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.

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 1** the 665LP longpass filter (50% T at 665nm) becomes a 605LP filter at a 45° angle of incidence.

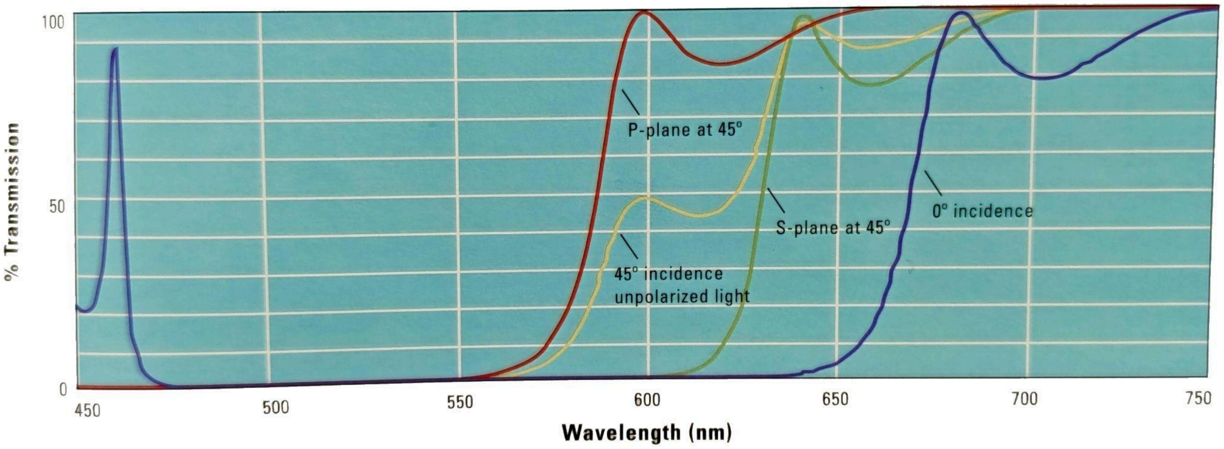

Figure 1: Angle of incidence Polarization Effects - Longpass Filter

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.

To a near approximation, the relationship between this shift and angle of incidence is described as:

$$\frac{\lambda_{\phi}}{\lambda_{0}} = \frac{\sqrt{N^{2} - Sin^{2}\phi}}{N}$$

Where: ϕ = angle of incidence
λ_ϕ = principal wavelength at angle of incidence ϕ
λ_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 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 2**. The actual shifts will vary slightly from calculations based solely on the above equation.

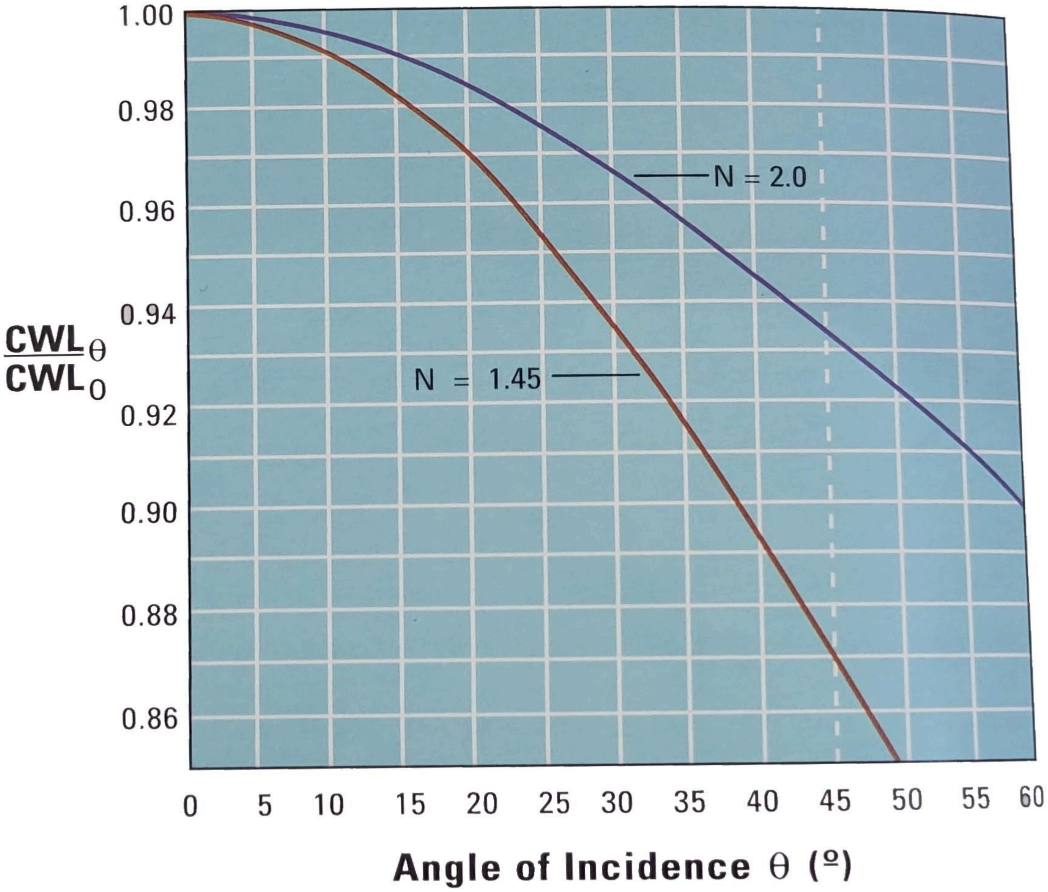

Figure 2: Angle of Incidence Effects

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 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 1 and 3** illustrate the effects of polarization on a longpass and a bandpass filter. Coating designs can minimize polarization effects when necessary.

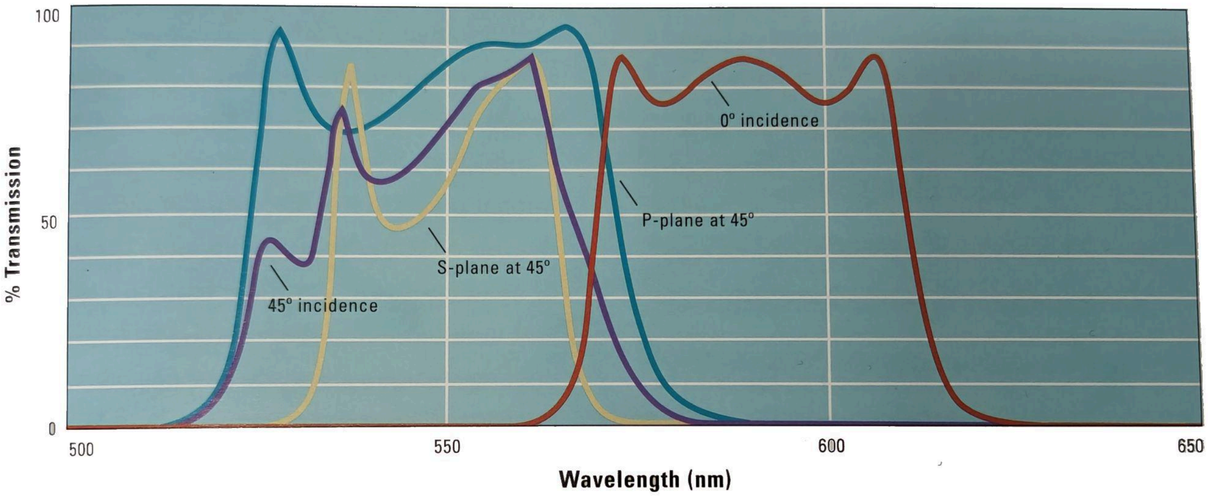

Figure 3: Angle of Incidence Polarization Effects - Bandpass Filters
A bandpass filter at normal incidence with a CWL at 590nm and a FWHM of 40nm. At 45° angle of incidence, in random polarization, the CWL is 547nm and the FWHM is 42nm. At 45° angle of incidence, there is a separation of the P- and S-planes of polarization.

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° of 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 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 operation 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 4** provide a good approximation.

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 4: Wavelength and Thermal Coefficients

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.

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.