Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713926090

Observations on the voltage response of a 90° twisted nematic cell using guided modes

Lizhen Ruan[a]; S. J. Elston[a]; J. R. Sambles[a]
[a] Thin Film and Interface Group, Department of Physics, University of Exeter, Exeter, England

To cite this Article Ruan, Lizhen , Elston, S. J. and Sambles, J. R.(1991) 'Observations on the voltage response of a 90° twisted nematic cell using guided modes', Liquid Crystals, 10: 3, 369 — 377
To link to this Article: DOI: 10.1080/02678299108026283
URL: http://dx.doi.org/10.1080/02678299108026283

LIQUID CRYSTALS, 1991, VOL. 10, NO. 3, 369–377

Observations on the voltage response of a 90° twisted nematic cell using guided modes

by LIZHEN RUAN, S. J. ELSTON and J. R. SAMBLES*
Thin Film and Interface Group, Department of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, England

(*Received 24 January 1991; accepted 5 May 1991*)

Using prism coupling to guided modes and surface plasmons we have examined in detail the director response of a 90° twisted nematic liquid crystal cell as a function of applied voltage. By careful comparison of angle scan reflectivity data with theoretical predictions generated from a combination of liquid crystal continuum theory and multilayer optics theory it has been possible to establish how the surface tilt changes with voltage, and also to observe changes in the optic constants due to changes in the order parameter with applied field.

1. Introduction

The twisted nematic arrangement has received much attention because it is such a vital ingredient of many simple display devices. Here, we have used the well-developed guided mode probing technique for the first time on a structure to examine in detail its behaviour at high voltages. The early foundational work on the continuum theory of twisted nematics was established by Leslie [1] who derived the behaviour in a magnetic field. This was followed by the classic work of Deuling [2] who developed an integral representation of the solution to the director configuration in an external field based upon the minimization of the free energy of the system, while Berreman [3] developed numerical codes to calculate from the director profile the optical properties of such twisted cells. His calculations are based upon numerical integration through the cell to obtain the director profile and then using a 4×4 transfer matrix technique with a cell modelled as many parallel thin slabs to predict the optical response. This procedure is numerically unstable for cells with thickness $> 10\lambda$, where λ is the wavelength of the incident radiation, in the presence of mode mixing, that is the incident single polarized (TM or TE) light exciting modes in the structure which have mixed TM (p) and TE (s) character. Ko and Sambles [4] have overcome this difficulty by using a rearranged version of the Berreman approach in which a scattering matrix is used instead. However, it is found that there are also computational difficulties in evaluating via Berreman's integral technique the director profile for voltages greater than four times the threshold voltage. This problem has been addressed by Preist *et al.* [5] who re-express the relevant integrals in a simple manner which allows them to be evaluated numerically at all voltages. With these two modifications to the basic Berreman approach relatively rapid computational procedures may be produced to model the cell's optical response at any voltage.

Previous tests of the basic Deuling theory for a 90° twist cell have been based on measuring its capacitance as a function of an applied magnetic field [6] and as a

* Author for correspondence.

function of an electric field [7], both sets of results being in good accord with calculation. Van Doorn and Heldens [8] applied a fixed voltage to a twisted nematic cell while measuring the transmission for various angles of incidence, with similar measurements being recorded by Baur *et al.* [9], once again good agreement between theory and experiment is obtained. Recently MacGregor [10, 11] has developed Berreman's model, taking into account the degree of orientational order of the liquid crystal in calculating the transmission of a cell. The overall agreement between theory and experiment is improved considerably when the order parameter correction is included in the modelling.

In this study we use the prism coupling technique with which we have previously elaborated the structure of parallel aligned nematic [12] and ferroelectric liquid crystal filled cells [13–15] to excite guided modes in a twisted nematic layer. As the momentum of the guided modes is sensitively dependent upon the profile of the refractive index of the liquid crystal layer, which itself depends upon the director profile, then the reflectivity, as a function of the angle of incidence may be used to examine in detail the deformation of the layer as a voltage is applied to the cell. The experimental results measured for the reflectivity as a function of angle are compared with theoretical curves generated using the liquid crystal modelling procedure developed by Preist *et al.* [5] together with the multilayer optics procedure of Ko and Sambles [4]. From such comparisons the optical constants of the liquid crystal are determined, as is the surface tilt, which increases with increasing applied field.

2. Experimental

A high refractive index ($n = 1{\cdot}8$ at 632·8 nm) equilateral glass prism was coated on one face with a thin layer (~ 50 nm) of high purity silver by conventional vacuum evaporation techniques. The optical constants and thickness of the film were determined by monitoring the reflectivity as a function of angle of incidence in the attenuated total reflection, Kretschmann [16] geometry and fitting the surface plasmon resonance results to Fresnel theory, having corrected for reflection at the entrance and exit faces of the prism. The complex dielectric constant, ε_{Ag}, and thickness, d_{Ag}, of the silver film were determined to be

$$\varepsilon_{Ag} = -17{\cdot}9(\pm 0{\cdot}1) + i0{\cdot}79(\pm 0{\cdot}05),$$

and

$$d_{Ag} = 57{\cdot}8(\pm 0{\cdot}5)\,\text{nm}.$$

A thin silicon oxide (SiO) liquid crystal aligning layer was deposited on to the silver film by vacuum evaporation at an angle of 60° to the substrate normal to produce a low surface tilt nematic alignment. The SiO layer displaces the surface plasmon resonance from the position measured for the silver film to higher angles and the new resonance may be compared with theory to determine the complex dielectric constant, ε_{SiO}, and the thickness, d_{SiO} of the SiO layer. The silver parameters already established were used as inputs to the fitting. However the SiO layer is nearly non-absorbing and hence it is difficult during the fitting process to distinguish increasing layer thickness and decreasing ε_{SiO}. To enable the value of ε_{SiO} to be determined, the layer thickness d_{SiO} was assumed to be 20 nm, as determined by a quartz crystal oscillator at the time of evaporation. This then gives

$$\varepsilon_{SiO} = 2{\cdot}49(\pm 0{\cdot}04) + i0{\cdot}003(\pm 0{\cdot}001).$$

Changing the SiO layer thickness clearly changes ε_{SiO}, but this has little effect on the final analysis provided a consistent combination of d_{SiO} and ε_{SiO} is used.

Having fully characterized the surface layer on the glass prism, the nematic liquid crystal was confined, as shown schematically in figure 1, between the prism and a glass plate coated with a similar aligning layer of SiO and a relatively thick, opaque layer of silver. The prism and glass plate were separated by 6 μm thick mylar spacers and were aligned so as to produce an $\sim 90°$ twist in the director orientation of the liquid crystal layer from one surface to the other. In order to produce uniform surface alignment the E7 liquid crystal (Merck, Poole) which filled the cell was heated into the isotropic phase before being slowly cooled into the nematic phase.

Having completed the cell its reflectivity was measured as a function of angle of incidence (θ in figure 1) for both TE and TM radiation (as described by Barnes and Sambles [17]) for a range of a.c. voltages. Typical measured reflectivities (marked by crosses) are shown as a function of angle of incidence along with theoretical values (the continuous curves) for a range of voltages in figure 2.

3. Results and discussion

First let us consider the reflectivity data in zero field (as shown in figures 2(*a*) and 2(*b*)), as this established the undistorted director configuration in the cell. With the director on the prism face oriented normal to the incident plane there are two regions of interest. First at higher incident angles (see figure 2(*a*)) there is the broad resonance of the surface plasmon-polariton (SPP) at the silver/SiO/nematic interface which is excited by TM radiation. Within it we find some modes which are almost purely TE in character. These are excited through the p–s mixing occurring in the cell resulting from it being twisted. The SPP mode position is dictated largely by $\varepsilon_\perp$ of the liquid crystal at optical wavelengths, that is n_O^2, while the TE modes for this configuration are dictated

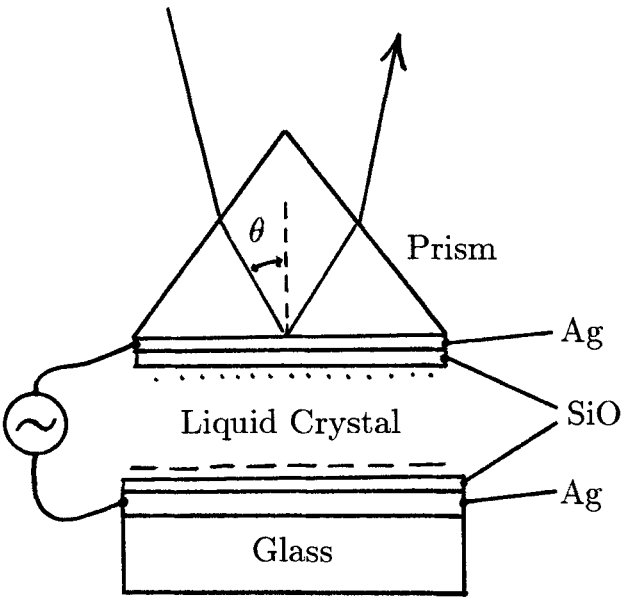
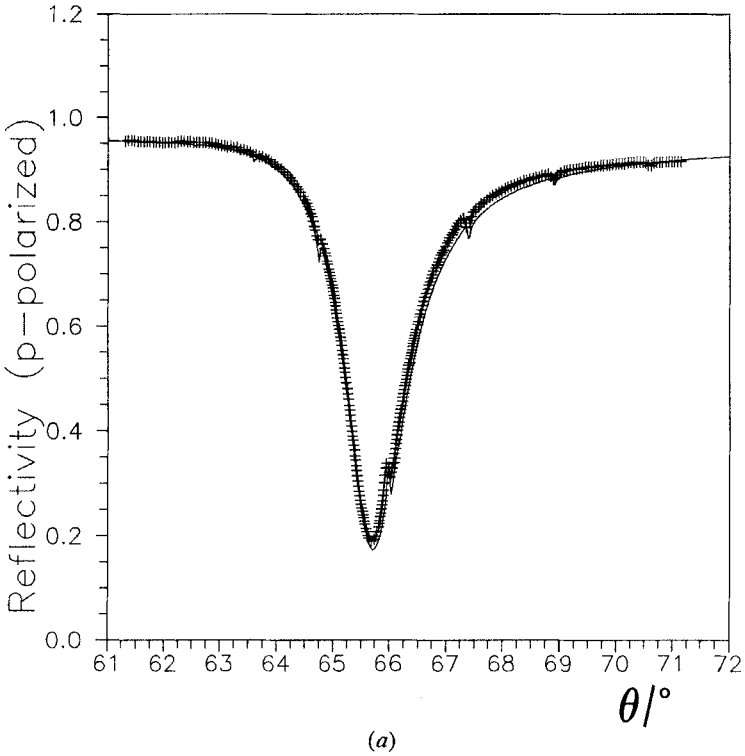
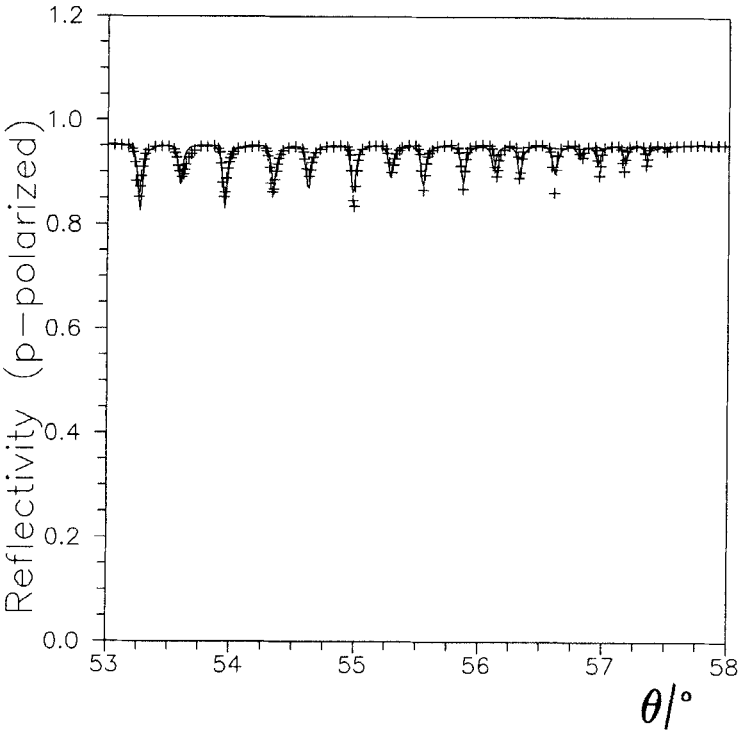


Figure 1. The sample construction. The light is incident on the prism/silver interface and couples into modes in the metal/dielectric/metal system. These are observed through dips in the reflectivity as a function of the angle of incidence θ.



(*a*)



(*b*)

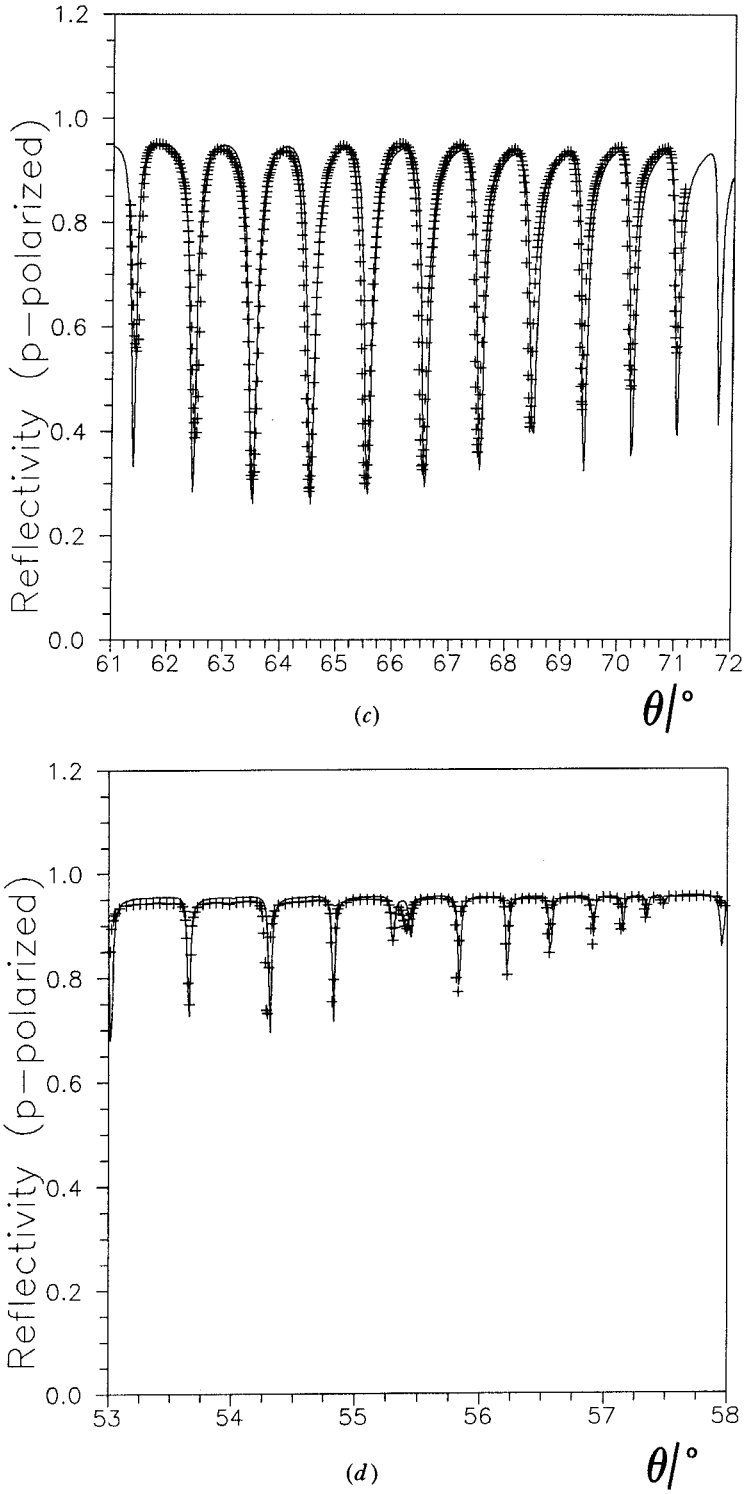


Figure 2. Fitted reflectivity data for an ~90° twisted nematic cell. For zero field we observe a deep SPP mode (*a*) and a series of TM-like guided modes (*b*), leading to the liquid crystal parameters and the cell thickness of 8·5 μm. For an applied field of 4 V across the cell the fitted data in the SPP region and TM-like guided modes region are shown in (*c*) and (*d*) respectively. (Note: Theoretical values are shown by the continuous lines and measured data by crosses.)

by $\varepsilon_{\|}$, that is n_e^2. Hence the cut-off mode position for the TE modes is beyond that for the TM modes and these TE-like modes are thus observed through p–s mixing as sharp resonances in the SPP dip. Secondly, at lower angles there is a series of sharp TM-like modes (see figure 2(*b*)), which are largely dictated by $\varepsilon_{\perp}$ at optical wavelengths. We now need to compare this data to the theoretically predicted reflectivity. To determine the latter the cell was modelled as 90 layers, each much less than one λ thick and treated as a uniform uniaxial layer. The prism and the silver/SiO layers were also incorporated in the model of the complete system. In zero field it was assumed, as a first approximation, that there is no surface tilt of the director and that the director twists uniformly across the thickness of the cell. The values of the liquid crystal thickness, $\varepsilon_{\perp}$, $\varepsilon_{\|}$ and the surface twist angles (which may not be exactly 90° and 0°) were adjusted until an adequate fit to the experimental data was obtained, using scattering matrix theory [4]. The best fit theoretical curves are shown in figures 2(*a*) and 2(*b*). These plots were obtained with the following values for the perpendicular and parallel optical dielectric constants and liquid crystal layer thickness, d_{LC},

$$\varepsilon_{\perp} = 2{\cdot}3105(\pm 0{\cdot}0002) + i0{\cdot}0006(\pm 0{\cdot}0002),$$

$$\varepsilon_{\|} = 3{\cdot}0020(\pm 0{\cdot}0002) + i0{\cdot}0006(\pm 0{\cdot}0002),$$

$$d_{LC} = 8{\cdot}50(\pm 0{\cdot}01)\,\mu\text{m},$$

and surface twists of 88° and 1·5° respectively, so that the total twist across the cell is 86·5° ± 0·5°. To obtain this initial fit the SiO parameters were adjusted slightly to take account of its porosity, the spaces originally filled with air being now filled by liquid crystal. Without this adjustment the theoretical SPP minimum occurs at the wrong angle.

Now consider the data shown in figures 2(*c*) and (*d*), which were obtained by applying a 4 V rms 20 kHz sine wave to the cell. It is clear that the SPP moves to higher angles and broadens resulting in deep modes over the angle range from 61–71°. This is simply because the director is tilting and an increase in effective ε is seen by the SPP. The director tilt and twist profiles at 4 V rms are shown in figure 3. These were calculated using the values of low frequency (20 kHz) dielectric constants and elastic constants listed in the table using the routines described by Preist *et al.* [5]. For a sufficiently high voltage the centre of the cell is almost fully homeotropically aligned while the two surface regions remain at 86·5° to each other. Importantly, it has been found that to fit data satisfactorily with the theory we need a small surface tilt which is a function of the applied voltage. In figure 4 this surface tilt angle is shown as a function of applied voltage together with the results obtained by Welford and Sambles [18] for an untwisted cell. These results have been scaled to the same effective voltage, since it is the *E* field and not the voltage directly that dictates the surface tilt. Because now, with the voltage applied, the important changing regions of the cell are near the surfaces a uniform split of the cell into equal thickness regions is not optimum, instead it is split into parallel slices which are equally spaced in tilt angle. At higher voltages the $\varepsilon_{\|}$ and $\varepsilon_{\perp}$ at optical frequencies also need adjusting because of two extra effects. First, there is some heating because of the finite cell conductivity, which tends to reduce $\varepsilon_{\|}$ (leaving $\varepsilon_{\perp}$ nearly constant, since for E7 it is constant for 20–28°C) and secondly there is an increase in the order parameter, *S*, which will increase $\varepsilon_{\|}$ and also decrease $\varepsilon_{\perp}$. This has been observed by MacGregor [10, 11] when modelling a twisted guest host system. The heating and increase in order parameter compete for influence upon $\varepsilon_{\|}$ leading to results which are difficult to interpret, while the increase in order parameter alone will

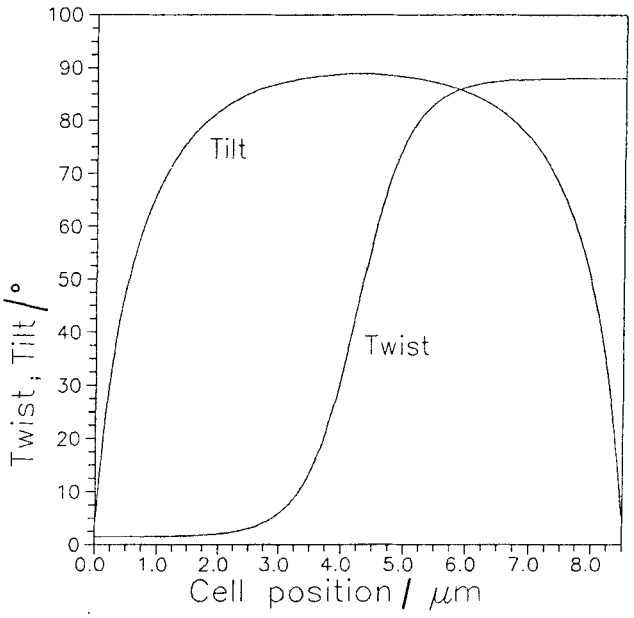


Figure 3. The twist and tilt profiles of the nematic director for an applied voltage of 4 V across the cell. Notice that at this voltage the director in the centre of the cell is nearly homeotropically aligned, an effect which increases for larger fields.

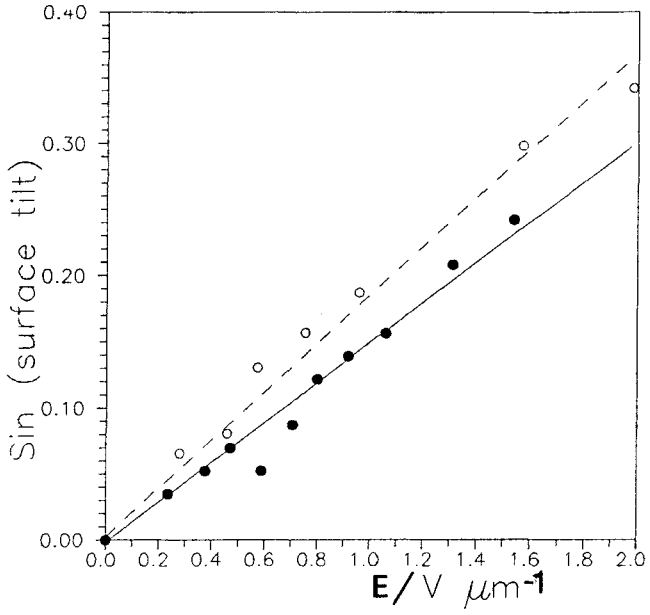


Figure 4. The variation of the surface tilt of the director with applied field, E. The data in this work are shown by the filled circles. Data from [18] are shown as open circles. The comparison is within the experimental error ($\pm 1°$), but it appears that the surface anchoring energy in our cell is a little higher.

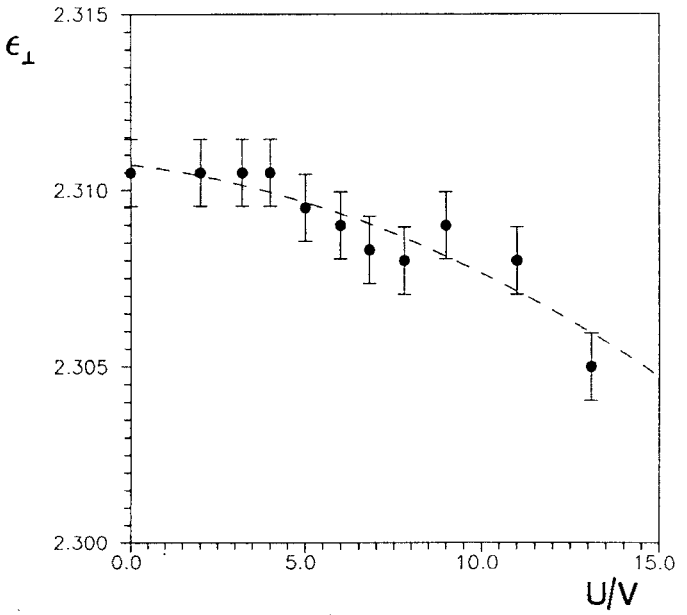


Figure 5. The variation of $\varepsilon_\perp$ at optical frequencies (that is n_0^2) with applied voltage, U, across the cell, indicating the increase in order parameter S with applied field. The variation of $\varepsilon_\parallel$ is not shown as the effect of increase in cell temperature with field dominates.

The low frequency (20 kHz) dielectric parameters and elastic constants for E7 at room temperature used in the calculations.

Parameter	Value
$\varepsilon_\parallel$	19·20
$\varepsilon_\perp$	5·09
$k_{11}/10^{-12}$ N	11·5
$k_{22}/10^{-12}$ N	17·1
$k_{33}/10^{-12}$ N	18·2

be expected to decrease $\varepsilon_\perp$. Figure 5 shows how the measured value of $\varepsilon_\perp$ changes with voltage. Above ~ 5 V, it decreases indicating an increase in S.

It should also be appreciated that while $\varepsilon_\parallel$ in the centre of the cell may increase and $\varepsilon_\perp$ decrease, near the edges of the cell this will not be the case since the director here is still nearly perpendicular to the field. We have not attempted to model this in any fashion simply because the incorporation of spatially varying $\varepsilon_\perp$ and $\varepsilon_\parallel$ leads to a non-unique solution for the fits to the data. The omission may account for the small discrepancies between data and the theory for particular modes at high voltages.

4. Conclusions

We have, for the first time, examined reflectivity in a 90° twisted nematic liquid crystal cell which supports guided modes. This has been compared with theory in order to model the director realignment which takes place in the cell under application of an a.c. voltage. As the voltage across the cell is increased it is necessary to incorporate finite surface tilt in the modelling of the cell (as in a parallel nematic [18]) and at still higher

voltages, equivalent to a field of $\sim 10^6\,\mathrm{V\,m^{-1}}$, there appears to be evidence for a changing order parameter (as seen by MacGregor [10, 11]), leading to a decrease in $\varepsilon_\perp$. These results indicate the limitations of using Deuling type theory for thin nematic filled cells subject to electric fields greater than this magnitude

Lizhen Ruan thanks the University of Exeter for supporting this work, S. J. Elston acknowledges support from the Wolfson Trust and J. R. Sambles is grateful to the SERC for financial support.

References

[1] Leslie, F. M., 1970, *Molec. Crystals liq. Crystals*, **12,** 57.
[2] Deuling, H. J., 1974, *Molec. Crystals liq. Crystals*, **27,** 81.
[3] Berreman, D. W., 1973, *J. opt. Soc. Am.*, **63,** 1374.
[4] Ko, D. Y. K., and Sambles, J. R., 1988, *J. opt. Soc. Am.* A, **5,** 1863.
[5] Preist, T. W., Welford, K. R., and Sambles, J. R., 1989, *Liq. Crystals*, **4,** 103.
[6] Gerristma, C. J., de Jeu, W. H., and Van Zanten, P., 1991, *Physics Lett.* A, **36,** 389.
[7] Meyerhofer, D., 1976, *Molec. Crystals liq. Crystals*, **34,** 13.
[8] Van Doorn, C. Z., and Heldens, J. L. A. M., 1974, *Physics Lett.* A, **47,** 135.
[9] Baur, G., Windscheid, F., and Berreman, D. W., 1975, *Appl. Phys.*, **8,** 101.
[10] MacGregor, A. R., 1988, *J. Phys.* D, **21,** 1458.
[11] MacGregor, A. R., 1988, *J. Phys.* D, **21,** 1659.
[12] Welford, K. R., and Sambles, J. R., 1989, *Liq. Crystals*, **2,** 91.
[13] Elston, S. J., Sambles, J. R., and Clark, M. G., 1989, *J. mod. Opt.*, **36,** 1019.
[14] Elston, S. J., and Sambles, J. R., 1989, *Appl. Phys. Lett.*, **55,** 1621.
[15] Elston, S. J., and Sambles, J. R., 1990, *Jap. J. appl. Phys.*, **29,** L. 641.
[16] Kretschmann, 1971, *Z. Phys.*, **241,** 313.
[17] Barnes, W. L., and Sambles, J. R., 1986, *Surf. Sci.*, **177,** 399.
[18] Welford, K. R., and Sambles, J. R., 1987, *Appl. Phys. Lett.*, **50,** 871.