



## INTERFERENCE FILTERS: WHAT THEY ARE AND HOW TO USE THEM

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, Melles Griot interference filters enable rapid and accurate measurement of spectral distributions. This combination has an enormous throughput advantage since the collecting area of filters is very large compared to instrumental slits. Additionally, interference filters make viewing and near-instantaneous recording of very spectrally selective images possible. 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 can 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 spacer, not in their stacks). Interference filters come in two basic types, edge filters and bandpass filters, which transmit a desired wavelength interval while simultaneously rejecting both longer and shorter wavelengths.

### 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 figure at the right 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

## Interference Filters

produces a transmission maximum. This occurs when the optical path difference is an integral number of whole wavelengths, i.e., when

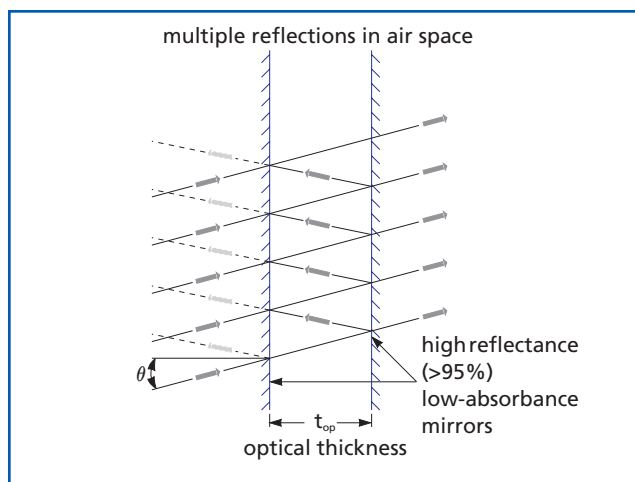
$$m\lambda = 2t_{\text{op}}\cos\theta$$

where  $m$  is an integer, often termed the order,  $t_{\text{op}}$  is the optical thickness, and  $\theta$  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. A simple Fabry-Perot interferometer transmission curve is shown on the next page. The ratio of successive peak separation to full width at half-maximum (FWHM) transmission peak is termed finesse. High reflectance results in high finesse, or high resolution.

In most Fabry-Perot interferometers, air is the medium between high reflectors; therefore, the optical thickness,  $t_{\text{op}}$ , 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.

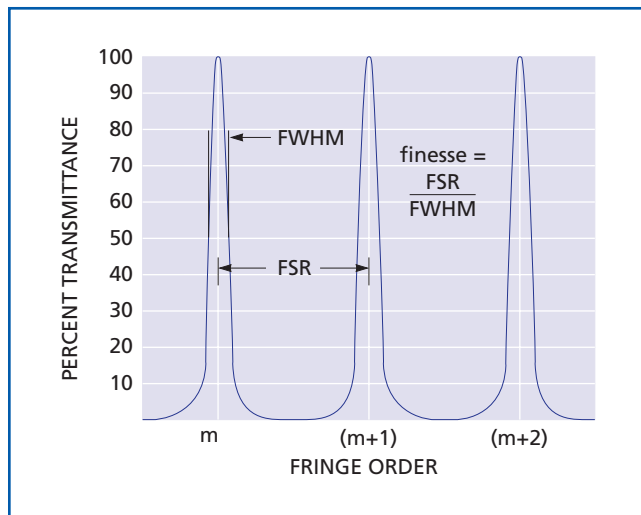


Schematic of a Fabry-Perot interferometer

## 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 quarterwave stacks with a broadband reflectance peaking at the design wavelength.

The entire assembly of two quarterwave 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 on top of the other, separated by an absentee layer, as shown in the figure on the next page, to form a multiple-cavity filter. The resulting overall transmittance passband is given approximately by the product of the passbands 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.



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

The figure on the next page shows a cross-sectional view of a typical two-cavity interference filter. The effect of the number of cavities on final passband shape, normalized to passband FWHM, is shown on page 13.28. The figure on page 13.27 shows a detailed structure of the all-dielectric multilayer bandpass filter film. H symbolizes precisely a quarter-wavelength optical thickness layer of a high-index material (typically zinc sulfide), while L symbolizes a precisely quarter-wavelength optical thickness layer of a low-index material (typically cryolite,  $\text{Na}_3\text{AlF}_6$ ). 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. 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. Depending on the center wavelength and FWHM, other filters may have many more layers than those illustrated.

## ADDITIONAL BLOCKING

Close to the passband, and on the long wavelength side, multi-layer blocking structures (usually metal dielectric hybrid filters) are used in Melles Griot passband filters to limit transmittance to 0.01%. 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 on page 13.28 showing the that change in performance with an increasing number of cavities is qualitatively useful, but the bandwidth table on page 13.28 gives quantitative data. This table applies to zinc sulfide ( $\text{ZnS}$ )/cryolite ( $\text{Na}_3\text{AlF}_6$ ) interference filters of any FWHM.

Although the table is strictly applicable from 400 nm to 1100 nm, Melles Griot ultraviolet filters, which are of different composition, have very similar characteristics. The table shows 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

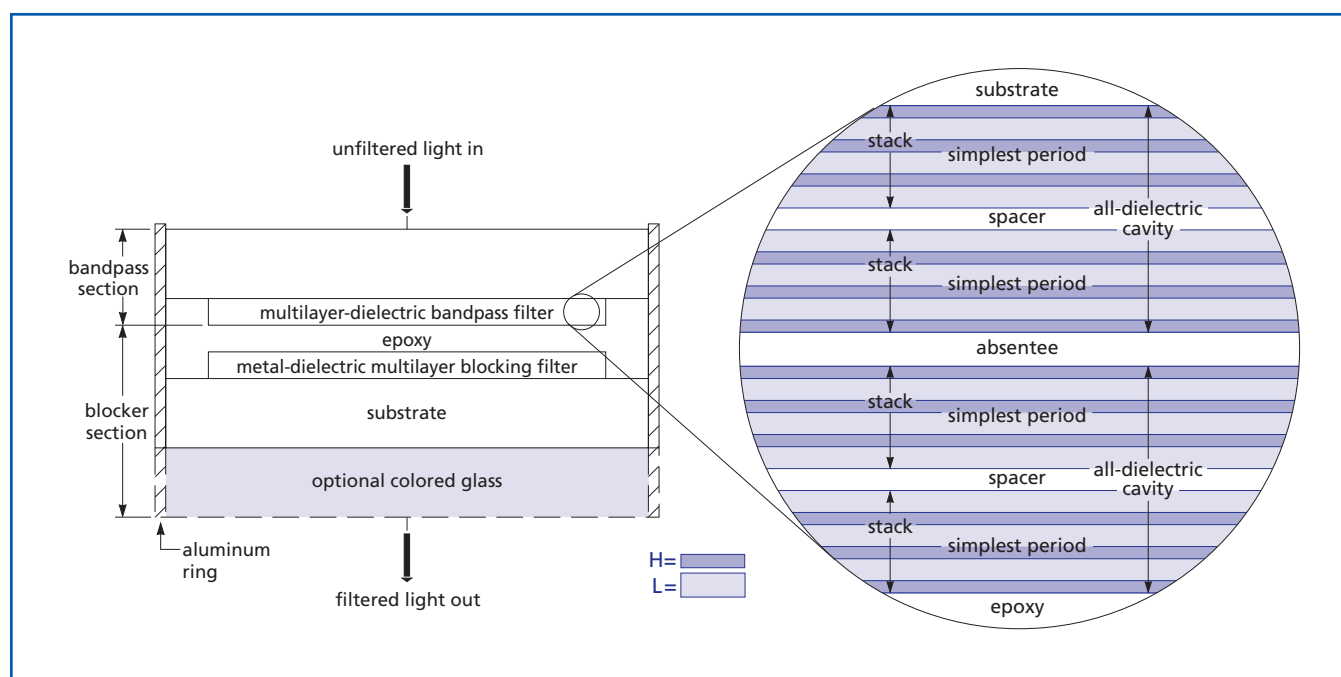
A common characteristic of single and multilayer dielectric coatings and interference filters is that transmittance and reflectance spectra shift to shorter wavelengths as they are tilted from normal to oblique incidence. This applies to both edge and bandpass filters. As tilt is increased in filters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

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 peak transmittance wavelength is slightly too long, tilt the filter. This ability 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

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

where  $n_c$  is spacer refractive index,  $t$  is the spacer thickness,  $\theta$  is the internal angle of incidence (measured within the cavity or spacer),  $m$  is the order number of interference (a nonzero positive integer), and  $\lambda$  is the wavelength of a particular resonance transmittance

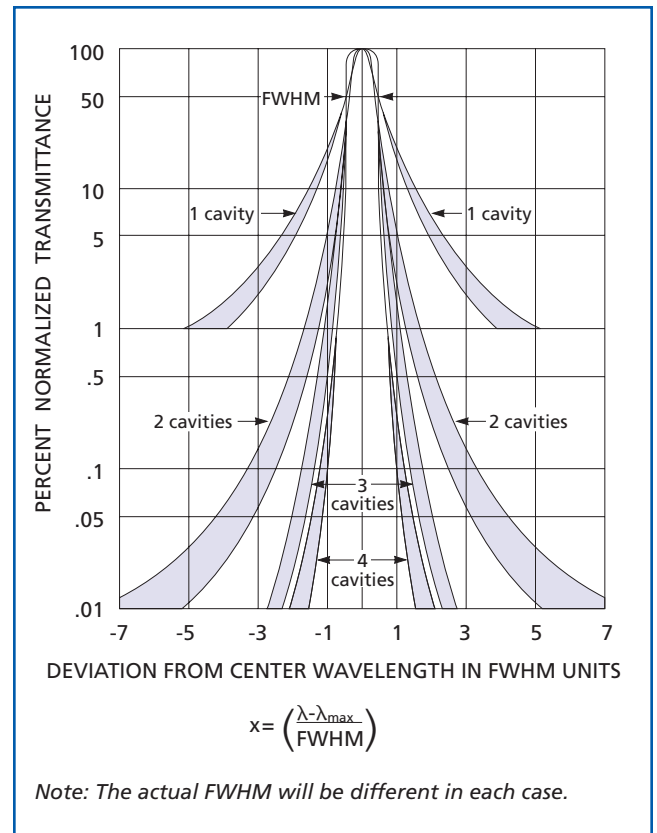


Cross section of a typical two-cavity pass interference filter

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.

#### Bandwidth at Various Normalized Transmitters

Number of Cavities	Normalized Transmittance Level (% of peak)	Multiplier for Full Bandwidth at Indicated Transmittance	
		Minimum	Maximum
1	90	0.3	0.35
	10	2.5	3.0
	1	8.0	10.0
2	90	0.5	0.6
	10	1.6	2.0
	1	2.8	3.5
	0.1	5.5	6.3
3	0.01	10.0	15.0
	90	0.7	0.8
	10	1.2	1.5
	1	1.9	2.2
	0.1	2.9	3.2
4	0.01	4.9	5.4
	90	0.85	0.9
	10	1.1	1.25
	1	1.5	1.65
	0.1	2.0	2.25
	0.01	3.5	4.25



Normalized log scale transmittance curves for ZnS/Na<sub>3</sub>AlF<sub>6</sub> bandpass interference filters of 10 nm FWHM as functions of the number of cavities used in filter construction

#### 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 FW1%M would be between 9.5 and 11.0 nm.

In terms of the external angle of incidence,  $\phi$ , it can be shown that the wavelength of peak transmittance at small angles of incidence is given by

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

where  $n_o$  is the external medium refractive index ( $n_o = 1.0$  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 simultaneously wide fields and narrow bandwidths are required. For example, if the desired monochromatic signal is to be at least 90% of  $T_{\text{peak}}$  throughout the field and the filter has a narrow 1.0-nm FWHM, angular radius is only about 2.5 degrees.

Most 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. Thermal coefficient is a function of wavelength, as shown in the following table.

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  $-50^\circ\text{C}$ . Thermal contraction will result in permanent filter damage below this temperature. High-temperature limits depend on filter design:  $70^\circ\text{C}$  is a safe and conservative limit for all filters. Some of our standard filters can accommodate temperatures up to  $125^\circ\text{C}$ . As a general rule, it is unwise to subject interference filters to thermal shock, especially as the lower limit of  $-50^\circ\text{C}$  is approached. Temperature change rates should not exceed  $5^\circ\text{C}$  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