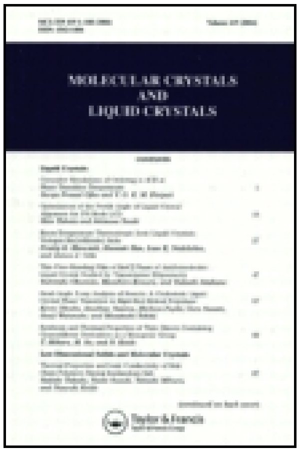

Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals

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

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Version of record first published: 04 Oct 2006

To cite this article: W. K. Choi, A. B. Davey, T. D. Wilkinson & W. A. Crossland (1997): Deformed Helix Ferroelectric Liquid Crystal Fabry Perot Etalons, Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals, 304:1, 329-337

To link to this article: http://dx.doi.org/10.1080/10587259708046978

Mol. Cryst. Liq. Cryst., 1997, Vol. 304, pp. 329–337
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DEFORMED HELIX FERROELECTRIC LIQUID CRYSTAL FABRY PEROT ETALONS

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Abstract Results obtained are reported and discussed for Deformed Helix Ferroelectric Liquid Crystal (DHFLC) Fabry Perot etalons which have improved cavity finesse using highly reflective dielectric mirrors. We show that, by the use of the cavities, the response times can be reduced to the order of 10μs with <10V applied voltages when the devices are used as optical switches. This is however only true for responses where the transmissions are switched from high to low, i.e. switching out of resonance. Moreover, a shorter pitch DHFLC, Roche FLC 9848, with higher tilt angle has also been used which has faster intrinsic response times and also improves the wavelength tuning range.

INTRODUCTION:

Deformed Helix Ferroelectric Liquid Crystals (DHFLCs)[1-2] have the attractive property of producing high speed analogue operation at very low voltages[3-8]. Under the application of an electric field, the helical structure is gradually deformed which leads to both a continuous rotation of the effective optic axis in the plane of the substrates and a change in the effective birefringence. Since the transmission of a Fabry Perot etalon for a given wavelength of incident light is sharply dependent on the cavity refractive index in a high finesse device (using highly reflective mirrors), it may be used to produce liquid crystal optical switches of very high contrast ratios with enhanced switching speeds[9]. The fact that DHFLCs can produce high speed switching even at low voltages together with the inherent birefringent change in the direction of incident light led us to propose[10] incorporating DHFLCs into Fabry Perot etalons in an attempt to obtain low voltage optical switches with enhanced switching speeds. This work was intended to develop electro-optic effects for application in liquid crystal on silicon VLSI[11], where the voltage supplies are limited. We showed[10] that the devices could switch in times between a hundred and a few hundred microseconds. Wavelength tuning was also found to be possible using both the ordinary and extraordinary refractive indices. The material used was Roche DHFLC 6304 with a pitch length of 0.35μm. The switching speeds reported were not particularly fast partly due to limitation by the material used and partly due to the poor cavity finesse obtained. In this paper, we report and discuss the results obtained for devices with improved cavity finesse using highly reflective (~98.5%) dielectric mirrors. Moreover, a shorter pitch DHFLC Roche FLC 9848 with higher tilt angle was also used which could give better wavelength tuning range and higher switching speeds.

DEFORMED HELIX FERROELECTRIC LIQUID CRYSTALS (DHFLCs):

DHFLCs have SmC* helical pitch length much shorter than the thickness of the liquid crystal devices such that the helical structure remains intact within the substrates. Due to the short pitch length of the helix compared with the wavelength of the visible light, the optical properties of DHFLCs are governed by the average over the pitch length of the helix. The incident light thus sees an average index ellipsoid with the effective optic axis along the helical axis. Under the application of an electric field, the helical structure in a DHFLC deforms due to the ferroelectric dipoles of the molecules aligning with the applied field, which leads to a rotation of the effective optic axis in the plane of the substrates. This allows analogue operation for devices based on the rotation of the optic axis between crossed polarisers. At the same time, as described in our previous paper[10], the two effective refractive indices ($n_{e(eff)}$ & $n_{o(eff)}$) also undergo changes. The effective extraordinary refractive index $n_{e(eff)}$ increases while the effective ordinary refractive index $n_{o(eff)}$ decreases as the electric field increases. The changes continue until the electric field reaches the critical value at which the helical structure is unwound completely.

DHFLC FABRY PEROT ETALONS:

Figure 1 shows the structure of a DHFLC Fabry Perot etalon. The structure consisted of a thin layer of liquid crystal sandwiched between two mirrored glass substrates. The glass substrates used were precoated with a highly reflective (~98.5% at 633nm) dielectric stack and ITO electrodes. The substrates were then spin coated with a thin layers of Nylon which, after baking, were rubbed unidirectionally to provide the alignment of the liquid crystal. Next, spacers were spun on one of the surfaces of the substrates in order to obtain the required thickness of the cavity. The two substrates were then assembled and the liquid crystal was filled into the cavity by capillary action under vacuum.

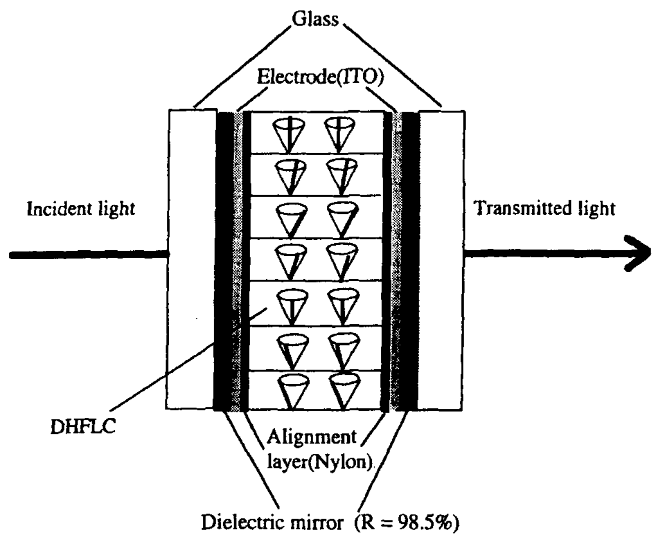

FIGURE 1 Structure of a DHFLC Fabry Perot etalon.

The DHFLCs used were Roche FLC 6304 and Roche FLC 9848 with pitch lengths of 0.35μm and 0.15μm respectively. The transition temperatures for the two materials were as follows: Roche FLC 6304 ------ X (-14°C) SmC*(59°C) SmA (64°C) I

Roche FLC 9848 ------ X (<-35°C) SmC* (65°C) SmA (66°C) I

The operating principle of a Fabry Perot etalon is interference of light waves after multiple reflections inside a reflective cavity[12]. For devices with highly reflective mirrors, most of the incident light will be reflected except when the resonance condition $2nd = m\lambda$ is satisfied, where n is the refractive index of the medium in the cavity, d is the thickness of the cavity, m is an integer and λ is the wavelength of the incident light. At this point the device is said to be 'on' resonance and ideally most of the incident light will be transmitted instead of being reflected. Thus, for a white incident light source, discrete wavelengths which satisfy the resonance condition will appear in the spectrum. By varying the refractive index of the cavity medium (liquid crystal in this case) using an applied electric field, the wavelengths transmitted can be varied and the devices behave as wavelength tuneable filters. Optical switches can be realised using a monochromatic light (e.g. a laser) such that the transmission can be switched between 'on' and 'off' resonance for that particular wavelength.

EXPERIMENTAL RESULTS:

1) Using a white light source:

The transmission of a 10μm DHFLC Fabry Perot etalon filled with Roche FLC 9848 was

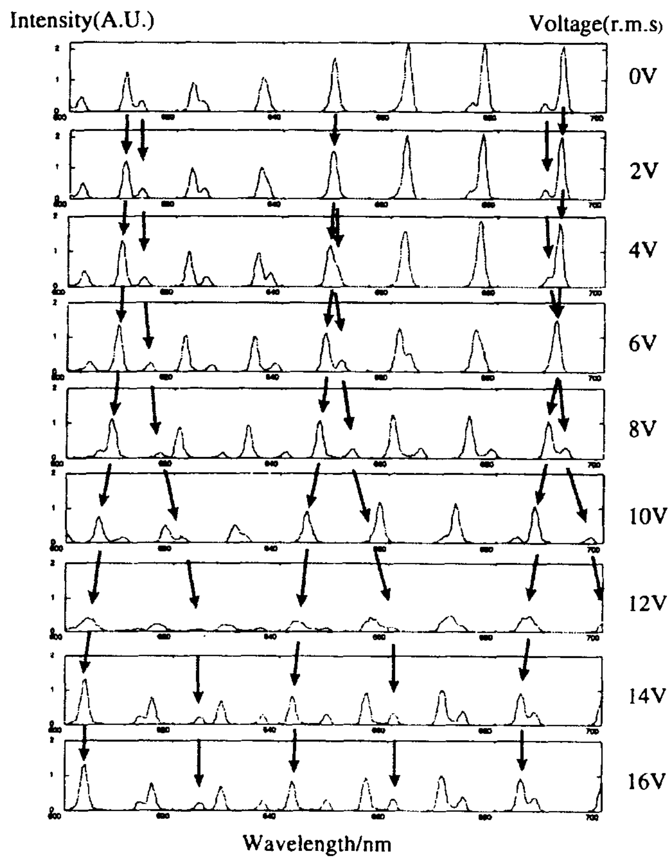

Figure 2 Shift of the resonant peaks under an applied 100Hz AC square wave electric field with incident light polarised perpendicular to the optic axis of the DHFLC ($n = n_{o(eff)}$). The peaks shift to the left correspond to resonance wavelengths where $n = n_{o(eff)}$. The small peaks shift to the right correspond to resonance wavelengths where $n = n_{e(eff)}$.

scanned using a white light source (Tungsten Halogen lamp) and an optical spectrum analyser (6100 series, Rees Instruments) at room temperature. The incident light was polarised perpendicular to the direction of the effective optic axis (refractive index = $n_{o(eff)}$) for the 'off' state. Figure 2 shows the shift of the resonant wavelengths under an applied 100Hz square wave electric field. The resonant wavelengths corresponding to n = $n_{o(eff)}$ decreased (shifted to the left) as the voltage increased due to the decrease in the value of $n_{o(eff)}$. At the same time there were also small resonant peaks due to $n_{e(eff)}$ that appeared alongside the major peaks due to $n_{o(eff)}$. These small peaks shifted to the right as the voltage increased due to the increase in $n_{e(eff)}$. On the other hand, when the incident light was polarised parallel to the optic axis for the 'off state', small resonant peaks due to $n_{o(eff)}$ appeared alongside the major peaks due to $n_{e(eff)}$. The appearance of these small peaks was probably due to the misalignment of the liquid crystal, this however will require confirmation by further investigation. The wavelength tuning stopped for voltages above the unwinding voltage (12V) where the helix was completely unwound. The distortion of the spectrum at the unwinding voltage was caused by the large increase in the response times due to the unwinding of the helix.

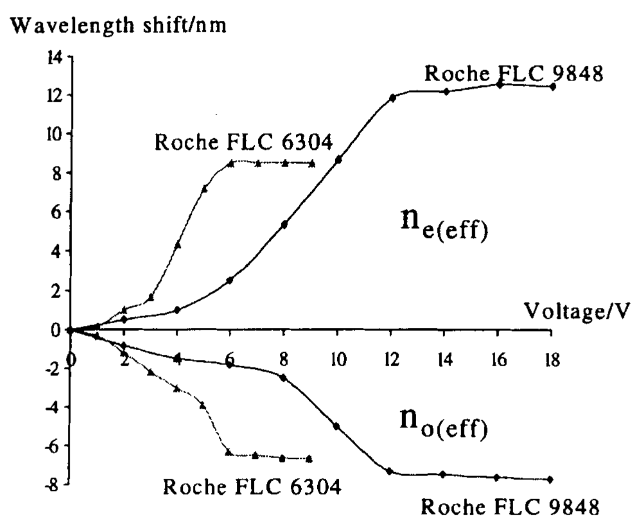

FIGURE 3 Comparison of the wavelength shift for Roche FLC 9848 and Roche FLC 6304 for wavelengths around 640nm.

Figure 3 shows a comparison of the wavelength tuning for the two DHFLCs of different pitch lengths with cavity thicknesses of 10μm. The wavelength tuning range was found to be higher for the shorter pitch material (Roche FLC 9848). This was due to the fact that the shorter pitch material had a higher tilt angle (cone angle) of 31° compared with 27° for the longer pitch material (Roche FLC 6304), which resulted in a larger change of refractive index from the initial 'off state' to the completely unwound state and hence a larger tuning range.

2) Using a laser:

Figure 4 shows the optical transmission of a DHFLC Fabry Perot etalon to a polarised He-Ne laser under the application of a pulsed voltage at room temperature. The light was polarised along the effective optic axis (refractive index = $n_{e(eff)}$) of the liquid crystal, Roche FLC 9848, with cavity thickness of 10μm. The operation of the DHFLC etalon can be described using the diagram shown in figure 5 which shows the variation of transmission of the etalon with the refractive index of the liquid crystal around a resonant peak. In the following, the term ON will be used to define the state when the device is 'on' resonance and similarly the term OFF will be used to define the 'off' resonance state. The device above was switched from OFF to ON (OFF/ON) under the applied pulsed voltage of 7.5V due to the increase in refractive index and was switched back from ON to OFF (ON/OFF) with the removal of the voltage as indicated in figure 5. The device thus behaved as an optical switch. Response times were the times, measured from the time when the applied voltage was changed, required to give a 90% change in the optical transmission. The measured OFF/ON response time was 186μs whereas the ON/OFF response time was 12μs. The latter response time was remarkably shorter since, as will be explained, it has been shortened compared with the former by the use of the Fabry Perot cavity. In general, it has been found that the response times for ON/OFF are often much shorter than the corresponding OFF/ON response times. Such asymmetry was observed before for other types of liquid crystal Fabry Perot etalons[9]. This can be explained by referring to the transmission characteristics of a high finesse Fabry Perot etalon as shown in figure 5. It can be seen from the figure that, for a 90% change in transmission, the ON/OFF response time is equal to only a fraction of the time required to switch the molecules from the initial ON state to the final OFF state, whereas the OFF/ON response time is almost the same as the time required to switch the molecules completely from the initial OFF state to the final ON state and thus is not reduced by the use of the cavity. However, using the transmission characteristics alone, we expected the optical rise time (10-90%) for OFF/ON to be similar to the fall time (90-10%) for ON/OFF. This was however not the case as the rise time for OFF/ON was clearly much longer than the fall time for ON/OFF. This can be understood using the fact that in both OFF/ON and ON/OFF cases, the DHFLC molecules moved very fast initially due to an initially high torque (from the electric field in the former case whereas associated with the release of the elastic energy stored in the deformed helix in the latter) acting on them but then slowed down before reaching the final positions as the torque diminished. Hence, the rate of refractive index change

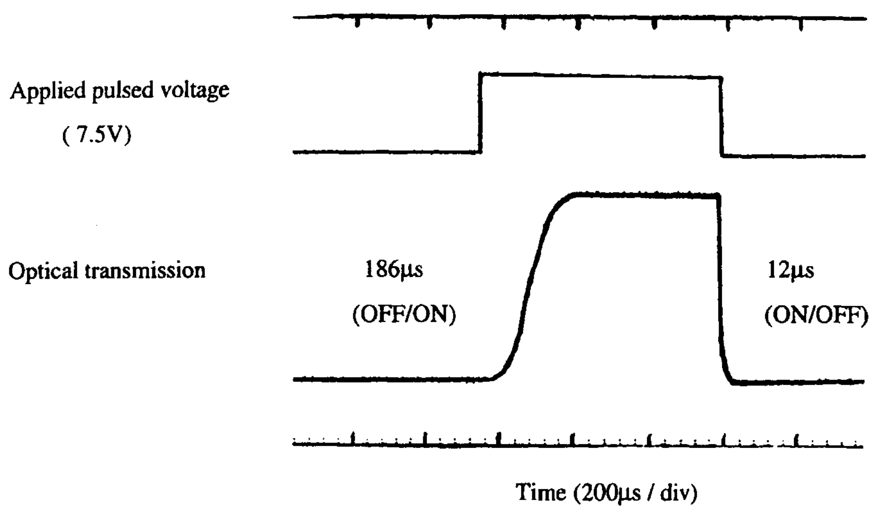

FIGURE 4 Optical transmission of a DHFLC Fabry Perot etalon under an applied pulsed voltage of 7.5V. (Biased at 1.2V. Cavity thickness = 10μm. DHFLC = Roche FLC 9848)

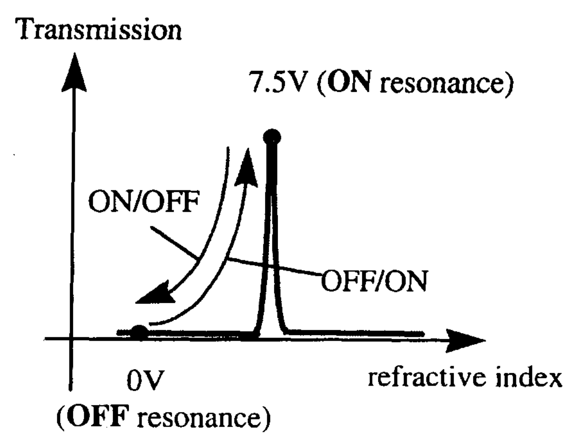

FIGURE 5 Diagram showing the operation of the etalon in figure 4 using the variation of transmission with refractive index in a DHFLC Fabry Perot etalon around a resonant peak.

also varied in the same manner. In the case of ON/OFF switching, the change of the optical transmission occurred during the initial stage of the switching where the DHFLC molecules moved very fast and thus resulted in short optical fall time. However, in the case of OFF/ON switching, the change of the optical transmission occurred mainly at the final stage of the switching where the molecules moved relatively slowly towards the final positions and hence the rate of transmission change was also much slower leading to the long optical rise time.

It is possible to make the OFF/ON and ON/OFF response times more symmetrical by switching from a point which is very close to the foot of a resonant peak. However, the amplitude of the applied voltage must then be reduced in order to avoid 'overshooting' of the transmission maximum, i.e. to maintain the final switching state at the top of a resonant peak. Therefore, the values obtained are not particularly fast due to the low applied voltage and the fact that the times are not reduced by the use of the cavity.

Although we have shown the case where the pulsed voltage switched the device from OFF to ON resonance, similar observations and results also applied for the case when the pulsed voltage was used to switch the device from ON to OFF resonance. In this case the ON/OFF response time referred to the optical response when the pulsed voltage was applied whereas the OFF/ON response time corresponded to the optical response when the voltage was removed. Again the ON/OFF response times were always much shorter than the corresponding OFF/ON response times.

In general, the ON/OFF response times of DHFLC etalons filled with shorter pitch Roche FLC 9848 were between 10 to 30μs and the OFF/ON response times were between 100 to 300μs with applied voltages < 10V. For devices filled with the longer pitch Roche FLC 6304, the ON/OFF response times and OFF/ON response times were often about 10μs and 100μs respectively slower than the times obtained for devices filled with the shorter pitch DHFLC This is believed to be due to the slower intrinsic response of the longer pitch DHFLC.

For the faster material contrast ratios of between 30:1 to 50:1 were measured using a photomultipler.

CONCLUSION:

We have shown that, by increasing the finesse of DHFLC Fabry Perot etalons with the use of highly reflective dielectric mirrors, significant reduction in the response times can be achieved with values in the order of 10μs under applied voltages of <10V when the devices are used as optical switches. However, the improvement in response times only applies to the responses where the transmissions are switched from ON to OFF (ON/OFF) resonances. Furthermore, we have shown that the wavelength tuning range can be increased by the use of a DHFLC with a higher tilt angle since a larger change of refractive index resulted under applied electric fields.

ACKNOWLEDGEMENT:

Prof. J.Funfschilling of Rolic, Switzerland is sincerely thanked for supplying the DHFLC mixtures for our research purpose. W.K.Choi gratefully acknowledges the receipt of the Hong Kong Croucher Foundation Scholarship.

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