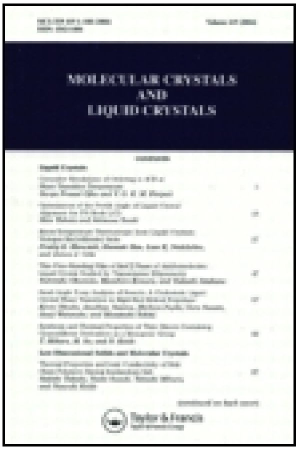

Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl19

Liquid Crystal Diffractive Elements

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Version of record first published: 24 Sep 2006.

To cite this article: Ian Mason & Guy Bryan-brown (1996): Liquid Crystal Diffractive Elements, Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals, 282:1, 331-342

To link to this article: http://dx.doi.org/10.1080/10587259608037587

Mol. Cryst. Liq. Cryst., 1996, Vol. 282, pp. 331–342
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LIQUID CRYSTAL DIFFRACTIVE ELEMENTS

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Abstract Liquid crystal phase effect devices have been an area of interest for some time. Our studies have involved creating phase effect diffractive elements and investigating their physical properties. These devices have been shown to possess high diffraction efficiencies at short wavelengths and to have short switching times. The research has included theoretical work which has shown very good agreement with our observations.

INTRODUCTION

There are many applications for switchable beam elements in optical systems[1]. These include switchable diffractive elements[2]. The use of liquid crystals in phase effect devices is well known[3] although primarily in displays of some sort. There are descriptions of diffraction based devices which have been constructed in order to have certain wavelength responses[4]. In this paper we outline the work done at DRA on designing, fabricating and assesing a novel design of liquid crystal device. Our devices use phase effects to provide the diffractive outcome. I shall describe our experiments and elaborate upon the success of our models in explaining the results we have obtained. I shall then discuss the areas where further research is required in order to achieve a more full understanding of our devices.

Theory

A simple analysis of a diffractive element proceeds as follows.

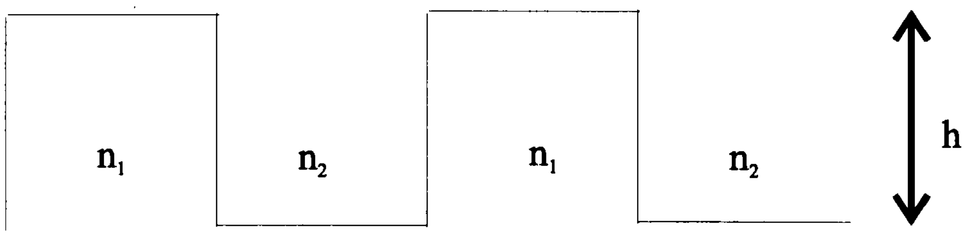

FIGURE 1 A simple phase grating

The grating illustrated has a depth h and consists of two regions having different refractive indices n_1 and n_2. Consider a plane wave impinging upon the grating at normal incidence. The emerging wavefront consists of regions of different phase. This phase difference Γ is given by[5].

$$\Gamma = h \times (n1 - n2) \quad (1)$$

If Γ is equal to $\lambda/2$ (where λ is the wavelength of the incident light) then the two portions of the wavefront will produce destructive interference in the zeroth order. This is well known and fuller explanations may be found elsewhere in the literature[5]. A nematic liquid crystal posses anisotropic refractive indices and this may be utilised in a switchable device to produce the above effects.

Cell fabrication

Our cells were constructed as shown in figure 1.

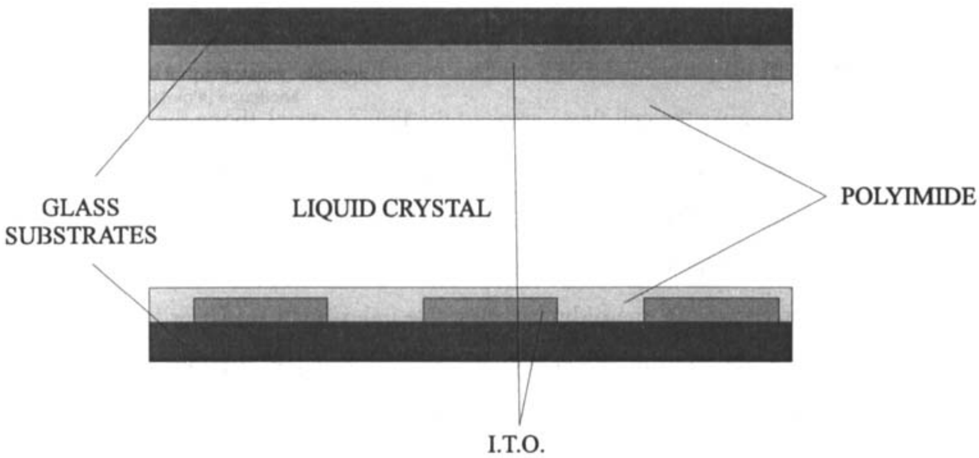

FIGURE 1 Phase grating cell

Indium Tin Oxide on a glass substrate of the type generally used in the fabrication of liquid Crystal cells was etched by ion beam milling to give a series of electrodes. The surface of this substrate was planarised by spinning down a polyimide layer which was then prepared and rubbed as normal for L.C. cell fabrication. The rubbing direction was set to be orthogonal to the I.T.O. electrode direction. An upper layer was prepared from a glass with I.T.O. substrate to which was added a polyimide layer which was rubbed as usual. A cell was then constructed from these two prepared substrates with the two rubbing directions set to be anti-parallel. Typically the track pitch was 10μm with cell thickness varying between 1.5 - 10μm. Once assembled, the cell was filled with Merck nematic liquid crystal BL036 and cell switching was investigated.

Cell characteristics

Our investigations of cell switching characteristics looked at three major features. These were the static and dynamic switching properties and also the behaviour of the diffracted orders. The mode of operation was designed to be the following.

With zero volts applied to the cells, all polarisations of light see a uniform refractive index in all parts of the cell and so no diffraction will take place. When a voltage is applied across the cell those areas of the liquid crystal above the I.T.O. switch from planar homogeneous to homeotropic, whilst the other areas remain homogeneous. That is the director becomes orthogonal to the plane of the cell substrates above the I.T.O. strips. Light polarised orthogonal to the cell rubbing direction still interacts with a uniform refractive index (the ordinary refractive index n_o). However light polarised along the rubbing direction of the cell sees a refractive index difference between the switched and unswitched areas of the cell and so a phase grating is apparent to it, and diffraction will occur

Static characteristics

Cells were set into our optical bench as shown in the diagram.

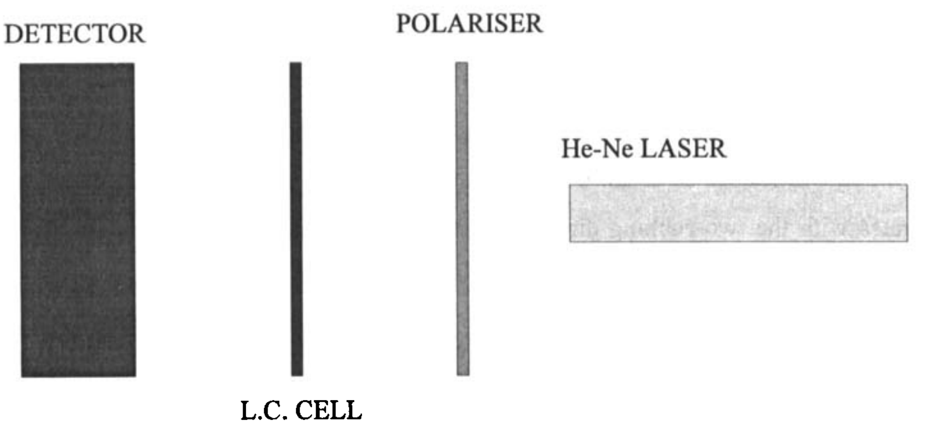

FIGURE 2 Optical bench setup

The He-Ne was of a power of 4mW at 632.8 nm. The detector was set sufficiently far from the cell such that only the zeroth diffracted order was incident upon it. The polariser could be rotated to control the polarisation of the light incident upon the liquid crystal cell. A signal of a set frequency was then applied across the cell. The signal amplitude was varied and the optical throughput monitored.

Static results.

An example of the results obtained when the polarisation direction of the light incident on the cell was set to be along the cell rubbing direction is shown in the graph below. The voltage is the rms value. At zero volts the insertion loss is mainly due to reflections. A threshold can be noted at 1.2 volts, after which there was a rapid drop in transmission with increasing voltage. After this point the optical throughput rises, it may be inferred that after this point the phase delay is greater than is necessary for destructive interference.

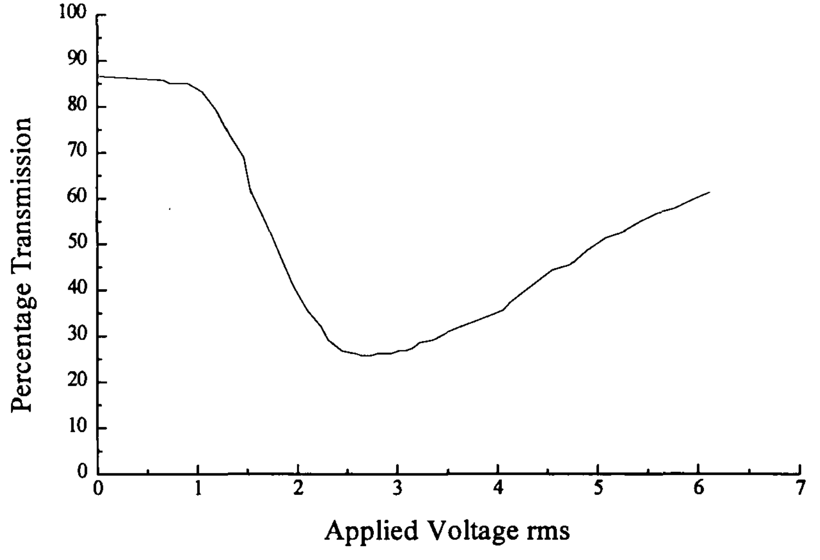

FIGURE 3 Static characteristics of a typical 1.5 μm thick phase grating cell.
(polarisation of the incident light along the cell rubbing direction)

When the polarisation direction of the incoming beam was set to be orthogonal to the rubbing direction of the cell the change in transmission with voltage was insignificant. Thus it is demonstrated in this experiment that diffraction occurs for only one polarisation of incoming light.

Other diffracted orders

The intensity of the light diffacted into the higher orders was also tested as a function of voltage. This gave results as shown in figure 4.

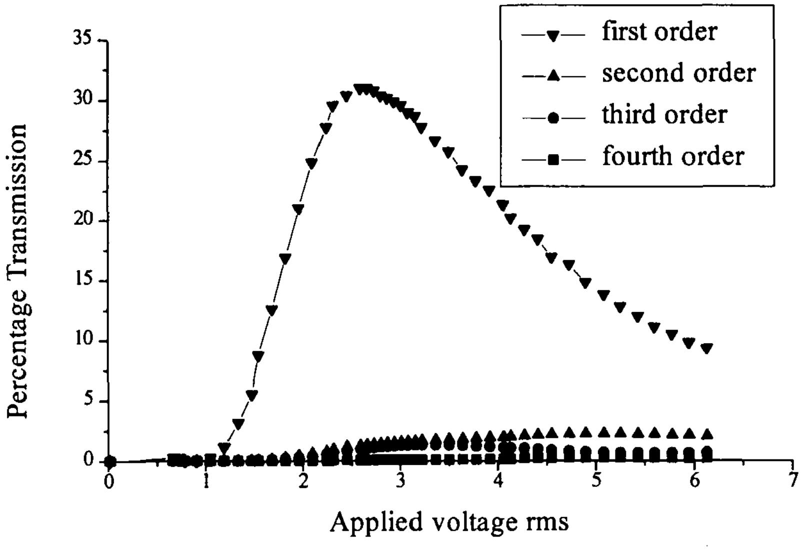

FIGURE 4 Transmission of higher orders as a function of voltage.

It was noted that the behaviour between the orders was not uniform. That is the shape of the response of each of the orders did not follow the same pattern. It was especially noted that in many cases as a voltage was applied the odd diffracted orders appeared first followed by the even orders. The appearence of only odd orders in the diffracted light is consistant with a square phase profile as shown in figure 5. At higher voltages, fringing fields occur in the structure and the square phase profile is lost, and hence the even orders appear in the pattern.

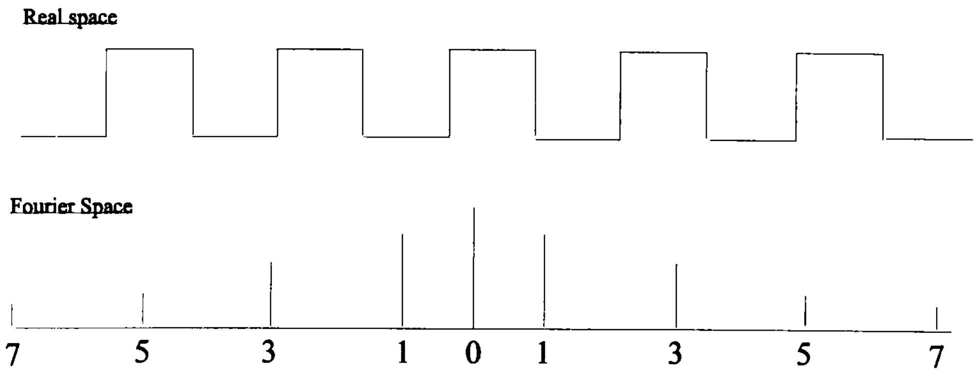

FIGURE 5 Fourier transform of a square profile grating

Wavelength response of the cells

These tests used a Perkin - Elmer Lambda 9 spectrophotometer to scan the wavelength of light incident upon the cell. The light was polarised along the cell rubbing direction and that none of the diffracted beams could enter the sample chamber beam exit ports. Plots were obtained of the wavelength response of the cells with and without voltages applied.

Theoretical considerations

Consider the simple system shown below in which we define a transmission function T(λ). where the light output is defined as[6].

$$I = T(\lambda)I_0 \qquad (2)$$

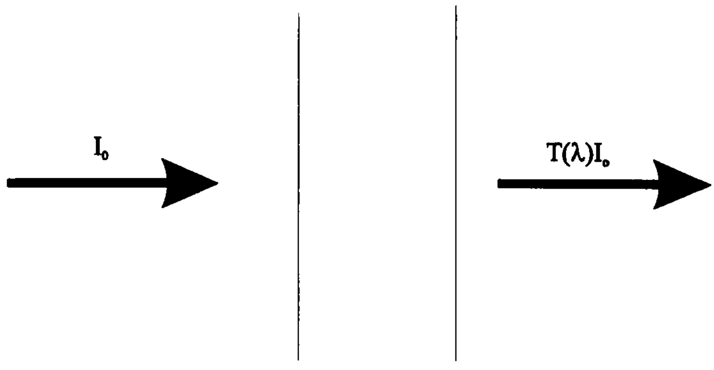

FIGURE 6 Optical transmission function

If the transmission function is describing a diffraction grating then the intensity transmitted in the zeroth order depends upon the profile of the grating over one period which may be represented by a function S(x) over one period of the grating $0 \le x < d$. Using the Kirchhoff approximation the transmission function is given by[7].

$$T(\lambda) = \left| \frac{1}{d} \int_0^d \exp\left[\frac{2\pi i S(x) \Delta n}{\lambda} \right] dx \right|^2 \tag{3}$$

Where Δn is the refractive index difference between the switched and the unswitched parts of the cell. As mentioned earlier it has been found that the gratings switch through a point where a square grating profile is obtained. The voltage at which this occured was noted. This square profile can be modelled in the above equation by setting:

$$S(x) = \begin{cases} 0 \to 0 \le x < d/2 \\ h \to d/2 \le x < d \end{cases} \tag{4}$$

This may be shown to be resolved as:

$$T(\lambda) = \cos^2\left(\frac{\Delta n \times h \times \pi}{\lambda}\right) \tag{5}$$

The following is an example plot fitted to the $\cos^2$ function.

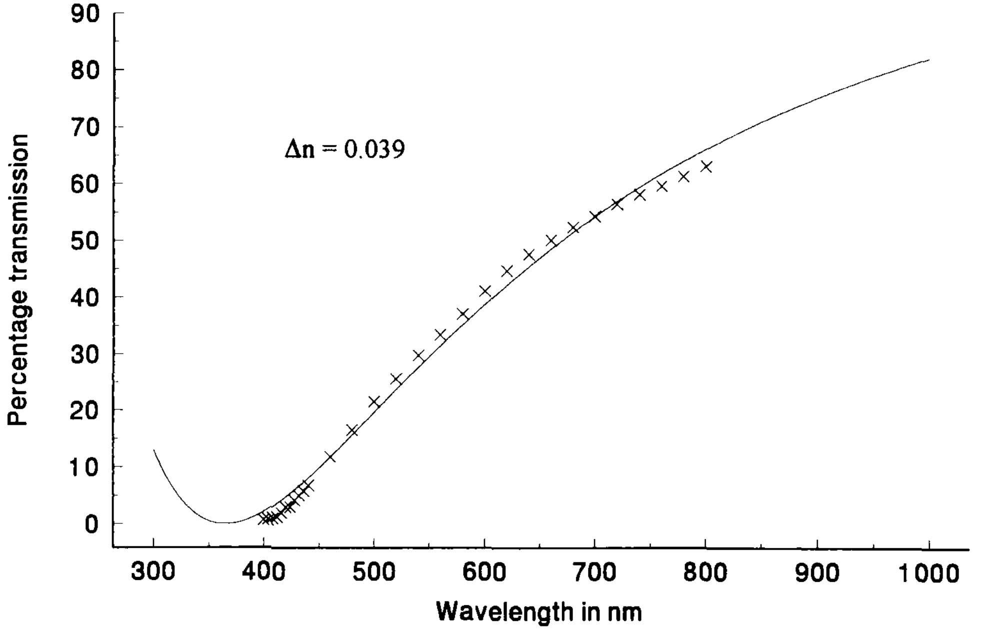

FIGURE 7 Response of a typical phase grating cell (thickness = 1.5μm)

It would appear that at the voltage setting required to produce the lowest cell throughput we were not accessing the full potential birefringence of the liquid crystal used in these devices (BL036, Δn = 0.27 @ 550 nm). The effects of higher voltages is an area requiring further investigation.

The fit of the theoretical curve shows that our simple theory has some merit, but since the theory presumes very simple behaviour of the liquid crystal in the switched cell there remains much to be done in terms of theory. This would especially relate to attempting to model the liquid crystal director profile during switching and relating this to the refractive index profile in the cell. It is highly unlikely that at higher voltages we are maintaining the square profile we have modelled and future work shall consider this point.

Dynamic response

Dynamic response was measured at several wavelengths using the apparatus in figure 2. The laser throughput with no cell in the system was used as our 100% transmission value. The cell was then placed into the beam such that the input polarisation direction was along the cell rubbing direction. The signal applied to the cell was set to switch between some arbitrary voltage and ground at a set frequency. By this it is meant that for example the signal switched between ground and 20v r.m.s. 1kHz sine wave at a frequency of 1Hz. The optical throughput of the cell was monitored as the signal was switched on and off and response times measured at 632.8, 543 and 441 nm by using He-Ne and He-Cd lasers.

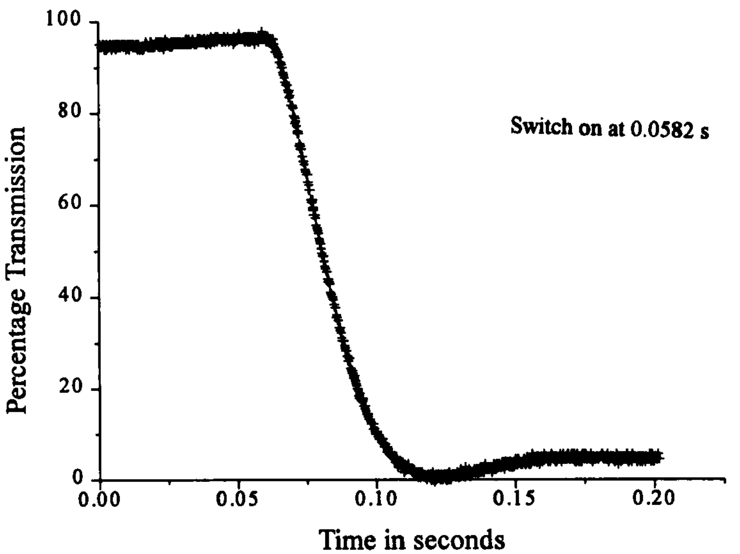

FIGURE 8 Response of a 1.5μm cell at 441 nm to 4 v applied at t=0.0582 s

As can be seen the response is very rapid and gives a maximum optical density of 3.15. Due to the mismatch of Δnd with $\lambda/2$ the transmission rises again after this minimum to 5% transmission.

The dynamic response can be modelled in the following way. It is assumed that the effective refractive index changes with time in a similar way to the charge on a capacitor during charging with the cell attaining a final refractive index mismatch of Δn_{final} and possesing a time constant τ. This will be therefore:

$$\Delta n_{eff} = \Delta n_{final}\left(1 - \exp^{\frac{-t}{\tau}}\right) \qquad (6)$$

This Δn_{eff} may be substituted directly into the $\cos^2$ equation and typical results are shown:

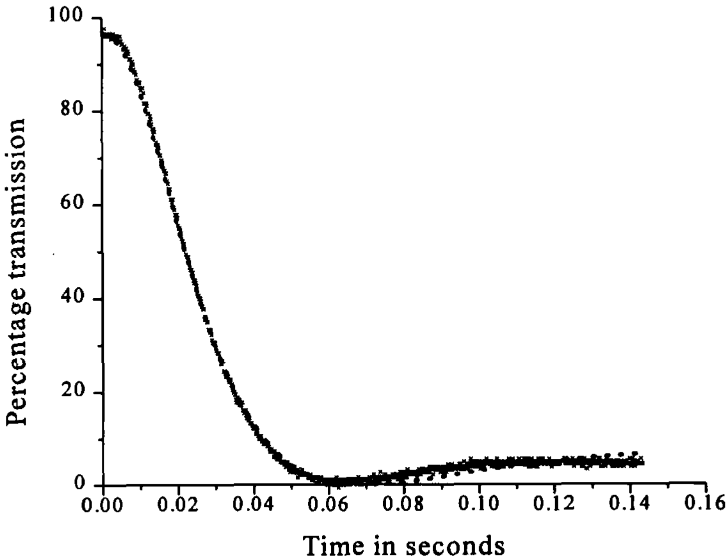

FIGURE 9 Response of a 2μm thick cell fitted to dynamic model

The model fit above gave a Δn_{final} of 0.13 and a time constant of 35 ms. Note that in the above graph the drive voltage was applied at t = 0.

CONCLUSION

Our work has been successful in modelling cell characteristics based on a simple geometrical diffraction theory. The diffraction patterns observed suggest that a simple square grating profile only exists at lower voltage levels. Both the static and dynamic cell response at a given wavelength suggest that the effective birefringence within our cells is 0.13. The liquid crystal used in these studies has a birefringence of 0.27 at visible wavelengths.

These observations suggest that significant switching is occuring in the inter-electrode gap. In the present device configuration we would expect to experience notable electrode edge effects leading to fringing fields. The presence of fringing fields accounts for the observed anomalous birefringence.

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ACKNOWLEDGEMENTS

The authors would like to thank all the members of the liquid crystal research group at DRA Malvern. Our thanks go especially to Graham Monnington and Peter Brett for cell construction and to Carl Brown for discussions on the theoretical aspects of this work.