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Electroclinic effects in a homogeneously aligned smectic A cell

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The electroclinic effect, in a material having a first order S_A to S_C^* transition, is studied using the half leaky guided mode geometry. Using an approximately 1 μm thick, homogeneously aligned cell, the voltage induced director twist is characterized at a few temperatures in the S_A phase. The mean field theory readily explains the data recorded at low fields where a linear dependence on voltage is found. However, at higher fields, an unexpected saturation occurs which is most likely caused by the influence of strong surface anchoring forces.

1. Introduction

Since Garoff and Meyer [1,2] discovered the electroclinic effect in chiral smectic A (S_A^*) liquid crystals, the phenomenon has received substantial attention. This is primarily because the switching speed obtainable with this effect is normally some ten to one hundred times faster than that found with surface stabilized ferroelectric liquid crystals [3] and also because there is a simple linear relationship between the applied field and the induced twist angle [4]. In a homogeneously aligned cell, the electroclinic effect in the S_A phase manifests itself as a progressively increasing twist of the primary director out of the direction collinear with the density wavevector as, under the application of the field, the S_A phase transforms into the chiral smectic C (S_C^*) phase. This effect becomes more pronounced as the temperature of the sample approaches that of the S_A to S_C^* phase transition.

So far, there exist several theoretical treatments of the electroclinic effect [1–3]. With the inclusion of only the first order term in θ^2 in the Landau expansion of the free energy the induced tilt angle varies linearly with field and rises rapidly close to the phase transition. However, this first order approximation has only been shown to work [4–9] for low fields and temperatures some distance from the phase transition. With the advent of new materials with strong electroclinic effects, a non-linear electroclinic effect has also been observed [6–8]. Lee, Patel [9] and Abdulhalim and Moddel [3] present an exact analysis of the induced tilt angle with the inclusion of terms up to θ^4 in the Landau expansion of the free energy. This allows a quantitative description of the non-linear behaviour of the tilt angle at high fields and near the phase transition.

In this present study we examine the electroclinic effect using the very sensitive half leaky guided wave technique [10] with the material C7 in a thin homogeneously aligned cell.

2. Experimental

The sample geometry used in this work is illustrated in figure 1. An approximately 1 μm thick layer of chiral liquid crystal C7 is sandwiched between a high index glass plate ($n_1 = 1{\cdot}733$ at 632·8 nm) and a low index glass substrate ($n_2 = 1{\cdot}459$ at 632·8 nm). These two different index plates, which provide the required half leaky geometry, are coated with a thin (~ 50 nm) layer of transparent conductor (indium tin oxide, ITO). On top of these electrodes are deposited layers of polyimide and nylon for the high index plate and just nylon for the low

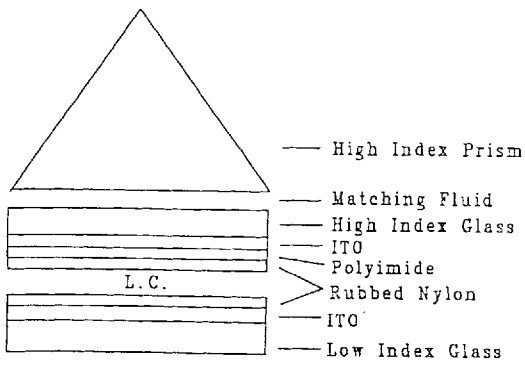

Figure 1. The sample cell construction used in the experiments.

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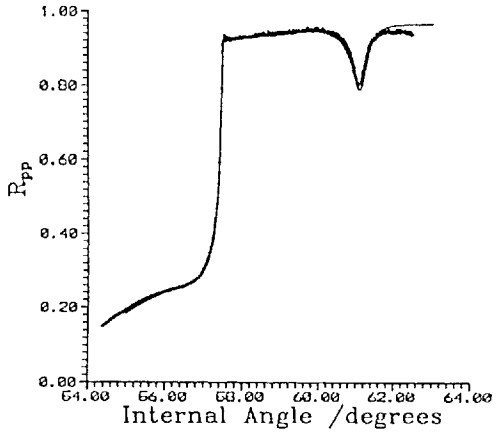
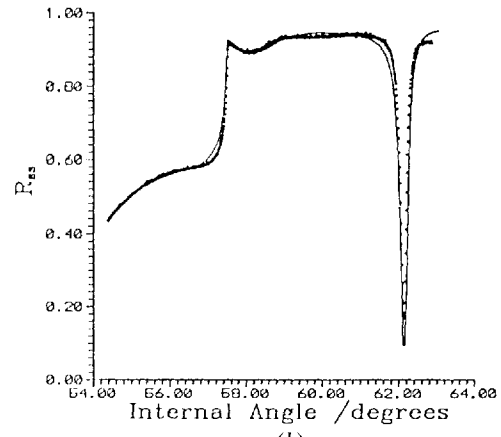
index substrate. The polyimide is there as an electrical buffer, while the two nylon layers are rubbed to provide low tilt homogeneous alignment of the liquid crystal. These insulating layers are expected to have a thickness of the order 25 nm. Once the two plates have been placed together in a clean room and the cell filled with C7, then the complete cell is placed into intimate optical contact with a high index prism using matching fluid.

This complete assembly is placed into a temperature controlled environment on a computer controlled rotating table and then heated into the isotropic phase (about 64°C). Then, following the procedure described in detail by Yang and Sambles [10], angle dependent reflectivities are recorded at a wavelength of 632·8 nm. In the isotropic phase, R_{ss} (s-polarized, transverse electric, input and output) and R_{pp} (p-polarized, transverse magnetic input and output) were recorded. These were then compared with modelling theory (see figure 2) to characterize the ITO, nylon and polyimide, as well as the isotropic phase of the liquid crystal.



(*a*)



(*b*)

Figure 2. Reflectivity data (*a*) R_{pp}, (*b*) R_{ss} (crosses) for the isotropic phase and theoretically fitted results (solid lines).

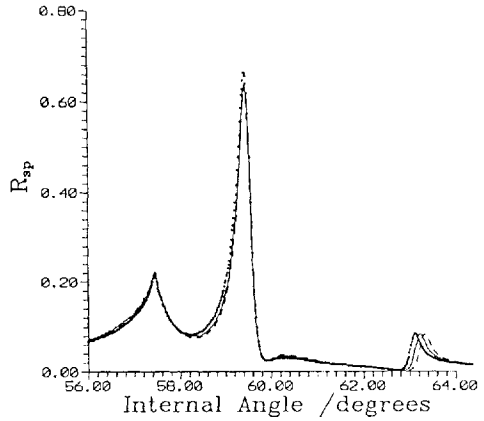


Figure 3. R_{sp} reflectivity data at 57·8°C as a function of the incident angle with no voltage applied (solid line), a DC applied voltage of 12·0 V (crosses) and a DC applied voltage of −12·0 V (dashed line).

Cooling slowly ($\sim 1{\cdot}0°C\,h^{-1}$) into the S_A phase gives a well-aligned mono-domain. Then with the rubbing direction of the cell aligned at 45° to the plane of incidence, both R_{ss} and the polarization conversion signal R_{sp} were recorded. The latter signal, which is very sensitive to director twist, is quite strong, peaking to about 60 per cent.

On applying a DC voltage to the cell, further angle dependent reflectivities are recorded and changes noted. In figure 3 we show three sets of R_{sp} data taken at 57·8°C at zero volts, and both plus and minus 12 V to illustrate the types of changes recorded. Full data sets were taken at six different temperatures in the S_A phase for voltages up to 20 V. In order to preclude any possible heating effects due to the large fields present in the cell, data acquisition time was minimized to 10 s for each angle scan.

3. Results

From the data recorded for the isotropic phase, together with multilayer optics modelling which gives theoretically predicted reflectivity curves to compare with data, we obtain the boundary layer parameters. From fits such as those shown in figure 2, we find the following sets of parameters: The ITO layer has a thickness of 49 nm with an optical permittivity of $\varepsilon = 3{\cdot}235 + i0{\cdot}018$, the polyimide film has a thickness of 20 nm with $\varepsilon = 2{\cdot}528 + i0{\cdot}001$, while the rubbed nylon film has a thickness of 26 nm and an anisotropic optical permittivity having values of $\varepsilon_{\parallel} = 2{\cdot}70 + i0{\cdot}001$ and $\varepsilon_{\perp} = 2{\cdot}17 + i0{\cdot}001$, with the uniaxial axis in the rubbing direction. From the rubbed nylon treatment, it is expected that the director of the S_A phase will be aligned homogeneously with perhaps a small surface tilt. Fitting the data at 57·8°C at zero volts with a uniform slab

model gives a director tilt of 2·2°, with the director aligned along the rubbing direction, a thickness of 0·96 μm and an optical permittivity of $\varepsilon_{\parallel}=2{\cdot}6081(\pm 0{\cdot}0002)+i0{\cdot}003(\pm 0{\cdot}001)$ and $\varepsilon_{\perp}=2{\cdot}2416(\pm 0{\cdot}0002)+i0{\cdot}00002(\pm 0{\cdot}00001)$ (see figure 4(*a*)).

Following this, data at finite voltages were fitted. It was found that fits were readily obtained by simply allowing the director in all of the cell to twist out of the initial direction in the plane normal to the electric field by the order of a few tenths of a degree. This director twist under the applied field is the induced twist. For example, at 57·8°C and 12 V an induced twist of 0·92° is required to fit theory to data, with no change in tilt (see figure 4(*b*)). Reversing the sign of the applied field simply reverses the induced twist direction (see figure 3). Fitting all the data thereby yields the induced twist angle at various voltages for the chosen temperatures. Figure 5 shows the voltage dependence of the induced twist for the six different temperatures, while figure 6 shows a selected set of data for a few chosen voltages.

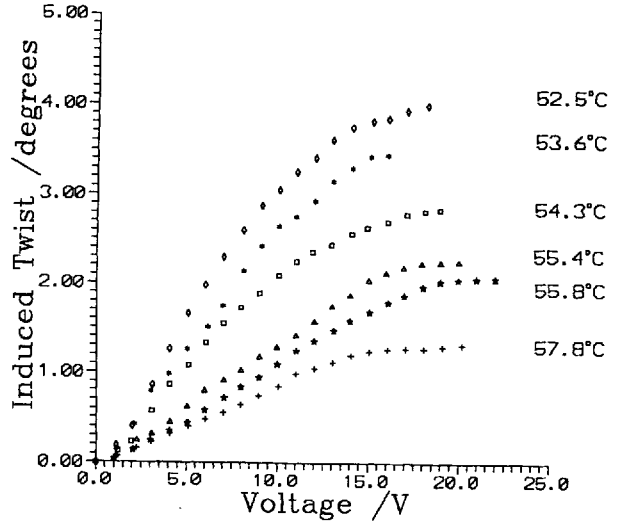


Figure 5. The voltage dependence of the induced twist for different temperatures in the S_A phase.

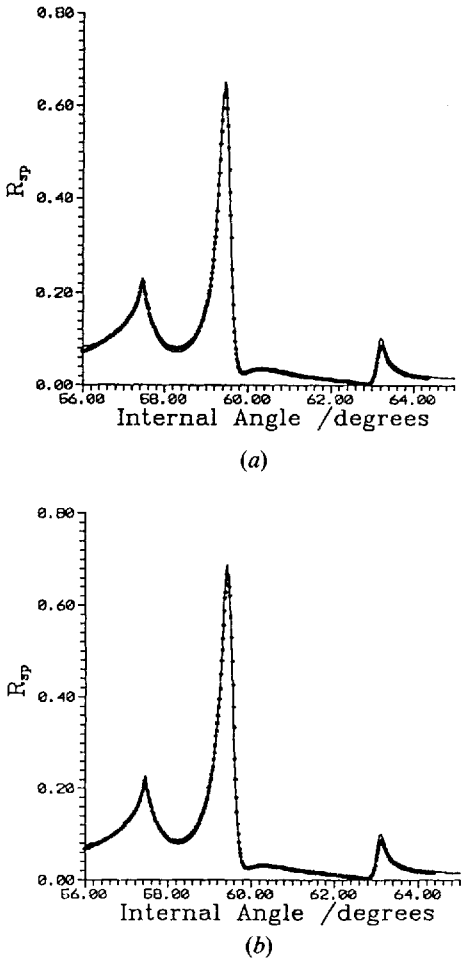


Figure 4. R_{sp} reflectivity data (crosses) at 57·8°C and theoretically fitted results (solid line) (*a*) for no voltage, (*b*) for a DC voltage of 12·0 V.

Examination of figure 5 reveals a linear dependence of the induced twist at low voltages, with a saturation occurring as the field is increased. Further, the closer the temperature is to the phase transition, the stronger the electroclinic effect, although as is apparent from figure 6, the increase as the phase transition temperature is approached is not that striking.

The linear dependence of the induced twist on applied field is readily explained in terms of Landau theory. Consider small induced twists θ; then expanding the free energy in terms of this twist we have

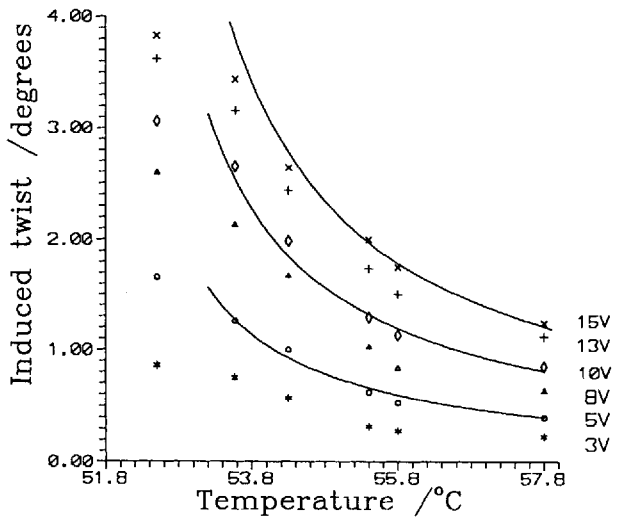


Figure 6. The temperature dependence of the induced twist for different voltages in the S_A phase.

$$F=\frac{1}{2}\alpha(T-T_c)\theta^2-\mu E\theta, \quad (1)$$

where T_c is the transition temperature, α is a mean field theory coefficient and μ is a structure coefficient which is dependent upon the material. Minimizing this simple free energy with respect to θ gives

$$\theta=\frac{\mu}{\alpha(T-T_c)}E=C_E E, \quad (2)$$

which describes the linear relationship between the induced twist and the electric field. C_E is normally called the electroclinic coefficient. This simple expression (2) may be expected to fit the data far from T_C and at low fields. Fitting the data of figure 5 in this manner gives for C7 a C_E at 52·5°C of $0{\cdot}563(\pm 0{\cdot}001)\times 10^{-8}\,\mathrm{m\,V^{-1}}$ and at 57·8°C of $0{\cdot}141(\pm 0{\cdot}001)\times 10^{-8}\,\mathrm{m\,V^{-1}}$. On the other hand, from equation (2) we have

$$\frac{1}{C_E}=\frac{\alpha}{\mu}(T-T_c) \quad (3)$$

and therefore from the temperature dependence of the inverse of C_E for temperatures far from the transition, we find the transition temperature T_c. Choosing the higher five temperatures from our data, we find this transition temperature to be (51·8 ± 0·1)°C (see figure 7). From figure 7 we also find that the constant α/μ is $1{\cdot}193\times 10^{8}\,\mathrm{V\,(m\,^{\circ}C)^{-1}}$ for C7. Also, in figure 7, we note the deviation from the straight line of the data point at 52·5°C. This is because this temperature is so near the phase transition that the lowest order mean field theory is no longer suitable.

With T_C now established, we compare in figure 6 induced tilt data against temperature with the theory from equation (2). Only the curves from theory for 5 V, 10 V and 15 V are shown for clarity. It is clear that, as expected, there is close agreement between theory and data for the high temperatures, with large discrepancies appearing as T_C is approached.

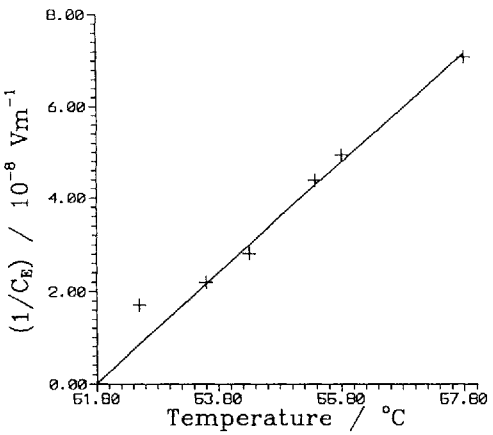


Figure 7. The temperature dependence of the inverse of C_E in the S_A phase.

For the higher fields, we also note an apparent saturation of the electroclinic effect. This is not readily explained by the introduction of higher order terms in the Landau free energy expansion along the lines of Abdulhalim and Moddel [3]. Their analysis would suggest that the high field behaviour would accord to $E^{1/3}$, but this does not fit our data. The most obvious explanation is that the surface alignment in our very thin cell is strongly constraining the effect. A further point to note is that C7 is a material with a first order S_A to S_C^* transition [11]. This means that for the homogeneously aligned cell, there is expected to be a finite and sudden jump in the director twist angle at some voltage, but this is not observed. Indeed the data of figure 5 point to a threshold voltage of the order 1 V before any induced twist is created at any temperature. This suggests a strong interplay between surface anchoring and bulk forces in this 1 μm cell. This implies that in order to utilize the electroclinic effect, a better understanding of surface anchoring needs to be established and optimum surface treatments found to allow relatively large induced twists, while also causing fast elastic recovery to the untwisted state.

4. Conclusions

Using the half leaky guided mode technique we have accurately characterized the electroclinic effect in a material with a first order S_A to S_C^* phase transition. The results at low fields are well explained by the lowest order mean field theory. The S_A to S_C^* transition temperature can be found from the temperature dependence of the electroclinic coefficients. However, the saturation of the induced twist at high fields is most likely to be associated with strong surface anchoring effects. Further, the magnitude of twist in the linear region is probably also suppressed. This suggests that care will have to be taken in preparing surfaces if the electroclinic effect is to be exploited to its maximum in thin cells.

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