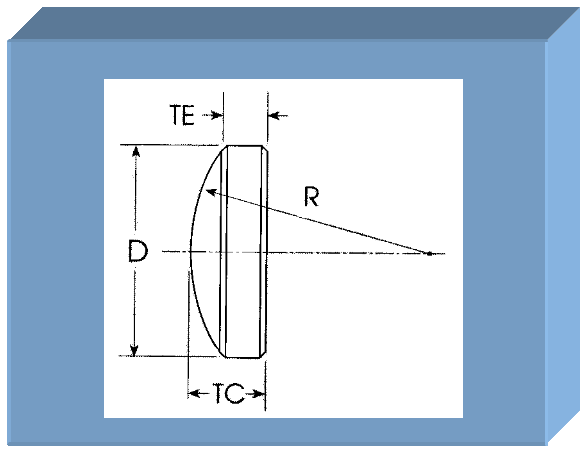
AIL-2-2026 Through AIL-2-2044

Fused Silica Lenses
Spherical Plano-Convex



Specifications

Material:	UV grade fused silica
Surface Figure:	Both surfaces λ /10 at 633 nm
Surface Quality:	Both surfaces 10-5 research grade
	Laser polish
Diameter Tolerance:	+ 0.00mm, -0.25mm
Thickness Tolerance:	± 0.25mm
Chamfer:	0.35mm at 45° typical
Clear Aperture:	Central 85% of diameter
Concentricity:	≤ 0.2mm
Focal Length Tolerance:	± 0.5%

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ARGUS INTERNATIONAL, LTD.

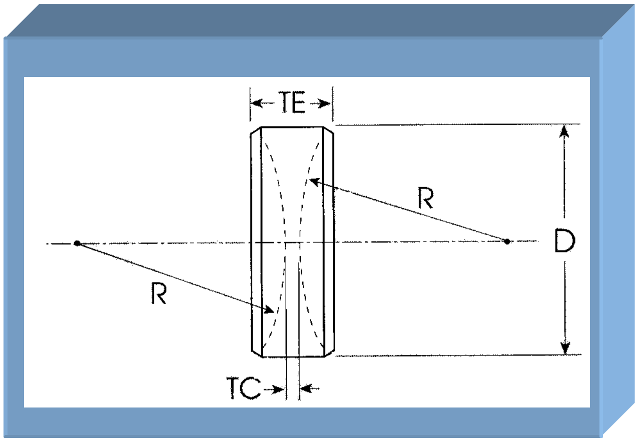
Fused Silica Lenses
Spherical Plano-Convex

Part Number	Nominal f	Diameter D	248 nm f	308 nm f	355 nm f	1064 nm f	Radius	TC	TE
AIL-2-2026	3.0	2.5	2.9	3.1	3.2	3.3	1.5	2.0	1.3
AIL-2-2027	6.0	4.0	6.1	6.4	6.5	6.9	3.1	1.5	0.8
AIL-2-2028	8.0	4.0	8.1	8.4	8.6	9.1	4.1	2.5	2.0
AIL-2-2029	10.0	5.0	10.2	10.7	10.9	11.6	5.2	3.9	3.3
AIL-2-2030	10.0	8.0	10.2	10.7	10.9	11.6	5.2	3.9	2.0
AIL-2-2031	12.0	7.5	12.6	13.2	13.4	14.2	6.4	2.2	1.0
AIL-2-2032	15.0	8.0	15.1	15.9	16.2	17.1	7.7	3.1	2.0
AIL-2-2033	15.0	10.0	15.1	15.9	116.2	17.1	7.7	3.8	2.0
AIL-2-2034	18.0	8.0	18.3	19.2	19.5	20.7	9.3	2.9	2.0
AIL-2-2035	20.0	10.0	20.3	21.2	21.6	22.9	10.3	3.9	2.6
AIL-2-2036	25.0	8.0	25.4	26.6	27.1	28.7	12.9	4.0	3.4
AIL-2-2037	25.0	10.0	25.4	26.6	27.1	28.7	12.9	4.0	3.0
AIL-2-2038	25.0	12.7	25.4	26.6	27.1	28.7	12.9	4.0	2.3
AIL-2-2039	25.0	15.0	25.4	26.6	27.1	28.7	12.9	4.9	2.5
AIL-2-2040	25.0	25.4	25.4	26.6	27.1	28.7	12.9	12.7	2.1
AIL-2-2041	25.0	25.4	25.8	27.0	27.5	29.1	13.1	11.4	1.5
AIL-2-2042	31.0	10.0	31.5	32.9	33.6	35.6	16.0	1.9	1.1
AIL-2-2043	35.0	8.0	35.4	37.1	37.8	40.0	18.0	1.5	1.0
AIL-2-2044	35.0	25.4	35.4	37.1	37.8	40.0	18.0	7.2	2.0

ARGUS INTERNATIONAL, LTD.

AIL-2-2045 Through AIL-2-2070

Fused Silica Singlet Lenses
Spherical Bi-Concave



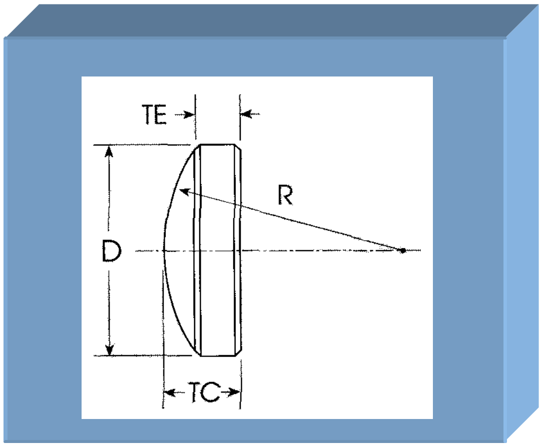
Specifications

Material:	UV grade fused silica
Surface Figure:	Both surfaces λ /10 at 633 nm
Surface Quality:	Both surfaces 10-5 research grade Laser polish
Diameter Tolerance:	+ 0.00mm, -0.25mm
Thickness Tolerance:	± 0.25mm
Chamfer:	0.35mm at 45° typical
Clear Aperture:	Central 85% of diameter
Concentricity:	≤ 0.2mm
Focal Length Tolerance:	± 0.5%

ARGUS INTERNATIONAL, LTD.

AIL-2-2071 Through AIL-2-2085

SF11 Singlet Lenses
Spherical Plano-Convex



Specifications

Material:	SF11
Surface Figure:	Both surfaces λ / 10 at 633 nm
Surface Quality:	Both surfaces 20-10
Diameter Tolerance:	+ 0.00 mm, - 0.25 mm
Thickness Tolerance:	± 0.25 mm
Chamfer:	0.35 mm at 45° typical
Clear Aperture:	Central 85% of diameter
Concentricty:	≤ 0.2 mm
Focal Length Tolerance:	± 0.5%

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SF11 Singlet Lenses

Spherical Plano-Convex

Part Number	Nominal f	Diameter	780 nm f	800 nm f	1300 nm f	1550 nm f	Radius	TC	TE
AIL-2-2071	5.0	5.0	5.3	5.4	5.5	5.5	4.1	2.0	1.1
AIL-2-2072	10.0	10.0	9.9	10.1	10.3	10.3	7.7	3.8	2.0
AIL-2-2773	15.0	10.0	14.8	15.0	15.4	15.4	11.5	3.8	2.7
AIL-2-2074	20.0	15.0	19.8	20.0	20.4	20.5	15.3	3.8	1.8
AIL-2-2075	25.0	15.0	24.7	25.0	25.5	25.6	19.1	3.8	2.3
AIL-2-2076	35.0	19.1	35.1	35.6	36.3	36.5	27.2	3.8	2.1
AIL-2-2077	50.0	25.4	49.2	49.8	50.9	51.2	38.1	3.8	1.6
AIL-2-2078	60.0	25.4	59.0	59.8	61.0	61.4	45.7	3.8	2.0
AIL-2-2079	76.0	25.4	75.1	76.1	77.7	78.1	58.2	3.8	2.4
AIL-2-2080	100.0	25.4	98.5	99.8	101.9	102.5	76.3	3.8	2.7
AIL-2-2081	125.0	25.4	123.9	125.5	128.2	128.9	96.0	3.8	3.0
AIL-2-2082	150.0	25.4	148.0	149.9	153.0	153.9	114.6	3.8	3.1
AIL-2-2083	175.0	25.4	173.1	175.4	179.0	180.1	134.1	3.8	3.2
AIL-2-2084	200.0	25.4	198.0	200.6	204.8	206.0	153.4	3.8	3.3
AIL-2-2085	250.0	25.4	245.2	248.3	253.5	255.0	189.9	3.8	3.4

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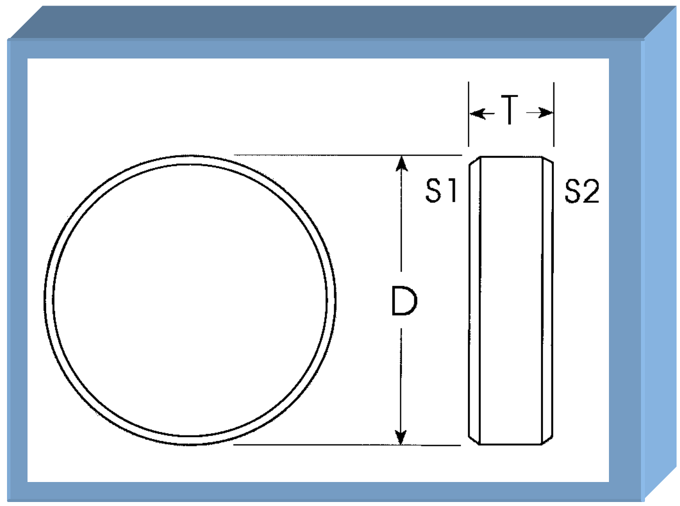
ARGUS INTERNATIONAL, LTD.

AIL-3-3001 Through AIL-3-3016

Harmonic Windows



Specifications

Material:	UV grade fused silica or BK7 glass
Surface Figure:	Both surfaces λ /10 at 633 nm
Surface Quality:	Both surfaces 10-5 research grade laser polish
Diameter Tolerance:	+ 0.000”, -0.010”
Thickness Tolerance:	± 0.010”
Wedge:	≤ 5 minutes of arc
Chamfer:	0.35 mm at 45° typical
Reflectance (S1, S2):	R ≤ 0.3 % 1064 nm and R ≤ 1.0% 532 nm (per surface)
Coating Material:	Electron beam deposited dielectrics
Adhesion:	Exceeds scotch tape test (MIL-c-675A)
Durability:	Exceeds eraser test (MIL-C-675A). Insoluble in water, Alcohol, acetone, detergent, and most acids except HF
Clear Aperture:	Central 85% of diameter

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ARGUS INTERNATIONAL, LTD.

Harmonic Windows

Part Number	Diameter	Thickness	Wavelength	Incident Angle In Degrees
AIL-3-3001	0.500”	0.250”	1064/532	0
AIL-3-3002	0.500”	0.375”	1064/532	0
AIL-3-3003	1.000”	0.250”	1064/532	0
AIL-3-3004	1.000”	0.375”	1064/532	0
AIL-3-3005	2.000”	0.250”	1064/532	0
AIL-3-3006	2.000”	0.375”	1064/532	0
AIL-3-3007	3.000”	0.500”	1064/532	0
AIL-3-3008	4.000”	0.500”	1064/532	0
AIL-3-3009	0.500”	0.250”	1064/532	45
AIL-3-3010	0.500”	0.375”	1064/532	45
AIL-3-3011	1.000”	0.250”	1064/532	45
AIL-3-3012	1.000”	0.375”	1064/532	45
AIL-3-3013	2.000”	0.250”	1064/532	45
AIL-3-3014	2.000”	0.375”	1064/532	45
AIL-3-3015	3.000”	0.500”	1064/532	45
AIL-3-3016	4.000”	0.500”	1064/532	45

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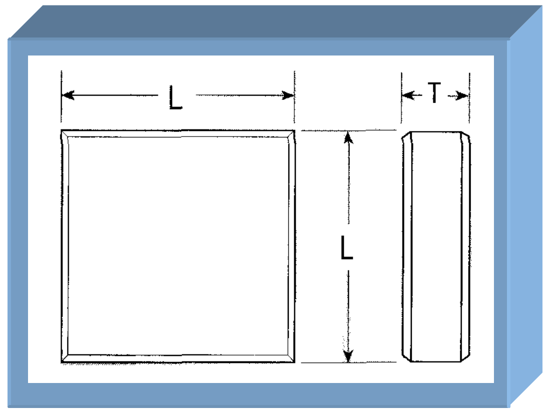
AIL-3-3017-Through-3-3024

Square Windows



Specifications

Material:	UV grade fused silica or BK7 glass
Surface Quality:	Both surfaces 10-5 research grade laser polish
Dimensional Tolerance:	+0.000”, -0.010”
Thickness Tolerance:	±0.010”
Wedge:	5 minutes of arc
Chamfer:	.35mm at 45°
Clear Aperture:	Central 85% of diameter

ARGUS INTERNATIONAL, LTD.

Square Windows

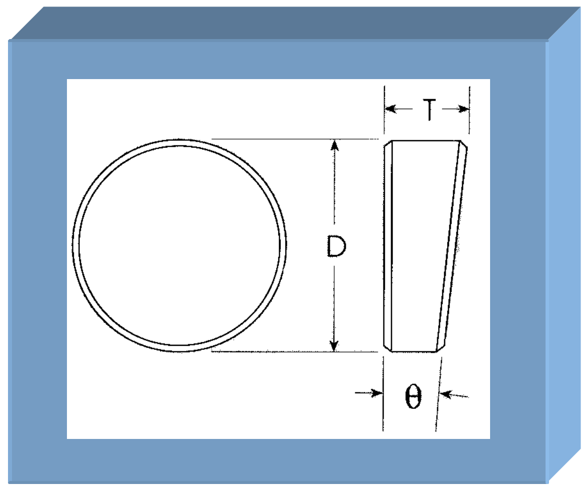
Fused Silica

Part Number	Length	Thickness	Surface Figure	Material
AIL-3-3017	0.500”	0.75”	λ/10	Fused Silica
AIL-3-3018	1.000”	2.0mm	λ/2	Fused Silica
AIL-3-3019	1.000”	0.250”	λ/10	Fused Silica
AIL-3-3020	2.000”	0.063”	1 λ	Fused Silica
AIL-3-3021	2.000”	2.0mm	1 λ	Fused Silica
AIL-3-3022	2.000”	0.200”	λ/2	Fused Silica
AIL-3-2023	2.000”	0.250”	λ/4	Fused Silica
AIL-3-3024	2.000”	0.375”	λ/10	Fused Silica

ARGUS INTERNATIONAL, LTD.

AIL-3-3050 Through AIL-3-3077

Large Wedge Windows
Wedge 1°, 2°, 3°



Specifications

Material:	UV grade fused silica or BK7 glass
Surface Figure:	Both surfaces λ /10 at 633 nm
Surface Quality:	Both surfaces 10-5 research grade laser polish
Diameter Tolerance:	+ 0.000”, - 0.010”
Thickness Tolerance:	± 0.010”
Wedge Tolerance:	± 6 minutes of arc
Chamfer:	0.35 mm at 45° typical
Clear Aperture:	Central 85% of diameter

Large Wedge Windows

Wedge 1,° 2,° 3°

Part Number	Wedge	Diameter	Thickness	Material
AIL-3-3050	1	1.000”	0.375”	Fused Silica
AIL-3-3051	1	1.000”	0.500”	Fused Silica
AIL-3-3052	1	1.500”	0.500”	Fused Silica
AIL-3-3053	1	2.000”	0.500”	Fused Silica
AIL-3-3054	1	3.000”	0.500”	Fused Silica
AIL-3-3055	2	1.000”	0.375”	Fused Silica
AIL-3-3056	2	1.000”	0.500”	Fused Silica
AIL-3-3057	2	1.500”	0.500”	Fused Silica
AIL-3-3058	2	2.000”	0.500”	Fused Silica
AIL-3-3059	2	3.000”	0.500”	Fused Silica
AIL-3-3060	3	1.000”	0.375”	Fused Silica
AIL-3-3061	3	1.000”	0.500”	Fused Silica
AIL-3-3062	3	1.500”	0.500”	Fused Silica
AIL-3-3063	3	2.000”	0.500”	Fused Silica
AIL-3-3064	3	3.000”	0.500”	Fused Silica
AIL-3-3065	1	1.000”	0.375”	BK7
AIL-3-3066	1	1.000”	0.500”	BK7
AIL-3-3067	1	1.500”	0.500”	BK7
AIL-3-3068	1	2.000”	0.500”	BK7
AIL-3-3069	2	1.000”	0.375”	BK7
AIL-3-3070	2	1.000”	0.500”	BK7
AIL-3-3071	2	1.500”	0.500”	BK7
AIL-3-3072	2	2.000”	0.500”	BK7
AIL-3-3073	3	1.000”	0.375”	BK7
AIL-3-3074	3	1.000”	0.500”	BK7
AIL-3-3075	3	1.500”	0.500”	BK7
AIL-3-3076	3	2.000”	0.375”	BK7
AIL-3-3077	3	2.000”	0.500”	BK7

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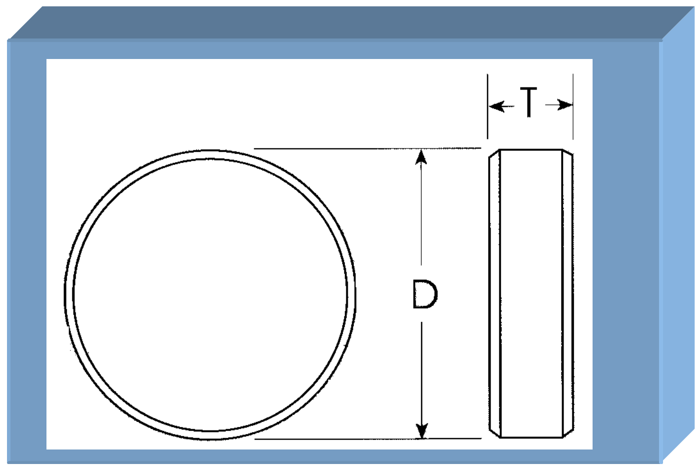
AIL-3-3078-3138

Plane Parallel Windows,
Wedge £ 10 seconds



Specifications

Material:	UVU grade MgF_2, UVU grade CaF_2, Suprasil 1, UV grade fused silica or BK7 glass
Surface Figure:	Specified in wave peak-to-valley at 633 nm
Diameter Tolerance:	+ 0.000”, -0.010”
Thickness Tolerance:	± 0.010”
Wedge:	≤ 10 seconds of arc
Chamfer:	0.35 mm at 45° typical
Clear Aperture:	Central 85% of diameter

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ARGUS INTERNATIONAL, LTD.

Plane Parallel Windows
Wedge £ seconds

Part Number	Diameter	Thickness	Surface Figure	Surface Quality	Material
AIL-3-3078	0.500”	0.250”	λ/10	20-10	MgF2
AIL-3-3079	1.000”	0.250”	λ/10	20-10	MgF2
AIL-3-3080	36.0mm	5.0mm	λ/10	20-10	MgF2
AIL-3-3081	1.500”	5.0mm	λ/10	20-10	MgF2
AIL-3-3082	2.000”	5.0mm	λ/10	20-10	MgF2
AIL-3-3083	2.000”	0.375”	λ/10	20-10	MgF2

Part Number	Diameter	Thickness	Surface Figure	Surface Quality	Material
AIL-3-3084	0.500”	0.250”	λ/10	20-10	CaF2
AIL-3-3085	1.000”	0.250”	λ/10	20-10	CaF2
AIL-3-3086	36.0mm	5.0mm	λ/10	20-10	CaF2
AIL-3-3087	1.500”	5.0mm	λ/10	20-10	CaF2
AIL-3-3088	2.000”	5.0mm	λ/10	20-10	CaF2
AIL-3-3089	2.000”	0.375”	λ/10	20-10	CaF2

Part Number	Diameter	Thickness	Surface Figure	Surface Quality	Material
AIL-3-3090	0.500”	0.250”	λ/10	10-5	Suprasil 1
AIL-3-3091	1.000”	0.250”	λ/10	10-5	Suprasil 1
AIL-3-3092	36.0mm	5.0mm	λ/10	10-5	Suprasil 1
AIL-3-3093	1.500”	0.375”	λ/10	10-5	Suprasil 1
AIL-3-3094	2.000”	0.375”	λ/10	10-5	Suprasil 1

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Part Number	Diameter	Thickness	Surface Figure	Surface Quality	Material
AIL-3-3095	0.500”	0.250”	λ/10	10-5	10-5
AIL-3- 3096	0.500”	0.375”	λ/10	10-5	10-5
AIL-3-3097	15.0 mm	11.0 mm	λ/10	10-5	10-5
AIL-3-3098	0.750”	0.250”	λ/10	10-5	10-5
AIL-3-3099	0.750”	0.375”	λ/10	10-5	10-5
AIL-3-3100	1.000”	1.0mm	λ/10	10-5	10-5
AIL-3-3101	1.000”	0.125”	λ/10	10-5	10-5
AIL-3-3102	1.000”	0.250”	λ/10	10-5	10-5
AIL-3-3103	1.000”	0.375”	λ/10	10-5	10-5
AIL-3-3104	1.000”	0.500”	λ/10	10-5	10-5
AIL-3-3105	36.0mm	5.0mm	λ/10	10-5	10-5
AIL-3-3106	1.500”	0.250”	λ/10	10-5	10-5
AIL-3-3107	1.500”	0.375”	λ/10	10-5	10-5
AIL-3-3108	1.500”	0.500”	λ/10	10-5	10-5
AIL-3-3109	2.000”	0.250”	λ/10	10-5	10-5
AIL-3-3110	2.000”	0.375”	λ/10	10-5	10-5
AIL-3-3111	2.000”	0.500”	λ/10	10-5	10-5
AIL-3-3112	3.000”	0.375”	λ/10	10-5	10-5
AIL-3-3113	3.000”	0.500”	λ/10	10-5	10-5
AIL-3-3114	4.000”	0.375”	λ/10	10-5	10-5
AIL-3-3115	4.000”	0.500”	λ/10	10-5	10-5
AIL-3-3116	6.000”	1.000”	λ/10	10-5	10-5

Part Number	Diameter	Thickness	Surface Figure	Surface Quality	Material
AIL-3-3117	7.75mm	4.0mm	λ/10	10-5	BK7
AIL-3-3118	0.500”	0.250”	λ/10	10-5	BK7
AIL-3-3119	0.500”	0.375”	λ/10	10-5	BK7
AIL-3-3120	15.0mm	11.0mm	λ/10	10-5	BK7
AIL-3-3121	0.750”	0.250”	λ/10	10-5	BK7
AIL-3-3122	0.750”	0.375”	λ/10	10-5	BK7
AIL-3-3123	1.000”	1.0mm	λ/4	10-5	BK7
AIL-3-3124	1.000”	0.250”	λ/10	10-5	BK7
AIL-3-3125	1.000”	0.375”	λ/10	10-5	BK7
AIL-3-3126	1.000”	0.50”	λ/10	10-5	BK7
AIL-3-3127	1.500”	0.125”	λ/10	10-5	BK7
AIL-3-3128	1.500”	0.250”	λ/10	10-5	BK7
AIL-3-3129	1.500”	0.375”	λ/10	10-5	BK7
AIL-3-3130	1.500”	0.500”	λ/10	10-5	BK7
AIL-3-3131	2.000”	0.250”	λ/4	10-5	BK7
AIL-3-3132	2.000”	0.375”	λ/10	10-5	BK7
AIL-3-3133	2.000”	0.500”	λ/10	10-5	BK7
AIL-3-3134	3.000”	0.375”	λ/10	10-5	BK7
AIL-3-3135	3.000”	0.500”	λ/10	10-5	BK7
AIL-3-3136	4.000”	0.375”	λ/10	10-5	BK7
AIL-3-3137	4.000”	0.500”	λ/10	10-5	BK7

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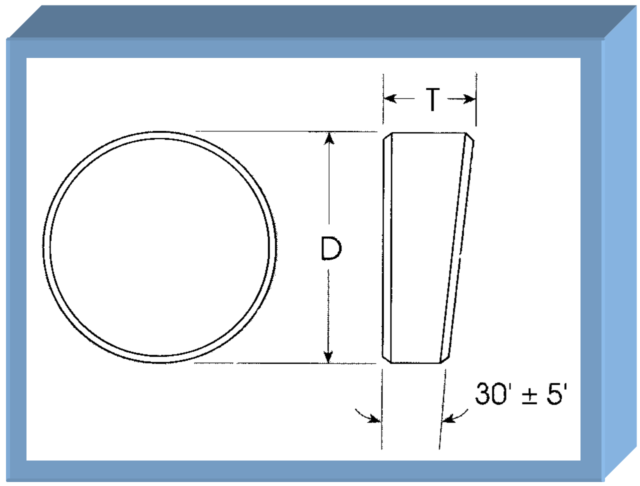
AIL-3-3139 Through AIL-3-3176

Inferometer Flats, Wedge 30 + 5 minutes



Specifications

Material:	Suprasil 1, UV grade fused silica, or BK7 glass
Surface Figure:	Both surfaces λ /10 at 633 nm
Surface Quality:	Both surfaces 10-5 research grade laser polish
Diameter Tolerance:	+ 0.000”, -0.010”
Thickness Tolerance:	± 0.010”
Wedge θ:	30 ± 5 minutes of arc
Chamfer:	0.35mm at 45° typical
Clear Aperture:	Central 85% of diameter

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Inferometer Flats, Wedge 30 + 5 minutes

Suprasil 1

Part Number	Diameter	Thickness	Material
AIL-3-3139	1.000”	0.375"	Suprasil 1
AIL-3-3140	1.500”	0.375"	Suprasil 1
AIL-3-3141	2.000”	0.375"	Suprasil 1

Fused Silica

Part Number	Diameter	Thickness	Material
AIL-3-3142	0.500”	0.250”	Fused Silica
AIL-3-3143	0.500”	0.375”	Fused Silica
AIL-3-3144	0.750”	0.125”	Fused Silica
AIL-3-3145	0.750”	0.250”	Fused Silica
AIL-3-3146	0.750”	0.375”	Fused Silica
AIL-3-3147	1.000”	0.125”	Fused Silica
AIL-3-3148	1.000”	0.250”	Fused Silica
AIL-3-3149	1.000”	0.375”	Fused Silica
AIL-3-3150	1.000”	0.500”	Fused Silica
AIL-3-3151	1.5000”	0.250”	Fused Silica
AIL-3-3152	1.5000”	0.375”	Fused Silica
AIL-3-3153	1.5000”	0.500”	Fused Silica
AIL-3-3154	2.000”	0.250”	Fused Silica
AIL-3-3155	2.000”	0.375”	Fused Silica
AIL-3-3156	2.000”	0.500”	Fused Silica
AIL-3-3157	2.000”	0.750”	Fused Silica
AIL-3-3158	3.000”	0.500”	Fused Silica
AIL-3-3159	4.000”	0.500”	Fused Silica
AIL-3-3160	6.000”	1.000”	Fused Silica

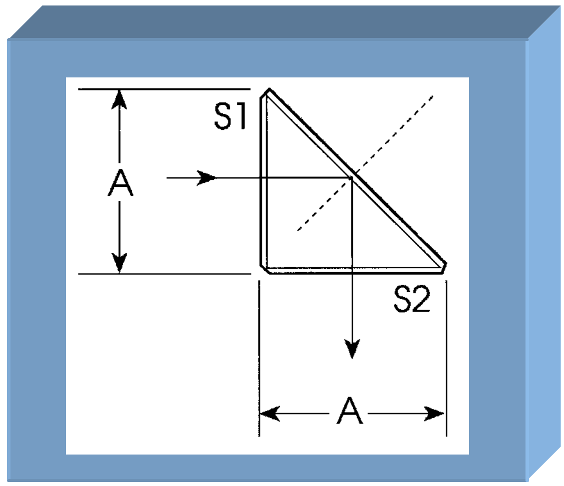
BK7

Part Number	Diameter	Thickness	Material
AIL-3-3161	0.500”	0.250”	BK7
AIL-3-3162	0.500”	0.375”	BK7
AIL-3-3163	0.750”	0.250”	BK7
AIL-3-3164	0.750”	0.375”	BK7
AIL-3-3165	1.000”	0.250”	BK7
AIL-3-3166	1.000”	0.375”	BK7
AIL-3-3167	1.000”	0.500”	BK7
AIL-3-3168	1.500”	0.250”	BK7
AIL-3-3169	1.500”	0.375”	BK7
AIL-3-3170	1.500”	0.500”	BK7
AIL-3-3171	2.000”	0.250”	BK7
AIL-3-3172	2.000”	0.375”	BK7
AIL-3-3173	2.000”	0.500”	BK7
AIL-3-3174	3.000”	0.500”	BK7
AIL-3-3175	4.000”	0.500”	BK7
AIL-3-3176	6.000”	1.000”	BK7

ARGUS INTERNATIONAL, LTD.

AIL-4-4001 Through AIL-4-4024

90° Bending Prism
Antireflection Coated



Specifications

Material:	BK7 glass or UV grade fused silica
Surface Figure:	Polished surfaces λ /4 at 633 nm
Surface Quality:	Polished surfaces 20-10
Dimensional Tolerance:	+ 0.000”, -0.010”
Angular Deviation:	± 3 minutes of arc
Chamfer:	0.35 mm at 45° typical
Clear Aperture:	Central 85% of dimension

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90 Degree Bending Prism

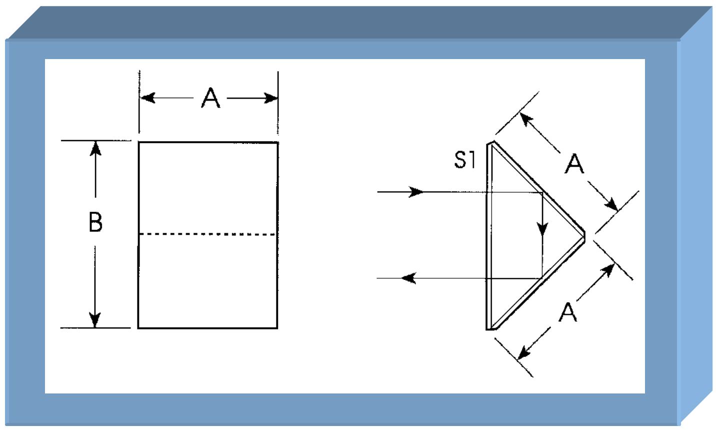
Antireflection Coated

PART NUMBER	DIMENSION	S1 ANDS2 ANTIREFLECTION COATING RANGE IN NM
AIL-4-4001	0.500”	248-355
AIl-4-4002	0.500”	425-675
AIL-4-4003	0.500”	488-515
AIL-4-4004	0.500”	500-800
AIL-4-4005	0.500”	532
AIL-4-4006	0.500”	532/1064
AIL-4-4007	0.500”	633
AIL-4-4008	0.500”	670-1064
AIL-4-4009	0.500”	830
AIL-4-4010	0.500”	860-1320
AIL-4-4011	0.500”	1064
AIL-4-4012	0.500”	1050-1600
AIL-4-4013	1.000”	248-355
AIL-4-4014	1.000”	425-675
AIL-4-4015	1.000”	488-515
AIL-4-4016	1.000”	500-800
AIL-4-4017	1.000”	532
AIL-4-4018	1.000”	532/1064
AIL-4-4019	1.000”	633
AIL-4-4020	1.000”	670-1064
AIL-4-4021	1.000”	830
AIL-4-4022	1.000”	860-1320
AIL-4-4023	1.000”	1064
AIL-4-4024	1.000”	1050-1600

ARGUS INTERNATIONAL, LTD.

AIL-4-4025 Through AIL-4--4048

180° Folding Prisms
Antireflection Coated



Specifications

Material:	BK7 glass or UV grade fused silica
Surface Figure:	Polished surfaces λ /4 at 633 nm
Surface Quality:	Polished surfaces 20-10
Dimensional Tolerance:	+ 0.000”, -0.010”
Angular Deviation:	± 3 minutes of arc
Chamfer:	0.35 mm at 45° typical
Clear Aperture:	Central 85% of dimension

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PHONE: 800 862-7487 - FAX: 831 461-4701
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180° Folding Prisms
Antireflection Coated

Part Number	Dimension A	Dimension B	S1 Antireflection Coating Range in nm
AIL-4-4025	0.500”	0.707”	248-355
AIL-4-4026	0.500”	0.707”	425-675
AIL-4-4027	0.500”	0.707”	488-515
AIL-4-4028	0.500”	0.707”	500-800
AIL-4-4029	0.500”	0.707”	532
AIL-4-4030	0.500”	0.707”	532/1064
AIL-4-4031	0.500”	0.707”	633
AIL-4-4032	0.500”	0.707”	670-1064
AIL-4-4033	0.500”	0.707”	830
AIL-4-4034	0.500”	0.707”	860-1320
AIL-4-4035	0.500”	0.707”	1064
AIL-4-4036	0.500”	0.707”	1050-1600
AIL-4-4037	1.000”	0.707”	248-355
AIL-4-4038	1.000”	0.707”	425-675
AIL-4-4039	1.000”	0.707”	488-515
AIL-4-4040	1.000”	0.707”	500-800
AIL-4-4041	1.000”	0.707”	532
AIL-4-4042	1.000”	0.707”	532/1064
AIL-4-4043	1.000”	0.707”	633
AIL-4-4044	1.000”	0.707”	670-1064
AIL-4-4045	1.000”	0.707”	830
AIL-4-4046	1.000”	0.707”	860-1320
AIL-4-4047	1.000”	0.707”	1064
AIL-4-4048	1.000”	0.707”	1050-1600

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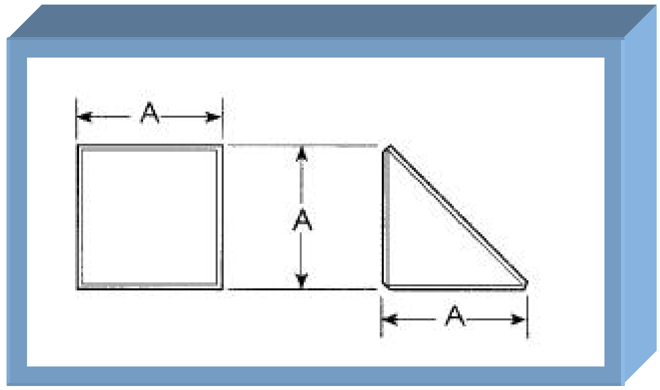
AIL-4-4049 Through AIL-4-4065

Right Angle Prisms
Uncoated



Specifications

Material:	Suprasil 1, UV grade fused silica, or BK7 glass
Triangular Surfaces:	Fine grind
Angular Deviation:	± 3 minutes of arc
Dimensional:	+ 0.000”, -0.010”
Chamfer:	0.35 mm at 45° typical
Clear Aperture:	Central 85% of dimensional

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Right Angle Prisms

Uncoated

Suprasil 1

Part Number	Dimension A	Surface Figure	Surface Quality	Material
AIL-4-4049	0.500”	λ/10	10-5	Suprasil 1
AIL-4-4050	1.000”	λ/10	10-5	Suprasil 1

Fused Silica

Part Number	Dimension A	Surface Figure	Surface Quality	Material
AIL-4-4051	0.500”	λ/10	10-5	Fused Silica
AIL-4-4052	1.000”	λ/10	10-5	Fused Silica
AIL-4-4053	1.500”	λ/10	10-5	Fused Silica
AIL-4-4054	2.000”	λ/10	10-5	Fused Silica

BK7

Part Number	Dimension A	Surface Figure	Surface Quality	Material
AIL-4-4055	5.0mm	λ/4	20-10	BK7
AIL-4-4056	6.0mm	λ/4	20-10	BK7
AIL-4-4057	8.0mm	λ/4	20-10	BK7
AIL-4-4058	10.0mm	λ/4	20-10	BK7
AIL-4-4059	12.0mm	λ/4	20-10	BK7
AIL-4-4060	0.500”	λ/4	20-10	BK7
AIL-4-4061	15.0mm	λ/4	20-10	BK7
AIL-4-4062	20.0mm	λ/4	20-10	BK7
AIL-4-4063	1.000”	λ/4	20-10	BK7
AIL-4-4064	1.500”	λ/4	20-10	BK7
AIL-4-4065	2.000”	λ/4	20-10	BK7

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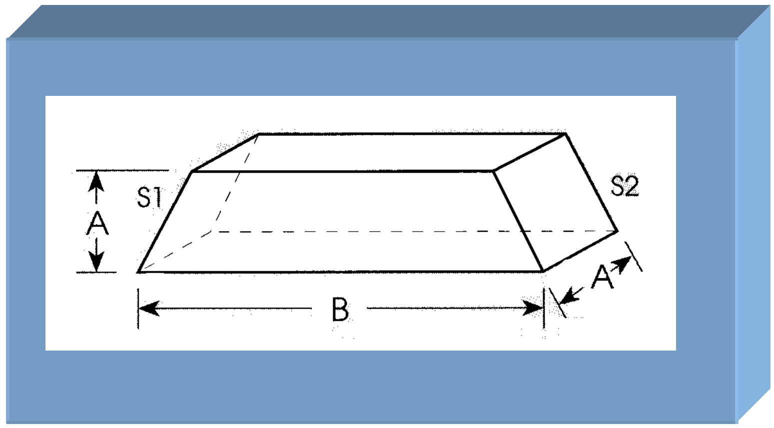
AIL-4-4085 Through AIL-4-4099

Dove Prisms



Specifications

Material:	BK7
Surface Figure:	Polished surfaces λ /4 at 633 nm
Surface Quality:	Polished surfaces 10-5 research grade laser polish
Dimensional Tolerance:	+ 0.000”, -0.010”
Angular Deviation:	± 3 minutes of arc
Chamfer:	0.35 mm at 45° typical
Clear Aperture:	Central 85% of dimension
Antireflection Coating:	Entrance and exit surfaces

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Dove Prisms

Part Number	Dimension A (mm)	Dimension B (mm)	Material	Antireflection Coating Range in nm
AIL-4-4085	6.0	25.0	BK7	450-694
AIL-4-4086	6.0	25.0	BK7	532
AIL-4-4087	6.0	25.0	BK7	1064
AIL-4-4088	8.0	33.6	BK7	450-694
AIL-4-4089	8.0	33.6	BK7	532
AIL-4-4090	8.0	33.6	BK7	1064
AIL-4-4091	10.0	42.0	BK7	450-694
AIL-4-4092	10.0	42.0	BK7	532
AIL-4-4093	10.0	42.0	BK7	1064
AIL-4-4094	12.7	53.3	BK7	450-694
AIL-4-4095	12.7	53.3	BK7	532
AIL-4-4096	12.7	53.3	BK7	1064
AIL-4-4097	25.4	106.7	BK7	450-694
AIL-4-4098	25.4	106.7	BK7	532
AIL-4-4099	25.4	106.7	BK7	1064

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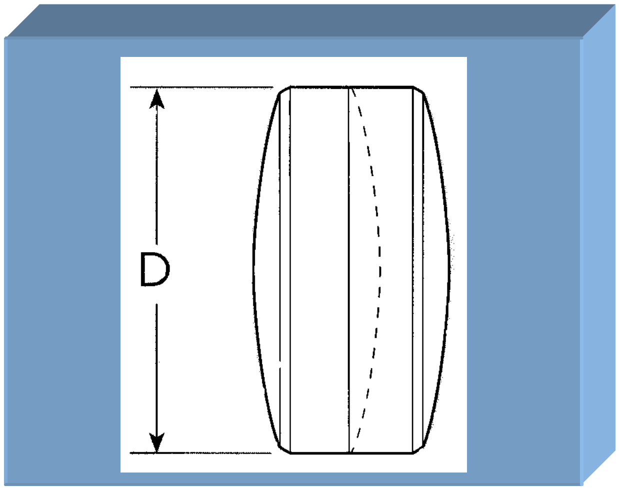
AIL-7-7015 Through AIL-7-7040

450-750nm Positive Aplanatic Cemented Doublet Achromats



Specifications

Material:	BK7 and SF2, SF6 or SF11
Surface Quality:	40-20
Diameter Tolerance:	+ 0.00mm, -0.25mm
Clear Aperture:	Central 85% of diameter
Field of View	4°
Antireflection Coating:	$R_{avg.} \leq$ 0.5% per surface, 450-750 nm

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450 – 750nm Positive Aplanatic Cemented Doublet Achromats

Part Number	Focal Length	Diameter	f/D
AIL-7-7015	25.0	6.35	4.6
AIL-7-7016	30.0	6.35	5.6
AIL-7-7017	50.0	12.7	4.6
AIL-7-7018	75.0	12.7	6.9
AIL-7-7019	100.0	25.4	4.6
AIL-7-7020	125.0	25.4	5.8
AIL-7-7021	150.0	25.4	6.9
AIL-7-7022	200.0	25.4	9.3
AIL-7-7023	200.0	50.8	4.6
AIL-7-7024	250.0	25.4	11.6
AIL-7-7025	250.0	50.8	5.8
AIL-7-7026	300.0	25.4	13.9
AIL-7-7027	300.0	50.8	6.9
AIL-7-7028	300.0	76.2	4.6
AIL-7-7029	500.0	25.4	23.2
AIL-7-7030	500.0	50.8	11.6
AIL-7-7031	500.0	76.2	7.7
AIL-7-7032	500.0	101.6	5.8
AIL-7-7033	1000.0	25.4	46.3
AIL-7-7034	1000.0	50.8	23.2
AIL-7-7035	1000.0	76.2	15.4
AIL-7-7036	1000.0	101.6	11.6
AIL-7-7037	1500.0	25.4	69.5
AIL-7-7038	1500.0	50.8	34.7
AIL-7-7039	2000.0	25.4	92.6
AIL-7-7040	2000.0	50.8	46.3

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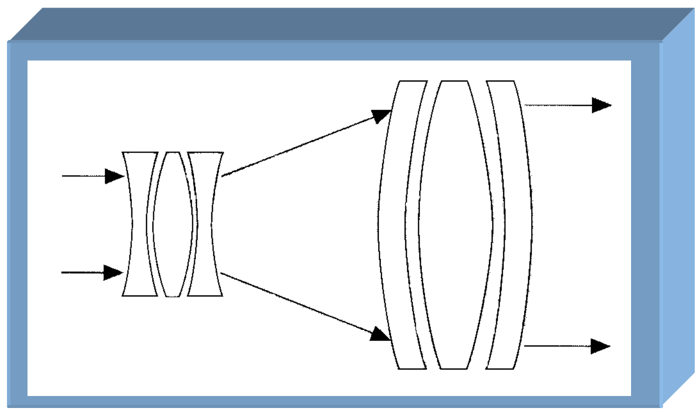
AIL-8-8001 Through AIL-8-8005

Dual Wavelength
Nd: YAG and Ti:Sapphire
Beam Expanders



Specifications

Material:
Transmitted Wavefront:
Transmission:
Antireflection Coating:
Housing Material:

Part Number	Input Aperture	Magnification Ratio	Exit Aperture	Housing Diameter	Housing Length
AIL-8-8001	4.0	3X	12.0	25.4	60
AIL-8-8002	4.0	5X	20.0	31.7	114
AIL-8-8003	4.0	10X	40.0	63.5	236
AIL-8-8004	10.0	3X	30.0	44.5	110
AIL-8-8005	10.0	5X	50.0	63.5	215

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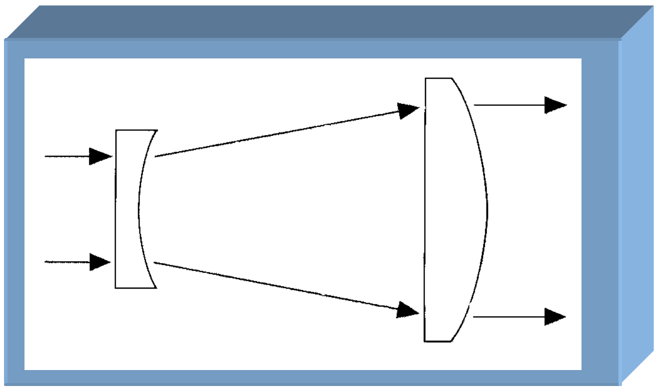
AIL-8-8006 Through AIL-8-8013

Laser Beam Expander



Specifications

Material: BK7 glass

Transmitted Wavefront: λ /10 at 633 nm for 1 /e^2 1mm beam diameter
Transmission: > 96%
Housing Material: Black anodized aluminum

Part Number	Input Aperture	Magnification Ratio	Exit Aperture	Outside Diameter	Housing Length
AIL-8-8006	7.0	2X	14.0	25.4	70.0
AIL-8-8007	7.0	3X	21.0	25.4	65.0
AIL-8-8008	7.0	4X	28.0	50.8	170.0
AIL8-8009	7.0	5X	35.0	38.1	145.0
AIL-8-8010	6.0	7X	42.0	50.8	325.0
AIL-8-8011	4.5	10X	45.0	50.8	290.0
AIL-8-8012	2.5	15X	37.5	50.8	365.0
AIL-8-8013	1.5	25X	37.5	50.8	510.0

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Aspherical Hybrid Plastic Lenses

We offer a variety of precision miniature plastic injection molded optics for a diversity of applications, such as high resolution CCD Camera Lens Systems using plastic aspherical lenses with very short focal lengths.

Our newly developed Aspherical Hybrid Plastic Lens system for CCD video camera systems for video conferencing or similar applications, will improve the image resolution and will decrease distortion or chromatic aberration in a very cost-effective way.

Using our Aspherical Hybrid Plastic Lenses will help you considerably to reduce the number of optical elements needed in a CCD camera lens system, resulting in improved performance at substantial cost savings in most designs.

In the following pages, you will find our most common in stock lens designs. We are also offering design consultation to solve any difficulty you encounter during project development.

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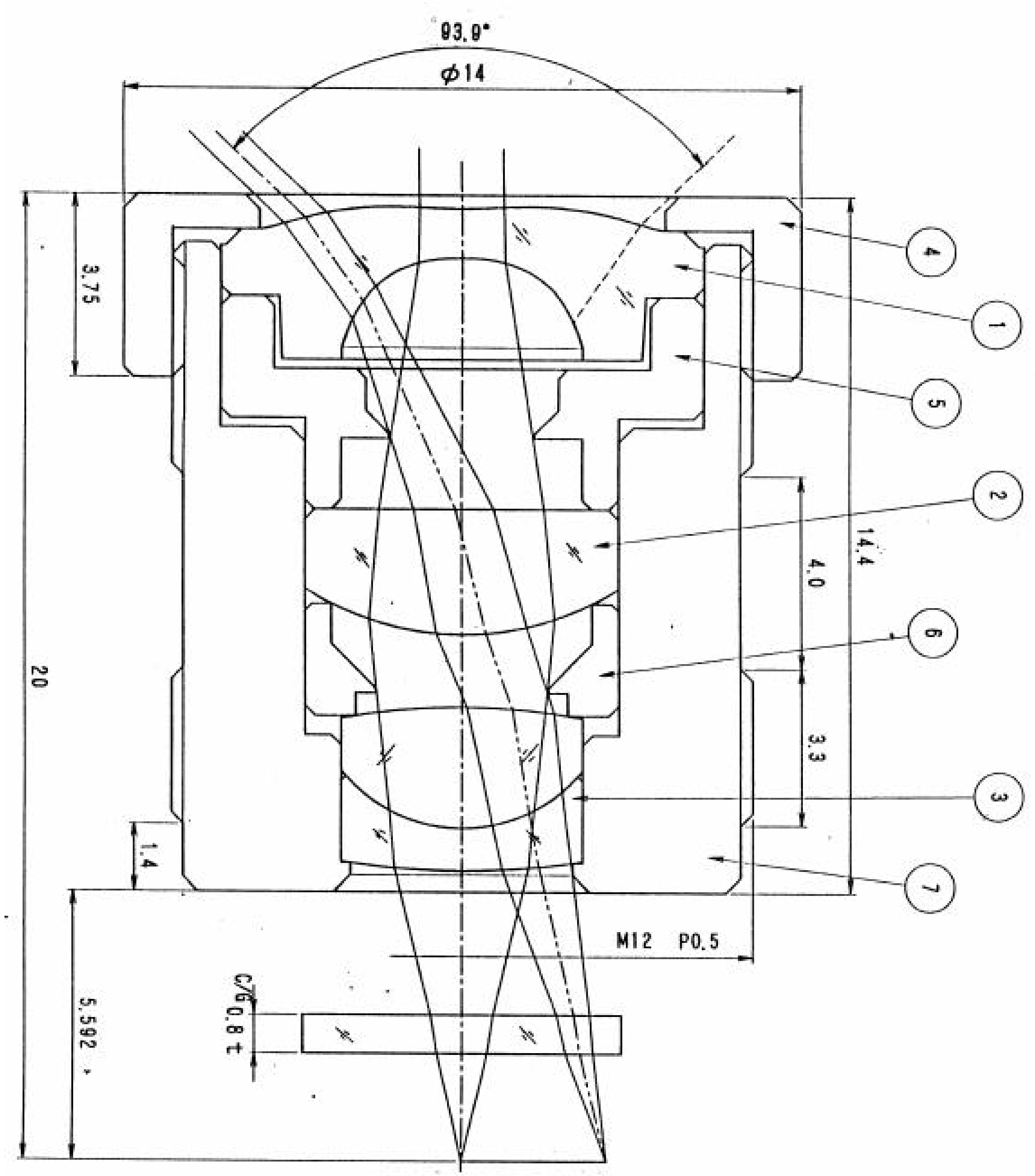
Aspherical Hybrid CCD Camera Lens



3720Q1

The special quality of hybrid CCD lens

- Modulation Transfer Function improved up to 90% in the center.
- Pixels up to 800k.
- Price competitiveness from using aspherical lens.
- Maintenance of high quality by precision plastic molding machines.
- Distortion decreased by using aspherical lenses.

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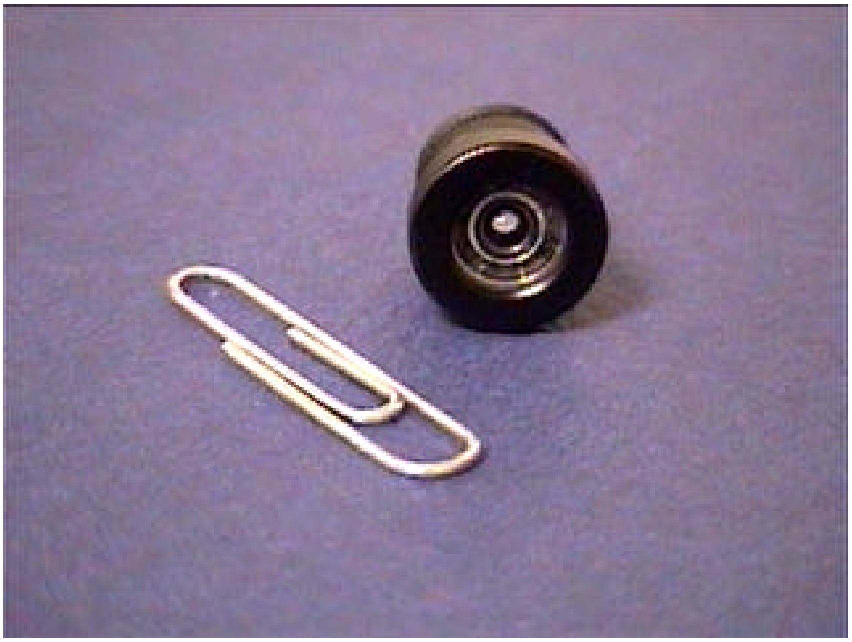
CCD & CMOS CAMERA LENS SPECIFICATIONS

\CONTENTS ITEM\	FOCAL LENGTH	BACK FOCAL LENGTH	VIEW ANGLE	APERTURE	IRIS	LENS CONSTRUCTION	REMARKS
AIL24520S	2.45mm	5.5mm	150°	2.0	FIXED	6 Group, 6 Element	Board Lens, Glass
AIL4318S	4.3mm	4.2mm	78°	1.8	FIXED	5G/5E	Board Lens, Glass
AIL8020S	8.0mm	5.2mm	40°	2.0	FIXED	4G/4E	Board Lens, Glass
AIL12020S	12mm	6.5mm	25°	2.0	FIXED	4G/4E	Board Lens, Glass
AIL3735S	3.7mm	3.43mm	90°	3.5	FIXED	1G/1E	Pinhole Lens
AIL5035S	5.0mm	5.2mm	90°	3.5	FIXED	1G/1E	Pinhole Lens
AIL5035S2	5.0mm	5.2mm	70°	3.5	FIXED	1G/1E	Pinhole Lens
AIL4018S	4.0mm	7.0mm	100°	1.8	FIXED	5G/5E	CCTV Lens
AIL6018S	6.0mm	10.0mm	1/2":82° 1/3":60°	1.8	FIXED	5G/5E	CCTV Lens
AIL8018S	8.0mm	11.0mm	1/2":60° 1/3":45°	1.8	FIXED	5G/5E	CCTV Lens
AIL8018S2	8.0mm	11.0mm	1/2":60° 1/3":45°	Max 1.4	Manual	5G/5E	CCTV Lens
AIL3720C	3.7mm	6mm	1/3":90°1/4":70° 1/5":56°	2.0	FIXED	3G/4E	Board Lens, Aspherical Hybrid
AIL3720Q1	3.7mm	5.5mm	1/3":92° 1/4":70° 1/5":56°	2.0	FIXED	3G/4E	Board Lens, Aspherical Hybrid
AIL4320S	4.3mm	5.13mm	1/4":60°	2.0	FIXED	4G/4E	Board Lens, Glass
AIL2525S	2.5mm	5.2mm	1/3":130°	2.5	FIXED	6G/6E	Board Lens, Glass
AIL2125S	2.1mm	5.6mm	1/3":150°	2.5	FIXED	6G/6E	Board Lens, Glass
AIL2520S	2.5mm	5.2mm	1/3":120°	2.0	FIXED	6G/6E	Board Lens, Glass
AIL4320S	4.3mm	6.4mm	1/3":78°	2.0	FIXED	4G/4E	Board Lens, Glass
AIL4318W	4.3mm	5.5mm	1/3":78°	1.8	FIXED	3G/4E	Board Lens, Aspherical Hybrid
AIL6020A	6.0mm	7.5mm	1/3":54°	2.0	FIXED	4G/4E	Board Lens, Glass
AIL6015S	6.0mm	6.4mm	1/3":54°	1.5	FIXED	4G/4E	Board Lens, Glass
AIL7018S	7.0mm	6.4mm	1/2":62° 1/3":46°	1.8	FIXED	5G/5E	Board Lens, Glass
AIL3745W	3.7mm	3.5mm	1/3":92° 1/4":70° 1/5":56°	4.5	FIXED	1G/1E	Pinhole Lens



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