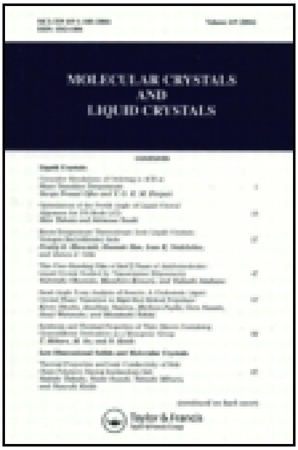

Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl19

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Version of record first published: 24 Sep 2006

Mol. Cryst. and Liq. Cryst., 2001, Vol. 368, pp. 255-262
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Electrically Tunable Optical Filter for Visible Wavelength using a Liquid Crystal Multiplexed to a Fabry-Perot Etalon

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Using the refractive index modulation in liquid crystals by an externally applied electric field, we show that a polymer dispersed liquid crystal (PDLC) can be used in a Fabry-Perot etalon to produce a tunable optical filter for use in the visible region. Voltage applied to the film changes the refractive index and the optical length of the cavity, converting the system into an interference filter with a variable frequency bandwidth. We demonstrate further that the wavelength can be tuned over 150 nm using less than 20 V of power.

Keywords: Fabry-Perot; PDLC; optical filter; Michelson interferometer

INTRODUCTION

The simplest form of an amplitude attenuator takes advantage of the inherent absorption window of the liquid crystal (LC) at specific wavelengths. This modulator consists of a voltage-controlled film that filters light coming from one optical fiber into another. With such an elementary arrangement it is possible to explore the modulation characteristics of a LC operating in a particular optical range. The main drawback of this approach is the limited spectral selection which depends only on the absorption band of the LC.

The ability to select a desired wavelength channel from a range of available spectral band is of great interest to advanced lightwave systems. This is particularly true for high-density wavelength-division multiplexed (HD-WDM) networks[1] in which components capable of wavelength selection is crucial. While several other devices have been proposed to achieve this wavelength selection[2-4] most require significant power to operate and have complex designs. For example, certain acousto-optical tunable filters require about 10 watts of power[2] although recent work suggests that these requirements can be relaxed.

An interesting system that can perform spectral band preference is a Fabry-Perot (FP) facility, a very powerful, yet versatile, spectroscopic tool. The basic property distinguishing the FP from other spectroscopic devices is simply that, for a given resolving power, only the wavelength resonant with the cavity is transmitted. The spectral selectivity of the FP has paved the way for a limited-range tunable Er:Yb laser.[5] By allowing a wider-range of mirror movement (in the order of 10^{-2} m) a multiplex Fabry-Perot interferometer (MFPI) has been developed, incorporating the wide spectral-bandwidth capability of the Michelson interferometer with the small size and high resolution of the FP.[6]

Tuning the transmitted wavelength range requires adjusting the optical cavity length by physically changing the gap between the two mirrors at both ends of the etalon. However, this procedure is beset with optical alignment difficulties. A better alternative is to construct a device in which the gap is still maintained but tuning is achieved by changing the refractive index in the cavity. To such an application, LC's are suitable candidates since a refractive gradient can be induced by applying an electric field. The goal, therefore, is to construct a tunable optical filter that can select a single wavelength from a group possessing a wide spectral range, much as a spectrometer does, but in a more cost effective and compact way.

METHODOLOGY

Coherent Illumination

The experimental set-up utilized to characterize the LC FP is illustrated in **Figure 1**, using a pre-fabricated PDLC cell.

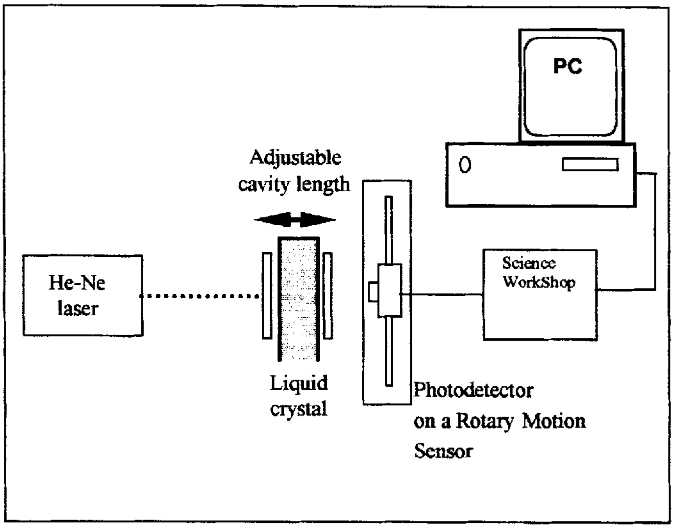


Figure 1 Optical set-up to derive the fringe shifts introduced by the LC FP

The etalon is illuminated by a Helium-Neon laser (Uniphase, 0.5 mW, 632.8 nm) to form circular interference patterns on the detector array. length of the etalon can be physically varied using a micrometer screw. The projected central fringe is then detected with a sampling frequency of 500 Hz using a PASCO photodetector mounted. The Science Workshop interface digitizes the analog signal and the relevant data are stored in the IBM/PC.

For a simple FP, it can be shown that the transmission (***T***) at a given wavelength (λ) is given by the Airy function[7, 8]

$$T = \frac{1}{1 + \frac{4R}{1-R}\sin^2\delta}$$

where $\delta = \phi + nk_0d$. Here R is the reflectivity of the mirrors, ϕ is the phase shift experience upon reflection, d is the cavity spacing, n is the index of refraction along the director axis and k_0 is the magnitude of the wave vector outside the cavity. It can be seen that the width of the transmission peak depends essentially on the reflectivity of the surfaces.

The transmission characteristics of the FP interferometer in the absence of the film is first derived. The normalized theoretical and experimental plots of T as a function of the cavity length d are shown in **Figure 2** for n=1.5 and R=0.8. The correspondence between the two curves is high, with a normalized mean squared error (NMSE)[9] of 1.54×10^{-2}.

The LC is then inserted within the cavity and a potential is applied across it. An applied voltage V induces an electric field which changes the bulk refractive properties of the LC. An increase in the index gradient extends the effective optical cavity length shifting the fringes. Such a phenomenon is evident in **Figure 3** where high voltages generate large changes on n which translate to fringe shifts. For V = 20, the increase in n corresponds to a cavity extension of 150 nm. The equivalent displacements of the different potentials are summarized in **Table 1**.

	V=5	**V=10**	**V=15**	**V=20**
Equivalent cavity displacement (nm)	15	30	60	150

Table 1 Effective cavity extension as a function voltage

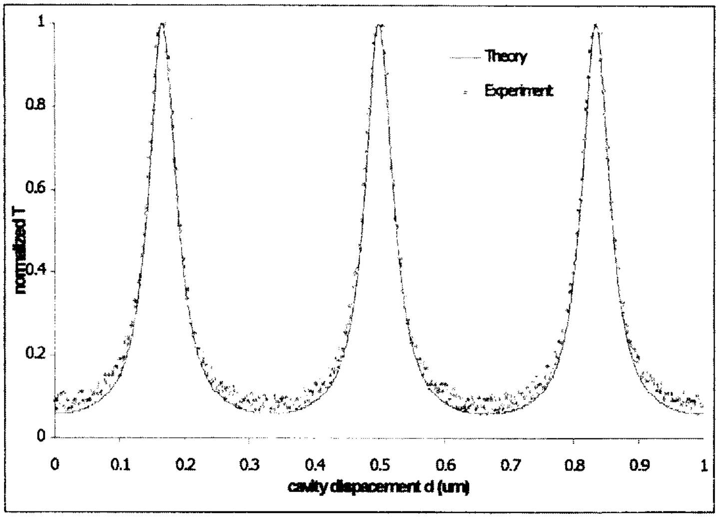


Figure 2 Theoretical and experimental transmission profiles of a FP interferometer in the absence of the LC
See Color Plate III at the back of the issue.

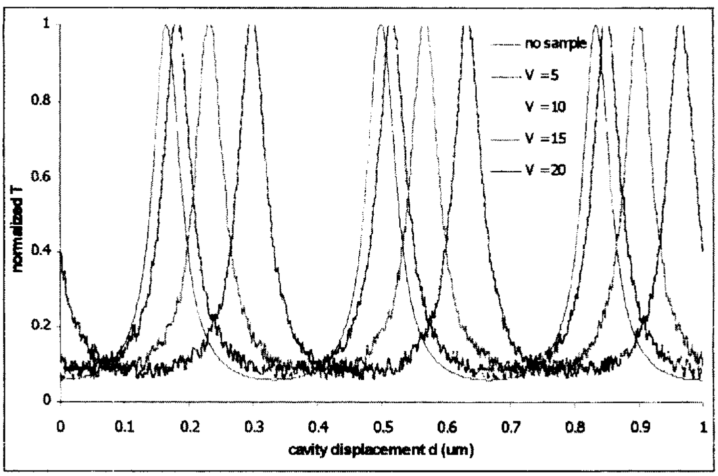


Figure 3 Experimental transmission profiles of a LC FP etalon for different applied voltages
See Color Plate IV at the back of the issue.

Incoherent illumination

The capability of the LC to alter the optical path length is now applied to the ubiquitous Michelson interferometer. This optical paragon uses the interference of waves to produce a measurement of optical path length difference between two interfering wavefronts. The optical diagram for the apparatus is illustrated in **Figure 4** in which a beam is split into two waves by a beam splitter and traverses the two arms respectively at distances L_1 and L_2 from the beamsplitter as shown.

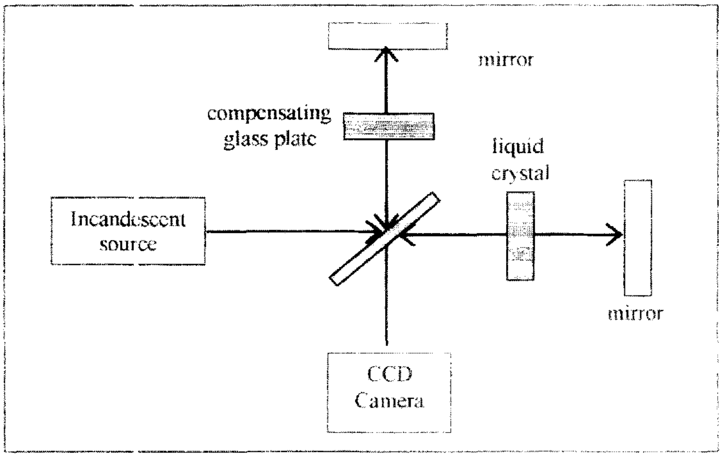
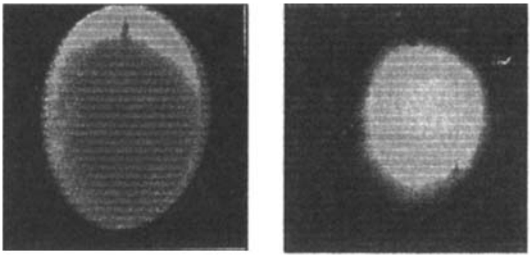


Figure 4 Liquid crystal Michelson interferometer

The sample is placed on one arm and balanced by a glass plate of equivalent thickness on the other. With the insertion of the LC the optical distance of one arm can be varied without moving the mirror, effectively fixing the system. As a test, an incandescent light source is utilized to obtain white light fringes which are frame-grabbed by the CCD camera. Because the interference pattern of an incandescent source contains the various peaks of all the colors, the color of the central spot changes as the path difference is varied. By increasing the applied potential to 20 V, we are able to observe the transition from the red peak (**Figure 5A**) to the green peak (**Figure 5B**). These results are different from a laser interference pattern.



A B

Figure 5 White light Michelson interference pattern, A) V=5 V and B) V=20 V
See Color Plate V at the back of this issue.

Noticeably, the fringes are not sharply defined and have changed color as the potential is increased. Beyond 25 V, there is no longer any fringe displacements because the LC's refractive index has reached its saturation limit and can no longer induce change in optical path length.

We estimate the coherence length of white light using[10]

$$l_c = \frac{\lambda_0^2}{2(\lambda_{max} - \lambda_{min})}$$

where l_c is the coherence length, λ_0 is the central wavelength and (λ_{max} - λ_{min} = 700 nm - 500 nm) define the effective range of the spectral visible band. With a central wavelength of 600 nm, the computed coherence length is l_c = 900 nm. This length is minute but it is still longer than the maximum cavity displacement that the LC can produce so disappearance of the fringes was not observed.

CONCLUSION

A tunable optical filter was designed and characterized by multiplexing the band-selectivity of a Fabry-Perot and the refractive index modulation in LC's by an externally applied electric field. Upon voltage application, a refractive change is catalyzed converting the system into an interference filter with a variable frequency bandwidth. Using a LC (PDLC) film, the developed LC FP could be tuned over 150 nm using less than 20 V of power. The same principle was applied to a Michelson interferometer under incoherent illumination. The viability of the LC to increase the optical path without mirror movement was tested and shown to produce a maximum displacement of 150 nm.

Provided the LC provides a linear refractive change with the potential, it is possible to develop a high-resolution Michelson interferometer which is compact and has no moving parts. The LC can replace the stepper motor that is employed to scan the mirror and from this it may be possible to construct a liquid crystal-based Fourier transform spectrometer.

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[9] $NMSE = \frac{\sum_i (x_i - y_i)^2}{\sum_i (x_i)^2}$ where x_i and y_i are the theoretical and experimental values, respectively.
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