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Optical System Design

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Optical System Design

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Second Edition



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Optical Thin Films

Introduction

Optical thin films have become an integral part of almost all optical components and systems manufactured today. Their primary function is to govern the spectral composition and the intensity of the light transmitted or reflected by the optical system. Properly applied to various optical surfaces in a given system, optical coatings can greatly enhance image quality and provide for a convenient way of spectrally manipulating light.

Since light behaves according to the laws of electromagnetic waves, the interaction of light with the media that it travels through, or is reflected from, is directly related to its wave nature, primarily the phenomena of *interference* and *polarization*. Whenever light interacts with a structure of thin films, interference occurs, and a degree of polarization will be a function of the angle of incidence. At normal incidence, no polarization will take place, unless the light is transmitted through a birefringent material (polarizing material, like some crystals and plastics). Besides polarization, at an oblique incidence there is a *spectral shift* of the reflectance or transmittance characteristic toward the shorter wavelength. This is due to the optical path difference between the waves reflected from either side of the film structure. This optical path difference is directly proportional to the cosine of the angle of refraction through the coating.

For an optical designer, besides the fact that the interference and polarization are the most fundamental physical principles in the theory

of thin films, an important characteristic is the amount of energy loss, or the *light absorbed* in the coating. In general, for any coating there is a relationship between the transmittance, T , the reflectance, R , and the absorptance, A , in the form of

$$T + R + A = 1 \quad (20.1)$$

where $0 \leq T, R, A \leq 1$.

For materials that are commonly known as *dielectrics*, the coefficient A in Eq. (20.1) is very close to zero, and they basically do not absorb any light. On the other hand, *metals*, besides being highly reflective (90 to 98%), act as light attenuators, and their coefficient of absorption is always greater than zero.

We will refer to Eq. (20.1) later on when we discuss different categories of optical thin films.

Designing Optical Coatings

Without getting into deep analysis of design methods of optical thin films, let us point out that the main building blocks in designing optical coatings are *quarter-wave optical thickness* (QWOT) layers of different materials. The high, medium, and low refractive index QWOT materials are usually denoted as H , M , and L , respectively. If there are two QWOT layers of the same material next to each other, they form a *half-wave optical thickness* (HWOT) layer. If only a fraction of QWOT appears in a design, say one half of H , it is represented as either $0.5H$ or $H/2$.

The long expressions for some designs can be represented in concise form. For example, a 15-layer longwave-pass filter on BK7 glass given by

$$\text{BK7} \left| \frac{H}{2} LHLHLHLHLHLHL \frac{H}{2} \right|_{\text{air}}$$

can be written as

$$\text{BK7} \left| \left(\frac{H}{2} L \frac{H}{2} \right)^7 \right|_{\text{air}}$$

where H and L refer to high and low index materials, such as TiO_2 and SiO_2 .

In principle, the computer programs that assist thin-film engineers in designing optical coatings are very similar to those used by optical designers. Optical design programs are more complex because there are

more variables (such as thickness, radius of curvature, refractive index) to simultaneously vary during the optimization. Further, they have a wider spectrum of the target functions to be satisfied at the end of the optimization (either in the form of the aberration functions, wavefront distortion, optical path difference, or the minimum spot size). Thin-film programs, on the other hand, deal with fewer variables (very often only thickness, rarely refractive index), and their target functions are usually in the form of either reflected or transmitted light intensity.

Thin-film computer programs are essential mathematical tools that enable coating engineers to efficiently, and in some cases very quickly, arrive at the best and most economical design once the problem has been formulated. But to successfully apply this math tool to coatings that are manufactured with high reproducibility, it is the engineer's knowledge of the coating materials and processes that determines the coating's final quality and conformity to the spectral and environmental requirements.

Various Categories of Optical Coatings

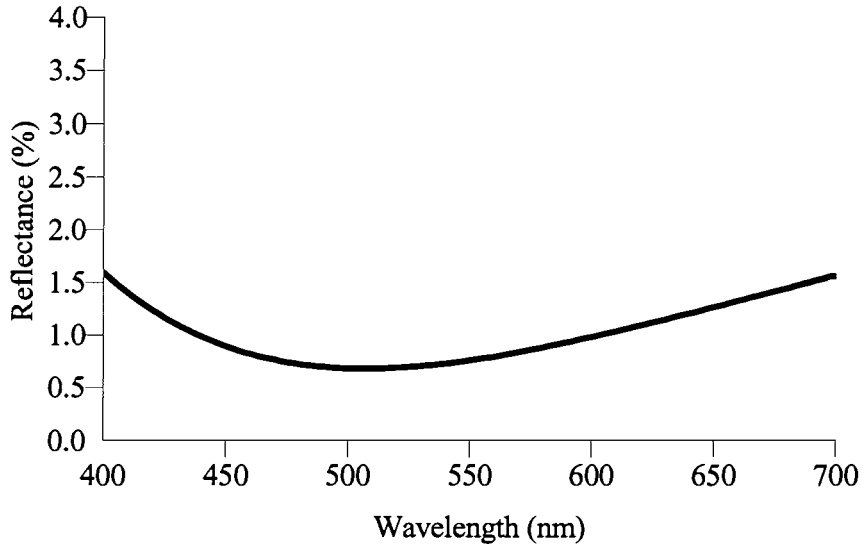
The most widely applied optical coating is the *antireflection* (AR) coating. Its primary purpose is to reduce the amount of reflected light from the optical surface. Its secondary role is to enhance physical and chemical properties of the surface to which it is applied.

Typically, uncoated glass has between 4 and 8% reflection from the surface. This can be reduced to about 1.0% reflection in the visible by applying a single layer of QWOT low-index material, usually magnesium fluoride (Fig. 20.1). A three-layer design can reduce the reflection in the visible even further (Fig. 20.2). The first layer consists of a QWOT medium-index material (for example, Al_2O_3) next to the glass. The second layer is a HWOT high-index material (for example, Ta_2O_5). The third layer is a QWOT low-index material (for example, MgF_2) as a top layer next to the air. This three-layer design falls in the category of the *broadband* (BB) antireflection coating, often denoted as BBAR coating.

If only one wavelength is considered, a two-layer design of high- and low-index materials will bring the reflection down to virtually zero value. With the layer next to the glass fairly thin (high-index material) and the layer facing the air side (low-index material) somewhat greater

Figure 20.1

Computed Reflectance at Normal Incidence of a Single Surface of SSK4 Glass ($n = 1.62$) Coated with a Single Layer of Magnesium Fluoride ($n = 1.38$) of Optical Thickness One Quarter-Wave at 510 nm. Design: SSK4|L|Air, AOI = 0°

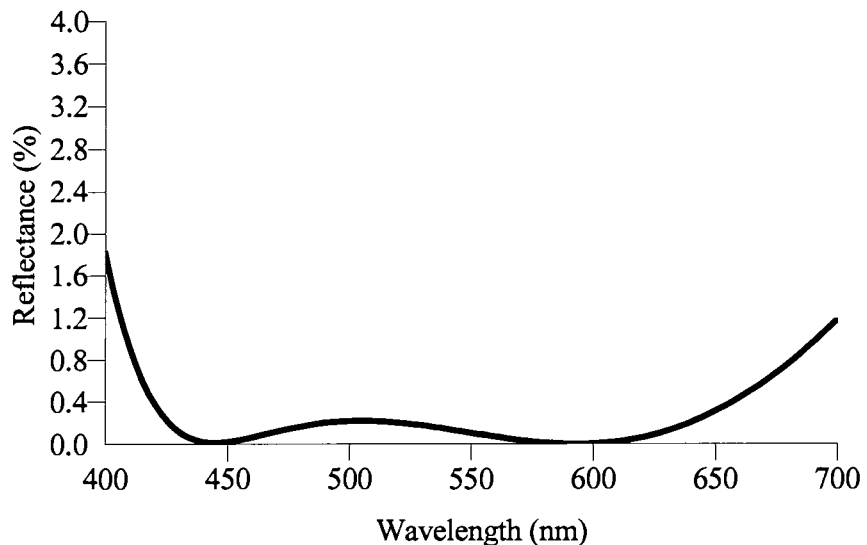


than a QWOT, a relatively broad minimum can be obtained (Fig. 20.3). These coatings are usually called *V* coatings.

For much broader antireflective coverage that would include the visible and a near-infrared region, many layers of high- and low-index materials are required. Their thicknesses are computer optimized and monitored

Figure 20.2

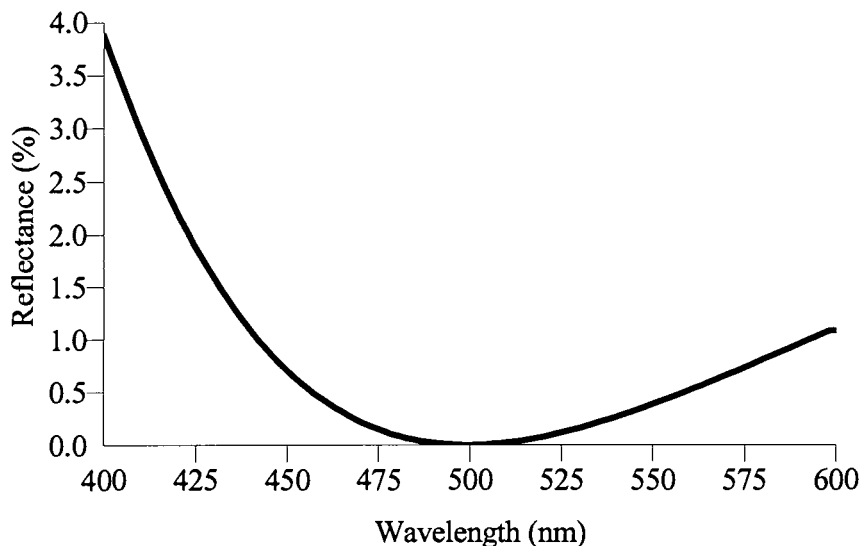
Three-Layer Antireflection Coating on BK7 Glass ($n = 1.52$). (Design: BK7|MHHL|Air at 510 nm, AOI = 0° , $n_H = 2.126$, $n_M = 1.629$, $n_L = 1.384$)



Optical Thin Films

Figure 20.3

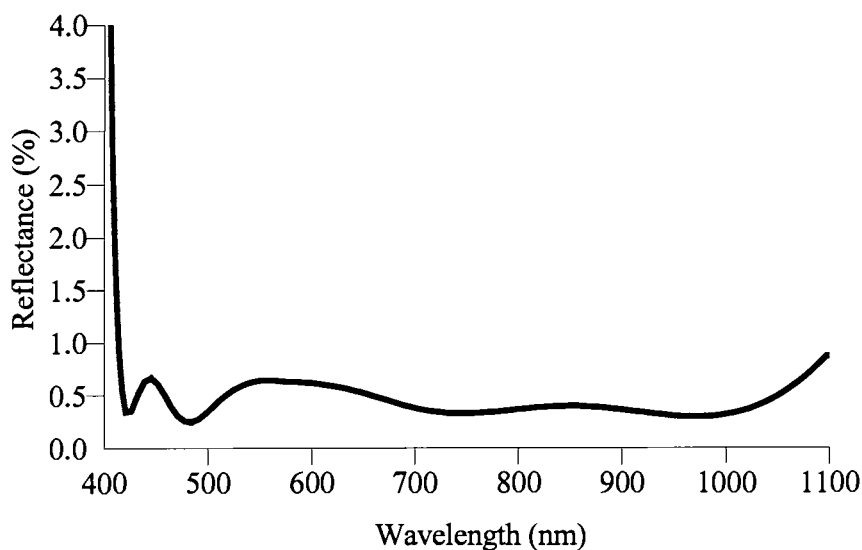
The Reflectance of a Two-Layer Antireflection Coating on BK7 Glass. (Design: BK7] 0.2681H 1.2702L | Air at 500 nm, AOI = 0°, $n_H = 2.127$, $n_L = 1.384$)



throughout the deposition process using either the quartz monitor or the combination of quartz and optical monitoring. For example, the BBAR coating that covers 450 to 1100 nm (Fig. 20.4) would require eight or more layers for the reflection to be less than 1.0% at any wavelength within the region.

Figure 20.4

Eight-Layer Antireflection Coating on BK7 Glass ($n = 1.52$). The Coating Consists of Two Materials of High- and Low-Refractive Index. This Design Has Been Computer Optimized and Has a Few Thin Layers (~20 nm) That Can Only Be Quartz Monitored. The Angle of Incidence Is 0°

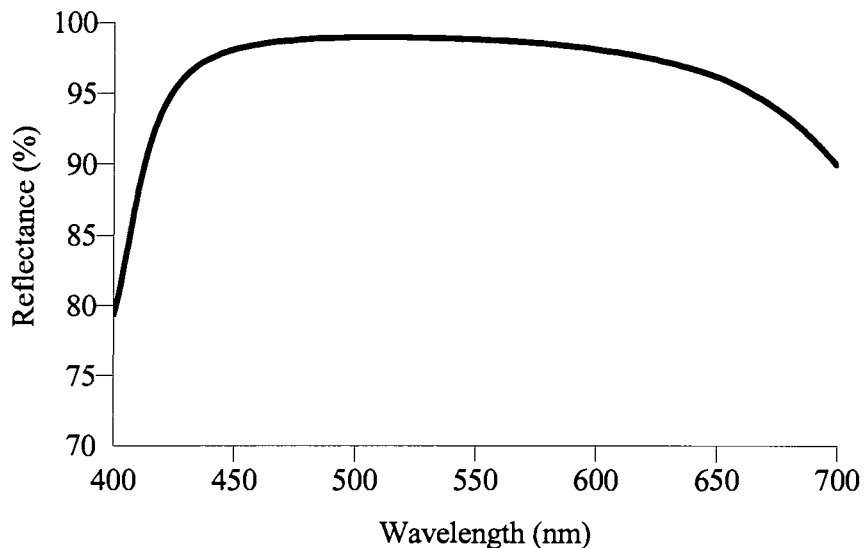


Another class of widely used thin-film coatings is the *metallic mirror*, usually consisting of aluminum. Aluminum is a relatively soft metal, so the coating is often protected with silicon dioxide. The reflectance of this coating is about 90%, but can be further increased by adding a few more layer pairs of high- and low-index materials (for example, TiO_2 and SiO_2) to boost reflectance to about 97 to 98% (Fig. 20.5). Since aluminum is a metal, there is a slight light loss associated with its use. This light loss, or absorption, is manifested as heat released within the coating. In certain applications, such as high-power lasers, mirrors should be free of absorption to a very high degree. This is achieved through the use of all-dielectric mirrors.

Dielectric mirrors consist of the sequence of the alternating high- and low-index materials (for example, TiO_2 and SiO_2). The more layer pairs in the stack, the higher the reflectance. *Cold mirrors* reflect shorter wavelengths and transmit longer wavelengths (Fig. 20.6). *Hot mirrors* transmit shorter wavelengths and reflect longer wavelengths (Fig. 20.7).

As in the field of electronic circuits, there are many different interference filters in a variety of optical applications. Sometimes the goal is to separate one portion of the spectrum from the other. This separation can be done at either normal incidence or oblique incidence. Whatever the case, the solution will be in the form of an *edge filter* or some kind of *dichroic beamsplitter*.

Figure 20.5
The Reflectance of an Enhanced Aluminum Mirror with Four Layers of High- and Low- Index on Top of Aluminum. The Thickness of the Aluminum Layer Is 80 nm. (Design: Al | 0.8LHLH | Air at 520 nm, AOI = 0°, $n_H = 2.446$, $n_L = 1.459$)



Optical Thin Films

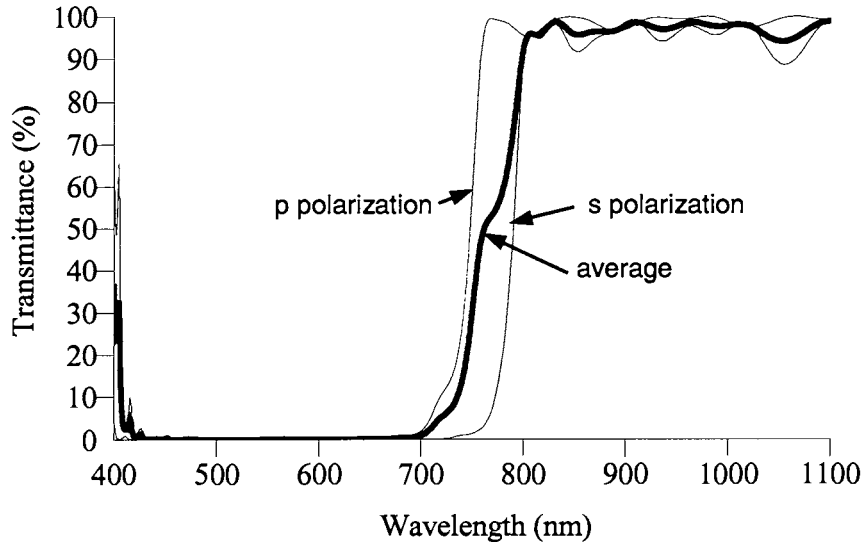
Figure 20.6

The Transmittance of 52-Layer Cold Mirror at a 45° Angle of Incidence. Design Is Given in Phase Thicknesses

(Degrees), and P_H and P_L Refer to TiO_2 and SiO_2 , Respectively.

[Design:

$\text{Air}|(100^\circ P_L)(74^\circ P_L 74^\circ P_H)^8(90^\circ P 90^\circ P_H)^8(108^\circ P 108^\circ P_H)^7(105^\circ P_L)(102^\circ P_H)(98^\circ P_L)(90^\circ P_H)(98^\circ P_L)(23^\circ P_H)$
[BK7 at 538 nm]



When there is a need to pass just one narrow bandwidth and reflect a portion of the spectrum on either side of it, use should be made of a *narrowband* interference filter, often called the *Fabry-Perot filter* (Fig. 20.8).

Recently, another class of interference filters has become of great importance in laser and fiber-optic applications: *notch filters*. They reflect

Figure 20.7

Calculated Transmittance of a 44-Layer Computer Optimized Hot Mirror. [Design:

$\text{Air}|(1.07L(2H2L)^8(2.6H)(2.64L)(2.8H)(2.46L)(2.14H)(2.2L)(2.6H)(2.6L)^3(2.6H)(2.74L)(2.9H)(2.9L)^5(2.74H)(3.08L)(0.4H)$
[BK7 at 415 nm, AOI = 0°, $n_H = 2.239$, $n_L = 1.463$]

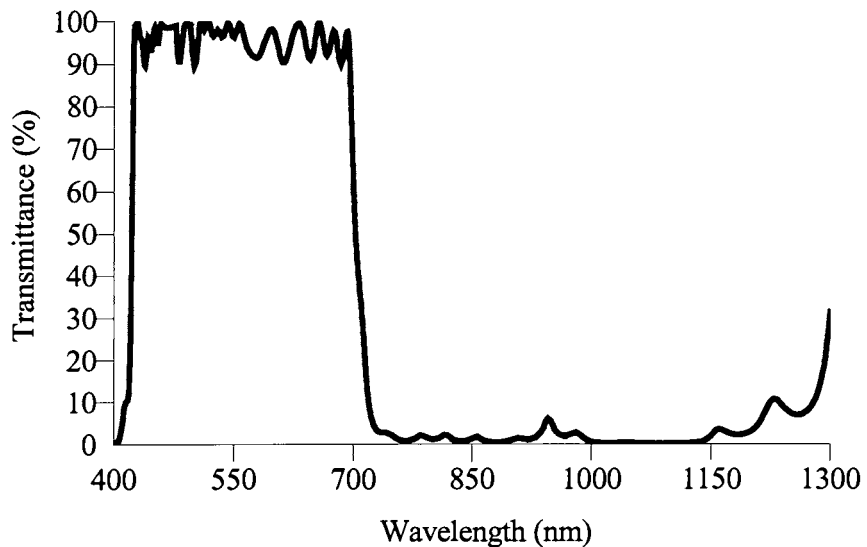
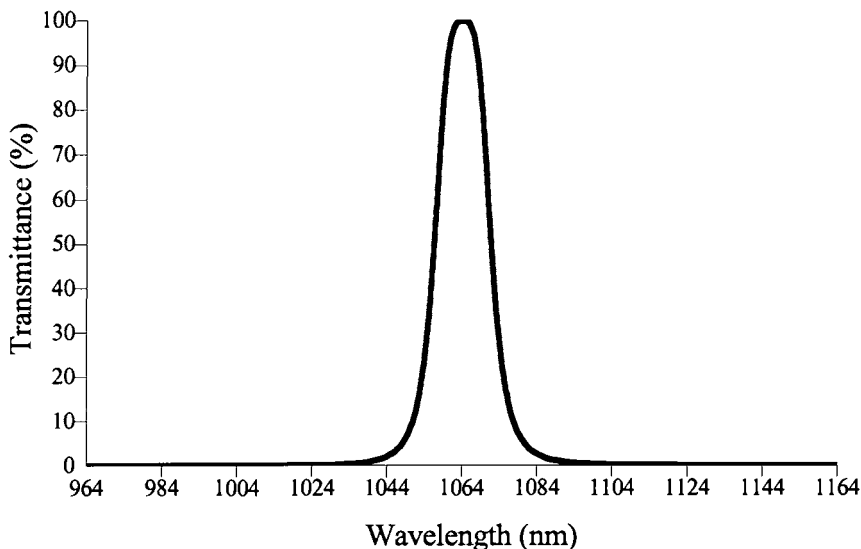


Figure 20.8

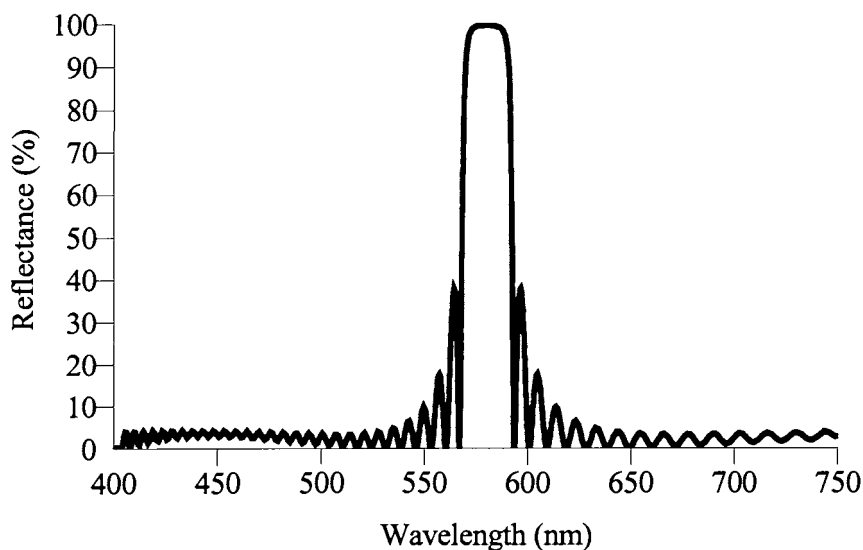
The Double-Cavity
Fabry-Perot Narrow-
band Interference Fil-
ter at 0° Angle of
Incidence [Design:
BK7|(HL)³HH(LH)³L
(HL)³HH(LH)³|BK7
at 1064 nm, AOI =
0°, $n_H = 2.253$, $n_L =$
1.449]



one or more narrow bands and transmit the wider regions around the rejection zone (Fig. 20.9). To maintain a narrowband characteristic of the rejection zone, this filter is often designed using low- and medium-index materials. This, in turn, requires many layers to achieve a high reflection. Essentially, their function is just the opposite of the narrowband filters.

Figure 20.9

Computed
Reflectance of a
Single-Notch Filter
[Design: BK7|
(L3M)³¹4L|Air at 580
nm, AOI = 0°, $n_M =$
1.626, $n_L = 1.457$]



With the advent of new polarizing devices in the area of electronic imaging, *polarizing beamsplitters* have become of significant importance. Their role is to maximize the s and minimize the p-reflectance of the unpolarized (randomly polarized) light over the narrow or broadband spectral region. The degree of polarization in transmission is

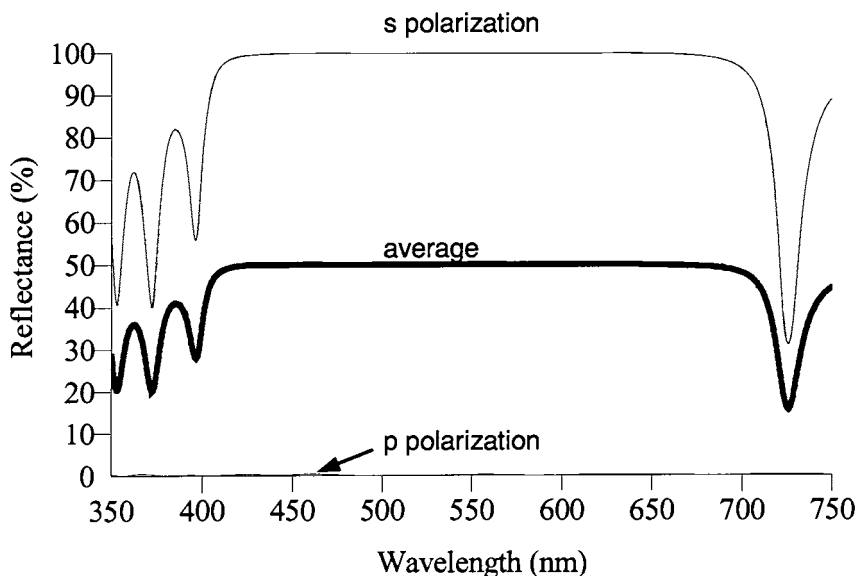
$$P_T = \frac{T_p - T_s}{T_p + T_s}$$

and in reflection

$$P_R = \frac{R_s - R_p}{R_s + R_p}$$

The *extinction ratio* indicates how well the polarizing beamsplitter discriminates between two planes of polarization. In transmission it is given as a ratio of T_p and T_s , and in reflection as a ratio of R_s and R_p . When the degree of polarization is very high, the reflected linearly polarized s-component and the transmitted linearly polarized p-component should each account for 50% of the incoming light intensity. Thus, an ideal polarizing beamsplitter acts as the 50/50 intensity beamsplitter, where each of the two emerging light beams are 100% linearly polarized (Fig. 20.10).

Figure 20.10
The Polarizing
Polychromatic
Cube Beamsplitter.
The Computed
Reflectance Repre-
sents a 15-Layer
Design Consisting of
Two Materials of
High and Low Refrac-
tive Index. The Angle
of Incidence is 52°



Optical Coating Process

Optical coatings are manufactured in high-vacuum coating chambers. Conventional processes require elevated substrate temperatures (usually around 300°C), whereas more advanced techniques, like ion-assisted deposition (IAD) are utilized at room temperatures. IAD processes not only produce coatings with better physical characteristics compared to conventional ones, but also can be applied to substrates made out of plastics. Figure 20.11 shows an operator in front of the optical coating



Figure 20.11

An Operator in Front of the Optical Coating Machine (Courtesy of LaCroix Optical Co., Batesville, Arkansas)

machine. Its main pumping system consists of two cryopumps. Control modules for electron-beam evaporation, IAD deposition, optical monitoring, heater control, pumping control, and automatic process control are in the foreground. Figure 20.12 shows the configuration of the hardware mounted on the base plate of a high-vacuum coating machine. Two electron-beam sources located at each side of the base are surrounded by circular shields and covered with shutters. The ion source is located in the middle. The optical monitor windows are in the front of the ion source. Figure 20.13 shows the upper part of the vacuum chamber,

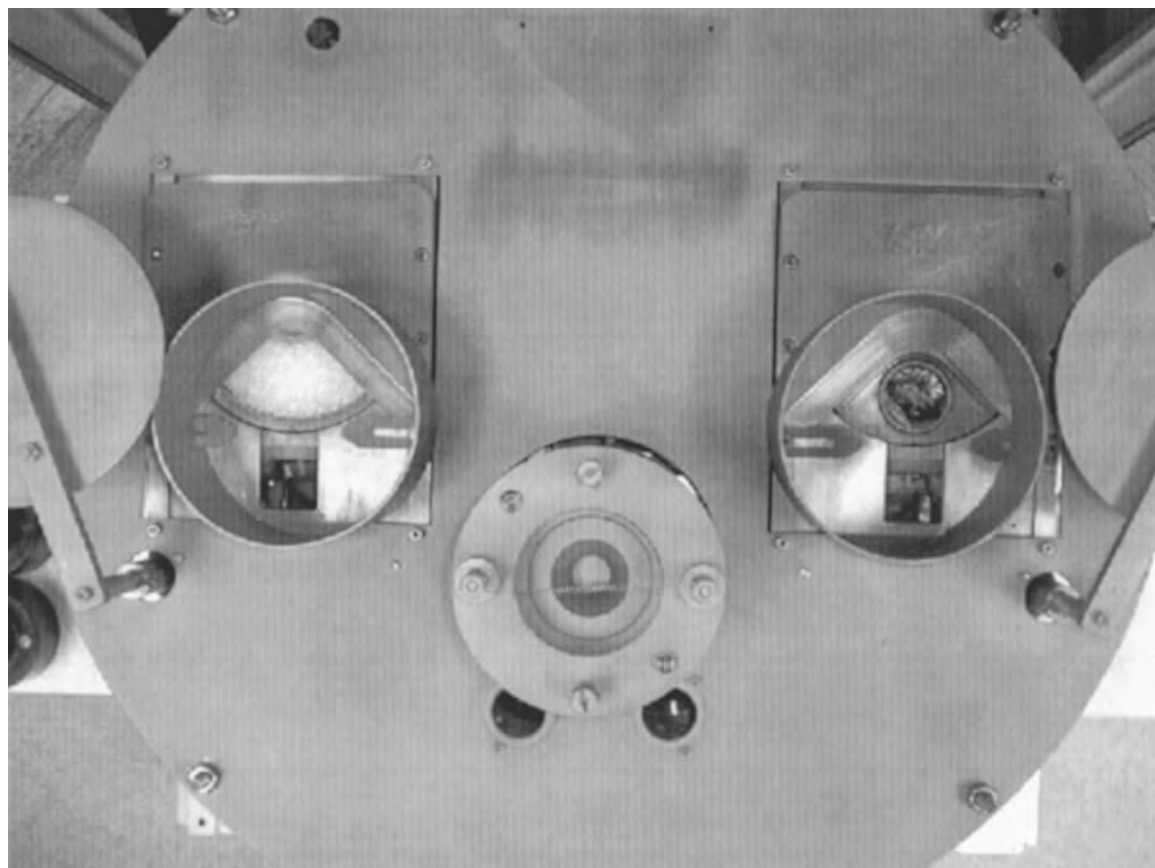


Figure 20.12

The Configuration of the Hardware Mounted on the Base Plate of a High-Vacuum Coating Machine (*Courtesy of LaCroix Optical Co., Batesville, Arkansas*)

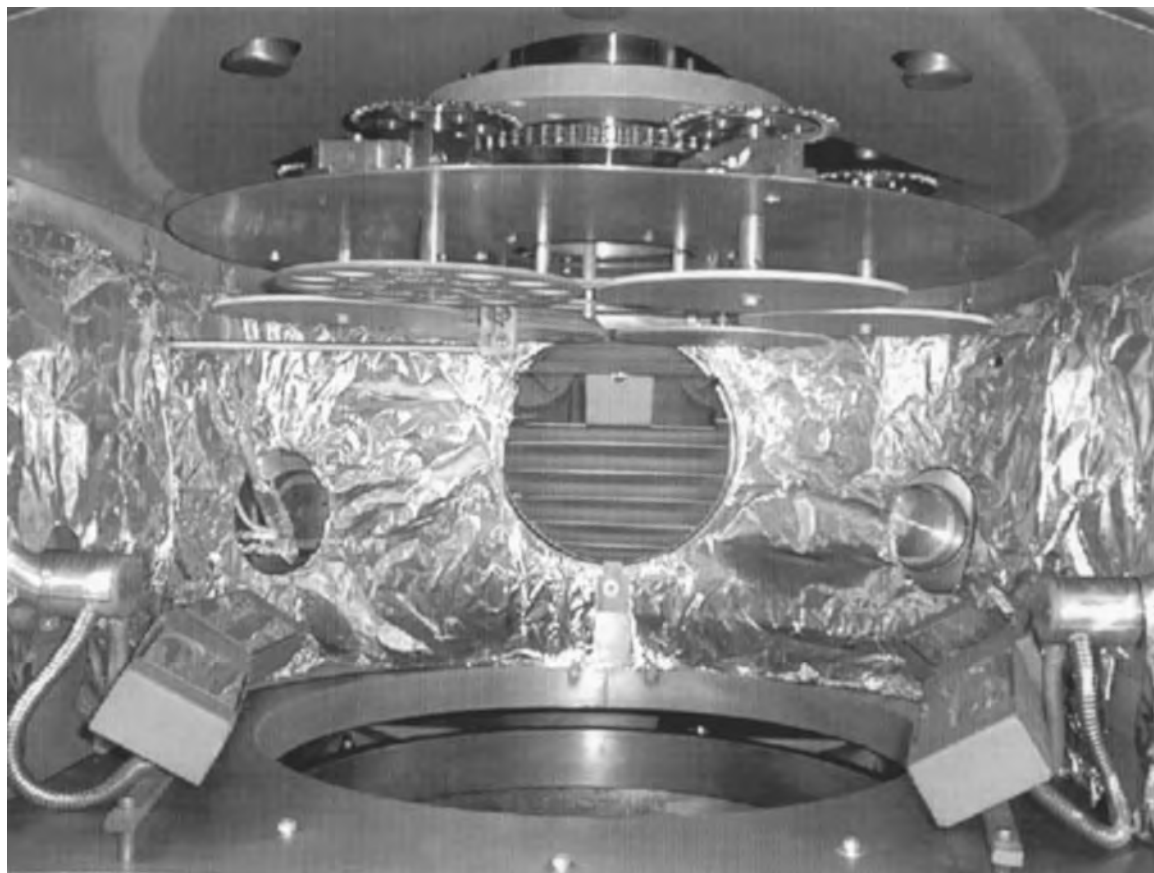


Figure 20.13

The Upper Part of the Vacuum Chamber Is Occupied by the Planetary System with Six Round Fixtures (*Courtesy of LaCroix Optical Co., Batesville, Arkansas*)

which is occupied by the planetary system with six round fixtures. Fixtures are loaded with optics to be coated. A use of a planetary system is a preferred way of maintaining a uniform distribution of the evaporated material across the area of the fixture. Fixtures turn around their common axis and revolve around their own axes. The optical and quartz monitors are in the middle of the planetary drive mechanism, the latter being obstructed by the drive hub. The large opening in the background leads to an additional high-vacuum pump. The substrate heating system consists of four quartz lamps, two at each side of the chamber.

The traditional methods of thin-film deposition have been thermal evaporation either by means of resistance-heated evaporation sources or by electron-beam evaporation. Film properties are determined mostly by the energies of the depositing atoms, which are only around 0.1 eV in conventional evaporation. IAD deposition results in direct deposition of ionized vapor and in adding activation energy to the growing film, typically in the order of 50 eV. Using the ion source, conventional electron-beam evaporation is improved by directing the flux from the ion gun to the surface of the substrate and growing film.

The optical properties of films, such as refractive index, absorption, and laser-damage threshold, depend largely on the microstructure of the coating. The film material, residual gas pressure, and substrate temperature can all affect the microstructure of the thin films. If the depositing vapor atoms have a low mobility on the substrate surface, the film will contain microvoids, which will be filled subsequently with water when the film is exposed to a humid atmosphere.

We define the *packing density* as the ratio of the volume of solid part of film to the total volume of film (which includes microvoids and pores). For optical thin films, it is usually in the range 0.75 to 1.0, very often 0.85 to 0.95, and rarely as great as 1.0. A packing density that is less than unity reduces the refractive index of evaporated material below the value of its bulk form.

During the deposition, the thickness of each layer is monitored either optically or by using a quartz crystal. Both techniques have advantages and disadvantages that are not discussed here. What they have in common is that they are done in a vacuum while the material is evaporated. Consequently, they represent the refractive index of evaporated material in a vacuum, not the one that the material will acquire after being exposed to humid air. Moisture adsorption in the film results in displacement of air from microvoids and pores, causing an increase in the refractive index of the film. Since the physical thickness of the film remains constant, this refractive index increase is accompanied by a corresponding increase in optical thickness, which in turn results in the spectral shift of the coating characteristic toward a longer wavelength. To minimize this spectral shift caused by the size and overall population of microvoids throughout the growing film, high-energy ions are employed to convey their momentum to the atoms of evaporating material, thereby largely increasing their mobility during the condensation at the substrate surface.

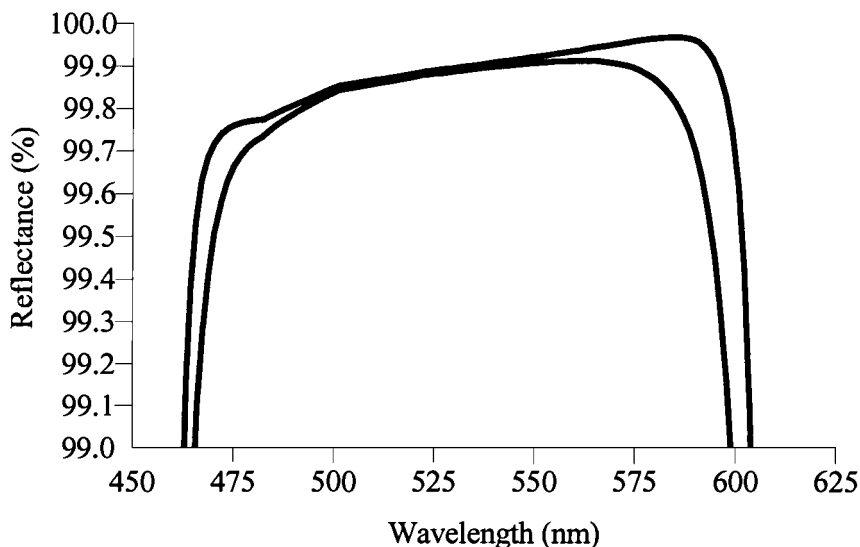
Coating Performance Versus Number of Layers

We have mentioned earlier that the optical coating materials fall into two groups: *dielectrics* and *metals*. All of the preceding various optical coatings, except some metal mirrors, utilize dielectric materials in their design. Among dielectrics, the most often used are oxides and fluorides. One technological problem associated with the deposition of high-index oxide materials is their tendency to dissociate into oxygen and some lower forms of the original oxide. To avoid absorption in the depleted coating and to keep the coefficient A in Eq. (20.1) as close as possible to zero, it is necessary to *reoxidize* material before it condenses on the substrate, thereby preserving the *stoichiometry* of the bulk material.

One could think that the greater the number of layers, the better the coating performance. However, *given the manufacturing technology, there is a limit to a maximum number of layers that will produce the coating with the best characteristics*. For an optical designer just using an optical design program, it becomes a relatively straightforward conclusion that adding more surfaces and glasses to a certain, already well-corrected lens, for example, a double gauss photographic lens, will cause the image to deteriorate. Thin-film programs do not take into account physical characteristics of the coating microstructure and the atomic and molecular forces that exist between layers of different materials and within each layer. Consequently, thin-film programs cannot predict the physical behavior of the final coating design as much as the optical design programs can predict and characterize the image quality of an optical system. To illustrate this, let us take an example of a high-reflection dielectric mirror. It consists of a sequence of layer pairs of high- and low-refractive index materials (for example, TiO_2 and SiO_2), where each layer is QWOT. Assuming absorbing media, 12 of these layer pairs (implying a coating consisting of 24 layers) would boost reflectance to 99.9% at 530 nm. Adding another eight layers would not result in any considerable improvement. This is shown in Fig. 20.14. This 32-layer coating would have the same reflection of 99.9% at 530 nm, higher absorption, and greater overall thickness. Although with the slightly broader characteristic, it would probably be inferior to the 24-layer design because of a greater possibility of crazing (breaking off the coating because of high-tensile stress) and higher absorption that offsets the gain in reflectance.

Figure 20.14

The Reflectances of Two Dielectric Mirrors at 0° Angle of Incidence. Design Wavelength Is 525 nm, and the Coefficient of Absorption of High-Index Material Is 0.00027. The Upper Curve Represents a 32-Layer Design BK7| $(HL)^{16}$ |Air, and the Lower One Represents a 24-Layer BK7| $(HL)^{12}$ |Air. The Refractive Indices of Two Materials Are 2.336 and 1.461



Specifying Coating Requirements

Accurate specification of coating requirements assumes an understanding of the coating function, the function of the optical component to which it is applied, and the coating usefulness in a particular application.

For example, to increase the transmittance of an optical glass surface in the visible domain to 99.0% or more would require a broadband antireflection coating (BBAR) from 400 to 700 nm, for which Eq. (20.1) can be written in the following form

$$T = 1 - R - A \geq 0.99$$

or

$$R + A \leq 0.01 \quad \text{from 400 to 700 nm} \quad (20.2)$$

The last inequality expresses the requirement that the sum of the reflectance and absorptance should not exceed 1.0% for any wavelength in the interval 400 to 700 nm. Very often Eq. (20.2) is written as

$$R \leq 1.0\% \quad \text{from 400 to 700 nm}$$

assuming that the absorptance is close to zero ($A \approx 0$). If the glass is BK7 and the angle of incidence (AOI) of the light striking the glass surface is between 0 and 15°, then the fairly complete and accurately formulated requirement would be in the form

BBAR on BK7 glass

$$R(400 \text{ to } 700 \text{ nm}) \leq 1.0\% \text{ @ AOI} = 0 \text{ to } 15^\circ$$

$$A \approx 0\%$$

To avoid some possible misinterpretations of the coefficient A , its maximum value can always be explicitly stated on the coating blueprint.

Relationship Between Production Cost, Tolerances, and Quality

The production cost per run of a particular coating is primarily determined by the size of the coating chamber, the manufacturing technology, and the complexity of the coating. Since the area of the coating chamber that can be used to coat parts is more or less directly proportional to the square of its radius, it follows that the bigger the chamber, the lower the price per coated lens. As an example, if the diameter of one chamber is twice the diameter of the other, then approximately four times more lenses can be coated in the first chamber than in the second one.

For some extremely stringent requirements, often found in the production of narrowband filters, it is not always possible to utilize the whole coating area within one chamber but rather one particular segment of it. This is because of the nonuniformity of the coating distribution across the chamber. Therefore, depending on the type of the coating, the capacity of the coating machine can be governed by the tolerances on the spectral characteristics of the coating.

For well-designed coating machines, the distribution of the spectral characteristic of evaporated material stays within $\pm 1\%$ of the nominal value. For example, the coating represented by Fig. 20.3 would have the range of reflectance minima from 495 to 505 nm. The inconsistency between different runs could further increase this range, say from 490 to 510 nm.

Besides the spectral conformity of the coated lens to the prescribed value, its quality is further governed by the least amount of coating voids, good adhesion and hardness, environmental stability, and the high packing density.

Different deposition techniques have been invented over the past 20 years in order to increase the packing density of evaporated material to the value close to unity. The most important ones are ion-assisted deposition (IAD), ion-beam deposition (IBD), and ion plating. We could finally say, the closer the packing density to unity, the more expensive the coating.

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Hardware Design Issues

There are many optical system design issues which relate directly to the ultimate hardware implementation, yet are different from the subjects we have covered thus far. It is important that the designer be reasonably fluent in these areas. They include the use of off-the-shelf optics, baffling and stray light control, and optomechanics.

Off-the-Shelf Optics

Off-the-shelf optics is, in effect, catalog optics. One of the significant advantages of off-the-shelf optics is that if what you need is in stock, you can have nearly immediate delivery. Unfortunately, the converse is also true: if what you need is *not* in stock, you may be faced with a long delivery time, perhaps in the order of 12 to 16 weeks.

The forms of off-the-shelf optics follow.

Precision Lens Assemblies

This first class of off-the-shelf optics includes relatively precision lenses such as camera lenses, relay lenses, enlarging lenses, and other multielement lens assemblies of reasonable quality. These lenses are most often mounted in nice-looking anodized housings, and may have adjustable f /numbers and focusing capability.

The optical and mechanical quality of these lenses may or may not be good. Just because the lenses are mounted in a beautiful black anodized housing with red, blue, green, and yellow engraving and just because the lenses are coated with a nice deep blue antireflection coating, there is no assurance whatsoever that the optical performance is any good. In addition, the focal length and f /number may or may not be per the specification. Moreover, the image quality may or may not be good. This is not to say that the specifications are not as advertised, nor is the performance necessarily poor; we only bring this up as a caution so that you are not misled by the external appearance of the lens assembly.

As with most off-the-shelf optics, these types of lenses are available almost immediately. If your lens is out of stock, delivery could take as long as 3 to 4 months, or longer, if indeed the same lens is ever again available. When you are dealing in a commercial commodity-like product line arena such as with 35-mm camera lenses, there is a rapid changeover in products, making future availability of a given lens a real questionable issue.

The cost of off-the-shelf optics in the form of completed lens assemblies can range from under \$100 to over \$500, or more, depending on manufacturing costs, volume, and, of course, quality. A good example of such a lens is a name brand 50-mm focal length $f/2.0$ 35-mm camera lens, which we used recently for a laboratory test. It cost less than \$200 and performed extremely well for the intended purpose. The lens had six elements, and while its housing was partially plastic, it seemed robust enough for most applications.

Single Elements and Achromatic Doublets

The major catalog companies have several hundred different single-element lenses and achromatic doublets available. They typically range from approximately 1.5- to 2000-mm focal length, in diameters from approximately 1.5 to 150 mm. Their optical quality and level of tolerances are generally reasonable for many nondemanding applications and they are generally available uncoated as well as antireflection coated. Do not, however, expect to find extremely high-precision optics in this commodity area.

The cost of catalog single elements and doublets of small diameters up to approximately 50 mm are in the order of \$60 to \$150 each. The cost of *custom* single elements and achromatic doublets can be approximately \$350 per element in low quantities, and delivery can be 6 to 8 weeks. Delivery in 1 week is available from several vendors, naturally at a premium

price. As soon as the quantities increase to between 50 and 100, the price of custom lenses drops to prices close to catalog levels.

Other Forms of Off-the-Shelf Optics

There are many other forms of off-the-shelf optics available, including prisms, windows, mirrors, beamsplitters, polarization components, filters, and more. Also, there is the relatively new class of microoptics available off the shelf such as laser diode collimators and focusing optics.

How to Effectively Work with Off-the-Shelf Optics

If you are careful in use of off-the-shelf optics, you can be highly successful. On the other hand, if you are too casual and don't pay attention to details, your project could easily end up in trouble. Some guidelines gleaned over the years follow.

Complete lens assemblies are the most difficult to deal with. Manufacturers, such as the major camera companies, simply will not share with anyone the lens design prescription. Your ability, therefore, to input the design into one of the lens design and analysis software programs and interface it with other off-the-shelf, or even custom optics, becomes difficult, if not impossible.

If not given by the manufacturer, you could certainly have some of the basic parameters measured such as the focal length, f /number, and entrance and exit pupil locations. While not trivial to characterize, these parameters can indeed be measured. However, what you cannot do easily is measure the residual lens aberrations in order to factor them into a more complex system model to be used with other lens groups. Thus, incorporating off-the-shelf lenses with custom lenses can lead to serious problems.

There is one very important matter that must be considered, and that is that a lens designed for one set of specifications or parameters may or may not perform well under different conditions. For example, if we procure a 35-mm focal length $f/2.8$ double gauss camera lens from a well-known manufacturer, and we then proceed to use it at a near-unit magnification to image postage stamps or integrated circuit chips onto a CCD sensor, we will likely be very disappointed in its performance. The

lens was most likely designed for an infinite object distance or a distant object, and at a unity magnification, it will most likely perform very poorly. In addition to spherical aberration, the lens will suffer seriously from astigmatism and other off-axis aberrations.

The same holds for other specifications. Again, using this camera lens as an example, if we use it over a wider field of view or a larger spectral band than it was designed for, we will likely have poor performance. In addition, there may be distortion, which is not an image quality issue but rather a mapping error. If your application requires a precision machine vision lens with low distortion, then this must be measured for the proposed off-the-shelf lens.

Working with Off-the-Shelf Singlets and Doublets

This task is far more straightforward than working with complex lens assemblies due to two factors:

1. Many of the lens design software packages have included the design prescriptions of singlets and achromatic doublets from most of the major catalog suppliers. For example, Zemax has resident lens prescriptions from Edmund Scientific, Melles Griot, Opto-Sigma, Rolyn, Newport Corporation, Coherent, Spectra Physics, and Linos Photonics. Fortunately, the suppliers of these lenses realize that they can serve the technical community far better by providing this information rather than being secretive.
2. The lenses are fundamentally simple lenses with little to be concerned about with respect to pupils for example. In addition, even if the prescription is not available, you could generate a candidate design and have a moderate level of confidence that the real lens will be close to the catalog lens.

For example, let's assume that you find in some new catalog an achromatic doublet which has a focal length of 78 mm and a diameter of 10 mm, but the catalog is not resident in your design package. If you are confident that the lens was designed for an infinite object distance, you could in a matter of a few minutes emulate it with reasonable confidence of the design being at least sufficiently close to the actual design to be useful in your computer modeling. You might, for example, select

BK7 glass for the crown element and SF2 glass for the flint and optimize it. The results should be reasonably close to the real lens.

In developing a lens design for which you intend to explore the potential of using off-the-shelf singlets and/or doublets, a good procedure to follow is to first perform the design yourself so as to meet the system's first-order and performance specifications. You may want to begin with a first-order design using so-called paraxial lenses, and later convert it to a real design. Once you feel comfortable with your design, then you need to evaluate the focal length of the singlets and/or doublets which you intend to match to off-the-shelf components. If you intend to use a planoconvex singlet, then in the design you should also use a planoconvex element; the same holds true for planoconcave lenses and equiconvex or equiconcave lenses. Now you need to look in one or more catalogs for lenses that match closely the parameters of your lenses (in particular, the focal length and diameter) and replace your lenses with the catalog lenses. Most of the software packages allow you to simply insert any off-the-shelf lens into an otherwise custom design. Make sure you pay attention to the lens orientation, or which way the crown and flint elements are oriented.

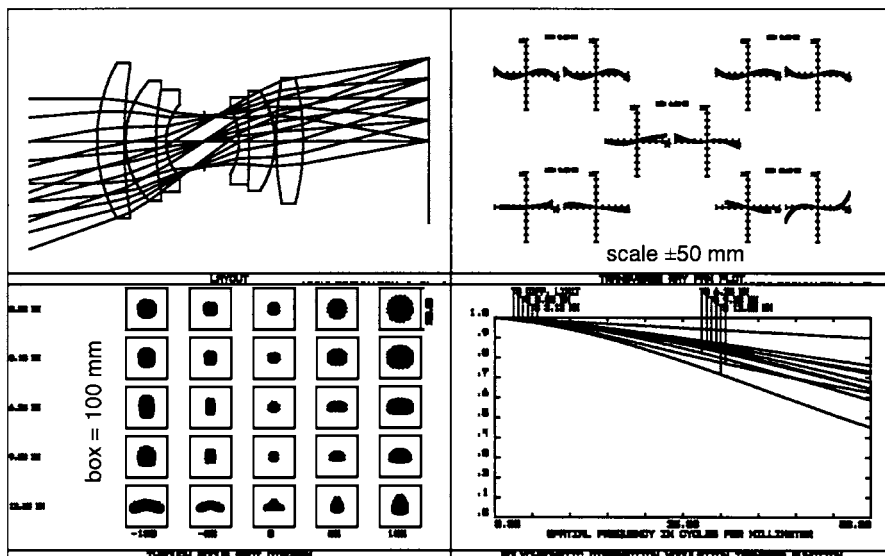
At this point, you may find that your performance and other specifications are adequately met, in which case you can freeze the design and procure the lenses. On the other hand, you may find that for one reason or another the design requires further optimization, in which case you need to comply. This may require customization of one or more lens groups for example. Often your final design might include a mix of off-the-shelf components as well as custom components. You will likely find that as you incorporate more off-the-shelf components into a given design, its performance will degrade from optimum. However, the important question to be answered is whether the performance is *good enough*.

Example of Lens Used at Conjugates Different from What It Was Designed

To illustrate some of the preceding issues, Fig. 21.1 shows the layout and performance for a 35-mm focal length $f/2.8$ double Gauss lens designed for an infinite object distance. Figure 21.2 shows the performance of the same lens with an object distance of 0.5 m. Note that the plot scales are maintained and are identical in all of the figures in this analysis, and the

Figure 21.1

A 35-mm Focal
Length $f/2.8$ Lens at
Infinity



modulation transfer function (MTF) data are plotted to 50 line pairs/mm. At first glance, the transverse ray aberrations look similar to the previous nominal design data, and indeed there is not a significant degradation. However, note that the MTF has suffered a significant drop, especially off axis. In Fig. 21.3, we show the same lens at a 100-mm object distance (this results in a demagnification of $3\times$). The performance is significantly

Figure 21.2

A 35-mm Focal
Length $f/2.8$ Lens at
500-mm Object
Distance

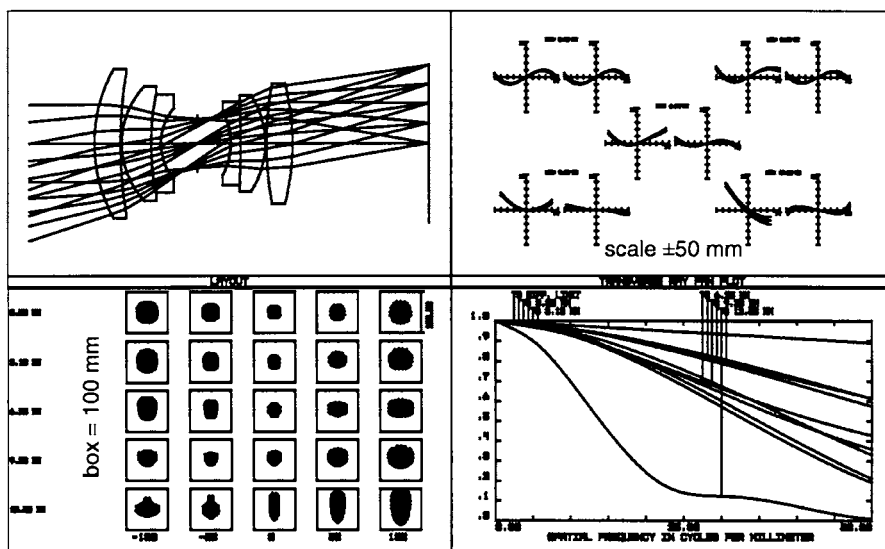
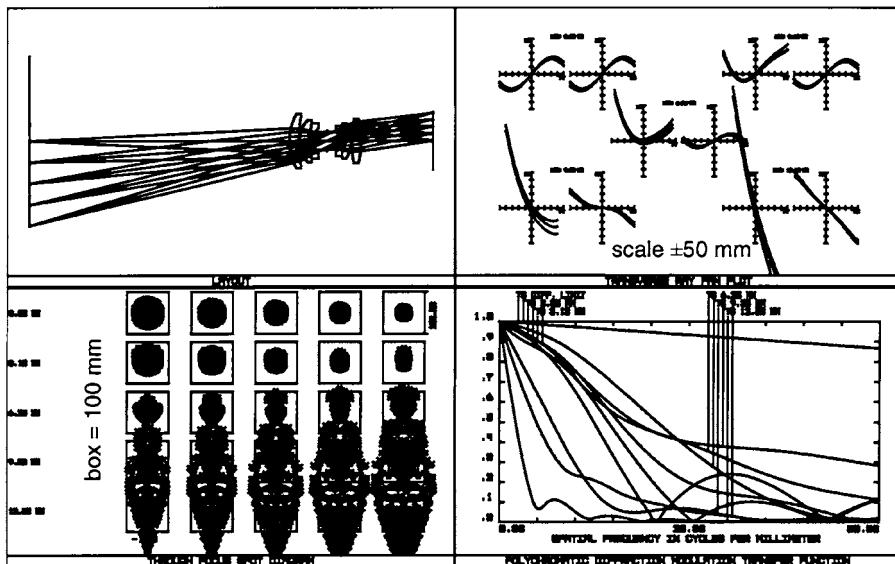


Figure 21.3

A 35-mm Focal
Length $f/2.8$ Lens at
100-mm Object
Distance



degraded from the nominal lens performance. Figure 21.4 shows the performance if the lens is used at a 1:1, or unity, magnification. In this case, the performance is extremely poor. At the edge of the field there is over an order of magnitude increase in spot diameter when the lens is used at 1:1 magnification!

Figure 21.4

A 35-mm Focal
Length $f/2.8$ Lens at
Unit Magnification
(32.41-mm Object
Distance)

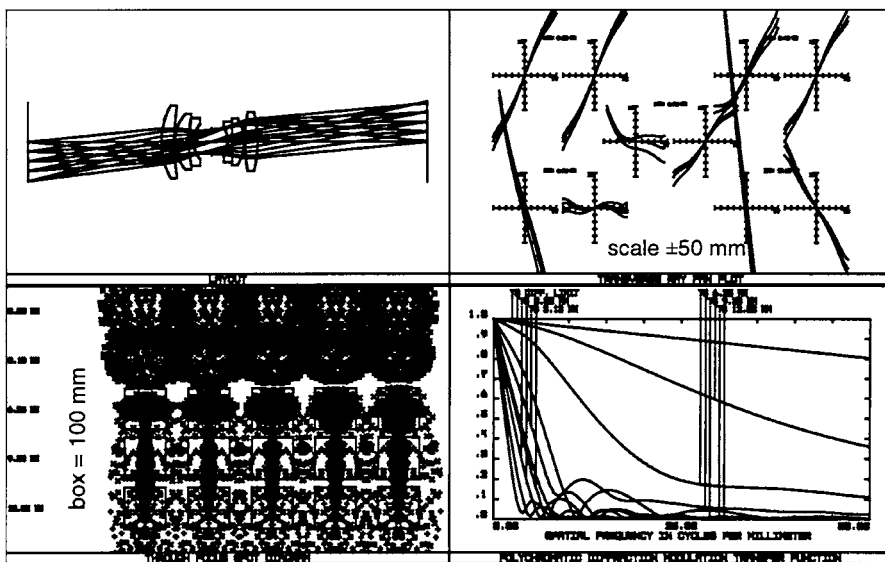


Figure 21.5

RMS Blur Diameter
for a 35-mm Focal
Length $f/2.8$ Lens As
a Function of Object
Distance

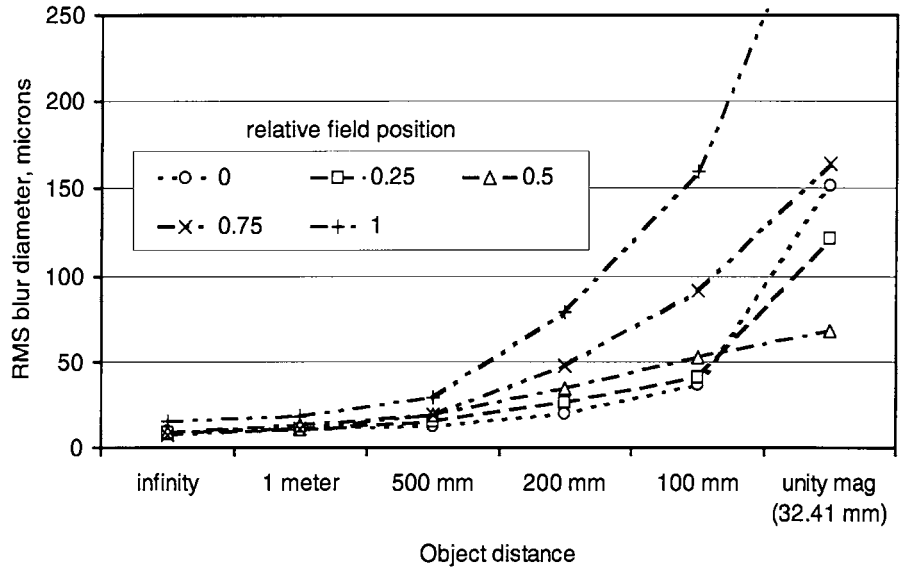


Figure 21.5 shows parametrically how the performance degrades as a function of object distance for the previous lens design example. Note that the nominal design gives an rms blur diameter of approximately $9\text{ }\mu\text{m}$ over most of the field of view. This doubles for the 0.5-m object distance, and for a 100-mm object distance the rms blur diameter increases to about $50\text{ }\mu\text{m}$ over the central region of the field of view. At the unit magnification position, due to the extreme aberrations introduced, the spot diameter ranges from 70 to about $340\text{ }\mu\text{m}$ at the edge of the field. If you were using a CCD chip with a $12\text{-}\mu\text{m}$ pixel pitch, an object distance of no more than 0.5 to 0.75 m would be viable in order to maintain a reasonable modulation at the Nyquist frequency.

Pupil Matching

In addition to the basic specifications, performance, and aberrations, the extremely important issue of entrance and exit pupils must be considered when working with off-the-shelf optics. Clearly, if you were simply using an off-the-shelf lens to image an object onto a CCD array, the location of the pupils is of little concern or interest. However, if you had a multiple-stage relay system, then the exit pupil of one stage must be coincident or

nearly coincident with the entrance pupil of the next stage, and so on. As we learned earlier, field lenses are indispensable in this task, as one of their primary roles is to reimage the exit pupil of one lens group into the entrance pupil of the next lens group. This issue can be of major concern when one or more of the off-the-shelf lenses are zoom lenses, since the pupils can translate or move over great distances as the lenses zoom, and having a mismatch in pupils is very likely, if not inevitable.

Development of a Lab Mockup Using Off-the-Shelf Optics

There are many situations where determining the level of performance of your system quickly is to your advantage. Situations where this approach is helpful are when validating important aspects of your specifications. For example, assume you are designing a new visual telescope. Parameters, which are important, include field of view, magnification, eye relief (clearance from the last element to the eye), and of course image quality. You could manufacture a prototype of your custom production design, which would likely take several months and cost many dollars. An alternate approach is to build up a unit using off-the-shelf optics. It should be straightforward to nearly meet the magnification and field-of-view specifications, and likely the eye relief too. The image quality may be degraded from your custom production design; however, the overall ability to assess the general nature of the system specifications and performance is often quite valuable. This is especially true for some of the specifications, such as field of view and magnification, which may have been based on a judgment or best-effort basis. You can take your mockup system outside and use it in a near-real functional environment. There is always an anticipated level of performance associated with every lens design, and your system performance can often be demonstrated using off-the-shelf optics.

Stray Light Control

The suppression of stray light is often ignored until it is too late, and then it becomes costly and time consuming to fix the problem. Good engineering in this area is imperative. The best way to learn the subject

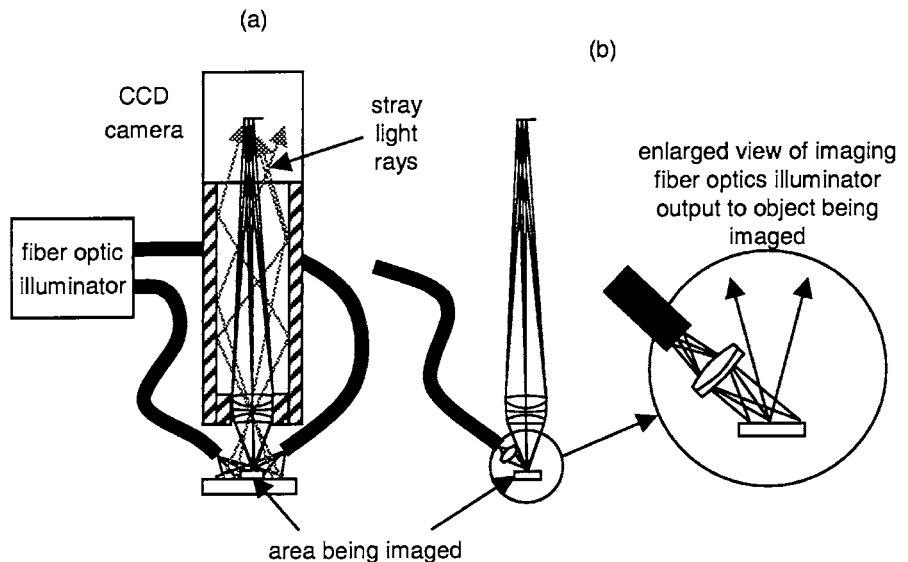
is through the following two examples: (1) a machine vision system and (2) a reflective Cassegrain telescope.

Machine Vision System

We will first relate a true story regarding a potentially serious stray light problem:

- We were called in to visit a colleague who said that he had just installed a new vision system and the contrast was badly degraded from prior systems. The system was very basic and consisted of a microscope objective and a CCD camera. The contrast was indeed poor on the video monitor.
- We first removed the camera from the tube assembly and looked in with our eye at a location similar to where the CCD chip was. It was immediately evident that there was a lot of stray light reflected from the interior of the tube assembly. While the tube interior was black anodized, at near-grazing angles of incidence black anodizing is quite reflective. Figure 21.6a shows the situation.

Figure 21.6
Example of Stray
Light Control in
Machine Vision
System



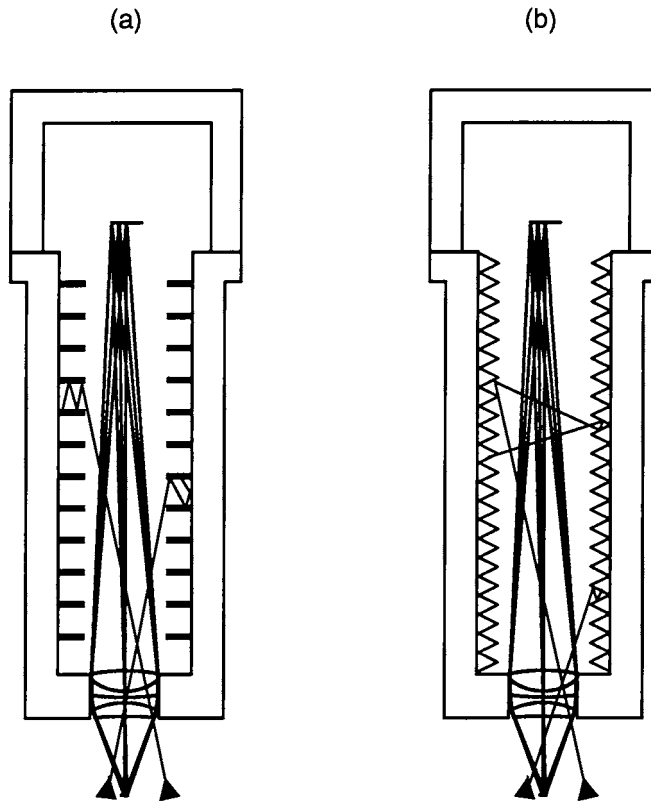
- We then asked our host if he had any flat black paper, and he did. We rolled the paper into a tube shape and put it into the anodized tube assembly. Visually, with our eye again looking into the tube, we found that the situation was indeed improved but not perfect.
- After reinstalling the camera, our host said, “wow, that’s a lot better ... but it isn’t as good as it used to be.” This was consistent with our observation.
- We then took a careful look at the overall system layout and we realized that the fiber-optic illuminators were illuminating an area far exceeding the object being imaged, as shown in Fig. 21.6a. We asked our host if he had a small positively powered singlet or doublet lens and he did. We then cut a small aperture in a piece of black paper and fastened it to the end of the fiber bundle. The lens was now used to reimage the aperture onto the object being imaged, as shown in Fig. 21.6b. A little experimentation with the magnification resulted in a situation where we were just overfilling the object area of interest.
- We now turned the system on and our host said, “wow, that’s better than it has ever been!”

If you were to design the microscope tube assembly for optimum stray-light attenuation, it would be best to incorporate baffle features on the interior of the tube, as shown in Fig. 21.7. Figure 21.7a shows a series of baffle structures similar to washers. This is one of the most efficient baffle forms; however, it is somewhat costly to machine or otherwise implement. Figure 21.7b shows a coarse thread with which we can derive good results. Note that we show the multiple bounce path of several representative rays, and in the case shown none of the rays reaches the CCD sensor until after three bounces, which is a good guideline. Do keep in mind that there will inevitably be scattering and diffraction coming from the tops of the threads, no matter how perfectly they are machined, and you will be better off with a coarse thread rather than a fine thread with more thread tops. One final tip: it will help if you make the inner diameter of the tube and associated baffles as large as possible.

Cassegrain Telescope

One system that always requires efficient stray-light baffling is the Cassegrain telescope, which was discussed in Chap. 8. Without baffling, there is generally a direct stray-light path from the object space to the

Figure 21.7
Use of Threads and
Baffles for Stray-Light
Attenuation in
Machine Vision
System



sensor; and that could be a serious problem. We generally use two basic baffles, one a conical baffle extending aft from the edge of the secondary mirror along the limiting imaging ray bundle, and the other a tubular baffle extending forward from the hole in the primary mirror.

In order to show how to baffle a Cassegrain, we first generated a candidate design. We selected an $f/8$ system with a 100-mm entrance pupil diameter covering a full 1° field of view. The goal for our baffles is that a limiting ray that just passes by the two baffles described earlier shall not directly strike the image plane. In order to quickly and efficiently reach a solution, we added a central obscuration to the computer model and traced 500 rays into the entrance pupil at each field of view. Figure 21.8a shows the model. Areas in black are fully populated with rays, and the clear regions extending aft from the secondary mirror and forward from the primary mirror are available for baffles.

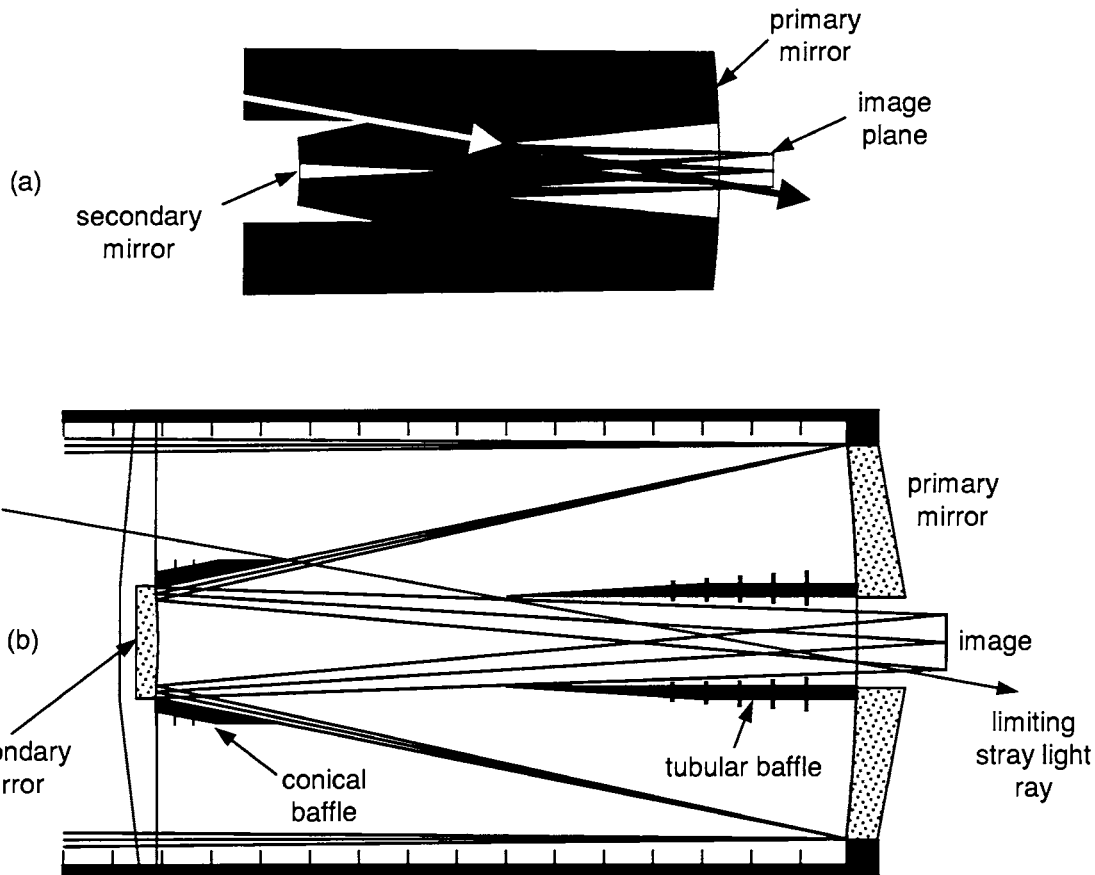


Figure 21.8
Stray-Light Baffling of Cassegrain Telescope

We show also the limiting ray which just clears the two baffle ends and reaches the image plane.

Figure 21.8b shows an implementation of this baffle. Note that we have added vane-type baffle segments as presented earlier in this chapter. We have also added an outer-tube assembly with interior baffling.

It is important to realize that good common sense and a little dedicated work will generally provide you with efficient stray-light baffling. If you need a specific attenuation factor, then you will need to use one

of the stray-light software packages. For example, in space applications, where a system may be observing a black sky to within a few degrees of the Sun, stray-light attenuation in the order of 10^{-15} or more is often required. We showed earlier in Fig. 8.7a configuration especially well suited for efficient stray-light attenuation. This system is a three-mirror configuration consisting of primary, secondary, and tertiary mirrors. Let us assume that we are in space looking within a few degrees of the Sun into a black sky. There will be a large amount of light scattered and diffracted from the edge of the primary mirror since it is receiving direct solar radiation. If we now locate a stop further aft in the system at an image of the primary and slightly reduced in size from the image of the primary mirror, we will effectively block this light from proceeding further through the system. This is known as a *Lyot stop* after the French astronomer Lyot. While Fig. 8.7 is not to scale, it does illustrate the principle involved.

Optomechanical Design

The design of the mechanics to support your imaging optics is extremely important. Design issues relating to the optomechanics are the following:

- The mechanics supports the lenses and/or mirrors in the system. In order to keep the image quality within the specification, every optical component must be held to its nominal position within the required tolerances, as derived from your tolerance analysis and system performance error budget.
- The mechanics, along with the optics, must perform over the required thermal environment. The designer must allow for thermal expansion and contraction of the optical components to prevent any catastrophic problems.
- Maintaining focus through temperature is very dependent on the optics as well as the mechanics, and athermalization may be required.
- The mechanics must fit within the desired packaging space and be within its weight goal.
- The mechanics must aid in attenuation of stray light. This is often accomplished by blackening the housing interior as well as threading and providing stray light baffles at strategic locations.

Figure 21.9 shows a typical housing for a projection lens. In use, a reflective display device is located to the left of the light-injection prism. The image generated on the display is then projected to a screen to the right of the lens system.

We have pointed out some of the important mechanical design features to incorporate into the design. These are

- In this design the aperture stop is between the two smaller elements, and we use a spacer as a physical aperture stop.
- The elements are held in place by a front-threaded retainer and a rear retainer.
- A thread is applied to the conical spacer between the two left-most powered lens elements. This threading is to attenuate any stray light which may be incident on the housing.

We show for reference a different lens housing in Fig. 21.10. Note in this lens the two left elements are bonded into the housing as evidenced

Figure 21.9

Typical Lens Housing

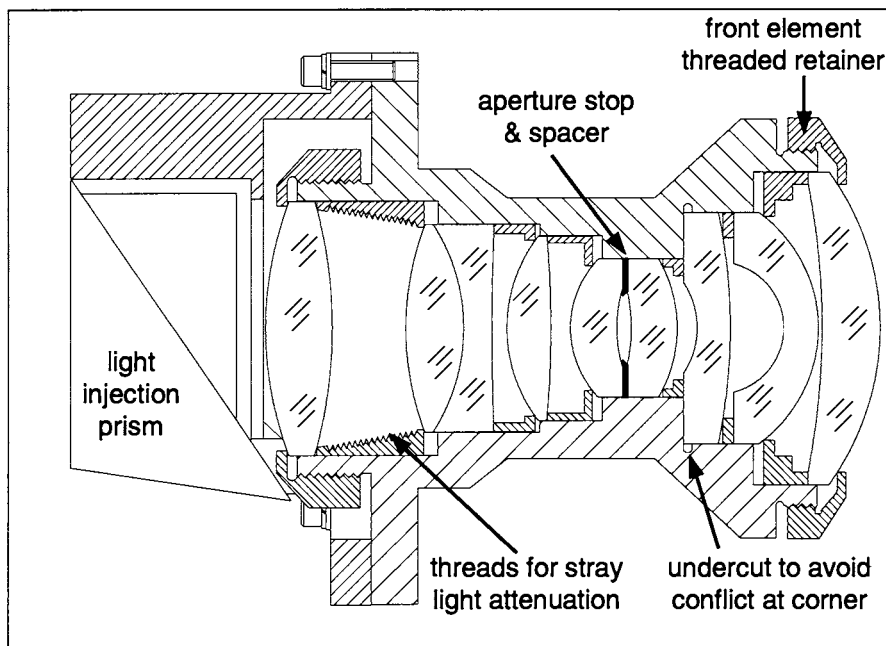
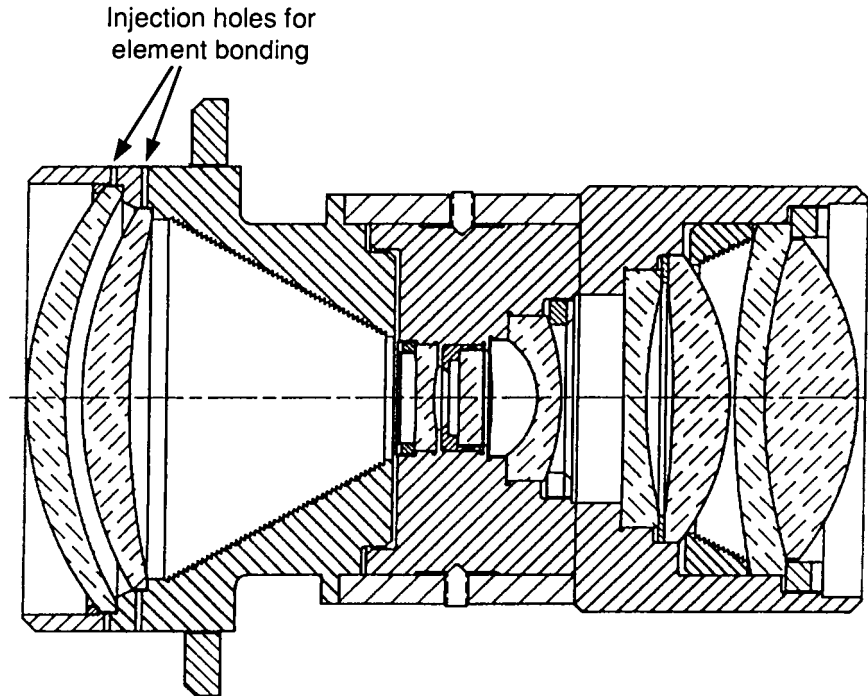


Figure 21.10Typical Lens Housing

by the two material-bond injection holes. The bond material is typically a semicompliant epoxy or RTV. This is done in situations where shock and vibration may be a problem. The elements are centered using shims or by rotating the housing on a precision air bearing and assuring that the runout of the housing and the elements are per the tolerance callout.

CHAPTER 24

Stray Light and Optical Scattering

Introduction

Stray light can be the curse of an optical system. The optical engineer may toil to optimize and build a system, only to have the performance destroyed by an unexpected glare, glint, or smear of light! It is often possible (but not always, so proceed cautiously!) to fix the causes of stray light in a system during the debug phase, once hardware is in hand. However, good engineering judgment and practice can be applied to minimize this effort and save resources in the latter phases of a project. This section discusses different causes of stray light in an optical system, how it can be described and managed, and finally how it is even possible to make use of it.

Stray Light Scatter Sources

The key to solving optical scattering problems in the optical system is to identify the source of the problem. In an ideal world, the designer would model all aspects of the system to ensure fully compliant performance is achieved before the build phase is attempted. However, such exhaustive modeling is usually not possible because it can be incredibly time consuming, and results can sometimes be misleading. Great care is required in interpreting the stray light model; this is discussed further in the

modeling section (see “Modeling & Analysis Techniques” section) which follows. In optical systems where stray light is expected to be an issue, there is often some level of empirical work required to ensure that the optical system performance is satisfactory. One should always plan for this debug and evaluation effort in a real optical system build and test.

Bounces and Ghosts

VISIBLE SYSTEMS A good place to start in evaluating an optical system for stray light is to check for double bounces or ghost images. Double bounce stray light reflection occurs when light is reflected from one optical surface backward and subsequently forward again toward the focal plane. See Figs. 24.1 and 24.2 for an example. The designer should check to ensure that the double bounce does not focus onto the focal plane. In practice the double bounce is seldom a problem in a visible optical imaging system, particularly if the optical elements are coated. However, it is always worth checking to make sure.

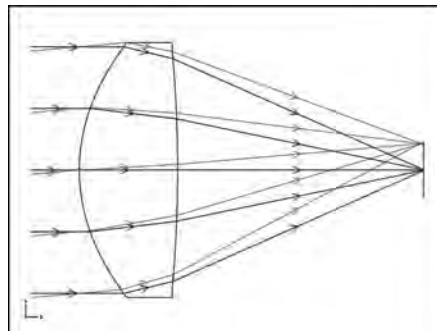
In the visible band, uncoated glass surfaces will provide a surface Fresnel reflection [$R(\%)$] computed from the following equation:

$$R(\%) = 100\% \cdot \left(\frac{n_{\text{GLASS}} - n_{\text{AIR}}}{n_{\text{GLASS}} + n_{\text{AIR}}} \right)^2 \quad (24.1)$$

For $n_{\text{AIR}} = 1$ and $n_{\text{GLASS}} = 1.5$ we have 4% reflection per surface.

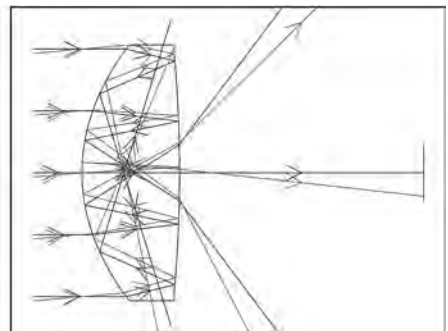
Figure 24.1 and 24.2

Double Bounce
Example Using a
Singlet



Single imaging two field points.

(24.1)



Double Bounce : Bounce off 2nd surface and then 1st surface does come to a focus, therefore is not a concern in this example.

(24.2)

Even a relatively low cost antireflection (AR) coating (for example, MgF_2 coating) will provide a peak transmission of at least 98%. The 2% reflection double bounced would be only 0.04% of the original energy. This gives a scatter signal to image signal ratio of 1:2500, that is, the scattered return is weak compared to the signal. If the scatter is not focused onto the imaging sensor, then the scatter signal further weakens compared to the image signal. In most cases, double bounce reflections will only show up as a scatter artifact on the image if a bright object is in the scene *and* this causes a double bounce reflection to focus on a dark part of the image.

In Figure 24.3 an example is provided where a commercial grade digital camera images a flashlight against a black background. This is a severe stray light test for an optical system. Whilst this system is not likely to be often used in this mode of operation, it does serve to highlight stray light artifacts which exist within an optical system. A halo around the flashlight is noted. This is caused by optical surface scatter from the lenses within the optical system. The blob of light noted to the left of the flashlight is a double bounce scatter within an element of the lens system; as the flashlight is moved to the right, the blob moves to the left.

Figure 24.3
Commercial Digital
Camera Exhibiting
Scatter Artifacts in Pres-
ence of Very Bright
Flashlight Object.
Note the Bright Halo
and Scatter Spot

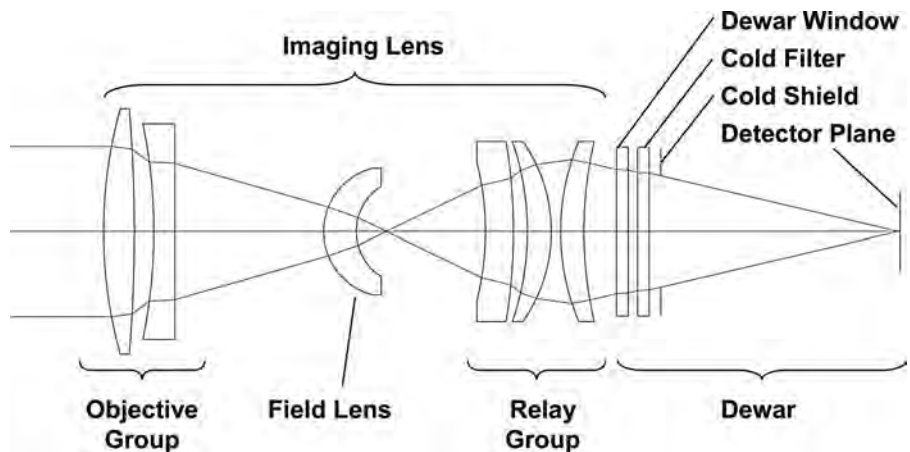


INFRARED SYSTEM CONSIDERATIONS AND NARCISSUS In infrared (IR) systems higher refractive index materials are typically used. Typical examples are Silicon ($n_{\text{Silicon}} \approx 3.42$ at $4 \mu\text{m}$) and Germanium ($n_{\text{Germanium}} \approx 4.02$ at $4 \mu\text{m}$). Uncoated in air, Silicon and Germanium have significantly larger Fresnel reflections at IR wavelengths than glass surfaces do in visible wavebands. A BK-7 glass surface in air exhibits approximately a 4% reflection in the visible waveband, compared to a 30 to 36% reflection for Silicon and Germanium, respectively. AR coating of IR materials is therefore imperative not only for ghost bounce scatter suppression but also to ensure good optical transmission through the IR lens system.

IR imagers offer a unique form of optical scatter which is worthy of special consideration. Most IR imagers operating in the 3 to $5 \mu\text{m}$ mid wave IR (MWIR) and 8 to $14 \mu\text{m}$ long wave IR (LWIR) bands use sensors which are cooled. When operating in these spectral bands objects the designer must remember that surfaces at room temperature are blackbody emitters; that includes the optical materials and the lens housing walls.

An example of a typical IR imaging system is provided in Fig. 24.4. Features of the imaging lens include a color corrected doublet lens (of Silicon and Germanium) in intermediate focus which is preceded by a field lens for aberration correction, and a relay group which reimages the intermediate focus onto the focal plane. The camera includes a Silicon entrance window, a cold filter, a cold shield (stop) and the detector plane. The components following the window are all maintained at a cold temperature.

Figure 24.4
Example of Infrared
Lens Design

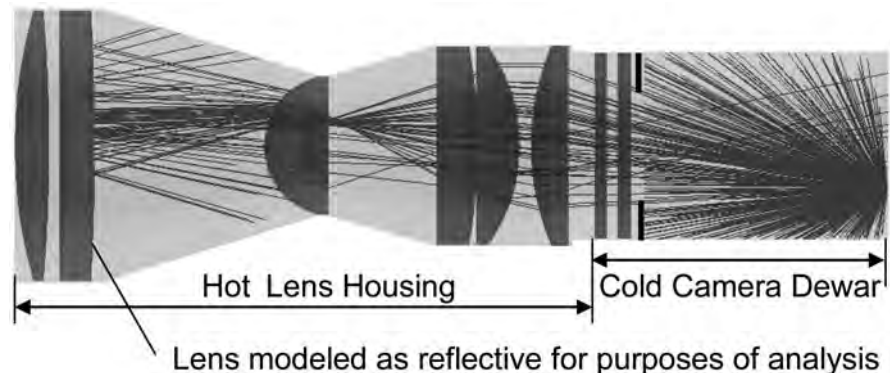


The intermediate focus is required to achieve a 100% cold shield efficient design. 100% cold shield efficiency means that any point on the detector plane which exits through the cold shield aperture will always pass through a lens and out into the scene. There is no direct path from the focal plane, through the cold shield and onto the hot housing wall.

In practice, there are several factors which cause thermal contributions to be coupled into the optical path, even in a 100% cold shield efficient nominal design. Fresnel reflections are the most significant contributors, especially if the optical elements are not properly coated. Other factors include contaminants on the optical surfaces, and the emissivity of the lens materials themselves (albeit that this is a low and unavoidable contribution), so minimizing the number of optical elements should always be part of the optical designers goal. Care should be taken of the optical coating performance with angle to ensure that it does not significantly fall off in transmission over the range of angles of incidence which each surface experiences.

Consider Fig. 24.5. There are several things to note on this figure. Firstly, a point has been set up as an imaginary source on the edge of the focal plane. This allows us to consider what this edge pixel on the detector will actually see. Firstly, we note that many possible ray paths terminate within the cold camera dewar. The dewar is cold, so no thermal signature is contributed by the ray paths which terminate on the dewar walls (or vice versa, start on the dewar walls and end on the detector). Now, again trace backward from the detector and consider the ray paths which exit through the cold shield. We see that these ray paths continue, without reaching the housing walls directly. Eventually we reach the second objective lens. This has been modeled

Figure 24.5
Narcissus—Examples
of "Hot" Housing and
"Cold" Detector



as a reflective element to examine the effect of the Fresnel reflection. Ray paths from this point are indirect paths. Now, tracing forward, we can see that it is possible for a ray which starts on the hot housing wall to undergo a Fresnel reflection and then reach the cold detector. This means that a hot housing wall will contribute some thermal signature to the detector. This contribution can be minimized by good optical AR coatings.

The background thermal signature obtained at any given point on the field is the sum of all of the “hot” housing and “cold” detector/dewar contributions. If every point on the detector plane experiences the same hot and cold sum, then a uniform offset would occur across the field. This can effectively be removed by applying an offset to the image.

Problems occur when there is a difference between the background thermal contributions across the focal plane. Imagine a point in the center of the detector, for which a Fresnel reflection focuses back down onto the detector; this point will experience a cold return. If at the same time a point at the edge of the detector experiences Fresnel reflections which do not hit the cold detector, but instead see hot wall structure, then a *hot* contribution will be experienced. In an image where white is displayed as hot, we will see a black hole in the center of an image which has not been uniformly corrected. This effect is known as *Narcissus*, named after the tragic figure from Greek mythology that fell in love with his own reflection. If your lens design ends up with Narcissus, it might well be a tragic sequel!

Nonuniformity correction (NUC) allows a background calibration image to be subtracted from all subsequent images; this is recorded when a uniform object scene is present. This allows the background effect to be removed, so long as the Narcissus profile across the detector field does not vary. Unfortunately, because the *hot* walls are often not in a thermally stabilized environment, the hot contribution to the edges of the pixels will vary, whilst the cold contribution at the center of the image does not because it is in the thermally stable environment of the cold dewar. If the hot walls now cool down, and the original uniform calibration data is applied, a hot center will be experienced, with comparatively cold image edges. In IR systems experiencing a wide thermal environment it is often necessary to acquire calibration data at several temperatures and to apply the closest NUC table, or otherwise interpolate between NUC sample points to ensure an appropriate uniformity correction is applied across the field. It should be noted also that the emissivity characteristics of the housing surface will also impact the

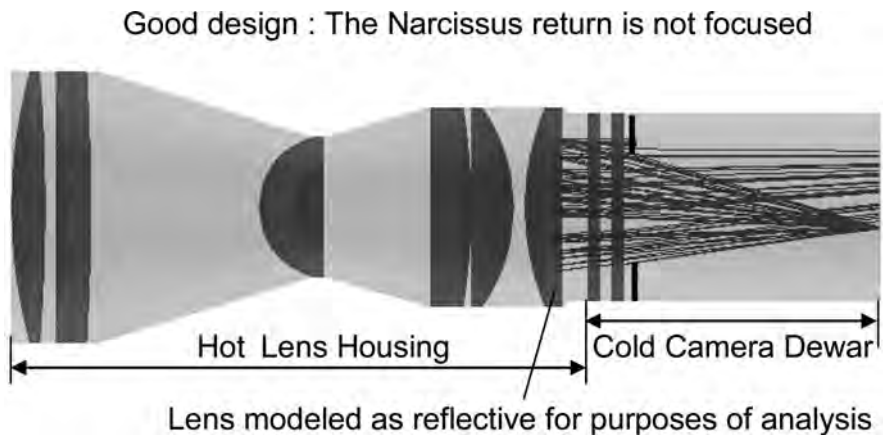
thermal contribution and may cause nonlinear variations in the overall Narcissus signal with environmental temperature.

As a final word, avoid the temptation of fixing everything electronically after the fact. Whilst electronic uniformity correction will aid the optical design, any corrections which are applied will eat up the available dynamic range detector. Good Narcissus design is, therefore, imperative if optimal performance is to be achieved from the IR optical system.

How to Minimize Narcissus in the Optical Design Narcissus is a special case and is in effect a single bounce consideration. A Narcissus return is unavoidable on axis. However, Narcissus can be effectively eliminated by spreading the cold return evenly across the detector. Figure 24.6 shows an example of an axis bundle which does not generate a focused Narcissus return. Whilst the elements in the eyepiece closest to the image plane are normally the elements to take the most care over, it is essential that Narcissus generated by Fresnel reflections be examined for all optical surfaces in the system.

Many optical design packages are now flexible enough to allow a nonsequential model to be generated where the housing walls and optical elements and the detector can be treated as optical sources. By examining the uniformity profiles obtained on the detector, it is possible to model the stray light paths which will cause a Narcissus effect.

Figure 24.6
Anti-Narcissus Design



Structural Scatter

Structural scatter can be more difficult to cope with. This is where the mechanical housing of the lens scatters unwanted light back into the optical path. The source causing the scatter may not even be in the geometrical path of the optical design.

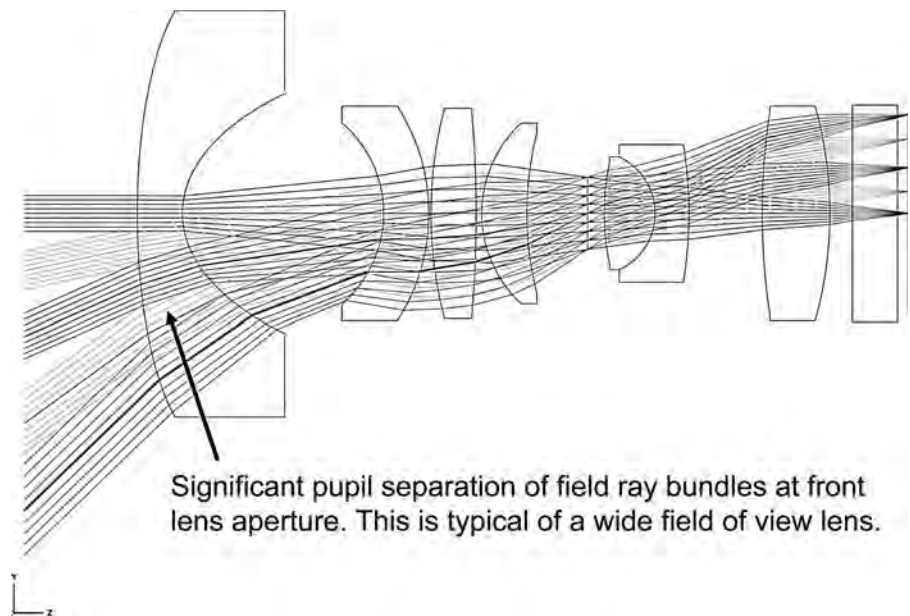
Structural scatter can be minimized using the following techniques:

- Rifling and blacking the lens inner barrel
- Using strategically placed baffles
- Applying blackening to the edges of the lenses
- Minimizing the pupil positional variation across the aperture at the first lens surface; this is particularly an issue in wider field of view lenses

Structural scatter is often observed in wide field of view systems. This is because the front lens aperture diameter is typically large with respect to the size of the field ray bundles entering the lens. See Fig. 24.7 for a typical example of a wide field of view lens which

Figure 24.7

Wide Field of View
Lenses Typically
Exhibit Significant
Pupil Separation at
the Front Aperture



exhibits a large amount of pupil separation at the front element. Such a large aperture increases the possibility of stray light to be coupled into the system.

Whilst the stray light may have no direct path to the focal plane, there is an increased probability of light entering the bore and experiencing structural scatter. If the front aperture is minimized, this can help in reducing the potential scatter pathways. The ideal solution from a stray light perspective is to have the stop reimaged at the front aperture. However, this may serve to over-constrain or over-complicate the optical design. Attempting to minimize the extent of the aperture will, however, help. Note that we are attempting to minimize the aperture diameter by controlling pupil separation, and not by reducing the entrance pupil diameter. Changing the entrance pupil diameter would slow the system thereby changing the fundamental optical performance of the lens.

Low Light Level Systems

Stray light becomes an acute problem when the strength of the stray light is large with respect to the object or signal being observed. This often occurs in systems where light levels are low and correspondingly the sensitivity of detectors is designed to be high and exposure times are increased.

Astronomical telescope systems are a good example of where detailed stray light modeling is required. Moon and star light hitting the telescope mirror support can lead to severe stray light problems. Astronomical telescopes use highly sensitive detectors, and often use long exposure times. Under these conditions even very low levels of optical scatter may be large compared to the signal strengths being detected. Often approach roads to telescopes require that lights are dimmed or turned off near to the facility to prevent accidental stray light from headlights entering the telescope structure.

Types of Scatter

Linear optical scatter can be characterized in two main groups, Rayleigh and Mie. These are described below. Linearity refers to linearity with respect to optical flux, that is, more light will give proportionally more

scatter. Nonlinear optical scattering phenomena such as Raman and Brillouin scattering are not discussed here. These forms of scattering are often significant in laser and fiber-optical communication applications.

Rayleigh Scattering

Light scattering caused by objects which are very small compared to the wavelength of light is known as Rayleigh scattering; aerosol gases are a good example. Lord Rayleigh defined scattering in terms of the following relationship:

$$\text{Rayleigh Scatter} \propto 1/\lambda^4 \quad (24.2)$$

This inverse fourth power dependency on wavelength explains why blue light is scattered more than red light. Consider white light incident on the Earth's atmosphere. Blue light is scattered more by the atmosphere than red light. From Eq. 24.2 we find that blue light at 450 nm scatters 4.4 times more than red light at 650 nm. Without the atmosphere, the sky would appear black during the daytime, just as was observed by astronauts on the surface of the moon. On Earth, the blue component of white light is scattered across the atmosphere, which is why the sky is blue! Furthermore, as the sun falls low on the horizon, the amount of atmosphere through which the sun's rays pass increases. This increases the amount of scattering, especially of the shorter wavelengths. With a greater loss of shorter wavelengths, the observer's perception is that the sun becomes more red; in actuality it is becoming less blue. This explains why the sun turns increasingly orange and through to red during a sunset.

Mie Scattering

Light scattering caused by objects which are large compared to the wavelength of light is known as Mie scattering. Generally speaking, Mie scattering becomes significant when the scattering particle is larger than approximately 1/10th of the wavelength of light.

Mie scattering theory is a general theory for scattering caused by any diameter of spherical particle. Mie scattering is particularly useful for colloids. This is a key form of scattering in optical fiber communications, where scattering must be minimized along long lengths of optical fiber to achieve good communication distances.

Modeling and Analysis Techniques

Ghost Analysis

Most optical ray tracing software packages provide some form of ghost analysis capability. In sequential optical models, a common technique often applied to the examination of double bounce ghosts, is to:

- Turn a refractive optical surface into mirror, to generate the first bounce
- Duplicate the preceding optical surfaces
- Turn a second optical surface into a mirror, to generate the second optical bounce
- Trace back to the focal plane

The number of combinations of single bounces increases with the number of refractive surface in the lens. Assuming n refractive surfaces, the number of double bounce combinations (DBC) is given by:

$$\text{DBC} = \sum_{i=1}^n (n - 1) \quad (24.3)$$

In each case the convergence of the rays on the focal plane is examined. If the spot is too small (typically a double bounce spot size of <1 mm diameter is too small), then the curvatures of the offending pair of double bounce surfaces must be modified to increase the double bounce spot size, thereby reducing the double bounce ghost problem.

In a single bounce analysis each surface is in turn converted to a mirror, and the position where the ray terminates is examined. A single bounce analysis is often used in systems where there is an illumination source and a detector in a separate optical channel.

The single bounce analysis can also be used for Narcissus analysis where the cold detector is converted to an optical source. In this way the cold signal can be designed to be defocused on the focal plane thereby reducing the Narcissus return. An alternative approach to Narcissus analysis is to turn each object into an emitter, including the housing walls; some software packages offer sufficient flexibility in the source shape definitions to make this possible. This approach allows each object to be modeled as a blackbody emitter, and can therefore be a more accurate approach.

Scatter Path Analysis

To ensure that structural scatter is not a problem, sample object field points are typically set up at a representative range of angles. An example of this is provided in Fig. 24.8.

Figure 24.8 highlights an optical path through the system which must be prevented. This can be achieved either by the addition of a lens hood or a structural baffle within the bore. In the example shown in the figure, the walls are modeled as mirrors or as highly specular surfaces. This allows the worst case ray paths to be identified. Further refinement is offered by modeling the walls as scattering objects. Eliminating single specular reflections and single diffuse reflections will suppress most scatter in most optical systems. Refining the analysis further to consider secondary scatter bounces may be required in scatter sensitive applications.

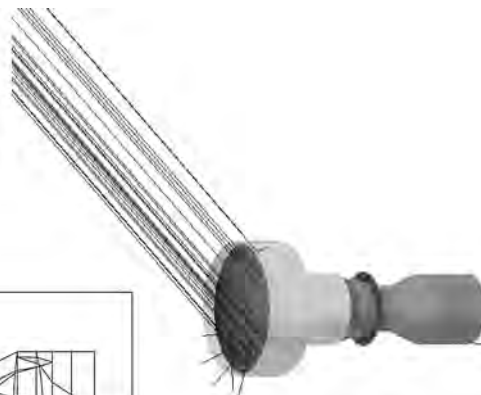
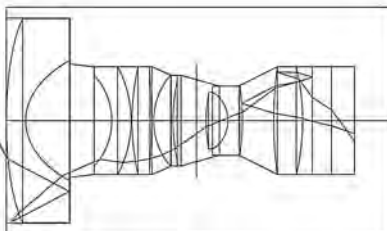
The sample field points selected should extend out of the geometrical field of view of the lens design. A bright source such as a lamp or the sun may still be scattered onto the focal plane via the structure.

Doublet and triplet lenses are worthy of special consideration when conducting a stray light analysis. In some cases a ray path will be found where total internal reflection (TIR) occurs internally in a lens element. In the case of a doublet or triplet element, the TIR condition

Figure 24.8

Example of Scatter Path Analysis Modeled Using Discrete Field Point Ray Bundle

Note : In this example, TIR in the first lens is a problem. The lens shape will have to change to suppress this. Structural scatter off the housing at the rear of the lens is also noted.



is affected by the optical cement used to bond the lenses together. This layer has to be considered carefully, especially in the case where the lens elements are of particularly high or low refractive index, that is, where the refractive indices of two bonded elements differ significantly from that of the optical adhesive. An optical cement will typically have a refractive index of approximately 1.5, up to 1.6 or so for a higher index optical cement. The seamless high index interface found in the optical model is in reality interspersed with a thin layer of lower refractive index material; a 50-mm-diameter lens may have a layer of approximately 25 μm thick. Whilst this layer has a negligible effect on the direct ray paths through the lens and so does not impact the lens imaging performance, it does change the critical angle at the interface. As such, TIR behavior is modified. In order to accurately trace stray light paths through the system, the doublet and triplet lenses need to be accurately modeled to include the optical cement layer. It is normally the easiest to conduct this analysis in a nonsequential stray light model.

Modeling Scatter—Watch The Magnitude!

When examining stray light sources it is important to estimate the relative magnitude of the stray light signal strength with respect to the image. In order to examine optical scatter within a model may require increasingly small sources to be set up. It is easy to lose track of the magnitude of the signal which actually reaches the source. It is a good practice to compute the scattered light in terms of the total scene energy. This provides a basis for normalizing the scattered energy which reaches the detector.



Veiling Glare

This is a form of optical surface scatter which occurs when object field point rays and rays from objects outside the geometrical field of view of the optical system strike a lens surface and are thereby scattered into the optical system. Veiling glare is generally low in structure and is, therefore, uniformly scattered over the focal surface. Despite the low structure of the glare, a reduction in image quality is observed. This

can be explained by considering the contrast equation (Eq. 24.4), then we have:

$$\text{Contrast} = \frac{I_{\text{MAX}} - I_{\text{MIN}}}{I_{\text{MAX}} + I_{\text{MIN}}} \quad (24.4)$$

By increasing both I_{MAX} and I_{MIN} , reduced the contrast occurs. This means that if I_{MAX} and I_{MIN} are increased by the same amount, effectively a bias offset, then the contrast is reduced. Consequently, even in the case where optical scatter within the optical system takes a uniform profile across the detector plane, a reduction in imaging performance occurs.

An example of veiling glare being encountered in an optical design was during the fabrication of a reasonably wide field of view prototype imaging lens which used a plastic aspheric lens on the front surface. To generate the proof of concept design at reasonable cost it was necessary to fabricate the aspheric profile using diamond machining, thereby avoiding the cost of the mold in the near term. It was found that contrast in the image was noticeably lower than expected. The problem was found to be due to veiling glare from the diamond machined surface. The good news is that when the lens was transitioned to a molded part, the problem was completely eliminated because the molded part surface roughness was far lower than that of the diamond turned part!

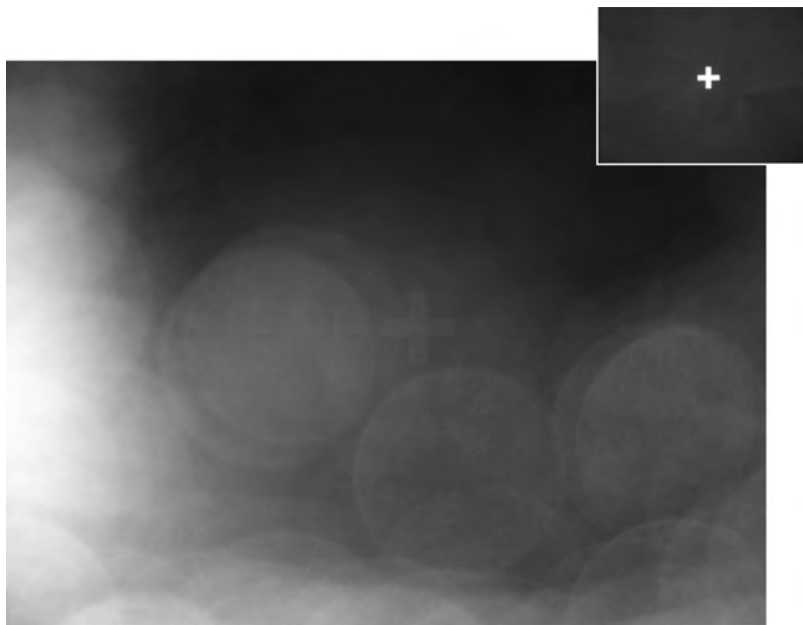
Cleanliness

Veiling glare can be caused by smearing contaminants and dust on front windows or near the pupil planes of a system. An example of this within a commercial grade digital camera can be seen in Fig. 24.9. In an optical system it is therefore wise to have a protective front window which can cope with regular cleaning without becoming damaged. For example, good quality single lens reflex (SLR) camera lenses often allow a removable UV filter to be mounted in front of the lens. This not only provides UV protection but also it serves as a protective and replaceable window. In rough environments use of a replaceable window component will prolong the overall system lifetime.

For any surface close to either the focal plane or an intermediate focal plane, special care must be taken to ensure good cleanliness. This is primarily to prevent dust particles from being directly imaged into the focal plane. In slow optical systems with small apertures cleanliness is a

Figure 24.9

Commercial Digital Camera Exhibiting Veiling Glare Due to Dust on Objective Lens. Inset Is the Image of the Diffusely Lit Test Scene—Black Felt with a White Cross (Obtain Focus)



priority. In such systems small dust particles may be a significant portion of the diameter of the pupil. The depth of field is large in a slow system, so several optical surfaces may contribute particle obscurations to any given field point. This may cause obscurations to occur in the image. The dust particles in slow systems are often likened to being “rocks in the image.”

Suppression Techniques

Three Bounce Rule

The key to scatter suppression is to create an opto-mechanical housing structure which maximizes the number of light absorbing surfaces that scattered light must strike before reaching the focal plane. If blackened housing surfaces, baffles, and thread pitches are correctly chosen, it is possible to effectively and with low cost, eliminate most sources of structural scatter. If there’s one rule to remember, it’s the “three-bounce rule.”

Three bounces of a 1% reflection will reduce the amount of light to *one millionth* of the original energy. This is a great rule of thumb for most scatter suppression applications!

Threads and Baffles

Threads can be an inexpensive and highly effective way of achieving the three bounce rule. However, the pitch of the thread is important. A thread can never be perfectly sharp, and so the tops of threads can be considered to be flat topped, effectively reflecting light back into the optical path. We can consider that the thread may not be much sharper than 0.025 mm on a top without requiring special fabrication and handling procedures. If the thread pitch is large, then the flat top frequency will be reduced along the length of a bore. Decreasing the pitch will conversely bring the flat tops closer together giving the bore more direct reflection surface area.

Choosing the angle of the thread also has some influence on scatter suppression performance. If the thread is too shallow, then three bounces are unlikely to occur when the light interacts with the thread. Furthermore, it is preferable to utilize where possible standard thread machining practices to minimize special machinist threading operations. A study of baffle placement has been provided in the next section.

Baffles can improve system performance significantly. The direct path analysis method discussed in “Scatter Path Analysis” section describes how to determine key locations for baffles. This is useful to identify primary scatter pathways and minimize debug time later.

A typical form of baffle commonly used in an optical system with an internal focus is a field stop. The field stop location is a natural break point in the optical design to mop up unwanted light.

TRADE-OFF STUDY—BAFFLE DESIGN The placement and number of baffles in an optical bore will influence the scatter suppression offered by those baffles. Figure 24.10 gives some examples of baffle structures within an optical bore. The relationship between the pitch of the baffle and the height of the baffle within a fixed diameter of bore is also important. For example, it is clear that a short baffle height (h) will require a smaller baffle separation or pitch (p) to affect a reasonable amount of optical scatter suppression. The relationship of (h/p) is a good metric to note then placing baffles within the structure.

Figure 24.10

Example of Baffle Structures in a Bore

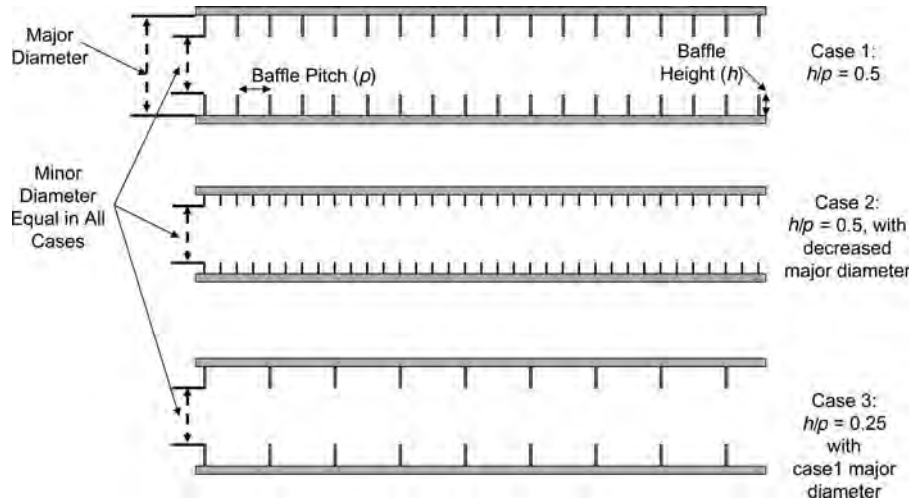
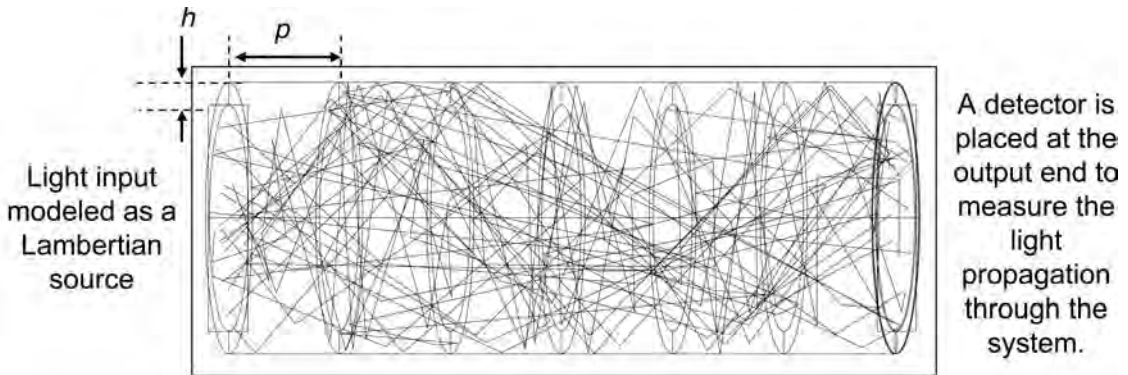


Figure 24.10 shows two examples where $h/p = 0.5$, that is, the baffle separation is double the baffle height. In the third example, a lower frequency of baffles provides an h/p ratio of 0.25. A lower value of h/p is likely to provide poorer scatter suppression.

To better understand the optimal spacing of baffles the following trade study was conducted:

A bore with no elements, containing only baffles was modeled. At one end was placed a Lambertian source and at the other, a single element detector. Baffles were placed in the tube with a fixed inner diameter and the spacing between them was varied; a baffle was always retained at the input and output face. The baffle major and minor diameters were fixed. Baffles were assumed to be infinitely thin, so top surface (flat-top) reflections are ignored. Diffuse and specular surface baffle profiles were both examined. The effectiveness of the baffles was assessed by examining the amount of scattered light which reached the detector. Results were normalized to the case of a perfectly specular baffle being located at each end of the tube. Light which passed directly to the detector was removed because it was not scattered. Light paths which experienced more than 100 bounces were eliminated. An example of the baffle test configuration is provided in Fig. 24.11.

The analysis shows that as more baffles are added and the pitch (p) between them reduces the amount of scattered light reaching the detector is reduced. The height of the baffle (h) is constant in the analysis.



To be certain of the effectiveness of baffles in a real system, then a stray light model is required. In this example, a tube containing no lenses is modeled. The tube and baffles in this case are highly specular and reflective. This allows the placement of the baffles to be better considered in isolation of simple absorption. A highly diffuse version of the model is also considered.

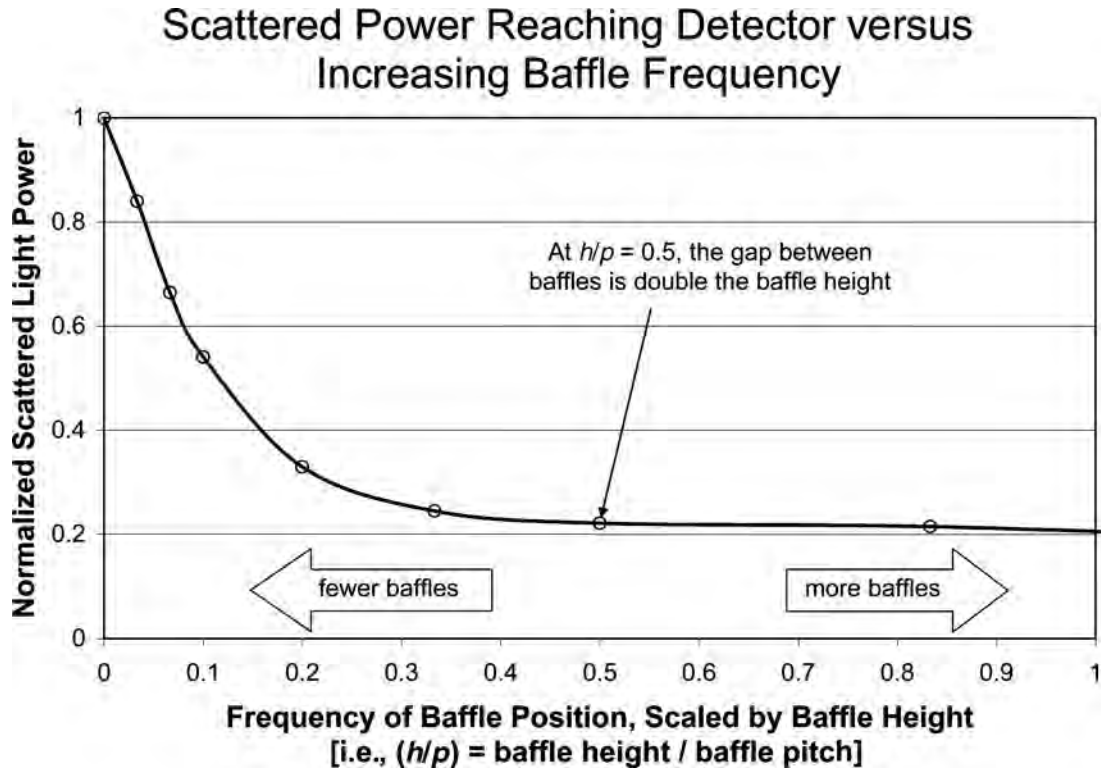
Figure 24.11

Baffle Analysis Configuration

Results are expressed in terms of the amount of scattered light power which reaches the detector, shown on the y-axis, versus the ratio of the height of the baffle to the pitch between them (h/p), shown on the x-axis. Results are provided in Fig. 24.12 for the case of a specular baffle.

Specular baffles would not be recommended for use in a real optical system. Specular baffles were chosen to examine how the positioning and number of baffles can influence scatter suppression independently of the baffle material type. It is of little surprise that the diffuse baffles achieve better absolute energy suppression than the specular baffles. A brief study comparing specular and diffuse baffles is provided in Fig. 24.13. The diffuse material scatters 90% of the radiation into a 90° cone, and 10% of energy is absorbed at each bounce. The specular scatter object reflects 99% of energy specularly, losing only 1% through absorption at each bounce.

The rate at which scatter suppression occurs with reduced baffle separation can be determined by examining the slope of Fig. 24.13. Reviewing Fig. 24.13 indicates a similar trend for both specular and diffuse baffles. When the height to spacing pitch ratio (h/p) reaches approximately 0.5 little further scatter suppression achieved by the addition of more baffles.

**Figure 24.12**

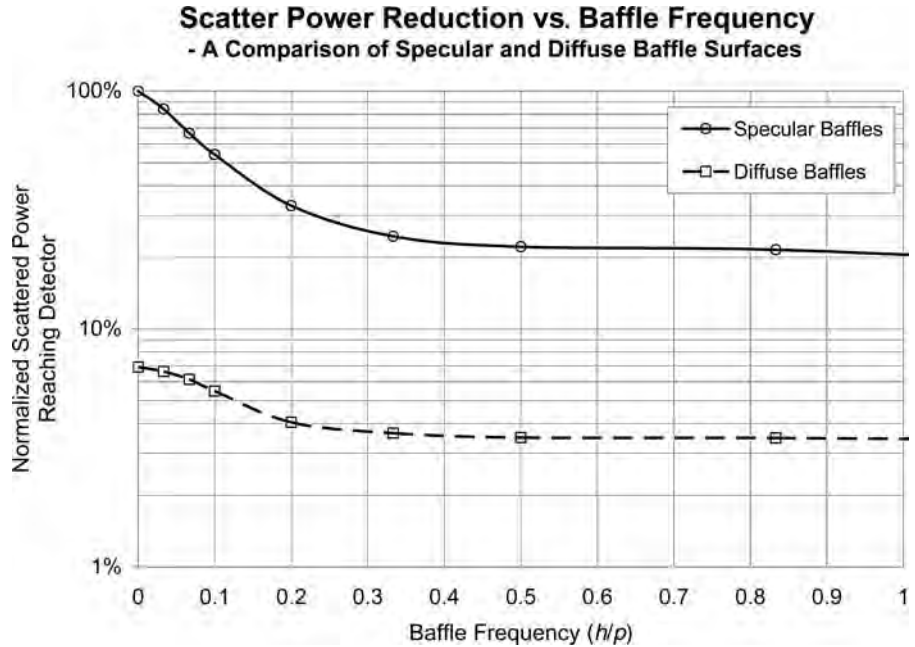
Analysis of Scatter Suppression with Frequency of Baffles along a Tube

The small amount of improvement offered by more baffles requires increasingly more complexity in the mechanical design. Furthermore, beyond $h/p = 0.5$, we move toward a scenario where the number of flat tops of the baffles would become significant; this treatment only considered infinitely thin baffles. The inevitable flat tops may begin to decrease baffle effectiveness. This is discussed further in “Thread Profiles” section for the case of threaded bores.

As discussed, this analysis assumes imperfect absorption from the baffles. Baffles are, however, typically good absorbers, or at least should be design to be. If we make the assumption that the baffles are 100% absorptive, then an optimal baffle geometry using a minimum number of baffles can be defined. This is now considered.

Figure 24.13

A Comparison of Diffuse and Specular Baffles

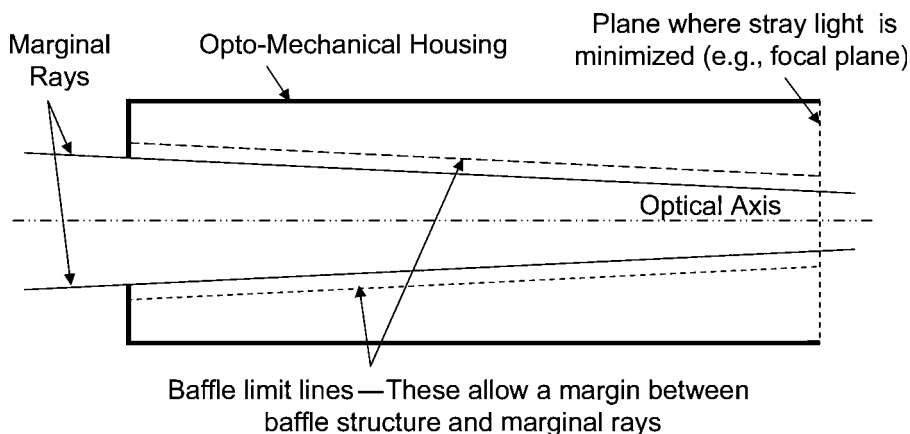


OPTIMAL BAFFLE GEOMETRY Assuming that the baffle surface can be made highly absorptive by surface roughening and blackening, it is possible to define an optimal baffle spacing arrangement. This uses the minimum number of baffles needed to block single structure reflections.

In Fig. 24.14 an optical system bore is shown, with the optical system marginal ray paths indicated. For simplicity, this is shown in a volume where there are no optical components. The optomechanical housing walls, the entrance aperture, and the marginal rays are defined. The focal plane is defined, but this could simply be an intermediate location where we want to ensure we have minimal stray light entering the optical system, that is, it could be the primary mirror location in a Cassegrain telescope system.

In Fig. 24.14 an allowance is provided for mechanical tolerances affecting the marginal ray locations with respect to the baffle locations. The baffles are, therefore, insets from the marginal ray line. The inset amount required will vary depending on the optical tolerances of the system. It is better to slightly undersize this baffle diameter at this stage. Erring on the side of caution is preferable because if the baffle diameter is too large the marginal rays will be vignetted.

Figure 24.14
An Optical System
Bore



To define the locations of the baffle, we work from the detector plane back toward the entrance aperture. The full focal plane is used in this description. The detector may, however, only cover the central portion of the focal plane. Use of the full diameter of the focal plane allows the baffling structure definition to be the most effective. Use of a final baffle immediately before the focal plane is common practice, not only for scatter suppression, but often such a component is used to assist in locating the detector with respect to the optical axis.

The direct line of sight paths to the detector plane are systematically eliminated from back to front. To define the location of the first baffle, "locator line 1" (LL1) is drawn, see Fig 24.15. LL1 is the pathway to the housing wall. Note, that locator lines defined here do not necessarily describe a specular reflection off the housing wall (that is, reflected

Figure 24.15
Locator Line 1
Defines Ideal Position
of First Baffle

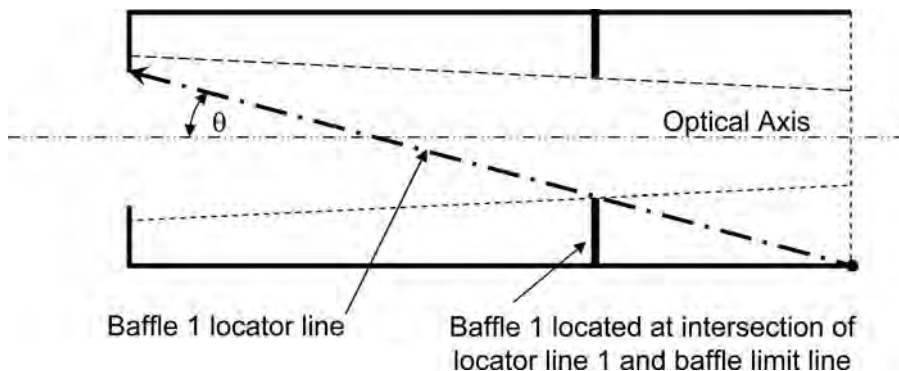
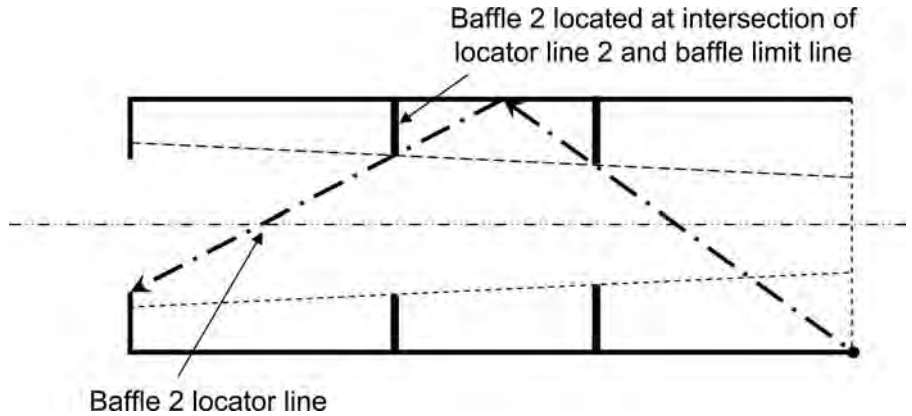


Figure 24.16

Locator Line 2
Defines Ideal Position
of Second Baffle



angle does not necessarily equal incident angle in the case of scattered light). The direct path from focal plane to entrance aperture may be a component of a Lambertian scatter, for example.

Baffle 1 as defined on Fig. 24.15 limits the field angles which can directly reach the focal plane to a maximum of $\pm\theta$ about the optical axis. The sensitivity of the tolerances of the baffle location along the optical axis are determined by the steepness of θ , that is, $dz = dh/\tan(\theta)$ and this should be considered when insetting the baffle limit lines from the marginal rays.

The second baffle location is defined by the intersection of locator line 2 and the baffle limit line on Fig. 24.16. Similarly the third baffle is defined by the intersection of the locator line 3 and the baffle limit line on Fig. 24.17. Figure 24.18 demonstrates that a fourth baffle is not required in this case.

Figure 24.17

Locator Line 3
Defines Ideal Position
of Second Baffle

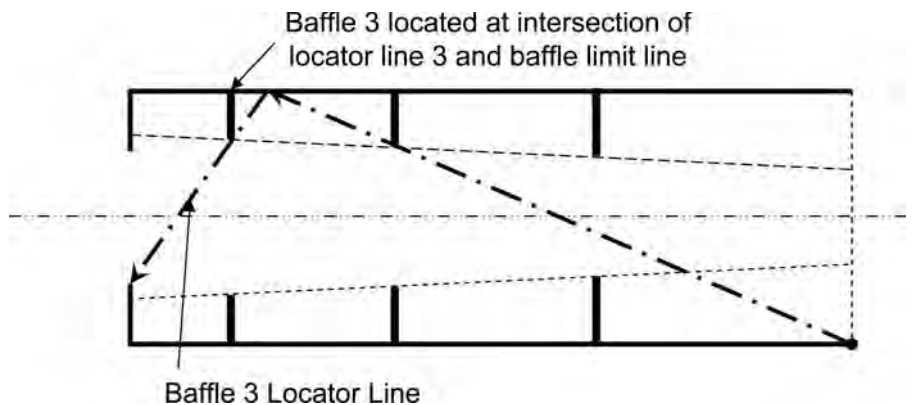
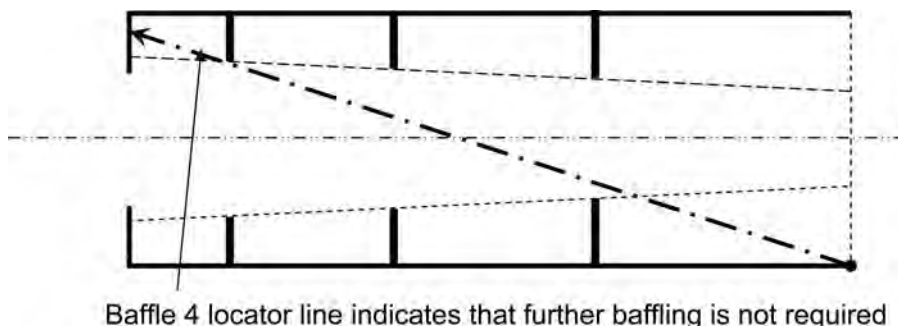


Figure 24.18

Locator Line 4 Indicates That No Further Baffles Are Required



If the marginal ray bundle within the housing is diverging, then more baffles may be required. This can be seen in Fig. 24.19.

Lastly, light entering this optimized baffle arrangement which experience specular reflections, will retro-reflect back toward the entrance aperture. This uses up two surface bounces. In order to be again directed toward the focal plane, a third and possible fourth bounce would be required. This baffle optimization can therefore be considered as a technique to optimize the design to meet the “Three Bounce Rule” discussed earlier.

BAFFLE PROFILE DESIGN Yes—it is even possible to optimize the profile of an individual baffle! Figure 24.20 shows a typical baffle profile.

Baffles are thin plates which are spaced along the inside of the optical housing providing a clear volume defined by the minor diameter. The diameter of the tube wall is referred to as the major diameter.

Figure 24.19

Diverging Marginal Rays Require an Increased Number of Optical Baffles

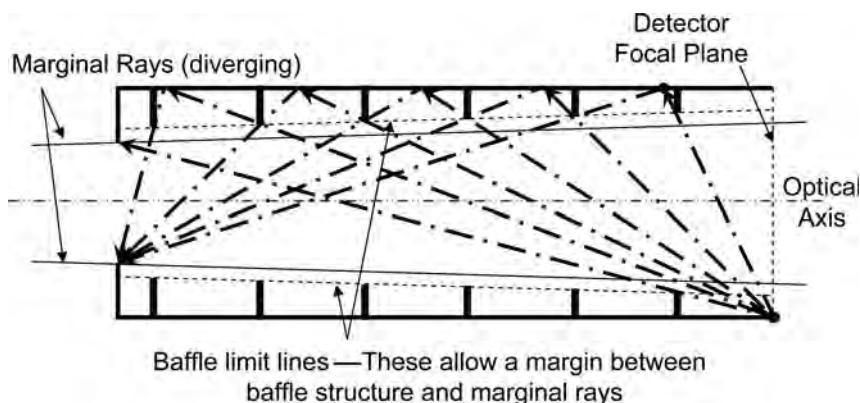
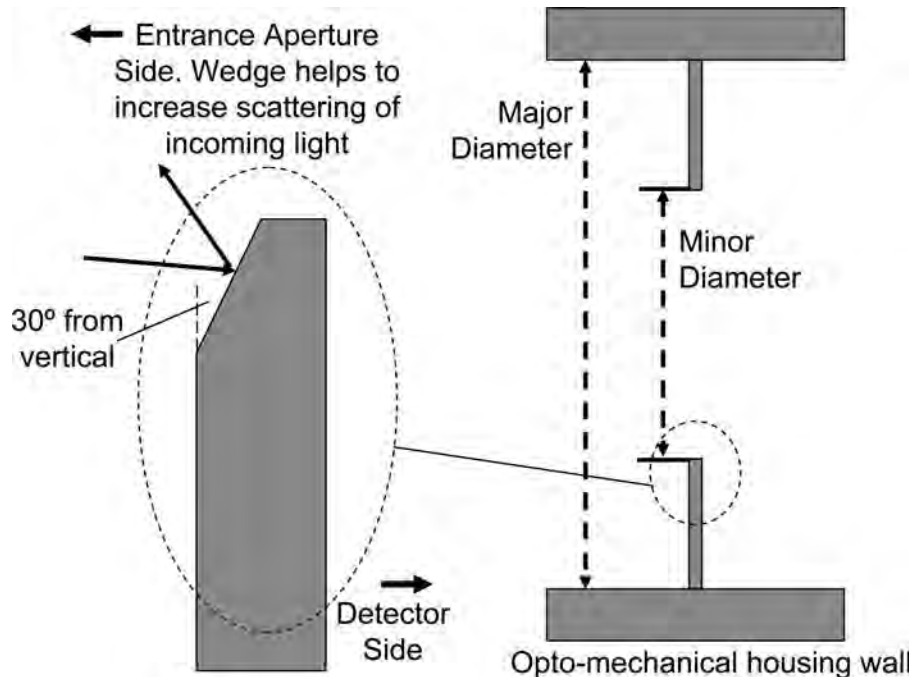


Figure 24.20
Typical Baffle Profile



Baffles have some limitations:

- They cannot be infinitely thin, nor can the tips be infinitely sharp.
- A reasonable machining limit for the sharpness of the baffle is in the range of 0.1 mm (0.004 in) to 0.25 mm (0.010 in).
- Sharper baffles become hard to make and are more difficult to handle.

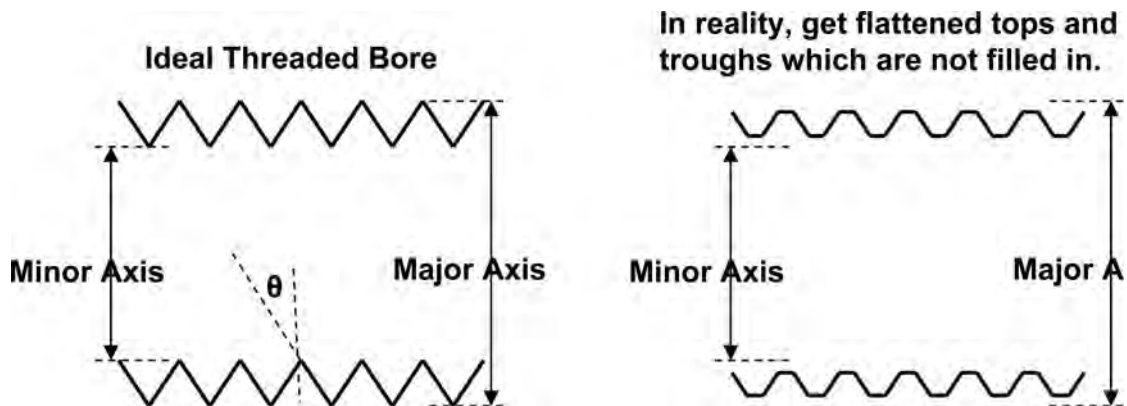
To avoid these difficulties it is often easier to have a baffle which is thicker, but reaches a point at the inner diameter. This can be achieved using a chamfer. The chamfered side of the baffle faces the entrance aperture. This helps to maximize the amount of light deflected into baffles or threaded structure in the walls. The effectiveness of this design profile would need to be modeled (or empirically evaluated) for any given case, but this is a good design practice applicable in most cases.

THREAD PROFILES Applying a thread to the inner bore of an opto-mechanical housing is an inexpensive technique for obtaining baffle suppression. Threads commonly applied to optical housings are in the range of 24 to 32 threads per inch (tpi), or 1 to 1.25 threads per millimeter (tpmm).

Typical machine threads have a pitch of between 45° to 60° , although custom threads can be generated. A typical thread profile is provided in Fig. 24.21a. In practice threads cannot be perfectly sharp. Figure 24.21b illustrates a typical thread, which will have a flattened top and a valley.

It is reasonable to expect the width of the flat to be in the range of ~ 0.1 mm (0.004 in) up to 0.25 mm (0.010 in). Care needs to be taken not to increase the pitch (that is, increase the tpi) of the thread too much. This will increase the total surface area of the flats, and hence lead to a surface which is overall more specular in nature.

A 45° thread angle provides a height to spacing (h/p) ratio 0.5, which agrees well with the baffle trade-off study optimal separation discussed in “Trade-Off Study—Baffle Design” section, where an h/p ratio of 0.5 was found to be optimal. Retaining the same h/p ratio of 0.5 using a 45° slope, but with a larger pitch increases the depth of the thread. Using an increased thread pitch will therefore require a large bore diameter. For this reason, threads of 24 to 32 tpi are preferred in most optical housings where space and volume are at a premium. A typical call-out for a thread on a drawing would be: “Cut antiglare thread 32 tpi” (1.26 tpm). This note tells the machinist that this thread doesn’t mate to another part. Note that at 32 tpi (1.26 tpm) with a flat tops and valleys of say 0.002 in (~ 50 μm), the ratio of flat spots to slopes is $1:1/(2 \times 0.05 \times 1.26) \approx 1:1/(2 \times 0.002 \times 32) \approx 1:7.8$, that is, approximately 12.8% of the bore will be acting as a near flat surface. The peak portion of this (that is, excluding the valleys) is half of this (6.4% in this example) and will be visible when



Figures 24.21
Ideal and Real Thread Profiles

directly viewing down the barrel. The valley portion increases the likelihood of scatter bouncing out of the thread furrow before three bounces have been achieved. If the peaks are not highly absorptive then stray light will be propagated on through the system from these peak sites.

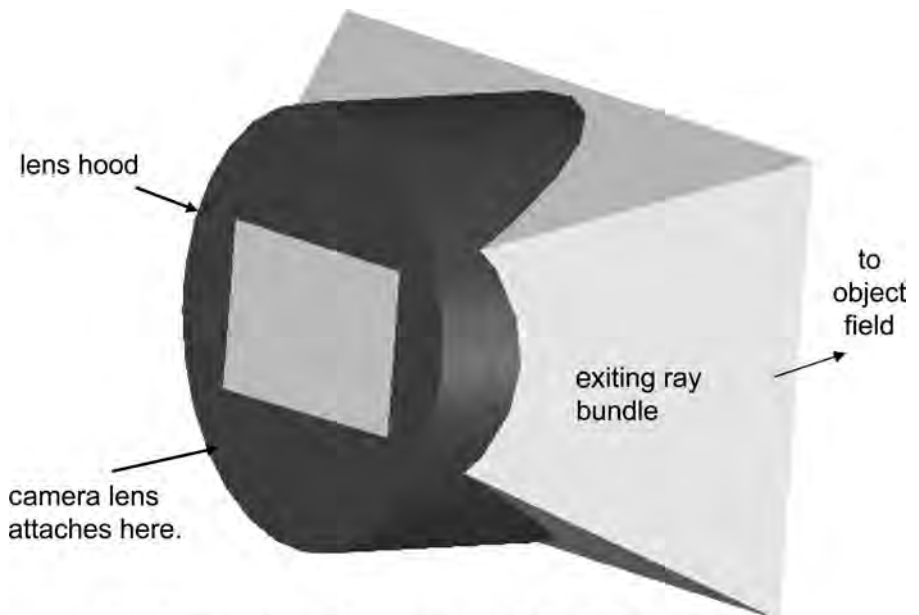
Tighter thread spacing will make this ratio of peaks and valleys to total bore length worse as threads will get closer together, but the flats and valleys will not become smaller.

Threads are usually used to augment scatter suppression in an optical system but usually some form of baffling is required to optimize scatter suppression. Threads can be considered helpful, but not a cure all, for optical scatter suppression.

Lens Hood Design

A lens hood is a very effective way to remove unwanted veiling glare from an optical system. An example of a fixed hood for a reasonably wide field of view lens is given in Fig. 24.22. As is typical of wide angle

Figure 24.22
Lens Hood Design



Pupil separation at front aperture of lens is large. A near rectangular ray bundle profile is described. This has been propagated to define the required hood characteristics.

lenses, the field bundles are largely separated at the front surface. The marginal rays of the system define a near rectangular shape at the front lens, this is in effect a projection to the rectangular aspect ratio of the sensor. The rectangular projection expands in size from the first lens surface toward the object. A conic section has been intersected with the image field marginal rays to determine the optimal hood shape. This maximizes veiling glare protection whilst ensuring that the fields required are not vignetted.

Care has to be taken to sufficiently oversize the hood profile to cope with manufacturing tolerance variations associated with the lens fabrication and assembly and of the hood fabrication and positioning onto the lens. On zooming systems the effectiveness of the hood is limited by the wide angle field of view. If the same hood is used in the narrow and wide field of view, then the narrow field of view will be sub-optimally protected. The narrower field of view can have a longer hood before vignetting of the edge of the field rays occurs. This shortcoming may be minimized if the hood changes shape when zooming, or if the objective retracts into the housing when zooming. However, this requires significant opto-mechanical design effort. It is sensible to make the inner bore of the lens hood matt black, or threaded black if possible.

If the optical engineer requires that a hood be used in the optical design, then it really does need to stay. Don't let the marketeers cut it back because they think it looks better without it (see Chap. 25)!

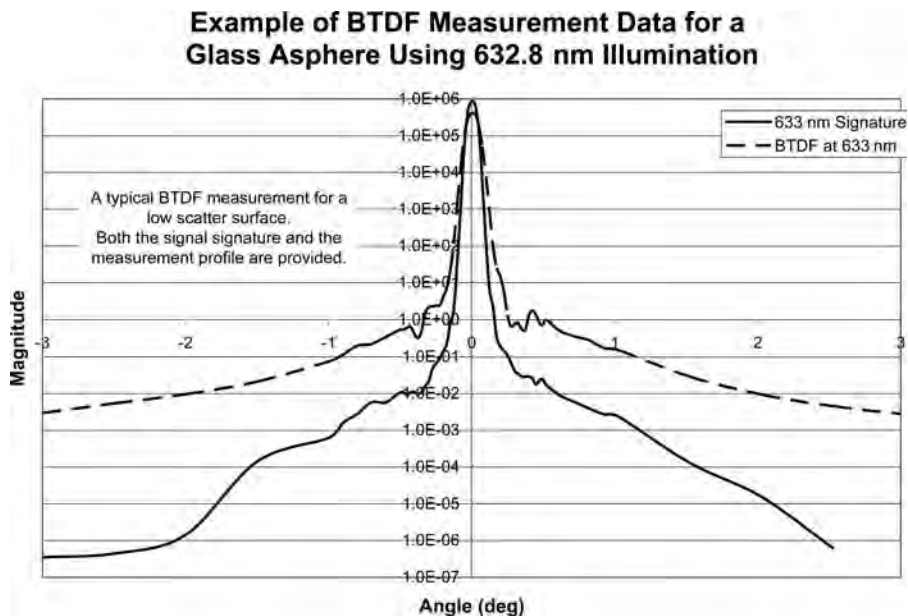
Material Characteristics

Material scatter characteristics can be well defined by *Bi-directional Reflectance Distribution Function* (BRDF) profiles. The *Transmission version BTDF* is typically used to characterize optical materials. An example of a BTDF profile is provided in Figs. 24.23 and 24.24.

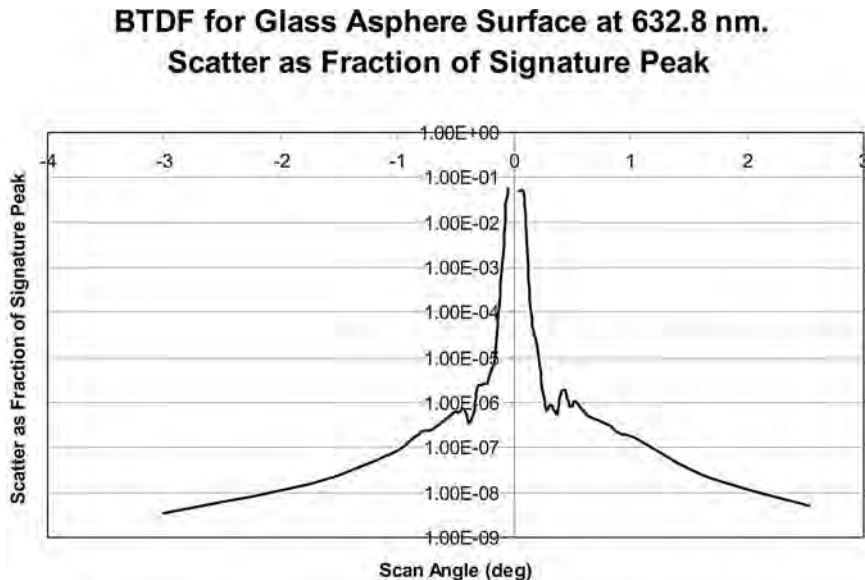
Figure 24.24 provides the scatter characteristics of a glass aspheric surface fabricated on N-BK7 glass. The other side of the element is a spherical lens which contributes little to the overall scatter profile in this case. The measurement is made by scanning the profile through a range of angles using detector mounted on a goniometer. Figure 24.25 describes a goniometer with a one-dimensional scan-axis apparatus. In the measurement example provided the source was a laser beam at

Figure 24.23

BTDF Profile for an
Aspheric Surface
Fabricated on N-BK7
Glass

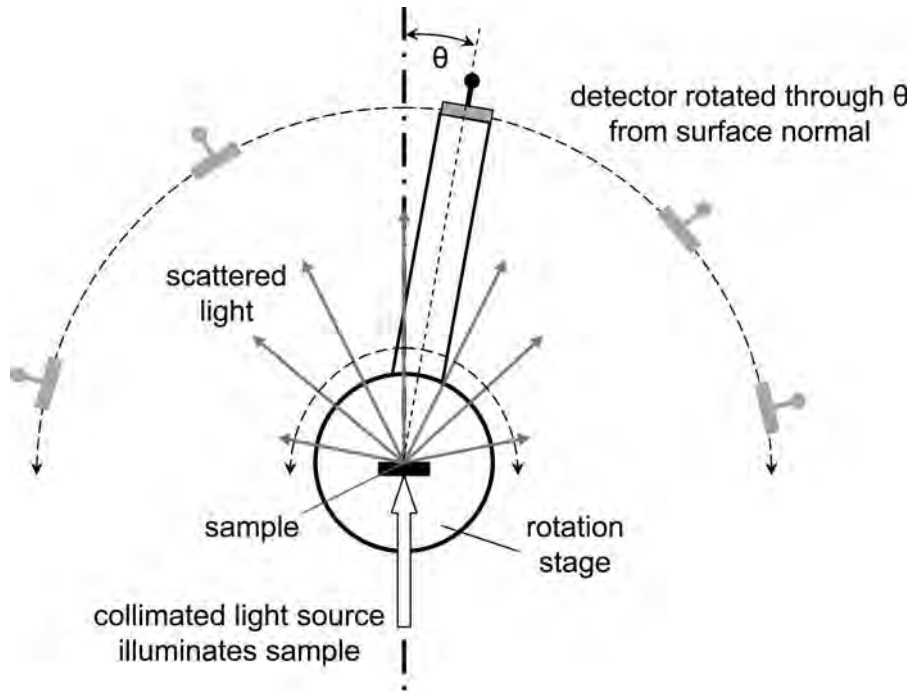
**Figure 24.24**

BTDF Profile with the
Signal Component
Removed



BTDF with signature peak removed. Data was not recoverable on axis because computational error became too large.

Figure 24.25
One-Dimensional
Goniometer Scatter
Measurement System



632.8 nm. This example shows a relatively narrow scatter angular profile and so the range of angles sampled was small. The large central peak has to be removed, and the revised profile is provided in Fig. 24.24.

A coarse surface profile will generate optical scatter over a full hemisphere (for an opaque) material. A transmissive scattering object will generate scatter for forward and backward, over full sphere.

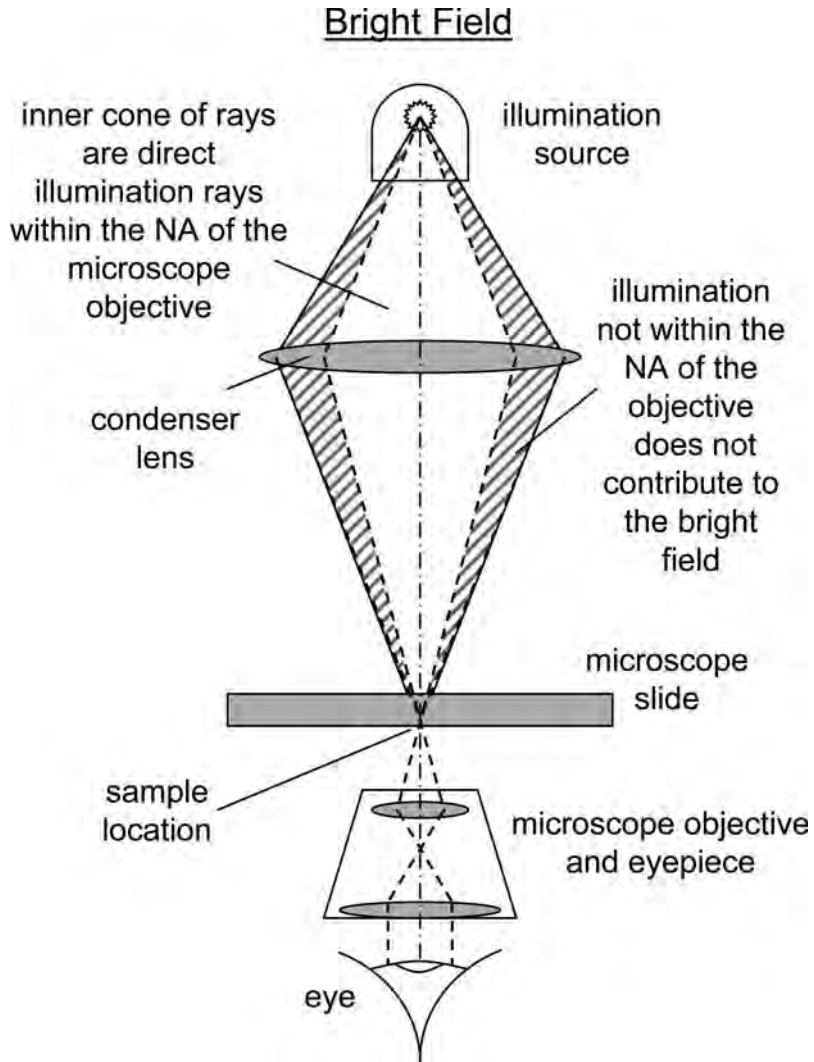
It is noted that in the surface scatter profile can be integrated. Examination of the TIS can be used to determine the surface roughness.

Bright Field and Dark Field

Optical scattering is not always encountered as an unwanted side effect. It is possible to use optical scattering beneficially to obtain improved contrast imagery.

Consider an example scenario, where an optical microscope is being used to image a biological contaminant found on an optical surface. Figure 24.26 describes a configuration where the sample is illuminated directly. The illumination source fills the numerical aperture (NA) of the microscope. This generates bright-field image of

Figure 24.26
Bright Field
Schematic



the sample. An example of an image obtained in the bright field is provided in Fig. 24.28. Bright field imagery is suitable when viewing sample where the transmission through the sample varies. The variation in the transmission profile generates the contrast in the observed image.

Figure 24.27

Dark Field Schematic

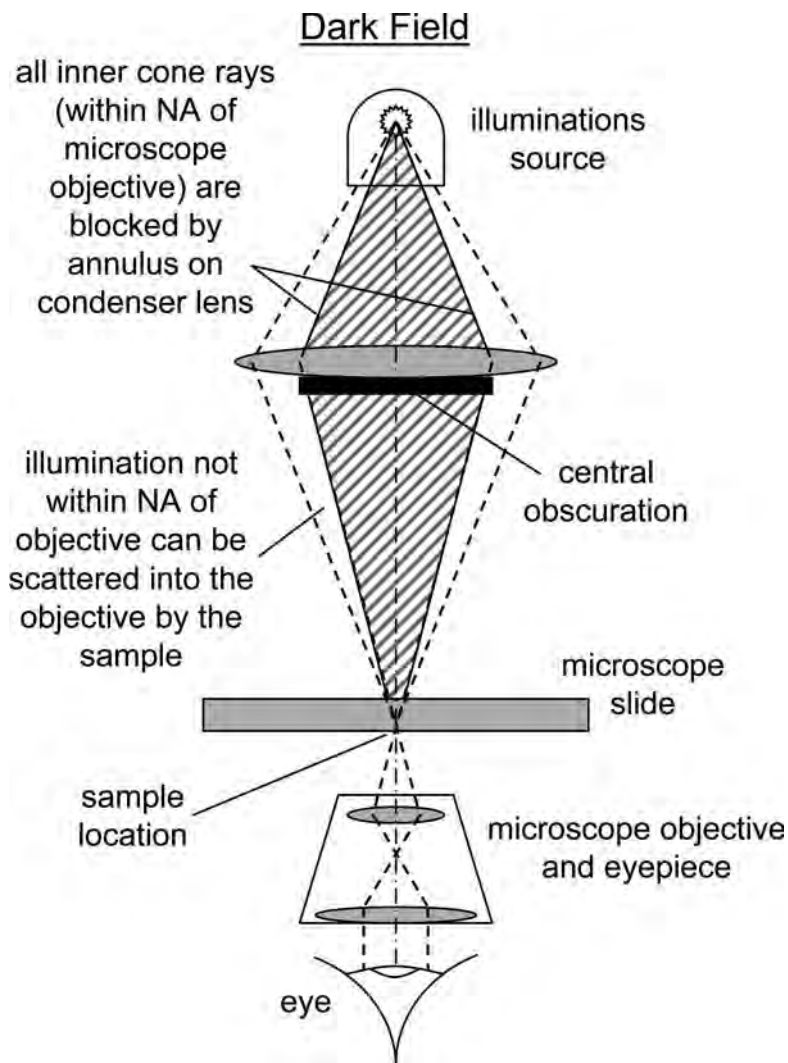


Figure 24.26 shows exactly the same sample, viewed with the same microscope, but the illumination cone has been altered. Here the illumination profile is an annulus, all of which lies outside of the NA of the microscope objective. Light will only enter the microscope if it is scattered back into the NA cone of the microscope objective. If the sample is removed, then the field will be completely dark, hence this is known as dark field imaging, or dark field microscopy. An example of an image obtained in the bright field is provided in Fig. 24.29. This type of illumination is useful for observing objects which exhibit low optical transmission variation making bright field imagery less suitable.

Figure 24.28
Bright Field Image
Example

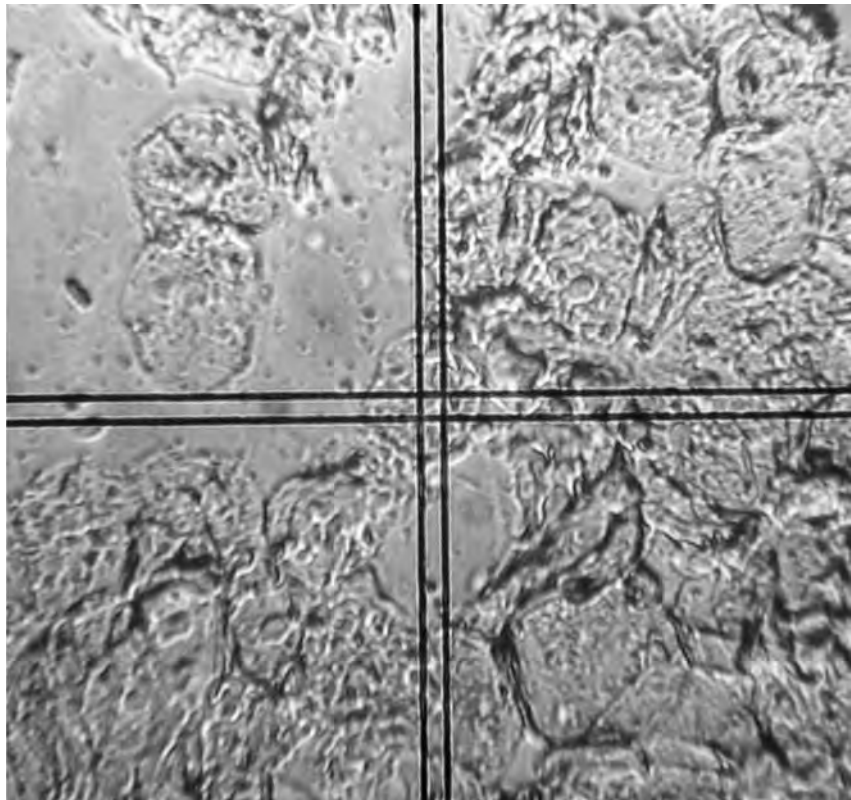
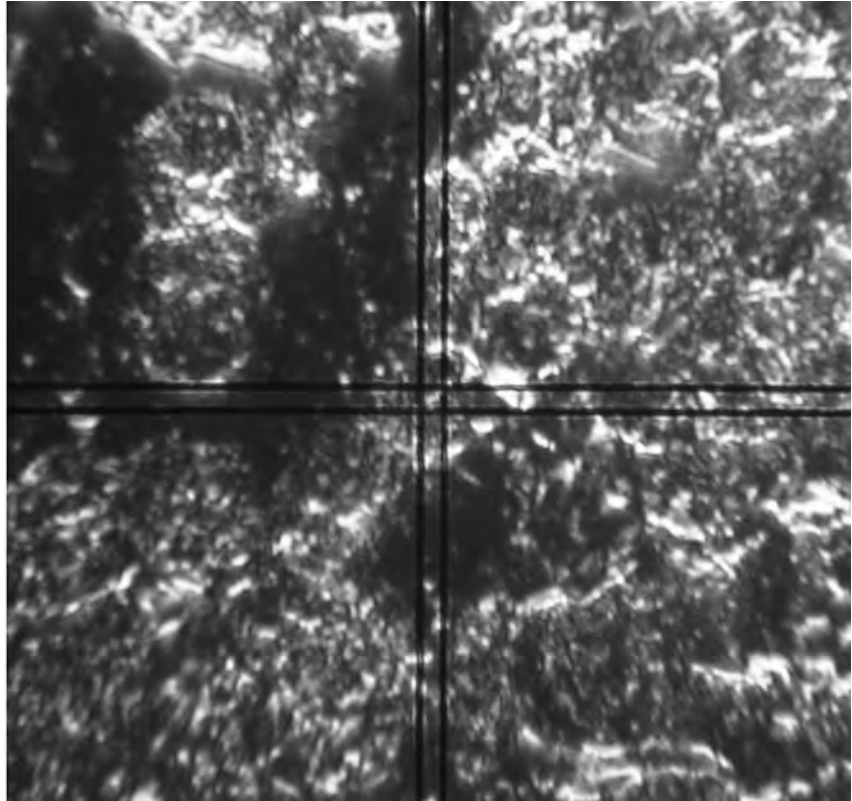


Figure 24.29
Dark Field Image
Example

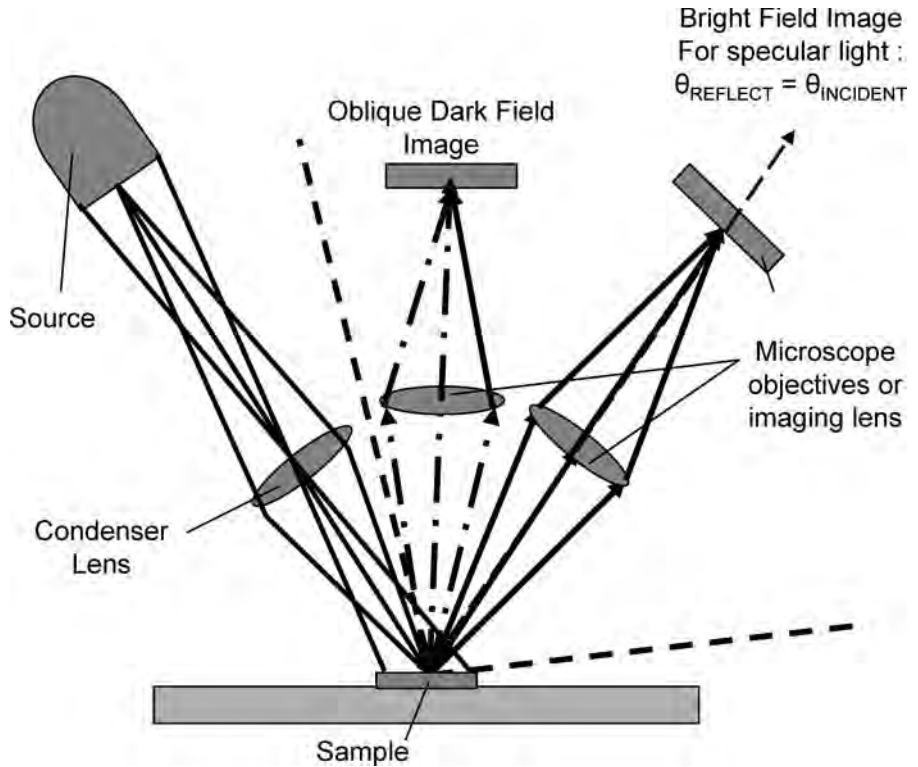


Obtaining both bright field and dark field imagery of a sample will often increase the overall understanding of the sample being viewed.

Figure 24.30 shows both bright field and dark field imagery. The bright field is achieved using the specularly reflected portion of the illumination cone. The dark field imagery is obtained using the diffusely scattered portion of the illumination cone. The dark field image uses an oblique illumination profile which is inherently asymmetrical. This is unlike the example provided in Fig. 24.27 where the illumination profile is a symmetrical annulus.

Figure 24.30

Bright and Oblique
Dark Field Imaging
System



How to Avoid Unwanted Stray Light

The following list summarizes tried and tested techniques to avoid scatter problems in an optical system:

- Use the three bounce rule!
- Check single bounces in the optical design.
 - Conduct single bounce analyses in IR systems to identify Narcissus contributions.
- Do not oversize optical elements within the optical system by more than is necessary to account for optical tolerances and mechanical mounting.
- Employ threads, baffles, and field stops where possible.

- Identify the key locations for thread and baffling positioning.
 - Use direct modeling to identify key stray light paths.
 - Ensure time for a prototype evaluation of stray light performance in prototype first article units. Empirical testing is the ultimate proof of success!
- Be careful about the thread pitch and/or baffle spacing. A pitch (or separation) to height ratio of 2:1 is optimal in most cases.
- Design the baffle locations to minimize stray light from direct ray paths.
- Blacken as many surfaces as possible.
 - Metallic surfaces should be black anodized as a minimum.
 - Consider using shedding free flocking materials. These can be applied for low costs and be highly effective. Consideration of the adherence of such materials may depend on the environment used.
 - Blacken lens edges and out of clear aperture surface mounting flats.
- Use AR coatings to minimize Fresnel reflections, especially in IR systems where higher refractive index materials are common.

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