OPTICAL FILTER DESIGN

APPLICATION NOTE

THIN-FILM THEORY

Light is known to have both particle-like and wave-like characteristics. Optical thin-film theory is based principally upon the wave-like characteristics of light. Key among these are reflection, refraction, and interference. All boundaries between media in which lightwaves travel create a division of reflected and transmitted portions of the energy. Those lightwaves not reflected are transmitted across the boundary to a medium with different electric and magnetic properties. These differences cause a refraction, or a change in the speed and angle of the lightwaves. A material's refractive index is derived by comparing the velocity of a lightwave in that medium to the velocity in a vacuum.

The amount of light reflected is related to the difference between the refractive indices of the media on either side of the boundary; greater differences create greater reflectivity. If there is an increase in refractive index across the boundary, the reflected lightwave undergoes a phase change of 180º; if there is a decrease, no phase change occurs. An optical thin-film coating is a stack of such boundaries, each producing reflected and transmitted components that are subsequently reflected and transmitted at other boundaries. If each of these boundaries is located at a precise distance from the other boundaries, the reflected and transmitted components are enhanced by interference.

Unlike "solid" particles, two or more lightwaves can occupy the same space. When lightwaves of equal wavelength occupy the same space, they interfere with each other in a manner determined by their difference in phase and amplitude. When two such lightwaves are exactly out of phase with each other—by 180°—they interfere destructively, and if their amplitudes are equal, they cancel each other by producing a wave of zero amplitude. When two such lightwaves are exactly in phase with each other, they interfere constructively, producing a lightwave of higher amplitude. An optical thin-film coating is designed so that the distances between the boundaries (often integral quarter-wavelengths) will control the phase differences of the multiple reflected and transmitted components. When this "stack of boundaries" is placed in a light path, constructive interference is induced at some selected wavelengths, while destructive interference is induced at others.

With the aid of thin-film design software, we apply optical thin-film theory to optimize various coating performance characteristics such as: a) the degree of transmission and reflection; b) the size of the spectral range over which transmission, reflection, and the transition between them occur; and c) the polarization effects at off-normal angles of incidence. These characteristics are influenced by the number of boundaries, the difference in refractive index across each boundary, and the various distances between the boundaries within a coating.

The Coating Process

We select coating materials for their transmissive, refractive, and absorptive characteristics at those wavelengths critical to the filter's application. The coating process requires that materials be selected for their evaporation and condensation properties as well.

A coating is produced in a vacuum chamber at a pressure typically less than 10-5 torr. The coating materials are vaporized by a resistive heating source or an electron beam. With careful control of conditions such as vaporization rate, pressure, temperature, and chamber geometry, the vapor cloud condenses uniformly onto rotating substrates, returning to the solid state.

As a layer of material is deposited, its increasing thickness is monitored optically. With exacting response to anticipated changes in the monitor signal, the operator stops deposition by shielding the material and turning off the thermal source (or electron beam), thereby precisely controlling the thickness of the layer. A multi-layer coating is produced by alternating this cycle (typically 20 to 70 times) with two or more materials.

Quarter-Wave Stack Reflector

The quarter-wave stack reflector is a basic building block of optical thin-film products. Composed of alternating layers of two or more dielectric materials—each layer with an optical thickness corresponding to one-quarter of the principal wavelength—this coating has highest reflection at the principal wavelength and transmission both higher and lower than the principal wavelength. At the principal wavelength, constructive interference of the multiple reflected rays maximizes the overall reflection of the coating; destructive interference among the transmitted rays minimizes the overall transmission.

Figure 1 illustrates the spectral performance of a quarter-wave stack reflector. Designed for maximum reflection of 550nm light waves, each layer has an optical thickness corresponding to one quarter of 550nm. This coating is useful for three types of filters: cut-on filters, rejection band filters, and blockers.

Fabry-Perot Interferometer

The solid Fabry-Perot interferometer, also known as a single-cavity coating, is formed by separating two thin-film reflectors with a thin-film spacer. In an all-dielectric cavity, the thin-film reflectors are quarter-wave stack reflectors made of dielectric materials. The spacer, which is a single layer of dielectric material having an optical thickness corresponding to an integral-half of the principal wavelength, induces transmission rather than reflection at the principal wavelength. Light with wavelengths longer or shorter than the principal wavelength undergoes a phase condition that maximizes reflectivity and minimizes transmission. The result is a passband filter. The size of the passband region, the degree of transmission in that region, and the degree of reflection outside that region are determined by the number and arrangement of layers. A narrow passband region is created by increasing the reflection of the quarter-wave stacks as well as increasing the thickness of the thin-film spacer.

In a metal-dielectric-metal (MDM) cavity, the reflectors of the solid Fabry-Perot interferometer are thin-films of metal and the spacer is a layer of dielectric material with an integral half-wave thickness. These are commonly used to filter UV light that would be absorbed by all-dielectric coatings.

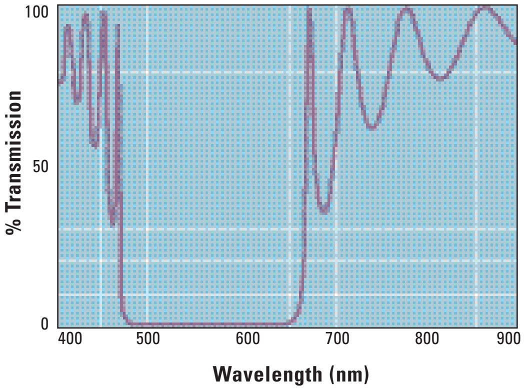

Figure 1: Quarter-Wave Stack Reflector

Twenty-three layers alternating between zinc sulfide (n=2.35) and cryolite (n=1.35), at a principal wavelength of 550nm. A slight design modification could be used to eliminate the dips in the transmission regions, optimizing the element for use as a longpass or a shortpass cut-on filter.

Multi-Cavity Passband Coatings

The multi-cavity passband coating is made by coupling two or more single-cavities with a matching layer. The transmission at any given wavelength in and near the band is roughly the product of the transmission of the individual cavities. Therefore, as the number of cavities increases, the cut-off edges become steeper and the degree of reflection becomes greater.

When this type of coating is made of all-dielectric materials, out-of-band reflection characteristically ranges from about (.8 x CWL) to (1.2 x CWL). If thin-films of metal, such as silver, are substituted for some of the dielectric layers, the metal's reflection and absorption properties extend the range of attenuation far into the IR. These properties cause loss in the transmission efficiency of the band.

The multi-cavity coating is used in many variations on bandpass filters. **Figure 2** illustrates the spectral performance of a 3-cavity bandpass filter. Three features used to identify bandpass filters are center wavelength (CWL); full width at half maximum transmission (FWHM), which characterizes the width of the passband; and peak transmission (%T).

Anti-Reflective Coatings

The anti-reflective coating is a thin-film that does the opposite of a reflector. At the principal wavelength(s), it creates destructive interference for the multiple reflected lightwaves and constructive interference for the multiple transmitted lightwaves. This type of coating is commonly applied to the surfaces of optical components such as lenses, mirrors, and windows. When deposited on the surface of an interference filter, the anti-reflective coating increases net transmission and reduces the intensity of ghost images. It should be noted that a properly designed longpass or shortpass filter is anti-reflective in its transmission.

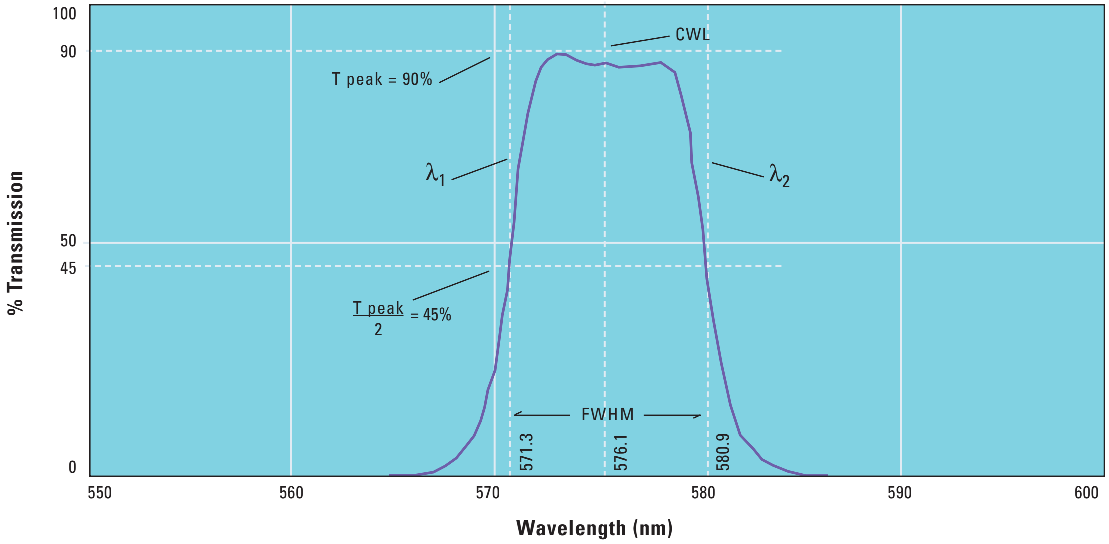

Figure 2: Multi-Cavity Passband Coating

A bandpass filter that was made by depositing alternating layers of zinc sulfide and cryolite on a glass substrate according to a 3-cavity Fabry-Perot interferometric design. The filter's CWL is located at 576.1nm; its FWHM is 9.6nm.

Partial Reflectors

When made from all dielectric materials, the partial reflector is similar to the quarter-wave stack reflector except that fewer layers transmit only a given portion of the incident light. The portion not transmitted is reflected, since virtually none of the light is absorbed. Partial beamsplitters used at off-normal angles of incidence are common to all dielectric partial reflectors. A 50/50 beamsplitter will reflect 50% and transmit 50% of the incident light over a given spectral range. A 60/40 will reflect 60% and transmit 40%. A partial reflector, made with thin-films of metal or a combination of metal and dielectric material, absorbs some portion of the incident light. A neutral density filter, coated with the metal alloy inconel, is a common metal partial reflector.

Front Surface Coatings

Front surface coatings are used when the light must interact with the coating before passing through the substrate. Reflective surface coatings eliminate multiple reflections in products such as mirrors and dichroic beamsplitters. They also reduce the amount of energy absorbed by the substrate in products such as hot mirrors and cold mirrors. Anti-reflective coatings, which reduce the degree of difference in refractive index at the boundary of a filter and its medium, are effective on both the front and back surfaces of a filter.

Refractory oxides, fluorides, and metals are surface coating materials chosen for their durability. Indeed, many optical components are protected by durable surface coatings. Common surface coatings have undergone testing that simulates many years of environmental stress with no observable signs of cosmetic deterioration and only minimal shift in spectral performance. Metal coatings are often overcoated with a layer of oxide or fluoride material to increase their durability.

Refractory oxide surface coatings, while eliminating additional substrates and their related problems, are inherently unstable as a result of coating densification and inconsistent reduction. The reactive coating process for oxides is critically dependent on deposition parameters at the physical chemistry level. Methods such as ion beam, sputtering, and plasma coating have been developed to improve coating stability through energetic bombardment to make the coating more dense. A minor process variable, however, can result in long-term inconsistency, such as wavelength drift, which is unacceptable in some instrument applications. Surface coatings can be more expensive because of long manufacturing cycles, but provide extreme durability, very good Transmitted Wavefront specifications, and can survive high temperature applications.

Protected Coatings

Dielectric coatings are protected by a cover glass laminated with optical grade cement. This allows use of materials which have wide ranging indices of refraction that result in increasing spectral control at a reasonable cost. A glass-to-glass lamination around the perimeter of the assembly, created by removing the coating at the edge, adds moisture protection and shear strength.

Dielectric materials suitable for optical thin-films yield the highest spectral performance of any materials. Research has shown that although more fragile than refractory oxides, a single pair of dielectric materials permit the most complicated and highest performing interference designs. Coating durability has historically been achieved by bonding a protective glass coverplate to the coated substrate. This laminated design limits performance to some degree, however, through the introduction of adhesives and a second layer of glass. The potential problems, which manufacturing processes attempt to control, include auto-fluorescence and transmitted wavefront distortion. On the positive side, protected dielectric coatings provide the end-user with deep out-of-band blocking, very high phase thickness coatings with low residual stress, minimal crazing and substrate deformation, consistent and stable spectral performance, and simplicity of deposition which results in affordable cost.

Color Absorption Glasses

Color absorption glasses attenuate some portion of the spectral range through absorption—either simple absorption by ions in true solution or strong scattering by microcrystals.

Extended Attenuation

When used with a light source or a detector that performs over a broad spectral range, it is often necessary to extend the range of attenuation provided by a single-coated surface. Additionally, an increased level of attenuation might be necessary if a high-intensity source or a highly sensitive detector is used. While some optical systems provide space for separate reflectors or absorbers, these attenuating, or blocking, components are often combined with the principal coating in a single assembly.

Adding attenuating components always results in some loss in transmission at the desired wavelengths. Therefore, blocking strategies are devised for an optimum balance of transmission and attenuation. For example, if a detector has no sensitivity beyond 1,000nm, the filter's blocking is designed only to that limit, conserving a critical portion of the throughput.

Extended attenuation sometimes is achieved by selecting materials that absorb the unwanted wavelengths but transmit the desired wavelengths. Absorptive color glasses are commonly used as coating substrates or laminated to filter assemblies. Thin-film coating materials sometimes provide attenuation by absorption. Also, dyes can be added to optical cement to provide absorption. The choices of absorbing media are many, yet limited. Absorbing media are ideal for some blocking requirements such as the "short wavelength side" of a visible bandpass filter. However, these materials don't provide the best levels of transmission, levels of absorption, or transition slopes in all situations. Furthermore, the temperature

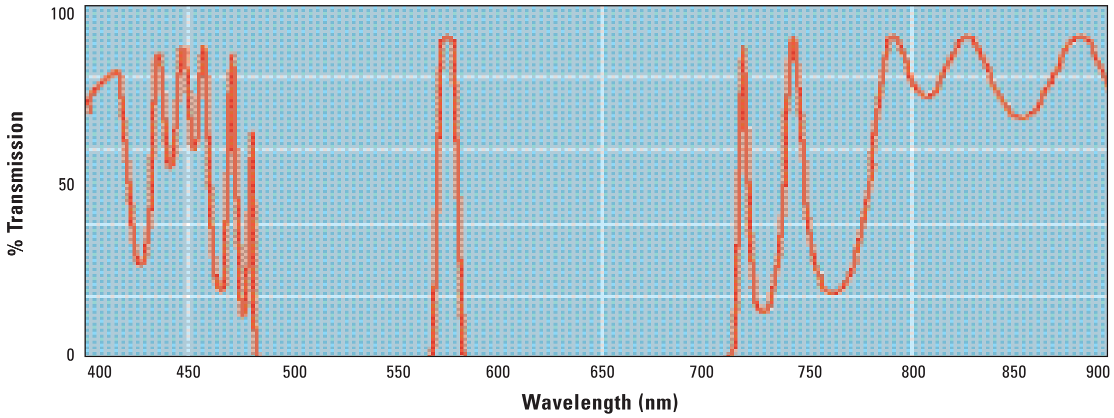

Figure 3: Bandpass Without Extended Attenuation

The limited range of attenuation of a single bandpass coated element with a CWL of 576.1nm and a FWHM of 9.3nm. The filter leaks unwanted light below 500nm and above 700nm.

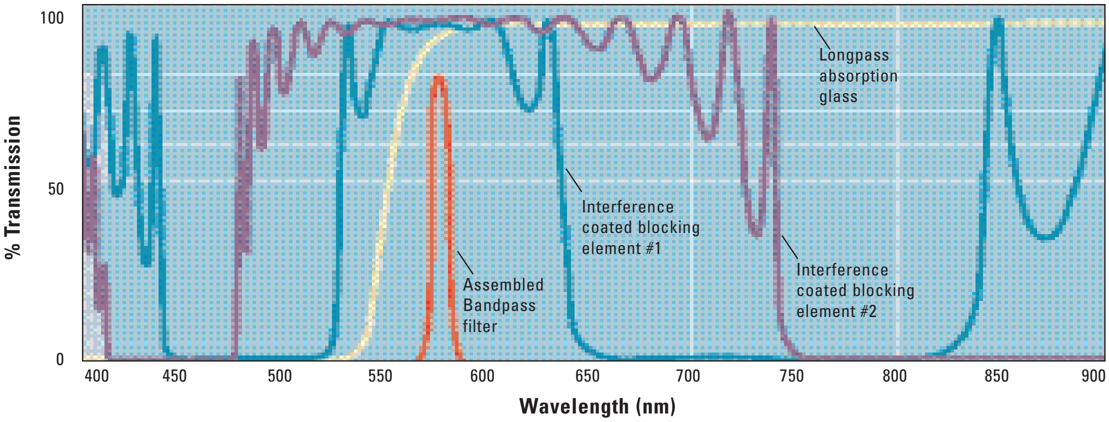

Figure 4: Bandpass With Extended Attenuation

The bandpass filter's region of attenuation is extended by the addition of blocking elements. The red curve represents the assembly of the bandpass element in Figure 3 and three blocking elements (#1, #2, and Longpass absorption glass). While light "leaks" are eliminated, notice how transmission is reduced.

increase caused by absorption can be great enough to cause significant wavelength shift or material damage.

Dielectric thin-film coatings—either longpass, shortpass, or very wide bandpass—are commonly used to extend attenuation throughout the required spectral region. Deposited onto substrates and laminated to the assembly, they are highly transmissive in the desired spectral region and highly reflective where the principal coating "leaks" unwanted wavelengths. **Figures 3 and 4** illustrate how several blocking components increase the attenuation of a principal filter component.

Metal thin-film bandpass coatings extend attenuation to the far IR (>100 microns). This approach is simpler than the all-dielectric method in that a single component attenuates a greater range. Metal layers are absorptive, however, and can reduce transmission at desired wavelengths to levels between 10% and 60%. A comparable all dielectric filter, blocked to the desired wavelength, would allow transmission of 45% to 85%.

Our two most common strategies for extending the attenuation of a single-coated surface are referred to as "blocking optimized," for filters used with detectors sensitive only in a limited region, and "blocking complete," for filters used with detectors sensitive to all wavelengths. An optimized blocked filter combines a color absorption glass for the short wavelength side of the passband with a dielectric reflector for the long wavelength side of the passband. A completely blocked filter includes a metal thin-film bandpass coating, which is often combined with a color absorption glass to boost short-wavelength attenuation.

Signal-To-Noise (S/N) Ratio

Signal-to-noise (S/N) ratio is often the most important consideration in designing an optical system. It is determined by:

$S/N = S \div (N1 + N2 + N3)$ where:

S = desired energy transmitted by the filter
N1 = unwanted energy transmitted by the filter
N2 = other light energy reaching the detector
N3 = other undesired energy affecting the output (e.g., detector and amplifier noise)

The optimum filter is one that reduces unwanted transmitted energy (N1) to a level below the external noise level (N2 and N3), while maintaining a signal level (S) well above the external noise.

Filter Orientation

In most applications, an interference filter should be placed with the most reflective, metallic looking surface toward the light source. The other surface usually can be distinguished by its more colored or opaque appearance. When oriented in this way, the thermal stress on the filter assembly is minimized. Spectral performance is unaffected by filter orientation. Typically, our filters are labeled with an arrow on the edge, indicating the direction of the light path. Special markings are made for those customers who require consistency with instrument design.

Incident Power

Excessive light energy can destroy a filter by degrading the coating or by fracturing the glass. Heat induced glass damage can be avoided by proper substrate selection and by ensuring that the filter is mounted in a heat conducting sink. Coating damage is more complicated and a coating's specific damage threshold is dependent on a number of factors including coating type, wavelength of the incident energy, angle of incidence, and pulse length.

For a given set of conditions, a surface oxide coating will be the most damage resistant. A protected dielectric coating will be the most susceptible to damage. Surface fluoride, surface metal, and protected metal coatings will fall between these two extremes. Extensive experience with laser applications guides the selection of substrate materials and coating design best suited to meet specific spectrophotometric and energy handling requirements.

Angle of Incidence and Polarization

Most interference coatings are designed to filter collimated light—parallel rays of light—at a normal angle of incidence where the coated surface is perpendicular to the light path. However, interference coatings have certain unique properties that can be used effectively at off-normal angles of incidence. Dichroic beamsplitters and tunable bandpass filters are two common products which take advantage of these properties.

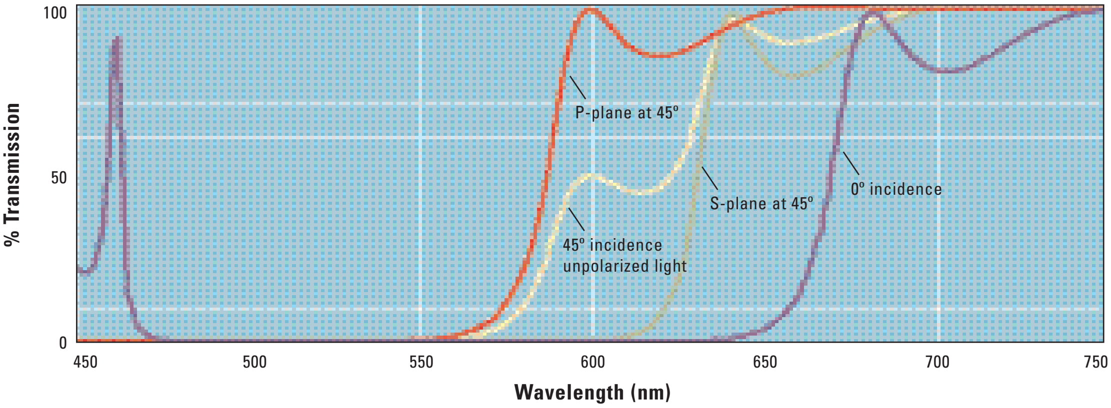

Figure 5: Angle of Incidence Polarization Effects—Longpass Filter
Longpass filter has cut-on at normal incidence of 665nm and at 45° incidence of 605nm. Graph illustrates the separation of the P- and S-planes of polarization at 45° angle of incidence.

The primary effect of an increase in the incident angle on an interference coating is a shift in spectral performance toward shorter wavelengths. In other words, the principal wavelength of all types of interference filters decreases as the angle of incidence increases. For example, in **Figure 5** the 665LP longpass filter (50% T at 665nm) becomes a 605LP filter at a 45° angle of incidence.
To a near approximation, the relationship between this shift and angle of incidence is described as:

$$\frac{If}{I0} = \frac{\sqrt{N2-Sin2\ f}}{N}$$

Where: f = angle of incidence
If = principal wavelength at angle of incidence f
I0 = principal wavelength at 0º angle of incidence
N = effective refractive index of the coating

The effective refractive index of a coating is determined by the coating materials used and the sequence of thin-film layers in the coating, both of which are variables in the design process. For filters with common coating materials such as zinc sulfide and cryolite, effective refractive index values are typically 1.45 or 2.0, depending upon which material is used for the spacer layer. This relationship is plotted in **Figure 6**. The actual shifts will vary slightly from calculations based solely on the above equation.

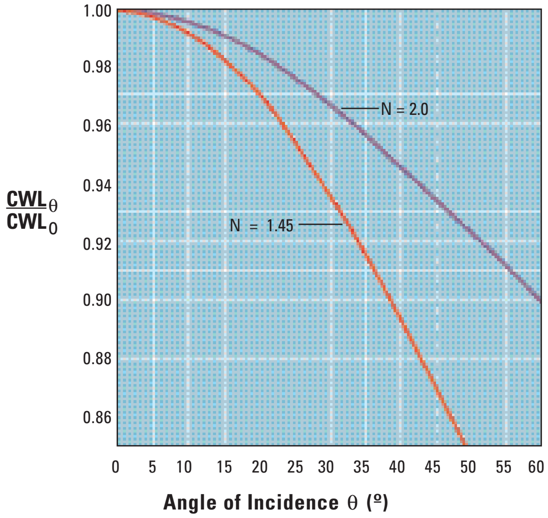

Figure 6: Angle of Incidence Effects
Decrease in CWL as a function of angle of incidence for two bandpass filters with the same coating materials (zinc sulfide and cryolite) but different effective refractive indices (N). N = 2.0 for the filter with a zinc sulfide spacer. N = 1.45 for the filter with a cryolite spacer.

A secondary effect of angle of incidence is polarization. At angles greater than 0º, the component of lightwaves vibrating parallel to the plane of incidence and reflection (P-plane) will be filtered differently than the component vibrating perpendicular to the plane of incidence (S-plane). The plane of incidence is geometrically defined by a line along the direction of lightwave propagation and an intersecting line perpendicular to the coating surface. Polarization effects increase as the angle of incidence increases. **Figures 5 and 7** illustrate the effects of polarization on a longpass and a bandpass filter. Coating designs can minimize polarization effects when necessary.

System Speed

As noted above, the filtering of collimated light rays at a greater angle of incidence produces a spectrum at a shorter wavelength. When filtering a converging rather than collimated beam of light, the spectrum results from the integration of the rays at all of the angles within the cone. At system speeds of f/2.5 and slower (cone angle of 23° or less), the shift in peak wavelength can be approximately predicted from the filter's performance in collimated light (i.e., the peak wavelength shifts about one-half the value that it would shift in collimated light at the cone's most off-axis angle).

In addition to the shift in peak wavelength, system speed can also have significant effect on both transmission and bandwidth. Faster system speeds result in a loss in peak trans-

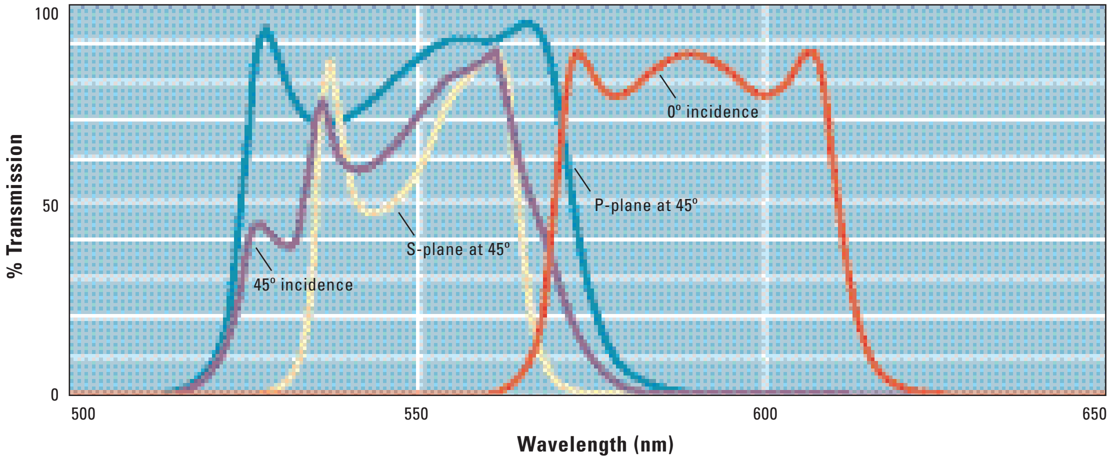

Figure 7: Angle of Incidence Polarization Effects—Bandpass Filters

A bandpass filter at normal incidence with a CWL at 590nm and a FWHM of 40nm. At 45° angle of incidence, in random polarization, the CWL is 547nm and the FWHM is 42nm. At 45° angle of incidence, there is a separation of the P- and S-planes of polarization.

mission, an increase in bandwidth, and a blue-shift in peak wavelength. These effects can be drastic when narrow-band filters are used in fast systems, and need to be taken into consideration during system design.

Temperature Effects

The performance of an interference filter shifts with temperature changes due to the expansion and contraction of the coating materials. Unless otherwise specified, filters are designed for an operating temperature of 20°C. Filters will withstand repeated thermal cycling, provided temperature transitions are less than 5°C per minute. An operating temperature range between -60°C and +60°C is recommended. Filters must be specifically designed for use at temperatures above 120°C or below -100°C. Although the shift is dependent upon the design of the coating, coefficients in **Figure 8** provide a good approximation.

Humidity Effects

Perhaps the greatest cause of filter deterioration is humidity, which can be absorbed by the coating. To protect “soft dielectric” coatings, a narrow 2mm “scribe” in the coating is removed around the filter’s perimeter, creating a glass to glass seal. In addition, several layers of proprietary moisture-rejecting sealants are then applied to the edge. To further prolong filter life, filters should be stored in a low to moderate (less than 70%) relative humidity environment whenever possible.

Filter Life

Laminated interference filters, particularly those with narrow-bands, are subject to gradual blue shift with age. This tendency is somewhat stabilized through a process of repeated heat cycling, or curing, at moderately high temperatures for short durations during the manufacturing process.

Wavelength range (nm)	**Thermal coefficient** (nm of shift per 1°C change)
300 – 400	0.016
400 – 500	0.017
500 – 600	0.018
600 – 700	0.019
700 – 800	0.020
800 – 900	0.023
900 – 1000	0.026

Figure 8: Wavelength and Thermal Coefficients

Prolonged exposure to light, particularly short UV wavelengths, results in solarization and reduced transmission. Whenever possible, we use substrates which are less prone to solarization, especially at the outer surfaces of filter assemblies. To further control solarization, protection from intense light is recommended when a filter is not in use.

Transmission and Optical Density

Accurate spectral measurements of sub-components and assemblies are critical to the production of high-precision filters. Transmission (T) and Optical Density (OD) are two common ways to express the throughput of a filter or filter assembly. Throughput is the portion of the total energy at a given wavelength that passes through the filter. A throughput value is always a portion of unity (less than 1 and greater than 0). When describing the transmitting performance of a filter (usually when throughput is 1%–99%), the preferred expression is “transmission.” When describing the attenuating performance of a filter (usually when throughput is less than 1%), the preferred expression is “optical density.” Transmission can be expressed either as a percentage (e.g., 90%) or decimally (e.g., .90). Optical density is always expressed as the negative logarithm of transmission. Unit conversions are:

$$\mathrm{OD} = -\log10\ T \quad \text{or} \quad T = 10\text{-}\mathrm{OD}$$

Image Quality Filters

A filter’s effect on the quality of an image results from the degree it distorts transmitted lightwaves.

In high-resolution imaging systems, filters require multiple layering of various materials (i.e., glasses, coating materials, optical cements, etc.) for high spectral performance. These materials if used indiscriminately can degrade a filter’s optical performance. This effect can be significantly diminished through material selection, design, process, and testing.

To enhance image quality we select optical grade materials with the highest degree of homogeneity, the lowest number of inclusions, and the best match in refractive index at contacted boundaries. Special coating designs minimize the required number of contacted surfaces that cause internal reflection and fringe patterns. Before coating and assembly, all glasses are polished to requisite flatness and wedge values. Our coating and assembly techniques assure uniformity in material as well as spectral properties. After the filter is assembled, transmitted wavefront distortion is diminished further through a cycle of polishing, evaluating, and repolishing both outer surfaces. Durable anti-reflective coatings are then deposited onto the outer surfaces, reducing the intensity of ghost images while boosting transmission. (See **Figure 9.**) The attainable level of optimal performance depends in part upon size, thickness, spectral region, and spectral demands of each particular filter.

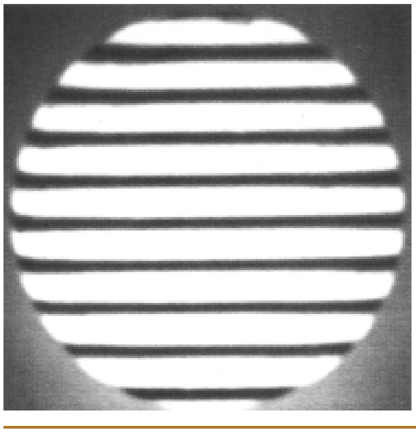

Figure 9: Transmitted Wavefront Interferogram

A transmitted wavefront interferogram of a narrow-band filter used for telephotometry. Transmitted wave front distortion is measured at the filter’s principal wavelength on a Broadband Achromatic Twyman-Green Interferometer. Although many interferometers can measure transmitted wavefront distortion, most are fixed at a single wavelength (often 633nm). For filters that don’t transmit this wavelength, these instruments must produce reflected, rather than transmitted, interferograms. Although reflected interferograms are often used to represent the quality of a transmitted image, there are no reliable means for such interpretation.

Optimizing Custom Filter Sets

Omega Optical specializes in the design and production of integrated filter sets for use in new instruments or unique research. Sets that perform serially (e.g., separating a source light and sending it along to further separations and channels) are optimized for combined performance. Over-attenuation, or redundant blocking, is avoided while signals and images are retained. Filter sets that function in parallel (e.g., when each filter isolates a particular spectral band from the same source) are optimized for uniform performance characteristics such as optical thickness, bandshape, throughput, sensitivity to system speed, sensitivity to temperature, and image quality. In addition, we can build these sets to "correct" for unbalanced system output by adjusting the throughput of each filter to the system's relative sensitivity at the principal wavelength.

Physical Configurations

Omega Optical offers a wide range of standard filter sizes depending on the product line, and has the capability to produce custom filters to nearly any dimension. Any shape—including rectangles, ellipses, filter-wheel segments, and free-form—is available in sizes ranging from 1mm on the shortest axis to 250mm on the longest axis. Thickness can be as minimal as 0.2mm for an exposed coated filter. It should be noted that an unusual size and/or thickness requirement is sometimes limiting to the performance of a finished filter.

The edges of our filters are treated with a proprietary organic polymer that chemically bonds to the various glasses and provides an opaque hermetic seal. We assemble our standard round filters into anodized aluminum rings. Other shapes and sizes are chamfered, sealed, and painted at their edge. For special mounting requirements, we fabricate a wide variety of rings, microscope cubes, instrument mounts, and filter wheels.

A conventional filter assembly, with all filter components laminated into a single unit, is sometimes limited by inadequate transmission of the desired signal, over-transmission of undesired signals, or overheating from the absorption of radiation. In many cases, these limitations can be overcome by arranging the filter components into a "baffle" configuration and using the interference coating property of selective reflectance.

Coatings and Special Substrates

In addition to our standard capabilities, we deposit many types of coatings on a variety of optical components such as fiber optics, pellicles, prisms, lenses, wedges, etalons, flats, spheres, and parabolas. We can produce or procure these components with state-of-the-art surface accuracy and in various materials such as ceramics, alloys, optical glasses, crystals, and plastics. We also coat customer-supplied substrates. In addition to any of our standard product coatings, we offer a range of anti-reflective, conductive, metal, UV wedge, and spectral profile coating services.