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# The director structure and electroclinic fast optical switching in a grating-coupled ferroelectric smectic liquid crystal cell

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Optical excitation of guided modes in a liquid crystal layer using grating-coupling gives sharp features in the angle-dependent reflectivity data. These features are strengthened by using a metallized grating to enhance coupling to the guided modes in the liquid crystal. In the present study the liquid crystal has a smectic A phase which exhibits fast electroclinic switching. Combining the sharp features in the reflectivity together with the electroclinic effect leads to fast, high contrast, optical switching which may open up potential for novel device structures.



## 1. Introduction

The optical excitation of waveguide modes in thin liquid crystal layers provides a powerful procedure for characterizing the details of director structure within the layer. Such studies have, for example, been used to explore the influence of different surface aligning layers [1–5] or the response of the director to applied electric fields [6–10].

Fitting angle-dependent reflectivity data obtained with prism coupling to model reflectivities predicted from proposed director profiles, gives very detailed information on the director structure through the cell. In addition, because the reflectivity is primarily controlled by the liquid crystal, then application of such liquid crystal waveguides in switchable optical devices has also been realized. However, for most practical applications the use of a bulky coupling prism is unacceptable, and its replacement by grating coupling as a means of exciting the waveguide modes within the voltage controllable liquid crystal layer may be favoured [11, 12]. Grating coupling is compact and may be used conveniently over large cell areas.

In addition to their role as light couplers, the gratings may also be used as aligning agents for the liquid crystal. While some work has been undertaken in this area [12–16] it is only in the last few years that theoretical optical modelling has been developed sufficiently to combine gratings with anisotropic liquid crystal layers [17–21]. Such modelling development allows the comparison of the optical response of grating-coupled liquid crystal cells with model theory, thereby giving the director structure in such cells in which the gratings also significantly affect the optical response.

Possibly the fastest optical response we may consider finding with a liquid crystal cell is optical switching using the electroclinic effect [22, 23]. We have already reported results of guided mode studies of this effect [8, 9] using prism-coupling; here we explore the effect in a grating-coupled structure. The cell to be studied contains a smectic A* liquid crystal aligned with rubbed polyimide and a grating. By suitable choice of geometry, sharp maxima are found in the angle-dependent polarization conversion (Transverse Electric, *s*, to Transverse Magnetic, *p*) reflectivity signals, which move in angle when a field is applied across the liquid crystal layer. Such an arrangement lends itself to high contrast, fast switching. Thus this study not only provides an exploration of the electroclinic effect in a smectic A* liquid crystal using grating-coupling to guided modes in the liquid crystal layer, but also it allows an examination of fast switching device potential.

## 2. Experimental

The cell geometry used in this study is illustrated in figure 1. Key to this structure is the bottom plate which has on its inner surface a gold diffraction grating of pitch 461.4 nm and groove depth 36.0 nm. This grating does not provide alignment; it is quite shallow and close to sinusoidal, having been produced interferographically in photoresist which is then overcoated with an opaque, ~150 nm thick, gold film by evaporation. This gold grating then acts as both an optical mirror and the lower electrode in the cell. The upper glass plate is of index 1.461 (at 632.8 nm wavelength), which is lower than that

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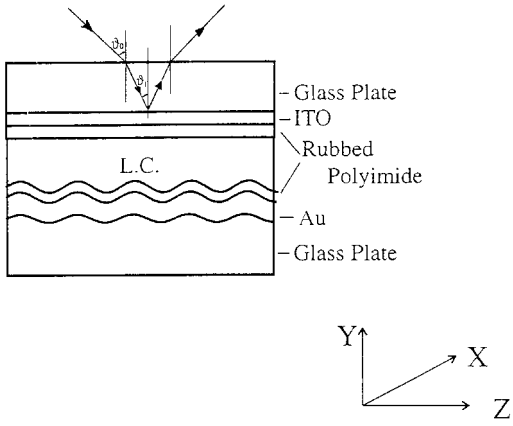



Figure 1. The liquid crystal cell structure used in this experiment.

of the liquid crystal. Thus the liquid crystal layer is in a true-guiding situation for light which may be totally internally reflected at the upper liquid crystal/low index glass interface and mirror reflected at the lower metal surface. The upper glass plate also has a thin (~50 nm) transparent indium tin oxide layer on its inner surface to act as the upper electrode. Both the upper flat plate and the gold grating are coated with a thin layer of polyimide (~30 nm), which does not planarize the grating since the layer is so thin and the grating pitch relatively long.

This polyimide layer is rubbed to provide alignment, the rubbing direction being the same on both surfaces and collinear with the grating grooves. To avoid damaging the gold layer, this rubbing was conducted quite gently and the polyimide is therefore expected to give weak anchoring [24, 25]. The two plates are assembled together in a clean room using ~3.5 μm thick mylar spacers with the rubbing directions antiparallel. This empty cell is then heated in vacuum to a temperature at which the chosen liquid crystal will be in its isotropic phase. In this case the material is mixture A180693-2 (supplied by DERA Malvern) which is a difluoroterphenyl host system with 10% of chiral dopant. This material is then contacted to the hot empty cell, capillary action causing it to flow into and fill the cell. The cell is then cooled to room temperature, briefly examined optically and transferred to the angle-dependent reflectivity monitoring equipment.

The completed cell is placed into a temperature controlled environment on a computer controlled rotatable table. With the grating grooves perpendicular to the plane of incidence so that the diffracted orders will all lie in this plane, the zeroth order reflectivity is monitored as a function of angle of incidence for linearly polarized radiation of wavelength 632.8 nm from a He-Ne laser. The first sets of data are recorded with the sample in the isotropic phase (114°C). Comparing both the s-polarized reflectivity data $R_{ss}$, and the p-polarized reflectivity data $R_{pp}$, with modelling theory, will for this simple isotropic phase yield several of the cell parameters. Fitted data for $R_{ss}$ at 114°C are shown in figure 2.

The sample is now cooled slowly (< 10°C $h^{-1}$) through the N* phase (104°C to 94°C) into the SmA phase giving a well aligned monodomain and further data are then recorded. Figure 3 shows data taken at 60°C in the form of the polarization conversion reflectivity signal $R_{sp}$ (s-polarization incident, p-polarization detected). This signal arises purely from twist and tilt of the director in the cell and is thus sensitive to the director profile. We also show in figure 4 the significant changes found in the $R_{sp}$ reflectivity at 60°C, when ± 20 V is applied to the cell; this allows the examination of the electroclinic effect. In addition to these scanned angle measurements, we have also undertaken measurements of voltage-dependent reflectivities at fixed angle. Setting the rotating table at

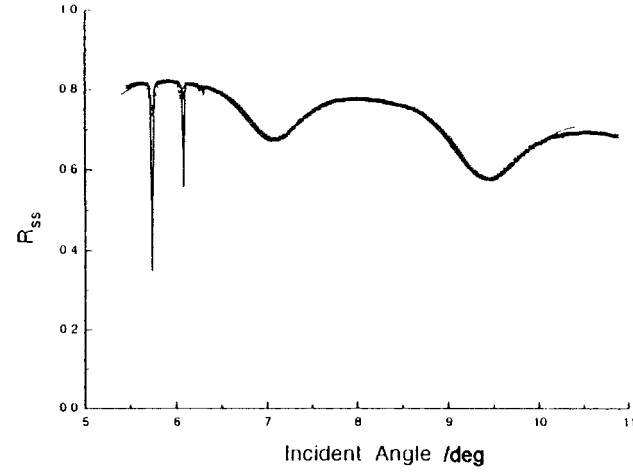



Figure 2. The reflectivity data $R_{ss}$ (crosses) in the isotropic phase and the theoretical fit (solid line).

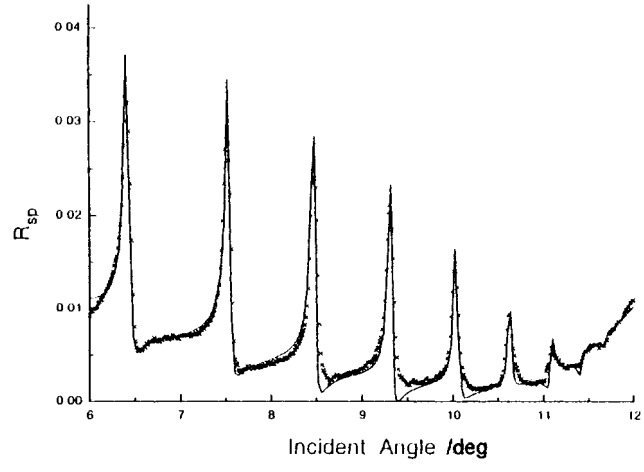



Figure 3. The reflectivity data $R_{sp}$ (crosses) in the SmA phase (60.0°C) and the theoretical fit (solid line).

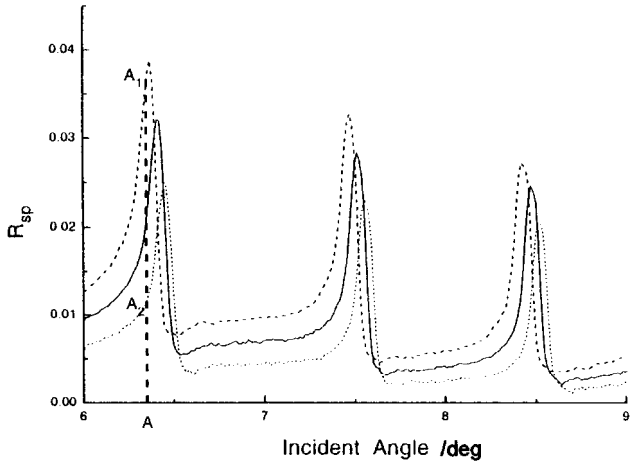



Figure 4. The reflectivity data $R_{sp}$ at 60.0°C for an applied voltage of +20 V (dotted line) and −20 V (dashed line), compared with the 0 V data (solid line).

an angle such that the detector is monitoring a strong resonance, for example, point A in figure 4, we applied a square wave electric field to the liquid crystal cell and monitored the temporal response of the optical reflectivity. Similar sets of data were also recorded at several temperatures in the SmA phase.

### 3. Results and discussion

In order to use the optical reflectivity data obtained from this cell to characterize the director profile in the liquid crystal, it is essential that the primary optical coupling surface, the gold diffraction grating, is well characterized. This is achieved before the cell is assembled by the optical excitation of surface plasmon–polaritons [26]. Fitting the angle dependent $R_{pp}$ reflectivity data for the gold grating surface to modelling theory, we find that it is a sinusoidal grating, having a groove depth of 36 nm with a pitch of 461.4 nm. (The gold is also characterized in this fitting and found to have an optical permittivity of $-9.8+$ il.28. This gold layer is opaque and thus is optically treated as being infinitely thick.) This grating is sufficiently deep to provide quite strong coupling of the incident radiation into guided modes in the liquid crystal layer. An examination of figure 1 reveals that light incident through the top plate may be diffracted by the grating into fully guided light in the liquid crystal. This guided light may then in turn be diffracted by the grating back into radiated light. The component of the wave vector of the diffracted light along the $z$-axis is given by:

$$k_z = n_0 k_0 \sin\theta_0 + \frac{2\pi}{\lambda_g}N = n_1 k_0 \sin\theta_1 + \frac{2\pi}{\lambda_g}N$$

where $\lambda_g$ is the grating period and $N = 0, \pm 1, \pm 2\ldots$, is the order of diffraction. It is clear from this that suitable choice of $\theta_0$ (angle of incidence) with the appropriate $N$, will couple light into guided modes thereby reducing the reflected intensity in the zero order beam. If the liquid crystal is characterized by an index $n_{LC}$ for light propagating exactly along the guide, then there is a range of incidence angles over which the guided modes for a particular order may exist.

$$k_0 n_{LC} > \left(k_0 n_0 \sin\theta_0 + \frac{2\pi}{\lambda_g}N\right) > k_0 n_1 .$$

In fact, since the effective index of the liquid crystal depends on the polarization and the angle of propagation, as well as being influenced by the optical properties of the thin boundary layers (ITO, polyimide), then the system is rather more complex than just described. Recently Harris *et al.* [21] developed a grating modelling theory to model the optical response of just such a complex structure. Using this modelling theory allows detailed comparisons between its predictions, based on an optical multilayer description of the system, and the experimental data. To help in fitting the data taken for the SmA phase, we first establish the boundary layer parameters by fitting the data obtained with the liquid crystal in the isotropic phase. Such a fit is shown by the continuous line in figure 2. This gives for the ITO layer a thickness of 50 nm with $\varepsilon = 3.2 + i0.015$, while the rubbed polyimide has a thickness of 26 nm and is strongly anisotropic with $\varepsilon_{\parallel} = 2.6 + i0.001$ and $\varepsilon_{\perp} = 2.0 + i0.001$, the uniaxial axis being along the rubbing direction.

With these parameters approximately established, we may then explore in detail the results from the SmA phase. When the plane of incidence is set perpendicular to the grating grooves, and with the expectancy that the liquid crystal director will be along the groove direction, we would anticipate no s to p conversion reflectivity signal. The data in figure 3, obtained with the sample at 60°C, show that this is *not* the case. This forces the conclusion that there is director tilt and twist out of the expected homogeneous alignment direction. Cooling the sample causes further increase in this s to p conversion signal.

From the multilayer diffraction grating theory incorporating uniaxial media for the present geometry, we find that the amplitudes of the sharp $R_{sp}$ modes are largely a direct measure of the director tilt from the overall plane of the cell, while the background level on which the modes sit is an indication of the director twist away from the grating groove direction. This background level is also sensitive to the birefringence. Beginning from a simple slab model for the director in the SmA phase, it was found that the only way a fit to the data could be achieved was by having both a twist away

from the grating groove direction and a finite director tilt. For example the data at 60°C require a twist of 4° and a tilt of 3°. In addition, two thin surface regions had to be introduced in which the director is different to that of the bulk of the cell. At 60°C these are approximated, on the ITO surface, as a 200 nm thick region with a tilt of 4° and a twist of only 2°. (This is probably a simplistic representation of a graded region.) On the grating surface, a region of thickness 200 nm is again modelled, but in this case with a reduced tilt of 2° and a twist of between 10° and 13°. In view of the gentle rubbing of this surface, one might expect rather weaker surface anchoring [24, 25] which will allow greater twist. However if the material is in the SmA phase then it is highly unlikely to twist by this amount, some 6° to 9° more than the bulk of the cell. This forces the conclusion that this particular ferroelectric liquid crystal adjacent to a grating surface aligns in a rather surprising manner.

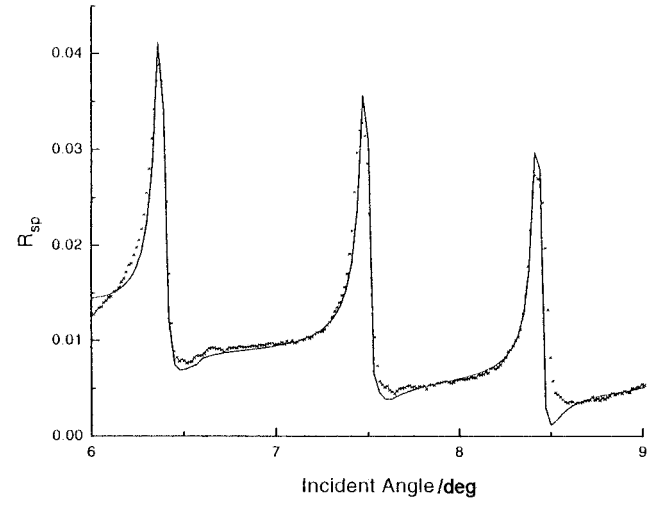
Now, with the cell in the SmA phase, voltages were applied, up to ± 20 V, between the gold and the ITO electrodes. The resulting electroclinic effect induces considerable changes in the $R_{sp}$ mode structure (see figure 4). Fitting the data for + 20 V (see figure 5) gives a director twist of 6°, out by 2° from the initial alignment direction. For the reverse field of – 20 V, the bulk director has a twist of only 1°, being then aligned by – 3° relative to the initial alignment direction. In table 1 we give the fitted director profiles at 60.0°C. At the lower temperature of 56.0°C, the director profiles for 0, + 20 and – 20 V applied field are given in table 2. In this case + 20 V twists the director at the centre of the cell by 6° while – 20 V twists it by – 6°.

From figure 4 it is clear that if the sample is set at some specific angle of incidence, such as A for example, then the application of a square wave electric field to the cell will produce a substantial change in optical intensity—a simple optical switch. The response time of this switch for temperatures from 57.0 to 60.0°C is of the order 2 μs. At 56.0°C, as expected on further temperature reduction, the switch time is about 5 μs. However at these lower temperatures, as is apparent from figure 6, the change of $R_{sp}$ with voltage is increased, thereby improving switching contrast. Thus for example, while at position A (figure 4) at 60.0°C there is a contrast of 3.2, at 57.0°C at positions B and B′, figure 6(*a*), there are contrasts of 8.7 and 15, respectively. Further reduction in temperature to 56.0°C, figure 6(*b*), gives contrasts of 27 and 33, respectively, for the two positions C and C′.

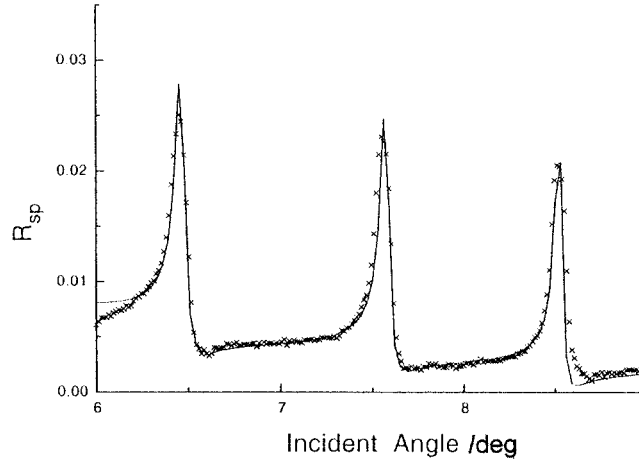
This cell thus illustrates the possibility of using grating-coupled polarization conversion modes together

Table 1. Director profiles required to fit the experimental reflectivity data at 60°C.

| Cell part | Twist/° | Tilt/° | Thickness/μm |
|---|---|---|---|
| $V = 0$ V | | | |
| Top surface layer | 2 | 4 | 0.2 |
| Main part | 4 | 3 | 3.68 |
| Bottom surface layer | 10–13 | 2 | 0.2 |
| $V = 20$ V | | | |
| Top surface layer | 3 | 4 | 0.2 |
| Main part | 6 | 3 | 3.70 |
| Bottom surface layer | 11 ~ 12 | 2 | 0.2 |
| $V = -20$ V | | | |
| Top surface layer | 1 | 4 | 0.2 |
| Main part | 1 | 3 | 3.70 |
| Bottom surface layer | 7 ~ 10 | 2 | 0.2 |




(*a*)

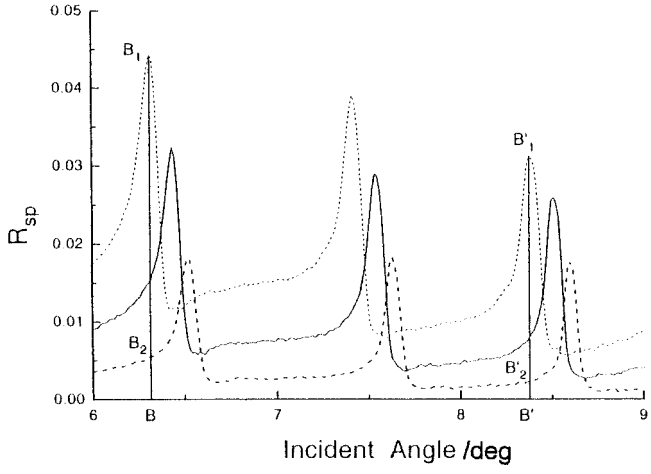



(*b*)

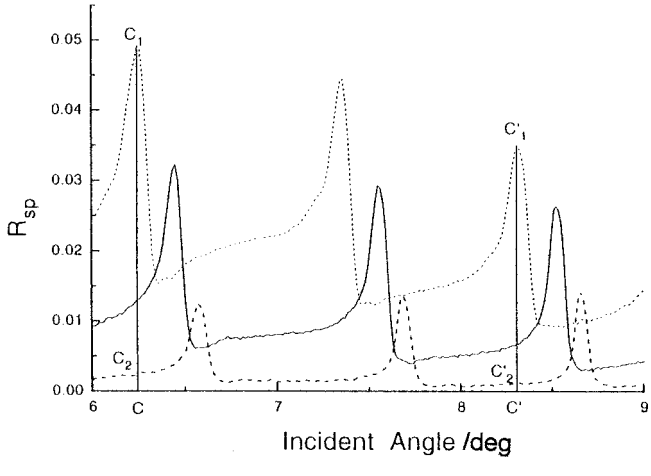
Figure 5. The reflectivity data $R_{sp}$ at 60.0°C for (*a*) + 20 V (crosses) and the theoretical fit (solid line), (*b*) – 20 V (crosses) and the theoretical fit (solid line).

Table 2. Director profiles required to fit the experimental reflectivity data at 56°C.

| Cell part | Twist/° | Tilt/° | Thickness/μm |
|---|---|---|---|
| $V = 0$ V | | | |
| Top surface layer | 2 | 4 | 0.2 |
| Main part | 4 | 3 | 3.73 |
| Bottom surface layer | 8 ~ 11 | 2 | 0.2 |
| $V = 20$ V | | | |
| Top surface layer | 6 | 4 | 0.2 |
| Main part | 10 | 3 | 3.73 |
| Bottom surface layer | 12 ~ 14 | 2 | 0.2 |
| $V = -20$ V | | | |
| Top surface layer | − 2 | 4 | 0.2 |
| Main part | − 2 | 3 | 3.73 |
| Bottom surface layer | 4 ~ 8 | 2 | 0.2 |




(*a*)




(*b*)

Figure 6. The reflectivity data $R_{sp}$ at (*a*) 57.0°C, (*b*) 56.0°C for 0 V (solid line) and voltages of + 20 V (dotted line) and − 20 V (dashed line).

with the electroclinic effect in a homogeneously aligned SmA phase to give quite high contrast, fast, optical switching.

## 4. Conclusions

Results are presented of the optical response of a smectic A liquid crystal aligned homogeneously with one surface being a highly reflective metal grating, and the other being transparent flat ITO. Optical coupling to sharp guided modes in the structure is via diffraction from the metallized grating. Angle-dependent reflectivity data are fitted using a multilayer optics grating theory incorporating an anisotropic liquid crystal. For the SmA phase, these results show strikingly that the majority of the cell does not align, as expected, along the rubbing direction, but is twisted off by about 4°. In addition there are then (≥ 200 nm) boundary regions. For the ITO surface there is probably a gradual twist from the initial alignment direction. For the grating surface a substantially increased (~ 10°) twist is found. These latter observations may suggest that there is a SmC* region in the proximity of the alignment surfaces.

On application of a voltage of ± 20 V across this 4.08 μm thick cell, a strong electroclinic effect is observed. This may be used, if the incidence angle is set correctly, to give good optical switching with high contrast and microsecond switching speed.

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