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Asymmetric tunable Fabry-Perot cavity using switchable polymer stabilized cholesteric liquid crystal optical Bragg mirror

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Abstract. Optical properties of an asymmetric Fabry-Perot (FP) cavity interferometer made up of a conventional metallic mirror and a polymer stabilized cholesteric liquid crystal (PSCLC) Bragg mirror have been investigated. The first FP cavity design comprises a gold mirror, an isotropic layer made up of the polymer glue, a quarter wave plate to convert the input linearly polarized modes into the circularly polarized modes inside the cavity, and the PSCLC Bragg mirror, all sandwiched between two indium tin oxide glass plates. The second FP cavity has a layer of conducting polymer deposited on the quarter-wave plate to apply the electric field only to the cholesteric stack. To have reflectivity above 95% in visible range we implement 30 layers of cholesteric liquid crystal in a planar Grandjean texture. The device compactness and the mirror parallelism due to the monolithic fabrication of FP are advantageous from the technical point of view. We test the FP tunability by shifting the resonance wavelength through an entire period; by applying electric field and/or by varying the temperature. © 2012 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: 10.1117/1.OE.51.3.034001]

Subject terms: Fabry-Perot; polymer stabilized cholesteric liquid crystals; Bragg mirrors; conducting polymer; tunable cavity.

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1 Introduction

In optical telecommunication the need for switchable reflecting devices has often been expressed for wavelength routing or optical monitoring.¹ The conventional method to realize these filters is to design a Bragg filter. However, these structures are obtained with very expensive technologies, as they are produced on substrates or photo-written in optical fibers. In this article, we test the cholesteric liquid crystal (CLC), which is a self-organized material owning the optical properties structurally well suited to reach these technical objectives: The CLC has almost the same properties as nematic except for a helical structure of the director. The helical axis is perpendicular to the director and this helix is characterized by the pitch. This periodic structure exhibits a periodic birefringence modulation that causes selective reflections of a circularly polarized light. The dielectric tensor is also undergoing a precession along the helical axis. Due to this structure, these liquid crystals have unique and very attractive optical properties. When a light beam is propagating along the helical axis, Bragg reflection occurs in the following wavelength range^{2,3}:

$$n_o P \leq \lambda \leq n_e P. \quad (1)$$

P is the pitch of the CLC and n_o and n_e are ordinary and extraordinary indices of the liquid crystal. When a left circularly polarized light is incident on the right-handed CLC it passes through without any reflection and vice

versa. If a left circularly polarized light is incident on a left-handed CLC it gets completely reflected. In case of cholesteric mirrors, the handedness is preserved contrary to traditional metallic mirrors where the handedness is reversed. Exact solutions for normal incidence can be found in Yeh and Gu.³ The reflection band has a finite value and is a function of optical anisotropy of the medium. The reflection function is an even function with sharp cut-off and side-lobes. The spectral range is given by,

$$\Delta\lambda = \Delta n P, \quad (2)$$

where Δn is the birefringence of the medium and P is the cholesteric pitch. The central wavelength of the Bragg reflection is given by,

$$\lambda_0 = \langle n \rangle P, \quad (3)$$

where $\langle n \rangle$ is the average refractive index of cholesteric layers and P is the helical pitch length. One of the mirrors in the structure is static while the other one is tunable; this gives rise to asymmetric structure. The cholesteric mirror is not only a mirror but also a tunable medium. From the future point of view, this mirror using CLC can be doped with color dyes to gain medium. Also, from the point of view of fabrication asymmetric structure holds an advantage as the entire filter is sandwiched between two glass plates. The tuning and lasing using CLCs was previously mentioned in Refs. 4 and 5.

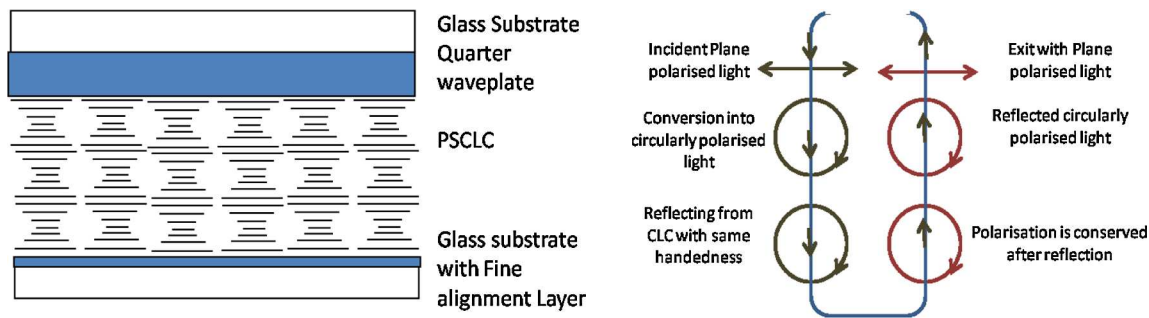


Fig. 1 Bragg mirror with PSCLC and quarter-wave plate.

2 Switchable Cholesteric Mirrors

2.1 Structure

Optical properties of CLC were used to test a switchable mirror. The first step of this study was to assemble a stack of quarter-wave plate and CLC layer. The quarter-wave plate transforms linear polarization into circular one. Moreover, the presence of a quarter-wave plate inside the cavity makes the device very compact.

The objectives are to characterize the optical properties of both the CLC and the quarter-wave plate. This half-cavity is the first step toward the switchable Fabry-Perot (FP) cavity. This structure is polarization sensitive as the input polarized light should enter at a 45-deg angle with respect to the quarter-wave plate. The reflection band is intrinsically restricted to the band gap of cholesteric structure but the quarter-wave plate, which converts linear into circular polarization, also has an intrinsic sensitivity versus the wavelength. However, straightforward calculations indicate that wave plate sensitivity can be neglected: For 10% of optical intensity losses due to wavelength compression in polarization conversion, we obtain a ratio $\Delta\lambda/\lambda_0 \cong 0.4$ where λ_0 is the central wavelength (560 nm) giving the exact phase shift of 90 deg. For simplicity, we test our device in visible range knowing that shifted the device to the infrared range can be easily processed. The Fig. 1 illustrates the fabrication of mirrors. Note the path of light in a linearly polarized mode entering at a 45-deg orientation with respect to the quarter-wave plate. We used a nematic liquid crystal to add to the CLC to get a pitch at appropriate wavelength in visible range. Merck's MDA-00-1445 CLC and MDA-00-1444 nematic liquid crystal were used to make the mixture. The concentration for giving reflection in visible range is: 80/20; MDA-00-1445/MDA-00-1444. Different percentages of RM257 (mesogenic polymer from Merck) were tested in the cholesteric mixture to optimize both switching and optical reflection. The optical indices of this material are $n_o = 1.508$, $n_e = 1.687$. The melting and clearing points for RM257 are 66 °C and 127 °C, respectively, and it has a very good miscibility with the host liquid crystal when mixed at higher temperatures. We added 0.1% of Igracure 651 photoinitiator to trigger the polymerization reaction. The need for using polymer in the cholesteric mixture reduces the defects like focal conics in the cholesteric structure. Improved response time is another advantage associated with the use of polymer, which will be justified later on in the article.

The quarter-wave plate for desired wavelength was deposited by spin coating using Merck's reactive mesogen

RMS-03-001C. The thickness of the film is 1.1 microns. This material has a birefringence of $\Delta n = 0.159$ at 589 nm. The coated film was polymerized under nitrogen atmosphere at 1 J/cm² of UV light. A cell with a thickness of 12 micron, equivalent to 30 periods of PSCLC, was fabricated and filled with mixture. After filling in nematic phase, the cholesteric texture exhibits defect lines (oily streaks) and hence we used the technique of shear alignment (i.e., making slight displacement of the substrates). The defect density is greatly reduced by this process and the mixture is then polymerized with UV radiation 5 mW/cm².

2.2 Impact of Polymer Stabilization

It can be observed in the following spectra (taken with the Ocean Optics HR 4000 Spectrometer) that the reflectivity of

Table 1 Switching and relaxation times for cholesterics with different polymer concentrations.

Polymer concentration %	Switching speed (μ s)	Relaxation TIME	Voltage
0	400	>10 sec	10
5	350	50 ms	50
10	300	30 ms	100

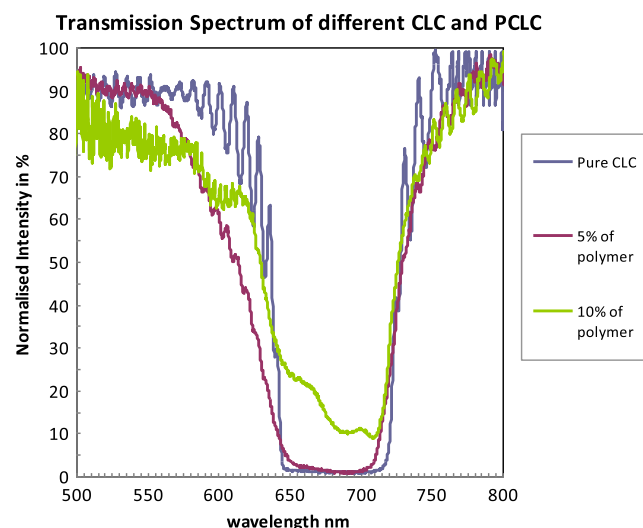


Fig. 2 Comparison of band gaps with and without polymer.

the Bragg mirror goes down by increasing the polymer concentration. Pure CLC shows perfectly in a Bragg mirror. While increasing the polymer slightly broadens the band edges because of the modification of the average refractive index, it nevertheless strengthens the Bragg mirror mechanically and speeds up the switching mechanism.⁶ Hence, we decided to use the 5% polymer CLC to build the FP cavities. (See Table 1 for more details on switching speeds.)

We verified the switchability and tunability of pure CLC and also polymer-stabilized CLC (PSCLC). The concentration of polymer used in the CLC mixture was 0% (pure CLC), 5%, and 10%. Following are the transmission spectra

of 0%, 5%, and 10% of polymer. As previously mentioned, we used RM257, a diacrylate mesogenic polymer from Merck Corporation. It can be observed in Fig. 2 that the bandgap for all the polymer concentrations broadens and that the blue shift in the band is observed as the applied electric field increases.

2.3 Impact on the Electrical Switching

The second impact concerns the switching mechanism of the cholesteric mirror. When the electric field is applied to cholesteric stack the planar alignment of molecules is

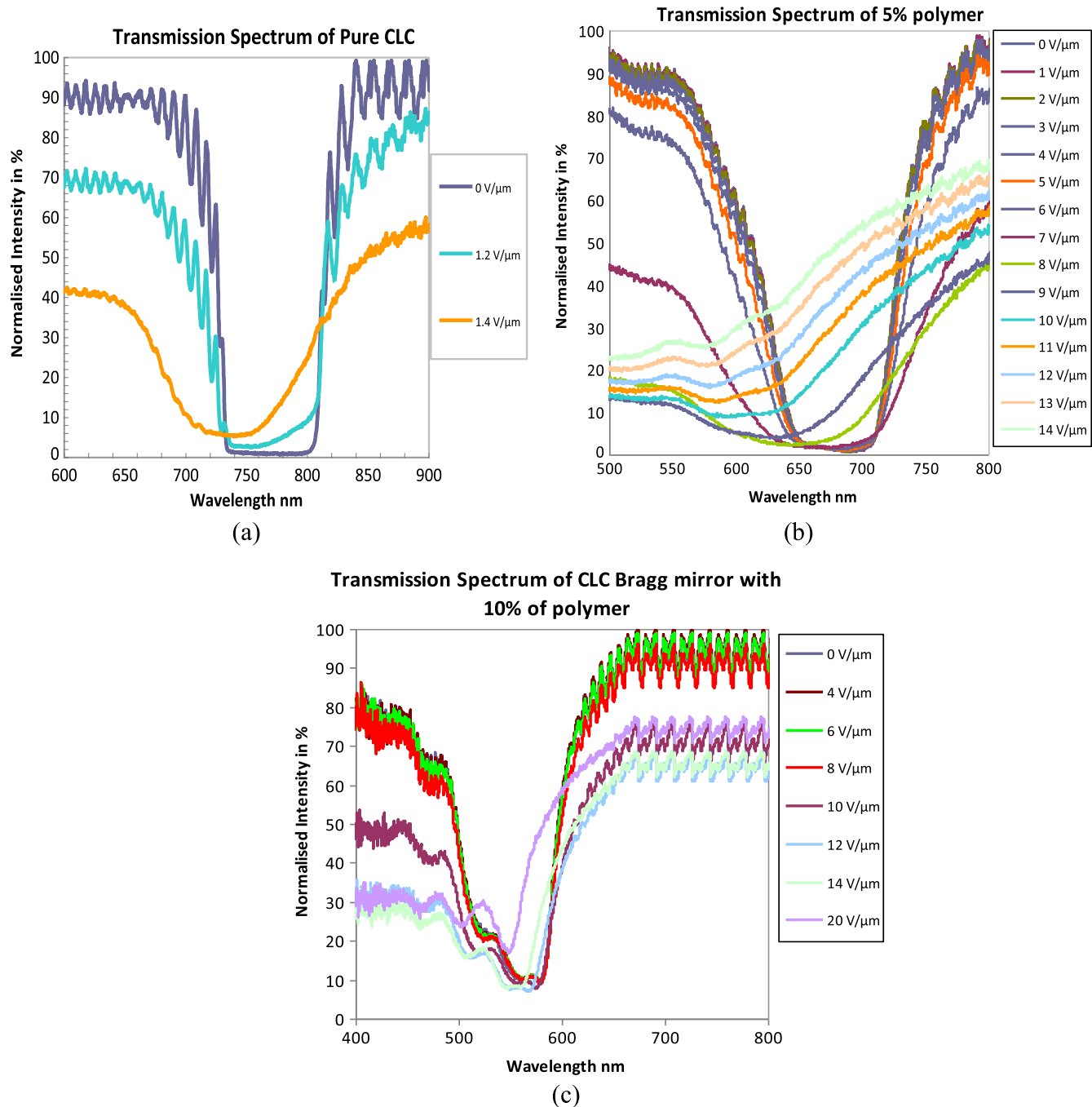


Fig. 3 (a) Response of Bragg mirror with 0% of polymer in CLC for applied electric field; (b) response of Bragg mirror with 5% of polymer in CLC for applied electric field; (c) response of Bragg mirror with 10% of polymer in CLC for applied electric field.

transformed in focal conics structure and increasing the electric field until a certain value of the electric field causes the homeotropic alignment of molecules. It should be noted that the electric field values required to tune and eventually switch the pure CLC (0% polymer) Bragg mirror are small. Although the switching speeds are quite fast for cholesterics, the relaxation time for pure CLC to come back in the planar orientation after removal of the electric field is extremely slow. (See Table 1 for more details.) Improved relaxation speeds were observed for cholesteric mirrors with 5% and 10% of polymer but at the cost of relatively higher electric field than for Bragg mirror with pure cholesteric liquid crystal. We applied a bipolar square pulse with an on-off state. Table 1 indicates the switching behavior of the cholesterics with different polymer concentrations.

The Fig. 3 shows response of Bragg mirror with different polymer concentrations for applied electric field. The cholesteric mirror with 10% polymer shows a poor reflectivity curve as compared to pure cholesterics, whereas the Bragg mirror with 5% polymer seems to be good trade-off as it shows good reflectivity and also sustains larger electric fields as compared to pure cholesterics. Moreover, the cholesteric mirror with 5% polymer shows much better relaxation time than the pure CLC. Therefore, we built the FP using 5% polymer.

The switching behavior of this stabilized cholesteric is clearly monostable with this concentration of polymer (the structure relaxes toward the planar texture when the voltage is turned off). Other modes as a result of bistable switching⁷ will be investigated later through modifying the mixture. It

should be noted that we have not explored different ways of electrical switching using CLCs such as bistable switching of CLCs in this article (see Yang and Wu),⁷ and this remains the subject of further investigation in our laboratory.

3 Switchable Asymmetrical FP Cavity

To increase the spectral selectivity, we test a FP structure. Here we have realized a FP using a cholesteric Bragg mirror at one side and a gold mirror on the other side. Previously, the fabrication of the FP cavity using cholesteric as Bragg mirror was explored,⁸ however, in that particular FP, a mixture of right- and left-handed CLC so that when an unpolarized light is on such a cholesteric structure half of the light will be reflected by the right-handed helix while the other half will be reflected by left-handed helix, thus causing complete reflection in the cholesteric stop band. This requires a quarter-wave plate inside the cavity, which justifies our choice. The monolithic fabrication and the presence of quarter-wave plate (45-deg orientation with respect to input polarization for converting it into a circular polarization) inside the cavity make it a novel technique of FP fabrication. We tried to achieve the tunability by using the temperature and the electric field. The tunable medium in this FP is the cholesteric Bragg mirror. It can be considered a half-switchable cavity as only one of the mirrors is switchable and tunable.

The Fig. 4 illustrates the fabrication of FP cavity, where the mode oscillates between the PSCLC mirror and the gold mirror. The quarter-wave plate was made using the same material as mentioned previously (i.e., RMS-03-001C). A

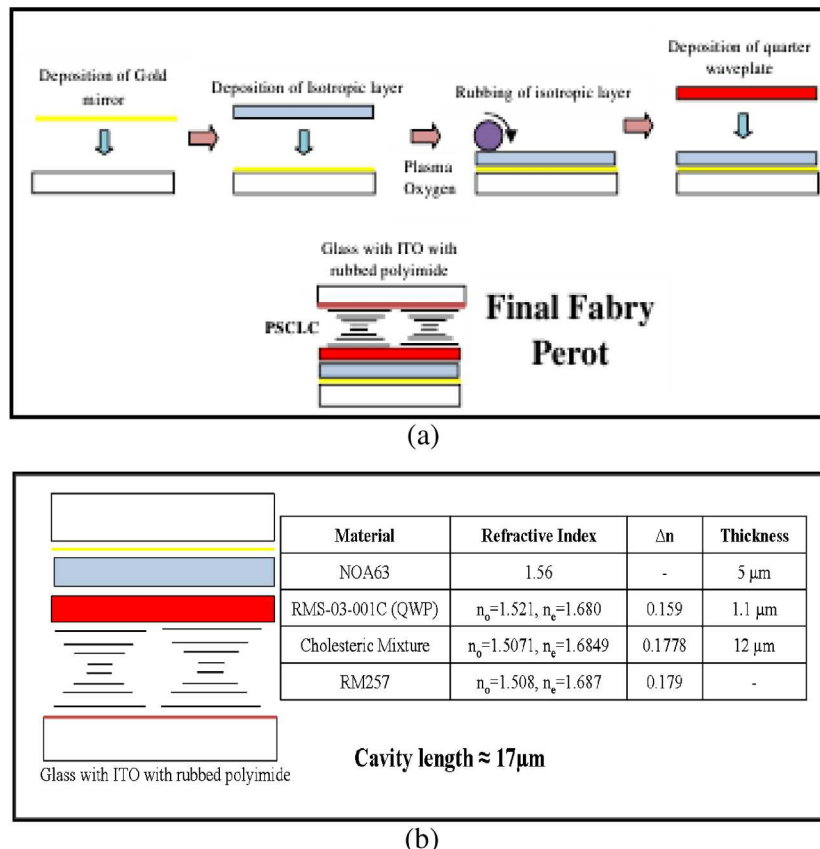


Fig. 4 (a) Fabrication of asymmetric tunable Fabry-Perot; (b) structure with refractive index profile of the cavity.

50-50 concentration solution of NOA63 and cyclopentanone was deposited on gold mirror and polymerized under a nitrogen atmosphere for 1 J/cm^2 to have a thickness of approximately $5 \text{ }\mu\text{m}$ to adjust the free spectral range (FSR). Plasma oxygen treatment improves the adhesion of the quarter-wave plate to the polymer glue. It should be noted that the plasma treatment should be made before the rubbing procedure; if it is done after rubbing then the plasma treatment destroys the local anisotropy created by rubbing. Both the glass substrates had transparent ITO electrodes. One of the glass substrates had a layer of polyimide SUNEVER 410 from Nissan chemicals. The quarter-wave plate served as another alignment layer. The cell was made using glass rod spacers of $12 \text{ }\mu\text{m}$, which corresponds to approximately 30 periods of CLC i.e., 30 pitch lengths of CLC. The cell was fabricated for making the electrical and temperature tunability experiments.

3.1 Temperature Tunability

We first demonstrate the tunability of FP with respect to temperature. The spectrum in Fig. 5 illustrates the red shift caused by the application of temperature. The pitch of the CLC depends upon the temperature. We have analyzed the dp/dT for this particular cholesteric sample. The shift for this particular cholesteric mixture is positive. We have obtained the change in wavelength with respect to the applied temperature (dp/dT) equal to $0.0914 \text{ nm/}^\circ\text{C}$.⁹ At temperatures below the isotropic temperature the cholesteric stop band is conserved as it undergoes red shift with a reduction of the stop band width linked to the birefringence decrease. Above the nematic-isotropic transition the cholesteric structure collapses and the stop band disappears. The width of FP peaks is approximately 3 nm and the free spectral range (FSR) is about 16 nm . The total shift of FP peaks observed over the range of nematic phase was 8 nm . This FP tunability results mainly from the optical birefringence variation of CLC. The Δn of CLC is temperature sensitive and decreases when temperature increases. The birefringence is $\Delta n = 0.17$. The spectral tunability of FP cavity is given by:

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta n}{n} \left(\frac{e}{L_{\text{eff}}} \right),$$

where e is the penetration length of cholesteric mirror and L_{eff} is the effective length of FP cavity. This length corresponds to the concatenation of the quarter-wave plate, the NOA63 film, and the penetration length in cholesteric mirror. The ratio $\left(\frac{e}{L_{\text{eff}}} \right) = 0.15$ gives a penetration length of about $1 \text{ }\mu\text{m}$. This estimated penetration length (the length up to which light penetrates in the CLC) is very small compared to the total thickness of CLC, however; to obtain a satisfying finesse of the FP cavity, maintaining a high reflectivity of CLC mirror is essential.

Although, the response of change in the peak with applied temperature is instantaneous, the temperatures applied to the cavity are high, which is not advantageous from the application point of view. Also, it would require a temperature-controlling system to maintain and achieve the required tunability. This would make the system much more complicated, therefore to achieve the tunability of the Bragg mirror, it would be advantageous to address the electrical aspects.

3.2 Electric Field Tunability

The initial texture of the CLC is planar and the electric field applied is parallel to the helix.¹⁰ Increasing electric field amplitude causes the helix to collapse and homeotropic state should finally be obtained with the intermediate focal conic state. According to the Fig. 6, it is obvious that the director has not reached the homeotropic alignment.

The observed free spectral range was 14 nm , which is close to the theoretical value of 16 nm . (It was calculated based on the cavity length and average refractive index of the entire cavity.) It can be observed that no tunability of FP peaks was observed at higher fields. The highest electric field value corresponds to voltage value of 320 V at this voltage the mirror is completely switched off to become transparent. However, considering such a high applied voltage value one would have to envisage another method to achieve the required tunability and switchability. This lack of tunabil-

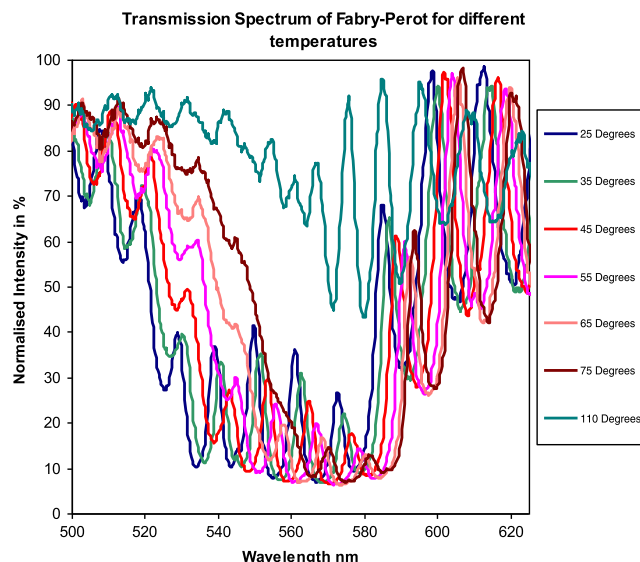


Fig. 5 Response of Fabry-Perot with respect to temperature.

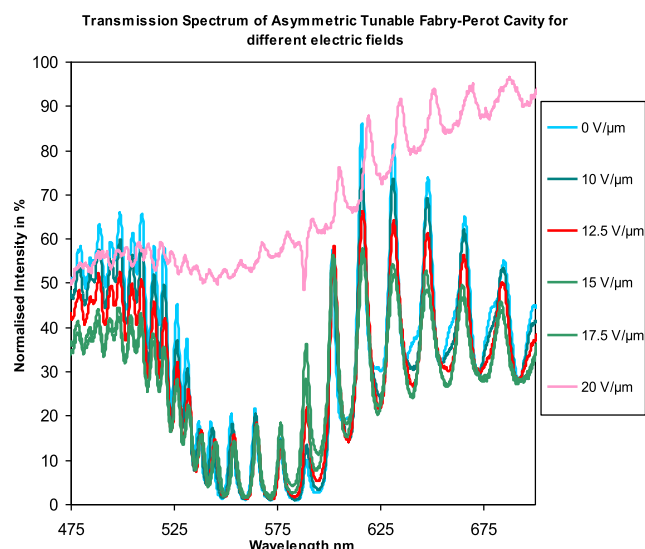


Fig. 6 Response of Fabry-Perot for applied electric field.

ity can be attributed to the fact that the interelectrode distance is too large. Because the voltage values involved are very high it is not an interesting FP system from an application point of view. Therefore, we decided to deposit conducting polymer layer on top of the quarter waveplate in order to apply the field directly on the cholesteric liquid crystal. The structure of the Fabry-Perot using cholesteric mirror remains more or less except the presence of the conducting polymer on quarter wave plate. Interestingly, conducting polymer served as an alignment layer.

4 FP Cavity Using Conducting Polymer

This process is similar to the previous one with an additional step: Deposition of the conducting polymer on the quarter-wave plate. We used Baytron PEDOT/PSS water-based solution to make the conducting polymer film. Previously, compatibility of this polymer with liquid crystal has been demonstrated in Ref. 11. Highly transparent (>90% in visible range) electrode makes it interesting from the fabrication point of view. The Fig. 7 shows Fabry-Perot using conducting polymer. This polymer was dissolved in water at a 1% to 3% solution. This solution was then dissolved in 10% to 90% of Ethylene glycol, and then diluted polyvinyl alcohol (PVA) was added to the solution. Plasma oxygen treatment on the waveplate is necessary to improve the surface adhesion to ensure a uniform deposition of conducting polymer. The

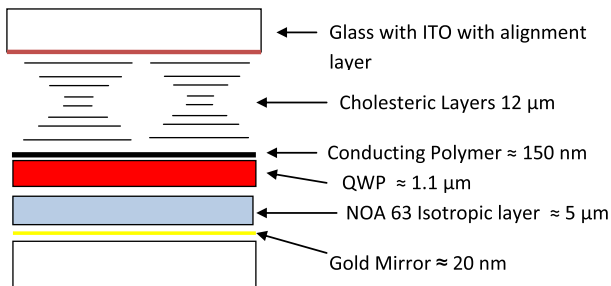


Fig. 7 Fabry-Perot using conducting polymer.

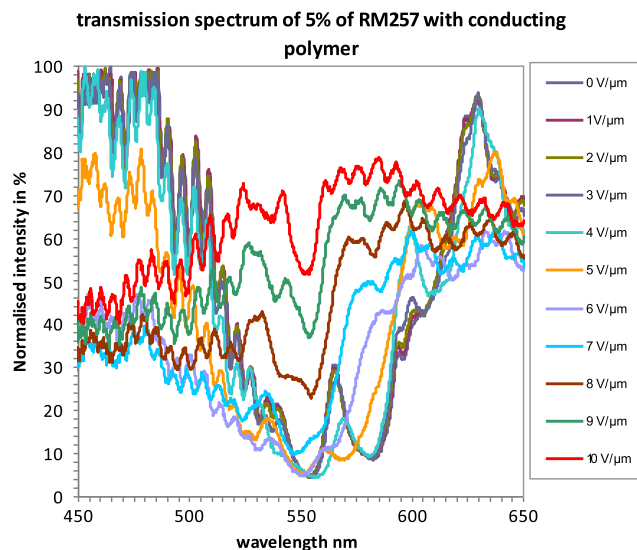


Fig. 8 Response of Fabry-Perot with conducting polymer for applied electric field.

Table 2 Refractive Indices of all the materials used successively in the Fabry-Perot.

Material	Refractive index (in visible region)	Δn
PEDOT-PSS	1.53	-
RMS-03-001C (Quarter wave plate)	$n_o = 1.521$, $n_e = 1.680$	0.159
NOA63 (Isotropic Region)	1.56	-
Cholesteric Mixture	$n_o = 1.5071$, $n_e = 1.6849$	0.1778
RM257	$n_o = 1.508$, $n_e = 1.687$	0.179

deposition of the entire mixture was carried out at 3000 RPM for 30 sec and then dried at 120 °C to 130 °C for 5 min on a heating stage to remove the excess solvent. This film was then rubbed to align the cholesteric stack.

4.1 Electric Field Response of FP with Conducting Polymer

This method of fabrication allowed the voltage values to be brought down considerably for complete switching of the field. The optical response of the FP mirror is heavily degraded as shown in Fig. 8. The main objective of attaining the tunability is still not evident from the spectrum analysis. Only 2 FP peaks can be observed with a very weak peak power and are seen at the band edge. The peak power and sharpness are decreased compared to the previous design, which can be due to an increase of optical losses or to an index mismatching between the quarter-wave plate, conducting polymer, and the cholesteric stack. As the voltage increases the peaks disappear, as focal conical structure causes the scattering of the light.

The presence of conducting polymer definitely has enabled us to switch easily the FP by the voltage. However, tunability is still not observed; also the number of peaks inside the cavity has gone down. This can be due to the fact that the monolithic fabrication, which leads to multicavities (i.e., different materials with index mismatch) were deposited on top of each other. Table 2 gives the values of refractive indices of all the materials used in fabrication.

Another possibility for reduction in peaks is the absorption of light inside the cavity. Therefore, improvements are possible in this current structure, perhaps first by reducing the thickness of the conducting polymer (as compared to current thickness, which is between 100 and 200 nm) and secondly by using electrodes with good index matching and low absorption.

5 Conclusions

We demonstrated the feasibility to fabricate a low-cost switchable mirror using CLC structure. The material is stabilized by an isotropic polymer network to obtain a reversible electrical switching. Moreover, the optical properties of this mirror can also be finely tailored by combining a mirror (metallic or dielectric) to a cholesteric mirror to fabricate a

switchable asymmetrical FP cavity. In case of Fabry-Perot using cholesteric Bragg mirror, we have shown the benefits and the need for including the quarter-wave plate inside the cavity. The switching principle can be either by electric field or thermal change. The tuning of the wavelengths has been observed only in case of temperature. As far as electrical addressing goes, no tunability is observed but the cholesteric mirror can be completely switched 'Off' using electric field. The first design requires very high voltages to switch; hence it is not enticing from the application point of view. Contrastingly, the second design allows a considerable reduction in electric field values to switch the FP completely. In regard to temperature control, a tunability of approximately 8 nm has been obtained. When considering electric field control, the reason for no tunability is probably due to the absence of director reorientation with respect to applied electric field or the focal conical defects. Therefore, the applied electric field cannot be used in such a structure to tune the FP but can be used to switch it. The drawback of these filters is that the input polarization requires control measures, which can be achieved by including a polarization diversity system for applications in optical telecommunication.

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Biographies and photographs of the authors not available.