A tunable liquid-crystal Fabry-Perot (FP) is one of such components such as gratings and prisms are fairly bulky even though they can perform their intrinsic functions remarkably well. For certain applications, it is very desirable to have a compact device that performs a similar function. A tunable liquid-crystal Fabry-Perot (FP) is one of such devices that can have high finesse, low-power consumption, and compactness. Recently, we have constructed such a liquid crystal (LC) device that has a wide tunability and good resolution.\(^1\) We have used this device for demonstrating its usefulness in communications for wavelength division multiplexing (WDM)\(^2,3\) and for electrically tuning an infrared source using a fiber ring laser.\(^4\) This type of the LC FP is, however, polarization sensitive which makes it less attractive for some applications such as for fiber optic communications in which the state of polarization may not be known. In this letter we report a different configuration for a LC FP which is polarization insensitive.

Nematic LCs are characterized by only the presence of orientational order along the average direction of the long axes of molecules, called the director\(^5\) which is represented by a unit vector \(\mathbf{n}\). In a simple geometry in which the molecules on two surfaces are parallel to each other, a nematic LC film behaves essentially as an uniaxial material whose refractive index along the director \(n\) can be changed by applying an external electric field. While the FP works well in this geometry, it is polarization sensitive. This is because the refractive index perpendicular to \(n\), respectively, when the director \(n\) is continuously twisted by \(90^\circ\) in going from one surface to the other. Above the Fredericks threshold\(^2\) the director \(n\) in the middle of the FP cavity tends to orient in a direction parallel to the field, and thus coincides with the light propagation direction. The molecules on the surfaces, however, remain undisturbed as long as the anchoring energy is strong, producing two thin birefringent layers at the surfaces. The thickness of the individual birefringent layer depends on the field strength.

For the simplest case where the light is propagating normal to the FP structure, two resonance conditions corresponding to two orthogonally polarized eigen modes are possible. For the twist nematic FP structure, these eigen modes are linearly polarized and are parallel and perpendicular to \(n\), respectively, when the wave guiding conditions are satisfied. These conditions are most easily defined in absence of the applied field since the director \(n\) remains perpendicular to the propagation direction. Under these conditions, the wave guiding would occur if \(\Delta n d > \lambda\), where \(\Delta n\) is the index anisotropy, \(d\) is the thickness of the LC, and \(\lambda\) is the wavelength of light. Thus, in the absence of an electric field, if the wave guiding occurs, two orthogonally polarized transmission peaks will be observed for a twist nematic FP structure. In the presence of the field, however, the effective anisotropy becomes smaller and even zero, thereby resulting in the breakdown of the resonance conditions. This leads to mode mixing, and the resultant eigen modes become a linear combination of the pure polarization modes. A direct consequence of this is that the effective index is for the two modes become equal, resulting in a single, polarization-independent index. Therefore, the two orthogonally polarized transmission bands of the twist nematic FP in the absence of the field, would change with the applied electric field in such a way that at high electric fields the two bands merge into one. Furthermore, these bands would begin to get depolarized with increasing the field because of mode mixing.

In the wave guiding regime, it can be shown that the transmission \(T\) at a given wavelength \(\lambda\) for radiation incident normal to the surface is given by\(^6\)

\[
T(\lambda) = \frac{\tau}{(1 - \rho)^2 + 4\rho \sin^2 \delta},
\]

where \(\delta = \phi + k_0 n d\). Here \(\tau\) and \(\rho\) are the transmittance and the reflectance, respectively. \(\phi\) denotes the phase shift experienced upon reflection, \(d\) the thickness of the uniaxial material, \(n\) the refractive index along or perpendicular to the director \(n\), and \(k_0\) the magnitude of the wave vector outside the layer. Since the refractive index along the director \(n\) and that perpendicular to it are separable, the total transmission is simply a sum of those two contributions. It can be seen from Eq. (1) that the width of the transmission
peak $\Delta \lambda$ depends essentially on the reflectivity of the surfaces, while the overall transmission is dictated by the absorption losses.

The free spectra range (FSR) (wavelength separation between successive transmission peaks) is different for the two modes and is determined by the optical thickness $nd$ of the étalon for each mode. This range depends on the order at which the interferometer is being operated, and it is given by

$$\text{FSR} = 2n \frac{d}{m(m+1)},$$

where $m$ is the order. The refractive index of LCs is typically in the range of 1.5–1.7. This, for a 25-µm-thick LC sample, the FSR is about 30 nm at the order $m \approx 15$.

We have constructed such a twist nematic FP étalon using a commercial nematic LC E7 (from EM Chemicals) to test the above ideas. The reflectors were made by using a dielectric stack. The mirror reflectivity was determined to be 98.5% in the 1.3–1.5 µm wavelength region. The electric field was applied to the LC using transparent indium-tin-oxide electrodes which were deposited on the glass plates prior to the deposition of the dielectric mirror stacks. An alignment layer was deposited on top of the dielectric mirror to promote the uniform alignment of the LC molecules. The LC was inserted into the FP cavity in its isotropic state as is commonly done in most liquid-crystal devices. The thickness of the cavity was estimated to be about 25 µm.

The device was characterized at room temperature using an optical spectrum analyzer (Advantest model Q8381). The light source was a 1.5 µm LED (Lasertron) which was used in conjunction with a multi-mode optical fiber and graded index (GRIN) rod lenses to couple the light in and out of the device. In this setup, no effort was made to minimize the coupling losses. The voltage applied to the LC was provided by a programmable voltage source (Wavetek model 75) controlled by a computer. The voltage was a square wave at 1 kHz. The spectrum was stored so that the Mauguin conditions are no longer satisfied. This ensures that the modes are decoupled. A further increase in the voltage beyond about 1.75 V results in a significant change in the orientation of the molecules so that the Mauguin conditions are no longer satisfied.

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Figure 1 shows typical transmission spectra obtained in the absence of an applied electric field. The top curve shows unpolarized spectrum, while the bottom two spectra are the polarized spectrum with the polarizer parallel (||) and perpendicular (⊥) to the birefringence $\theta$, respectively. The data clearly show that the linear combination of the bottom two spectra produces the unpolarized spectrum shown at the top. Furthermore, the complete separation of the two modes indicates that the eigen modes are polarized parallel and perpendicular to $\theta$ (or $\pi$) in the absence of an applied field. This is expected since the wave guiding conditions are satisfied, i.e., $0.2 \times 2.5 \mu m > 1.5 \mu m$, where $\Delta n = 0.2$, $d = 25 \mu m$, and $\lambda = 1.5 \mu m$ were used. From the free spectral range corresponding to these two modes, the birefringence was determined to be $0.21 \pm 0.02$, which is consistent with the previously reported value for this material in the infrared region. Note that the birefringence, in this case, is simply the ratio of the two free spectral range of the two modes.

The transmission wavelength can be changed by a small electric field as illustrated in Fig. 2. The positions of all the peaks in wavelength, which appear in an unpolarized spectrum, are plotted as a function of the field strength. At a fixed voltage, for example, at 0.7 V, six peaks are observed. These peaks are divided into two groups corresponding to the higher order FP modes. At very low voltages the peak positions do not change significantly until a critical value of the field, the Fredericks threshold, is reached. The threshold is about 1.0 V and corresponds to the onset of a molecular distortion in the bulk of the FP cavity. This distortion results in an effective index change for the mode polarized along $\theta$. However, the distortion is small, and thus the Mauguin criterion for the wave guiding is satisfied. This ensures that the modes are decoupled.

FIG. 2. Position of the transmission peaks in the unpolarized spectrum as a function of the voltage for a 25 µm liquid-crystal Fabry-Perot étalon in the low voltage regime. The two arrows indicate the Fredericks threshold and the onset of mode mixing.
eigen modes are no longer polarized either along $\hat{b}$ nor perpendicular to $\hat{b}$. Note that the magnitude of the required voltage for mode mixing depends on the wavelength of the light. Around 2.5 V the spectrum begins to evolve in such a way that produces a pair of transmission peaks which merge into one at higher voltages. These peaks correspond to elliptically polarized modes within the cavity because of the mode coupling. Thus, an arbitrary linearly polarized light would produce both the peaks. At still higher voltages the eigen modes in the cavity again become linearly polarized and lie parallel and orthogonal to $\hat{b}$, respectively. The peak transmission for these two modes becomes identical since the optical path length is the same in the high field regime. This is clearly shown from experimental data depicted in Figs. 3(a) and 3(b), which are the transmission spectra of the FP in the high voltage regime ($>2$ V). The polarized spectrum in Fig. 3(a) is essentially identical to the unpolarized one shown in Fig. 3(b), indicating that the FP is indeed polarization insensitive in this region. With a linewidth of about 0.5 nm and a tunable range of about 15 nm, the effective finesse is of the order of 30.

The speed of selection from one wavelength to the other is dictated by how fast the molecules can be reoriented. While several factors such as the dielectric anisotropy of the LC, the voltage applied, and the thickness of the cell significantly influence the response time, it is typically of the order of milliseconds in nematic LCs. The advantage of the device described above is that it is compact and small, and it requires practically no power. The power requirement mainly involves charging and discharging of a capacitor at a rate of about 1 kHz. The actual power would depend on the size of the device and it is estimated to be of the order of microwatts for the device studied.

In summary, we have demonstrated that a low-power LC-based electrically tunable FP étalon can be used as a wavelength tuning device, particularly in the infrared region. This device is polarization insensitive and of interest for lightwave communications. The polarization insensitive tuning range is about 15 nm (FSR of the order of 30 nm) and a spectral passband width is around 0.5 nm. With appropriate designs, different FSRs and passband widths of the FP étalons can be achieved for specific applications. In addition to the polarization insensitivity, the device has other unique advantages such as relatively easy fabrication of an array of individually tunable étalons which could be useful for high-density WDM optical networks as well as for optical signal processing in the wavelength domain.