## Optical Filters for OEM Instrumentation: Technical Guide

This section is intended to provide a basic understanding of some of the principles, limitations, and benefits of optical coating technology. We believe that someone with a complete understanding of the complexities of filtering light with interference coatings will best equipped to take advantage of our technology, products, and capabilities.

**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
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.

## TYPES OF COATINGS

### *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.

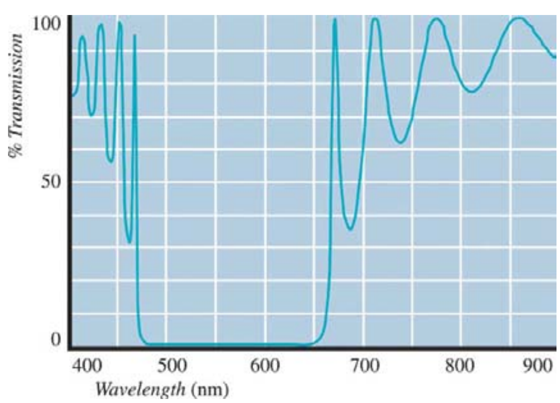


***Figure 1** : Quarter-wave stack reflector on a glass substrate. Twenty-three layers alternating between zinc sulfide (n=2.35) and cryolite (n=1.35), at a principal wavelength of 550nm. A slight design modification could be used to eliminate the dips in the transmission regions, optimizing the element for use as a longpass or a shortpass cut-on filter.*

*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.

### *Solid 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


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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.

### *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 [0.8 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.

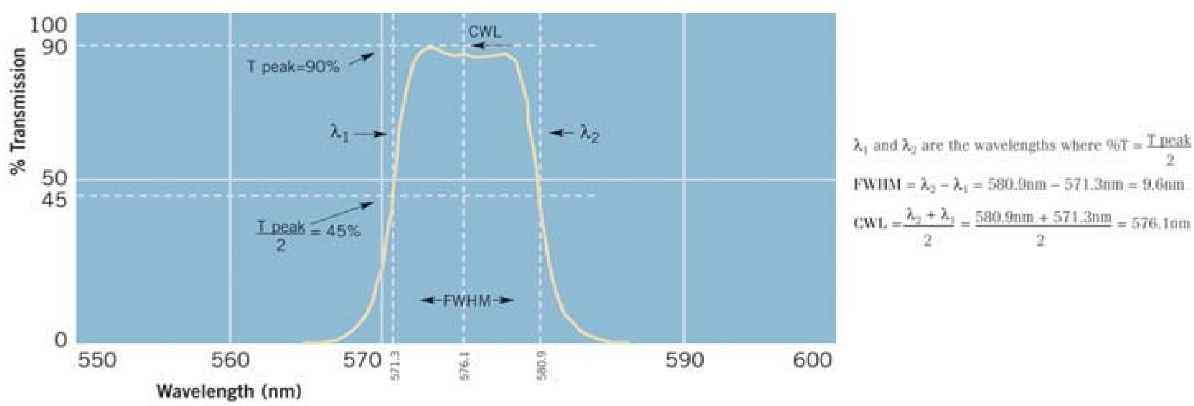


***Figure 2**: A bandpass filter that was made by depositing alternating layers of zinc sulfide and cryolite on a glass substrate according to a three-cavity Fabry-Perot interferometric design. The filter's CWL is located at 576.1nm; its FWHM is 9.6nm.*

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; 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.

### *Partial Reflectors*

The partial reflector, when made from all dielectric materials, 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 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.

## COMBINING COATINGS AND GLASSES

A majority of Omega filters are made by combining more than one interference coating with substrates, cover glasses, and/or color absorption glasses.

### *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 100 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.

### *Protected Coatings*

"Soft" coatings are protected by a cover glass laminated with optical grade cement. This allows use of "soft dielectric" 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.

### *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 micro-crystals.

## EVALUATING SPECTRAL PERFORMANCE

Accurate spectral measurements of sub-components and assemblies are critical to the production of high-precision filters.

***Transmission & Optical Density***

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 equal to between 1 % and 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:

$$OD = -\log^{10} T \qquad \text{or} \qquad T = IO^{-OD}$$

*Figure 4* provides a chart converting %T to OD.

**Conversion Table**

| Optical Density | Percent Transmission | Optical Density | Percent Transmission | Optical Density | Percent Transmission | Optical Density | Percent Transmission | Optical Density | Percent Transmission | Optical Density | Percent Transmission | Optical Density | Percent Transmission | Optical Density | Percent Transmission |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.00 | 100.00 | 0.50 | 31.62 | 1.00 | 10.00 | 1.50 | 3.162 | 2.00 | 1.000 | 2.50 | 0.3162 | 3.00 | 0.1000 | 3.50 | 0.0316 |
| 0.01 | 97.72 | 0.51 | 30.90 | 1.01 | 9.772 | 1.51 | 3.090 | 2.01 | 0.9772 | 2.51 | 0.3090 | 3.01 | 0.0977 | 3.51 | 0.0309 |
| 0.02 | 95.50 | 0.52 | 30.20 | 1.02 | 9.550 | 1.52 | 3.020 | 2.02 | 0.9550 | 2.52 | 0.3020 | 3.02 | 0.0955 | 3.52 | 0.0302 |
| 0.03 | 93.33 | 0.53 | 29.51 | 1.03 | 9.333 | 1.53 | 2.951 | 2.03 | 0.9333 | 2.53 | 0.2951 | 3.03 | 0.0933 | 3.53 | 0.0295 |
| 0.04 | 91.20 | 0.54 | 28.84 | 1.04 | 9.120 | 1.54 | 2.884 | 2.04 | 0.9120 | 2.54 | 0.2884 | 3.04 | 0.0912 | 3.54 | 0.0288 |
| 0.05 | 89.13 | 0.55 | 28.18 | 1.05 | 8.913 | 1.55 | 2.818 | 2.05 | 0.8913 | 2.55 | 0.2818 | 3.05 | 0.0891 | 3.55 | 0.0289 |
| 0.06 | 87.10 | 0.56 | 27.54 | 1.06 | 8.710 | 1.56 | 2.754 | 2.06 | 0.8710 | 2.56 | 0.2754 | 3.06 | 0.0871 | 3.56 | 0.0275 |
| 0.07 | 85.11 | 0.57 | 26.92 | 1.07 | 8.511 | 1.57 | 2.692 | 2.07 | 0.8511 | 2.57 | 0.2692 | 3.07 | 0.0851 | 3.57 | 0.0269 |
| 0.08 | 83.18 | 0.58 | 26.30 | 1.08 | 8.318 | 1.58 | 2.630 | 2.08 | 0.8318 | 2.58 | 0.2630 | 3.08 | 0.0832 | 3.58 | 0.0263 |
| 0.09 | 81.28 | 0.59 | 25.70 | 1.09 | 8.128 | 1.59 | 2.570 | 2.09 | 0.8128 | 2.59 | 0.2570 | 3.09 | 0.0813 | 3.59 | 0.0257 |
| 0.10 | 79.43 | 0.60 | 25.12 | 1.10 | 7.943 | 1.60 | 2.512 | 2.10 | 0.7943 | 2.60 | 0.2512 | 3.10 | 0.0794 | 3.60 | 0.0251 |
| 0.11 | 77.62 | 0.61 | 24.55 | 1.11 | 7.762 | 1.61 | 2.455 | 2.11 | 0.7762 | 2.61 | 0.2455 | 3.11 | 0.0776 | 3.61 | 0.0245 |
| 0.12 | 75.86 | 0.62 | 23.99 | 1.12 | 7.586 | 1.62 | 2.399 | 2.12 | 0.7586 | 2.62 | 0.2399 | 3.12 | 0.0750 | 3.62 | 0.0239 |
| 0.13 | 74.13 | 0.63 | 23.44 | 1.13 | 7.413 | 1.63 | 2.344 | 2.13 | 0.7413 | 2.63 | 0.2344 | 3.13 | 0.0741 | 3.63 | 0.0234 |
| 0.14 | 72.44 | 0.64 | 22.91 | 1.14 | 7.244 | 1.64 | 2.291 | 2.14 | 0.7244 | 2.64 | 0.2291 | 3.14 | 0.0724 | 3.64 | 0.0229 |
| 0.15 | 70.79 | 0.65 | 22.39 | 1.15 | 7.079 | 1.65 | 2.239 | 2.15 | 0.7079 | 2.65 | 0.2239 | 3.15 | 0.0708 | 3.65 | 0.0223 |
| 0.16 | 69.18 | 0.66 | 21.88 | 1.16 | 6.918 | 1.66 | 2.188 | 2.16 | 0.6918 | 2.66 | 0.2188 | 3.16 | 0.0692 | 3.66 | 0.0218 |
| 0.17 | 67.61 | 0.67 | 21.38 | 1.17 | 6.761 | 1.67 | 2.138 | 2.17 | 0.6761 | 2.67 | 0.2138 | 3.17 | 0.0676 | 3.67 | 0.0214 |
| 0.18 | 66.07 | 0.68 | 20.89 | 1.18 | 6.607 | 1.68 | 2.089 | 2.18 | 0.6607 | 2.68 | 0.2089 | 3.18 | 0.0661 | 3.68 | 0.0218 |
| 0.19 | 64.57 | 0.69 | 20.42 | 1.19 | 6.457 | 1.69 | 2.042 | 2.19 | 0.6457 | 2.69 | 0.2042 | 3.19 | 0.0646 | 3.69 | 0.0204 |
| 0.20 | 63.10 | 0.70 | 19.95 | 1.20 | 6.310 | 1.70 | 1.995 | 2.20 | 0.6310 | 2.70 | 0.1995 | 3.20 | 0.06310 | 3.70 | 0.0199 |
| 0.21 | 61.66 | 0.71 | 19.50 | 1.21 | 6.166 | 1.71 | 1.950 | 2.21 | 0.6166 | 2.71 | 0.1950 | 3.21 | 0.0617 | 3.71 | 0.0195 |
| 0.22 | 60.26 | 0.72 | 19.05 | 1.22 | 6.026 | 1.72 | 1.905 | 2.22 | 0.6026 | 2.72 | 0.1905 | 3.22 | 0.0603 | 3.72 | 0.0190 |
| 0.23 | 58.88 | 0.73 | 18.62 | 1.23 | 5.888 | 1.73 | 1.862 | 2.23 | 0.5888 | 2.73 | 0.1862 | 3.23 | 0.0588 | 3.73 | 0.0186 |
| 0.24 | 57.54 | 0.74 | 18.20 | 1.24 | 5.754 | 1.74 | 1.820 | 2.24 | 0.5754 | 2.74 | 0.1820 | 3.24 | 0.0575 | 3.74 | 0.0182 |
| 0.25 | 56.23 | 0.75 | 17.78 | 1.25 | 5.623 | 1.75 | 1.778 | 2.25 | 0.5623 | 2.75 | 0.1773 | 3.25 | 0.0562 | 3.75 | 0.0178 |
| 0.26 | 54.95 | 0.76 | 17.38 | 1.26 | 5.495 | 1.76 | 1.738 | 2.26 | 0.5495 | 2.76 | 0.1738 | 3.26 | 0.0550 | 3.76 | 0.0174 |
| 0.27 | 53.70 | 0.77 | 16.98 | 1.27 | 5.370 | 1.77 | 1.698 | 2.27 | 0.5370 | 2.77 | 0.1698 | 3.27 | 0.0537 | 3.77 | 0.0169 |
| 0.28 | 52.48 | 0.78 | 16.60 | 1.28 | 5.248 | 1.78 | 1.660 | 2.28 | 0.5248 | 2.78 | 0.1660 | 3.28 | 0.0529 | 3.78 | 0.0166 |
| 0.29 | 51.29 | 0.79 | 16.22 | 1.29 | 5.129 | 1.79 | 1.622 | 2.29 | 0.5129 | 2.79 | 0.1622 | 3.29 | 0.0513 | 3.79 | 0.0162 |
| 0.30 | 50.12 | 0.80 | 15.85 | 1.30 | 5.012 | 1.80 | 1.585 | 2.30 | 0.5012 | 2.80 | 0.1585 | 3.30 | 0.0501 | 3.80 | 0.0158 |
| 0.31 | 48.98 | 0.81 | 15.49 | 1.31 | 4.898 | 1.81 | 1.549 | 2.31 | 0.4898 | 2.81 | 0.1549 | 3.31 | 0.0489 | 3.81 | 0.0155 |
| 0.32 | 47.86 | 0.82 | 15.14 | 1.32 | 4.786 | 1.82 | 1.514 | 2.32 | 0.4786 | 2.82 | 0.1514 | 3.32 | 0.0478 | 3.82 | 0.0152 |
| 0.33 | 46.77 | 0.83 | 14.79 | 1.33 | 4.677 | 1.83 | 1.479 | 2.33 | 0.4677 | 2.83 | 0.1479 | 3.33 | 0.0468 | 3.83 | 0.0148 |
| 0.34 | 45.71 | 0.84 | 14.45 | 1.34 | 4.571 | 1.84 | 1.445 | 2.34 | 0.4571 | 2.84 | 0.1445 | 3.34 | 0.0457 | 3.84 | 0.0145 |
| 0.35 | 44.67 | 0.85 | 14.13 | 1.35 | 4.467 | 1.85 | 1.413 | 2.35 | 0.4467 | 2.85 | 0.1413 | 3.35 | 0.0446 | 3.85 | 0.0141 |
| 0.36 | 43.65 | 0.86 | 13.80 | 1.36 | 4.365 | 1.86 | 1.380 | 2.36 | 0.4365 | 2.86 | 0.1380 | 3.36 | 0.0436 | 3.86 | 0.0138 |
| 0.37 | 42.66 | 0.87 | 13.49 | 1.37 | 4.266 | 1.87 | 1.349 | 2.37 | 0.4266 | 2.87 | 0.1349 | 3.37 | 0.04266 | 3.87 | 0.0135 |
| 0.38 | 41.69 | 0.88 | 13.18 | 1.38 | 4.169 | 1.88 | 1.318 | 2.38 | 0.4169 | 2.88 | 0.1318 | 3.38 | 0.0417 | 3.88 | 0.0132 |
| 0.39 | 40.74 | 0.89 | 12.88 | 1.39 | 4.074 | 1.89 | 1.288 | 2.39 | 0.4074 | 2.89 | 0.1288 | 3.39 | 0.0407 | 3.89 | 0.0129 |
| 0.40 | 39.81 | 0.90 | 12.59 | 1.40 | 3.981 | 1.90 | 1.259 | 2.40 | 0.3981 | 2.90 | 0.1259 | 3.40 | 0.0398 | 3.90 | 0.0126 |
| 0.41 | 38.90 | 0.91 | 12.30 | 1.41 | 3.890 | 1.91 | 1.230 | 2.41 | 0.3890 | 2.91 | 0.1230 | 3.41 | 0.0389 | 3.91 | 0.0123 |
| 0.42 | 38.02 | 0.92 | 12.02 | 1.42 | 3.802 | 1.92 | 1.202 | 2.42 | 0.3802 | 2.92 | 0.1202 | 3.42 | 0.0380 | 3.92 | 0.0120 |
| 0.43 | 37.15 | 0.93 | 11.75 | 1.43 | 3.715 | 1.93 | 1.175 | 2.43 | 0.3715 | 2.93 | 0.1175 | 3.43 | 0.0371 | 3.93 | 0.0117 |
| 0.44 | 36.31 | 0.94 | 11.48 | 1.44 | 3.631 | 1.94 | 1.148 | 2.44 | 0.3631 | 2.94 | 0.1148 | 3.44 | 0.0363 | 3.94 | 0.0114 |
| 0.45 | 35.48 | 0.95 | 11.22 | 1.45 | 3.548 | 1.95 | 1.122 | 2.45 | 0.3548 | 2.95 | 0.1122 | 3.45 | 0.0355 | 3.95 | 0.0112 |
| 0.46 | 34.67 | 0.96 | 10.96 | 1.46 | 3.467 | 1.96 | 1.096 | 2.46 | 0.3467 | 2.96 | 0.1096 | 3.46 | 0.0347 | 3.96 | 0.0109 |
| 0.47 | 33.88 | 0.97 | 10.72 | 1.47 | 3.388 | 1.97 | 1.072 | 2.47 | 0.3388 | 2.97 | 0.1072 | 3.47 | 0.0339 | 3.97 | 0.0107 |
| 0.48 | 33.11 | 0.98 | 10.47 | 1.48 | 3.311 | 1.98 | 1.047 | 2.48 | 0.3311 | 2.98 | 0.1047 | 3.48 | 0.0331 | 3.98 | 0.0105 |
| 0.49 | 32.36 | 0.99 | 10.23 | 1.49 | 3.236 | 1.99 | 1.023 | 2.49 | 0.3236 | 2.99 | 0.1023 | 3.49 | 0.0324 | 3.99 | 0.0102 |
| 0.50 | 31.62 | 1.00 | 10.00 | 1.50 | 3.162 | 2.00 | 1.000 | 2.50 | 0.3162 | 3.00 | 0.1000 | 3.50 | 0.0316 | 4.00 | 0.0100 |

***Figure 4***: Conversion Table for %T to OD.


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**OPTICAL FILTERS & OPTICAL SYSTEM DESIGN**

We design and produce filters for many different applications. Each application has specific requirements; many applications are complex and demanding. The level of performance attained in an optical system depends upon the integration of the filter design with the performance of other system components. This section introduces some areas of consideration that are basic to this effort.

***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 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 5 and 6* illustrate how several blocking components increase the attenuation of a principal filter component.

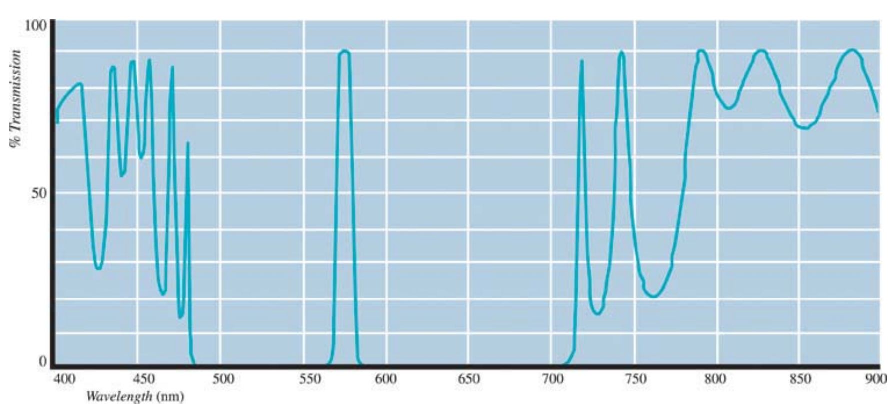


***Figure 5**: The limited range of attenuation of a single bandpass coated element with a CWL of 576.1nm and a FWHM of 9.3nm. The filter leaks unwanted light below 500nm and above 700nm.*

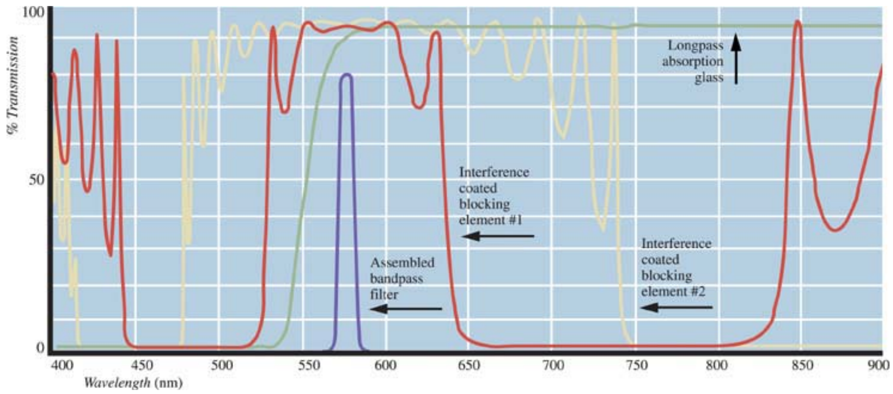


***Figure 6****: The bandpass filter's region of attenuation is extended by the addition of blocking elements. The solid black curve represents the assembly of the bandpass and three blocking elements (Blocking element #1, Blocking element #2, and Longpass Absorption glass). While light "leaks" are eliminated, notice how transmission is reduced.*

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 + (NI + N2 + N3) where:

S = desired energy transmitted by the filter
NI = 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 (NI) 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 have 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. An immersed dielectric coating will be the most susceptible to damage. Surface fluoride, surface metal, and immersed 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 & Polarization*

Most interference coatings are designed to filter collimated light (i.e. parallel rays of light) at a normal angle of incidence (i.e. 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.

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, the 665LP longpass filter (50% T at 665 nm) in *figure 8* 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:

$$\frac{\lambda_{\varnothing}}{\lambda_0} = \frac{\sqrt{N^2 - \sin^2 ø}}{N}$$

Where: ø = angle of incidence

$\lambda_{\varnothing}$ = principal wavelength at angle of incidence ø

$\lambda_0$ = principal wavelength at 0° 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 can be influenced 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 7*. The actual shifts will vary slightly from calculations based solely on the above equation.


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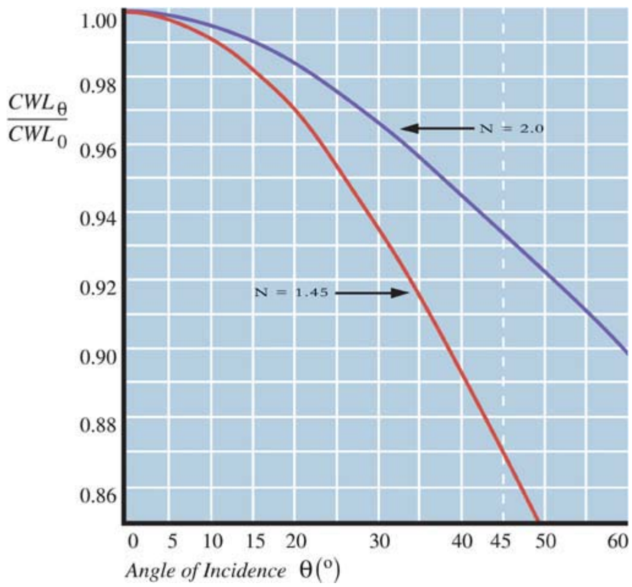


***Figure 7:*** *Decrease in CWL as a function of angle of incidence for two band pass filters with the same coating materials (zinc sulfide and cryolite) but different effective refractive indices (N). N = 2.0 for the filter with a zinc sulfide spacer. N = 1.45 for the filter with a cryolite spacer.*

A secondary effect of angle of incidence is *polarization*. At angles greater than $0^0$, 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 8 and 9* illustrate the effects of polarization on a long pass and a bandpass filter. Coating designs can minimize polarization effects when necessary.

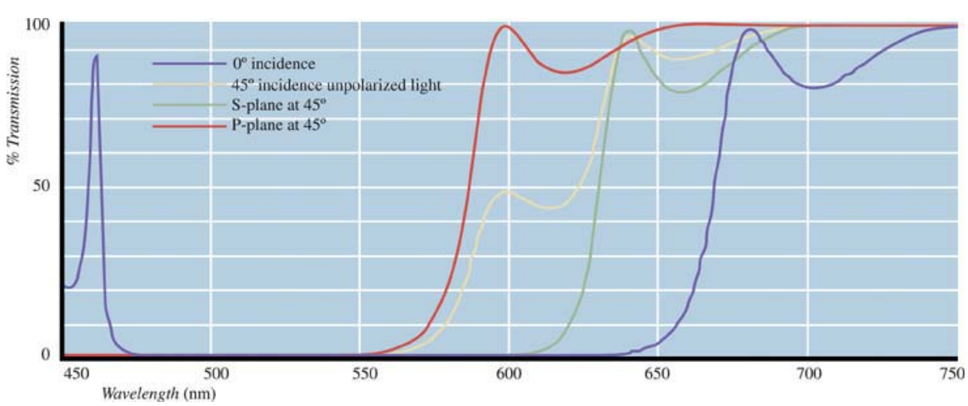


***Figure 8:*** *Longpass filter has cut-on at normal incidence of 665nm and at 45° incidence of 605nm. Graph illustrates the separation of the P- and S-planes of polarization at 45° angle of incidence.*

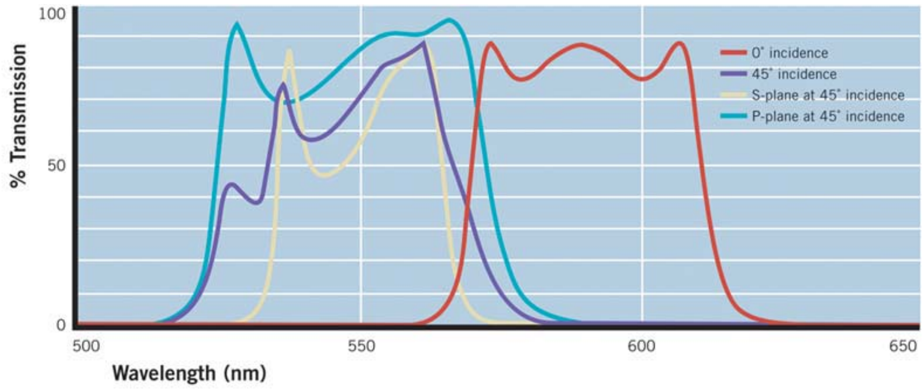


***Figure 9****: A bandpass filter at normal incidence with a CWL at 590nm and a FWHM of 40nm. At 45° angle of incidence, in random polarization, the CWL is 547nm and the FWHM is 42nm. At 45° angle of incidence, there is a separation of the p- and s- planes of polarization.*

***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 transmission, an increase in bandwidth, and a blue-shift in peak wavelength. These effects can be drastic when narrowband 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. Although the shift is dependent upon the design of the coating, the following coefficients provide a good approximation:

**Table 1**

| **Wavelength range (nm)** | **Thermal co-efficient** (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 |


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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.

### *Humidity Effects*

Perhaps the greatest cause of filter deterioration is humidity, which can be absorbed by the coating. To protect immersed coatings, a narrow 2mm "scribe" in the coating is removed around the filter's perimeter, creating a glass-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.

### *Age Effects*

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

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


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