Optical Coatings

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Optical Coatings

The vast majority of optical components are made of various types of glass, and the majority of those components 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 to 5 percent of incident light is reflected at each surface. Consequently, for designs using more than a few components, losses in transmitted light level 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 percent 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 to the optical surface). 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 for minimal overall thickness to reduce mechanical stresses that might distort the optical surfaces or cause detrimental polarization effects. The most resilient materials should be used. Great care must be taken in coating fabrication to produce high-quality, nongranular, even layers.

CVI Melles Griot is a leading supplier of precision optical components and multielement optical systems. It would not have been possible to achieve our market-leading position without 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 Melles Griot 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 Melles Griot continually monitors and incorporates new technology and equipment to be able to offer our customers the most advanced coatings available.

The CVI Melles Griot 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 SYRUS*pro* 1100™, CVI Melles Griot 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 Melles Griot to discuss your requirements with one of our qualified applications engineers.

SYRUSpro™ coater

The Reflection of Light

REFLECTIONS AT UNCOATED SURFACES

Whenever light is incident on the boundary between two media, some light is reflected and some is transmitted (undergoing refraction) into the second medium. 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 (θ_1) equals the angle of reflection (θ_r). This is illustrated in figure 5.1, which shows reflection of a light ray at a simple air/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

$$\frac{(1-p)}{(1+p)} \qquad (5.1)$$

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

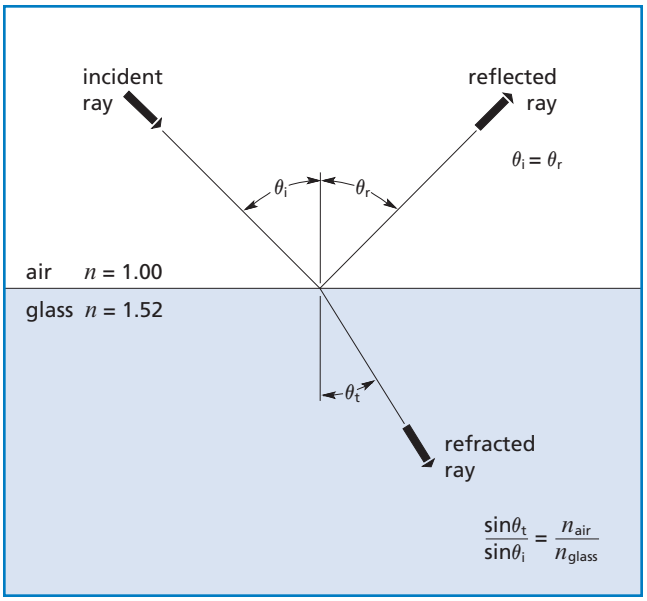


Figure 5.1 **Reflection and refraction at a simple air/glass interface**

The greater the disparity between the two refractive indexes, the greater the reflection. For an air/glass interface, with glass having a refractive index of 1.5, the intensity of the reflected light will be 4 percent of the incident light. For an optical system containing ten such surfaces, the transmitted beam will be attenuated to approximately 66 percent 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/glass or air/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/air interface, or flint glass in the case of a flint/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:

$$r_s = \left[\frac{\sin(\theta_1-\theta_2)}{\sin(\theta_1+\theta_2)}\right]^2 \qquad (5.2)$$

$$r_p = \left[\frac{\tan(\theta_1-\theta_2)}{\tan(\theta_1+\theta_2)}\right]^2. \qquad (5.3)$$

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

$$r = \left(\frac{n-1}{n+1}\right)^2. \qquad (5.4)$$

It can easily be seen that, for a refractive index of 1.52 (crown glass), this gives a reflectance of 4 percent. This important result reaffirms that, in general, 4 percent 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 5.2.

It can be seen that the reflectance remains close to 4 percent over about 25 degrees incidence, and that it rises rapidly to nearly 100 percent at grazing incidence. In addition, note that the p-component vanishes at 56° 39′.

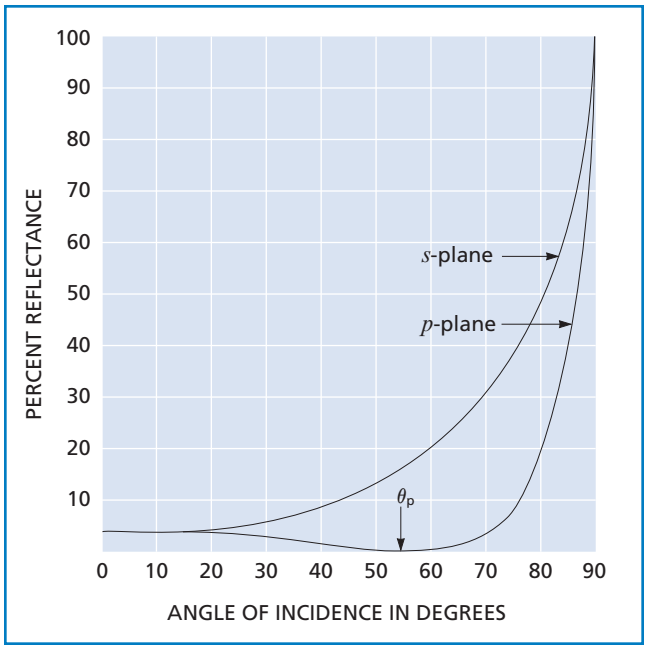


Figure 5.2 **External reflection at a glass surface ($n = 1.52$) showing *s*- and *p*-polarized components**

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 5.3.

This leads to the expression for Brewster's angle, θ_B:

$$\theta_1 = \theta_B = \arctan(n_2 / n_1) \quad . \tag{5.5}$$

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 percent.

INTERNAL REFLECTION AT A 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 5.4.

The angle at which the emerging refracted ray is at grazing incidence is called the critical angle (see figure 5.5). For an external medium of air or vacuum ($n = 1$), the critical angle is given by

$$\theta_c(\lambda) = \arcsin\left(\frac{1}{n(\lambda)}\right) \tag{5.6}$$

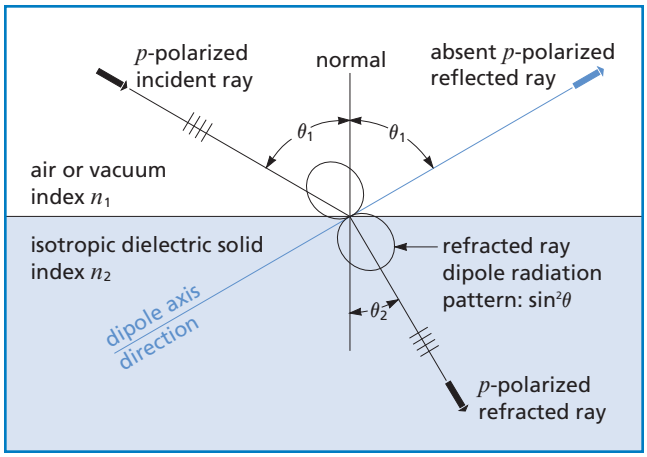


Figure 5.3 **Brewster's angle: at this angle, the *p*-polarized component is completely absent in the reflected ray**

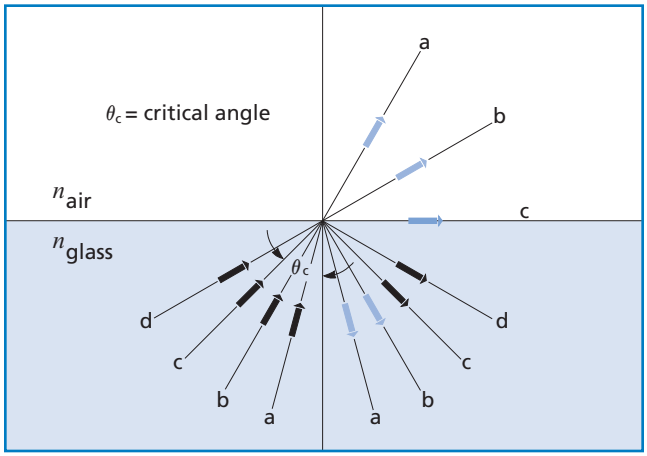


Figure 5.4 **Internal reflection at a glass surface ($n = 1.52$) showing *s*- and *p*-polarized components**

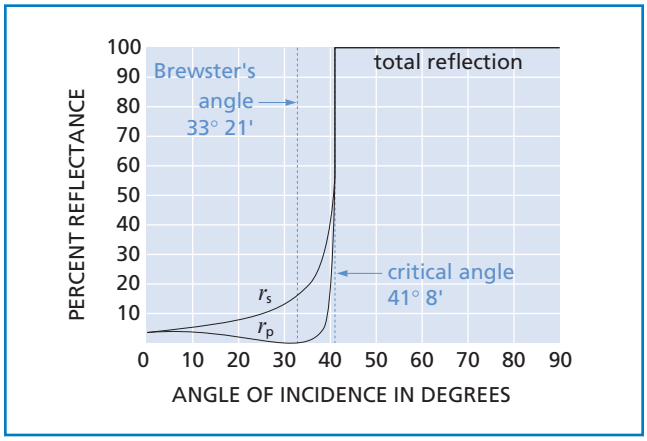


Figure 5.5 **Critical angle: at this angle, the emerging ray is at grazing incidence**

and depends on the refractive index n_λ, 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-degree 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 5.6.

Light waves that are exactly out of phase with one another (by 180 degrees or π 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.

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.

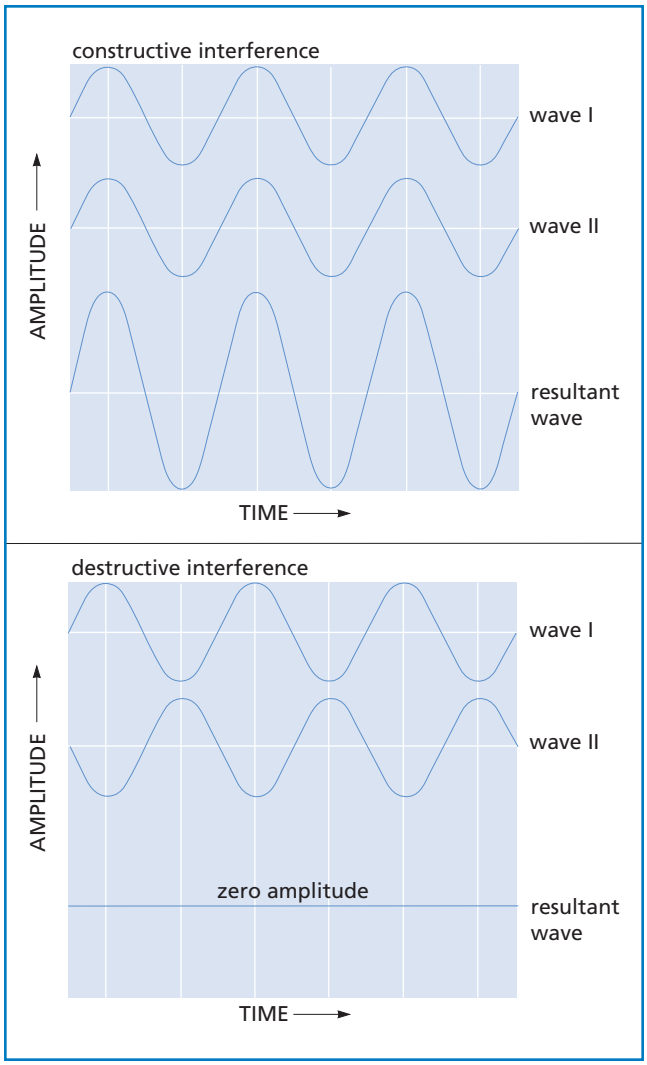
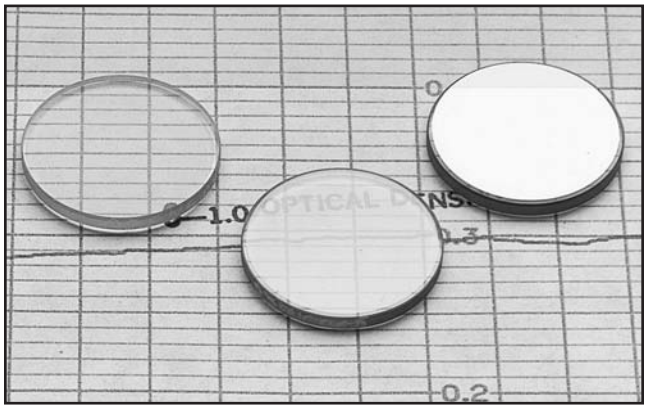


Figure 5.6 **A simple representation of constructive and destructive wave interference**



CVI Melles Griot offers a variety of single- and multiple-layer 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 of light will be reflected at the rear surface, as shown in figure 5.7. 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 5.8). 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:

$$n = \frac{c_{\text{vacuum}}}{c_{\text{medium}}}. \qquad (5.7)$$

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 λ 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 π 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.

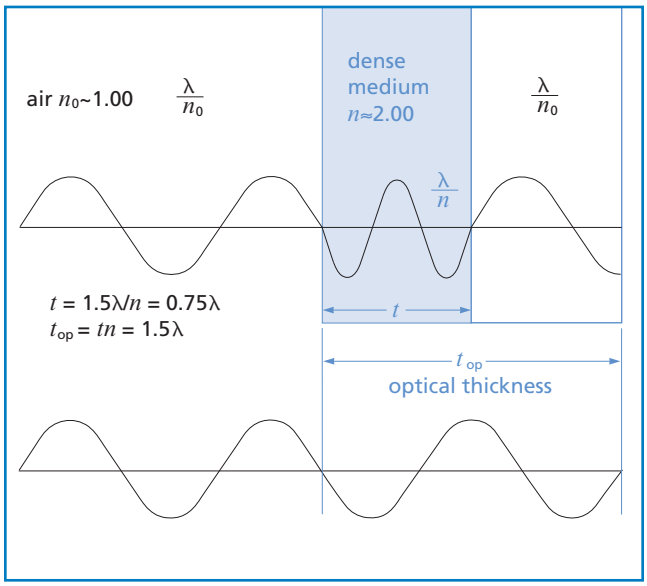


Figure 5.7 **Front and back surface reflections for a thin film at near-normal incidence**

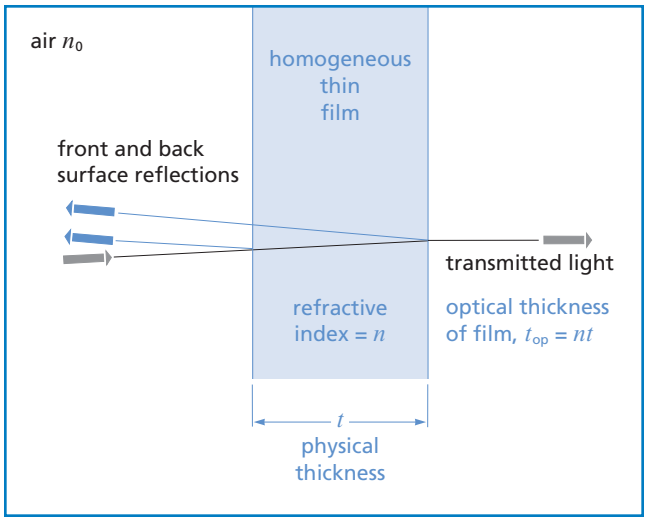


Figure 5.8 **A schematic diagram showing the effects of lower light velocity in a dense medium (in this example, the velocity of light is halved in the dense medium $n = n/n_0$, and the optical thickness of the medium is 2 × the real thickness)**

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 2π), then the reflected intensity will be a maximum, and the transmitted beam will be reduced accordingly.

Spectrophotometry used to measure the spectral performance of thin-film coating designs

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 degrees (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 5.9. 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-degree phase shift, $2tn_c = N\lambda/2$ and $tn_c = N\lambda/4$ where $N = 1, 3, 5 \ldots$

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

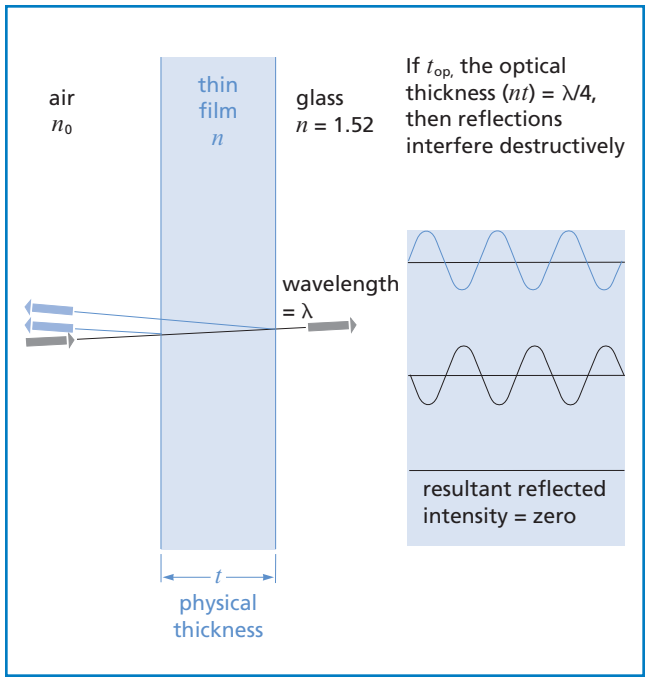


Figure 5.9 **Schematic representation of a single-layer antireflection coating**

REFRACTIVE INDEX

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

$$\left(\frac{1-p}{1+p}\right)^2 \times \text{the incident intensity} \qquad (5.8)$$

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

$$\frac{n_{air}}{n_{film}} = \frac{n_{film}}{n_{substrate}} \quad . \qquad (5.9)$$

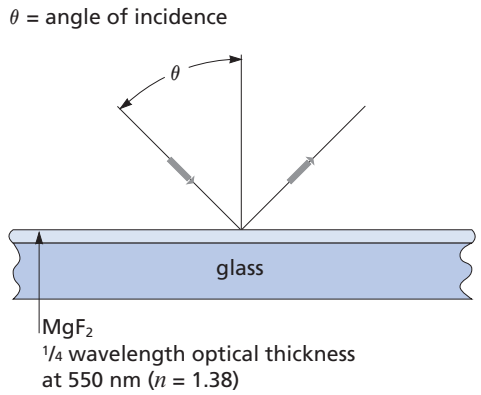
Since the refractive index of air is 1.0, the thin antireflection film ideally should have a refractive index of

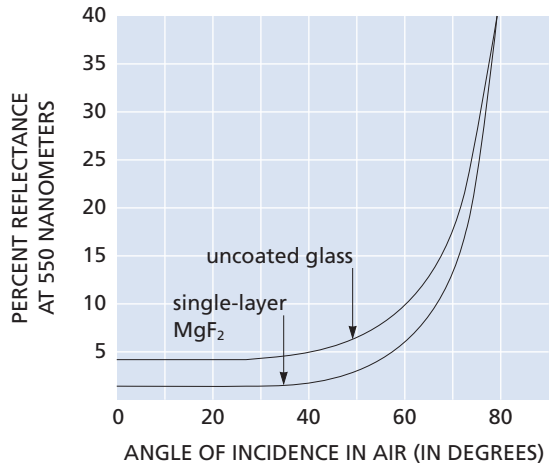
$$n_{film} = \sqrt{n_{substrate}} \quad . \qquad (5.10)$$

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 reflect from 4 to 5 percent of visible light. A high-quality MgF_2 coating can reduce this value to 1.5 percent. 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 5.10).





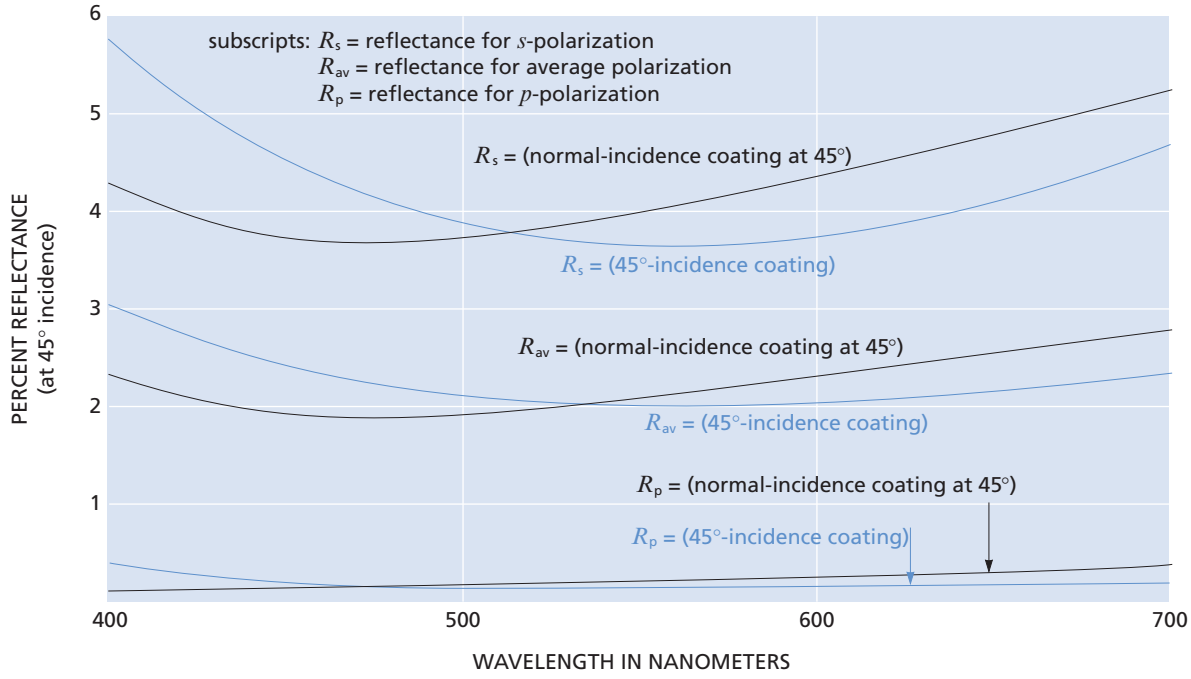


Figure 5.10 **MgF_2 performance at 45° incidence on BK7 for a normal-incidence coating design and for a coating designed for 45° incidence (design wavelength: 550 nm)**

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 Melles Griot, 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

$$n_o = 1.36957 + \frac{(3.5821)\ (10^{-3})}{(\lambda - 0.14925)} \qquad (5.11)$$

$$n_e = 1.381 + \frac{(3.7415)\ (10^{-3})}{(\lambda - 0.14947)} \qquad (5.12)$$

for the ordinary and extraordinary rays, respectively, where λ is the wavelength in micrometers.

The index for the amorphous phase is the average of the crystalline indexes:

$$n = n(\lambda) = \frac{1}{2}(n_o + n_e). \qquad (5.13)$$

The value 1.38 is the universally accepted amorphous film index for MgF_2 at a wavelength of 550 nanometers, assuming a thin-film packing density of 100 percent. 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 Melles Griot 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 5.11.

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

$$R = \left(\frac{n_a n_s - n_f^2}{n_a n_s + n_f^2} \right)^2 \qquad (5.14)$$

regardless of the state of polarization of the incident radiation. The reflectance is plotted in figure 5.12 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 5.13.

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

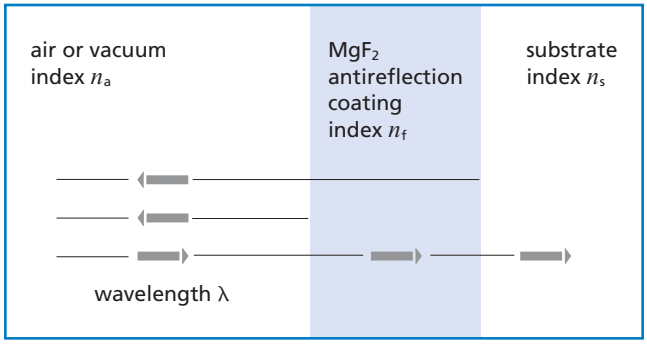


Figure 5.11 **Reflectance at normal incidence**

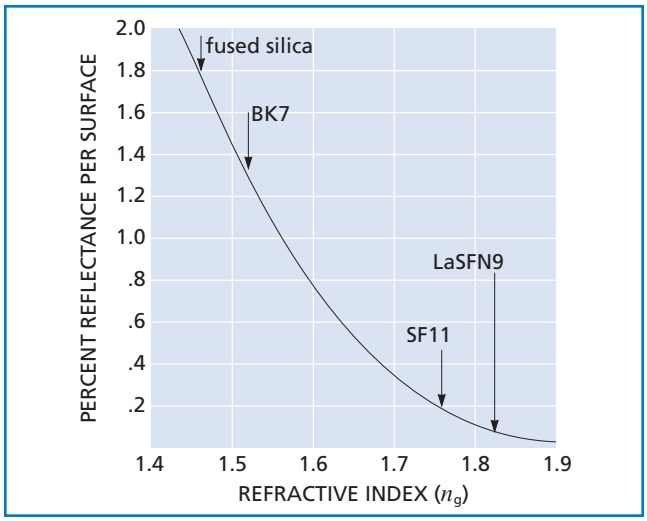


Figure 5.12 **Reflectance at surface of substrate with index n_g when coated with a quarter wavelength of magnesium fluoride (index n=1.38)**

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 θ_{1d} is the angle of refraction within the thin film:

$$\theta_{2d} = \arcsin\left(\frac{n_1(\lambda_d)\sin\theta_{1d}}{n_2(\lambda_d)}\right) . \tag{5.15}$$

As θ_1 is reduced from θ_{1d} to zero, the reflectance extremum shifts in wavelength from λ_d to λ_n, where the subscript n denotes normal incidence.

The wavelength is given by the equation

$$\lambda_n = \left(\frac{n_2(\lambda_n)}{n_2(\lambda_d)}\right)\left(\frac{\lambda_d}{\cos\theta_{2d}}\right) . \tag{5.16}$$

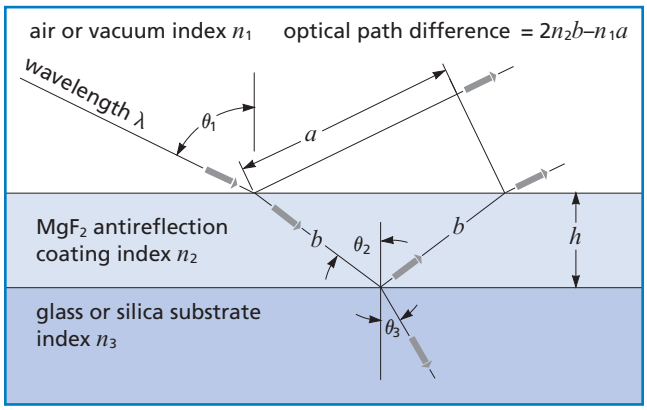


Figure 5.13 **Reflectance at oblique incidence**

Corresponding to the arbitrary angle of incidence θ_1 and arbitrary wavelength λ are angles of refraction in the coating and substrate, given by

$$\theta_2 = \arcsin\left(\frac{n_1(\lambda)\sin\theta_1}{n_2(\lambda)}\right) \tag{5.17}$$

and

$$\theta_3 = \arcsin\left(\frac{n_1(\lambda)\sin\theta_1}{n_3(\lambda)}\right) . \tag{5.18}$$

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

$$r_{12p} = \frac{n_2\cos\theta_1 - n_1\cos\theta_2}{n_2\cos\theta_1 + n_1\cos\theta_2} \tag{5.19}$$

$$r_{23p} = \frac{n_3\cos\theta_2 - n_2\cos\theta_3}{n_3\cos\theta_2 + n_2\cos\theta_3} \tag{5.20}$$

$$r_{12s} = \frac{n_1\cos\theta_1 - n_2\cos\theta_2}{n_1\cos\theta_1 + n_2\cos\theta_2} \tag{5.21}$$

$$r_{23s} = \frac{n_2\cos\theta_2 - n_3\cos\theta_3}{n_2\cos\theta_2 + n_3\cos\theta_3} . \tag{5.22}$$

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

$$R_p = \frac{r_{12p}^2 + r_{23p}^2 + 2r_{12p}r_{23p}\cos(2\beta)}{1 + r_{12p}^2 r_{23p}^2 + 2r_{12p}r_{23p}\cos(2\beta)} \tag{5.23}$$

$$R_s = \frac{r_{12s}^2 + r_{23s}^2 + 2r_{12s}r_{23s}\cos(2\beta)}{1 + r_{12s}^2 r_{23s}^2 + 2r_{12s}r_{23s}\cos(2\beta)} \tag{5.24}$$

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

$$\beta = \frac{2\pi}{\lambda} n_2(\lambda) h \cos\theta_2 . \tag{5.25}$$

The average reflectance is given by

$$\bar{R} = \frac{1}{2}(R_p + R_s) . \tag{5.26}$$

By applying these formulas, reflectance curves can be calculated as functions of either wavelength λ or angle of incidence θ_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 5.14, the second and third reflections are both exactly 180 degrees 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:

$$\frac{n_1^2 n_3}{n_2^2} = n_0 \qquad (5.27)$$

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 5.14.

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.

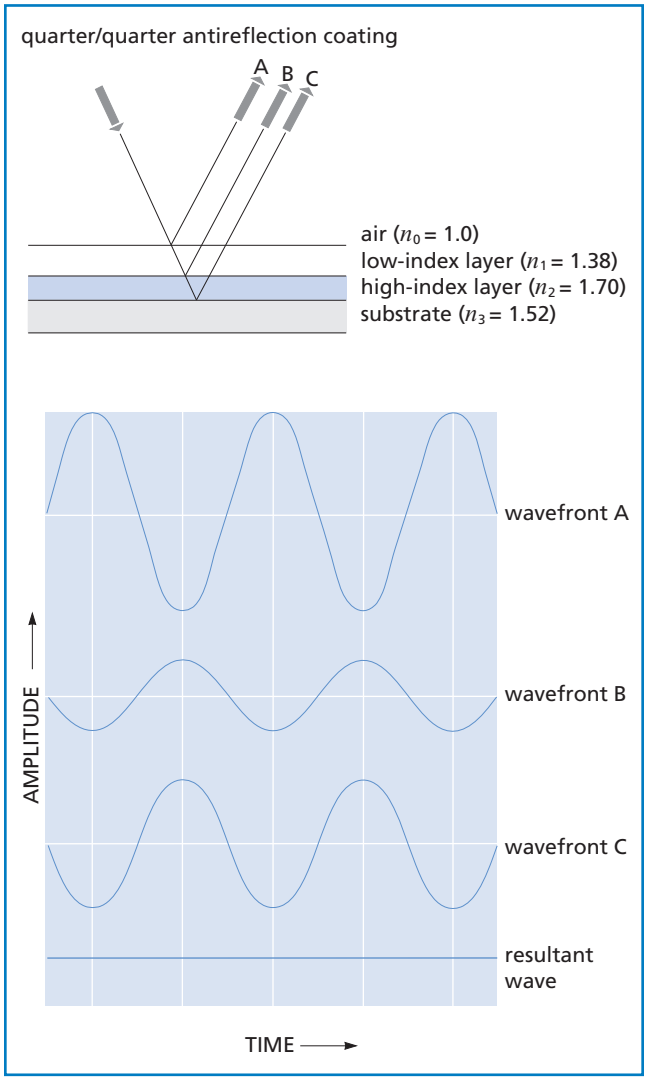


Figure 5.14 **Interference in a typical quarter/quarter coating**

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 degrees respectively. For two wavefronts to completely cancel each other, as in a single-layer antireflection coating, a phase shift of exactly 180 degrees is required. Where three or more reflecting surfaces are involved, complete 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 5.15, 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 Melles Griot 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 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.

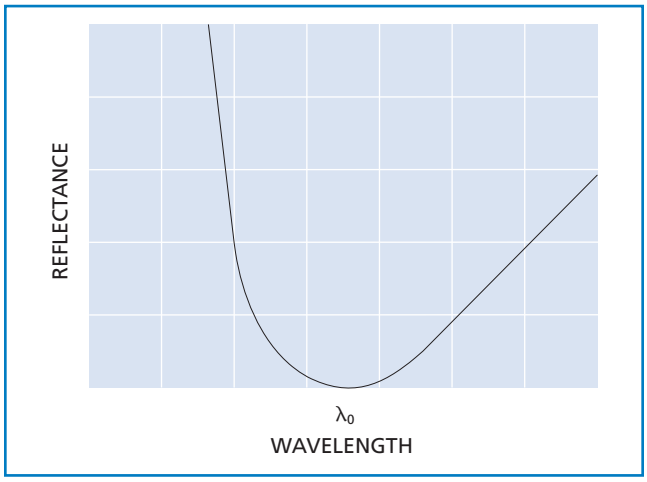


Figure 5.15 **Characteristic performance curve of a V-coating**

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 5.16. 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, 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.

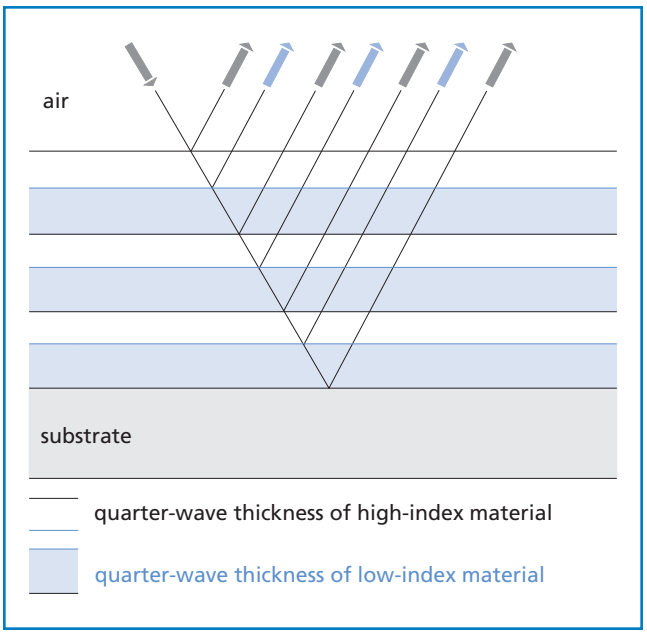


Figure 5.16 **A simple quarter-wave stack**

Because of the materials chosen for the multilayer stack, the durability and abrasion resistance of such films are normally superior to those of metallic films.

PERFORMANCE CURVE

The reflection versus wavelength performance curve of a single dielectric stack has the characteristic flat-topped, inverted-V shape shown in figure 5.17. 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 (5.28)

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

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 inherent 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

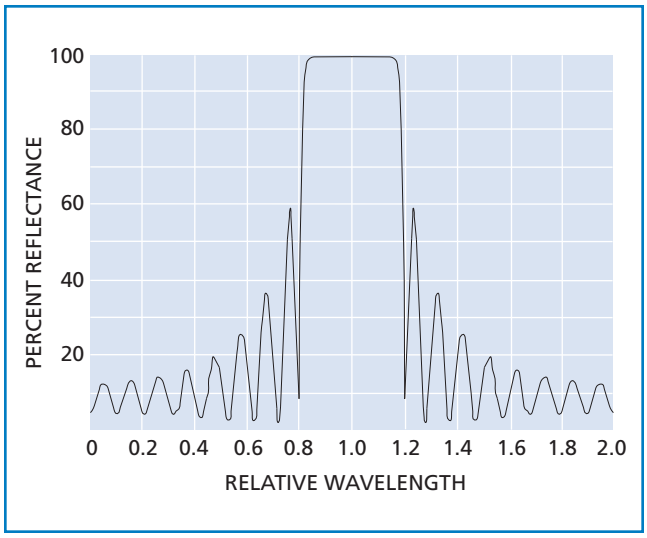


Figure 5.17 **Typical reflectance curve of an unmodified quarter-wave stack**

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.

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 5.18).

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.

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

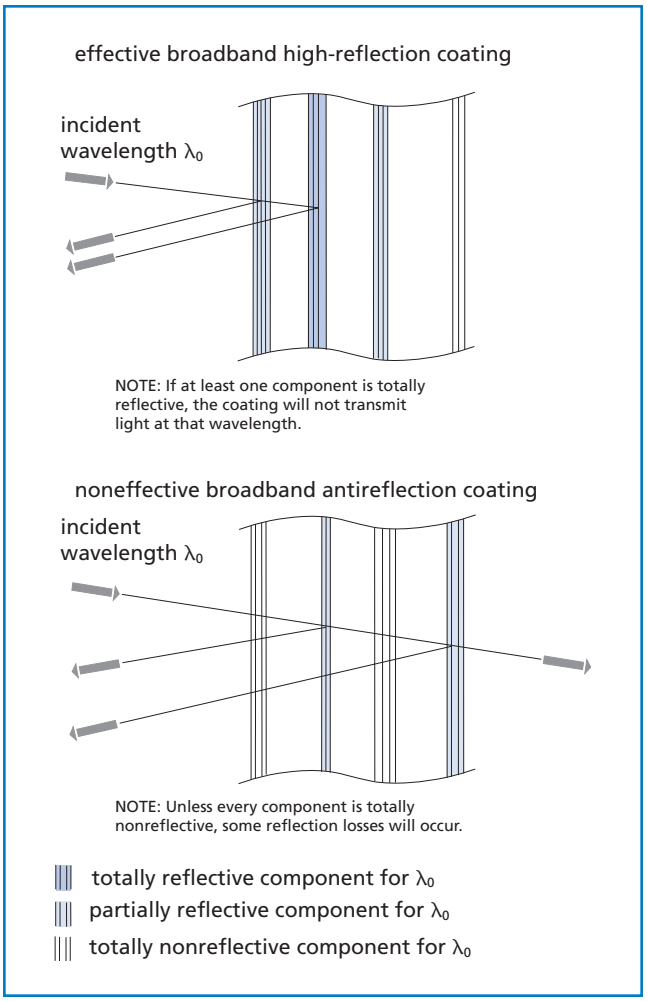


Figure 5.18 **Schematic multicomponent coatings with only one component exactly matched to the incident wavelength, λ. The high-reflection coating is successful; the antireflection coating is not.**

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 percent 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 coat-

ings 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.

High-reflectance or partially reflecting coatings are frequently used at oblique angles, particularly at 45 degrees, 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 5.19).

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.

EDGE FILTERS AND HOT OR COLD MIRRORS

In many optical systems, it is necessary to have a wavelength filtering system that transmits all light of wavelengths longer than a reference wavelength or transmits light at wavelengths shorter than a reference wavelength. These types of filters are often called short-wavelength or long-wavelength cutoff filters.

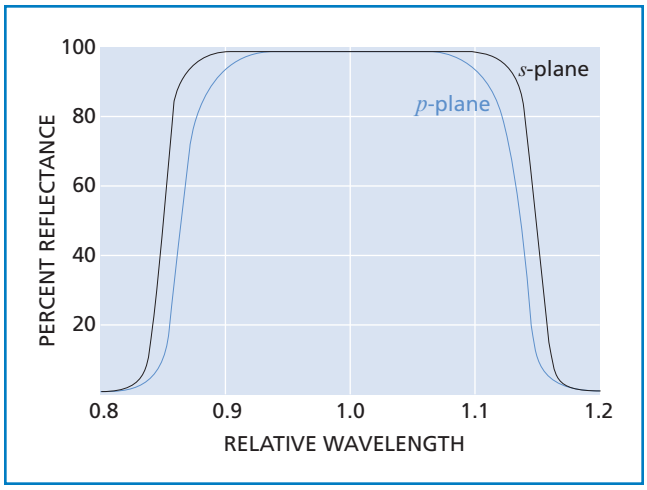


Figure 5.19 **The *s*-polarization reflectance curve is always broader and higher than the *p*-polarization reflectance curve.**

Traditionally, such absorption filters have been made from colored glasses. CVI Melles Griot offers a range of these economical and useful filters. Although they are adequate for many applications, they have two drawbacks: they function by absorbing unwanted wavelengths, which may cause reliability problems in such high-power situations as projection optics; also the edge of the transmission curve may not be as sharp as necessary for many applications.

Thin films acting as edge filters are now routinely manufactured using a modified quarter-wave stack as the basic building block. CVI Melles Griot produces many custom edge filters specially designed to meet customers' specifications. A selection suitable for various laser applications is offered as standard catalog items.

This type of thin-film filter is used in high-power image-projection systems in which the light source often generates intense amounts of heat (infrared and near-infrared radiation). Thin-film filters designed to separate visible and infrared radiation are known as hot or cold mirrors, depending on which wavelength region is rejected. CVI Melles Griot offers both hot and cold mirrors.

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 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 5.20 shows the transmission curve of a typical CVI Melles Griot interference filter, the 550-nm 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.

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 degrees) 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.

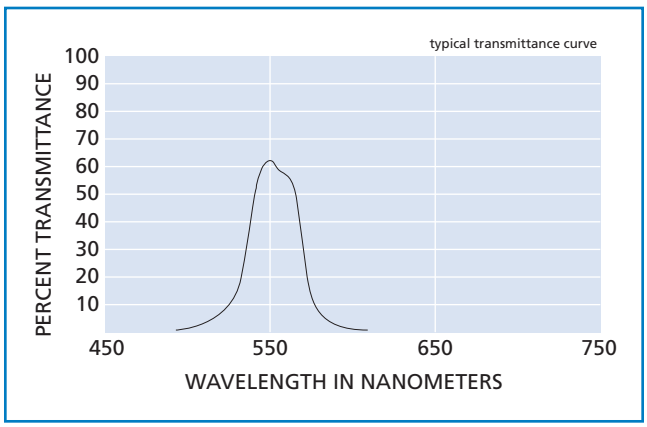


Figure 5.20 **Spectral performance of an interference filter**

CVI Melles Griot 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 percent.

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 half-wave 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 hard-coated 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.

Thin-Film Production

VACUUM DEPOSITION

CVI Melles Griot manufactures thin films by a process known as vacuum deposition. Uncoated substrates are placed in a large vacuum chamber capable of achieving a vacuum of at least 10^{-6} torr. At the bottom of the chamber is the source of the film material to be vaporized, as shown in figure 5.21. The substrates are mounted on a series of rotating carousels, arranged so that each substrate sweeps in planetary style through the same time-averaged volume in the chamber.

THERMAL EVAPORATION

The evaporation source is usually one of two types. The simpler, older type relies on resistive heating of a thin folded strip (boat) of tungsten, tantalum, or molybdenum which holds a small amount of the coating material. During the coating process, a high current (10-100 A) is passed through the boat, thermally vaporizing the coating material. Because the chamber is at a greatly reduced pressure, there is a very long, mean-free-path for the free atoms or molecules, and the heavy vapor is able to reach the moving substrates at the top of the chamber. Here it condenses back to the solid state, forming a thin uniform film.

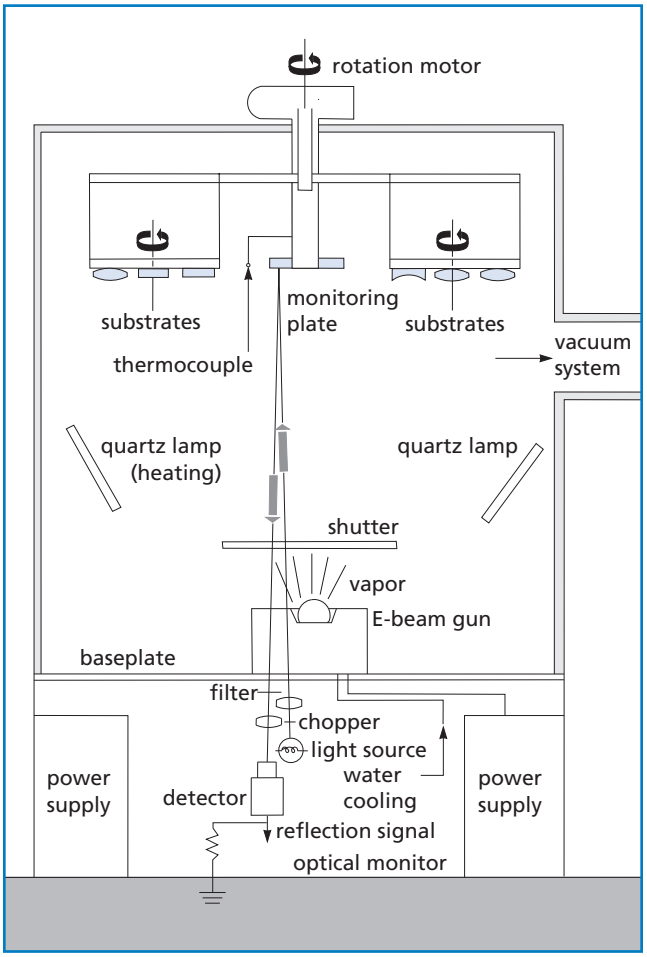


Figure 5.21 **Schematic view of a typical vacuum deposition chamber**

Several problems are associated with thermal evaporation. Some useful substances can react with the hot boat, which can cause impurities to be deposited with the layers, changing the optical properties of the resulting thin-film stack. In addition, many materials, particularly metal oxides, cannot be vaporized this way because the material of the boat (tungsten, tantalum, or molybdenum) melts at a lower temperature than the material to be vaporized. Instead of a layer of zirconium oxide, a layer of tungsten would be deposited on the substrate.

SOFT FILMS

Until the advent of electron bombardment vaporization, only materials that melted at moderate temperatures (2000°C) could be incorporated into thin-film coatings. Unfortunately, the more volatile low-temperature materials also happen to be materials that produce softer, less durable coatings. Consequently, early multilayer coatings deteriorated fairly quickly and required undue amounts of care during cleaning. More importantly, higher performance designs, with performance specifications at several wavelengths, could not be produced easily owing to the weak physical properties and lack of durability of such materials.

ELECTRON BOMBARDMENT

Electron bombardment has become the accepted method of choice for advanced optical-thin-film fabrication. This method is capable of vaporizing even difficult-to-vaporize materials such as titanium oxide and zirconium oxide. Using large cooled crucibles precludes or eliminates the chance of reaction between the heated coating material and the metal of the boat or crucible.

A high-flux electron gun (1 A at 10 kV) is aimed at the film material contained in a large, water-cooled, copper crucible. Intense local heating melts and vaporizes some of the coating material in the center of the crucible without causing undue heating of the crucible itself. For particularly involatile materials, the electron gun can be focused to intensify its effects.

Careful control of the temperature and vacuum conditions ensures that most of the vapor will be in the form of individual atoms or molecules, as opposed to clusters of atoms. This produces a more uniform coating with better optical characteristics and improved longevity.

PLASMA ION-ASSISTED BOMBARDMENT

Plasma ion-assisted deposition (PIAD) is a coating technique, often applied at low temperatures, which offers unique benefits in certain circumstances. Ion assist during the coating process leads to a higher atomic or molecular packing density in the thin-film layers (increasing index of refraction), minimizes wavelength shift, and achieves the highest adhesion levels and the lowest absorption available. This performance level is particularly crucial in many semiconductor, microelectronics, and telecommunications applications.

The lack of voids in the more efficiently packed film means that it is far less susceptible to water-vapor absorption. Water absorption by an optical coating can change the index of refraction of layers and, hence, the optical properties. Water absorption can also cause mechanical changes that can ultimately lead to coating failure.

Ion-assisted coating can also be used for cold or low-temperature processing. Eliminating the need to heat parts during coating allows cemented parts, such as cemented achromats, to be safely coated. From a materials standpoint, PIAD is often used when depositing metal oxides, metal nitrides, pure metals, and nonmetal oxides. Therefore, PIAD can significantly improve the performance of antireflection coatings, narrow- and wide-passband filters, edge filters, dielectric mirrors, abrasion-resistant transparent films, gain-flattening filters, and Rugate (gradient) filters.

ION-BEAM SPUTTERING (IBS)

Ion-beam sputtering is a deposition method using a very high-kinetic energy ion beam. The target is external to the ion source which allows for independent or automated control of the ion energy and flux. The energy and flux of ions is composed of neutral atoms which allow either insulating or conducting targets to be sputtered directly onto the substrate, this allows for a wide range of coating options.

The high energy flux impacts the target source and ejects atoms directly towards the intended substrate. Direct sputtering provides a high level of accuracy and repeatability over numerous coating runs. IBS deposition produces dense coating layers with almost no scatter or absorption which minimizes or eliminates spectral shift due to moisture absorption. In addition, the coating density and durability allows for high-damage threshold coating designs.

MAGNETRON SPUTTERING

Magnetron sputtering is a thin film deposition process that utilizes a magnet behind a cathode to trap free electrons in a circuitous magnetic field close to the target surface. A metered gaseous plasma of ions or neutral particles is introduced and the accelerated electrons collide with the neutral gas atoms in their path. These interactions cause ionizing collisions and drive electrons off the gas atoms. The gas atom becomes unbalanced and will have more positively charged protons than negatively charged electrons.

The positively charged ions are accelerated towards the negatively charged electrode and impact the target material. The energy transfer is greater than the binding energy of the target material, causing the release of free electrons, erosion of the target material, and ultimately the sputtering process. The ejected source material particles are neutrally charged and therefore unaffected by the negative magnetic field. The ejected atoms are transferred to a substrate into densely packed coating layers resulting in little or no spectral shift caused by moisture absorption. The release of free electrons feed the formation of ions and the propagation of the plasma. Due to close proximity the percentage of confined electrons that cause ionizing collisions dramatically increases. This allows for very high deposition rates at which the target material is eroded and subsequently deposited onto the substrate.

Magnetron sputtering has the advantages of exceptional uniformity, high deposition rates, low deposition pressure, and low substrate temperature allowing a wide variation of industrial production.

MONITORING AND CONTROLLING LAYER THICKNESS

A chamber set up for multilayer deposition has several sources that are preloaded with various coating materials. The entire multilayer coating is deposited without opening the chamber.

A source is heated, or the electron gun is turned on, until the source is at the proper molten temperature. The shutter above the source is opened to expose the chamber to the vaporized material. When a particular layer is deposited to the correct thickness, the shutter is closed and the source is turned off. This process is repeated for the other sources.

Optical monitoring is the most common method of observing the deposition process. A double-beam monochromator-photometer monitors, at application-specific wavelengths, the optical characteristics of a witness sample located within the vacuum chamber. In certain cases, the detection system can directly monitor the changing optical characteristics of the actual substrate being coated. During operation, a beam of light passes through the chamber and is incident on the witness sample or the substrate to be coated. Reflected and/or transmitted light is detected using photomultiplier detectors and phase-sensitive detection techniques to maximize signal-to-noise ratio.

As each layer is deposited onto the witness sample, the intensity of reflected and/or transmitted light oscillates in a sinusoidal manner due to optical interference effects. The turning points represent quarter- and half-wave thicknesses at the monitoring wavelength. Deposition is automatically stopped when the reflectance and/or transmittance of the reference surface achieves a prescribed value. Highly accurate optical monitoring is essential for the production and optimization of specific optical effects, such as setting the exact edge position of an interference filter or sharp-cutoff reflector.

SCATTERING

Reflectance and transmittance are usually the most important optical properties specified for a thin film, closely followed by absorption. However, the degree of scattering caused by a coating is often the limiting factor in the ability of coated optics to perform in certain applications. Scattering is quite complex. The overall degree of scattering is determined by imperfections in layer interfaces, bulk substrate material characteristics, and interference effects between the photons of light scattered by these imperfections, as shown in figure 5.22.

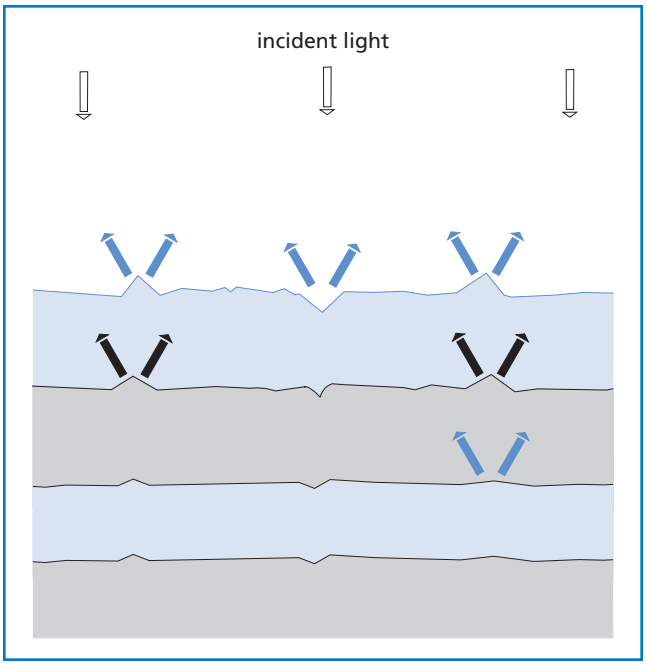


Figure 5.22 **Interface imperfections scattering light in a multilayer coating**

Scattering is also a function of the granularity of the layers. Granularity is difficult to control as it is often an inherent characteristic of the materials used. Careful modification of deposition conditions can make a considerable difference in this effect.

The most notable example of applications in which scattering is critical are intracavity mirrors for low-gain lasers, such as certain helium neon lasers, and continuous-wave dye lasers.

TEMPERATURE AND STRESS

Mechanical stress within the thin-film coating can be a major problem. Even with optimized positioning of the optics being coated and careful control of the source temperature and vacuum, many thin-film materials do not deposit well on cold substrates causing stresses within the layers. This is particularly true of involatile materials. Raising the substrate temperature a few hundred degrees improves the quality of these films, often making the difference between a usable and a useless film. The elevated temperature seems to allow freshly condensed atoms (or molecules) to undergo a beneficial but limited amount of surface diffusion.

Optics that have been coated at an elevated temperature require very slow cooling to room temperature. The thermal expansion coefficients of the substrate and the film materials are likely to be somewhat different. As cooling occurs, the coating layer or layers contract at different rates which produces stress. Many pairs of coating materials also do not adhere particularly well to each other owing to different chemical properties and bulk packing characteristics.

Temperature-induced stress and poor interlayer adhesion are the most common thickness-related limitations in optical thin-film production. Ignoring such techniques as ion-assisted deposition, stress must be reduced by minimizing overall coating thickness and by carefully controlling the production process.

INTRINSIC STRESS

Even in the absence of thermal-contraction-induced stress, the layers often are not mechanically stable because of intrinsic stress from interatomic forces. The homogeneous thin film is not the preferred phase for most coating materials. In the lowest energy state, molecules are aligned in a crystalline symmetric fashion. This is the natural form in which intermolecular forces are more nearly in equilibrium.

In addition to intrinsic molecular forces, intrinsic stress results from poor packing. If packing density is considerably less than percent, the intermolecular binding may be sufficiently weak that it makes the multilayer stack unstable.

PRODUCTION CONTROL

Two major factors are involved in producing a coating that performs to a particular set of specifications. First, sound design techniques must be used. If design procedures cannot accurately predict the behavior of a coating, there is little chance that satisfactory coatings will be produced. Second, if the manufacturing phase is not carefully controlled, the thin-film coatings produced may perform quite differently from the computer simulation.

At CVI Melles Griot, great care is taken in coating production at every level. Not only are all obvious precautions taken, such as thorough precleaning and controlled substrate cool down, but even the smallest details of the manufacturing process are carefully controlled. Our thoroughness and attention to detail ensure that the customer will always be supplied with the best design, manufactured to the highest standards.

QUALITY CONTROL

All batches of CVI Melles Griot coatings are rigorously and thoroughly tested for quality. Even with the most careful production control, this is necessary to ensure that only the highest quality parts are shipped.

Our inspection system meets the stringent demands of MIL-I-45208A, and our spectrophotometers are calibrated to standards traceable to the National Institute of Standards and Technology (NIST). Upon request, we can provide complete environmental and photometric testing to MIL-C-675 and MIL-M-13508. All are firm assurances of dependability and accuracy.

CVI Melles Griot Antireflection Coatings

Broadband Multilayer Antireflection Coatings

Broadband antireflection coatings provide a very low reflectance over a broad spectral bandwidth. These advanced multilayer films, are optimized to reduce overall reflectance to an extremely low level over a broad spectral range.

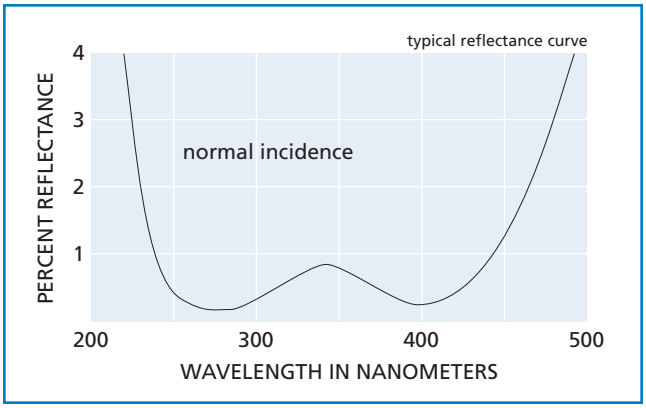
There are two families of broadband antireflection coatings from CVI Melles Griot. HEBBAR™ and BBAR.

HEBBAR™ Coatings

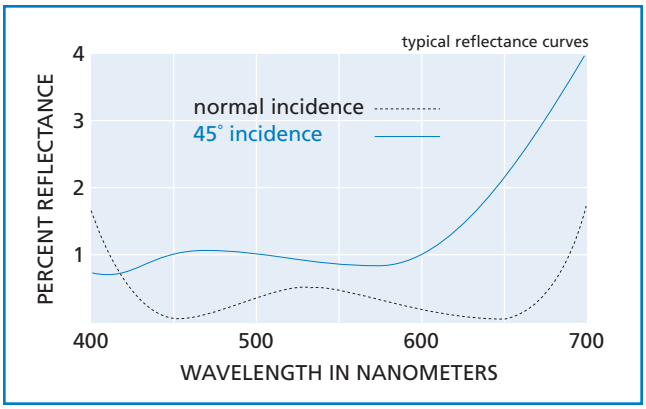
HEBBAR coatings exhibit a characteristic double-minimum reflectance curve covering a spectral range of some 250 nm or more. The reflectance does not exceed 1.0 percent, and is typically below 0.6 percent, over this entire range. Within a more limited spectral range on either side of the central peak, reflectance can be held to well below 0.4 percent. HEBBAR coatings are relatively insensitive to angle of incidence. The effect of increasing the angle of incidence (with respect to the normal to the surface) is to shift the curve to slightly shorter wavelengths and to increase the long wavelength reflectance slightly. These coatings are extremely useful for high numerical-aperture (low f-number) lenses and steeply curved surfaces. In these cases, incidence angles vary significantly over the aperture.

The typical reflectance curves shown below are for BK7 substrates, except for the ultraviolet 245-440 nm and 300-500 nm coatings which are applied to fused silica substrates or components. The reflectance values given below apply only to substrates with refractive indices ranging from 1.47 to 1.55. Other indices, while having their own optimized designs, will exhibit reflectance values approximately 20 percent higher for incidence angles from 0 to 15 degrees and 25 percent higher for incidence angles of 30 + degrees.

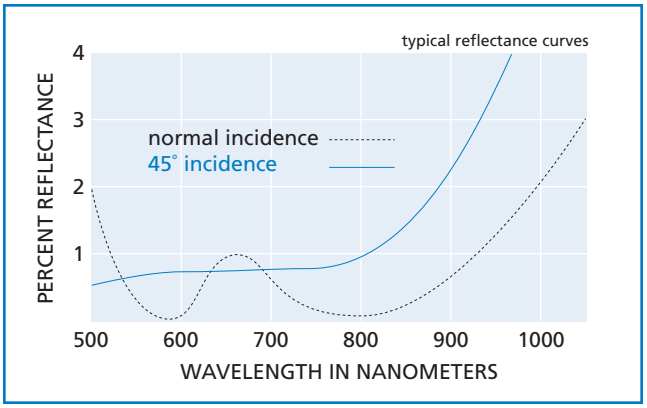
To order a HEBBAR coating, append the coating suffix given in the table below to the product number. In some instances it will be necessary to specify which surfaces are to be coated.



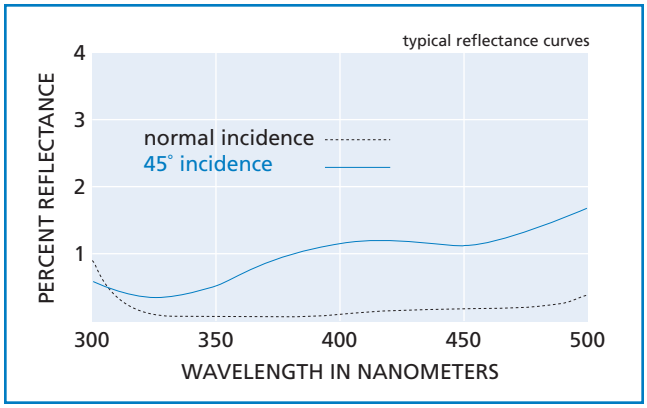
- **HEBBAR™ coating for 245 to 440 nm**
- $R_{avg} < 0.5\%$, $R_{abs} < 1.0\%$
- Damage threshold: 3.5 J/cm^2, 10-nsec pulse at 355 nm typical



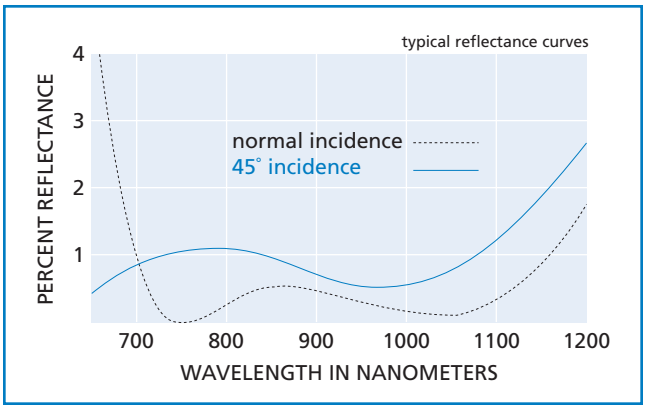
- **HEBBAR™ coating for 415 to 700 nm**
- $R_{avg} < 0.4\%$, $R_{abs} < 1.0\%$
- Damage threshold: 3.8 J/cm^2, 10-nsec pulse at 532 nm typical



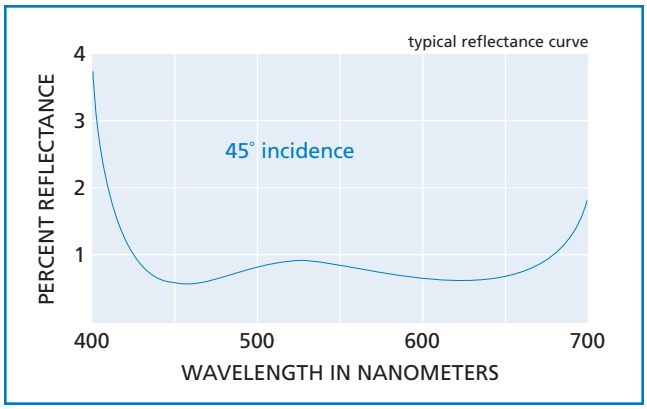
- **HEBBAR™ coating for 780 to 850 nm diode lasers**
- $R_{avg} < 0.25\%$, $R_{abs} < 0.4\%$
- Damage threshold: 6.5 J/cm^2, 20-nsec pulse at 1064 nm typical



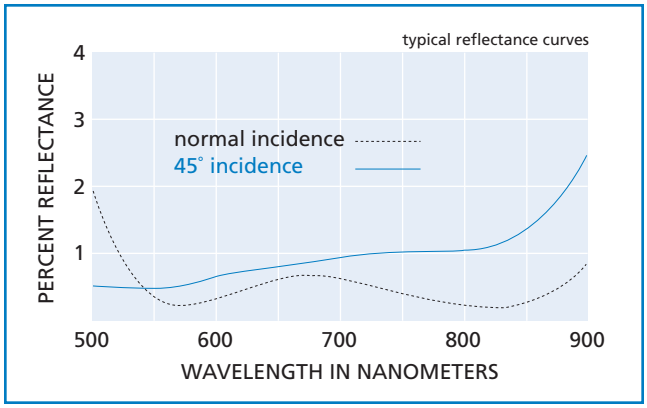
- **Specialty HEBBAR™ coating for 300 to 500 nm**
- $R_{abs} < 1.0\%$
- Damage threshold: 3.2 J/cm^2, 10-nsec pulse at 355 nm typical



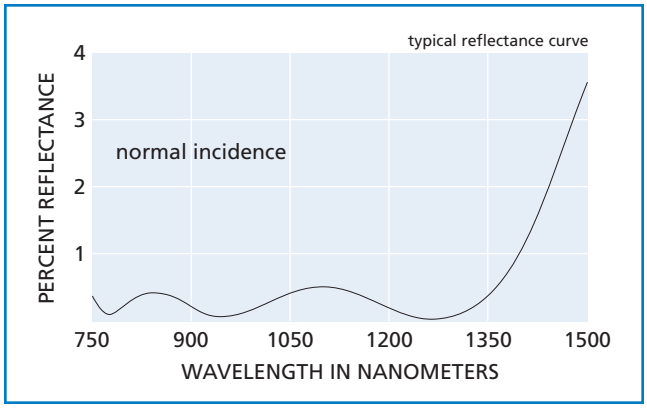
- **HEBBAR™ coating for 750 to 1100 nm**
- $R_{avg} < 0.4\%$, $R_{abs} < 0.6\%$
- Damage threshold: 6.5 J/cm^2, 20-nsec pulse at 1064 nm typical



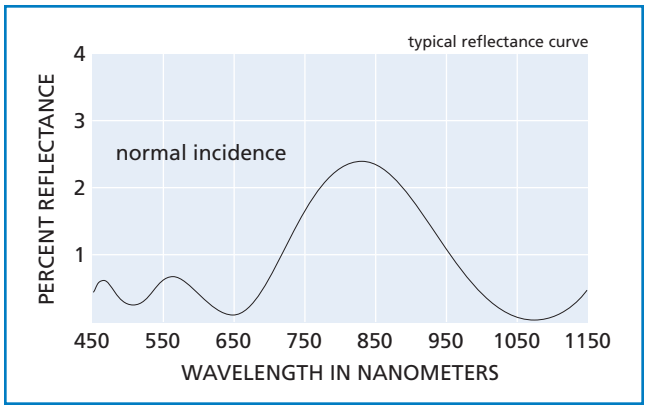
- **Specialty HEBBAR™ coating for 425 to 670 nm optimized for 45°**
- $R_{avg} < 0.6\%$, $R_{abs} < 1.0\%$
- Damage threshold: 3.8 J/cm^2, 10-nsec pulse at 532 nm typical



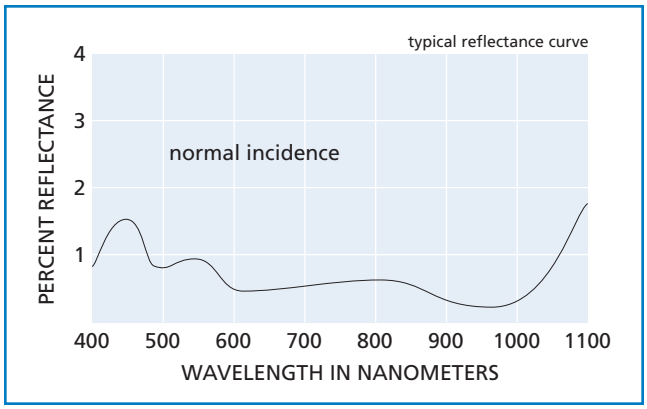
- **Specialty HEBBAR™ coating for 660 to 835 nm diode lasers**
- $R_{avg} < 0.5\%$, $R_{abs} < 1.0\%$
- Damage threshold: 3.8 J/cm^2, 10-nsec pulse at 532 nm typical



- **Dual Band HEBBAR™ coating for 780 to 830 nm and 1300 nm**
- $R_{abs} < 0.5\%$ @ 780 – 830 nm and 1300 nm
- Damage threshold: 5.4 J/cm^2, 20-nsec pulse at 1064 nm typical



- **Dual Band HEBBAR™ coating for 450 to 700 nm and 1064 nm**
- $R_{abs} < 1.25\%$ @ 450 – 700 nm, $R_{abs} < 0.25\%$ @ 1064 nm
- Damage threshold: 1.3 J/cm^2, 10-nsec pulse at 532 nm typical; 5.4 J/cm^2, 20-nsec pulse at 1064 nm typical



- **Extended HEBBAR™ coating for 420 to 1100 nm**
- $R_{avg} < 1.0\%$, $R_{abs} < 1.75\%$
- Damage threshold: 4.5 J/cm^2, 10-nsec pulse at 532 nm typical; 6.5 J/cm^2, 20-nsec pulse at 1064 nm typical

Standard HEBBAR™ Coatings

Description	Wavelength Range (nm)	Reflectance (%)	Optimized for Angle of Incidence (degrees)	COATING SUFFIX FORMER‡	COATING SUFFIX REPLACED BY
HEBBAR™ 245-440nm	245-440	R_{avg} <0.50	0	/072	HE-245-440
HEBBAR™ 415-700nm	415-700	R_{avg} <0.40	0	/078	HE-415-700
HEBBAR™ 780-850nm	780-850	R_{avg} <0.25	0	/076	HE-780-850
HEBBAR™ 750-1100nm	750-1100	R_{avg} <0.40	0	/077	HE-750-1100

‡ Former Melles Griot part number is replaced by new CVI Melles Griot part number

Specialty HEBBAR™ Coatings, optional designs for OEM and Prototype applications

Description	Wavelength Range (nm)	Reflectance (%)	Optimized for Angle of Incidence (degrees)	COATING SUFFIX FORMER‡	COATING SUFFIX REPLACED BY
HEBBAR™ 300-500nm	300-500	R_{abs} <1.0	0	/074	HE-300-500
HEBBAR™ 425-670nm	425-670	R_{avg} <0.60	45 UNP	/079	HE-425-675-45UNP
HEBBAR™ 660-835nm	660-835	R_{avg} <0.50	0	/075	HE-660-835

‡ Former Melles Griot part number is replaced by new CVI Melles Griot part number

Dual Band HEBBAR™ Coatings

Description	Wavelength Range (nm)	Reflectance (%)	Optimized for Angle of Incidence (degrees)	COATING SUFFIX FORMER‡	COATING SUFFIX REPLACED BY
HEBBAR™ 450-700nm and 1064nm	450-700 and 1064	R_{avg} <0.60	0	/083	HE-450-700/1064
HEBBAR™ 780-830nm and 1300nm	780-830 and 1300	R_{avg} <0.40	0	/084	HE-780-830/1300

‡ Former Melles Griot part number is replaced by new CVI Melles Griot part number

Extended-Range HEBBAR™ Coating

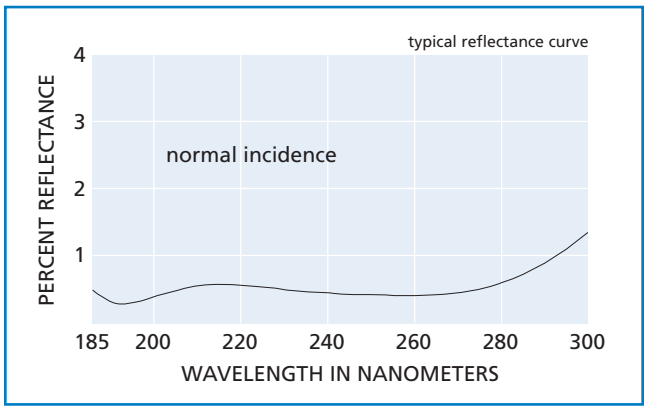
Description	Wavelength Range (nm)	Reflectance (%)	Optimized for Angle of Incidence (degrees)	COATING SUFFIX FORMER‡	COATING SUFFIX REPLACED BY
HEBBAR™ 420-1100nm	420-1100	R_{avg} <0.50	0	/073	HE-420-1100

‡ Former Melles Griot part number is replaced by new CVI Melles Griot part number

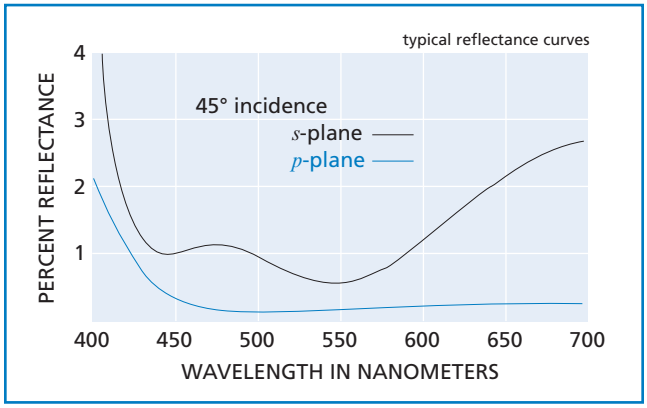
BBAR-Series Coatings

CVI Melles Griot offers six overlapping broad band antireflection (BBAR) coating designs covering the entire range from 193 nm to 1600 nm. This includes very broad coverage of the entire Ti:Sapphire region. The BBAR coatings are unique in the photonics industry by providing both a low average reflection of ≤0.5% over a very broad range and also providing the highest damage threshold for pulsed and continuous wave laser sources (10J/cm^2, 20ns, 20Hz at 1064nm and 1MW/cm^2 CW at 1064nm respectively). Typical performance curves are shown in the graphs for each of the standard range offerings. If your application cannot be covered by a standard design, CVI Melles Griot can provide a special broad band antireflection coating for your application.

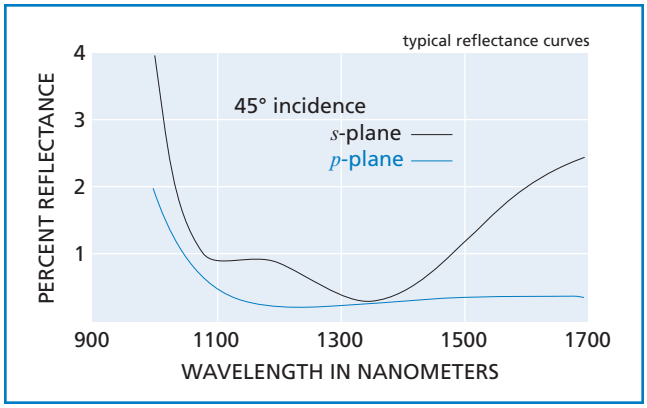
CVI Melles Griot also provides three mid infrared and far infrared broad band antireflection coatings from 2.0 μm to 12.0 μm. These coatings are available on a wide range of materials including Si, Ge, ZnS, ZnSe, or CaF_2. Our standard coatings cover 2 to 2.5 μm, 3 to 5 μm and the 8 to 12 μm region. Custom coatings are also available for mid and far infrared applications.



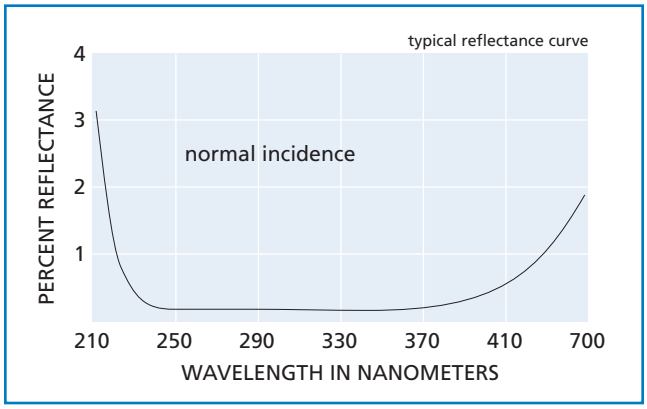
BBAR 193-248 coating for the UV region (0° incidence)



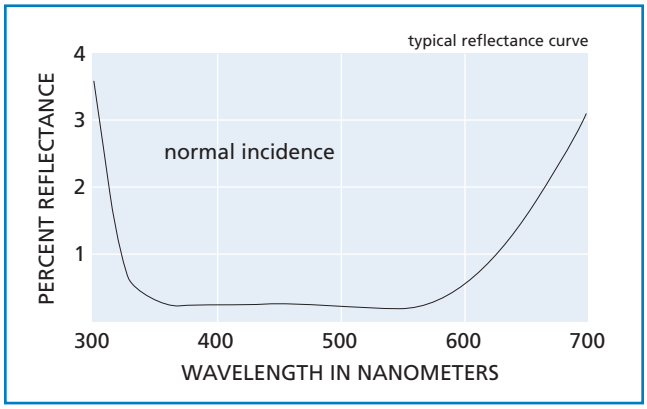
BBAR/45 425-675 coating for the visible region (45° incidence)



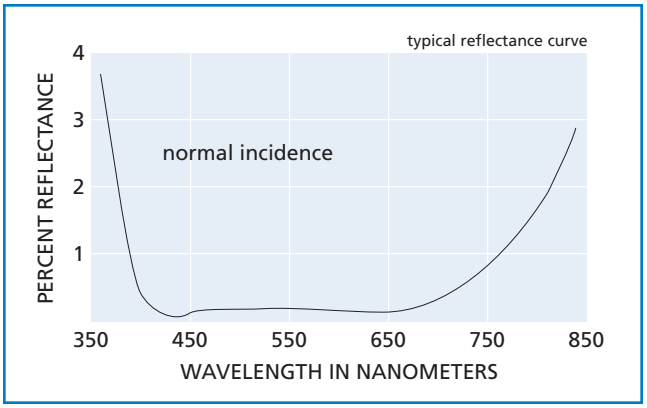
BBAR/45 1050-1600 coating for the NIR region (45° incidence)



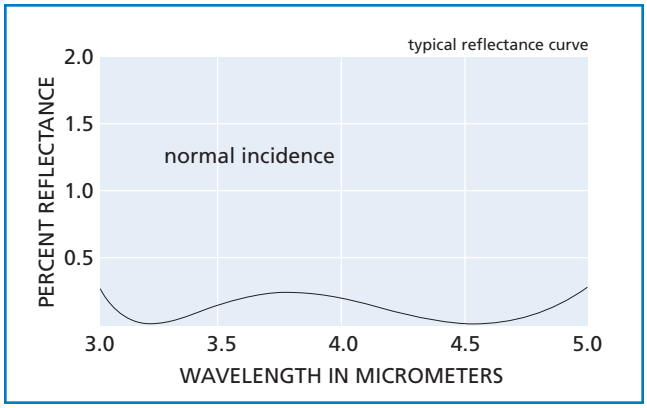
BBAR 248-355 coating for the UV region (0° incidence)



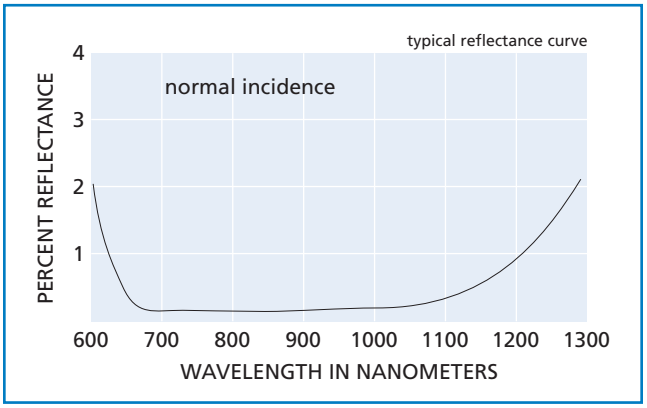
BBAR 355-532 coating for the UV region (0° incidence)



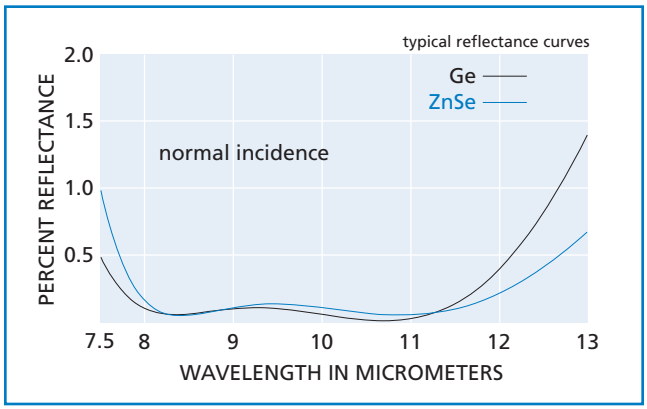
BBAR 425-675 coating for VIS and NIR regions (0° incidence)



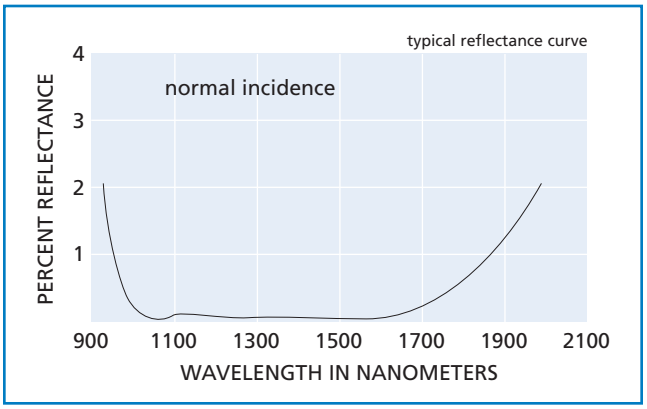
BBAR 3500-5000 coating for the IR region (0° incidence)



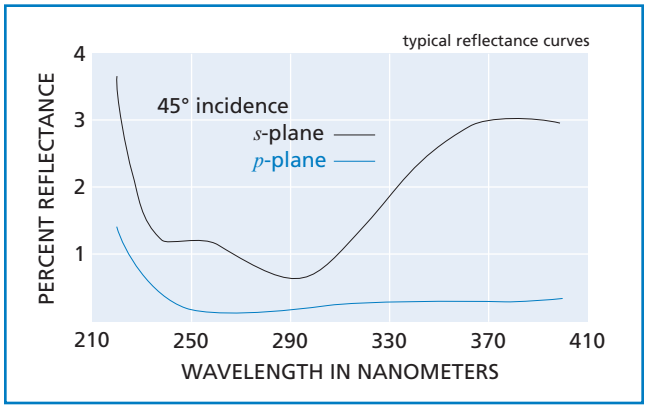
BBAR 670-1064 coating for VIS and NIR regions (0° incidence)



BBAR 8000-12000 coating for the IR region (0° incidence)



BBAR 1050-1600 coating for VIS and NIR regions (0° incidence)



BBAR/45 248-355 coating for the UV region (45° incidence)

V-Coatings

CVI Melles Griot V-type AR Coatings are the best choice for a single laser wavelength or multiple, closely-spaced wavelengths. Examples are the principle argon laser lines at 488nm and 514nm, the neodymium transitions in a variety of host materials at 1047-1064nm, and the individual excimer laser lines.

CVI Melles Griot will manufacture V-Type AR coatings for wavelengths from 193nm to 10.6μ.

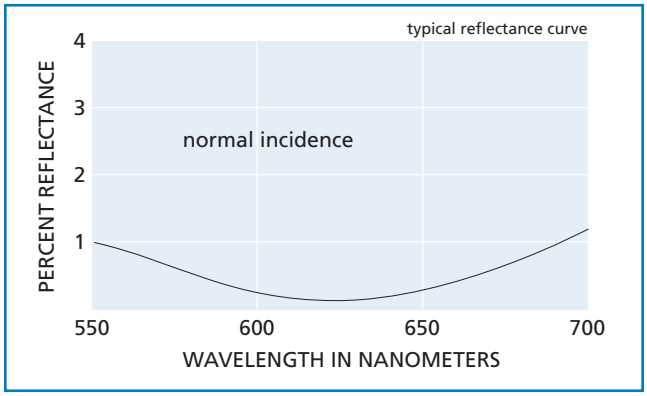
V-type AR coatings on Fused Silica, Crystal Quartz, Suprasil, and BK7 have damage threshold of 15J/cm^2 at 1064nm, 20ns, 20Hz. Typical performance can often exceed 20J/cm^2.

Damage thresholds for AR coatings on SF11 and similar glasses are limited not by the coating, but by the bulk material properties. Our damage testing has shown a damage threshold for SF11 and similar glasses to be 4J/cm^2.

When ordering, be sure to specify the following:

- Wavelength
- Substrate material
- Angle of incidence
- Polarization
- Fluence in J/cm^2

The reflectance curve for a typical V-coating, on BK7 glass, designed for operation at 632.8 nm is shown below.



Example of a V-coating for 632.8 nm

- Near-zero reflectance at one specific wavelength and incidence angle
- Maximum reflectance often less than 0.1%
- Standard coatings available for most laser lines
- Custom center wavelengths at specific angles of incidence available per request

The following table lists the former Melles Griot standard V-coating designs for zero degree and the new CVI Melles Griot coating suffix.

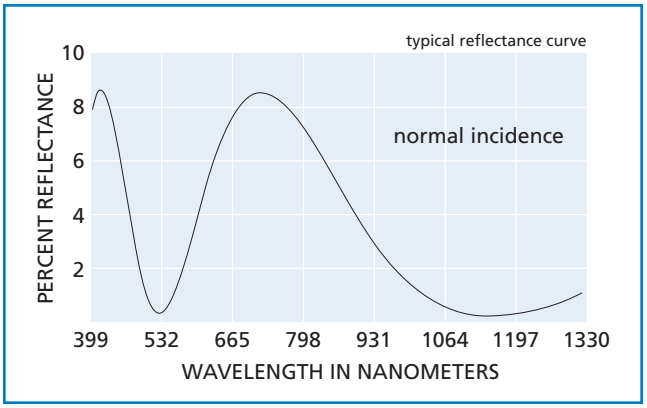
V-Coating Center Wavelengths

Wavelength (nm)	Laser Type	Maximum Reflectance (%)	COATING SUFFIX FORMER‡	COATING SUFFIX REPLACED BY
193	ArF	0.5	/101	193-0
248	ArF	0.25	/102	248-0
266	Nd 3rd harmonic	0.25	/103	266-0
308	XeCl	0.25	/104	308-0
351	Ar ion	0.25	/105	351-0
364	Ar ion	0.25	/107	364-0
442	HeCd	0.25	/111	442-0
458	Ar ion	0.25	/112	458-0
466	Ar ion	0.25	/113	466-0
473	Ar ion	0.25	/114	473-0
476	Ar ion	0.25	/115	476-0
488	Ar ion	0.25	/116	488-0
496	Ar ion	0.25	/117	496-0
502	Ar ion	0.25	/118	502-0
514	Ar ion	0.25	/119	514-0
532	Nd 2nd harmonic	0.25	/122	532-0
543	HeNe	0.25	/121	543-0
633	HeNe	0.25	/123	633-0
670	GaAlAs	0.25	/128	670-0
694	Ruby	0.25	/124	694-0
780	GaAlAs	0.25	/163	780-0
830	GaAlAs	0.25	/166	830-0
850	GaAlAs	0.25	/167	850-0
904	GaAs	0.25	/125	904-0
1064	Nd	0.25	/126	1064-0
1300	InGaAsP	0.25	/168	1300-0
1523	HeNe	0.25	/169	1523-0
1550	InGaAsP	0.25	/169	1550-0

‡ Former Melles Griot coating suffix is replaced by new CVI Melles Griot coating suffix

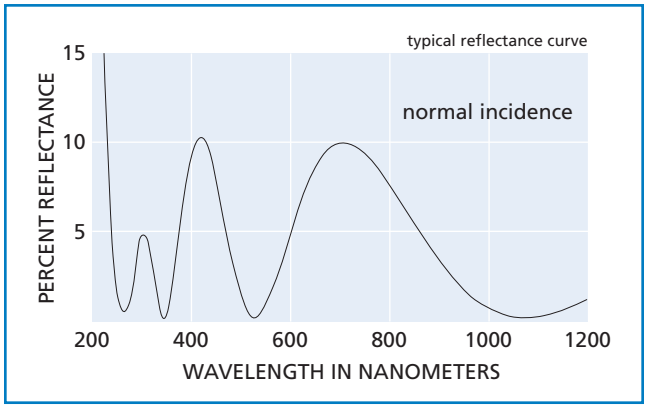
Double-V and Triple-V Coatings

CVI Melles Griot offers Double-V and Triple-V multilayer antireflection coatings for use in Nd:YAG laser systems at normal incidence. Highly damage resistant, electron beam deposited dielectrics are used exclusively as coating materials. As shown in the curves, the antireflection peaks at the harmonics are quite narrow. Also, due to the coating design and dispersion, they do not fall exactly at a wavelength ratio of 1 : 1/2 : 1/3. Consequently, the reflectivity specifications of these AR coatings are not as good as V-coatings for any one wavelength. CVI Melles Griot offers these Double-V coatings on W2 windows, in all standard sizes. Contact CVI Melles Griot for the performance of 45° Double-V and Triple-V AR coatings or for other harmonic combinations.



Double-V antireflection coating for 532 nm and 1064 nm

- Designed for normal incidence
- $R < 0.3\%$ 1064 nm
- $R < 0.6\%$ at 532 nm
- Damage threshold 5 J/cm^2 at 532 nm
- Damage threshold 10 J/cm^2 at 1064 nm



Triple-V antireflection coating for 355 nm, 532 nm, and 1064 nm

- Designed for normal incidence
- $R < 0.3\%$ 1064 nm
- $R < 0.6\%$ at 532 nm
- $R < 1.5\%$ at 355 nm

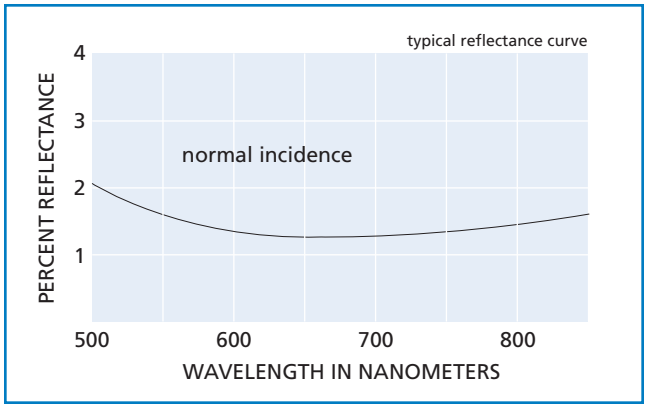
Single-Layer MgF_2 Coatings

Magnesium fluoride (MgF_2) is commonly used for single-layer antireflection coatings because of its almost ideal refractive index (1.38 at 550 nm) and high durability. These coatings can be optimized for 550 nm for normal incidence, but as can be seen from the reflectance curves, they are extremely insensitive to wavelength and incidence angle.

Single-layer antireflection coatings for use on very steeply curved or short-radius surfaces should be specified for an angle of incidence approximately half as large as the largest angle of incidence encountered by the surface.

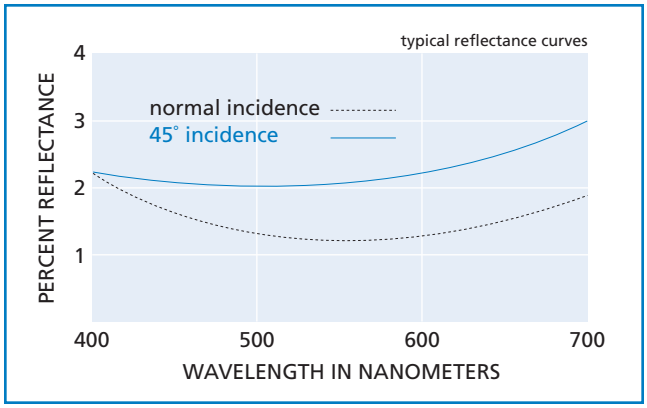
Single-Layer MgF_2 Antireflection Coating Normal Incidence

Wavelength Range (nm)	Maximum Reflectance on BK7 (%)	Maximum Reflectance on Fused Silica (%)	COATING SUFFIX
400–700	2.0	2.25	SLMF-400-700
520–820	2.0	2.25	SLMF-520-820



Single-layer MgF_2 520-820 nm coating

- Optimized for 670 nm, normal incidence
- Useful for most visible and near-infrared diode wavelengths
- Highly durable and insensitive to angle
- Damage threshold: 13.2 J/cm^2, 10-nsec pulse at 532 nm typical



Single-layer MgF_2 400-700 nm coating

- Popular and versatile antireflection coating for visible wavelengths
- Highly durable and most economical
- Optimized for 550 nm, normal incidence
- Relatively insensitive to changes in incidence angle
- Damage threshold: 13.2 J/cm^2, 10-nsec pulse at 532 nm typical

High-Reflection Coatings

Metallic High-Reflection Coatings

CVI Melles Griot offers eight standard metallic high-reflection coatings formed by vacuum deposition. These coatings can be used at any angle of incidence and can be applied to most optical components. To specify this coating, simply append the coating suffix number to the component product number.

Metallic reflective coatings are delicate and require care during cleaning. Dielectric overcoats substantially improve abrasion resistance, but they are not impervious to abrasive cleaning techniques. Clean, dry, pressurized gas can be used to blow off loose particles. This can be followed by a very gentle wipe using deionized water, a mild detergent, or alcohol. Gentle cleaning with an appropriate swab can be effective.

CVI Melles Griot Coating Chambers

CVI Melles Griot thin-film coating chambers have

- Multiple e-beam sources
- Optical and crystal controls
- Residual-gas analyzers
- Mass-flow controls
- Quartz substrate heaters
- Compound planetary rotation capabilities

Metallic High-Reflection Coatings

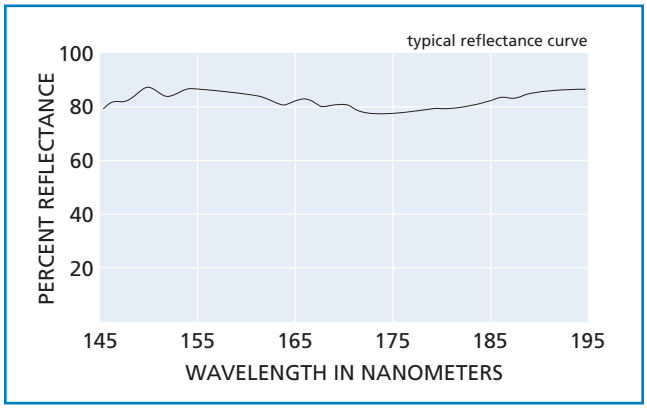
Coating Type	Wavelength Range (nm)	Average Reflectance (%)	Damage Threshold* Pulsed (J / cm^2)	Damage Threshold* cw (MW / cm^2)	Former Coating Suffix	PRODUCT CODE
Vacuum UV Aluminum	157	> 80	not tested	not tested		VUVA
Deep UV Aluminum	193	> 90	not tested	not tested		DUVA
UV Enhanced Aluminum	250–600	85	0.3	22.0	/028	PAUV
Protected Aluminum	400–10,000	90	0.5	22	/011	PAV
Enhanced Aluminum	450–650	92	0.3	12.0	/023	EAV
Protected Silver	400–20,000	95	1.6	73.0	/038	PS
Protected Gold	650–10,000	95.0	0.4	17.0	/055	PG
Bare Gold	700–20,000	99	1.1	48.0	/045	PG-BARE

**PAUV coating: 10-nsec pulse at 355 nm; all others: 20-nsec pulse at 1064 nm typical*

CVI Melles Griot State-of-The-Art Coating Capabilities

The photos below depict thin-film deposition systems available at CVI Melles Griot optics manufacturing sites.

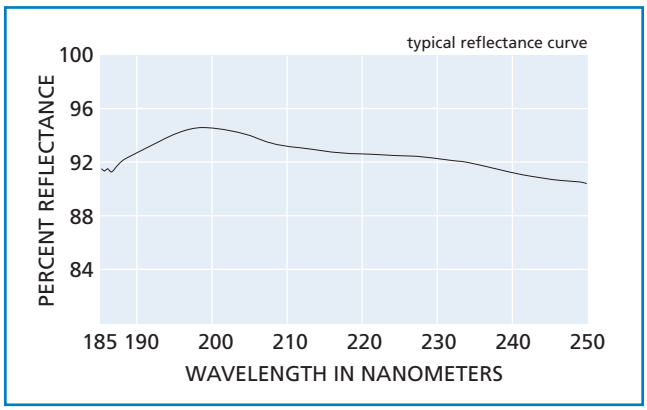
Vacuum UV Aluminum (VUVA)



- Enhanced performance for 157 nm
- Provides consistently high reflectance throughout the vacuum ultraviolet, visible, and near-infrared regions
- Dielectric overcoat minimizes oxidation and increases abrasion resistance
- R > 80% 157 nm

Based on CVI Melles Griot high density aluminum coating technology, VUVA mirrors are designed for optimized performance at 157 nm. Certification of performance at wavelength is available for an additional charge. Call CVI Melles Griot for details.

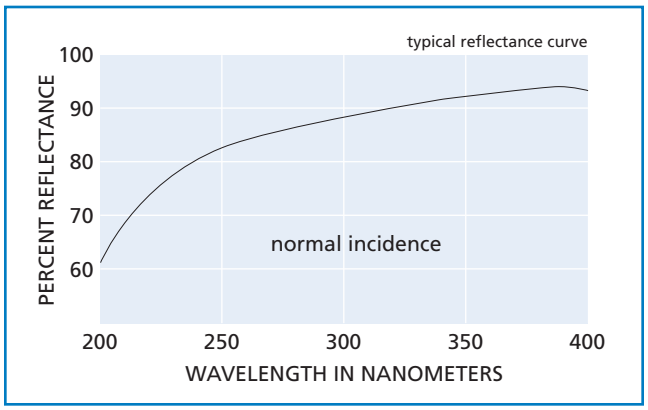
Deep UV Aluminum (DUVA)



- Enhanced performance for 193 nm
- Provides consistently high reflectance throughout the vacuum ultraviolet, visible, and near-infrared regions
- Dielectric overcoat minimizes oxidation and increases abrasion resistance
- R > 90% 193 nm, R_{ave} ≥85% at 400–1200 nm

Based on CVI Melles Griot high-density Al coating technology, broadband DUVA mirrors provide significantly higher 193-nm reflectance and durability than standard UV-protected Al mirrors. Choose build-to-print or off-the-shelf optics for your ellipsometry, spectroscopy, and semiconductor lithography or metrology applications.

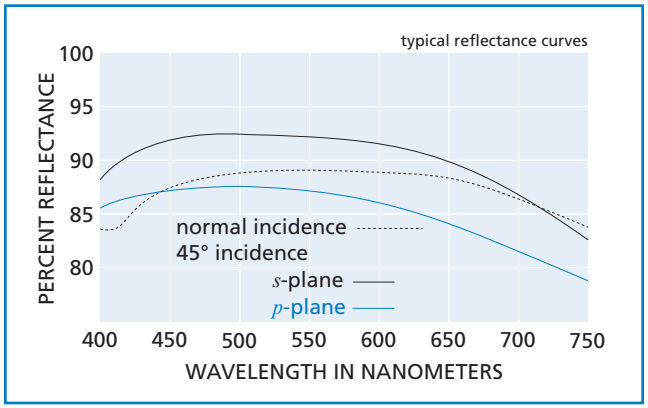
Ultraviolet Protected Aluminum (PAUV)



- Maintains reflectance in the ultraviolet region
- Dielectric overcoat prevents oxidation and increases abrasion resistance
- R_{avg} > 86% from 250 to 400 nm
- R_{avg} > 85% from 400 to 700 nm
- Damage threshold: 0.07J/cm^2, 10-nsec pulse (5.7 MW/cm^2) at 355 nm typical

The protective dielectric layer prevents oxidation and improves abrasion resistance. While the resulting surface is not as abrasion resistant as our protected aluminum it can be cleaned with care.

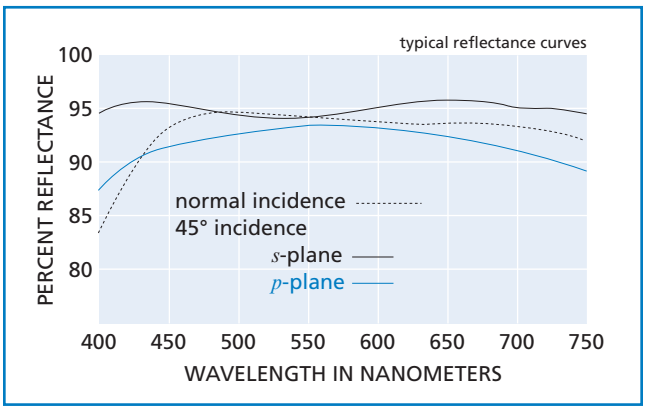
Protected Aluminum (PAV)



- The best general-purpose metallic reflector for visible to near-infrared
- Protective overcoat extends life of mirror and protects surface
- R_{avg} > 90% from 400 to 10.0μm
- Damage threshold: 0.3J/cm^2, 10-nsec pulse (21 MW/cm^2) at 532 nm typical; 0.5 J/cm^2, 20-nsec pulse (22 MW/cm^2) at 1064 nm typical

Protected aluminum is the very best general-purpose metallic coating for use as an external reflector in the visible and near-infrared spectra. The protective film arrests oxidation and helps maintain a high reflectance. It is also durable enough to protect the aluminum coating from minor abrasions.

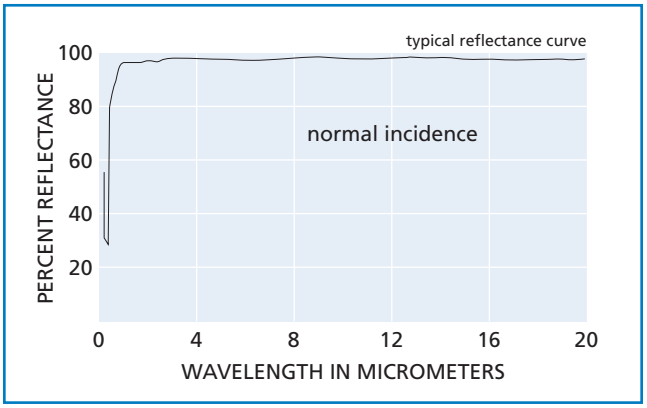
Enhanced Aluminum (EAV)



- Enhanced performance in the mid-visible region
- Durability of protected aluminum
- R_{avg} > 92% from 450 to 650 nm
- Damage threshold: 0.4J/cm^2, 10-nsec pulse (33 MW/cm^2) at 532 nm typical; 0.3 J/cm^2, 20-nsec pulse (12 MW/cm^2) at 1064 nm typical

By coating the aluminum with a multilayer dielectric film, reflectance is increased over a wide range of wavelengths. This coating is well suited for applications requiring the durability and reliability of protected aluminum, but with higher reflectance in the mid-visible regions.

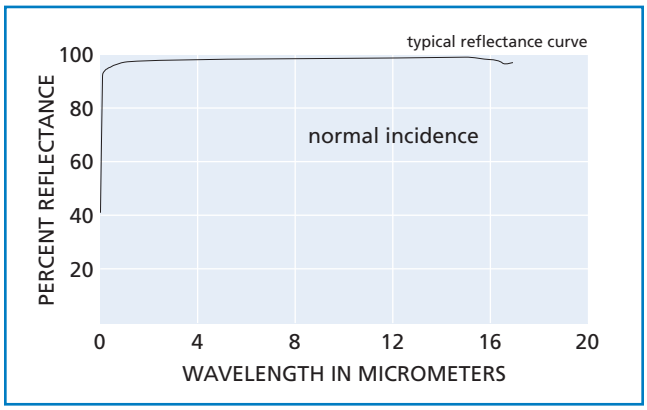
Protected Silver (PS)



- Extremely versatile mirror coating
- Excellent performance for the visible to infrared region
- R_{avg} > 95% from 400 nm to 20 μm
- Can be used for ultrafast Ti:Sapphire laser applications
- Damage threshold: 0.9 J/cm^2, 10-nsec pulse (75 MW/cm^2) at 532 nm typical; 1.6 J/cm^2, 20-nsec pulse (73 MW/cm^2) at 1064 nm typical

CVI Melles Griot uses a proprietary coating and edge-sealing technology to offer a first-surface external protected silver coating. In recent tests, the protected silver coating has shown no broadening effect on a 52-femtosecond pulse. This information is presented as an example of performance for femtosecond applications, but no warranty is implied.

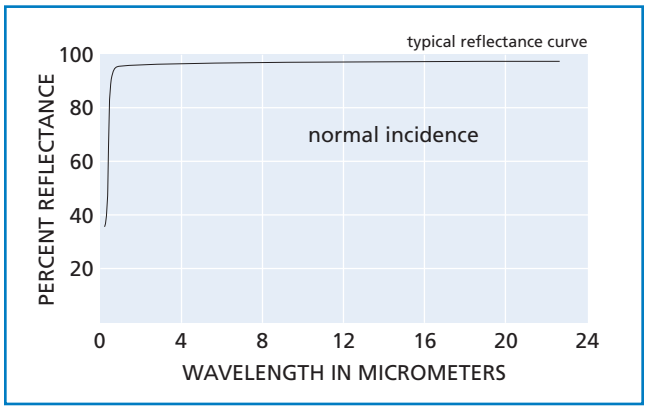
Protected Gold (PG)



- Protective overcoat extends coating life
- $R_{avg} \geq$ 95.0% from 650 nm to 10 μm
- Damage threshold: 0.4 J/cm^2, 20-nsec pulse (17 MW/cm^2) at 1064 nm typical

The CVI Melles Griot proprietary protected gold mirror coating combines the natural spectral performance of gold with the durability of hard dielectrics. Protected gold provides over 95% average reflectance from 650 nm 10 μm. At a wavelength of 3 μm, the PG coating was tested for laser-induced damage and was found to withstand up to 18 $\pm$ 2 J/cm2 with a 260-μs pulse (0.4 MW/cm2). These mirrors can be cleaned regularly using standard organic solvents, such as alcohol or acetone.

Bare Gold (PG-BARE)



- Widely used in the near, middle, and far infrared
- Effectively controls thermal radiation
- R_{avg} > 99% from 700 nm to 20 μm
- Damage threshold: 1.1 J/cm^2, 20-nsec pulse (48 MW/cm^2) at 1064 nm typical

Bare gold combines good tarnish resistance with consistently high reflectance throughout the near, middle, and far-infrared regions. Because bare gold is soft and scratches easily CVI Melles Griot recommends using flow-washing with solvents and clean water or blowing the surface clean with a low-pressure stream of dry air for cleaning the coated mirror surface.

MAXBRIte™ Coatings (MAXB)

MAXBRIte™ (multilayer all-dielectric xerophilous broadband reflecting interference) coatings are the best broadband mirror coatings commercially available. The MAXBRIte™ coatings are available for four broad regions. 245 nm to 390 nm, 420 nm to 700 nm, 480 nm to 700 nm, and 630 nm to 850 nm. They all reflect over 98 percent of incident laser radiation within their respective wavelength ranges.

These coatings exhibit exceptionally high reflectances for both *s*- and *p*-polarizations. In each case, at the most important laser wavelengths and for angles of incidence as high as 45 degrees, the average of *s*- and *p*-reflectances exceeds 99 percent. For most applications, they are superior to metallic or enhanced metallic coatings.

The MAXB-248-390 ultraviolet MAXBRIte coating provides superior performance for a broad range of ultraviolet applications using some of the excimer lasers, third and fourth harmonics of most solid-state lasers, and mercury and xenon lamps.

The MAXB-420-700 MAXBRIte coating is particularly useful for helium cadmium lasers at 442 nm, or the blue lines of argon-ion lasers.

The MAXB-480-700 MAXBRIte coating is suitable for instrumental and external laser-beam manipulation tasks. It is the ideal choice for use with tunable dye and parametric oscillator systems.

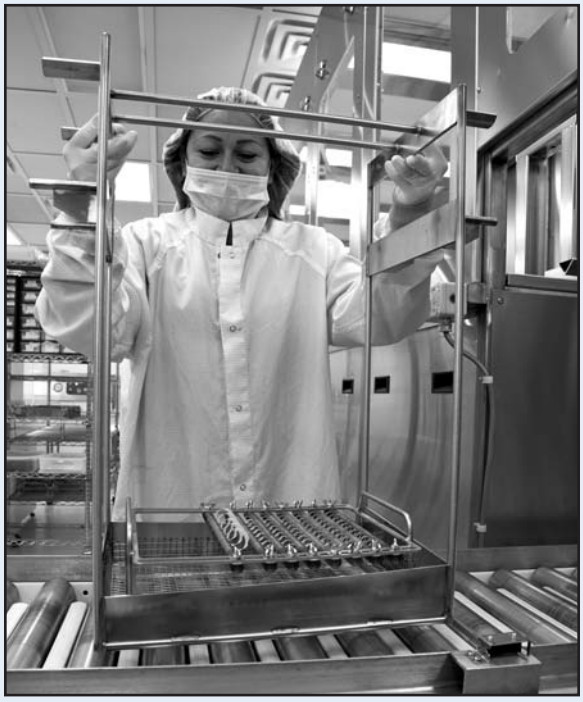
The MAXB-630-850 MAXBRIte coating covers all the important visible and near-infrared diode laser wavelengths from 630 to 850 nm. This broadband coating is ideal for applications employing nontemperature-stabilized diode lasers where wavelength drift is likely to occur. The MAXB-630-850 also makes it possible to use a HeNe laser to align diode systems.

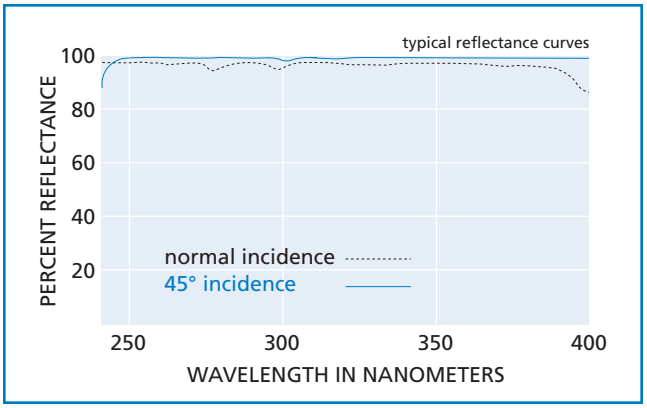
The ultraviolet MAXB-245-390 coating provides superior performance for ultraviolet applications. It is ideal for use with many of the excimer lasers, as well as third and fourth harmonics of most solid-state lasers. It is also particularly useful with broadband ultraviolet light sources, such as mercury and xenon lamps. Due to mechanical stresses within this advanced coating, it is limited to substrates having a surface figure accuracy specification of no greater than $\lambda/4$ (versus an absolute standard).

The extended MAXB-420-700 coating offers superior response below 500 nm, and it is particularly useful for helium cadmium lasers at 442 nm, or the blue lines of argon-ion lasers. Like MAXB-245-390, mechanical stresses in this complex coating limit its use to substrates with a surface figure accuracy specification of no greater than $\lambda/4$.

Optics Glass Cleaning

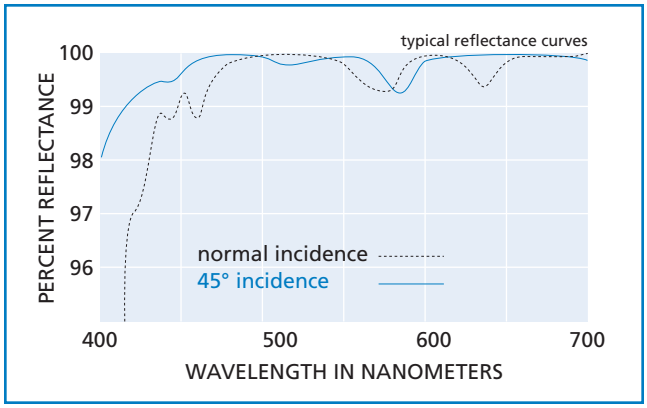
CVI Melles Griot removes all contamination from substrates prior to coating with a high-volume, seven-stage enclosed HEPA-filtered aqueous glass cleaner.





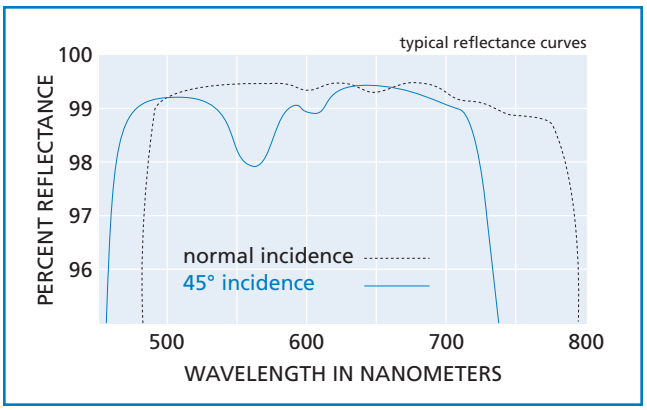
MAXB-245-390 coating

- R_{avg} > 98% from 245 to 390 nm
- Damage threshold: 0.92 J/cm^2, 10-nsec pulse at 532 nm typical



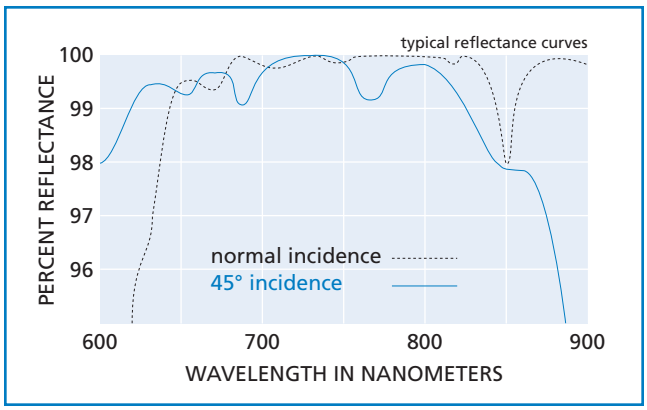
MAXB-420-700 coating

- R_{avg} > 98% from 420 to 700 nm
- Damage threshold: 0.4 J/cm^2, 10-nsec pulse at 532 nm typical



MAXB-480-700 coating

- R_{avg} > 98% from 480 to 700 nm
- Damage threshold: 0.92 J/cm^2, 10-nsec pulse at 532 nm typical



MAXB-630-850 coating

- R_{avg} > 98% from 630 to 850 nm
- Damage threshold: 0.92 J/cm^2, 10-nsec pulse at 532 nm typical

Laser-Line MAX-R™ Coatings

Laser-line MAX-R™ coatings have been upgraded to higher damage threshold designs. While maintaining the high reflectivity and same optimized coating for angles of incidence at 0 degrees or 45 degrees, the damage thresholds have been significantly improved. The table below has been created to identify the new product codes. Please refer to the product code index for the additional specifications for these mirrors. If you have any additional questions please contact our customer service representatives for assistance.

- Highest possible reflectance achieved at specific laser wavelengths and typical angles of incidence
- Standard MAX-R™ coatings available for popular laser wavelengths, at both 0-degree and 45-degrees angle of incidence
- Custom coatings available from 193 to 1550 nm

Product Upgrade

The Laser-Line MAX-R™ mirrors have been upgraded to fit within our broader offering of laser-line mirrors. A full list of the former Melles Griot part numbers and the new CVI Melles Griot part numbers has been included in the Mirror section of this catalog under Laser-Line MAX-R™.

Laser-Line MAX-R™ Coatings, Normal Incidence

Wavelength (nm)	Laser Type	Minimum Reflectance R_p (%) 0° Incidence	Minimum Reflectance R_p (%) 0° ± 15° Incidence	Former Coating Suffix ‡	PRODUCT CODE
193	ArF	97.0	94.0	/201	ARF
248	KrF	98.0	95.0	/202	KRF
266	Nd 4th harmonic	98.0	95.0	/203	Y4
308	XeCl	99.0	96.0	/204	XECL
351	Ar ion	99.0	96.0	/205	AR3
364	Ar ion	99.0	96.0	/207	AR3
442	HeCd	99.3	99.0	/209	HC1
458	Ar ion	99.5	99.3	/211	AR2
466	Ar ion	99.5	99.3	/213	AR2
473	Ar ion	99.5	99.3	/215	AR2
476	Ar ion	99.5	99.3	/217	AR2
488	Ar ion	99.5	99.3	/219	AR1
496	Ar ion	99.5	99.3	/221	AR1
502	Ar ion	99.5	99.3	/222	AR1
514	Ar ion	99.5	99.3	/223	AR1
532	Nd 2nd harmonic	99.5	99.3	/225	Y2
543	HeNe	99.5	99.3	/226	CV
633	HeNe	99.5	99.3	/229	HN
670	GaAlAs	99.5	99.3	/228	LDM
780	GaAlAs	99.3	99.0	/233	LDM
830	GaAlAs	99.3	99.0	/237	LDM
1064	Nd	99.2	99.0	/241	Y1
1300	InGaAsP	99.2	99.0	/245	LDM
1523, 1550	HeNe, InGaAsP	99.2	99.0	/247	LDM

‡ Former Coating Suffix number has been replaced by new CVI Melles Griot Part Code. Please refer to the part number structure in the product code sections.

Laser-Line MAX-R™ Coatings, 45-Degree Incidence

Wavelength (nm)	Laser Type	Minimum Reflectance R_p (%) 45° Incidence	Minimum Reflectance R_p (%) 45° ± 15° Incidence	Former Coating Suffix ‡	PRODUCT CODE
193	ArF	97.0	94.0	/251	ARF
248	KrF	98.0	95.0	/252	KRF
266	Nd 4th harmonic	98.0	95.0	/253	Y4
308	XeCl	98.0	95.0	/254	XECL
351	Ar ion	98.0	96.0	/255	AR3
364	Ar ion	98.0	96.0	/257	AR3
442	HeCd	99.0	98.0	/259	HC1
458	Ar ion	99.3	98.0	/261	AR2
466	Ar ion	99.3	98.5	/263	AR2
473	Ar ion	99.3	98.5	/265	AR2
476	Ar ion	99.3	98.5	/267	AR2
488	Ar ion	99.3	98.5	/269	AR1
496	Ar ion	99.5	98.5	/271	AR1
502	Ar ion	99.5	98.5	/272	AR1
514	Ar ion	99.5	98.5	/273	AR1
532	Nd 2nd harmonic	99.5	98.5	/275	Y2
543	HeNe	99.5	98.5	/276	CV
633	HeNe	99.5	98.5	/279	HN
670	GaAlAs	99.0	98.5	/278	LDM
780	GaAlAs	99.0	98.5	/283	LDM
830	GaAlAs	99.0	98.5	/287	LDM
1064	Nd	99.0	98.0	/291	Y1
1300	InGaAsP	99.0	98.5	/295	LDM
1523, 1550	HeNe, InGaAsP	99.0	98.5	/297	LDM

‡ Former Coating Suffix number has been replaced by new CVI Melles Griot Part Code. Please refer to the part number structure in the product code sections.

Ultrafast Coating (TLMB)

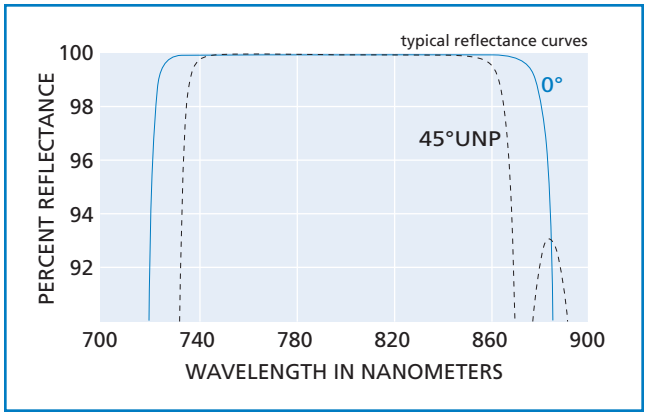
CVI Melles Griot has developed a new coating for ultrafast laser systems operating in the near-infrared spectral region. This all-dielectric coating, centered at 800 nm, minimizes pulse broadening for ultrafast applications. The coating also offers exceptionally high reflectance for both *s*- and *p*-polarizations in the 750 nm to 870 nm spectral region.

The ultrafast coating is ideal for high-power Ti:sapphire laser applications. This coating is superior to protected and enhanced metallic coatings because of its ability to handle higher powers.

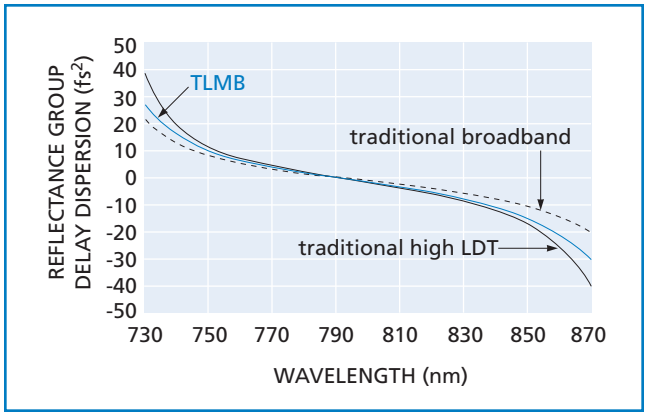
Ultrafast Coating (TLMB)

Wavelength Range (nm)	Minimum Reflectance R_p (%)	Angle of Incidence (degrees)	Pulse Broadening (%)	Former Coating Suffix ‡	Product Code
770–830	99.0	45	<18.0	/091	TLMB

‡ Former Coating Suffix number has been replaced by new CVI Melles Griot Part Code. Please refer to the part number structure in the product code sections.



TLMB Ultrafast coating



A comparison of Reflectance Group Delay Dispersion vs. Wavelength of traditional broadband, traditional high LDT, and the CVI Melles Griot TLMB Ultrafast mirror

Optical Filter Coatings

Absorption, Transmittance, and Optical Density

Absorption, particularly wavelength-selective absorption, is an important factor in the function of many of the filters described in the catalog. The two most commonly used absorbers are thin metallic films and "colored" glass. Some metallic films, such as Inconel®, chromium, and nickel, are particularly insensitive to wavelength for absorption. On the other hand, the amount of absorption by colored glass can vary by as much as several orders of magnitude in only tens of nanometers.

Metallic films, colored glasses, and thin dielectric films (sometimes all in the same unit) are used in CVI Melles Griot filters. These filters include wavelength-invariant varieties (neutral-density filters) and various wavelength-selective filters (colored-glass, high-pass and low-pass filters, edge filters, dichroics, and interference filters).

ABSORPTION

All materials will absorb radiation in some parts of the electromagnetic spectrum. The amount of absorption depends on the wavelength, the amount of absorbing material in the radiation path, and the absorption of that material at that wavelength. Materials that absorb some visible wavelengths appear colored. For purposes of this catalog, colored glass refers to glass that is a wavelength-selective absorber in the near-ultra-violet to the near-infrared region.

Absorption occurs when the electric field of a light wave interacts with absorbing atoms or molecules in an oscillating dipole interaction. The photon is absorbed and the atom or molecule is placed in an excited state. This process occurs only at resonant wavelengths. In a solid or liquid absorber, excitation energy is dissipated as heat (vibrations of particles). Therefore, filters that rely mainly on absorption are not ideal for high-power laser applications. The intense local heating can lead to structural damage.

TRANSMITTANCE

As a beam of light passes through an absorbing medium, the amount of light absorbed is proportional to the intensity of incident light times the absorption coefficient. Consequently, the intensity of an incident beam drops exponentially as it passes through the absorber. This is often expressed as Beer's law:

$$T_i = 10^{-\alpha c x}$$

where T_i is internal transmittance, α is the absorption coefficient, c is the concentration of absorbers, and x is the overall thickness of the absorbing medium. Clearly α, and hence T_i, are wavelength dependent. For solid absorbing mediums, $c = 1$.

Internal transmittance is the transmittance of an optical element when surface (coated or uncoated) losses are ignored. The measured transmittance of the element (including surface effects), transmittance, is called external transmittance, T.

Alternatively, a filter is defined by the amount of light it blocks, as opposed to the amount of light it transmits. This parameter is opacity, which is simply the reciprocal of the transmittance, $1/T$.

The transmittance of a series of filters is the product of their individual external transmittance, $T_1 \times T_2 \times T_3$, etc. Because transmittance (and hence opacity) is multiplicative, and since transmittance may extend over many orders of magnitude, it is often more convenient to use a logarithmic expression to define transmittance.

OPTICAL DENSITY

Optical density, or "density," is the base 10 logarithm of opacity:

$$D = \log(1/T)$$

As optical density increases, the amount of light blocked by the filter (by reflection and/or absorption) increases. The most important point to note is that optical density is additive. If several filters are stacked in series, their combined optical density is the sum of the individual optical densities.

Optical density is particularly useful for neutral-density (ND) filters. These filters, which have a very flat wavelength response, are used to attenuate light in a calibrated, chromatically invariant fashion. ND filters are supplied in sets of various calibrated densities. Combinations of these filters can be used to produce many different calibrated optical densities.

Inconel® is a registered trademark of EM industries, Inc.

Interference Filters

Interference filter applications are extremely diverse, including disease diagnosis, spectral radiometry, calorimetry, and color separation in television cameras. Used with even the least expensive broadband photometers or radiometers, CVI Melles Griot interference filters enable rapid and accurate measurement of the amplitude of specific spectral lines. This combination has an enormous throughput advantage since the collecting area of filters is very large compared to instrumental slits. Additionally, interference filters enable the viewing and near-instantaneous recording of very spectrally selective images. Spatial and spectral scanning instruments can provide similar images but take much longer.

Narrowband interference filters permit isolation of wavelength intervals a few nanometers or less in width, without dispersion elements such as prisms or gratings. For example, a single line in the emission spectrum of a flame can be monitored without confusion from other nearby lines, or the signal from a laser communications transmitter can be received without interference from a brightly sunlit landscape. Colored-glass and gelatin filters are incapable of such discrimination.

Interference filters are multilayer thin-film devices. While many interference filters may be correctly described as "all dielectric" in construction, metallic layers are often present in auxiliary blocking structures. Broadband interference filters almost always contain a metallic layer (in their spacers, not in their stacks). Interference filters come in two basic types, which transmit a desired wavelength interval while simultaneously rejecting both longer and shorter wavelengths, and edge filters.

FABRY-PEROT INTERFEROMETER

Narrowband interference filters (bandpass filters) operate with the same principles as the Fabry-Perot interferometer. In fact, they can be considered Fabry-Perot interferometers since they usually operate in the first order.

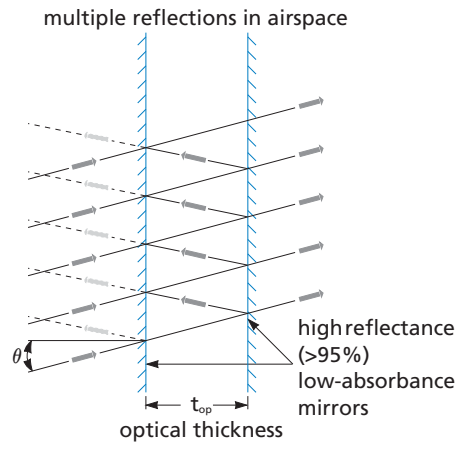
The Fabry-Perot is a simple interferometer, which relies on the interference of multiple reflected beams. The accompanying figure shows a schematic Fabry-Perot cavity. Incident light undergoes multiple reflections between coated surfaces which define the cavity. Each transmitted wavefront has undergone an even number of reflections (0, 2, 4, . . .). Whenever there is no phase difference between emerging wavefronts, interference between these wavefronts produces a transmission maximum. This occurs when the optical path difference is an integral number of whole wavelengths, i.e., when

$$m\lambda = 2t_{op}\cos\theta$$

where m is an integer, often termed the order, t_{op} is the optical thickness, and θ is the angle of incidence. At other wavelengths, destructive interference of transmitted wavefronts reduces transmitted intensity toward zero (i.e., most, or all, of the light is reflected back toward the source).

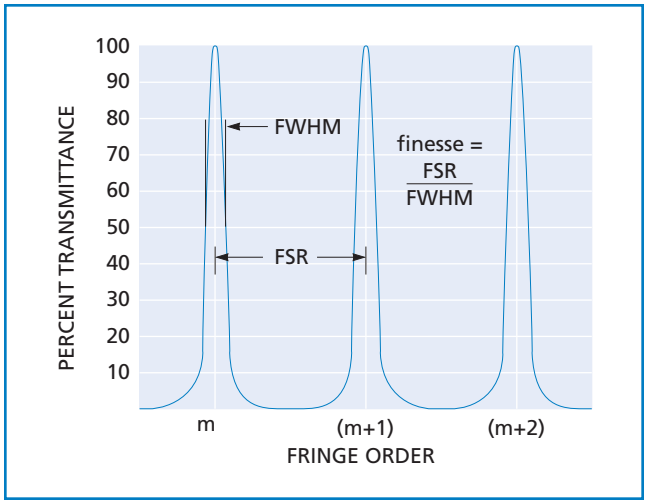
Transmission peaks can be made very sharp by increasing the reflectivity of the mirror surfaces. In a simple Fabry-Perot interferometer transmission curve (see figure), the ratio of successive peak separation to full width at half-maximum (FWHM) transmission peak is termed finesse. High reflectance results in high finesse (i.e., high resolution).

In most Fabry-Perot interferometers, air is the medium between high reflectors; therefore, the optical thickness, t_{op}, is essentially equal to d, the physical thickness. The air gap may vary from a fraction of a millimeter to several centimeters.The Fabry-Perot is a useful spectroscopic tool. It provided much of the early motivation to develop quality thin films for the high-reflectance mirrors needed for high finesse. Fabry-Perot interferometers can be constructed from purely metallic coatings, but high absorption losses limit performance.



Schematic of a Fabry-Perot interferometer

continued

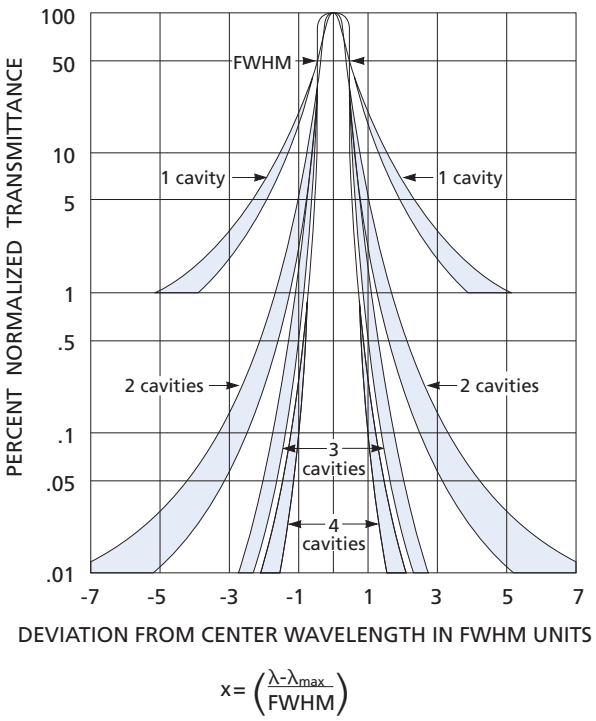


Transmission pattern showing the free spectral range (FSR) of a simple Fabry-Perot interferometer

BANDPASS FILTER DESIGN

The simplest bandpass filter is a very thin Fabry-Perot interferometer. The air gap is replaced by a thin layer of dielectric material with a half-wave optical thickness (optimized at the wavelength of the desired transmission peak). The high reflectors are normal quarter-wave stacks with a broad-band reflectance peaking at the design wavelength.

The entire assembly of two quarter-wave stacks, separated by a half-wave spacer, is applied to a single surface in one continuous vacuum deposition run. By analogy with interferometers, the simplest bandpass interference filters are sometimes called cavities. Two or more such filters can be deposited one on top of the other, separated by an absentee layer, to form a multiple-cavity filter. Increasing the number of cavities has a significant effect on the shape of the passband (see figure). The resulting overall passband transmittance is given approximately by the product of the pass-bands of individual cavities. The advantages of multiple-cavity filters are steeper band slopes, improved near-band rejection, and "square" (not Gaussian or Lorentzian) passband peaks. This last result, especially desirable in intermediate-bandwidth filters, is achieved in part by reducing stack reflectance, which broadens individual cavity passbands.The construction of a typical two-cavity interference filter, along with an exploded view showing the detailed structure of the all-dielectric multilayer band-pass filter film, is shown in the accompanying figure. H symbolizes a precisely quarter-wavelength optical thickness layer of a high-index material (typically zinc sulfide, ZnS), while L symbolizes a precisely quarter-wavelength optical thickness layer of a low-index material (typically cryolite, Na_3AlF_6). The spacer is a layer of high-index material of half-wavelength thickness, and the absentee, or coupling, layer is a layer of low-index material of half-wavelength thickness. Here, wavelength refers to the wavelength of peak transmittance. Layers are formed by vacuum deposition. The aluminum rings protect the edges, and epoxy cement protects the films from moisture and laminates the bandpass and blocker sections together.



Note: The actual FWHM will be different in each case.

Effect of number of cavities on passband shape for typical interference filters with 10-nm FWHM

continued

ADDITIONAL BLOCKING

Close to the passband, and on the long wavelength side, multilayer blocking structures (usually metal dielectric hybrid filters) are used in CVI Melles Griot passband filters to limit transmittance to 0.01 percent. More stringent blocking is possible, but this increases filter cost and compromises maximum transmission. Colored glass is often used to suppress transmission on the short wavelength side of the passband.

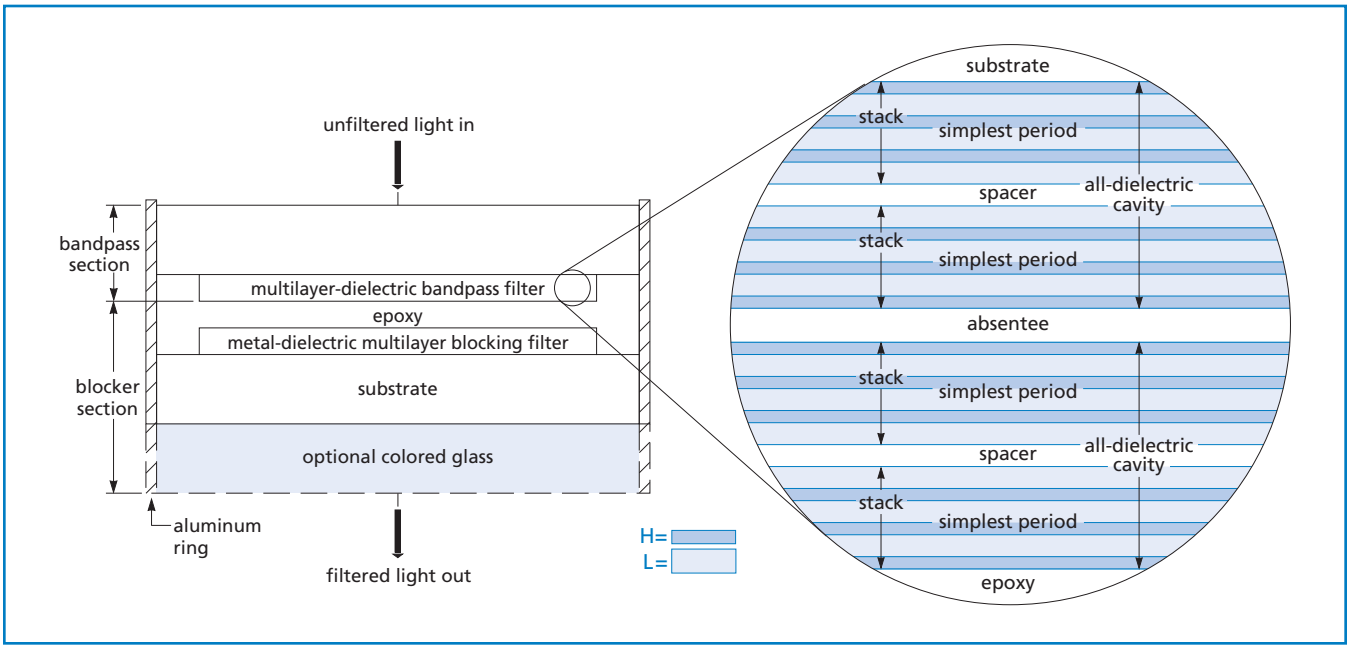
TABLE OF NORMALIZED PASSBAND SHAPE

The graph showing change in filter performance as a function of the number of cavities is qualitatively useful, but the following bandwidth table gives quantitative data. This table applies to zinc sulfide (ZnS)/cryolite (Na_3AlF_6) interference filters of any FWHM.

Although the table is strictly applicable from 400 nm to 1100 nm, CVI Melles Griot ultraviolet filters, which are of different composition, have very similar characteristics. The table shows the functional dependence of normalized passband shape on the number of cavities used in filter construction, with FWHM arbitrary but held fixed. Because transmittance is normalized to peak value, the table is applicable to blocked and unblocked filters. To apply the table to a specific filter, simply multiply by peak transmittance. Both minimum and maximum full bandwidths are shown at various normalized transmittance levels. The difference between minimum and maximum full bandwidths allows for spacer material choice and filter-to-filter variation. Normal incidence is assumed. Beyond the spectral range displayed here, our filters of two-, three-, and four-cavity construction are supplied with blocking structures that limit absolute transmittance to less than 10^{-4}.

WAVELENGTH DEPENDENCE ON ANGLE OF INCIDENCE

A common characteristic of single and multilayer dielectric coatings and interference filters is that transmittance and reflectance spectra shift to shorter wavelengths as they are tilted from normal to oblique incidence. This applies to both edge and bandpass filters. As tilt is increased in filters constructed with metallic layers, the transmittance peak splits into two orthogonally polarized peaks which shift to shorter wavelengths at different rates. CVI Melles Griot narrowband filters are made with all-dielectric multilayers to prevent this transmittance split from occurring.



Cross section of a typical two-cavity interference filter

continued

Bandwidth at Various Normalized Transmittances

Number of Cavities	Normalized Transmittance Level (% of peak)	Minimum	Maximum
1	90	0.30	0.35
	10	2.50	3.00
	1	8.00	10.00
2	90	0.50	0.60
	1	2.80	3.50
	0.1	5.50	6.30
	0.01	10.00	15.00
3	90	0.70	0.80
	1	1.90	2.20
	0.1	2.90	3.20
	0.01	4.90	5.40
4	90	0.85	0.90
	1	1.50	1.65
	0.1	2.00	2.25
	0.01	3.50	4.25

The shift to shorter wavelengths at oblique incidence is very useful in tuning bandpass filters from one wavelength to another, or adjusting the half-power point wavelengths of edge filters in collimated light. If the to shift wavelength enhances the usefulness to interference filter sets. Each filter in variable bandpass sets can be angle tuned down to the normal incidence transmission wavelength of the next filter in the set. Wavelengths of transmittance peaks or cavity resonances for Fabry-Perot interferometers and bandpass interference filters are approximately governed, for observers within the cavity or spacer, by the equation

$$2n_e t\cos\theta = m\lambda$$

where n_e is the spacer refractive index, t is the spacer thickness, θ is the internal angle of incidence (measured within the cavity or spacer), m is the order number of interference (a positive integer), and λ is the wavelength of a particular resonance transmittance peak. This equation is often called the monolayer approximation. The formula can be satisfied simultaneously for many different order number and wavelength combinations. Corresponding to each such combination there is, in principle, a different resonance transmittance peak for an unblocked filter. For an all-dielectric filter there are, between cavity resonance transmittance peaks, additional broader peaks that correspond to the wavelengths at which the dielectric stacks are ineffective as resonant reflectors. Only a single resonance transmittance peak is selected for use and allowed to appear in the output spectrum of a complete (blocked) interference filter. Blocking techniques are highly effective.

FWHM Example

A three-cavity filter at the 1% normalized transmittance level (1% of peak) would have a nominal full bandwidth (full width at 1% of maximum) between the limits of 1.9 and 2.2. If the FWHM were 5.0 nm, the full width at 1% of maximum would be between 9.5 and 11.0 nm.

High-Volume or Special Filters for OEMs

CVI Melles Griot can supply filters listed in this section in volume to OEM users. Volume users frequently do not require an individual spectrophotometer curve for each filter.

CVI Melles Griot can also supply custom interference filters. When specifying a custom filter, please give us the center wavelength, FWHM, blocking, minimum peak transmission, and size. Each of these factors has a significant impact on cost and therefore should not be specified more tightly than required by the application.

continued

In terms of the external angle of incidence, ϕ, it can be shown that the wavelength of peak transmittance at small angles from normal incidence is given by

$$\lambda = \lambda_{max}\sqrt{1 - \left(\frac{n_0}{n_e}\right)^2 \sin^2\phi}$$

where n_0 is the external medium refractive index ($n_0 = 1.0$ in air) and n_e is the spacer effective refractive index. The difference $\lambda_{max} - \lambda$ is the angle shift. The spacer effective index is dependent on wavelength, film material, and order number because of multilayer effects. The effective index and actual refractive index of spacer material is not equivalent, although the same symbol n_e is used for both. By curve-fitting the second formula above (from which t is absent) to measured angle shifts at small angles, the effective index and angle at which blocker displacement of the peak becomes significant can, in principle, be found. In the absence of actual measurements, the formula probably should not be trusted much beyond five or ten degrees. With suitable interpretation, the formula can be applied to prominent landmarks in transmittance and reflectance spectra of edge filters, multi- and single-layer coatings, and all interference filters.

In many applications, angle shifts can be safely ignored. Advanced radiometer designs are necessary only when wide fields and narrow bandwidths are simultaneously required. For example, if the desired monochromatic signal is to be at least 90 percent of T_{peak} throughout the field and the filter has a narrow 1.0-nm FWHM, the angular radius is only about 2.5 degrees. Most CVI Melles Griot filters use a high-index spacer (usually zinc sulfide) to minimize angle shift. Some use low-index spacers (usually cryolite) to achieve higher transmittance or narrower bandwidths.

CORRECT INTERFERENCE FILTER ORIENTATION

A good rule of thumb, especially important if there is risk of overheating or solarization, is that interference filters should always be oriented with the shiniest (metallic) and most nearly colorless side toward the source in the radiant flux. This orientation will minimize thermal load on the absorbing-glass blocking components. Reversing filter orientation will have no effect on filter transmittance near or within the passband.

TEMPERATURE EFFECTS, LIMITS, AND THERMAL SHOCK

The transmittance spectrum of an interference filter is slightly temperature dependent. As temperature increases, all layer thicknesses increase. At the same time, all layer indices change. These effects combine in such a way that the transmittance spectrum shifts slightly to longer wavelengths with increasing temperature. The thermal coefficient is a function of wavelength, as shown in the following table.

CVI Melles Griot interference filters are designed for use at 20°C. Unless bandpass filters with extremely narrow FWHMs are used at very different temperatures, the transmittance shifts indicated in the table are negligible. Our standard interference filters can be used at temperatures down to −50°C. Thermal contraction will result in permanent filter damage below this temperature. High-temperature limits depend on filter design: 70°C is a safe and conservative limit for all filters. Some of our standard filters can accommodate temperatures up to 125°C. As a general rule, it is unwise to subject interference filters to thermal shock, especially as the lower limit of −50°C is approached. Temperature change rates should not exceed 5°C per minute.

Temperature Dependence of Peak Transmittance

Wavelength (nm)	Temperature Coefficient of Shift (nm per °C)
400	0.016
476	0.019
508	0.020
530	0.021
557	0.021
608	0.023
630	0.023
643	0.024
710	0.026
820	0.027

continued

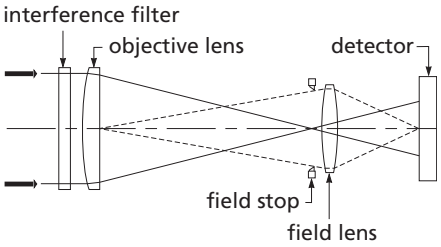
CVI Melles Griot Clean-Room Standards

To ensure that we provide the highest quality, all optical coating, cleaning and inspection of substrate material takes place in Class 1000 and 10,000 clean-rooms. Class 100 laminar flow benches are used during final inspection and components packaging.

APPLICATION NOTE

Interference Filter Usage

Narrowband interference filters are extremely angle sensitive. The transmittance of a filter with a FWHM of 1.0 nm will decrease by 10 percent, at the transmission wavelength, for field angles of only 2.5 degrees. For field angles of 5 degrees, the transmittance decreases collimated portions of optical paths by over 90%. It is important, therefore, to use narrowband interference filters. The illustration shows the design of a narrow-field spectral radiometer for infinite conjugate ratio use, and it indicates the proper interference filter location. The radiometer consists of an interference filter, objective lens, field lens, field stop, and detector. The field lens, which images the objective lens onto the detector's sensitive area, ensures uniform illumination of the detector. The field of view is limited by a field stop placed close to the field lens.



Neutral-Density Filters

Neutral-density (ND) filters attenuate, split, or combine beams in a wide range of irradiance ratios with no significant dependence on wavelength. These carefully prepared filters find wide application for precise attenuation or control of light. For example, beams can be attenuated to levels where photometers or radiometers are most accurate and linear, thereby extending their useful range.

All CVI Melles Griot ND filters pass stringent optical and mechanical tests. Individual ND filters and ND filter sets are in stock and ready to ship. Our applications engineers will be pleased to assist you in the selection and application of standard or custom filters.

Optical density (D) is defined as the base 10 logarithm of the reciprocal of transmittance (T):

$D = \log(1/T)$, or $T = 10^{-D}$.

Optical density is analogous to the definition of decibel as used in electronics. ND filters used in combinations are additive if multiple reflections between filters do not occur in the direction of interest. The reciprocal of transmittance, $1/T$, is called opacity. Also in widespread use is relative optical density, D_r, the difference between density D of a coated substrate and density D_0 of an uncoated region of the same substrate:

$$D_r = D - D_0$$
$$\text{or } D = D_r + D_0.$$

In terms of refractive index n,

$$D_o = 2 \log \frac{(n+1)^2}{4n}.$$

At 550 nm, D_0 is typically about 0.0376 for BK7, and about 0.0309 for synthetic fused silica. Relative density D_r, not absolute density D, is the quantity that appears on individual microdensitometer traces supplied with CVI Melles Griot circular variable filters, because many variable filter applications require focal plane position or plate aberration constancy. This requirement prohibits removal or perforation of the substrate to achieve D=0.0 accurately. In such instruments, performance is referenced to a blank, and density differences, not the densities themselves, are important.

Transmittance and density values may, like reflectance values, refer to either small angular fields (specular or undeviated values) or very large angular fields (diffuse or hemispherical values). The measurements that determine hemispherical values include both specular and scattered contributions. Density and relative density values for CVI Melles Griot ND filters are specular values based on external transmittance.

Because of Beer's and Fechner's laws (sensation proportional to logarithm of stimulus, applicable to vision as a special case), it has been historically convenient to use the logarithmic density scale, instead of a transmittance scale. While optical density is dimensionless, the notation 0.50 D is sometimes used to mean 0.50 density units, or simply a density of 0.50.

Two or more ND filters can be used to achieve values of transmittance or density not otherwise available.If they are arranged so that multiple reflections between them do not occur in the direction of interest, transmittance values are multiplicative, whereas optical densities are additive. By combining various filters, many separate density values may be achieved.

CVI Melles Griot provides two types of ND filters: metallic (reflective) and glass (absorptive).

METALLIC NEUTRAL-DENSITY FILTERS

All CVI Melles Griot metallic ND filters are made with BK7-fine annealed glass, or optical-quality synthetic fused silica. Vacuum deposition is used to apply a thin film of several special metallic alloys to the substrate. These alloys have been chosen to create a spectral-density curve that is flatter over a wider range than the curves of most pure metals. Substrate materials are chosen for homogeneity, transmittance uniformity, finishing characteristics, and (in the case of synthetic fused silica) ultraviolet transmittance.

Substrates are polished to minimize light scattering. Metallic ND filters can be used at any wavelength between 200 and 2500 nm (fused silica), or between 350 and 2500 nm (BK7). Their operation depends on absorption in, and reflection from, the thin metallic film.

When used in high-intensity beams, ND filters should be oriented with the metallic film facing toward the source to minimize substrate absorption and heating. Alloy films are corrosion resistant and do not age at normal temperatures. Adhesion of alloy films to their substrates is tenacious and unaffected by moisture and most solvents from −73°C (−100°F) to +150°C (302°F). Exposure to higher temperatures should be avoided because it causes film oxidation and increased transmittance. These filters are not suitable for use with high-power pulsed lasers.

ABSORPTIVE NEUTRAL-DENSITY FILTERS

Absorptive ND filters provide an alternative to metallic ND filters. The neutrality of the filter is a function of material and thickness. Since there can be large variations between glass melts, actual thickness and glass material may vary in order to guarantee optical density. These filters are recommended for low-power applications only, because of their absorbing properties.

FILTER SET CONTENTS

Each individual filter is checked, and an optical density spectrophotometer curve from the coating run is included with each filter. Measured ranges are from 200 to 700 nm for sets on synthetic fused silica, and from 350 to 700 nm for sets on BK7 substrates. Individual spectrophotometer curves are available on special request.

Some sets include a blank (uncoated) substrate of the same material and thickness used for the filters. This blank is often very helpful for aligning and focusing optical systems before inserting the ND filter.

Each ND filter set is packaged in a wooden case.

Laser-Induced Damage

CVI Melles Griot conducts laser-induced damage testing of our optics. Although our damage thresholds do not constitute a performance guarantee, they are representative of the 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 given is the peak fluence (energy per square centimeter), pulse width, peak irradiance (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), and the test wavelength is the wavelength of the laser used to incur the damage. The peak irradiance is the energy of each pulse divided by the effective pulse length, which is from 12.5 to 25 percent longer than the pulse FWHM. All tests are performed at a repetition rate of 20 Hz for 10 seconds at each test point. 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 substrate, 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 make the decision process easier. First, the substrate material is very important. Higher damage thresholds can be achieved using fused silica instead of BK7. Second, consider the coating. Metal coatings have the lowest damage thresholds. Broadband dielectric coatings, such as the HEBBAR™ and MAXBRIte™ are better, but single-wavelength or laser-line coatings, such as the V coatings and the MAX-R™ coatings, are better still. If even higher thresholds are needed, then high-energy laser (HEL) coatings are required. If you have any questions or concerns regarding the damage levels involved in your applications, please contact a CVI Melles Griot applications engineer.

OEM and Special Coatings

CVI Melles Griot maintains advanced coating capabilities. In the last few years, CVI Melles Griot 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 Melles Griot excels at producing repeatable, high-quality coatings at competitive prices.

USER-SUPPLIED SUBSTRATES

CVI Melles Griot not only coats catalog and custom optics with standard and special coatings but also applies these coatings to user-supplied substrates. A significant 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 Melles Griot 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 Melles Griot coating facilities involves special coatings designed and manufactured to customer specifications. These designs cover a wide range of wavelengths, from the infrared to deep ultraviolet, and applications ranging from basic research through the design and manufacture of industrial and medical products. The most common special coating requests are for modified catalog coatings, which usually involve a simple shift in the design wavelength.

TECHNICAL SUPPORT

Expert CVI Melles Griot 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.