# TECHNICAL GUIDE

# COATING BACKGROUNDER

# OPTICAL COATINGS

The vast majority of optical components are made of various types of glass, and most are coated with thin layers of special materials. The purpose of these coatings is to modify the reflection and transmission properties of the components' surfaces.

Whenever light passes from one medium into a medium with different optical properties (most notably refractive index), part of the light is reflected and part of the light is transmitted. The intensity ratio of the reflected and transmitted light is primarily a function of the change in refractive index between the two media, and the angle of incidence of the light at the interface. For most uncoated optical glasses, 4-5% of incident light is reflected at each surface. Consequently, for designs using more than a few components, transmitted light losses can be significant. More important are the corresponding losses in image contrast and lens resolution caused by reflected ghost images (usually defocused) superimposed on the desired image. Applications generally require that the reflected portion of incident light approach zero for transmitting optics (lenses), 100% for reflective optics (mirrors), or some fixed intermediate value for partial reflectors (beamsplitters). The only suitable applications for uncoated optics are those where only a few optical components are in the optical path, and significant transmission inefficiencies can be tolerated.

In principle, the surface of any optical element can be coated with thin layers of various materials (called thin films) in order to achieve the desired reflection/transmission ratio. With the exception of simple metallic coatings, this ratio depends on the nature of the material from which the optic is fabricated, the wavelength of the incident light, and the angle of incidence of the light (measured from the normal). There is also polarization dependence to the reflection/transmission ratio when the angle of incidence is not normal to the surface.

A multilayer coating, sometimes made up of more than 100 individual fractional-wavelength layers, may be used to optimize the reflection/transmission ratio for a specific wavelength and angle of incidence or to optimize it over a specific range of conditions.

Today's multilayer dielectric coatings are remarkably hard and durable. With proper care and handling, they can have a long life. In fact, the surfaces of many high-index glasses that are soft or prone to staining can be protected with a durable antireflection coating. Several factors influence coating durability. Coating designs should be optimized to minimize thickness and reduce mechanical stresses that may distort the optical surfaces or cause detrimental polarization effects. Resilient material must used. Great care must be taken in coating fabrication to produce high-quality, nongranular, even layers.

CVI Laser Optics is a leading supplier of precision optical components and multielement optical systems. We have achieved our market-leading position by having an extensive knowledge of the physics of thin-film coatings and without the advanced production systems and methods required to apply such coatings in production. With state-of-the-art coating facilities CVI Laser Optics not only is able to coat large volumes of standard catalog and custom optical components, but also is able to develop and evaluate advanced new coatings for customers' special requirements.

Although our optical-coating engineers and technicians have many years of experience in designing and fabricating various types of dielectric and metallic coatings, the science of thin films continues to evolve. CVI Laser Optics continually monitors and incorporates new technology and equipment to be able to offer our customers the most advanced coatings available.

The CVI Laser Optics range of coatings currently includes antireflection coatings, metallic reflectors, all-dielectric reflectors, hybrid reflectors, partial reflectors (beamsplitters), and filters for monochromatic, dichroic, and broadband applications.With new and expanded coating capabilities, including the new deep-UV-optimized Leybold SYRUSpro 1100™, CVI Laser Optics offers the same high-quality coatings to customers who wish to supply their own substrates. As with any special or OEM order, please contact CVI Laser Optics to discuss your requirements with one of our qualified applications engineers.

# THE REFLECTION AND REFRACTION OF LIGHT

## REFLECTIONS AT UNCOATED SURFACES

Whenever light is incident on the boundary between two media, some light is reflected and some is transmitted into the second medium, undergoing refraction. Several physical laws govern the direction, phase, and relative amplitude of the reflected light. For our purposes, it is necessary to consider only polished optical surfaces. Diffuse reflections from rough surfaces are not considered in this discussion.

The law of reflection states that the angle of incidence ($\theta_1$) equals the angle of reflection ($\theta_r$). This is illustrated in figure 1.1, which shows reflection of a light ray at a simple air to glass interface. The incident and reflected rays make an equal angle with respect to the axis perpendicular to the interface between the two media.

## INTENSITY

At a simple interface between two dielectric materials, the amplitude of reflected light is a function of the ratio of the refractive index of the two materials, the polarization of the incident light, and the angle of incidence.

When a beam of light is incident on a plane surface at normal incidence, the relative amplitude of the reflected light, as a proportion of the incident light, is given by

$$\frac{(1-p)}{(1+p)} \qquad (1.1)$$

where $p$ is the ratio of the refractive indexes of the two materials ($n_1/n_2$). Intensity is the square of this expression.

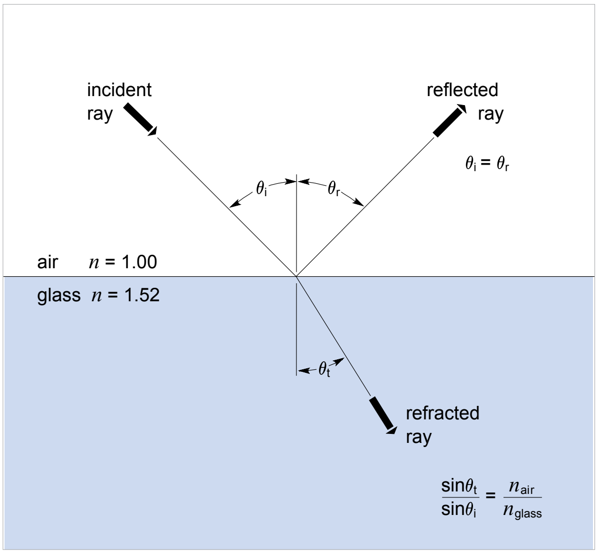


Figure 1.1 Reflection and refraction at a simple air to glass interface

The greater the disparity between the two refractive indexes, the greater the reflection. For an air to glass interface, with glass having a refractive index of 1.5, the intensity of the reflected light will be 4% of the incident light. For an optical system containing ten such surfaces, the transmitted beam will be attenuated to approximately 66% of the incident beam due to reflection losses alone, emphasizing the importance of antireflection coatings to system performance.

## INCIDENCE ANGLE

The intensity of reflected and transmitted beams at a surface is also a function of the angle of incidence. Because of refraction effects, it is necessary to differentiate between external reflections, where the incident beam originates in the medium with a lower refractive index (e.g., air in the case of an air to glass or air to water interface), and external reflection, where the beam originates in the medium with a higher refractive index (e.g., glass in the case of a glass to air interface, or flint glass in the case of a flint to crown-glass interface), and to consider them separately.

## EXTERNAL REFLECTION AT A DIELECTRIC BOUNDARY

Fresnel's laws of reflection precisely describe amplitude and phase relationships between reflected and incident light at a boundary between two dielectric media. It is convenient to think of the incident radiation as the superposition of two plane-polarized beams, one with its electric field parallel to the plane of incidence ($p$-polarized), and the other with its electric field perpendicular to the plane of incidence ($s$-polarized). Fresnel's laws can be summarized in the following two equations, which give the reflectance of the $s$- and $p$-polarized components:

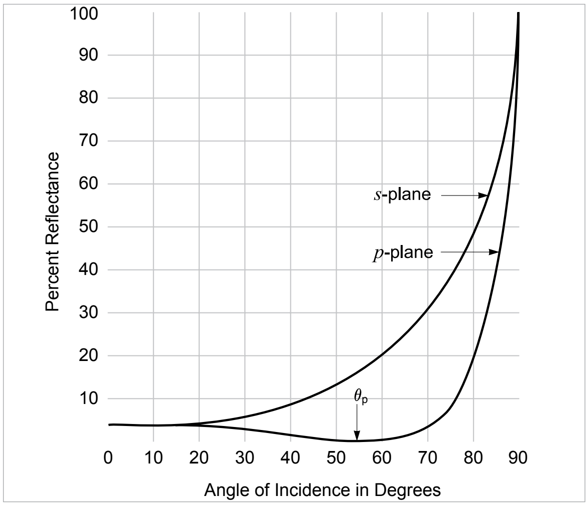


Figure 1.2 External reflection at a glass surface (n = 1.52) showing *s*- and *p*-polarized components

$$r_s = \left[\frac{\sin(\theta_1 - \theta_2)}{\sin(\theta_1 + \theta_2)}\right]^2 \quad (1.2)$$

$$r_p = \left[\frac{\tan(\theta_1 - \theta_2)}{\tan(\theta_1 + \theta_2)}\right]^2 \quad (1.3)$$

In the limit of normal incidence in air, Fresnel's laws reduce to the following simple equation:

$$r = \left(\frac{n-1}{n+1}\right)^2. \quad (1.4)$$

It can easily be seen that, for a refractive index of 1.52 (crown glass), this gives a reflectance of 4%. This important result reaffirms that, in general, 4% of all illumination incident normal to an air-glass surface will be reflected. The variation of reflectance with angle of incidence for both the *s*- and *p*-polarized components, plotted using the formulas above, is shown in figure 1.2.

It can be seen that the reflectance remains close to 4% up to about 25° angle of incidence, and that it rises rapidly to nearly 100% at grazing incidence. In addition, note that the *p*-component vanishes at 56°.

This angle, called Brewster's angle, is the angle at which the reflected light is completely polarized. This situation occurs when the reflected and refracted rays are perpendicular to each other ($\theta_1 = \theta_2$ = 90°), as shown in figure 1.3.

This leads to the expression for Brewster's angle, $\theta_B$:

$$\theta_1 = \theta_B = \arctan(n_2 / n_1) \quad (1.5)$$

Under these conditions, electric dipole oscillations of the *p*-component will be along the direction of propagation and therefore cannot contribute to the reflected ray. At Brewster's angle, reflectance of the *s*-component is about 15%.

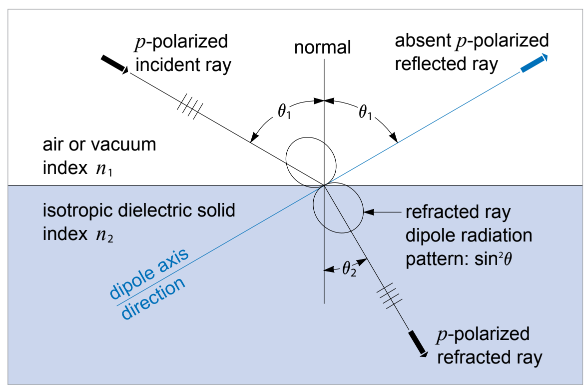


Figure 1.3 Brewster's angle: at this angle, the *p*-polarized component is completely absent in the reflected ray

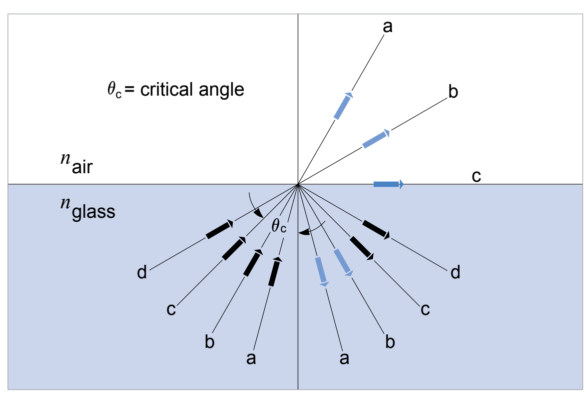


Figure 1.4 Internal reflection at a glass surface (n = 1.52) showing *s*- and *p*-polarized components

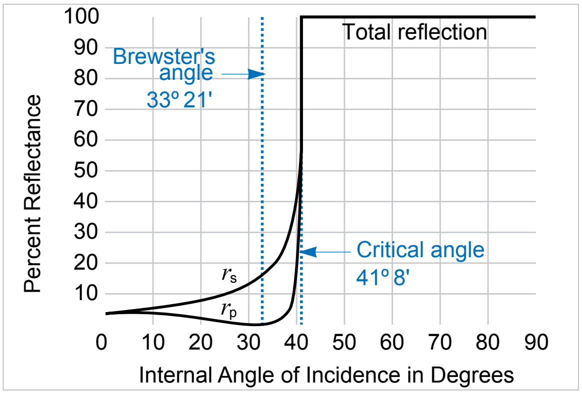


Figure 1.5 Critical angle: at this angle, the emerging ray is at grazing incidence

## INTERNAL REFLECTION AT DIELECTRIC BOUNDARY

For light incident from a higher to a lower refractive index medium, we can apply the results of Fresnel's laws in exactly the same way. The angle in the high-index material at which polarization occurs is smaller by the ratio of the refractive indices in accordance with Snell's law. The internal polarizing angle is 33° 21' for a refractive index of 1.52, corresponding to the Brewster angle (56° 39') in the external medium, as shown in figure 1.4.

The angle at which the emerging refracted ray is at grazing incidence is called the critical angle (see figure 1.5). For an external medium of air or vacuum ($n$ = 1), the critical angle is given by

$$\theta_c(\lambda) = \arcsin\left(\frac{1}{n(\lambda)}\right) \quad (1.6)$$

and depends on the refractive index $n_\lambda$, which is a function of wavelength. For all angles of incidence higher than the critical angle, total internal reflection occurs.

## PHASE CHANGES ON REFLECTION

There is another, more subtle difference between internal and external reflections. During external reflection, light waves undergo a 180° phase shift. No such phase shift occurs for internal reflection (except in total internal reflection). This is one of the important principles on which multilayer films operate.

## INTERFERENCE

Quantum theory shows us that light has wave/particle duality. In most classical optics experiments, the wave properties generally are most important. With the exception of certain laser systems and electro-optic devices, the transmission properties of light through an optical system can be well predicted and rationalized by wave theory.

One consequence of the wave properties of light is that waves exhibit interference effects. Light waves that are in phase with one another undergo constructive interference, as shown in figure 1.6.

Light waves that are exactly out of phase with one another (by 180° or $\pi$ radians) undergo destructive interference, and, as shown in the figure, their amplitudes cancel. In intermediate cases, total amplitude is given by the vector resultant, and intensity is given by the square of amplitude.

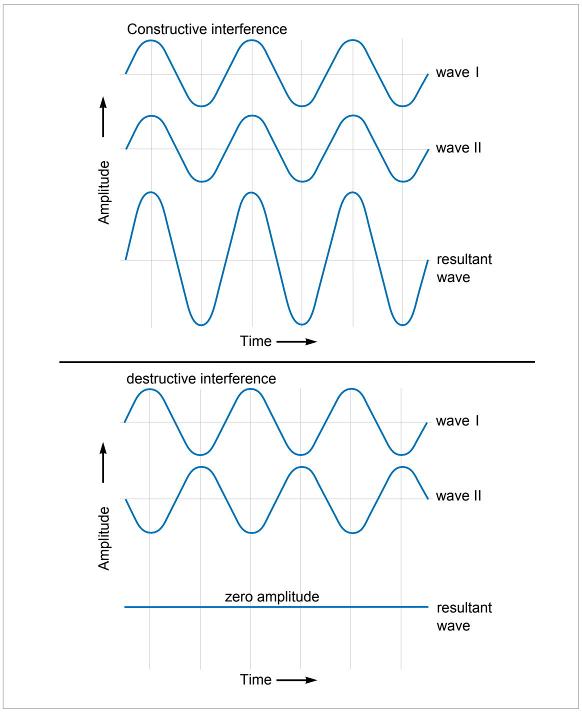


Figure 1.6 A simple representation of constructive and destructive wave interference

Various experiments and instruments demonstrate light interference phenomena. Some interference effects are possible only with coherent sources (i.e., lasers), but many are produced by incoherent light. Three of the best-known demonstrations of visible light interference are Young's slits experiment, Newton's rings, and the Fabry-Perot interferometer. These are described in most elementary optics and physics texts.

In all of these demonstrations, light from a source is split in some way to produce two sets of wavefronts. These wavefronts are recombined with a variable path difference between them. Whenever the path difference is an integral number of half wavelengths, and the wavefronts are of equal intensity, the wavefronts cancel by destructive interference (i.e., an intensity minimum is produced). An intensity minimum is still produced if the interfering wavefronts are of differing amplitude, the result is just non-zero. When the path difference is an integral number of wavelengths, the wavefront intensities sum by constructive interference, and an intensity maximum is produced.

## THIN-FILM INTERFERENCE

Thin-film coatings may also rely on the principles of interference. Thin films are dielectric or metallic materials whose thickness is comparable to, or less than, the wavelength of light.

CVI Laser Optics offers a variety of single- and multilayer antireflection and high-reflection coatings

When a beam of light is incident on a thin film, some of the light will be reflected at the front surface, and some light will be reflected at the rear surface, as shown in figure 1.7. The remainder will be transmitted. At this stage, we shall ignore multiple reflections and material absorption effects.

The two reflected wavefronts can interfere with each other. The degree of interference will depend on the optical thickness of the material and the wavelength of the incident light (see figure 1.8). The optical thickness of an element is defined as the equivalent vacuum thickness (i.e., the distance that light would travel in vacuum in the same amount of time as it takes to traverse the optical element of interest). In other words, the optical thickness of a piece of material is the thickness of that material corrected for the apparent change of wavelength passing through it.

The optical thickness is given by $t_{op} = tn$, where t is the physical thickness, and n is the ratio of the speed of light in the material to the speed of light in vacuum:

$$n = \frac{c_{\text{vacuum}}}{c_{\text{medium}}}. \qquad (1.7)$$

To a very good approximation, n is the refractive index of the material.

Returning to the thin film at normal incidence, the phase difference between the external and internal reflected wavefronts is given by $(t_{op}/\lambda)\times 2\pi$, where $\lambda$ is the wavelength of light. Clearly, if the wavelength of the incident light and the thickness of the film are such that a phase difference of $\pi$ exists between reflections, the reflected wavefronts interfere destructively and overall reflected intensity is a minimum. If the two interfering reflections are of equal amplitude, the amplitude (and hence intensity) minimum will be zero.

In the absence of absorption or scatter, the principle of conservation of energy indicates that all "lost" reflected intensity will appear as enhanced intensity in the transmitted beam. The sum of the reflected and transmitted beam intensities is always equal to the incident intensity.

Conversely, when the total phase shift between two reflected wavefronts is equal to zero (or multiples of $2\pi$), then the reflected intensity will be a maximum, and the transmitted beam will be reduced accordingly.

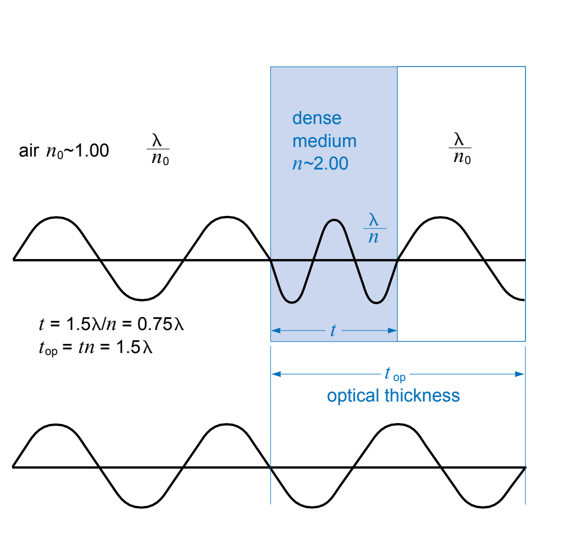


Figure 1.7 Front and back surface reflections for a thin film at near-normal incidence

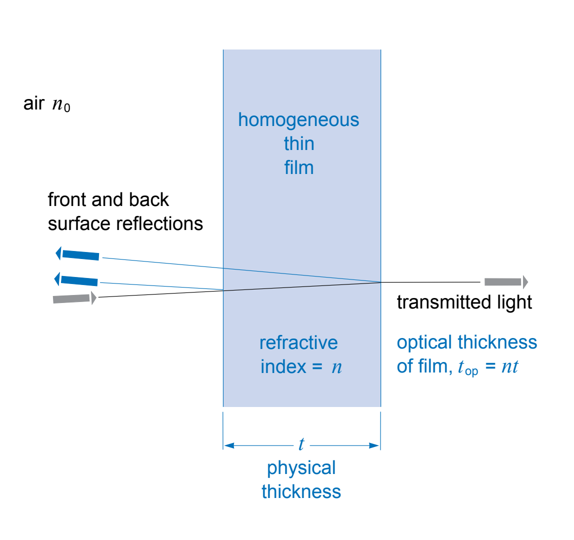


Figure 1.8 A schematic diagram showing the effects of lower light velocity in a dense medium (in this example, the velocity of light is halved in the dense medium n = n/$n_0$, and the optical thickness of the medium is 2 x the real thickness)

## SINGLE-LAYER ANTIREFLECTION COATINGS

The basic principles of single-layer antireflection coatings should now be clear. Ignoring scattering and absorption,transmitted energy = incident energy–reflected energy.

If the substrate (glass, quartz, etc.) is coated with a thin layer (film) of material, and if the reflections from the air/film interface and from the film/substrate interface are of equal magnitude and 180° (π radians) out of phase, then the reflected waves will cancel each other out by destructive interference, and the intensity of the transmitted beam will approach the intensity of the incident beam.

### FILM THICKNESS

To eliminate reflections at a specific wavelength, the optical thickness of a single-layer antireflection film must be an odd number of quarter wavelengths. This requirement is illustrated in figure 1.9. The reflections at both the air/film and film/substrate interfaces are "internal" (low index to high index) and the phase changes caused by the reflections themselves cancel out. Consequently, the net phase difference between the two reflected beams is determined solely by their optical path difference $2tn_c$, where $t$ is the physical thickness and $n_c$ is the refractive index of the coating layer. For a 180° phase shift, $2tn_c = N\lambda/2$ and $tn_c = N\lambda/4$ where N=1, 3, 5 . . .

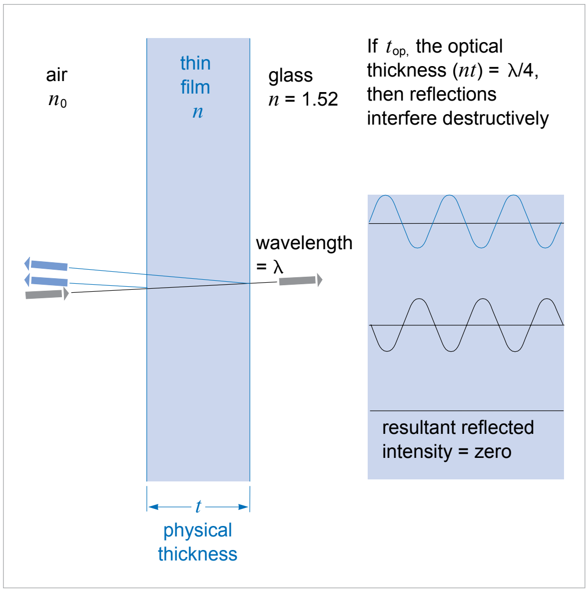


Figure 1.9 Schematic representation of a single-layer antireflection coating

Single-layer antireflection coatings are generally deposited with a thickness of λ/4, where λ is the desired wavelength for peak performance. The phase shift is 180° (π radians), and the reflections are in a condition of exact destructive interference.

### REFRACTIVE INDEX

The intensity of the reflected beam from a single surface, at normal incidence, is given by

$$\left(\frac{1-p}{1+p}\right)^2 \times \text{the incident intensity} \quad (1.8)$$

where $p$ is the ratio of the refractive indexes of the two materials at the interface.
For the two reflected beams to be equal in intensity, it is necessary that $p$, the refractive index ratio, be the same at both the interfaces

$$\frac{n_{\text{air}}}{n_{\text{film}}} = \frac{n_{\text{film}}}{n_{\text{substrate}}} \quad (1.9)$$

Since the refractive index of air is 1.0, the thin antireflection film ideally should have a refractive index of

$$n_{\text{film}} = \sqrt{n_{\text{substrate}}} \quad (1.10)$$

Optical glasses typically have refractive indexes between 1.5 and 1.75. Unfortunately, there is no ideal material that can be deposited in durable thin layers with a low enough refractive index to satisfy this requirement exactly ($n$ = 1.23 for the optimal antireflection coating on crown glass). However, magnesium fluoride ($MgF_2$) is a good compromise because it forms high quality, stable films and has a reasonably low refractive index (1.38) and low absorbance at a wavelength of 550 nm.

Magnesium fluoride is probably the most widely used thin-film material for optical coatings. Although its performance is not outstanding for all applications, it represents a significant improvement over an uncoated surface. At normal incidence, typical crown glass surfaces

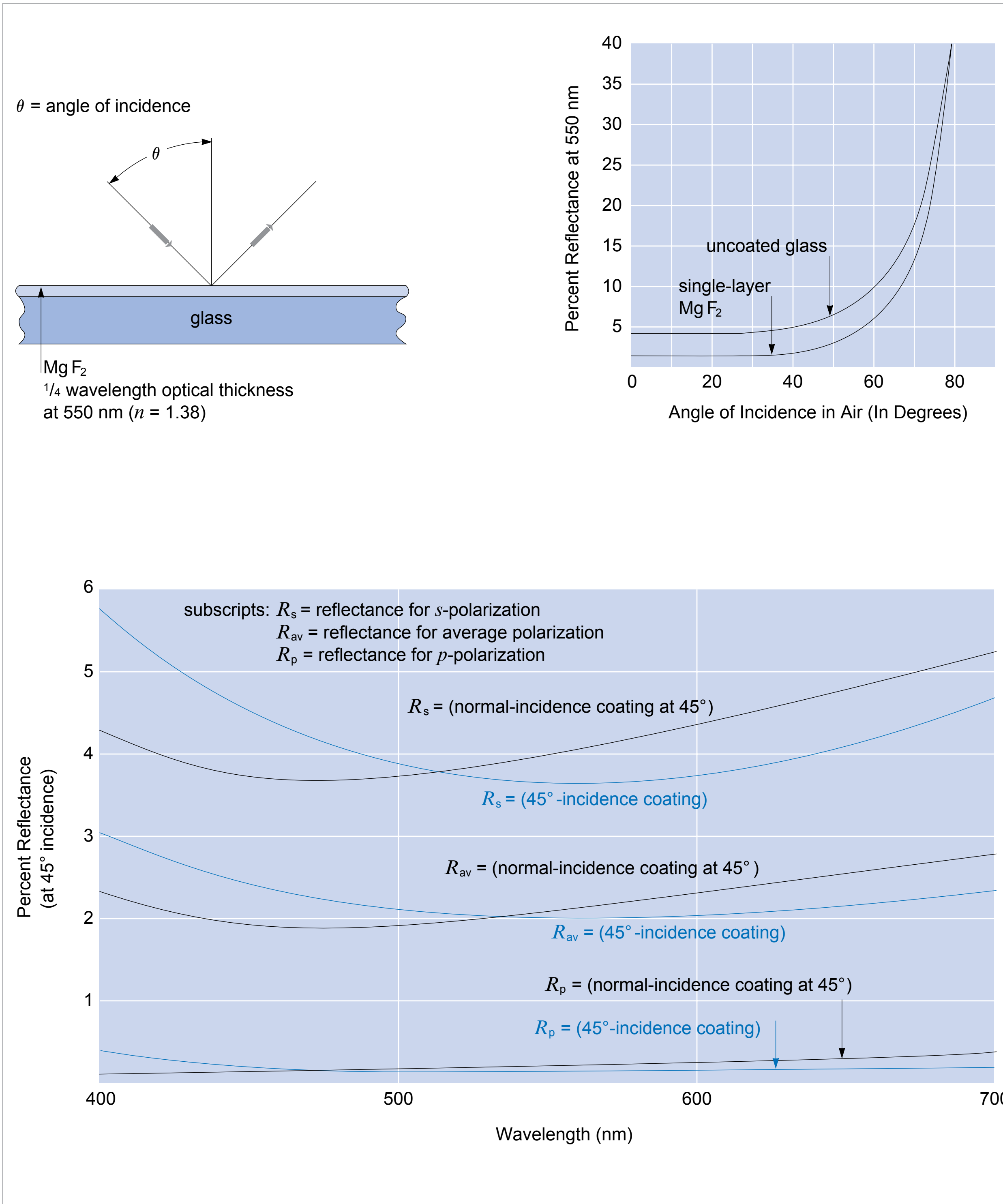


Figure 1.10 $MgF_2$ performance at 45° incidence on BK7 for a normal-incidence coating design and for a coating designed for 45° incidence (design wavelength: 550 nm)

reflect from 4 to 5% of visible light. A high-quality $MgF_2$ coating can reduce this value to 1.5%. For many applications this improvement is sufficient, and higher performance multilayer coatings are not necessary.

Single-layer quarter-wavelength coatings work extremely well over a wide range of wavelengths and angles of incidence even though the theoretical target of zero-percent reflectance applies only at normal incidence, and then only if the refractive index of the coating material is exactly the geometric mean of the indexes of the substrate and of air. In actual practice, the single layer quarter-wave $MgF_2$ coating makes its most significant contribution by improving the transmission of optical elements with steep surfaces where most rays are incident at large angles (see figure 1.10).

## ANGLE OF INCIDENCE

The optical path difference between the front and rear surface reflections of any thin-film layer is a function of angle. As the angle of incidence increases from zero (normal incidence), the optical path difference is increased. This change in optical path difference results in a change of phase difference between the two interfering reflections, which, in turn, causes a change in reflection.

## WAVELENGTH DEPENDENCE

With any thin film, reflectance and transmission depend on the wavelength of the incident light for two reasons. First, since each thin-film layer is carefully formed at a thickness of a quarter of the design wavelength for optimal single-wavelength performance, the coating is suboptimal at any other wavelength. Second, the indexes of refraction of the coating and substrate change as a function of wavelength (i.e., dispersion). Most up-to-date thin-film coating design optimization programs, such as those used by CVI Laser Optics, include the capability to account for material dispersion when calculating thin-film performance and monitoring the thin film deposition process.

## COATING FORMULAS

Because of the practical importance and wide usage of single-layer coatings, especially at oblique (non-normal) incidence angles, it is valuable to have formulas from which coating reflectance curves can be calculated as functions of wavelength, angle of incidence, and polarization.

## COATING DISPERSION FORMULA

The first step in evaluating the performance of a single-layer antireflection coating is to calculate (or measure) the refractive index of the film and substrate at the primary or center wavelength of interest. In our example, we will assume that the thin film may be considered to be homogeneous. The refractive index of crystalline $MgF_2$ is related to wavelength by the Lorentz-Lorenz formulas

$$n_o = 1.36957 + \frac{(3.5821)\,(10^{-3})}{(\lambda - 0.14925)} \quad (1.11)$$

$$n_e = 1.381 + \frac{(3.7415)\,(10^{-3})}{(\lambda - 0.14947)} \quad (1.12)$$

for the ordinary and extraordinary rays, respectively, where $\lambda$ is the wavelength in micrometers.
The index for the amorphous phase is the average of the crystalline indexes:

$$= n(\lambda) = \frac{1}{2}(n_o + n_e). \quad (1.13)$$

The value 1.38 is the universally accepted amorphous film index for $MgF_2$ at a wavelength of 550 nm, assuming a thin-film packing density of 100%. Real films tend to be slightly porous, reducing the net or actual refractive index from the theoretical value. Because it is a complex function of the manufacturing process, packing density itself varies slightly from batch to batch. Air and water vapor can also settle into the film and affect its refractive index. For CVI Laser Optics $MgF_2$ coatings, our tightly controlled procedures result in packing densities that yield refractive indexes that are within three percent of the theoretical value.

## COATED SURFACE REFLECTANCE AT NORMAL INCIDENCE

For a thin-film coating having an optical thickness of one-quarter wavelength for wavelength λ, let $n_a$ denote the refractive index of the external medium at that wavelength (1.0 for air or vacuum) and let $n_f$ and $n_s$, respectively, denote the film and substrate indexes, as shown in figure 1.11.

For normal incidence at wavelength λ, the single-pass reflectance of the coated surface can be shown to be

$$R = \left( \frac{n_a n_s - n_f^2}{n_a n_s + n_f^2} \right)^2 \quad (1.14)$$

regardless of the state of polarization of the incident radiation. The reflectance is plotted in figure 1.12 for various substrate types (various indexes of refraction).

## COATED SURFACE REFLECTANCE AT OBLIQUE INCIDENCE

At oblique incidence, the situation is more complex. Let $n_1$, $n_2$, and $n_3$, respectively, represent the wavelength-dependent refractive indexes of the external medium (air or vacuum), coating film, and substrate as shown in figure 1.13.

Assume that the coating exhibits a reflectance extremum of the first order for some wavelength $\lambda_d$ and angle of incidence $\theta_{1d}$ in the external medium. The coating is completely specified when $\theta_{1d}$ and $\lambda_d$ are known.

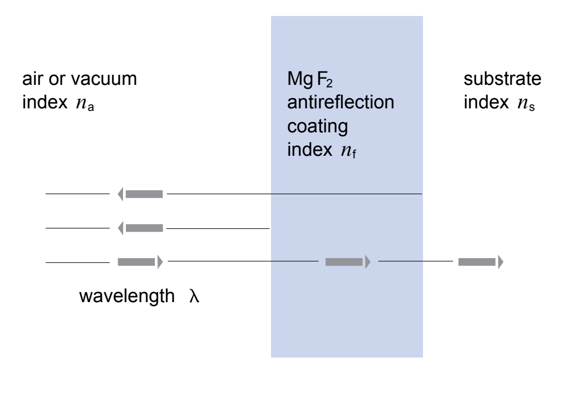


Figure 1.11 Reflectance at normal incidence

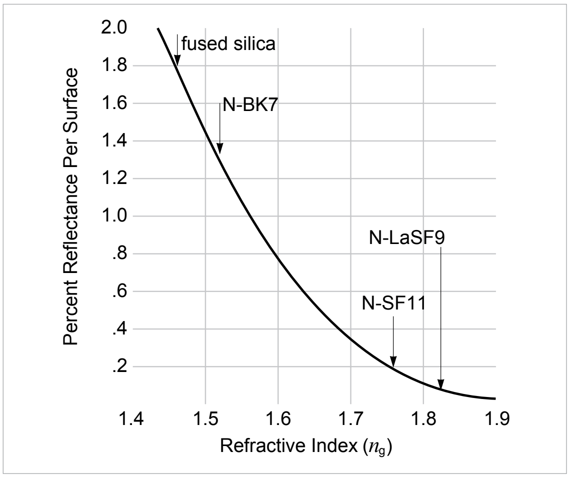


Figure 1.12 Reflectance at surface of substrate with index $n_g$ when coated with a quarter wavelength of magnesium fluoride (index n=1.38)

The extremum is a minimum if $n_2$ is less than $n_3$ and a maximum if $n_2$ exceeds $n_3$. The same formulas apply in either case. Corresponding to the angle of incidence in the external media $\theta_{1d}$ is the angle of refraction within the thin film:

$$\theta_{2d} = \arcsin\left( \frac{n_1(\lambda_d)\sin\theta_{1d}}{n_2(\lambda_d)} \right) . \quad (1.15)$$

As $\theta_1$ is reduced from $\theta_{1d}$ to zero, the reflectance extremum shifts in wavelength from $\lambda_d$ to $\lambda_n$, where the subscript n denotes normal incidence.
The wavelength is given by the equation

$$\lambda_n = \left( \frac{n_2(\lambda_n)}{n_2(\lambda_d)} \right) \left( \frac{\lambda_d}{\cos\theta_{2d}} \right) . \quad (1.16)$$

Corresponding to the arbitrary angle of incidence $\theta_1$ and arbitrary wavelength λ are angles of refraction in the coating and substrate, given by

$$\theta_2 = \arcsin\left( \frac{n_1(\lambda)\sin\theta_1}{n_2(\lambda)} \right) \quad (1.17)$$

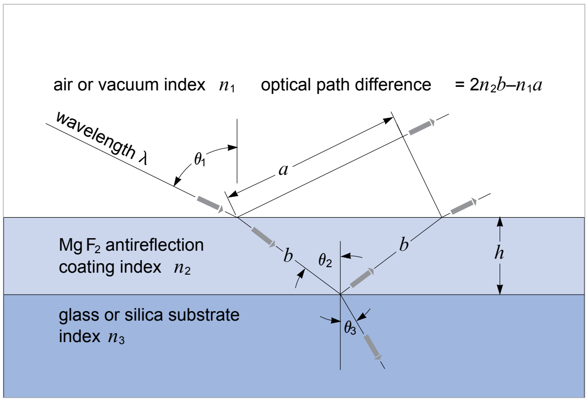


Figure 1.13 Reflectance at oblique incidence

and

$$\theta_3 = \arcsin\left(\frac{n_1(\lambda)\sin\theta_1}{n_3(\lambda)}\right) \qquad (1.18)$$

The following formulas depict the single-interface amplitude reflectance for both the *p*- and *s*-polarizations:

$$r_{12p} = \frac{n_2\cos\theta_1 - n_1\cos\theta_2}{n_2\cos\theta_1 + n_1\cos\theta_2} \qquad (1.19)$$

$$r_{23p} = \frac{n_3\cos\theta_2 - n_2\cos\theta_3}{n_3\cos\theta_2 + n_2\cos\theta_3} \qquad (1.20)$$

$$r_{12s} = \frac{n_1\cos\theta_1 - n_2\cos\theta_2}{n_1\cos\theta_1 + n_2\cos\theta_2} \qquad (1.21)$$

$$r_{23s} = \frac{n_2\cos\theta_2 - n_3\cos\theta_3}{n_2\cos\theta_2 + n_3\cos\theta_3}\ . \qquad (1.22)$$

The subscript "12p," for example, means that the formula gives the amplitude reflectance for the *p*-polarization at the interface between the first and second media.

The corresponding reflectance for the coated surface, accounting for both interfaces and the phase differences between the reflected waves, are given by

$$R_p = \frac{r_{12p}^2 + r_{23p}^2 + 2r_{12p}r_{23p}\cos(2\beta)}{1 + r_{12p}^2 r_{23p}^2 + 2r_{12p}r_{23p}\cos(2\beta)} \qquad (1.23)$$

$$R_s = \frac{r_{12s}^2 + r_{23s}^2 + 2r_{12s}r_{23s}\cos(2\beta)}{1 + r_{12s}^2 r_{23s}^2 + 2r_{12s}r_{23s}\cos(2\beta)} \qquad (1.24)$$

Where β (in radians) is the phase difference in the external medium between waves reflected from the first and second surfaces of the coating

$$\beta = \frac{2\pi}{\lambda} n_2(\lambda) h \cos\theta_2\ . \qquad (1.25)$$

The average reflectance is given by

$$\bar{R} = \frac{1}{2}(R_p + R_s) \qquad (1.26)$$

By applying these formulas, reflectance curves can be calculated as functions of either wavelength λ or angle of incidence $\theta_1$.

# MULTILAYER ANTIREFLECTION COATINGS

Previously, we discussed the basic equations of thin-film design and their application to a simple magnesium fluoride antireflection coating. It is also useful to understand the operation of multilayer coatings. While it is beyond the scope of this chapter to cover all aspects of modern multilayer thin-film design, it is hoped that this section will provide the reader with insight into thin films that will be useful when considering system designs and specifying cost-effective real-world optical coatings.

Two basic types of antireflection coating are worth examining in detail: the quarter/quarter coating and the multilayer broadband coating.

## THE QUARTER/QUARTER COATING

This coating is used as an alternative to the single-layer antireflection coating. It was developed because of the lack of available materials with the indexes of refraction needed to improve the performance of single-layer coatings. The basic problem associated with single-layer antireflection coatings is that the refractive index of the coating material is generally too high, resulting in too strong a reflection from the first surface which cannot be completely canceled through destructive interference with the weaker reflection from the substrate's top or first surface. In a two-layer coating, the first reflection is canceled through destructive interference with two weaker out-of-phase reflections from underlying surfaces. A quarter/quarter coating consists of two layers, both of which have an optical thickness of a quarter wave at the wavelength of interest. The outer layer is made of a low-refractive-index material, and the inner layer is made of a high-refractive-index material (compared to the substrate). As illustrated in figure 1.14, the second and third reflections are both exactly 180° out of phase with the first reflection.

Multilayer coating performance is calculated in terms of relative amplitudes and phases, which are summed to give the overall (net) amplitude of the reflected beam. The overall amplitude is then squared to give the intensity. If one knows the reflected light intensity goal, how does one calculate the required refractive index of the inner layer? Several methodologies have been developed over the last 40 to 50 years to calculate thin-film coating properties and converge on optimum designs. The field has been revolutionized in recent years through the availability of powerful PC's and efficient application-specific thin-film-design software programs.

When considering a two-layer quarter/quarter coating optimized for one wavelength at normal incidence, the required refractive indexes for minimum reflectivity can be calculated easily by using the following equation:

$$\frac{n_1^2 n_3}{n_2^2} = n_0 \qquad (1.27)$$

where $n_0$ is the refractive index of air (approximated as 1.0), $n_3$ is the refractive index of the substrate material, and $n_1$ and $n_2$ are the refractive indices of the two film materials, as indicated in figure 1.14.

If the substrate is crown glass with a refractive index of 1.52 and if the first layer is the lowest possible refractive index, 1.38 ($MgF_2$), the refractive index of the high-index layer needs to be 1.70. Either beryllium oxide or magnesium oxide could be used for the inner layer, but both are soft materials and will not produce very durable coatings. Although it allows some freedom in the choice of coating materials and can give very low reflectance, the quarter/quarter coating is constrained in its design owing to the lack of materials with suitable refractive index and physical or durability properties. In principle, it is possible to deposit two materials simultaneously to achieve layers of almost any required refractive index, but such coatings are not very practical. As a consequence, thin-film engineers have developed multilayer and special two-layer antireflection coatings that allow the refractive index of each layer and, therefore, coating performance to be optimized.

## TWO-LAYER COATINGS OF ARBITRARY THICKNESS

Optical interference effects can be characterized as either constructive or destructive interference, where the phase shift between interfering wavefronts is 0° or 180° respectively. For two wavefronts to completely cancel each other, as in a single-layer antireflection coating, a phase shift of exactly 180° is required. Where three or more reflecting surfaces are involved, complete

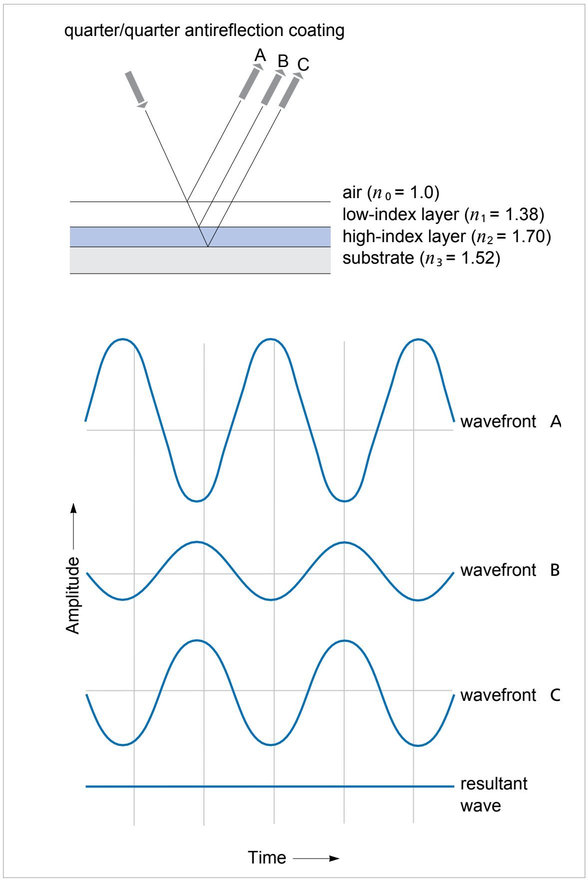


Figure 1.14 Interference in a typical quarter/quarter coating

cancellation can be achieved by carefully choosing the relative phase and intensity of the interfering beams (i.e., optimizing the relative optical thicknesses). This is the basis of a two-layer antireflection coating, where the layers are adjusted to suit the refractive index of available materials, instead of vice versa. For a given combination of materials, there are usually two combinations of layer thicknesses that will give zero reflectance at the design wavelength. These two combinations are of different overall thickness. For any type of thin-film coating, the thinnest possible overall coating is used because it will have better mechanical properties (less stress). A thinner combination is also less wavelength sensitive.

Two-layer antireflection coatings are the simplest of the so-called V-coatings. The term V-coating arises from the shape of the reflectance curve as a function of wavelength, as shown in figure 1.15, which resembles a skewed V shape with a reflectance minimum at the design wavelength.

V-coatings are very popular, economical coatings for near monochromatic applications, such as optical systems using nontunable laser radiation (e.g., helium neon lasers at 632.8 nm).

## BROADBAND ANTIREFLECTION COATINGS

Many optical systems (particularly imaging systems) use polychromatic (more than one wavelength) light. In order for the system to have a flat response over an extended spectral region, transmitting optics are coated with a dichroic broadband antireflection coating. The main technique used in designing antireflection coatings that are highly efficient at more than one wavelength is to use "absentee" layers within the coating. Additional techniques can be used for shaping the performance curves of high reflectance coatings and wavelength-selective filters, but these are not applicable to antireflection coatings.

## ABSENTEE LAYERS

An absentee layer is a film of dielectric material that does not change the performance of the overall coating at one particular wavelength. Usually that particular wavelength is the wavelength for which the coating is being optimized. The absentee layer is designed to have an optical thickness of a half wave at that specific wavelength. The "extra" reflections cancel out at the two interfaces because no additional phase shifts are introduced. In theory, the performance of the coating is the same at that specific design wavelength whether or not the absentee layer is present.

At other wavelengths, the absentee layer starts to have an effect for two reasons: the ratio between physical thickness of the layer and the wavelength of light changes with wavelength, and the dispersion of the coating material causes optical thickness to change with wavelength. These effects give the designer extra degrees of freedom not offered by simpler designs. The complex, computerized, multilayer antireflection coating design techniques used by CVI Laser Optics are based on the simple principles of interference and phase shifts described in the preceding text. Because of the properties of coherent interference, it is meaningless to consider individual layers in a multilayer coating. Each layer is influenced by the optical properties of the


Figure 1.15 Characteristic performance curve of a V-coating

other layers in the multilayer stack. A complex series of matrix multiplications, in which each matrix corresponds to a single layer, is used to mathematically model the performance of multilayer thin-film coatings

There also are multiple reflections within each layer of a coating. In the previous discussions, only first-order or primary reflections were considered. This oversimplified approach is unable to predict accurately the true behavior of multilayer coatings. Second-, third-, and higher-order terms must be considered if real coating behavior is to be modeled accurately.

## HIGH-REFLECTION COATINGS

High-reflection coatings can be applied to the outside of a component, such as a flat piece of glass, to produce a first-surface mirror. Alternately, they can be applied to an internal surface to produce a second-surface mirror, which is used to construct certain prisms.

High-reflection coatings can be classified as either dielectric or metallic coatings.

### DIELECTRIC COATINGS

High-reflectance dielectric coatings are based upon the same principles as dielectric antireflection coatings. Quarter-wave thicknesses of alternately high- and low-refractive-index materials are applied to the substrate to form a dielectric multilayer stack, as shown in figure 1.16. By choosing materials of appropriate refractive indexes, the various reflected wavefronts can be made to interfere constructively to produce a highly efficient reflector.

The peak reflectance value is dependent upon the ratio of the refractive indices of the two materials, as well as the number of layer pairs. Increasing either increases the reflectance. The width of the reflectance curve (as a function of wavelength) is also determined by the films' refractive index ratio. The larger the ratio is, the wider the high-reflectance region will be.

Over limited wavelength intervals, the reflectance of a dielectric coating easily can be made to exceed the highest reflectance of a metallic coating. Furthermore,

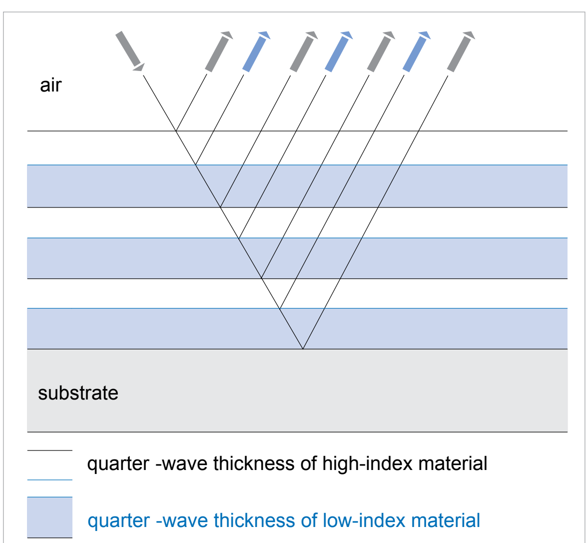


Figure 1.16 A simple quarter-wave stack

the coatings are effective for both $s$- and $p$-polarization components, and can be designed for a wide angle of incidence range. However, at angles that are significantly distant from the design angle, reflectance is markedly reduced.

### PERFORMANCE CURVE

The reflection versus wavelength performance curve of a single dielectric stack has the characteristic flat-topped, inverted-V shape shown in figure 1.17. Clearly, reflectance is a maximum at the wavelength for which both the high- and low-index layers of the multilayer are exactly one-quarter-wave thick.

Outside the fairly narrow region of high reflectance, the reflectance slowly reduces toward zero in an oscillatory fashion. The width and height (i.e., peak reflectance) of the high-reflectance region are functions of the refractive-index ratio of the two materials used and the number of layers actually included in the stack. The peak reflectance can be increased by adding more layers, or by using materials with a higher refractive index ratio. Amplitude reflectivity at a single interface is given by

$$\frac{(1-p)}{(1+p)}$$

where (1.28)

$$p=\left(\frac{n_H}{n_L}\right)^{N-1}\times\frac{n_H^2}{n_S},$$

where $n_S$ is the index of the substrate and $n_H$ and $n_L$ are the indices of the high- and low-index layers. $N$ is the total number of layers in the stack. The width of the high-reflectance part of the curve (versus wavelength) is also determined by the film index ratio. The higher the ratio is, the wider the high-reflectance region will be.

### SCATTERING

The main parameters used to describe the performance of a thin film are reflectance and transmittance plus absorptance, where applicable. Another less well-defined parameter is scattering. This is hard to define because of the inherently granular properties of the materials used in the films. Granularity causes some of the incident light to be lost by diffraction effects. Often it is scattering, not mechanical stress and weakness in the coating, that limits the maximum practical thickness of an optical coating.

## BROADBAND COATINGS

In contrast to antireflection coatings, the inherent shape of a high-reflectance coating can be modified in several different ways. The two most effective ways of modifying a performance curve are to use two or more stacks centered at slightly shifted design wavelengths or to fine-tune the layer thicknesses within a stack.

There is a subtle difference between multilayer antireflection coatings and multilayer high-reflection coatings, which allows the performance curves of the latter to be modified by using layer thicknesses designed for different wavelengths within a single coating. Consider a multilayer coating consisting of pairs, or stacks of layers, that are optimized for different wavelengths. At any given wavelength, providing at least one of the layers is highly reflective for that wavelength, the overall coating will be highly reflective at that wavelength. Whether the other components transmit or are partially reflective at that wavelength is immaterial. Transmission of light of that wavelength will be blocked by reflection of one of the layers.

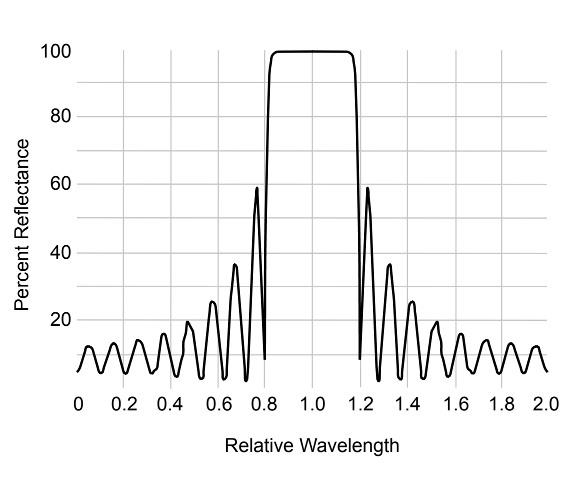


Figure 1.17 Typical reflectance curve of an unmodified quarter-wave stack

On the other hand, in an antireflection coating, even if one of the stacks is exactly antireflective at a certain wavelength, the overall coating may still be quite reflective because of reflections by the other components (see figure 1.18).

This can be summarized by an empirical rule. At any wavelength, the reflection of a multilayer coating consisting of several discrete components will be at least that of the most reflective component. Exceptions to this rule are coatings that have been designed to produce interference effects involving not just the surfaces within the two-layer or multilayer component stack, but also between the stacks themselves. Obvious examples are narrowband interference filters.

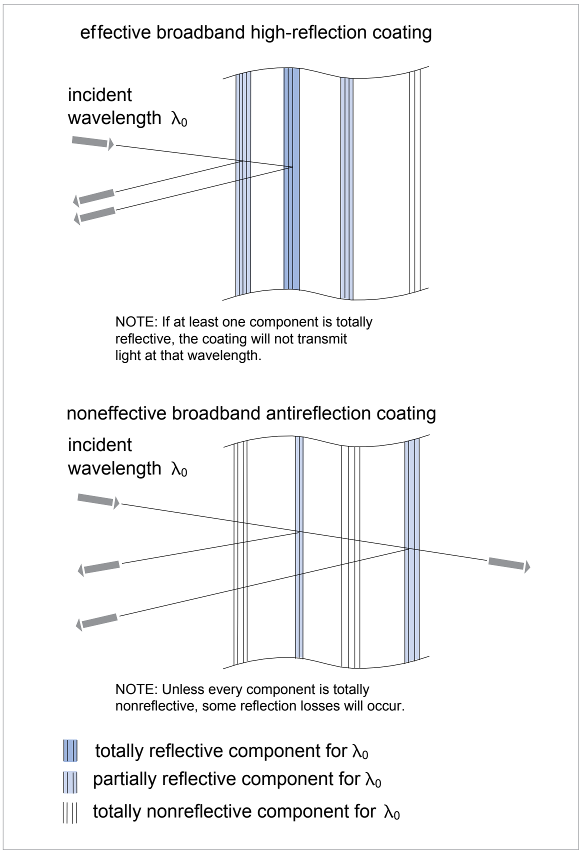


Figure 1.18 Schematic multicomponent coatings with only one component exactly matched to the incident wavelength, $\lambda$. The high-reflection coating is successful; the antireflection coating is not.

## BROADBAND REFLECTION COATINGS

The design procedure for a broadband reflection coating should now be apparent. Two design techniques are used. The most obvious approach is to use two quarter-wave stacks with their maximum reflectance wavelengths separated on either side of the design wavelength. This type of coating, however, tends to be too thick and often has poor scattering characteristics. This basic design is very useful for dichroic high reflectors, where the peak reflectances of two stacks are at different wavelengths.

A more elegant approach to broadband dielectric coatings involves using a single modified quarter-wave stack in which the layers are not all the same optical thickness. Instead, they are graded between the quarter-wave thickness for two wavelengths at either end of the intended broadband performance region. The optical thicknesses of the individual layers are usually chosen to follow a simple arithmetic or geometric progression. By using designs of this type, multilayer, broadband coatings with reflectance in excess of 99% over several hundred nanometers are possible. In many scanning dye laser systems, high reflectance over a large wavelength region is absolutely essential. In many non-laser instruments, all-dielectric coatings are favored over metallic coatings because of their high reflectance. Multilayer broadband coatings are available with high-reflectance regions spanning almost the entire visible spectrum.

## POLARIZATION EFFECTS

When light is incident on any optical surface at angles other than normal incidence, there is always a difference in the reflection/transmission behavior of *s*- and *p*-polarization components. In some instances, this difference can be made extremely small. On the other hand, it is sometimes advantageous to design a thin-film coating that maximizes this effect (e.g., thin-film polarizers). Polarization effects are not normally considered for antireflection coatings because they are nearly always used at normal incidence where the two polarization components are equivalent.

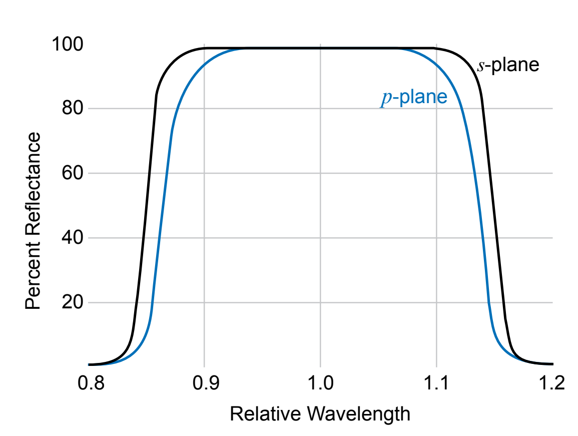


Figure 1.19 The s-polarization reflectance curve is always broader and higher than the p-polarization reflectance curve

High-reflectance or partially reflecting coatings are frequently used at oblique angles, particularly at 45°, for beam steering or beam splitting. Polarization effects can therefore be quite important with these types of coating.

At certain wavelengths, a multilayer dielectric coating shows a remarkable difference in its reflectance of the *s*- and *p*-polarization components (see figure 1.19). The basis for the effect is the difference in effective refractive index of the layers of film for *s*- and *p*-components of the incident beam, as the angle of incidence is increased from the normal. This effect should not be confused with the phenomenon of birefringence in certain crystalline materials, most notably calcite. Unlike birefringence, it does not require the symmetric properties of a crystalline phase. It arises from the difference in magnitude of magnetic and electric field vectors for *s*- and *p*-components of an electromagnetic wave upon reflection at oblique incidence. Maximum *s*-polarization reflectance is always greater than the maximum *p*-polarization reflectance at oblique incidence. If the reflectance is plotted as a function of wavelength for some arbitrary incidence angle, the *s*-polarization high reflectance peak always extends over a broader wavelength region than the *p*-polarization peak. Many dielectric coatings are used at peak reflectance wavelengths where polarization differences can be made negligible. In some cases, the polarization differences can be put to good use. The "edge" region of the reflectance curve is a wavelength region in which the *s*-polarization reflectance is much higher than the *p*-polarization reflectance. This can be maximized in a design to produce a very efficient thin-film polarizer.

## INTERFERENCE FILTERS

In many applications, particularly those in the field of resonance atomic or molecular spectroscopy, a filtering system is required that transmits only a very narrow range of wavelengths of incident light. For particularly high-resolution applications, monochromators may be used, but these have very poor throughputs. In instances where moderate resolution is required and where the desired region(s) is (are) fixed, interference filters should be used.

An interference filter is produced by applying a complex multilayer coating to a glass blank. The complex coating consists of a series of broadband quarter-wave stacks, which act as a very thin, multiple-cavity Fabry-Perot interferometer. Colored-glass substrates can be used to absorb unwanted light. Figure 1.20 shows the transmission curve of a typical CVI Laser Optics interference filter, the 550nm filter from the visible-40 filter set. Notice the notch shape of the transmission curve, which dies away very quickly outside the high-transmission (low-reflectance) region.

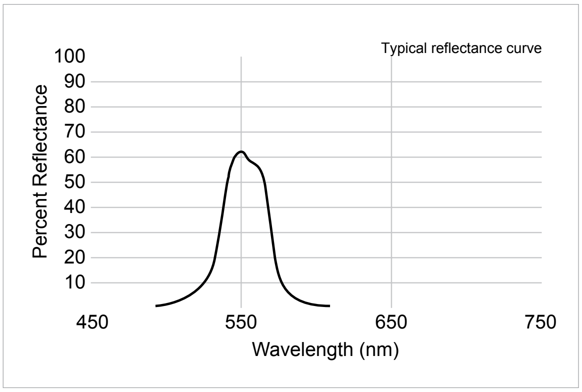


Figure 1.20 Spectral performance of an interference filter

## PARTIALLY TRANSMITTING COATINGS

In many applications, it is desirable to split a beam of light into two components with a selectable intensity ratio. This is performed by inserting an optical surface at an oblique angle (usually 45°) to separate reflected and transmitted components. In most cases, a multilayer coating is applied to the surface in order to modify intensity and polarization characteristics of the two beams.

An alternative to the outdated metallic beamsplitter is a broadband (or narrowband) multilayer dielectric stack with a limited number of pairs of layers, which transmits a fixed amount of the incident light. Just as in the case of metallic beamsplitter coatings, the ratio of reflected and transmitted beams depends on the angle of incidence. Unlike a metallic coating, a high-quality film will introduce negligible losses by either absorption or scattering. There are, however, two drawbacks to dielectric beamsplitters. The performance of these coatings is more wavelength sensitive than that of metallic coatings, and the ratio of transmitted and reflected intensities may be quite different for the *s*- and *p*-polarization components of the incident beam. In polarizers, this can be used to advantage. The difference in partial polarization of the reflected and transmitted beams is not important, particularly when polarized lasers are used. In beamsplitters, this is usually a drawback. A hybrid metal-dielectric coating is often the best compromise.

CVI Laser Optics produces coated beamsplitters with designs ranging from broadband performance without polarization compensation, to broadband with some compensation for polarization, to a range of cube beamsplitters that are virtually nonpolarizing at certain laser wavelengths. These nonpolarizing beamsplitters offer unparalleled performance with the reflected *s*- and *p*-components matched to better than 5%.

## METALLIC COATINGS

Metallic coatings are used primarily for mirrors and are not classified as thin films in the strictest sense. They do not rely on the principles of optical interference, but rather on the physical and optical properties of the coating material. However, metallic coatings are often overcoated with thin dielectric films to increase the reflectance over a desired range of wavelengths or range of incidence angles. In these cases, the metallic coating is said to be "enhanced."

Overcoating metallic coatings with a hard, single, dielectric layer of halfwave optical thickness improves abrasion and tarnish resistance but only marginally affects optical properties. Depending on the dielectric used, such overcoated metals are referred to as durable, protected, or hardcoated metallic reflectors.

The main advantages of metallic coatings are broadband spectral performance, insensitivity to angle of incidence and polarization, and low cost. Their primary disadvantages include lower durability, lower reflectance, and lower damage threshold.

# LASER-INDUCED DAMAGE

CVI Laser Optics regularly conducts laser-induced damage testing of our optics. Although our damage thresholds do not constitute a performance guarantee, they are representative of the expected damage resistance of our coatings. Occasionally, in the damage threshold specifications, a reference is made to another coating because a suitable high-power laser is not available to test the coating within its design wavelength range. The damage threshold of the referenced coating should be an accurate representation of the coating in question.

For each damage threshold specification, the information typically provided is peak fluence energy (in units of energy per square centimeter), pulse width, peak irradiance (in power per square centimeter), and test wavelength. The peak fluence is the total energy per pulse, the pulse width is the full width at half maximum (FWHM), the peak irradiance is the energy of each pulse divided by the effective pulse length, which is approximately 12.5 to 25 percent longer than the pulse FWHM, and the test wavelength is the wavelength of the laser used to incur damage on the test optic, respectively. Tests are typically performed at a repetition rate of 10Hz for 10 seconds at each test site along the same coated optical surface. This is important because longer durations can cause damage at lower fluence levels, even at the same repetition rate.

The damage resistance of any coating depends on the substrate (i.e. material, surface quality, bulk material properties, etc.), wavelength, and pulse duration. Improper handling and cleaning can also reduce the damage resistance of a coating, as can the environment in which the optic is used. These damage threshold values are presented as guidelines and no warranty is implied. When choosing a coating for its power-handling capabilities, some simple guidelines can be followed to assist in the decision making process as follows:

1. Higher damage thresholds are usually seen using Fused Silica as opposed to N-BK7
2. Dielectric coatings will perform better than metallic coatings
    - Broadband dielectric coatings will typically perform worse than coatings optimized for a laser line
    - Coating Materials play a large role in determining expected LDT, thus different wavelengths will perform better than others though similar in function
3. Contamination on top of the coating or between the coating and substrate surface will affect
4. Optics with worse scratch-dig specification will be more susceptible to laser damage

## OEM AND SPECIAL COATINGS

CVI Laser Optics maintains advanced coating capabilities. In the last few years, CVI Laser Optics has expanded and improved these coating facilities to take advantage of the latest developments in thin-film technology. The resulting operations can provide high-volume coatings at competitive prices to OEM customers, as well as specialized, high-performance coatings for the most demanding user. The most important aspect of our coating capabilities is our expert design and manufacturing staff. This group blends years of practical experience with recent academic research knowledge. With a thorough understanding of both design and production issues, CVI Laser Optics excels at producing repeatable, high-quality coatings at competitive prices.

### USER-SUPPLIED SUBSTRATES

CVI Laser Optics not only coats catalog and custom optics with standard and special coatings but also applies these coatings to user-supplied substrates. A portion of our coating business involves applying standard or slightly modified catalog coatings to special substrates.

### HIGH VOLUME

The high-volume output capabilities of the CVI Laser Optics coating departments result in very competitive pricing for large-volume special orders. Even the small-order customer benefits from this large volume. Small quantities of special substrates can be cost-effectively coated with popular catalog coatings during routine production runs.

### CUSTOM DESIGNS

A large portion of the work done at the CVI Laser Optics coating facilities involves special coatings designed and manufactured to customer specifications. These designs cover a wide range of wavelengths, from the deep ultraviolet to infrared, and applications ranging from basic research through the design and manufacture of industrial, semiconductor, and medical products. A common special coating request is for modified catalog coatings, which usually involve a simple shift in the design wavelength.

### TECHNICAL SUPPORT

Expert CVI Laser Optics applications engineers are available to discuss your system requirements. Often a simple modification to a system design can enable catalog components or coatings to be substituted for special designs at a reduced cost, without affecting performance.