

# Novel tunable liquid crystal Fabry-Perot filters for Fiber-Optical system

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## Abstract

We propose new tunable liquid crystal Fabry-Perot filters for fiber-optical telecommunication application. The filters have a low insertion loss, fast response time, wide tunable range to cover total c-band, or L-band, or both. They are solid-state filters without moving parts and the tuning voltages are low.

**Keywords:** Liquid Crystal, Fabry-Perot, Tunable Filter, WDM, Tunable Laser, Channel Monitoring

## Introduction

Tunable filters with a wide tunable range that cover the whole C-band, or L-band, or both, have been found wide applications in fiber optical communication system, mainly in three domain: tunable laser, wavelength division multiplexing systems (WDM), and channel monitoring. Due to the growing demand in bit-rate and number of channels in WDM system, tunable narrow band pass filters are required[1].

So far a lot of efforts have been made to make tunable filters based on Fabry-Perot principle[2,3,4]. The tunable optical filters using a LiNbO<sub>3</sub> torsional actuator[2] need a high driving voltage up to 500 volts and has a narrow tunable range. The tunable filter[4] reported by M. Iodice is a temperature-tuned silicon etalon filter with a narrow passband however a narrow free spectral range, and tuning speed was not reported.

We have successfully combined the liquid crystal technology with the Fabry-Perot to make tunable liquid crystal Fabry-Perot (LCFP) interferometers that have been proven to be competitive in spectroscopy, LIDAR and IR imaging [5,6]. This technology is adaptable to optical networking and telecommunications by the development of etalons with NIR transmission, and development of tandem and parallel etalon stacks[7]. The advantages of the tunable liquid crystal Fabry-Perot filter are: high resolution and wide free spectral range and tunable range, fast response time, solid state (no moving parts), low driving voltage.

## Principles and Modeling

The Fabry-Perot etalon is comprised of two optical glasses with high-reflection coating, the two high-reflection surfaces are separated by a certain distance. When light passes through the etalon, the interference arising from the multi-reflection will let certain wavelengths pass through and reflect the other wavelengths. When the incident light is not collimated, the intensity of light  $I(\theta, \lambda)$  coming through an ideal Fabry-Perot etalon (one with no defects) is given by

$$I(\theta, \lambda) = I_0(\lambda) \frac{1}{1 + (2F/\pi)^2 \sin^2(\delta/2)} \quad \text{with} \quad \delta = \frac{4\pi n d \cos(\theta)}{\lambda} \quad (1)$$

Where  $\lambda$  is the light's wavelength,  $I_0(\lambda)$  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 Equation. (6)). 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.

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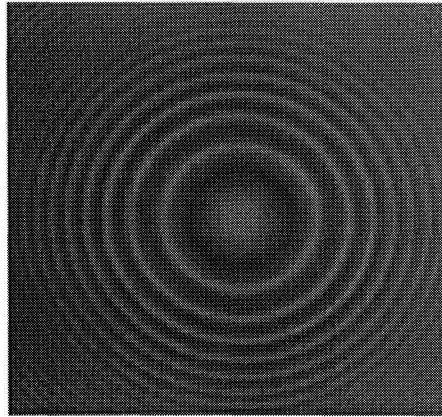


Figure 1: Image of the interference pattern produced by a Fabry-Perot with monochromatic light.

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

$$FOV = \sqrt{\frac{8\delta\lambda}{\lambda}} \quad (2)$$

where  $\delta\lambda$  is the spectral resolution of the etalon. Figure 2 shows a typical model response of a  $3\mu\text{m}$ -wide gap etalon when light comes in at normal incidence for a given refractive index inside the gap. The Free Spectral Range (FSR) is defined as the wavelength difference of the two neighboring constructive interference, or transmission peak and is characterized predominantly by the gap of the etalon. The condition for the constructive interference is determined by:

$$\frac{2nd}{\lambda} = m \quad (3)$$

Where  $n$  is the refractive index,  $d$  is the gap,  $\lambda$  is the wavelength and  $m$  is the order number. Thus the FSR between the  $m$ -th order and the  $m+1$ -th order is given by:

$$FSR = \frac{2nd}{m(m+1)} \quad (4)$$

Normally  $m$  is a big number, so it becomes:

$$FSR = \Delta\lambda = \frac{\lambda^2}{2nd} \quad (5)$$

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

$$F = \frac{\Delta\lambda}{\delta\lambda} \quad (6)$$

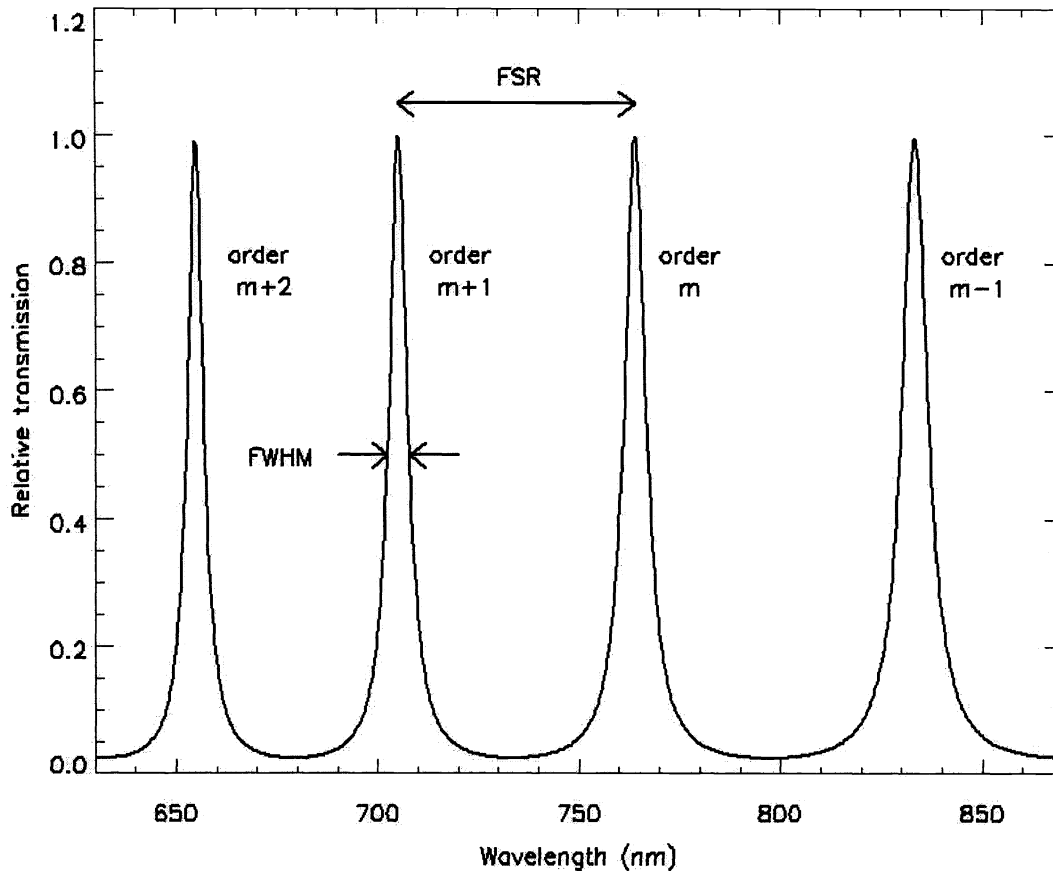


Figure 2. Model Response of a 3 $\mu$ m-wide gap etalon

Nematic liquid crystals have optical anisotropy, or birefringence. They exhibit double refraction, light polarized parallel to the director has a different index of refraction than light polarized perpendicular to the director. The director is along the same direction as the surface rubbing directions when both the alignment surfaces are rubbed in the same directions. Nematic liquid crystals also show dielectric anisotropy, the dielectric constants parallel and perpendicular to the nematic director are not the same. The dielectric anisotropy introduces body torque on the molecules in the presence of external field, which in turn gives rise to the director re-orientation. Under the external field, the director of the liquid crystal with a positive dielectric anisotropy tends to be aligned parallel to the external field, while the director of the liquid crystal with a negative dielectric anisotropy tends to be aligned perpendicular to the external field.

Thus by filling the etalon cavity with the nematic liquid crystal, the refraction index of the extraordinary component of light will change with the applied voltage. Based on the equation (3), the wavelength of transmission peak is tunable with the different applied voltage, or we can electrically choose any channel to pass through. We need to mention here that normally we need a polarizer to be placed parallel to the alignment direction of the liquid crystal to pass through the extraordinary mode of light and block the ordinary mode that is not tunable. For tunable laser and system monitoring, the polarization dependence is not a key problem, and there are solutions to make polarization-independent tunable filters for WDM system. We will discuss it in the later part of the paper. Figure 3 shows the structure of the liquid crystal etalon.

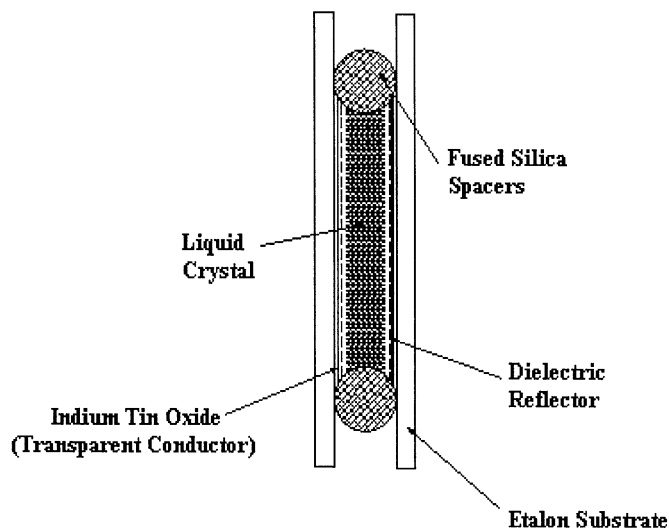


Figure 3. The structure of the liquid crystal etalon

Figure 4 is a modeling result of how average refraction index inside the etalon cavity will change with the applied voltage. The extra-ordinary refraction index and the ordinary refraction index used in the modeling is 1.79 and 1.53, respectively. It shows the maximum voltage is only about 10 volts to cover the total tunable range. The tunable range in determined by the liquid crystal material alone can be estimated by:

$$\Delta\lambda = \frac{\Delta n}{n} \lambda \quad (7)$$

If we put  $\Delta n = 0.26$ ,  $n = 1.6$  and  $\lambda = 1.55$  micron into equation (7), we will find that the tunable range can be as large as 250 nm, though finally the tunable range will be limited by the free spectral range.

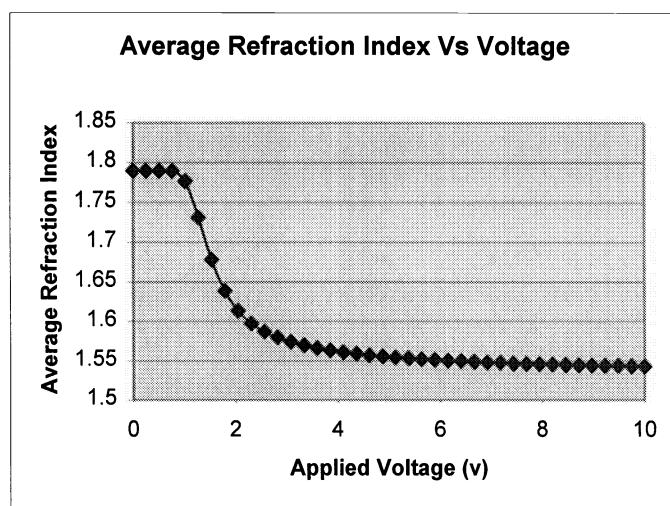


Figure 4 Modeling result of how average refraction index will change with the applied voltage

For an ideal Fabry-Perot etalon, the finesse  $F$  only depends on the surface reflectivity. However in the real case, the optical surface is never perfect, so finesse  $F$  of the etalon is also dependent on the surface quality (roughness, defects,...) and the parallelism of the two surfaces. Thus for the high resolution etalon, the free spectral range is limited by the aforesaid parameters. In order to expand the free spectral range, we can use two etalons in series, the one with a larger 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.

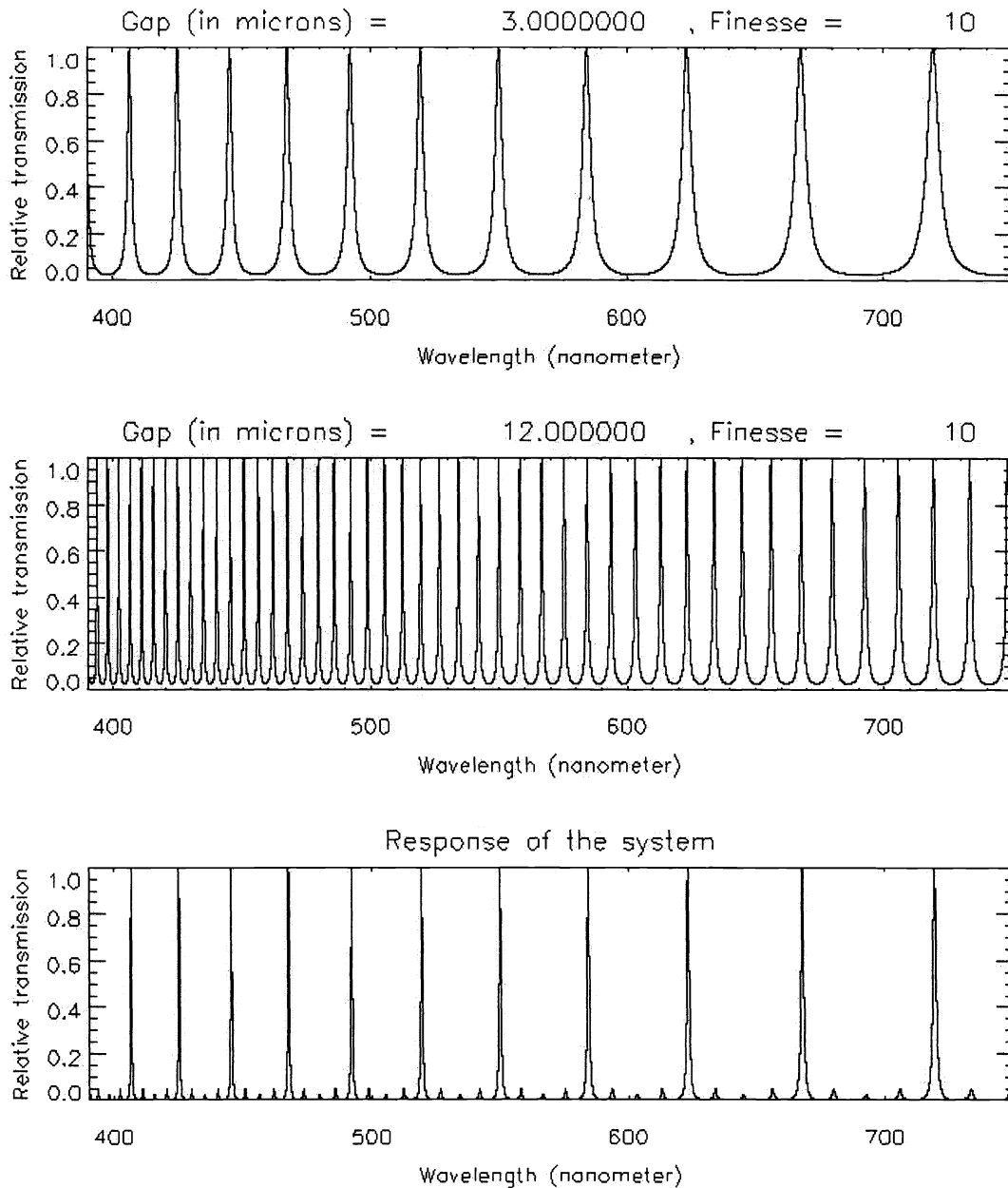


Figure 5 Modeling of two etalon system with the gaps of 3 micron and 12 micron.

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

$$FSR = A \times FSR_{resol} = B \times FSR_{supp} \quad (8)$$

Where  $FSR_{resol}$  and  $FSR_{supp}$  are the free spectral ranges of the resolving and suppression etalon respectively. If B = 1, the suppression etalon does define 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 the twin-etalon system, the FSR of the resolving etalon has now been expanded by the factor A, and so has the number of available spectral resolution element. The factor A will henceforth be called the FSR expansion factor. Figure 5 shows a modeling of two etalon system, one with the gap of 3 micron and the other with a gap of 12 micron.

### Tunable Filters Fabricated

We have fabricated a lot of tunable filters in visible range before and recently have made efforts to adjust the design to fabricate the tunable filters in NIR range. One of the most recent tunable filter (one-etalon system) is designed for tunable laser. We have successfully modified the high-reflection coating design to cover the working range that is: 1520 nm to 1570 nm. We also optimized the liquid crystal material and alignment polyimide to minimize the transmission loss. The final testing of our customer gives a good result as described in the table 1.

Parameter	Measured Value
Plate Diameter	10mm
Center Wavelength	1550nm
Test Area	0.2 square-mm
Insertion Loss	1.5db
Free Spectral Range	4 THz (37nm)
Spectral Resolution	108 GHz (1.2 nm)
Finesse	31
Response time	20 ms

Table 1. Testing result of tunable LCFP for tunable laser

Figure 6 shows the testing result of another tunable LCFP filter. The free spectral range is 79 nm that is the actual tunable range. The actual resolution is better than it seems in the figure 6 because the testing in is limited by the resolution of the monochrometer in our lab.

### Tunable Filters to be Fabricated

We are continuing our efforts to improve the performance of the filters that is targeted at the market of tunable laser and channel monitoring. On the other hand, we are in the progress of fabricating tunable filters with two-etalon system to get a higher resolution for the WDM optical random switch. Recent ITU standards (G. 692) specify WDM channels of 50 and 100 Ghz channel spacing centered at 193 Thz or 1553nm. A 50 Ghz channel is a bandpass of 0.4 nm, well within the capability of the two-etalon stacks. The task will be supported by the SBIR funding. Figure 7 shows how the random 2x2 optical switch can be realized through the tunable LCFP filters.

Figure 8 shows how to realize the n x n random optical WDM switch [7]. Based on the mature liquid crystal display (LCD) technology, it is easy to etch the ITO surface with different pixels, each pixel is matched to a channel with a fiber coupled into and out of the system.

Transmission of LSA Etalon

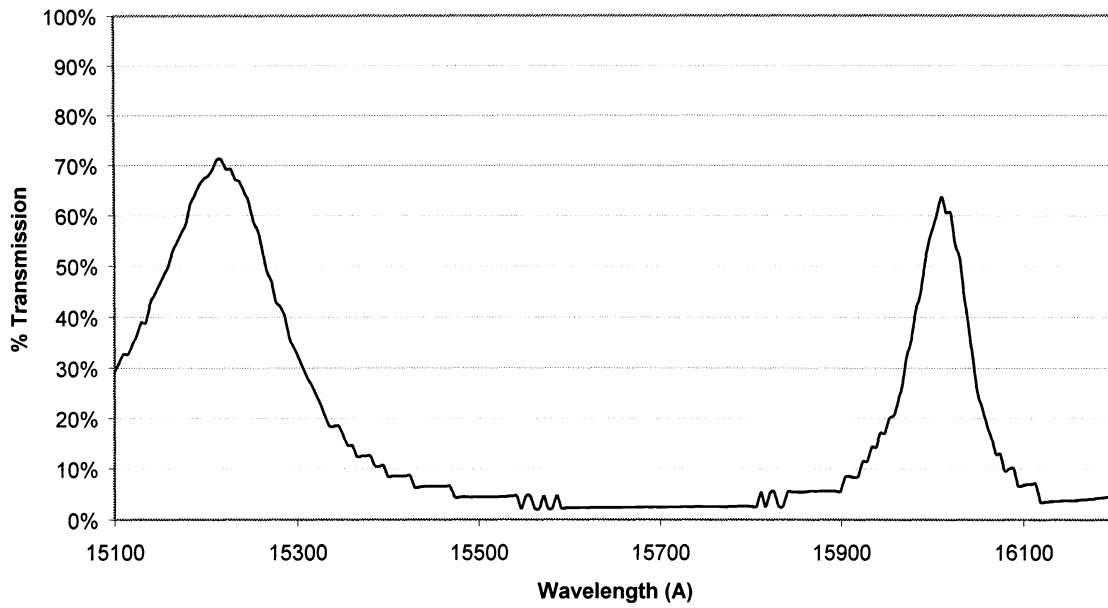


Figure 6 Spectral Response of one tunable LCFP filter.

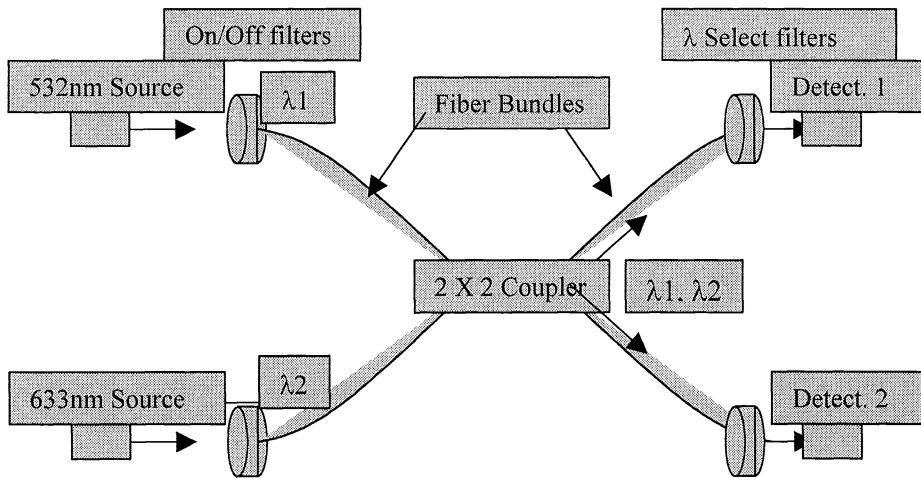


Figure 7 Schematic of 2x2 OXC to be constructed.

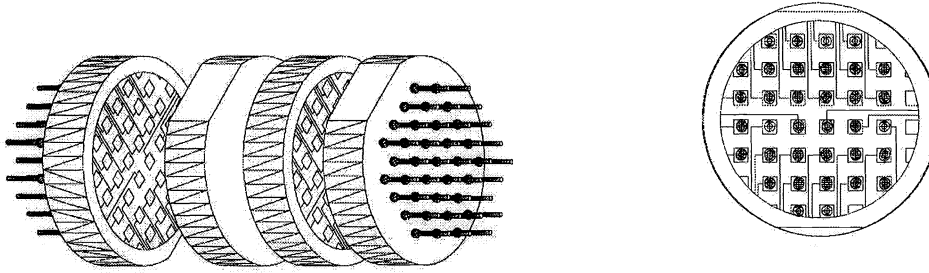


Figure 8 One etalon etched into pixels to realize the random WDM switch.

### Discussion: Polarization Insensitive

For WDM system, one challenge for the tunable filters is the polarization independence, because the state of polarization of the channel signal may be unknown in the system. Fortunately, several methods have been discussed to make the polarization-insensitive Fabry-Perot devices[8]. One of them is to use a calcite crystal to split the light source (polarization direction unknown) into two components with orthogonal polarization directions, then each component is passing through a tunable LCFP filter with an alignment direction of the liquid crystal the same as the polarization direction. After each component passing through a single LCFP filter, the two components are recombined through another calcite crystal. More efficient way to do this is using the two neighboring pixels described in Fig. to match the two polarized components of one channel. The two pixels need to have alignment layers perpendicular to each other and the multi-domain technology in LCD production is a good solution to achieve it. Twisted Nematic Structure inside the Fabry-Perot cavity is another solution[8.9], though it only works in the high-voltage range and decrease the tunable wavelength range.

### Conclusions:

Tunable liquid crystal Fabry-Perot (LCFP) filters have been proved very competitive devices for tunable laser, channel monitoring and WDM optical switch. Our modeling and testing results show that tunable LCFP filters is a good solution for tunable laser, channel monitoring, and random WDM switch, with the advantage of high resolution, wide tunable range, low driving voltage.

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