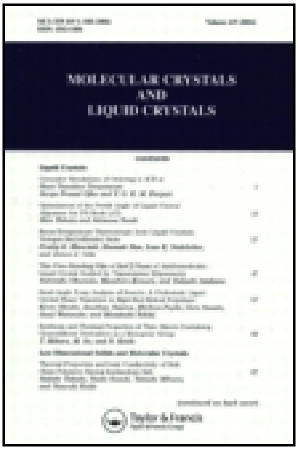

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S. J. Elston [a] & J. R. Sambles [a]

[a] Thin Film and Interface Group, Department of Physics, University of Exeter, Stocker Road, Exeter, EX4 4QL, England

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The Configuration in a Ferroelectric Liquid Crystal Cell in Terms of a Rigid Chevron Structure

S. J. ELSTON and J. R. SAMBLES

Thin Film and Interface Group, Department of Physics, University of Exeter, Stocker Road, Exeter, EX4 4QL England

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Reorientation of the optic tensor configuration in a ferroelectric liquid crystal (FLC) cell is investigated under the application of a DC field. This is performed by the excitation of guided optic modes in a thin FLC layer. A careful analysis of the structure is performed by comparison of reflectivity data (showing the mode excitation) to theory for a variety of proposed models of the optic tensor profile. It is seen that the only way in which the data can be explained is by the retention of the chevron structure in the smectic layering under the application of a field. The FLC is seen to reorient within this structure for moderate fields, leaving a pinned point in the middle of the sample at the chevron cusp. This shows that simple models which allow the smectic layer structure to distort under field application are inadequate, and provides direct optical observation of the chevron structure.

Keywords: ferroelectric liquid crystal, optic modes, director profile, chevron structure

1. INTRODUCTION

It is now generally accepted that the structure in a parallel-sided, ferroelectric liquid crystal (FLC) cell involves a chevron structure in the smectic layering. Having determined (as discussed elsewhere)[1] that the optic tensor structure within the liquid crystal layer in a thin FLC cell is consistent with this chevron structure observed in X-ray scattering work, it is useful to consider the effect of the application of a static (DC) field across a FLC layer. The situation under a forward biased field is considered, i.e., a field applied in the direction in which the FLC dipole is already switched. (The reverse bias direction is not a static situation; even with a small reverse bias field switching will occur).[2] The results have been outlined in a previous letter[3] and are more fully discussed here.

Due to the presence of the spontaneous dipole in the FLC and dielectric induction, some distortion of the optic tensor profile will take place. This will be limited by two things:

(1) Elastic forces within the FLC material will limit the distortion, since with no field applied, the material is in an undistorted state (other than the cusp

in the smectic layering at the chevron point). Movement away from this will cost elastic energy. This distortion can take two forms:

(*a*) Realignment of the mechanical director, and hence optic tensor profile, within the smectic layering. This is similar to the elastic distortion in a nematic.[4]

(*b*) Distortion of the smectic layering itself. This may also in turn induce further distortion in the optic tensor profile.

(2) Surface anchoring forces will tend to retain the undistorted state. Again these may pertain to either the optic tensor or the smectic layering, or both. From the zero field results it seems that the optic tensor in-plane condition at the surface is stronger than the surface alignment direction anchoring condition,[1] although there may be some thin boundary layer present.

It should be noted that only the elastic distortion case is considered here; even so, due to the complexities of the distortion involved, it is very difficult to model theoretically the effect of the application of a field. For example work at Strathclyde[5] has shown that even in the case of infinitely rigid smectic layers, there are eleven elastic constants involved, and these are difficult to evaluate experimentally. An alternative approach will therefore be made to the problem. Various empirical models for the optic tensor configuration under the application of a field can be considered. The correct or incorrect nature of proposed models can then be evaluated by comparison with reflectivity data (to be explained in section 2) taken under the application of a field across the cell. There are several models which can be tried. The possibilities that the smectic layering forming the chevron structure could begin to straighten out (removing the cusp), or that the smectic layering bends etc., under the application of a field, must be considered.[6,7] It is then hoped that comparison of such modelling with data will allow the correct nature of the distortion of the optic tensor configuration in a cell to be established.

The resulting empirical model for distortion of the optic tensor profile under a

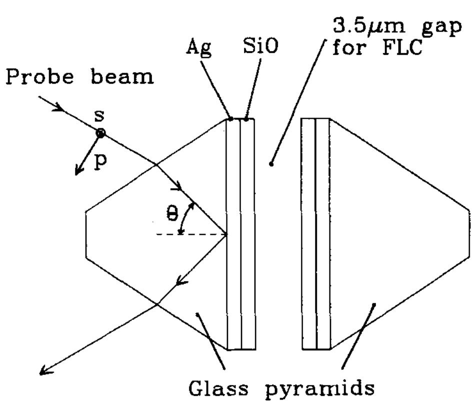

FIGURE 1 The experimental arrangement of the FLC cell. The glass pyramids have a refractive index $n = 1.8$. The evaporated silver layers are ~47 nm thick with a dielectric constant at 632.8 nm (He/Ne laser) of $\varepsilon \simeq -17.5 + 0.7i$. The SiO aligning layers are ~20 nm thick with a refractive index $n = 1.55$; the surface alignment direction is perpendicular to the plane of the illustration.

DC field will then provide a starting point for the consideration of theoretical modelling of the distortion. This would be very useful, since, with the standard technique of polarised optical transmission, it is very difficult to characterise the optic tensor structure in a cell under an applied field. It is therefore difficult to evaluate the exact nature of a model required to describe the tensor profile. Contradictory modelling has previously been presented to model similar sets of data taken by the polarised optical transmission technique. It has been seen that this type of data can be adequately modelled with both bookshelf geometry[8] and chevron geometry (including distortion in the smectic layering)[6,7] models of the structure in a FLC cell. This clearly indicates the need for further investigation.

2. EXPERIMENTAL TECHNIQUE

Consider the liquid crystal cell shown in Figure 1. In this system, it is possible to excite and propagate resonant guided modes and surface plasmon-polaritons (SPPs).[9] The resonant guided modes are propagating Fabry Perot modes excited between the silver layers. These extend right across the FLC layer and so are sensitive to optic properties of the whole of the layer. They can be excited with either p-polarised (TM) or s-polarised (TE) light. If the optic tensor in the FLC is orthogonalised in the plane of propagation, this will then excite either pure TM or pure TE modes. If however the optic tensor is not orthogonal in this frame, then the excited modes may be of mixed polarisation. The SPP is a surface localised electromagnetic oscillation which can be supported at the interface between media of opposite dielectric constant[10] such as silver and liquid crystal.[9] Since it is surface localised, the SPP is sensitive to optic properties of the FLC near the surface. It is only excited with p-polarised light, unless the optic tensor off-diagonal terms couple between TM and TE fields, in which case s-polarised light may excite it.

Modes are observed by examining the reflectivity of the cell as a function of angle of incidence; when a mode is excited there is a dip in the reflectivity. This can then be compared to a theoretical reflectivity function calculated using a method which models the cell as a stack of thin layers of dielectric material.[11,12,13] Rapid variations in tensor profile through the cell are modelled by making each layer thickness $\ll$ the wavelength of light in the region of rapid change. In this way it is possible to model satisfactorily the continuous nature of the change in orientation of the liquid crystal director. For the present study, the cell is oriented with the nematic surface alignment direction perpendicular to the plane of light propagation. Then in the S_C^* phase at room temperature, the FLC layer is equivalent to a uniaxial slab of material which is twisted from the surface alignment direction. The reflectivity as a function of angle of incidence for p-polarised light will show a relatively broad SPP resonance, the width being due to the high absorption of silver at optical wavelengths. Also superimposed on this will be a series of sharper dips due to the excitation of resonant guided modes. These modes are not pure TM modes however. Due to the twist of the FLC optic tensor from the surface alignment axis, there now exist off-diagonal terms in the optic tensor in the cell. These off-diagonal terms can couple between p and s polarised fields, and the modes are no longer of pure polarisation, but are mixed. The sharp dips through the SPP are due to the excitation of TE-like modes through these cross coupling terms. Energy coupled into the system through the excitation of the SPP resonance then further couples into propagating TE-like modes in the FLC layer. Observation of this type of reflectivity curve is therefore very powerful, since in the same curve, there are the SPP excitation, which is a probe of surface optical properties, and the TE-like guided modes which extend across the FLC layer and so probe the optical properties within the layer. Now when a DC field is applied across the FLC layer some reorganisation of the optic tensor profile across the layer will result. This will change the angles at which the various modes are excited, leading to information on the new structure in the FLC.

The cell is built from two high index glass pyramids (n = 1.8) with silver films evaporated on them. These then have SiO aligning layers evaporated at 60° incident angle to form a good zero tilt alignment in the nematic phase. The cell is constructed with thin mylar spacers to form an air gap of ~3.6 μm. This is then filled with the FLC (here BDH mixture SCE3) in the isotropic phase. This is slowly cooled through the nematic and smectic A phases to the S_C^* phase at room temperature. At this temperature the optic constants of the FLC are n_o = 1.500 and n_e = 1.691 with a uniform twist of about 13° across the cell, except for possible thin boundary regions which are ignored here.[1] A voltage is now applied to the silver electrodes to create a DC field across the cell, and the reflectivity as a function of angle of incidence is observed.

Data taken with a voltage of 1.5V applied between the silver electrodes is illustrated in Figure 2. This is shown, together with data taken through the SPP with

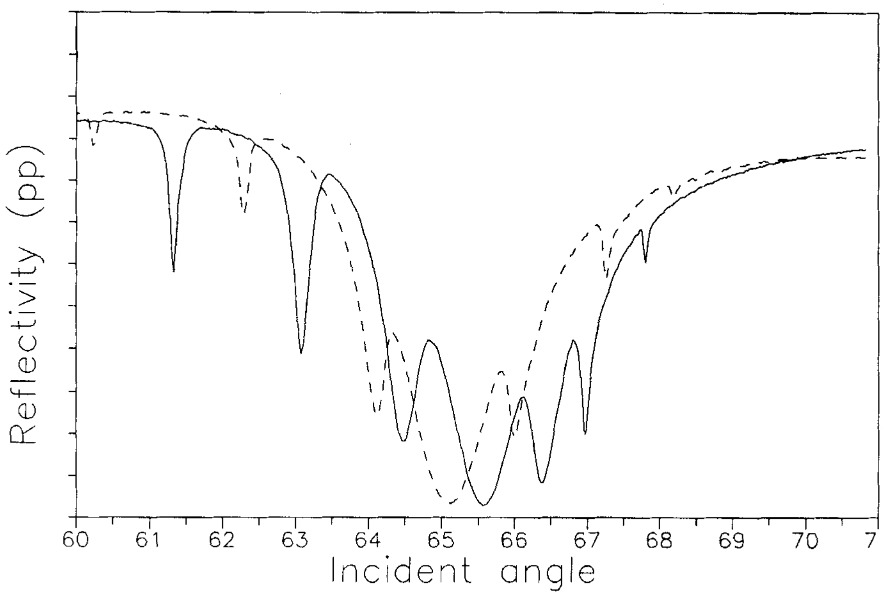

FIGURE 2 R_{pp} data (reflectivity for p-polarised light) taken with a SCE3 filled cell oriented such that the surface alignment direction is perpendicular to the plane of light propagation, with 1.5V applied across the cell; data with no field applied are shown by the dashed line.

no field applied, for comparison (dashed line in Figure 2). Clearly, in this is seen a movement of the resonant guided modes to the left with application of a voltage, i.e., to lower angle. So a distortion in the optic tensor profile has taken place. The mixed guided modes have become, in general, broader in angle spread; this may be an indication that the optic tensor is no longer uniformly aligned, but it is difficult to derive structural information directly from the data set.

Initially a data set with 3V applied across the cell will be considered as typical of that for any applied field. This can be compared with theoretical reflectivity calculations for a variety of empirical models of the optic tensor configuration, in an attempt to evaluate the structure present in the cell.

3. MODELLING THE STRUCTURE

Initially a uniform slab model is considered for data taken with the voltage applied.

It is possible that, under the application of a DC field, the optic tensor rotates

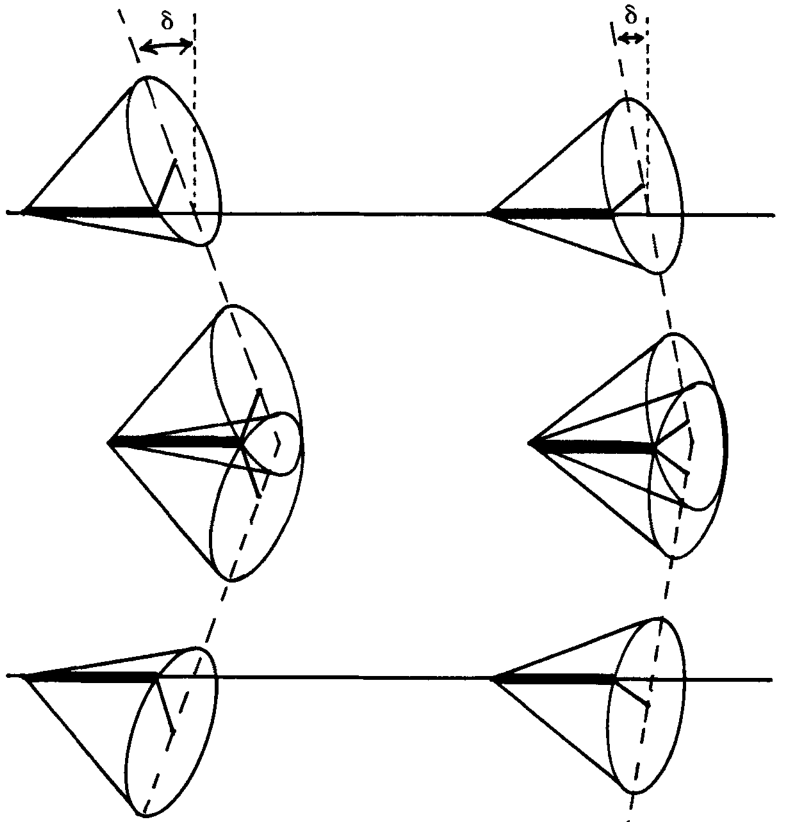

FIGURE 3 Changing the smectic layer tilt δ results in a change in the twist angle χ throughout the cell, if the flat-in-the-plane condition is held. This could provide a mechanism for the increase in twist angle seen in a conventional cell under the application of a DC field.

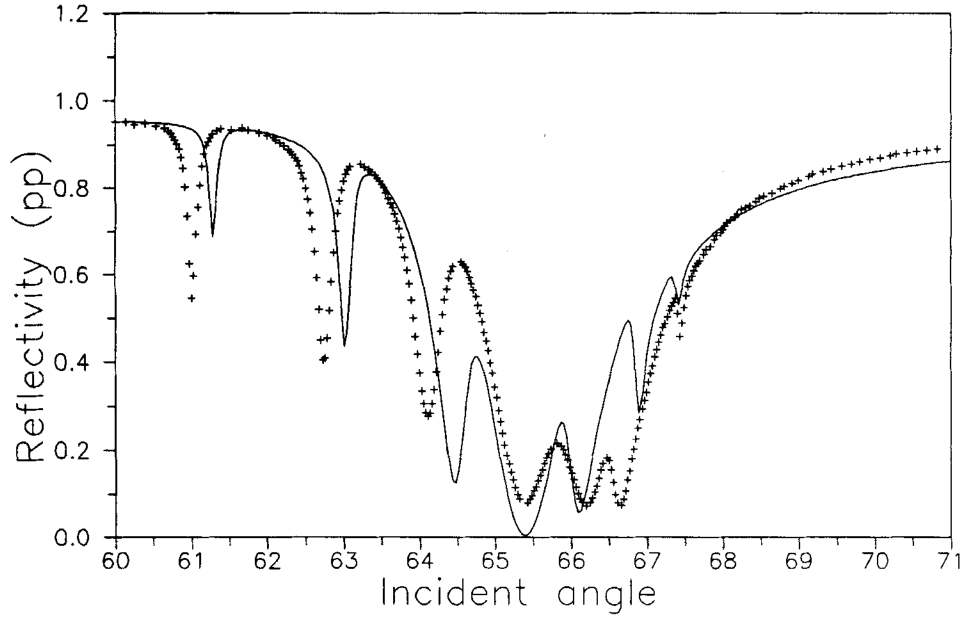

FIGURE 4 Fit between R_{pp} data taken at 3V and theoretical calculation for a twisted uniform uniaxial slab model for the FLC layer, with $\chi = 20.5°$. (The data are the crosses and the theoretical reflectivity curve is the continuous line). Clearly this is not an adequate model of the situation.

around the side of the cone to allow the dipole to align more nearly parallel to the field. Then if the flat in-the-surface-plane condition is to be retained, the smectic layers tilt angle could reduce.[6] This is illustrated in Figure 3 which shows how a change in the smectic layer tilt δ can lead to a change in the twist angle χ. The result of this process would be the retention of an optically uniaxial uniform slab of material under the application of a DC field, but with an increased twist angle χ. This would be consistent with transmission work, where the extinction angle for a cell between crossed polarisers is seen to increase on application of a DC field. Using this model, with the optic tensor constants found for SCE3, leads to a resulting fit to the data for 3V applied across the cell shown in Figure 4.

In this, the twist angle χ is chosen to place the first excited s-like mixed guided mode at approximately the correct angle. Clearly, this is not an adequate fit to the data and therefore the uniform slab approximation is not good for the case of an applied DC field across a FLC cell. This indicates that the assumption that the FLC smectic layering distorts to allow the retention of an optically uniform slab with the optic tensor major axis parallel to the surface plane is incorrect.

This simple observation is of great importance. It has often been assumed that the optic tensor is tilted when no field is applied (i.e., in the relaxed state of the cell), for example in the bookshelf model with surface pre-tilt.[14] It would then be expected to be forced to lie parallel to the plane of the cell surfaces when a field is applied, due to the presence of the spontaneous polarisation in the FLC material. This however is clearly incorrect. Since a simple slab of uniaxial material with optic tensor major axis lying in the plane of the cell surfaces is adequate to model the

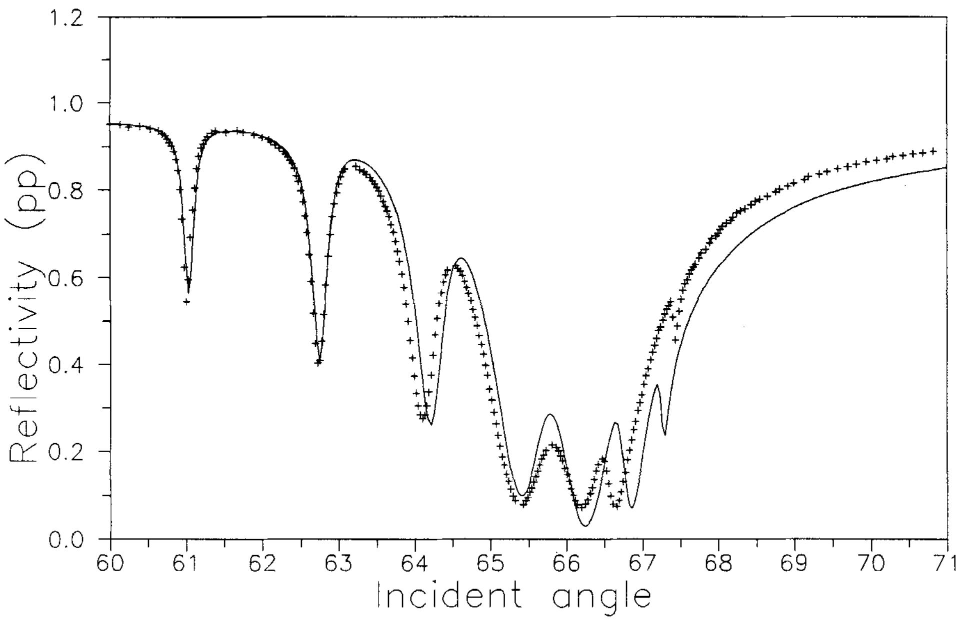

FIGURE 5 Fit between R_{pp} data and theory for SCE3 cell with 3V applied across the silver electrodes. The model is a uniform twisted and tilted slab of uniaxial material. This shows that models which retain a uniform director orientation throughout the cell are inadequate.

cell when no field is applied,[1] but inadequate to model the field-applied data, the indication is quite the reverse.

The addition of tilt to the structure under the DC field is feasible since the presence of the chevron tilt in the smectic layers leads to a tilted cone axis at zero volts. When the optic tensor rotates around the cone with a field applied, the cone axis may not change tilt angle to compensate entirely and retain the flat in-the-surface-plane situation. The result is that the optic tensor major axis will tilt relative to the cell surfaces when a field is applied. Assuming again uniformity of the configuration across the FLC layer, though there may be a tilt sign change at the middle of the cell which is optically irrelevant, a tilted and twisted uniform slab model is considered. The resulting fit to data taken at 3V for a tilt angle of ~7° and a twist angle of ~21° is shown in Figure 5.

It is seen however that this is still inadequate to model the data taken. There is however an improvement over the simple untilted model case. This may imply that tilt is present in the cell under the application of a field.

Although the above consideration of tilt in the optic tensor improved the fit to the data, this does not necessarily imply the correct nature of such a model. It is therefore necessary to consider the more general case of flat-in-the-surface-plane models. It has been proposed that modelling which retains flat-in-the-surface-plane conditions on the optic tensor profile and allows the smectic layers to distort can explain all known electro-optical effects.[6] This does not however require that the optic tensor configuration be identical to a uniform slab of material. There can be variation of the twist angle χ across the FLC layer, together with appropriate distortion of the smectic layering, which retains the flat-in-the-plane condition. For example surface anchoring and elastic resistance to deformation in the optic tensor structure of the FLC layer could result in a hump-back twist profile, with a greater increase in twist in the bulk of the FLC layer. Alternatively, there could also be resistance to distortion at the chevron cusp, and a double hump twist profile would result. This latter proposition is reasonable if the flat-in-the-plane uniform slab fit (shown in Figure 4) is considered. Here it is seen that the second s-like guided mode is particularly in error. It is noted that with the first s-like mode at the correct angle, the third is also at a reasonable position; however the second mode needs to be at a lower angle. Alternatively, if in this model the twist angle were chosen to place the second mode at the correct angle, then though the higher order modes would be better placed, the first and third modes would be in error.

The first and third s-like modes have E-field peaks in the middle of the cell, whereas the second mode has an E-field minimum in the middle of the cell. Considering the above note that the second order mode is required to be excited at a relatively lower angle, or the first and third modes excited at relatively higher angles, the implication is that the region in the middle of the cell is of higher optic dielectric constant. Now in this perpendicular orientation of the cell, for s-like modes, this can be achieved if the region of the middle in the cell distorts less than the outer regions, i.e., if less twist/tilt occurs in the middle of the cell, then a larger component of the optic tensor lies perpendicular to the plane of light propagation. This is consistent with the proposal of a restricted movement at the chevron cusp.

A model is therefore considered where the flat-in-the-plane condition is retained, and a restriction of the movement of the optic tensor in the middle of the cell is introduced. The fit between data and theory obtained from this (not shown) is a little superior to the uniform twist model shown earlier in Figure 4, but does not fully explain the data. Other similar flat-in-the-plane models also prove inadequate to model the data taken here.

Comment

It is not surprising that a simple flat-in-the-plane model (as proposed by W.J.A.M. Hartmann)[6] can explain most electo-optic data, which is taken in experiments with transmission between crossed polarisers and integrates across the cell, and are therefore dependent mainly on twist. (Though the comment by Hartmann that the smectic layer bending in such a model provides a mechanism for the fast relaxation seen in FLCs[6] cannot be correct. If the smectic layers were to bend and retain flat-in-the-plane configurations, then the smectic layer elasticity would have to be less than that due to nematic type distortion). The data taken here are sensitive also to changes in tilt in the cell, and the failure to model the data using a profile in which the optic tensor major axis lies parallel to the surface throughout the FLC layer indicates that this is not a true assumption. This, together with the improvements seen earlier when tilt was introduced into the uniform slab model, indicates that tilt of the optic tensor is indeed present in the cell when a field is applied.

4. RETENTION OF THE CHEVRON STRUCTURE

It has been seen from observations starting with the uniform twisted slab model that:

(*a*) Introduction of tilt of the optic tensor axes improves the fit to the data.
(*b*) Restraint of the region in the middle of the cell around the chevron cusp improves the fit to the data.

Modelling will now be considered which allows for both of these by retaining the chevron structure in the smectic layering under the application of a DC forward biased field. The effect of a DC field on the smectic layering has previously been examined in X-ray scattering work, and it was seen that the smectic layering did not noticeably distort at fields of up to $\sim 3 \times 10^6$ Vm^{-1}.[15] If this is the case, then there is a pinned point in the middle of the cell where the smectic layers meet at the chevron cusp. This can be considered in two ways:

(1) Maclennan and others treat the chevron interface as a further surface in the cell.[16] Then there is no need for continuity of the optic tensor profile across the interface. A surface energy term could be included to model its form, as Maclennan used in his chevron switching analysis.[16]
(2) Continuity of the optic tensor profile could be retained across the chevron cusp. This would be reasonable on the basis that the FLC layer is a continuous medium, and a discontinuity in the optic tensor (and hence mechanical director) profile may not be allowed due to the continuum nature of the material. This then, under the retention of the chevron structure without distortion, leads to a point in the middle of the cell at the chevron cusp where no distortion takes place under the application of a field. This point is pinned at a twist angle χ defined by the cone angle θ and the chevron layer tilt angle δ, where χ is the zero field twist angle. This second possibility is identical to the first, under the limit of an infinite anchoring energy at the internal surface.

On the basis of the continuous nature of the FLC layer, the second proposal seems more reasonable. However, since it is the limiting case of the first, the first will initially be considered.

In addition to the above points concerning the chevron interface, the form of the distortion within the FLC layer must be considered. Retaining the chevron structure, the optic tensor is constrained to move around the cone within the smectic layers, with the cone axis tilted from the surface plane by the smectic layer angle δ. The only degree of freedom is the rotation about the cone, defined by the azimuthal angle ϕ. Here however, in order to help visualisation of the optic tensor configuration present, the twist/tilt profile for the optic tensor will be discussed. Then if the tilt as a function of position within the cell is calculated, the twist at any point (and azimuthal angle ϕ) can be determined, knowing the cone angle θ and smectic layer tilt angle δ.

Now what form is reasonable for the twist/tilt across the cell? Since the theory for description of distortion within a FLC layer is rather inadequate, being usually a one elastic constant approximation,[17] an analogy with the nematic case will be considered. For a parallel-aligned nematic cell, a reasonable first approximation to the true tilt under an applied field is given by the following analytical form:

$$\text{tilt}(z, V) \sim \arctan\left(A(V)\sin\left(\frac{z\pi}{d}\right)\right)$$

where

z is the position within the cell.
d is the cell thickness.
A is some function of V which varies with voltage.
V is the applied rms field.

The situation here is analogous to this. There is in both the nematic and S_C^* cases a bulk, interaction forcing term due to an applied field; in the nematic case, this is a purely dielectric term, and in the ferroelectric case, this has both dielectric and dipolar components. This is resisted by a bulk elastic term; in the nematic case this is described by the Frank constants,[4] but is not well understood in the S_C^* case.

It has also been observed that in a nematic liquid crystal, the surface anchoring terms can be included by the introduction of imaginary surfaces outside the cell.[18] In this case, this leads to:

$$\text{tilt} \sim \arctan\left(A \sin\left(\frac{z(\pi - 2B)}{d} + B\right)\right)$$

where B controls the 'artificial' thickness of the cell. Here a similar form can be introduced for each half of the FLC cell. It is however necessary to treat the cell surfaces and the chevron interface separately; therefore the 'B' in the above equation must be split in order to allow for this. It is also necessary to introduce a scaling factor for the tilt, since the maximum value is no longer $\pi/2$. The resulting form for the tilt in each half of a chevron cell is then:

$$\text{tilt} = \frac{2}{\pi} C \arctan\left(A \sin\left(\frac{z(\pi - B_2)}{d} + B_1\right)\right)$$

where the introduction of $(2/\pi)C$ allows control of the maximum tilt present. Now d is the cell half thickness and the calculation of tilt is done in one half of the cell, and repeated with a reverse in sign in the second half of the cell. The value of B_1 allows for the cell surfaces; if $B_1 = 0$, then the surface anchoring energy is infinite, and if $B_1 = \pi/2$, then the surface anchoring energy is zero. B_1 can lie between these limits, representing the anchoring force at the surfaces. The value of B_2 allows for the chevron interface; if $B_2 = B_1$, then the anchoring at the chevron interface is infinitely rigid, and corresponds to the requirement of continuity of optic tensor profile across the chevron interface. If $B_2 = B_1 + \pi/2$ then the 'surface' anchoring energy at the chevron cusp is zero, and the chevron interface is completely free. B_2 can lie between these limits, representing the anchoring at the chevron interface.

It is necessary to calculate the optical response for a cell modelled with these forms for the optic tensor profile in order to compare with the data and hence evaluate them. Variation of the values of the parameters which define the optic tensor profile in this form will, it is hoped, allow the nature of the tensor profile in the cell to be evaluated. The optical calculation is carried out by splitting the FLC layer into ~90 thin slabs, calculating the twist/tilt for each of these, and hence calculating the theoretical reflectivity forms.

Fitting the theory to the data in this way allows the best values of the constants A, B_1 and C and B_2 in the above empirical form for tilt to be determined. Doing this for example for the 3V applied data set leads to the fit shown in Figure 6. This was obtained for:

$$A = 3.0$$

$$B_1 = 0.35 \text{ rads}$$

$$B_2 = 0.35 \text{ rads}$$

$$C = 14.0°$$

Notice that here A has no units, and C is quoted in degrees, while the surface

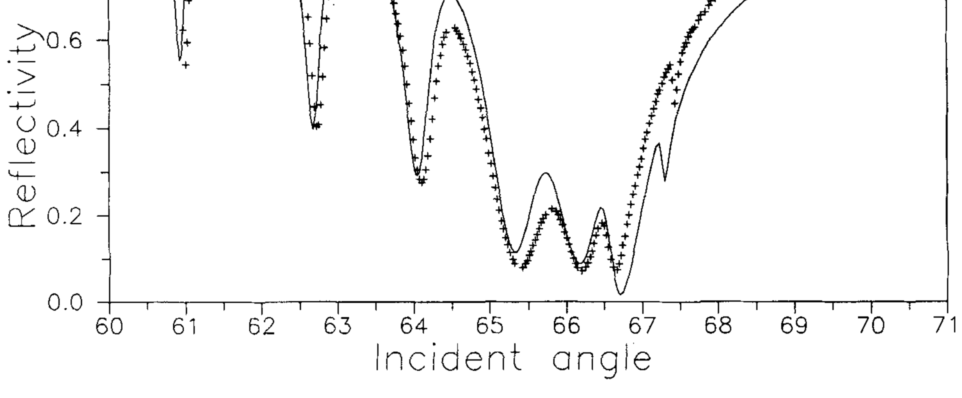

FIGURE 6 Fit to the set of R_{pp} data for SCE3 with 3V applied across the cell, using the empirical form for tilt with the chevron structure in the smectic layering rigidly fixed. This leads to a pinned point in the middle of the sample.

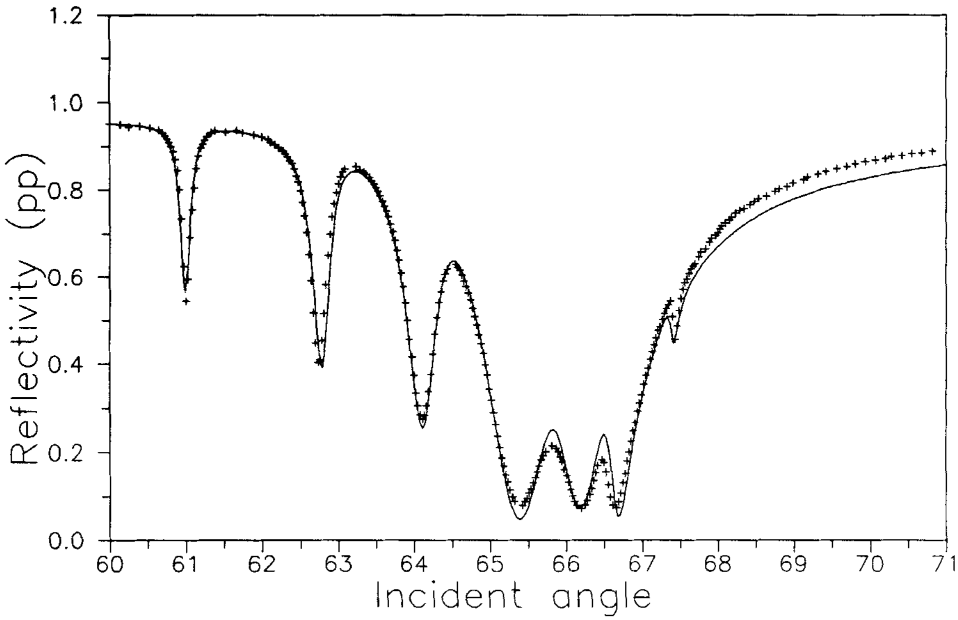

FIGURE 7 Fit to R_{pp} data for SCE3 at 3V, using the modified form of the tilt profile across the FLC layer, leading to an improved quality of fit. This retains the chevron structure in the smectic layering, and keeps the differential of the optic tensor profile continuous throughout.

anchoring terms B_1 and B_2 are quoted in radians. This is a little better fit to the data than that seen before (compare with Figure 5). Also importantly, it is seen that $B_2 = B_1$, this means that the anchoring energy at the chevron cusp is infinite—or more correctly that the FLC optic tensor (and hence mechanical director) is continuous across the chevron interface.

There are still discrepancies between the positions of the theoretical mixed modes and those in the data. Again odd order modes are slightly displaced, with the first s-like mixed mode requiring to be shifted less under the application of the field relative to the even order modes. This once more indicates that, since odd order modes have an E-field peak in the middle of the cell, less movement of the optic tensor at the cell centre under an applied field (away from the relaxed zero volt position) is required. So even with $B_1 = B_2$ in the above equation, corresponding to the requirement for continuity of the optic tensor profile across the chevron cusp as outlined in the second point above, the odd order modes are displaced too far. Since the optic tensor at the chevron cusp has now been pinned at the zero volt twist angle, and distortion in the smectic layers' chevron structure could only allow this to increase, how can the above requirement be attained? The only option left is for the width over which the pinned point is influential to be increased.

This can be achieved by squaring the sin term in the above empirical equation describing the tilt, which has the effect of making the differential of the tilt continuous across the interface. Then the equation describing the tilt in each half of

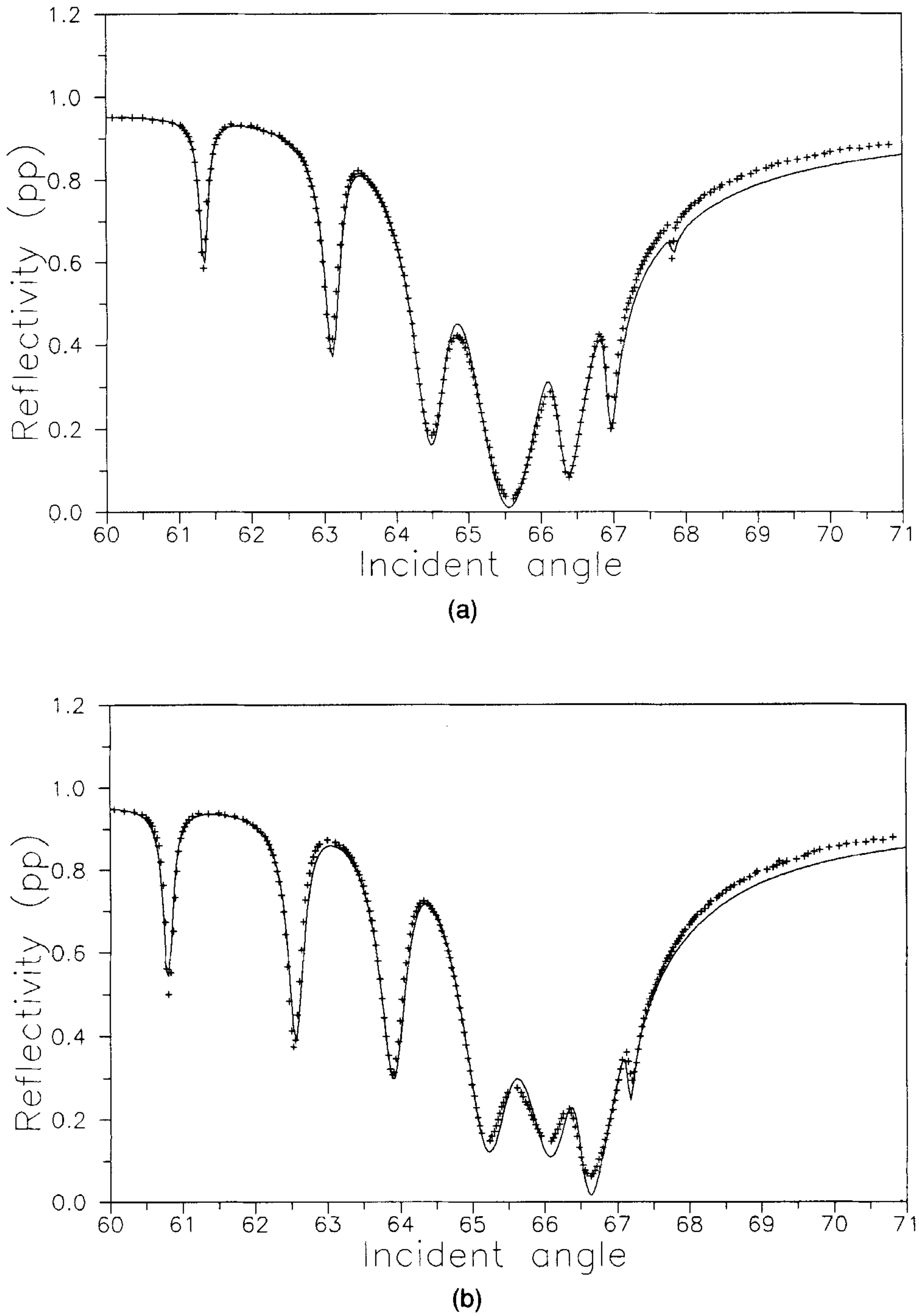

FIGURE 8 R_{pp} fitted data using the improved empirical form for the optic tensor profile for (*a*) 1.5V applied across the cell, (*b*) 5V applied across the cell, showing the reasonable quality of fit obtained for small fields.

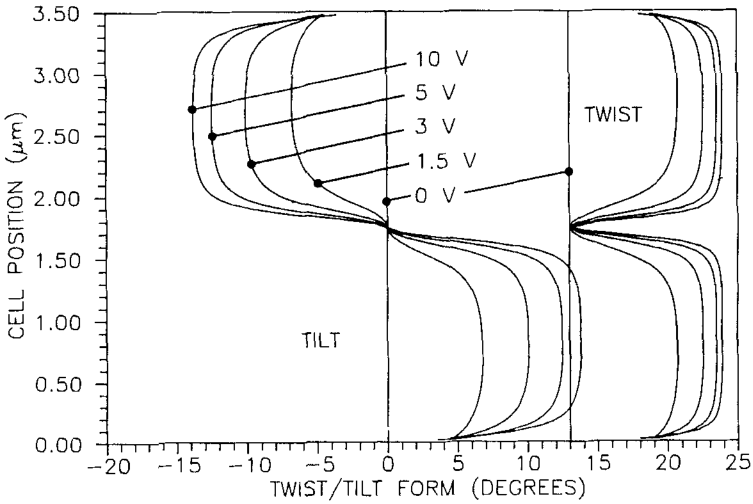

FIGURE 9 The derived twist/tilt profiles across the FLC layer of SCE3. This shows the development of the profile with applied field. The 'flat-topped' nature of the distortion is seen, as is the continuous differential of the profile across the chevron cusp.

the cell becomes:

$$\text{tilt} = \frac{2}{\pi} C \arctan \left(A \sin^2 \left(\frac{z(\pi - B)}{d} + B \right) \right)$$

where B_1 and B_2 have been replaced by B, and the sin term has been squared. This form, empirically derived from the above observations, can now be used to model the twist/tilt profile in the cell to compare with the data. The $\sin^2$ term will widen the region over which the chevron pinned point influences the profile. Again, fitting can be performed by variation of the parameters A, B and C.

The introduction of this form greatly improves the quality of the fit to the data taken with 3V applied across the cell. There is no longer a large difference between the positions of the theoretical mixed modes and the data. Using this a fit to the 3V data is shown in Figure 7.

With this type of fitting procedure, very interesting fits to data taken with between 0 and 20V applied across the FLC layer are accomplished. The low voltage range (up to ~5V) shows very good agreement between data and theory, as seen at 3V in Figure 7 and at other voltages in Figure 8. This is acceptable, and indicates that this is a good model for the optic tensor profile in the cell at low voltages. Data taken with up to ~10V applied across the cell shows a reasonable fit to theory, with only a small deviation in the quality of fit at 10V. The resulting twist/tilt profiles across the cell with varying voltage are shown in Figure 9. The nature of the resulting twist/tilt profiles will be discussed in section 5. The quality of fits for up to ~10V shows that the form for twist/tilt used here is reasonable. *This also confirms unambiguously the chevron structure of the smectic layering in the cell, the* *existence of the necessary pinned point in the middle being reasonable for this structure only.*

Above an applied voltage of 10V, the fits degrade, and the fitting parameters are no longer reasonable. It is believed that this is an indication that the chevron layering structure is being significantly distorted at higher fields. This is not surprising since it is generally observed that restructuring of the smectic layering in a FLC cell takes place at above ~10V.[15] After the application of 20V across the cell, the zero field state no longer returns to its original situation, i.e., the distortion is no longer elastic. To model the zero field state after 20V has been applied across the FLC layer, the uniform slab twist angle has to be increased from $\chi \sim 13°$ to $\chi \sim 15°$. So clearly a permanent distortion has taken place in the smectic layering.

It has been seen above that with the chevron cusp in the middle of the cell, retention of the smectic layering when a field is applied allows a reasonable description of the optic tensor profile in a FLC cell. However, it is necessary to compare this with a model where the cusp is not in the centre of the cell in order to determine if this is indicated in the data taken. In the case when no field is applied across the cell, the position of the chevron cusp is optically irrelevant; wherever the cusp is in the chevron, a uniform twist angle for the optic axis can exist across the FLC layer.[15] However, when a forward bias DC field is applied, any asymmetry present may be manifest in data such as that taken here, since the pinned point in the optic tensor structure would no longer be in the middle of the cell.

Modelling of this nature indicates that if the cusp is shifted from the centre of the cell by just a few percent of the total FLC layer thickness, there is very little change in the form of the SPP and guided modes reflectivity curves. However, shifting the cusp position by more than about five percent of the cell thickness (here that is ~0.17 μm) does have a significant effect. It is interesting to note that the effect on the reflectivity curve is not the same for the two offsets; in normal transmission work it would be impossible to detect the difference. If these curves are compared to the fitted data for 3V applied across the FLC layer shown in Figure 7 it is seen that the effect of the asymmetry is slightly detrimental.

So it is observed that a small shift in the position of the chevron cusp away from the middle of the cell (up to about five percent of cell thickness) is not detectable with these data. Modelling with greater shifts in the cusp position however is detrimental to the fit between theory and data. Therefore in this sample, the chevron interface is very near to the centre of the FLC layer, and if it were offset by greater than ~0.17 μm this would be observed.

5. IMPLICATIONS OF RESULTS

The optical observation of retention of the chevron structure under the application of a DC field is very important. Firstly it again confirms the existence of the chevron structure in the smectic layering of a thin FLC cell. This is difficult to observe with conventional optical techniques involving examination of the transmission of a FLC cell placed between crossed polarisers, as these do not in general yield spatial information about the optic tensor configuration. Since this structure is retained in this material at fields up to $\sim 3 \times 10^6$ Vm^{-1}, the layering is quite rigid. The formation of the chevron structure is due to the density wave in the material changing pitch between the S_A and S_C^* phases. Since this is held when a field is applied across the material, the pitch of the density wave is clearly quite important. This is not surpising, since a change in the pitch would in general involve a change in the local density of the fluid, which is not favourable. When the chevron structure in SCE3 is distorted with large fields, this is not an elastic process; the relaxed zero field structure is permanently changed.

Any continuum fluid mechanics modelling of the FLC material must take into account the rigidity in the smectic layering observed.

The continuity of the optic tensor twist/tilt across the chevron interface, as seen in the twist/tilt profiles for SCE3 shown in Figure 9, is also important. It indicates that modelling which replaces the chevron interface with an internal surface and surface anchoring conditions may be incorrect.[16] The anchoring energy at such an artificial surface would need to be such that the 'in-the-plane' condition on the optic tensor is always held, since where the smectic layers meet at the chevron cusp, the FLC optic tensor must lie in the plane of the cell surfaces if its twist/tilt profile is to be continuous at this point. Hence the modelling of the interface as a

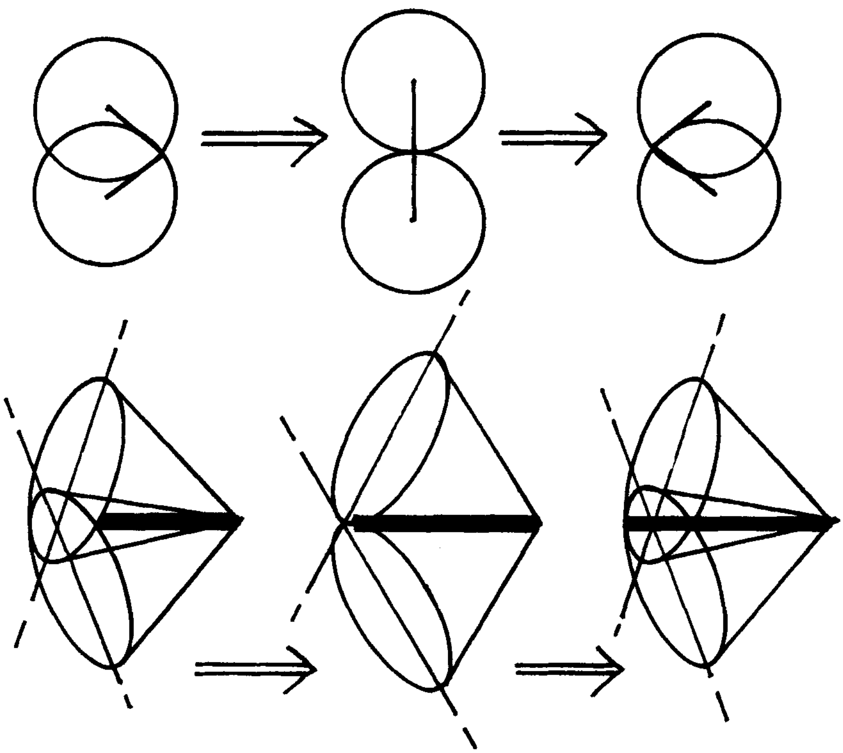

FIGURE 10 Possible switching process for a FLC cell which is consistent with the continuity of optic tensor profile observed here under static fields. This allows a brief back-bending of the smectic layering in the centre of the cell during the switching process.

surface with finite in-plane anchoring energies is incorrect. This also has important implications for the switching processes in a chevron structure FLC cell. The switching process has been modelled as though the chevron cusp were an internal surface, and the optic tensor rotates around the cone away from this surface in opposite directions in the top and bottom halves of the cell during switching.[16] This breaks the continuity of the tilt profile across the cell. So if the twist/tilt profile needs to be continuous, as the data here implies, this is an erroneous model. It is then however difficult to see how the material can switch from one side of the cone intersection at the chevron cusp to the other. It may be that the process involves a brief back bending of the chevron structure at the chevron interface during switching, to allow continuity of the optic tensor profile,[6] illustrated in Figure 10. This may also occur at the domain walls between states switched in opposite directions within a FLC cell.

This may be important when modelling the static and particularly the switching processes in FLC cells. The continuum mechanics developed for FLC materials will need to retain continuity of optic tensor, and hence mechanical director, within the cell.

Examination of Figure 9 shows that the differential of the twist/tilt profiles across the FLC layer is continuous at the chevron cusp. This was introduced by squaring the sin term in the empirical form in order to broaden the region of influence of the pinned point, but is also physically relevant. Since it seems that the optic tensor profile is continuous across the chevron cusp, it is not unexpected that there is correlation of the optic tensor across it. If this is the case, then the 'mechanical director' is effectively continuous across this point. So the elastic deformation of the optic tensor profile also needs to be continuous across the chevron interface. This would also have to be taken into account in continuum theory modelling.

It is seen in Figure 9 that fitting the empirical forms for the twist/tilt profile to the data led to a development of the twist/tilt profile which is rather 'flat topped' at all applied fields. In work with the application of fields to nematic filled cells, it is seen that, at first, the tilt begins to develop in an approximately sinusoidal way, tending to become flat topped at higher fields due to the limit of 90° tilt.[18] A similar effect might be expected in FLC cells, with the tilt having a finite limit, due to the limit of $\phi = 0$ at the side of the smectic cone. However the 'flat topped' nature of the profile at all fields indicates the presence of another interaction. In the FLC case, this is due to the self interaction of the spontaneous polarisation in the FLC material, and is a strong indication of the reasonable nature of the empirical fitting procedure performed here. The dipole-dipole interaction in the FLC material favours a uniform profile across the layer in the cell. For example, the electric energy in a one dimensional system is:

$$F_{electric} = \frac{\varepsilon_0 V^2}{2\int_0^d \frac{1}{\varepsilon_{zz}}\,dz} - \frac{V\int_0^d \frac{P_z}{\varepsilon_{zz}}\,dz}{\int_0^d \frac{1}{\varepsilon_{zz}}\,dz} + \frac{\left(\int_0^d \frac{P_z}{\varepsilon_{zz}}\,dz\right)^2}{2\varepsilon_0\int_0^d \frac{1}{\varepsilon_{zz}}\,dz} - \frac{1}{2\varepsilon_0}\int_0^d \frac{P_z^2}{\varepsilon_{zz}}\,dz$$

where

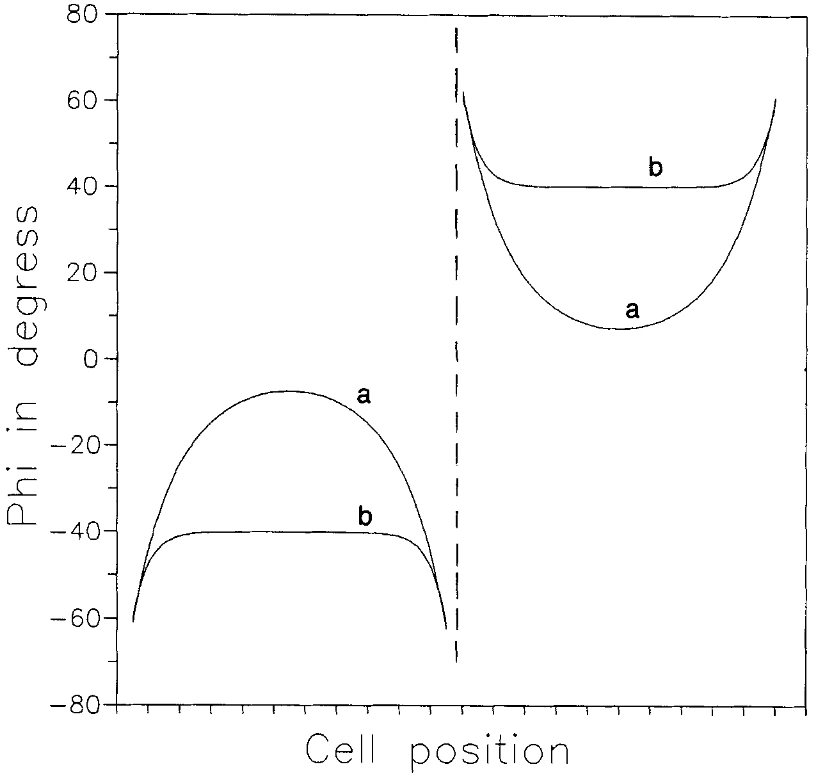

FIGURE 11 Illustration of the difference when the dipole self interaction terms are (*a*) ignored, and (*b*) included in the modelling of theoretical ϕ profiles in an FLC cell. This shows that the flat-topped nature of the empirical profiles obtained agree with the presence of a strong dipole-dipole interaction.

V is the applied voltage across the cell.
d is the cell thickness.
P_z is the component of the dipole in the z-direction.
ε_{zz} is the dielectric tensor component in the z-direction.

If in this $P_z(z)$ and $\varepsilon_{zz}(z)$ are constant across the FLC layer, the third and fourth terms cancel, minimising the electric energy.[19] This corresponds to a uniform state of the optic tensor profile.

Figure 11 illustrates the azimuthal angle (ϕ) profiles across a cell with and without the dipole-dipole interaction included, using a one elastic constant approximation for deformation elastic energy. This type of model is too simple to explain fully the structure observed in this work, but serves well to illustrate the difference seen when dipole-dipole self interaction is included. The flat top nature in ϕ, with the inclusion of the latter, is evident, and this will lead to flat top twist/tilt profiles. Hence it is seen that the inclusion of the dipole self interaction energy will be important in the continuum theory of FLC materials.

6. SUMMARY

In this paper, distortion of the optic tensor profile present in a FLC cell under the application of a DC field has been considered. This has resulted in the important discovery that the optic tensor is pinned at the cusp of the chevron and that the chevron structure is retained under the application of moderate fields ($< \sim 3 \times 10^6$ Vm^{-1}). This important observation unambiguously confirms the presence of the chevron formation in the smectic layering. For the material under investigation here (SCE3) this pinning is very rigid. Alternative work with the experimental BDH mixture 783 has shown a little elastic distortion in the smectic layering[20]; this may have to be allowed for when modelling the optic tensor profile under an applied field for cells containing certain FLC materials. It is seen here that the region around the chevron interface is very important and that the differential of the optic tensor profile across the chevron interface is continuous (The switching process may possibly be accommodated by a brief backbending in the smectic layering). Also the profile under an applied field is clearly affected by the self energy of dipole-dipole interaction in the FLC material.

The results seen here indicate the power of the guided mode technique, the optic tensor profiles observed being difficult to determine by the use of polarised optical microscopy.

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