

## 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.

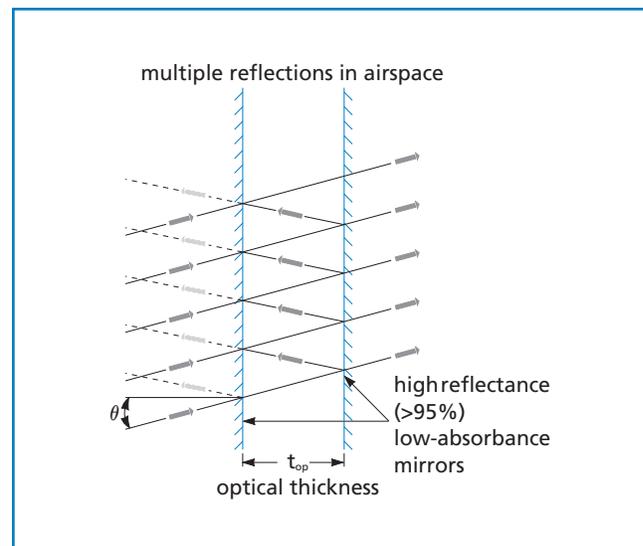
The Fabry-Perot is a simple interferometer, which relies on the interference of multiple reflected beams. The accompanying figure shows a schematic Fabry-Perot cavity. Incident light undergoes multiple reflections between coated surfaces which define the cavity. Each transmitted wavefront has undergone 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  $\theta$  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).

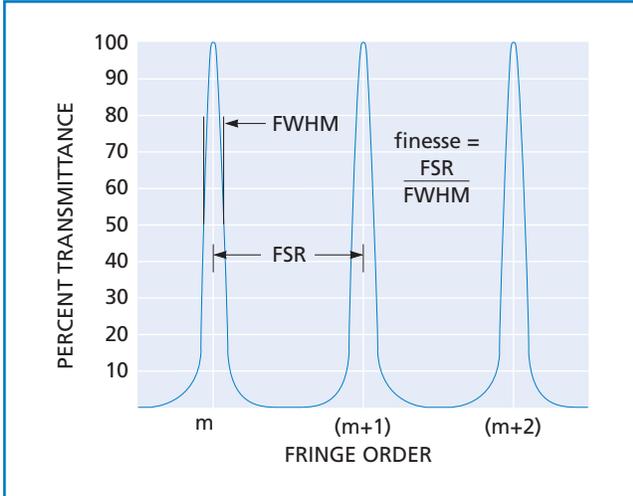
Transmission peaks can be made very sharp by increasing the reflectivity of the mirror surfaces. In a simple Fabry-Perot interferometer transmission curve (see figure), the ratio of successive peak separation to full width at half-maximum (FWHM) transmission peak is termed finesse. High reflectance results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

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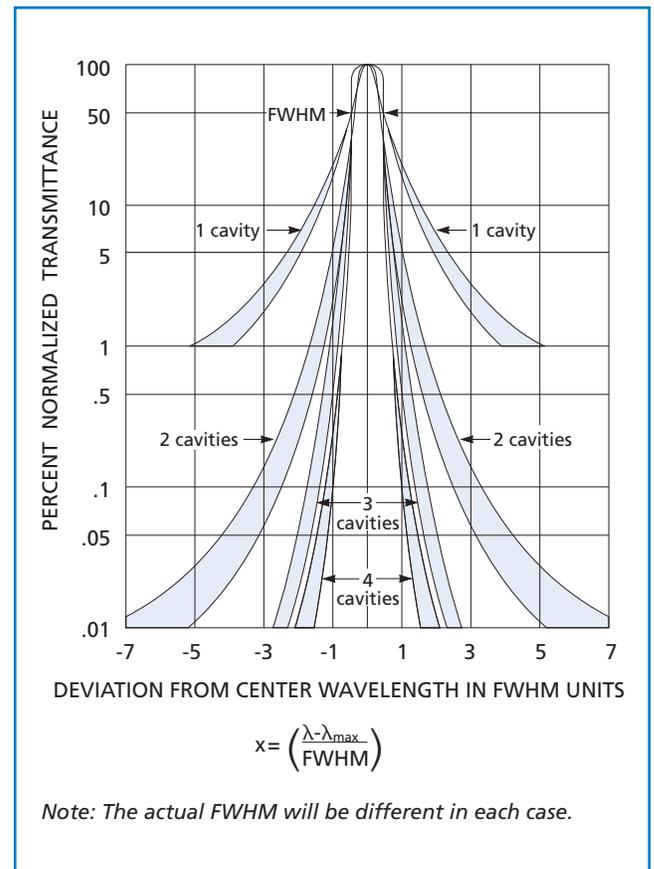
Transmission pattern showing the free spectral range (FSR) of a simple Fabry-Perot interferometer

**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 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. The construction of a typical two-cavity interference filter, along with an exploded view showing the detailed structure of the all-dielectric multilayer bandpass 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<sub>3</sub>AlF<sub>6</sub>). 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

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### 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

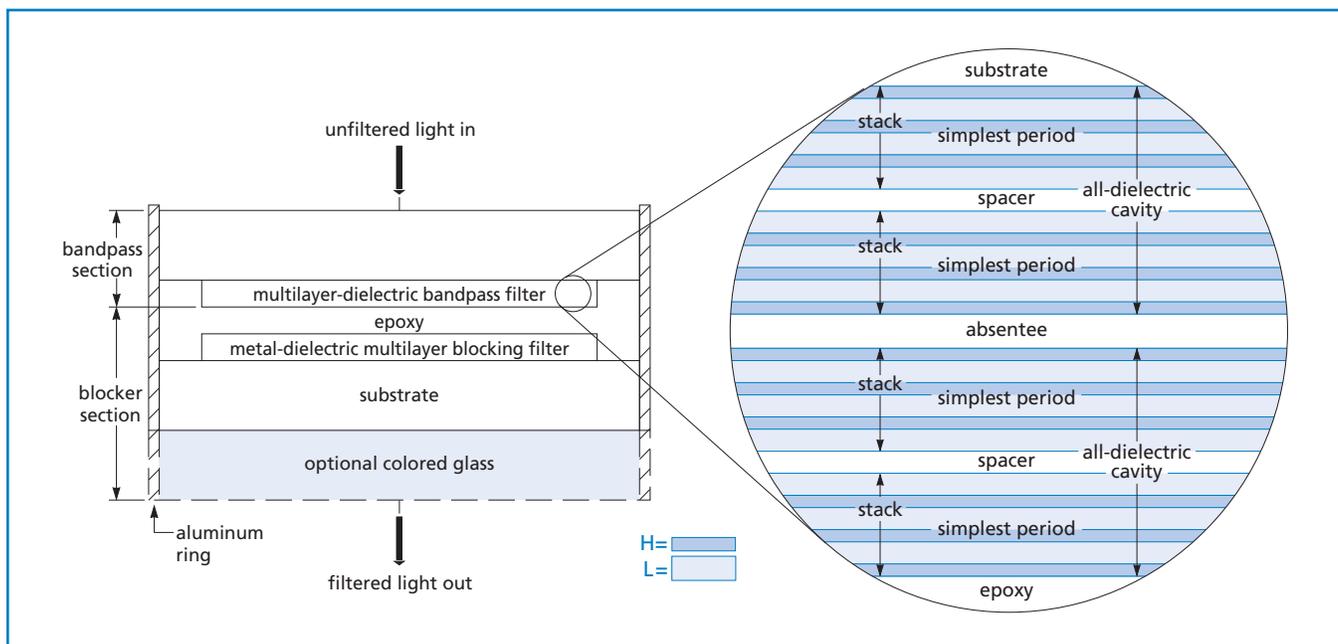
The graph showing change in filter performance as a function of the number of cavities is qualitatively useful, but the following bandwidth table gives quantitative data. This table applies to zinc sulfide (ZnS)/cryolite ( $\text{Na}_3\text{AlF}_6$ ) interference filters of any FWHM.

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

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**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,  $\theta$  is the internal angle of incidence (measured within the cavity or spacer),  $m$  is the order number of interference (a positive integer), and  $\lambda$  is the wavelength

**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.

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.

**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.

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In terms of the external angle of incidence,  $\phi$ , 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  $T_{\text{peak}}$  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

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### 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.

