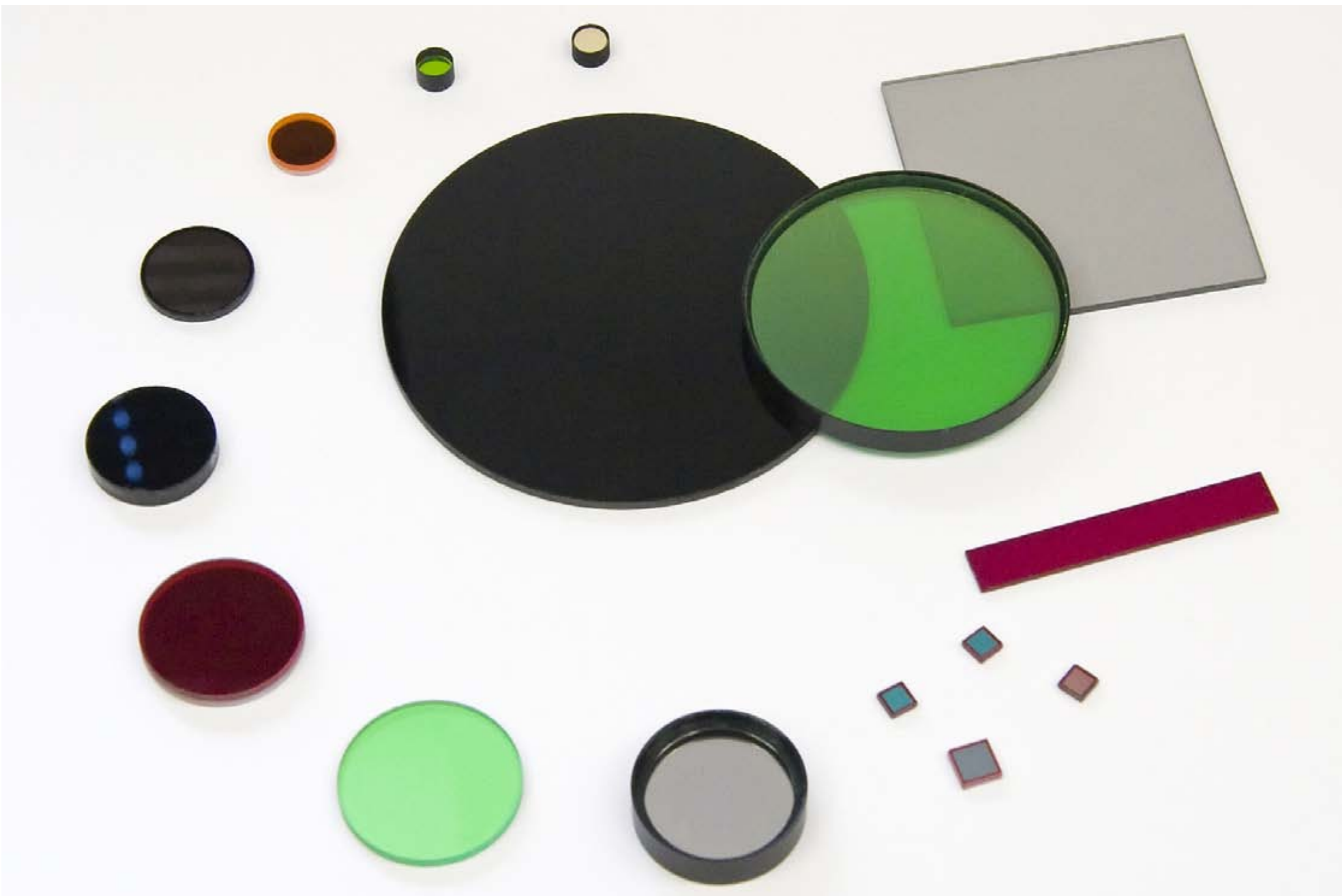
Optical Filter Guide



SpectroFilm

Vacuum Deposited Thin Films
for Research and Industry

34 Dunham Road, Billerica, MA 01821 • www.SpectroFilm.com
(978) 670-7192 Fax (978) 670-7365

SpectroFilm

Vacuum Deposited Thin Films
for Research and Industry

Thin Film Optical Interference Filters and Coatings

• Research and Development

• Computer Aided Design

• Technical Assistance

• Central Wavelengths 254-2500 nm

• High Volume Production

• Advanced Manufacturing

• Manufacturing Support

• Military Inspections

In the high technology world of constant change, one element, the "High Precision Optical Interference Filter" has remained essentially unchanged for almost 40 years.

These extremely compact optical elements offer a number of advantages over other types of elements designed to isolate discreet spectra.

Advantages

• 5 to 500 times higher energy transmission than ruled and holographic grating monochronometers.

• 10 to 1000 times better out-of-band rejection of unwanted wavelengths resulting in 10,000-100,000 to 1 signal to noise ratios (40-50 db attenuation) This is due to the materials used in the manufacture of interference filters.

• Passbands are highly defined, (approaching square wave) passing from maximum attenuation to maximum transmission and back again more quickly than other spectral isolation methods.

• Interference filters experience 1/10 the amount of spectral shift with temperature experienced by absorptive filters.

Limitations

• Evaporated films are soft and somewhat hydroscopic, but with care in manufacturing and use, can last 10+ years.

• Depending on application, and coating complexity, interference filters of this type can be more expensive.

The following is designed to aid engineers in the specification of bandpass filters and to show some of the choices and trade-offs available. Each filter specification is discussed and details shown each affects or is affected by other parameters.

Those familiar with filter design and operation may use this booklet as a technical discussion paper to review various technical aspects of filters.

The central portion of this booklet provides a partial listing of filters available by half bandwidth. Please note that the filters described in this section are for reference and provide only a portion of the total capabilities of SpectroFilm.

Optical Interference Filters: The Old / New Technology

Optical Interference filters take advantage of the same principles that cause oil films on water or soap bubbles to change colors. By modifying the interface of a substance and its environment with a third material, reflectivity of the substance can be significantly altered.

EXAMPLE:
n1 = air
n2 = substrate
n3 = modifying material

if
n1<n3<n2 reflection at cwl will be ***reduced***

if
n1<n3>n2 reflection at cwl will be ***increased***

By depositing many layers of high and low index materials selective transmission and or reflection of wavelengths occurs.

The thin-film coatings produced at SpectroFilm are produced by evaporating dielectric and/or metal materials onto a substrate which is under vacuum. The thickness of the materials deposited is precisely controlled by monitoring the transmission of a monochromatic beam of light (the monitor wavelength) through the substrate. Other monitoring methods can be used but may vary in efficiency.

By altering the number and arrangement of evaporated layers, the spectral performance of the substrate can be significantly modified. Difference in the designs can yield long and short wavelength pass filters, single and multiple rejection band filters, anti-reflection coatings, and pass band filters in a variety of bandwidths and transmissions.

The fundamental element of a thin-film coating is the reflective quarterwave stack. By depositing alternating layers of high and low index materials, reflectivity at the monitor wavelength is increased. This basic element can be used to create high performance dichroic or long/short wavelength pass filters.

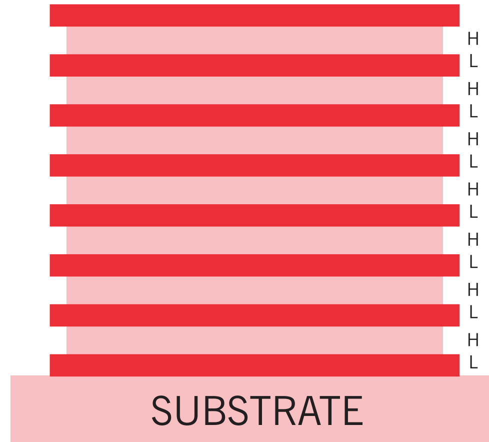
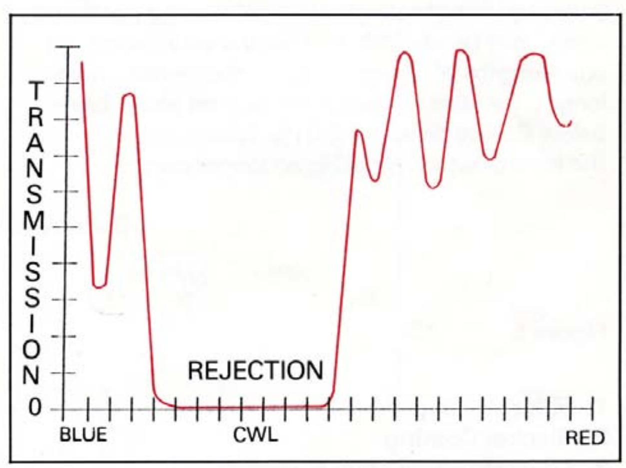


Figure 1. Quarter wave stack of alternating high and low index layers. Resultant spectral response shown.

When two reflective stacks are joined by a thin-film spacer layer, the reflective stacks create a FabryPerot interferometer that transmits at the monitor wavelength rather than reflects. These combined stacks are called cavities. By increasing the number of layers within a cavity and the number of cavities of a given design, performance of the coating will alter considerably.

Figure 2 Rejection created by quarter wave reflective stack



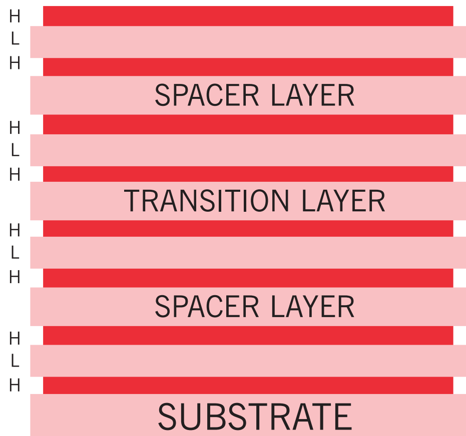
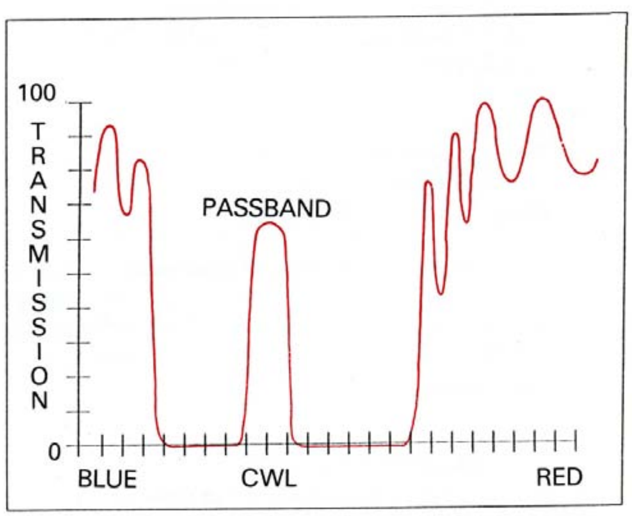


Figure 3. A simplified two cavity design.

For further information please refer to sections discussing Half Bandwidth, Pass Band Shape and Blocking.

Figure 4 Unblocked multiple cavity filter coating



The Generic Visible Filter

The generic interference filter depicted in figure 5 consists of three general elements – two coatings and an absorptive material. (Please note that the figure is for reference only and that there are a variety of different methods and materials for filter assembly.)

The first coating (”filter”) (figure 5, line 1) is the actual passband filter coating which defines the passband shape, half bandwidth, and central wavelength. At wavelengths of .8 and 1.2 times the central wavelength, the filter will begin to transmit again. Levels below optical density 4 (0.01% Trans) are considered the level at which blocking no longer occurs.

The second coating (”blocker”) (figure 5, line 2) is another wider filter which provides blocking of wavelengths on both sides of the filter but is primarily used for blocking from the passband out to the red or longer wavelengths.

The last element (”low side”) (figure 5, line 3) is an absorptive material such as colored glass which will block from the passband towards the low wavelengths and the blue edge of the detector range.

When put in series, the “filter” out-of-band transmissions are effectively eliminated by the “blocker” and the shorter wavelengths transmitted by the blocker are rejected by the “lowside”.

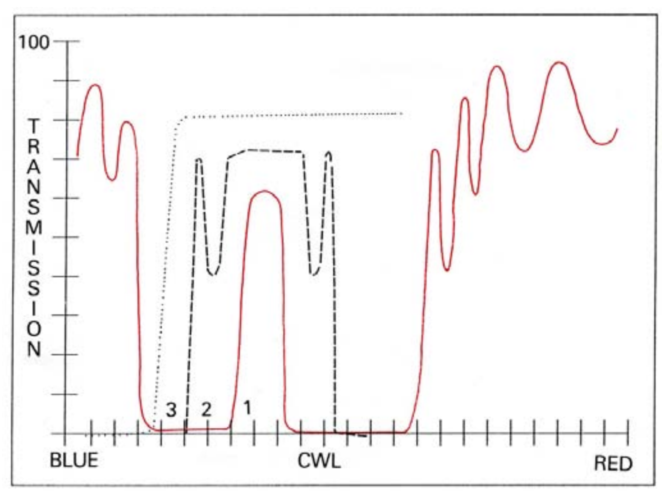


Figure 5 Overlay of various elements that make up a filter

1. **Filter Coating**
2. **Blocker Coating**
3. **Lowside Absorptive Material**

Center Wavelength (CWL)

This is the easiest of the specifications to set. It is defined as the mean wavelength between two relative 50% transmission points on the . It may be specified using any of the following:

5320.0 angstroms
532.0 nanometers
0.532 microns

Filters are specified in angstroms or nanometers from the vacuum ultra violet to about 2.0 microns. Mid and far infrared filters are expressed in microns.

Temperature, and the angle of light incident to the filter, heavily affects some filters. Tolerances should be designed to account for these variables within the operating range of the instrument. (See sections on Angle of Incidence and Operating Temperature)

The narrower the bandwidth, the tighter this tolerance generally needs to be. Typically a CWL tolerance of 10-20% of the bandwidth is appropriate. In instances where tighter than normal tolerances are specified, the trade-offs may be cost and time.

In some cases a greater importance is assigned to the out-of-band blocking of other lines or wavelengths with little restriction on CWL. This is often true for fluorescence applications where blocking is critical and the passbands can be moved slightly.

Half Bandwidth (HBW)

Also known as Half Power Bandwidth (HPBW) and Full Width at Half of Maximum transmission (FWHM). This is the interval between the relative 50 percent transmission points of the passband. Tolerances of 10 to 20 percent are typical although tighter tolerances are available and often dictate a higher cost.

Narrow bandwidth filters are often used to isolate discrete spectral lines and by their complexity are more expensive than wider filters. If there is no unwanted radiation near the line of interest possible consideration should be given to using a wider filter for the job. Additionally, wider bandwidth filters exhibit higher transmissions.

Passband Shape

Passband shape is primarily a function of the number of cavities in the filter design. The greater the number of cavities, the more square the shape. As the number of cavities increase,the base of the passband narrows and the top will widen.

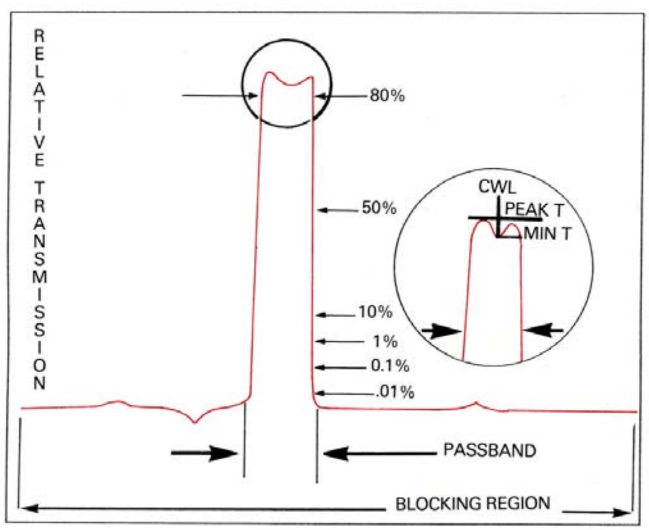


Figure 6

CUSTOM PASSBAND COATINGS

HBW (NM)	HBW TOL.	CAV	CWLs	CWL TOL.	BLOCK 1 μ	BLOCK FIR	Effective Index
1	+/−.2	2	400- 430	+.2/−0	20	15	1.45
1		2	430- 480		30	20	1.45
1		2	480- 550		40	30	2.10
1		2	550-1100		55	40	2.10
1	+/−.2	3	480- 550	+.2/−0	40	30	2.10
1		3	550- 950		50	35	2.10
1.5	+/−.3	2	260- 300	+.4/−0	25	10	1.45
1.5		2	390- 400	+.3/−0	—	15	1.45
1.5		2	400- 430		25	20	1.45
1.5		2	430- 480		35	25	1.45
1.5		2	480- 550		45	30	2.10
1.5		2	550-1100		55	35	2.10
2	+/−.5	2	360- 380	+.4/−0	—	25	1.45
2		2	380- 400		35	25	1.45
2		2	400- 430		40	25	1.45
2		2	430- 480		40	30	1.45
2		2	480- 550		45	35	2.10
2		2	550-1100		55	35	2.10
2	+/−.5	3	430- 480	+.4/−0	40	30	1.45
2		3	480- 550		45	35	2.10
2		3	550- 950		50	35	2.10
2		3	950-1100		50	30	2.10
3	+/−.5	2	325- 360	+.5/−0	—	20	1.45
3		2	360- 400		—	20	1.45
3		2	400- 430		35	20	1.45
3		2	430- 480		40	35	1.45
3		2	480- 950		55	45	2.10
3		2	950-1100		50	40	2.10
3	+/−.5	3	430- 480	+.5/−0	40	30	1.45
3		3	480- 550		50	40	2.10
3		3	550- 900		55	45	2.10
3		3	900-1000		50	40	2.10
5	+/−.5	2	300- 320	+1/−0	—	20	1.45
5		2	320- 340		—	25	1.45
5	+/−1	2	340- 380	+1/−0	—	30	1.45
5		2	380- 400		—	30	1.45
5		2	400- 480		40	30	1.45
5		2	480- 550		50	40	2.10
5		2	550- 900		55	45	2.10
5		2	900-1100		50	40	2.10
5	+/−1	3	400- 430	+1/−0	35	30	1.45
5		3	430- 480		40	30	1.45
5		3	480- 550		50	40	2.10
5		3	550- 900		55	40	2.10
5		3	900-1100		50	40	2.10
10	+/−2	3	300- 340	+/−2	—	30	1.45
10		3	340- 400		—	35	1.45
10		3	400- 430		50	40	1.45
10		3	430- 480		55	45	1.45
10		3	480- 550		60	50	2.10
10		3	550- 900		70	50	2.10
10		3	900-1100		60	45	2.10
10		2	1100-2300		60	40	2.10
12	+/−2	4	220- 260	+/−2	—	20	1.45
12		3	260- 320		—	15	1.45
20	+/−4	3	380- 400	+/−2	—	30	1.45
20		3	400- 430		50	35	1.45
20		3	430- 480		60	40	1.45
20		3	480- 550		65	45	1.45
20		3	550- 750		70	50	1.45
20		3	750- 900		70	50	2.10
20		3	900-1100		60	40	2.10
20		2	1100-2300		60	40	2.10
25	+/−5	3	220- 320	+/−2	—	20	1.45
50	+/−10	5	340- 400	+/−5	—	35	1.45
50		5	400- 430		50	45	1.45
50		5	430- 480		0	50	1.45
50		5	480- 520		5	50	1.45
50		5	520- 900		70	50	2.10
50		3	900-1100		60	50	1.45
50		3	1100-2300		60	40	1.45
80	+/−20	5	460- 750	+/−10	70	—	1.45
80		4	750-1500		70	—	2.10

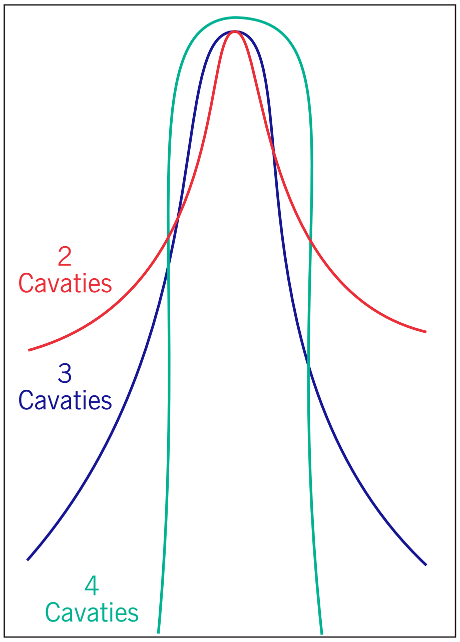


Figure 7. Relative bandpass shape and near band attenuation of filters with multiple cavaties in the visible. Note the square passband shape of the four cavity filter versus the two cavity filter design.

As the number of cavities increase, the top of the passband will exhibit a certain amount of “ripple” or waviness. When the shape of the passband is important or when a certain amount of transmission is required across a number of wavelengths, the minimum transmission at the 70-90% of maximum transmission BW can be specified to limit waviness.

Likewise, certain applications require that a filter exhibit a certain bandwidth at a point between .01-10% of maximum transmission. In certain instances, specifications of additional points on a passband may add to the cost of the filter depending upon the resulting complexity.

Transmission

This is the actual amount of light passing through the filter expressed as a percentage of the light incident upon the filter at a particular wavelength. For the purpose of this discussion we refer to the desired in-band transmission as opposed to out-of-band transmission.

The transmission of a particular filter depends on the application in which it is used. Some maybe as high as 95% while others may be as low as 1%. Examples follow:

Bandwidth of a filter coating

Full width at trans level = CWL × Factor

cavities	transmission	factor
2	90%	0.5 - 0.6 of HBW
	10%	1.6 - 2.0
	1%	2.8 - 3.5
	0.1%	5.5 - 6.3
	0.01%	10.0 -15.0
3	90%	0.7 - 0.8
	10%	1.2 - 1.5
	1%	1.9 - 2.2
	0.1%	2.9 - 3.2
	0.01%	4.9 - 5.4
	0.001%	10.0 -15.0
4	90%	0.85- 0.9
	10%	1.1 - 1.5
	1%	1.5 - 1.65
	0.1%	2.0 - 2.25
	0.01%	3.5 - 4.25

Figure 8

One instrument manufacturer might wish to reduce the amount of costly computer control for their instrument and increase speed by specifying filters that inversely match the spectral response of their silicon detector. Filters of this type create an artificial base line transmission from which all readings could be matched without the instrument recalibrating (resetting the base line) after every change in wavelength. Filters towards blue wavelengths tend to be wider and have high transmission. As the wavelengths move toward the red, they are increasingly attenuated as the spectral sensitivity of the detector and lamp output increases.

An astronomer using a Charge Coupled Device (CCD) array would need average blocking out-of-band and as much transmission as possible in-band. By doing this, they would be able to capture every available photon from a distant source thereby reducing instrument rental costs to the lowest possible.

Increasingly, manufacturers find that transmission becomes secondary to the need for high signal-to-noise ratios. By providing deeper levels of out-of-band blocking, low-level in-band signals can be isolated from nearby signals. This is particularly true for fluorescence applications where the excitation wavelength and the insertion power of a laser or xenon light source may be thousands to millions of times stronger than the emission of the sample (sometimes measured in) and spectrally very close to one another. Please see the section on Ultra High Discrimination Filters.

Out-of-Band Transmission (Blocking)

A passband filter is designed to allow light within a specified region to pass while effectively blocking unwanted wavelengths both longer and shorter than the central wavelength. The ratio of in-band transmission (desired) to the out-of-band transmission (undesired) is called the signal to noise ratio. For sophisticated instruments, it is the single most important parameter to be considered when specifying a filter and is considered extremely important by us at SpectroFilm.

A variety of terms are used to specify out-of-band transmission (blocking) and they compare as follows:

Transmission (percent)	Rejection (exponential)	Attenuation (decibles)	Optical Density
100.0000	0	0	0
10.0000	10^{-1}	10	1
1.0000	10^{-2}	20	2
.1000	10^{-3}	30	3
.0100	10^{-4}	40	4
.0010	10^{-5}	50	5
.0001	10^{-6}	60	6

Because there is a certain amount of fluctuation in the transmission out-of-band, the terms above are generally specified as an average within a range of wavelengths or as a maximum allowable level.

This range of blocking is generally a combined consideration of the light source (sun, lamp, laser, spark, to name a few) and the spectral response region of the detector being used (Film, Eye, PMT, photovoltaic, etc).

All sources vary in intensity versus wavelength. Some like the tungsten filament lamp emit in broad ranges of wavelengths whereas others emit discreet lines at specific wavelengths. Variation in intensity can also change as a function of the temperature of the filament.

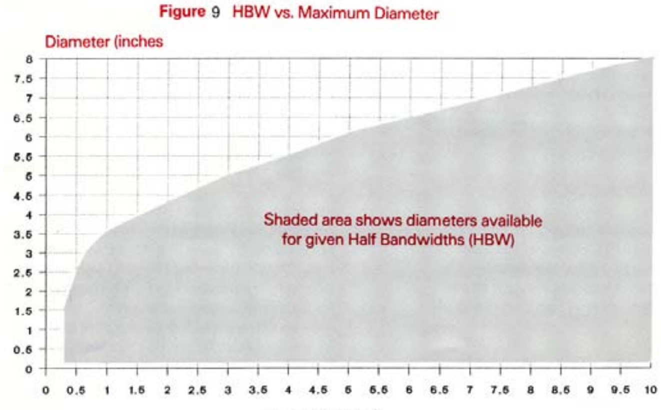
Detectors also vary greatly from one to another and can have certain variances from unit to unit depending on type. Sensitivity and range vary with detector.

Angle Of Incidence

A filter is always a part of an optical system. As light is manipulated, turned, and focused, the angle at which the light impinges upon the filter may affect how the filter performs. Most filters are used in systems where the light is not collimated. The angle may be as small as a few milliradians to as much as 45 degrees.

The CWL of the filter will shift toward shorter (blue) wavelengths as the angle of incidence increases and is a function of the effective index of refraction of the materials used in the construction of the interfering layers. The lower the numerical value of the index, the faster the shift.

Figure 9 HBW vs. Maximum Diameter



Max Dia of one piece in the visible

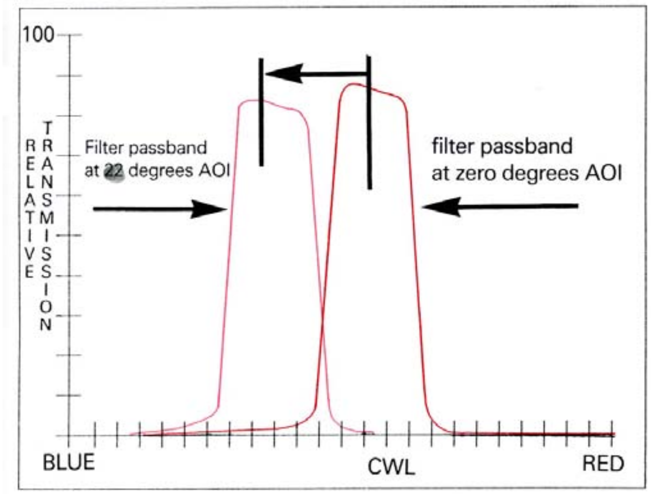


Figure 10

The amount of shift may be calculated using the following formula:

$$Lamda_1 = Lamda_0 \, (1 - Sin^2 i \; / \, eff^2)^{\;1/2}$$

where:
i = angle of incidence
$Lamda_1$ = resulting wavelength at angle i
$Lamda_0$ = central wavelength at normal incidence
eff = effective index of the filter

Some applications make use of the change of central wavelength as a function angle. Astronomers use this effect to see the doppler shift of light emitted from celestial bodies as they move toward or away from the observer and to measure that speed.

If the application requires that the wavelength of interest maintain its intensity within a range of wavelengths, somewhat wider bandwidth filters might be required.

Lastly, filter performance with angle and polarized light will alter the transmission and the bandwidth of the filter.

Temperature

Temperature effects on interference filters take two forms – reversible and irreversible.

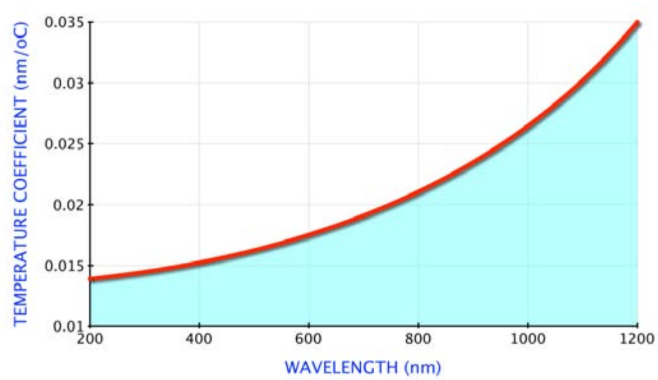
Filters exposed to relatively mild changes in temperature can be extremely useful, as the filter tends to change wavelength as a function of the temperature. This is also a technique used by astronomers to measure doppler shift. As a general guideline, filters will shift .02nm per °C. This is a function of the number and types of layers deposited on the substrate.

If a filter is exposed to high temperatures for an extended length of time, the filter can be irreversibly changed to a shorter wavelength.

Filters regardless of bandwidth will exhibit a minor shift towards the blue over time. For most instruments, this is irrelevant; however, for narrowband filters this may shift the central wavelength of the filter from the wavelength of interest. SpectroFilm takes advantage of this natural process by heating or baking narrow band filters into position. Although this will stabilize the central wavelength of the filter, some additional aging may occur but at a rate 100-1000 times slower than without baking.

Precision filters are generally a laminated sandwich design of various elements. The epoxy bonding the filters together will be damaged if exposed to temperatures of approximately 120 degrees Celsius even for short periods of time. Instrument development and design should include some method of cooling the filter if it must be placed in a position of high temperature.

The limits of temperature for a laminated filter can be as high as +50 degrees C to below -50 degrees C. In all cases, the rate of temperature change should be held to a maximum of 5-10 degrees C.



Physical

SpectroFilm is a manufacturer of custom filters and produces filters in the sizes and shapes specified by our customers. It is important to note that small filters in quantity are less expensive than larger filters.

Most instrument manufacturers place bandpass filters as physically close to the detector as possible and specify a size comparable to the detector size.

Other Filter Specifications

The majority of filters produced by SpectroFilm are photometric filters where only the isolation of certain spectra is required. Generally the physical characteristics are 80/50 scratch dig and 5-10 waves an inch across the face of the filter. Imaging filters for use with a variety of detectors may require the addition of many other optical specifications and often changes in the methods used to make the filters.

Flatness, parallelism, pin holes, and surface quality are some of the additional specifications.With the exception of pin holes (which reduce the overall depth of blocking in some photometric applications), these specifications are not required for photometric filters.

The manner in which coatings are deposited on substrates can affect the quality of an imaging system. In fast systems, F6 and faster, filters can generally be photometric type filters.

In systems f10 and slower the technical requirements for filters increases to its highest, in that filter coatings are either deposited on one substrate or are physically located as close as possible to one another. One of the trade offs in an imaging system filter is transmission. Due to the number of layers required to make narrow band filters, coatings on single substrates require that metal blocking be used. This type of blocking achieves deeper levels of blocking out-of-band with fewer layers than dielectric blocking. It also serves to limit in-band transmission.

Dielectric blocking allows a higher transmission but due to the number of layers to make the filter, should be deposited on separate substrates. This separation of coatings may cause multiple internal reflections which may degrade performance of the system.

In general, if 1/4 wave flatness is required of a filter after it is finished, the elements must first be assembled and the external surfaces polished to specification. As mentioned before,temperature degrades the laminates holding a filter together and to achieve a “hard” AR coating requires temperatures in excess of 300 degrees C. The trade off is that only a "soft" AR coating can now be deposited.

Newer cold AR coating technologies are being developed, primarily ion packing, which yield equally hard AR coatings.

When coatings are deposited, the atoms of the materials tend to stack themselves in microscopic columns. Pin holes are tiny voids in the coating columns that allow unfiltered light to pass. All coatings if inspected under high enough magnification will give indication of pinholes. Specification of “no visible pinholes” implies under rear illumination with a bright light source that no pin holes will be observable to the unaided eye.

The level of pinhole examination and filter rejection may increase the cost of filters.

Ultra High Discrimination Filters

SpectroFilm has worked with a number of research groups world wide in the development of filters that provide high transmissions, very deep out-of-band attenuation levels and highly defined passband shapes for applications where the desired output signal is weak and easily buried by other undesirable spectral signals. The six or more cavity filters are commonly used in fluorometric analysis instrumentation such as flow cytometers, fluorescent microscopes and other instruments designed to excite a sample and read the resultant Stokes shifted emission characteristics.

Commonly, the difference between the key excitation wavelength and the Stokes shifted emission wavelength is relatively small and impossible to discriminate using the standard 3 cavity filters. This lack of discrimination is due to the relative slowness with which the a 3 cavity filter passes from maximum transmission to maximum attenuation with relation to 6 or more cavity filters which exhibit virtually square passband shapes. This allows the two filters to be placed spectrally close to one another while providing the lowest level of cross-talk between the channels.

Typically, filters with 6 or more cavities exhibit greater than 50 percent transmission in the visible, with combined out-of-band blocking in excess of 1Oe-8 (0.000001% transmission)between the pass bands. This level can be further enhanced in some instances with the introduction of a high performance .

SpectroFilm has dedicated considerable effort in the development of optical filters that reduce or eliminate the amount of "AUTO-fluorescence" or the fluorescence of the filters themselves.Due to the nature of some fluorescence instruments (primarily the type and intensity of the excitation source), filter elements can be made to fluoresce thereby contaminating the readings obtained or completely obscuring the desired readings.

Each High Discrimination filter is assembled to reduce auto-fluorescence based on information provided by users about the inner workings of the instruments in which they are used.

SpectroFilm has developed High Discrimination filters for a wide variety of applications and our technical staff is available to develop filters for new applications.

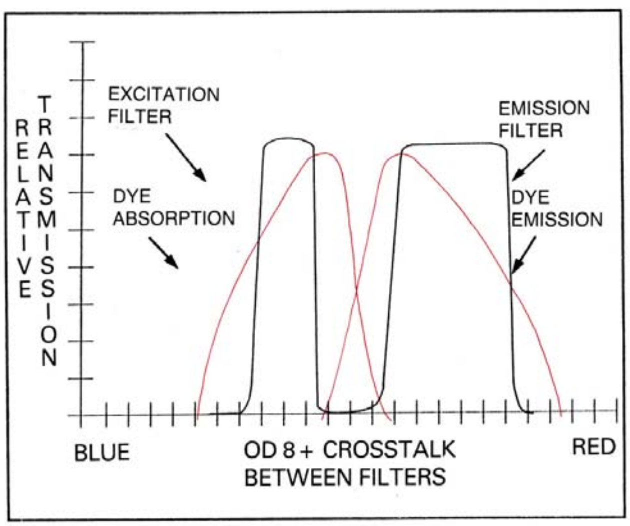


Figure 11

FIGURE 11. Optical filter spectral curves overlaying absorption and emission spectra of a flourescent dye. Filters are designed to give maximum transmission while providing maximum attenuation at the wavelength of the other filter. Note that the filters are off the maximum absorption and emission spectra to allow maximum attenuation out-of-band.

Durability

Filters and optical coatings can be interpreted as performing in a variety of ways depending upon who is analyzing the filter.The Military Specifications below have become the standard by which all filter users can tell manufacturers how their filters and coatings will perform when tested to a known standard. The key specifications are listed below.

MIL-C-675A – Coating of Optical Elements ( ), discusses durability to salt spray and humidity.

MIL-STD-810C – Military Standard, Environmental Test Methods – standardizes testing methods for determining resistance to environments in military operations. Interference film testing is generally modified to 5 cycles, however SpectroFilm filters will with stand higher testing to 10+ cycles.

MIL-0-13830A – Optical Components for Fire Control Instruments: General Specification Governing the Manufacture, Assembly, and Inspection of – defines surface imperfections (scratch and dig) as well as testing and inspection methods on substrates with a short discussion of imperfections in optical coatings.

MIL-M-13508C – Mirror, Front Surface Aluminized: For Optical Elements - defines typical durability requirements and testing procedures for front surface coating hardness and adherence.

MIL-F-48616 – Filter (Coatings), Infrared Interference, General Specification For defines performance of interference filter coatings for infrared filters.

MIL-1-45208A provides guidance for the development of in-house inspection plans. SpectroFilm is capable of instituting full Military inspection as specified by the customer.

MIL-STD-45662A defines standards for measurement test equipment calibration. These are standards traceable to the National Bureau of Standards and Technology although natural standards are also allowed with sufficient documentary support of the calibration method.