Fabry–Perot etalon with polymer cholesteric liquid-crystal mirrors

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We present what we believe to be the first implementation of a Fabry–Perot (FP) etalon using polymer cholesteric liquid-crystal mirrors. These polymer mirrors have each been fabricated onto a single substrate, which allows the FP cavity spacing to be only a few micrometers wide. For the experimental results presented, cavity lengths of 13.8 and 7.6 μm yield near-infrared free spectral ranges of 24.8 and 45.6 nm, respectively. The measured finesse of 14.31 is approaching the limitation imposed by the reflectivity of the mirrors. © 1999 Optical Society of America

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Cholesteric liquid crystals were the first liquid-crystalline phase observed.[1] These materials occur naturally, but they can also be synthesized by addition of chiral dopant to a nematic liquid-crystal host. Consequently, they are often called chiral nematics. The cholesteric structure can be thought of as layers of planar-aligned nematic liquid crystals. The directors within the layers trace out a helix with an axis perpendicular to the nematic planes. A complete 360° reorientation of the local directors along the helical axis is termed the pitch, p. These materials exhibit some unique optical properties, such as large optical activity and selective reflection, owing to the periodic variation of the local optic axis along the helix.[2]

Selective reflection occurs because the periodic structure forms a unique Bragg grating. The grating periodicity is experienced only by light having a circular polarization of the same handedness as the helix of the cholesteric liquid crystal. Consequently, light of orthogonal handedness is transmitted. The cholesteric liquid-crystal film reflects properly polarized light maximally at the wavelength (in the medium) corresponding to the length of the pitch:

$$\frac{\lambda_0}{\bar{n}} = p\,. \tag{1}$$

Here $\bar{n}$ is the average index of the nematic layers. Additionally, significant reflection occurs over the band

$$\frac{\lambda_0}{n_e} \le \lambda \le \frac{\lambda_0}{n_o}\,, \tag{2}$$

where n_o and n_e are the optical indices of the nematic layers. Wavelengths within this band that have the proper circular polarization will not propagate into the cholesteric liquid crystal and are reflected without a change in handedness, unlike the case of reflection from conventional mirrors. The strength of the reflection depends on the thickness of the cholesteric film, as does the shape of the reflection band.[3] The unique property of selective reflection in cholesteric liquid crystals has been used in several applications.[4]

Recently, it has become possible to attach liquid-crystal molecules to a cyclic polysiloxane backbone.[5] This results in a crosslinkable polymer that exhibits a cholesteric liquid-crystalline texture. Curing the polymer into the glass phase results in a solid film. Proper fabrication of these polymer cholesteric liquid crystal (PCLC) films onto a single substrate can produce band-limited polarization-selective mirrors. The optical quality of these PCLC mirrors is excellent, as is demonstrated by the implementation of the Fabry–Perot etalon discussed here.

The ability to obtain polymer cholesteric film on a single substrate by use of the procedure that we have developed suggests that a closely spaced etalon with a large free spectral range can be implemented by use of PCLC mirrors. A passive PCLC etalon was first suggested by Mosini and Tabiryan.[6] We have proposed extending the concept to tunable filters.[7] Here, the proof-of-principle implementation of a passive Fabry–Perot etalon that uses PCLC mirrors, each on a single substrate, is presented for what we believe to be the first time.

A schematic of the PCLC etalon is shown in Fig. 1. The two mirrors used in this implementation are approximately 7 μm thick and reflect more than 75% of left-hand circularly polarized incident light over a band from 1027 to 1093 nm. The maximum reflectivities for these mirrors are 82% at $\lambda_0 = 1058$ nm for the first mirror and 80% at $\lambda_0 = 1067$ nm for the second. Index-matching fluid chosen based on material supplier specifications to be as close as possible to the PCLC was placed between the mirrors, which were gapped by use of 12-μm glass rod spacers. Although it was not considered by the authors of Ref. 6, index matching is critical for polarization purity.[8]

The top part of Fig. 2 shows the experimental transmission spectrum for the PCLC Fabry–Perot

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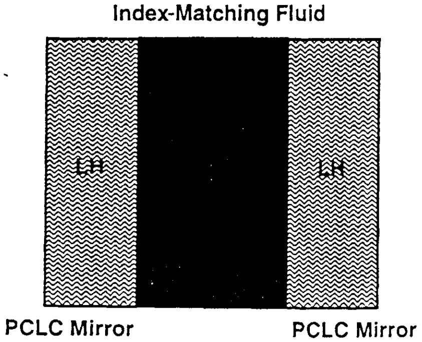

Fig. 1. Schematic detailing the construction of the PCLC etalon.

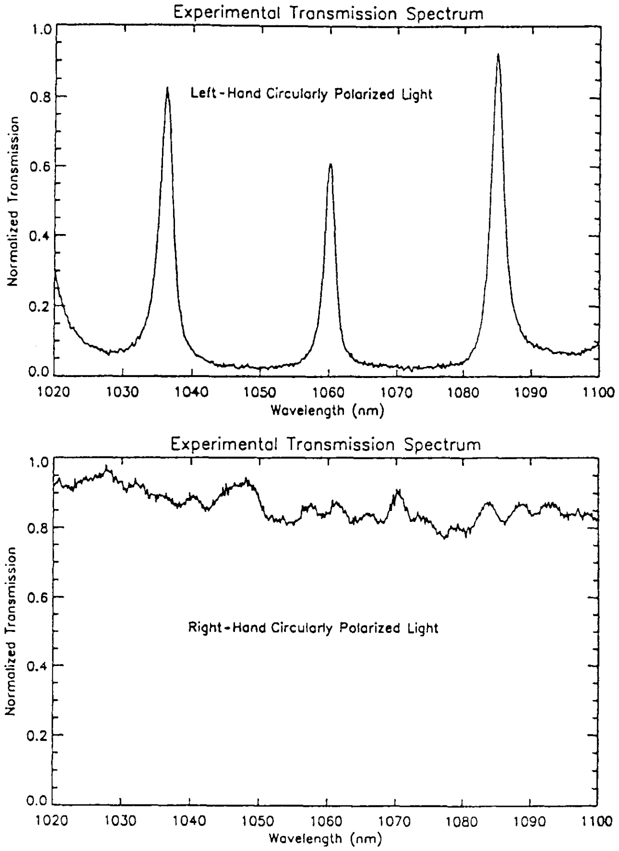

Fig. 2. Normalized experimental transmission spectrum for left-hand circularly polarized light (top) and right-hand cicularly polarized light (bottom) incident on the passive etalon with PCLC mirrors. Note the relatively featureless transmission of the right-hand circularly polarized light.

etalon normalized to left-hand circularly polarized input light. Light from a tungsten filament source was collimated and then linearly polarized to −45° by a Glan–Thompson prism polarizer. This was followed by a quarter-wave Fresnel rhomb, which changed the light to left circular polarization. The circularly polarized light was sent through a pinhole to the Fabry–Perot etalon. A 20× microscope objective coupled the transmitted light to the fiber input of an Ando Model AQ6315A optical spectrum analyzer. For the transmission spectrum shown in the top part of Fig. 2 the free spectral range is 24.8 nm, and the FWHM is 1.974 nm, resulting in a finesse of 12.56. This spectrum indicates that the cavity is approximately 13.8 μm thick.

Shown in the bottom part of Fig. 2 is the transmission through the Fabry–Perot etalon for right-hand circularly polarized light. Ideally the right-handed light transmission should be unity, but Fresnel losses reduced it to 75–85% throughout the wavelength region of interest. The relatively featureless transmission of right-handed light demonstrates the polarization sensitivity of the mirrors.

To provide feedback regarding the behavior of this etalon, we used the 4 × 4 matrix formalism of Berreman[9] to model the etalon. The theoretical results are shown in Fig. 3. The loss in transmission where the mirrors are most reflective is due to changes in the state of polarization that occur when the refractive indices of the cavity and the cholesteric mirror are not perfectly matched.

We improved the finesse of the prototype etalon by placing the Fabry–Perot etalon in a cell-gapping jig and applying pressure. Using the jig improved mirror parallelism and decreased the spacing between the mirrors, resulting in an increase in the finesse. The measured free spectral range indicates a cavity length of approximately 7.6 μm. The PCLC films are relatively soft, and application of pressure appears to have embedded the spacers in the films. The transmission spectrum for improved finesse is shown in Fig. 4. The free spectral range was increased to

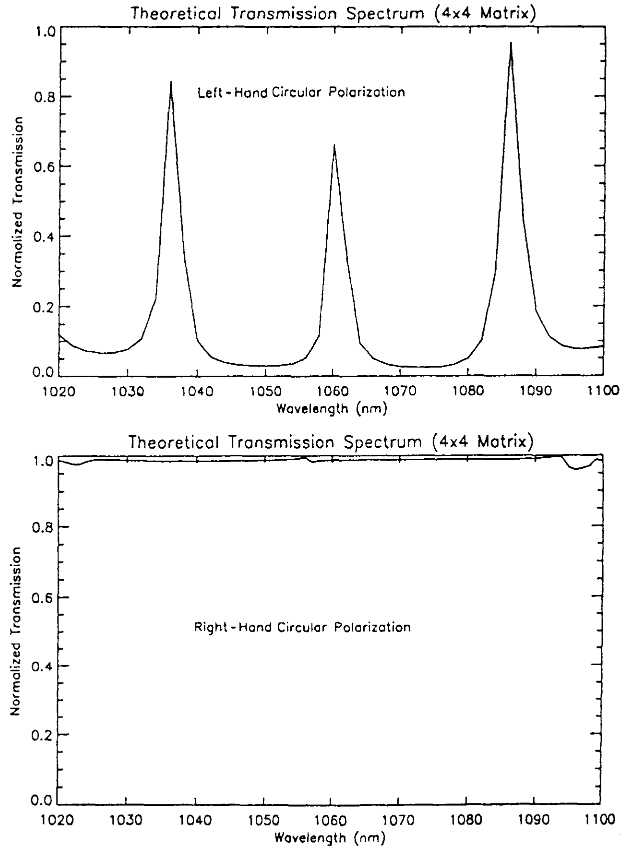

Fig. 3. Normalized transmission spectrum predicted by 4 × 4 matrix theory for the experimental conditions of Fig. 2: top, left-hand polarized light incident and bottom, right-hand polarized light incident.

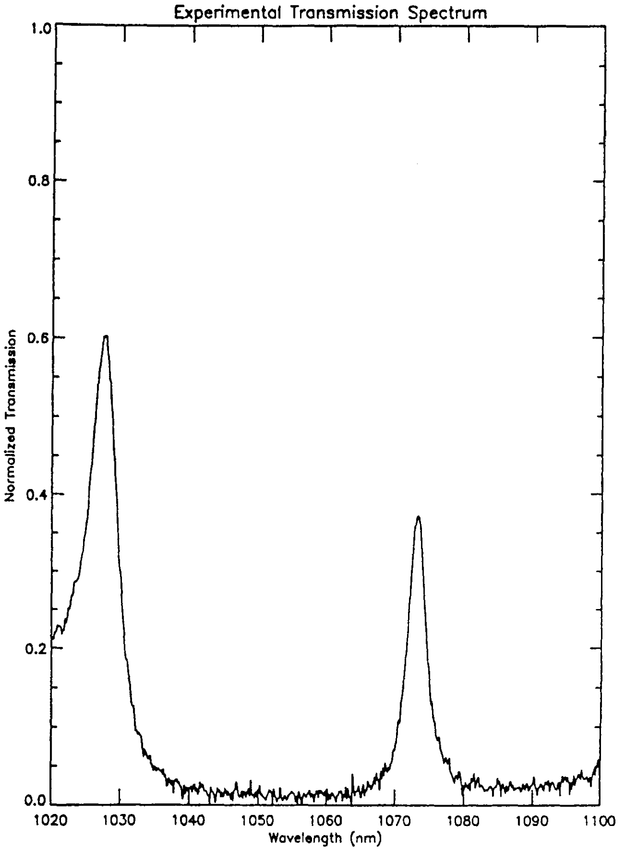

Fig. 4. Normalized experimental transmission spectrum showing improved finesse and contrast ratio for the passive PCLC etalon.

45.6 nm, and the FWHM was 3.187 nm, resulting in a finesse of 14.31.

The theoretical reflective finesse limit of a Fabry–Perot etalon is given by

$$F = \frac{\pi (R_0)^{1/2}}{1 - R_0}, \tag{3}$$

where $R_0 = (R_1 R_2)^{1/2}$ is the geometric mean of the two mirror reflectivities. For the mirrors used here the theoretical reflective finesse is 14.88. Note that the transmission near the center of the reflection band is decreased from ~60% of left circularly polarized light in Fig. 2 to 40% in Fig. 4. However, the contrast ratio between the peak transmission and the average out-of-band transmission improved from 40:1 to 62:1.

The proof-of-principle experiment presented here clearly demonstrates that the optical quality of the PCLC mirrors is suitable for implementing resonant devices. Future research will include the use of the polarization sensitivity of the PCLC mirrors and the rotative switching of chiral smectic liquid crystals to implement tunable-wavelength filters,[10] which can readily be made polarization independent.[7]

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