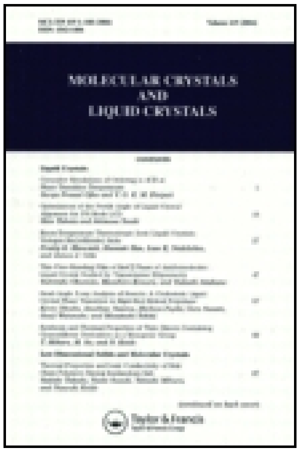

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POLARIZATION MODES IN LIQUID CRYSTAL FABRY-PEROT STRUCTURES

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ABSTRACT : Generally when anisotropic material such as liquid crystals are confined in a Fabry-Perot cavity, the transmission through the device becomes sensitive to the input polarization. While continuous tunability of the refractive index is possible by applying a small electric field across the liquid crystal, It is found that under certain circumstances a forbidden gap in transmission wavelength is observed. It is shown that this occurs because of mode mixing brought by slightly twisted uniaxial structure disposed between the Fabry-Perot structure. A theoretical model is presented to explain the experimentally observed data with excellent agreement.

The Fabry-Perot (FP) resonator is a common optical structure, extensively used in devices such as lasers and filters. The properties of FP resonators are well known; however, much of our knowledge is for cases where the optical material within the cavity is optically isotropic. The operation of the FP resonator remains simple and straight forward for cases where the material within the cavity is anisotropic, but uniaxial. In this case, for light propagating perpendicular to the mirror plane, the transmission of the resonator is understood by considering two orthogonal linear polarization components of the input light. This has been recently shown to be the case in a tunable filter made from a FP cavity containing liquid crystals[1]. By controlling the surface boundary conditions, liquid crystals (LCs) can easily be distorted to obtain physically twisted structures. When such a structure is used inside a FP cavity, the transmission properties of the device show some interesting and unique properties. In this paper we first present the experimental results on twisted structures of nematic liquid crystals in a Fabry-Perot cavity and then explain the observed transmission properties of these structures as a function of applied field using a theoretical model. It will be shown that excellent agreement between theory and experiments is observed.

Nematic LCs are characterized by the presence of orientational order along the average direction of the long axes of molecules, called the director[2], and represented by a unit vector $\vec{n}$. Well oriented sample is obtained by confining the LC in a container whose surfaces have been treated to impart well defined director orientation since the director orientation is easily influenced by weak surface forces. In a simple geometry in which the molecules on two surfaces are parallel to each other, a nematic LC film behaves as an uniaxial material. The refractive index n_e for light polarized along the director $\vec{n}$ changes by applying an external electric field. On the other hand, the refractive index n_o for light polarized along the perpendicular direction remains constant even in presence of an applied electric field. When this structure is combined with dielectric mirrors, a polarization sensitive LC FP structure is produced[1]. In this structure, the eigenmodes are linearly polarized and lie parallel and perpendicular to $\vec{n}$. Thus light of arbitrary polarization, on entry into such a device, will propagate through the device as two waves that lie along these two axes. Each of these components will be transmitted or reflected by the resonator independently. In such a tunable filter the transmission peaks of the FP for the parallel polarization component are tuned by an applied voltage, while those for the perpendicular component are unaffected. Figure 1 shows the transmission spectrum of a 10 μm thick Fabry-Perot in which the director configuration at the two surfaces is parallel to each other.

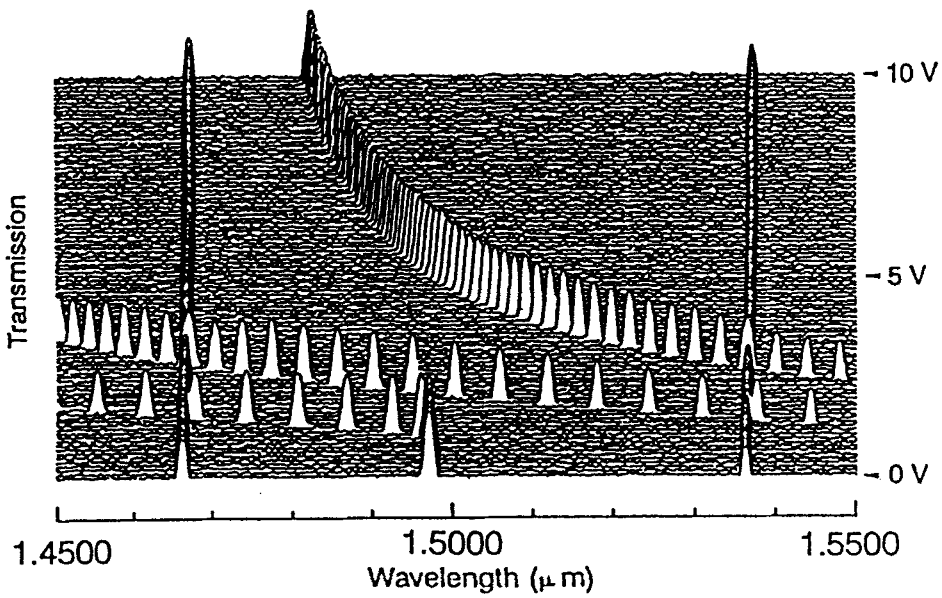

Fig. 1 *Measured transmission spectra of a liquid crystal Fabry-Perot etalon 10 μm thick with a relative rotation of 0 degrees between the molecular alignment direction at the two surfaces, for applied voltages between 0 and 10 Volts.*

Now consider a case where the director orientation at the two surfaces are not collinear but make an angle θ with respect to each other, so that the director is twisting across the cell, as shown in Fig. 2a. Here it is easy to show [3] that the polarization eigenmodes in the cavity are still linearly polarized and lie parallel and perpendicular to $\vec{n}$, if $\Delta n \cdot P >> \lambda$, where $\Delta n = n_e - n_o$, P is the pitch of the twist and λ is the wavelength. Thus linearly polarized light entering parallel to the director at one surface will emerge rotated by angle θ at the other. An external electric field will tend to align the LC molecules along the propagation

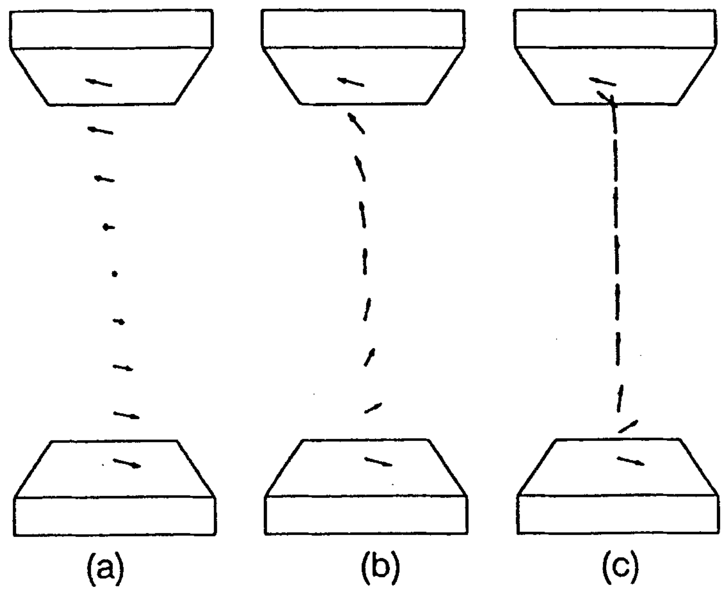

Fig. 2 *A schematic description of the director in a cell with a twist between the two boundaries. (a) No external field, a uniform twist of the director. (b) Small external field, the director is tilted out of the plane. (c) Strong field, the director in the center is perpendicular to the surface. The twist disappears, the director tilts in two planes defined by the boundary conditioning.*

direction of the light, however because of the boundary condition at the interfaces, this alignment will be maximized at the center of the cell, as shown in Fig. 2b. The net effect is that $\Delta n(E)$ at the center decreases with increasing electric field, and the inequality stated above may no longer be satisfied. Once the applied field is strong enough, we should expect the director at the center of the cell to be aligned with the field, as shown in Fig. 2c. In that case, we expect the optical changes to occur predominantly near the mirrors. Clearly once the cell center has been fully aligned with the field, the twist is eliminated, and the tilt of the director from its boundary value occurs along a plane normal to the surfaces and parallel to the director at the surface. We expect, then, that a FP resonator with twisted nematic LC should exhibit different optical properties at weak and strong fields, and while the weak field response should be very similar to the untwisted structure, the strong field response could be different. In recent experiments[4] we have shown that this in fact is the case, and that at particular voltage and anti-crossing behavior is observed. This behavior is yet another example of optical level crossing which has recently been reviewed.[5]

To investigate the transmission properties as a function of applied fields, we constructed a liquid crystal Fabry-Perot structure such that the director at the surfaces in absence of an applied electric field was offset by about 20 degree angle. The details of the construction is essentially the same as described previously [1]. The thickness of the liquid crystal layer was about 32 microns, which

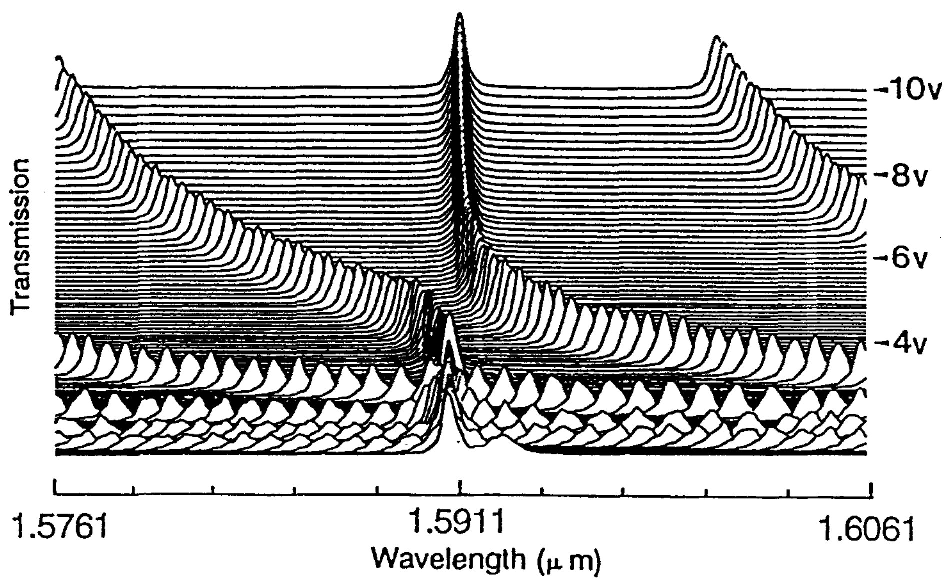

Fig. 3 *Unpolarized transmission spectra of a liquid crystal Fabry-Perot etalon 32 μm thick with a relative rotation of 18 degrees between the molecular alignment direction at the two surfaces, for applied voltages between 0.5 and 10 Volts.*

was maintained by glass spacers. The liquid crystal material was E7 nematic liquid crystal with refractive indices[6] $n_o = 1.5$ and $n_e = 1.7$. The transmission spectrum of the device was measured at room temperature using an optical spectrum analyzer (Advantest model Q8381). The light source was a 1.5 μm LED (Lasertron) which was used with a multi-mode optical fiber and GRIN rod lenses to couple the light in and out of the device. 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 as a function of applied voltage for further analyses.

Fig. 3 and 4 shows the transmission spectra and its variation with applied fields for unpolarized and polarized light. The spectrum is taken in the region where the transmission due to the two modes is expected to coincide. The unpolarized spectrum show that the transmission corresponding to the light polarized parallel to $\vec{n}$ changes fairly rapidly below 4V, and there is little evidence of mode mixing. However above this voltage the mode mixing is clearly evident by the anti-crossing observed around 5 volts. In the polarized spectrum the mode mixing is much more easily identified. In this case it is easy to see at least two distinct anti-crossings at around 2V and around 5V. In Fig. 5 we show the peak positions as a function of applied voltage to the Fabry-Perot structure. For the most part one of the peaks remains essentially fixed, while the other is tunable, except near the region where the anti-crossing occurs. This behavior is essentially identical to that of a perfect uniaxial structure ($\theta = 0$) except when modes are at close proximity.

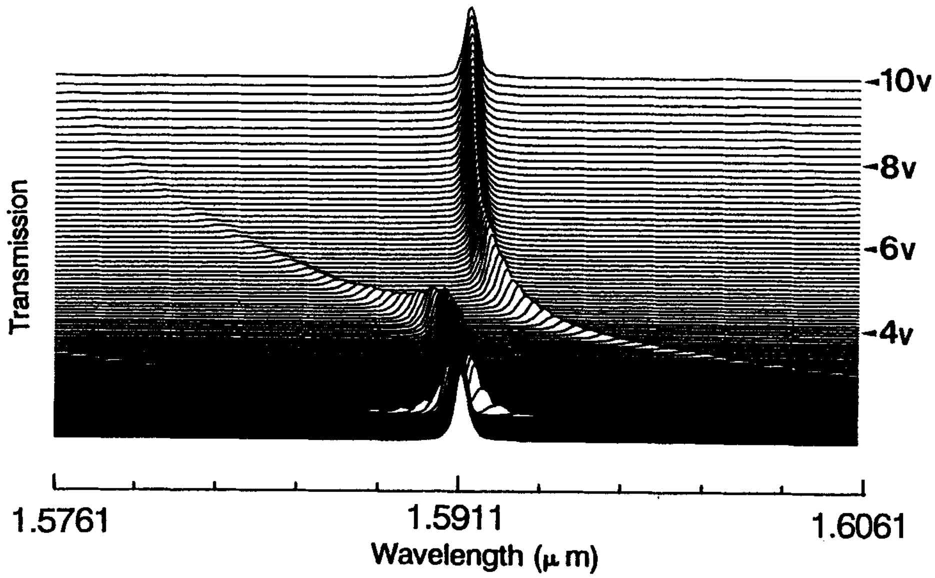

Fig. 4 *Polarized transmission spectra of a liquid crystal Fabry-Perot etalon 32 μm thick with a relative rotation of 18 degrees between the molecular alignment direction at the two surfaces, for applied voltages between 0.5 and 10 Volts.*

Since the most notable anti-crossing is observed at high field value, where the tunable resonance has completed all but the last FSR of its scan, in our previous study we assumed that the director in the bulk of the cell is perpendicular to the cell surface, and that all the optical activity takes place near the mirrors. Thus there was no twist in the molecular orientation and the whole cell was modelled by two identical uniaxial sections rotated with respect to each other by an angle θ. We used this approach to prove that the polarized light transmitted through the Fabry-Perot is always linearly polarized although it may be rotated with respect to the input polarization axis.

To model the resonator under all conditions, we need to solve for the director orientation as a function of the applied field. This problem has been solved previously[7-9] by several authors but here we use a numerical technique outlined in Ref. 9 to solve for the twist angle $\omega(z)$ and the tilt angle $\theta(z)$ at a distance z from the surface. To calculate the polarization transformation for light traveling through the resonator, the structure is divided into N layers; the director is assumed to be uniform within each of the layers. The round trip phase and polarization transformation is calculated then using a Jones matrix algebra.

$$\vec{v}' = \overleftrightarrow{M}\,\vec{v} \,, \qquad (1)$$

where

$$\vec{v} = \begin{pmatrix} v_x \\ v_y \end{pmatrix} , \qquad (2)$$

is the vector describing the input light polarization, $\vec{v}'$ is the polarization vector after a round trip, and the matrix $\overleftrightarrow{M}$ is given by

$$\overleftrightarrow{M} = \overleftrightarrow{T}(\theta_1)\,\overleftrightarrow{R}(\omega_1-\omega_2)\cdots\overleftrightarrow{T}(\theta_{N-1})\,\overleftrightarrow{R}(\omega_{N-1}-\omega_N)\,\overleftrightarrow{T}(\theta_N)\,\overleftrightarrow{T}(\theta_N) \quad (3)$$
$$\overleftrightarrow{R}(\omega_N-\omega_{N-1})\,\overleftrightarrow{T}(\theta_{N-1})\cdots\overleftrightarrow{R}(\omega_2-\omega_1)\,\overleftrightarrow{T}(\theta_1)\ .$$

Here $\overleftrightarrow{R}$ is the rotation matrix,

$$\overleftrightarrow{R}(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}, \quad (4)$$

and $\overleftrightarrow{T}$ is the propagation matrix describing the phase retardation in propagation over a distance d,

$$\overleftrightarrow{T} = \begin{pmatrix} e^{i\phi_o} & 0 \\ 0 & e^{i\phi_e} \end{pmatrix}. \quad (5)$$

Here the phase retardation normal to the director is $\phi_o = 2\pi n_o d/\lambda$, and the retardation in the perpendicular direction is given by $\phi_e = 2\pi n_e(\theta) d/\lambda$, with

$$\frac{1}{n_e^2(\theta)} = \frac{\cos^2(\theta)}{n_o^2} + \frac{\sin^2(\theta)}{n_e^2}. \quad (6)$$

The eigenmodes of the resonator are given by the requirement $\vec{v}' = \vec{v}$. This leads to an eigenmode equation which can be solved for the resonant wavelengths. Each of these resonant wavelengths is characterized by an eigenpolarization, i.e. a polarization state that returns to itself after a round trip in the resonator. It can be shown that these eigenpolarizations are always linear, for all values of θ and V

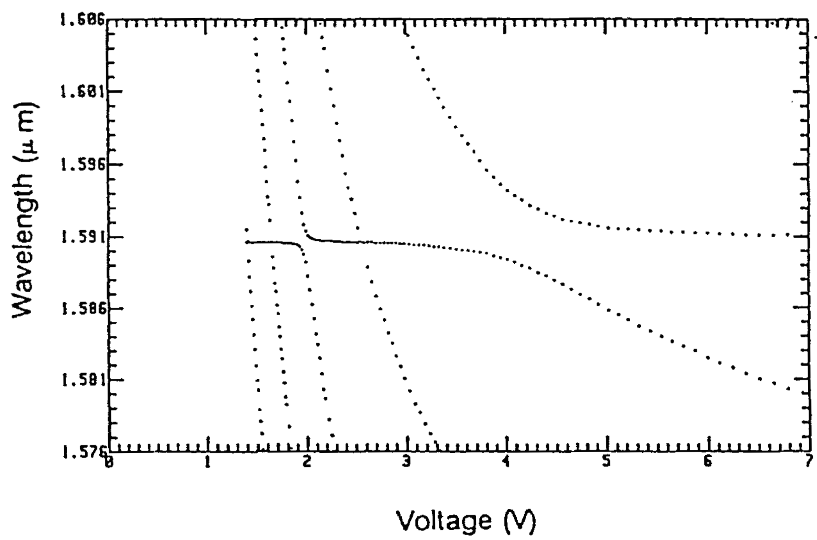

Fig. 5 Measured peak wavelength position versus applied voltage for a 32 μm thick etalon with a relative rotation of 18 degrees between the molecular alignment direction at the two surfaces.

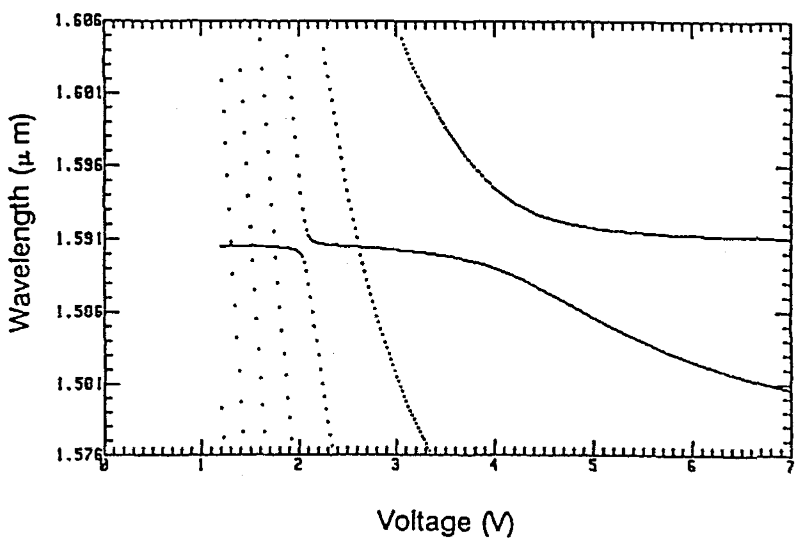

Fig. 6 *Calculated peak wavelength position versus applied voltage for a 32 μm thick etalon with a relative rotation of 18 degrees between the molecular alignment direction at the two surfaces.*

We have used such a model to calculate the transmission through a Fabry-Perot resonator with properties identical to our experimental device. In our calculations we have used N=32, which gave a good approximation to the continuous polarization transformation. Figure 6 shows the calculated resonances for a cell with parameters similar to our experimental device. The spectra are shown only for field values high enough where the assumptions that went into this derivation are expected to hold. From Fig. 6 we can see that most of the features in the experimental device is explained, including the anti-crossing that is obtained when the retardation in each half- cell is $\lambda/4$, i.e. $\psi=\pi/4$. At that point the eigenmodes are polarized at 45° with respect to $\vec{n}$, and each polarization component shows the two eigenmodes with equal intensity. Anti-crossing occur every time that the two waveplates act as circular polarizers, i.e. when $\psi=\pi/4, 3\pi/4, \cdots$, and indeed additional anti-crossings are observed in the calculated resonances. We have verified that the main features seen in Fig. 6 are obtained for any value of the twist angle θ. The gap between the anti-crossing resonances does depend on θ, and it disappears when theta=0 (no twist), as expected for a perfect uniaxial structure.

In conclusion, we have investigated the modes of a Fabry-Perot resonator that contains a nematic liquid crystal and their tuning with external electric field. We showed that when the molecules are aligned in the cell, there are one set of modes that tune with the applied field. We also showed that even a small twist of the director along the cell cause a gap in the continuous tuning of the resonance. This gap appears as a typical anti-crossing of the two resonant modes, which can traced to the polarization mixing of the eigenmodes at that field bias.

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