Properties of SSI's Liquid Crystal Tunable Filters

At Scientific Solutions Inc. we strive to provide our customers with tunable filters that satisfy their specific needs. This process begins with extensive modeling of the expected performance of our filters. To better serve our customers, it is very important that they be aware of the advantages and limitations of our filters. The following document outlines the optical properties of our Liquid Crystal Fabry-Perot etalon (LCFP).

The intensity of light $I(\theta,\lambda)$ coming through an ideal Fabry-Perot etalon (one with no defects) is given by

(1) $$I(\theta,\lambda) = I_{\circ}(\lambda)\frac{1}{1+(2F/\pi)^2\sin^2(\delta/2)} \text{ with } \delta = \frac{4\pi nd\cos(\theta)}{\lambda}$$ [*Roesler*, 1974]

where λ is the wavelength of the radiation, $I_o(\lambda)$ is the intensity in the center of each Hadinger fringes, d is the plate separation, n is the index of refraction of the material between the etalon plates and F is the finesse of the etalon (defined in Eq. (2)). When the light source is monochromatic, the Fabry-Perot lets the light through only at specific incidence angles. Imaging the output of the Fabry-Perot produces a series of circular fringes such as those shown in Figure 1. As the wavelength of the light decreases, the diameters of the rings increase until they eventually occupy the space left vacant by the next adjacent external ring. As this happens, a new ring appears in the center of the pattern to replace the old one.

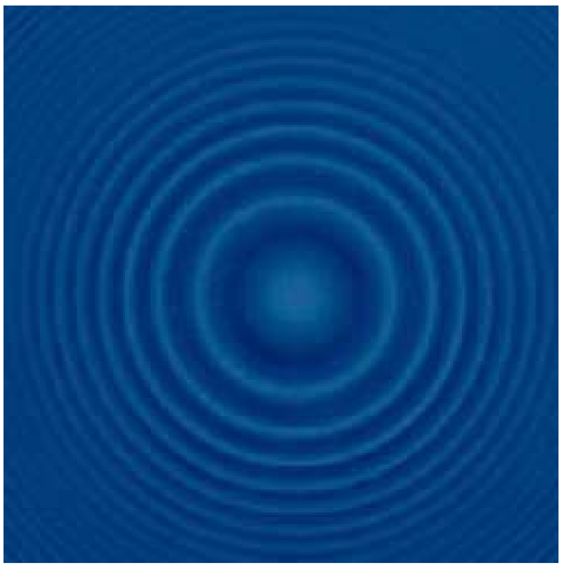

Figure 1: Interference pattern produced by a Fabry-Perot with monochromatic light.

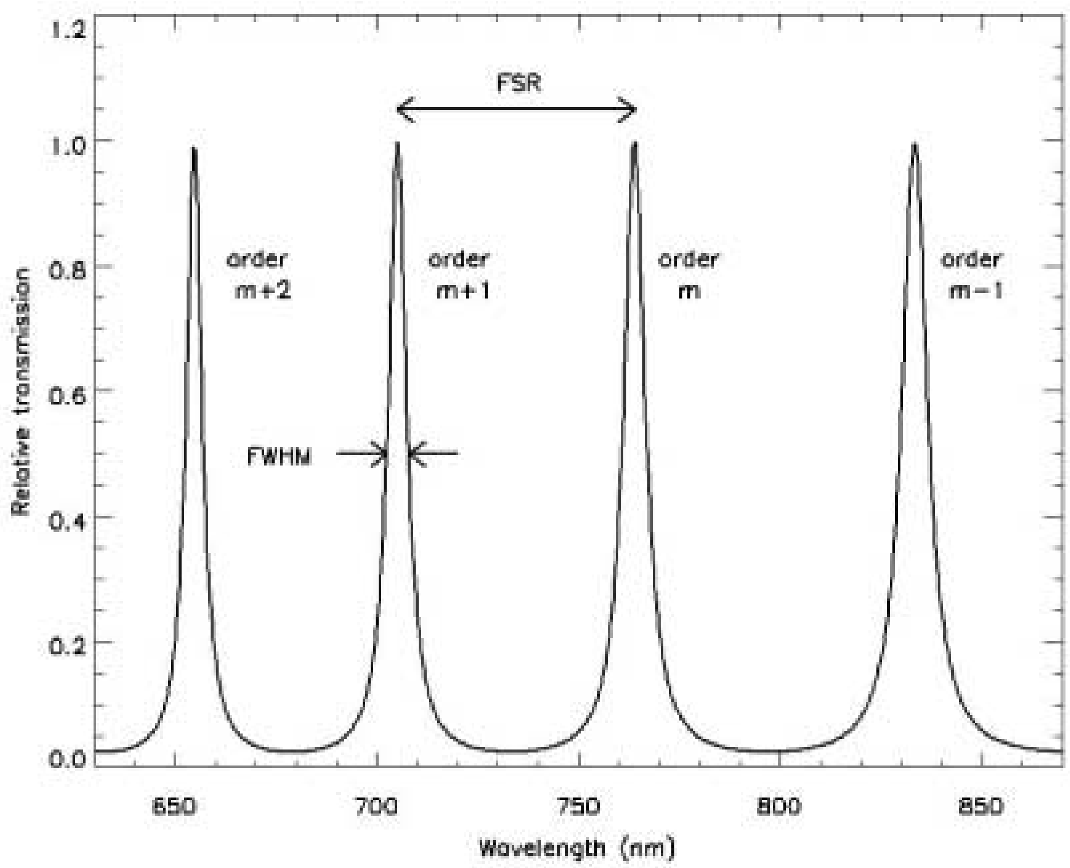

Figure 2: Relative model transmission response of an etalon with a 3 μm-wide gap.

Hence, two light sources separated by a specific wavelength interval will produce the same pattern. This specific wavelength interval is called a Free Spectral Range (FSR) and is characterized predominantly by the gap of the etalon. A Fabry-Perot lets through at different angles all radiation spectrally separated by less than one FSR.

To use the Fabry-Perot etalon as a filter, it is customary to restrict the incidence angle of the radiation to match that of the innermost ring, or spectral element. The resulting field-of-view (FOV) is given by

$$FOV = \sqrt{\frac{8}{\lambda} \times \delta\lambda} \qquad \text{[}\textit{James and Sternberg}\text{, 1969]}$$

where $\delta\lambda$ is the spectral resolution of the etalon. Figure 2 shows a typical model response of a 3μm-wide gap etalon when light comes in at normal incidence for a given index of refraction of the liquid cystal (LC). As the index of refraction of the LC inside the resonant gap of the etalon varies, the location of the different transmission peaks shifts thus enabling one to tune the transmission peaks of the Fabry-Perot to different wavelengths.

The spectral resolution $\delta\lambda$ of the Fabry-Perot is characterized by the Full Width at Half-Maximum (FWHM) of a transmission peak. One common way of expressing the performance of an etalon is by its finesse. The finesse, *F*, of the Fabry-Perot etalon is given by

(2) $$F = \frac{\Delta\lambda}{\delta\lambda}$$ *[Roesler*, 1974]

where $\Delta\lambda$ is the free spectral range and $\delta\lambda$ is the spectral resolution element, or the spectral width, of the instrument function. The FSR of a single Fabry-Perot etalon is given by

(3) $$\Delta\lambda = \frac{\lambda^2}{2nd}$$

The Fabry-Perot transmit many orders (… , m-2, m-1, m, m+1, m+2, …), where two adjacent orders are spectrally separated by one FSR. To isolate a particular wavelength when observing a broadband radiation source, it is necessary to place an order-sorting filter in front of the system. In the example shown in Figure 2, one could have a filter with a bandpass from 655 to 702 nm, one from 703 to 762 nm, and yet another one from 763 to 832 nm, each of which only lets one order through. Failing to do so would result in several different wavelengths coming through the Fabry-Perot with no way of telling them apart.

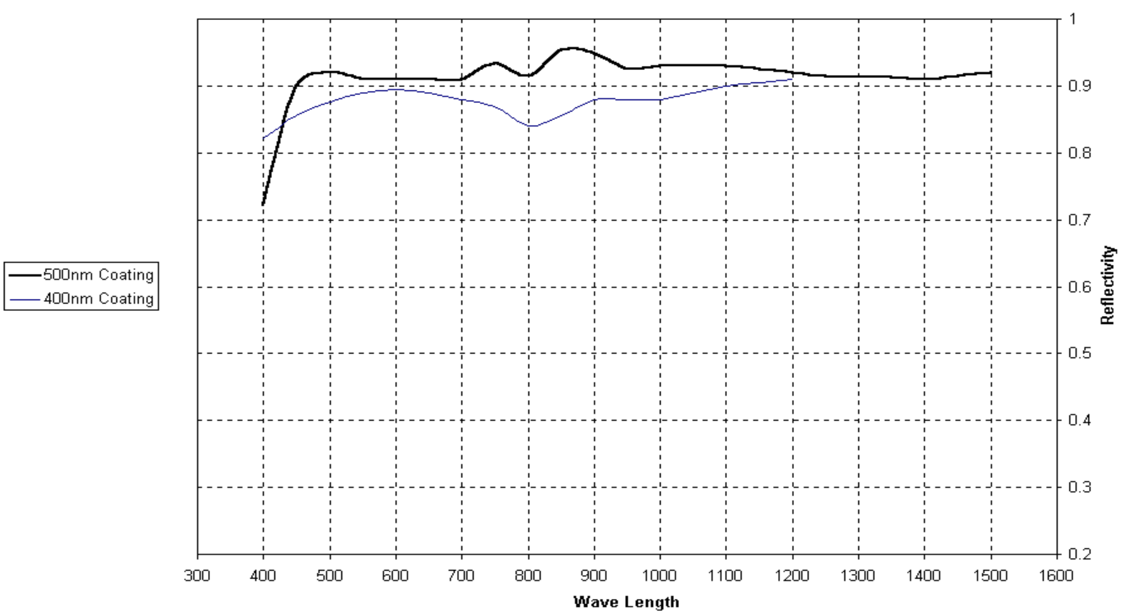

Figure 3: Broadband reflective coatings developed by SSI for the LCFP. Note that the 400nm coating actually extends to 1600nm.

To design a LCFP system for a specific application, several requirements need to be specified. First, the wavelength range over which the LCFP operates according to specifications, called the operating range, must be defined. The operating range is determined solely by the properties of the High Reflective (HR) coating applied to the extremely flat surface of the Fabry-Perot etalon. Scientific Solutions, Inc. offers a wide range of coatings for different wavelength regions from the near-ultraviolet to the near-infrared, as well as the mid- (3-5 micron) and long-wave infrared (7-12 micron). Figure 3 shows the reflectivity of two common broadband coatings that SSI has developed. Coatings can be custom designed as required by the application.

Second, the desired spectral resolution at a given wavelength must be specified. Knowing the finesse that can be achieved at a specific wavelength, the FSR of the etalon can be determined from Eq. (2). For example, if a spectral resolution of 0.1 nm is desired at 600 nm where a finesse of 10 can be achieved, that implies that the FSR of the etalon must be 0.1 nm x 10 = 1 nm. The finesse can not be arbitrarily large. Increasing the reflectivity of the HR coating increases the finesse of the etalon but decreases the peak transmission of the filter. Furthermore, the surface roughness of the etalon plates and the parallelism of the etalon plates are all factors that limit the final finesse of the LCFP. Table 1 shows the maximum finesse that SSI can quote as a function of wavelength when the incident light occupies 80% of the diameter of the filter. Higher finesses can be achieved when the incident light occupies a smaller fraction of the diameter of the filter.

Wavelength	Finesse
400 nm	8
600 nm	10
800 nm	12
1200 nm	15
1500 nm	20
MWIR (3 – 5 micron)	Available upon request
LWIR (7 – 12 micron)	Available upon request

Table 1: Achievable finesse at different wavelengths, for a beam with a diameter occupying 80 % of the diameter of the etalon.

The spectral resolution of the etalon must be specified at a specific wavelength because it varies with wavelength. This occurs because the FSR itself varies with wavelength. Figure 4 shows the FSR as a function of wavelength for etalons with different gaps. The spectral resolution can be obtained by dividing the FSR by the finesse. SSI has built tunable filters with gaps as small as 3 microns and as large as 5 cm. Should the FSR of a single etalon that achieves the desired spectral resolution be too narrow, one can place a suppression etalon in series with the resolving etalon to increase the FSR of the system while maintaining the spectral resolution. Figure 5 displays a modeled response of a twin-etalon system that uses etalons with gaps of 3 and 12 microns. The etalon with the largest gap, known as the resolving etalon, defines the spectral resolution of the system. The etalon with the smallest gap, known as the suppression etalon, suppresses some of the orders of the resolving etalon. The result is a system with the spectral resolution of the resolving etalon and a FSR larger or equal to that of the suppression etalon. The latter depends on the ratio of the FSR of the two etalons with respect to each other.

Suppose that the ratio of the FSR of the suppression etalon to the resolving etalon can be expressed as ratio of integers A/B, where A and B do not have a common divisor. The FSR of the twin etalon system is then given by

$$FSR = A \times FSR_{resol} = B \times FSR_{\sup p} \tag{4}$$

where FSR_{resol} and FSR_{supp} are the free spectral ranges of the resolving and suppression etalon respectively. If B = 1, the suppression etalon defines the FSR of the system, otherwise the FSR of the system will be larger than that of the suppression etalon by a factor of B. In a twin etalon system, the FSR of the resolving etalon and the number of available spectral resolution elements are both expanded by the factor A, henceforth called the "FSR expansion factor".

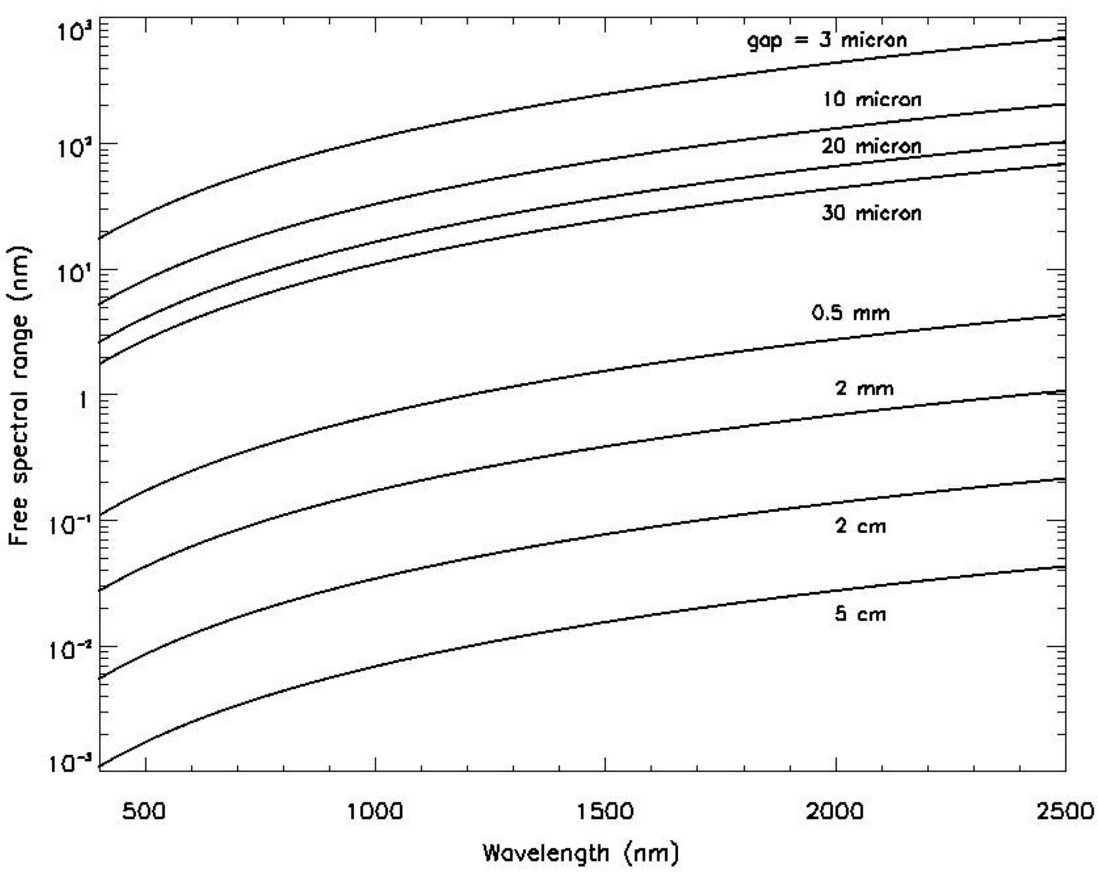

Figure 4: Free Spectral Range as a function of wavelength for one etalon with different gaps.

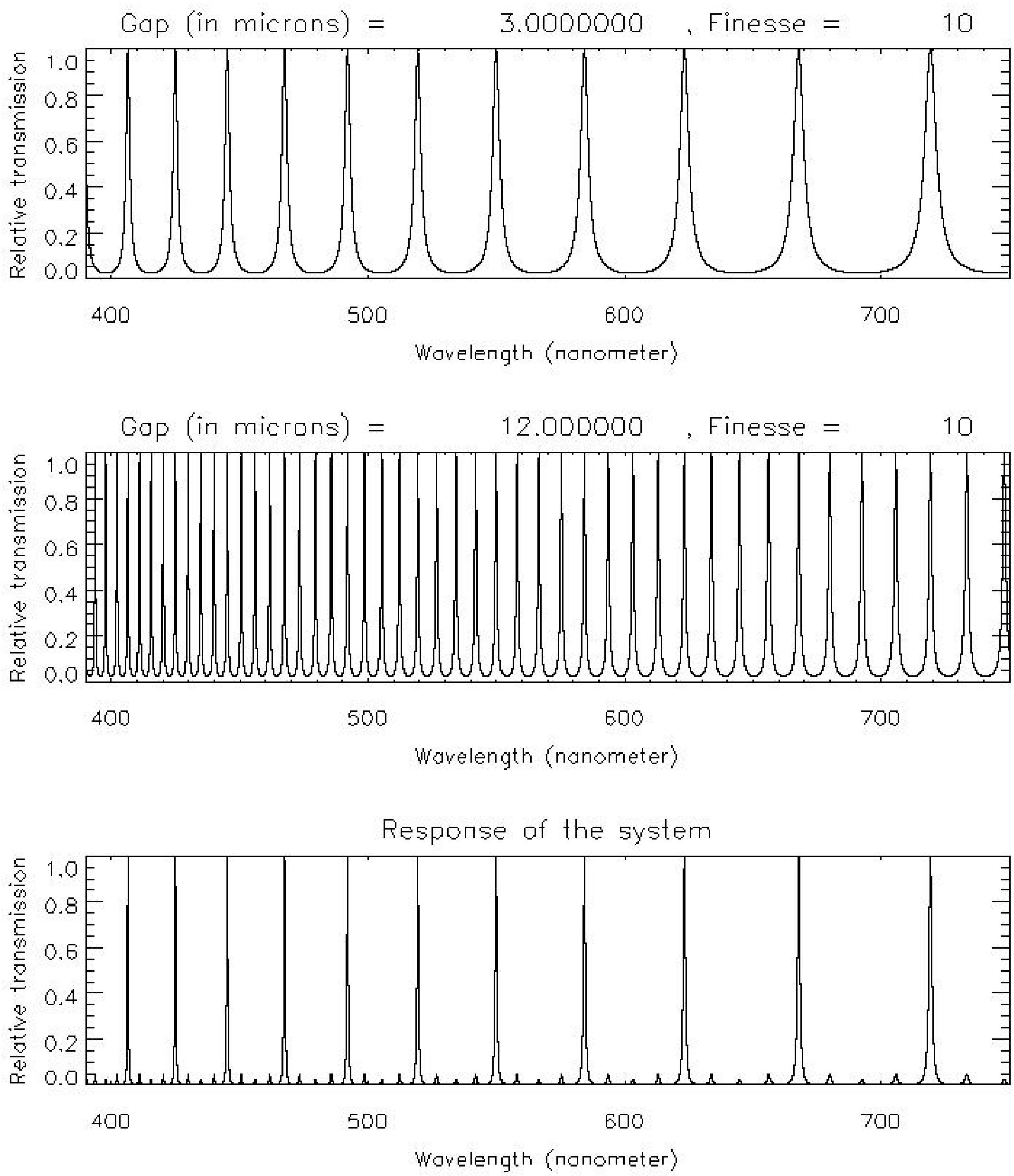

Figure 5: Model illustrative of a two-etalon system.

In the case of the 3 and 12 micron gap twin etalon example (Fig. 5), the 3 micron gap etalon has a FSR exactly 4 times that of the resolving etalon. Combined with a finesse of 10 for the resolving etalon, 4 x 10 = 40 resolution elements now exist within the FSR of the system, instead of the 10 given by the finesse of a single etalon system.

As the name implies, the suppression etalon does not completely remove the intermediate orders of the resolving etalons: it merely suppresses them to various degrees and creates ghosts observed between the main transmission peaks of the system. Barring the hinderance of these ghosts, the FSR of the resolving etalon could be arbitrarily expanded within the limits of available gap sizes. Figure 6 shows the strength of the strongest ghosts as a function of the FSR expansion factor and for different finesses of the etalons for a twin etalon system. If one wants a system at 800 nm, where a finesse of 12 can be achieved, with ghosts less than 5% of the maximum transmission peak, Fig. 6 shows that the FSR expansion factor can be as high as 5.

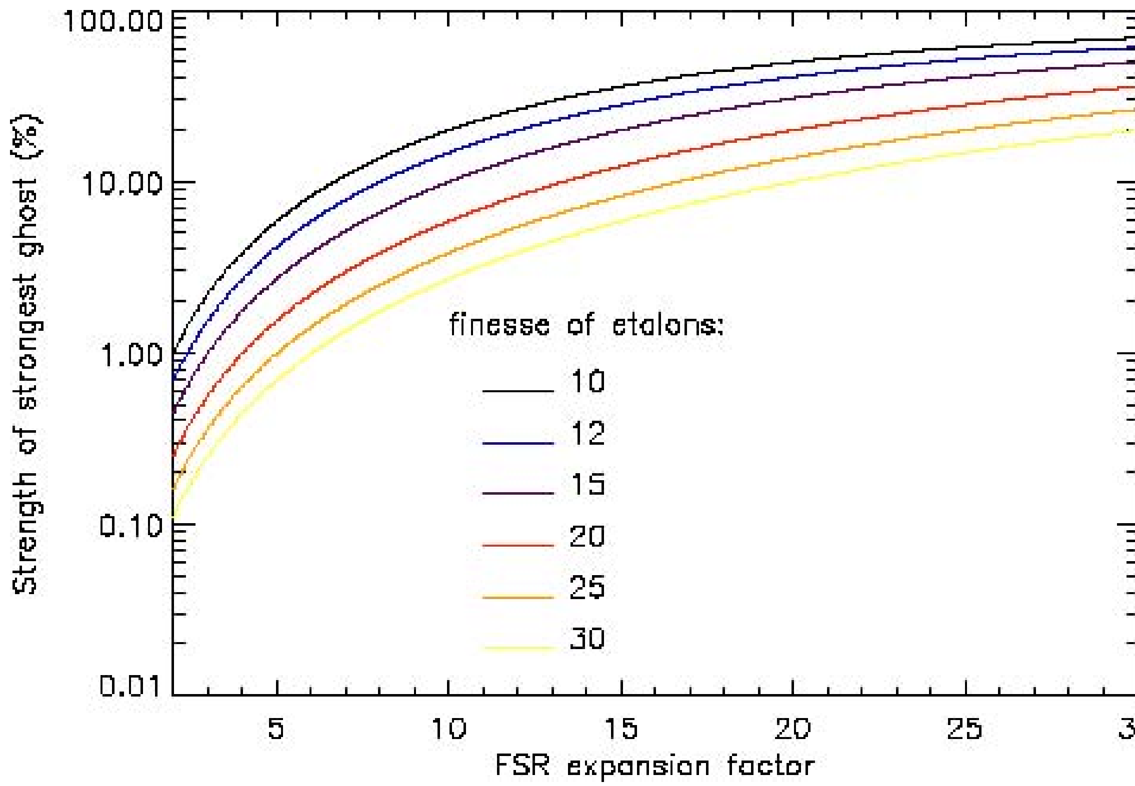

Figure 6: Strength of the strongest ghost relative to the maximum transmission peak as a function of FSR expansion factor and finesse of the etalons for a twin etalon system.

To determine how many etalons need to be placed in series to meet the specifications of a given application, it is necessary to know what FSR is desired. The number, N, of spectral resolution elements contained in one FSR can then be obtained by

$$N = \frac{\Delta\lambda}{\delta\lambda} \tag{5}$$

where $\Delta\lambda$ is the FSR and $\delta\lambda$ is the spectral resolution. Table 2 lists the conditions that N must satisfy for different systems. For the 800 nm system mentioned above, the achievable finesse is 12 and the maximum FSR expansion factor is 5, so that A×F = 60. By looking at Table 2, if the required number of elements N is less than or equal to 12, then a single-etalon system will be sufficient. If N is more than 12 but less than 60, a twin etalon system is required. If N is higher than 60, 3 or more etalons will be needed. Due to their complexity, three or more have not been discussed. One should simply be aware that a system with three or more etalons in series allows one to obtain more spectral elements inside one FSR than does a twin or single etalon system.

Condition	Number of etalons in series in a system
$N \leq F$	1
$F \leq N \leq (A \times F)$	2
$(A \times F) \leq N$	3 or more

Table 2: Conditions for the number of etalons needed in a system. N comes from Eq. (5), F is the finesse achievable at a given wavelength (Table 1) and A is the FSR expansion factor (Fig. 6).

The greatest advantage of SSI's tunable filters is that they are extremely easy to tune. A simple change in the AC voltage applied across the gap of the etalon is sufficient to change the orientation of the liquid crystal and hence the index of refraction within the gap. Note that only one of the two polarization states of the incoming light actually sees this index change. The other state does not and hence is not tunable. TO USE THE LIQUID CRYSTAL FABRY-PEROT, IT IS NECESSARY TO PLACE A POLARIZER IN SERIES TO BLOCK OUT THE NON-TUNABLE POLARIZATION STATE. The orientation of the polarizer can be optimized by running successive voltage scans at a given wavelength with the LCFP for various orientations of the polarizer, and picking the orientation that produces the greatest contrast with voltage seen in the LCFP response.

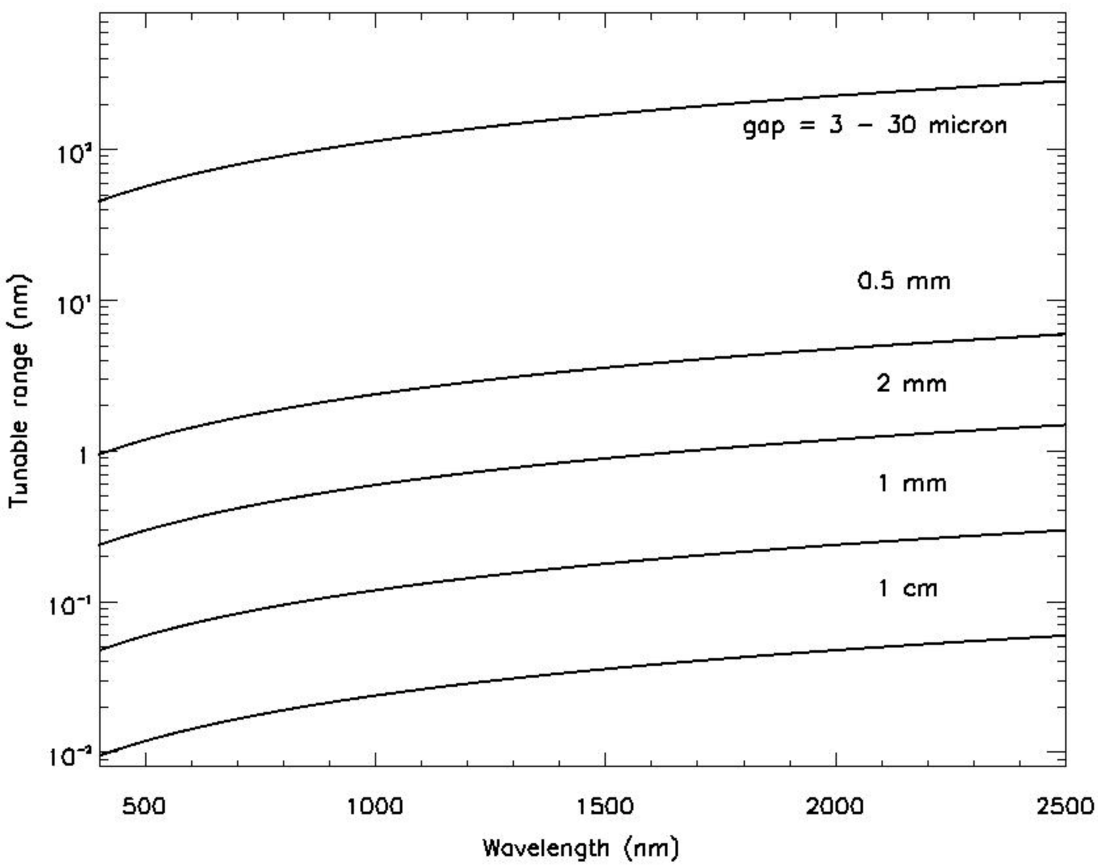

Figure 7: LCFP tunable range as a function of wavelength for different gap sizes.

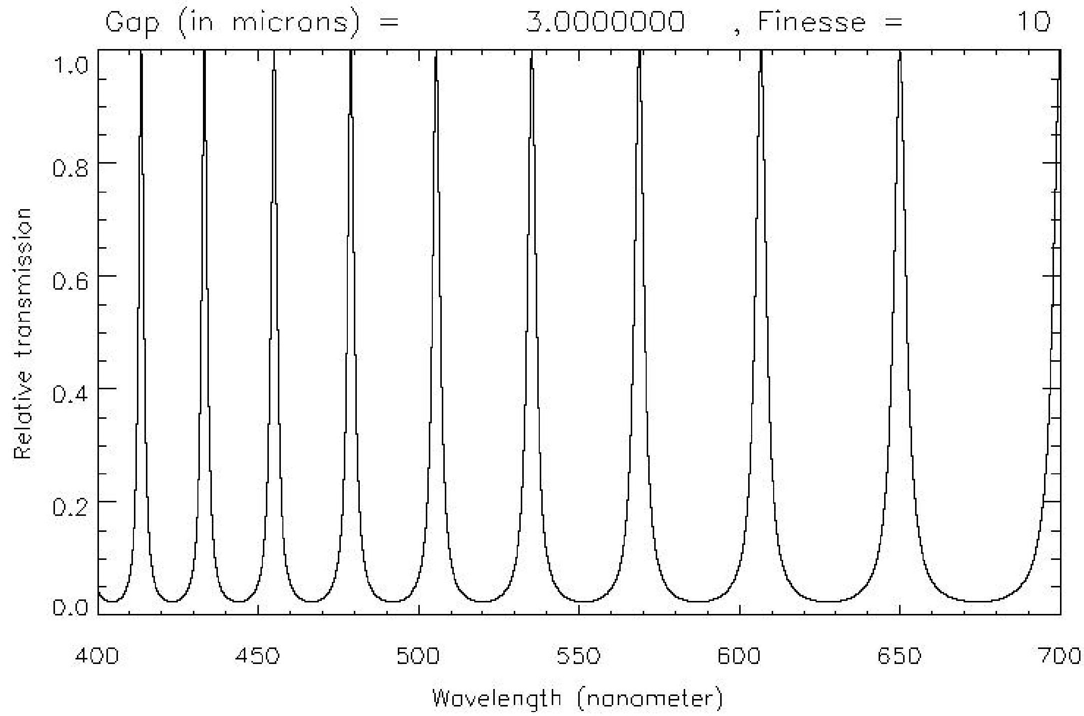

Figure 8: Model of a single-etalon device with a gap size of 3 micron.

The tunable range of the LCFP is shown in Fig. 7 as a function of wavelength for different gap sizes. For a system with more than one etalon, the tunable range of the system is the widest tunable range among those of the etalons in the system. Note that the tunable range must be larger than the FSR, otherwise some wavelength regions may not be accessible to the LCFP. In cases where the tunable range does not cover the operating range of the LCFP, an order-sorting filter must be used in series with the LCFP to isolate different wavelength regions within the operating range. The order-sorting filter in question should have a bandpass smaller than the FSR of the LCFP at that wavelength.

Hence, to summarize, three different ranges are of importance to the LCFP:

- Tunable range: wavelength interval over which the LCFP can tune (dependent on the LC inside the etalon gap and the wavelength).
- Free Spectral Range: wavelength interval inside of which each spectral element is distinct (dependent on wavelength and etalon gap size).
- Operating range: wavelength region where the LCFP operates to specifications (dependent on the applied coating).

To illustrate how these three ranges interact, let's consider the following problem. Suppose that a device for chemical or medical imaging is desired for use in the Visible from 400 to 700 nm. The operating range will need to extend at least from 400 to 700 nm. However, the tunable range in the visible even for the smallest gap etalon, is less than 100 nm (from Fig. 7). Clearly, several order-sorting filters are required to divide the operating range in different smaller regions over which the system can tune. To minimize the number of order-sorting filters, the FSR must be as large as possible without being larger than the tunable range. Our single etalon system that provides the largest FSR is an etalon with a gap of 3 microns. The expected response is shown in Fig. 8. About 10 orders fit within the operating range, so about 10 order sorting filters would be required.

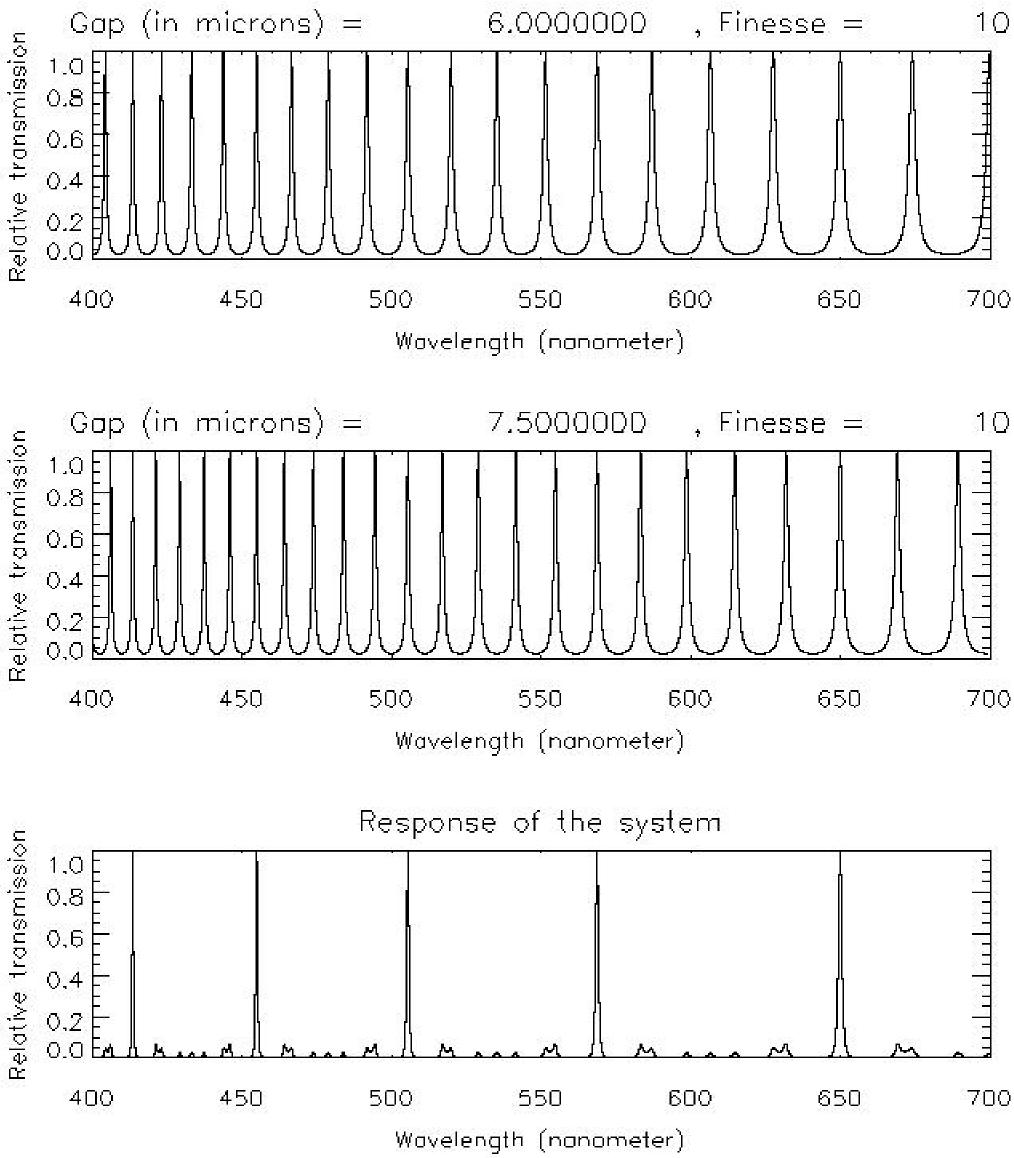

Figure 9: Model response of a twin-etalon system that provides the largest FSR in the visible.

To minimize the number of order sorting filters, the FSR of the system must be further increased - a twin etalon device is required. However, the FSR can not be arbitrarily increased otherwise the FSR would become greater than the tunable range. The optimal solution involves a twin etalon device whose etalons have gap sizes of 6 and 7.5 microns. The resulting FSR is equivalent to that of a single etalon with a gap size of 1.5 micron, or twice that of the 3 micron gap etalon.