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Modelling monopolar and bipolar switching in ferroelectric liquid crystal devices using a three variable theory

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The switching process in ferroelectric liquid crystal devices takes place through the formation and evolution of domains, which can be modelled using a three variable approach. Here we discuss details of the model which are necessary in order to reproduce the domain nucleation and switching times as a function of applied voltage for both monopolar and bipolar pulses. We show that in order to reproduce data correctly the model must incorporate a complex empirical elastic stress term.

1. Introduction

Since the discovery of surface stabilised (SS) ferroelectric liquid crystal (FLC) structures by Clark and Lagerwall [1] some fifteen years ago, there has been relatively little progress in the development of commercial products. The multiplexibility, increased viewing angle, lower power consumption and faster switching speeds in comparison with currently available nematic and supertwist nematic displays are features yet to be exploited. One of the difficulties has been the lack of development of a full and useable continuum theory; this is in contrast to nematic devices where a rigorous theory allows both understanding of various device parameters and accurate prediction of electro-optic performance.

The types of structure which form in FLC devices depend critically on the constraining influences of the alignment layers and the phase sequence of the material used. Materials which exhibit a S_A to S_C^* phase transition undergo layer shrinkage across this transition, and, as a consequence, chevron type structures form [2]. Our interests focus on the switching behaviour of the so-called C2 structure [3], which is commonly used in device development. Such a structure is obtained by using an aligning polymer which leads to a small but finite surface tilt. The smectic layering forms a chevron type structure with the layers tilted away from the surface alignment tilt direction, allowing the director near the surface to fulfil the combined constraints of lying on the smectic cone and in the alignment direction. There is then a single internal interface at the chevron cusp, where switching between two stable states takes place.

When observed between crossed polarizers, two opposite polarization states can be seen, which are idealistically referred to as BLACK and WHITE. On application of an electric field to a device in one of its stable states, say BLACK, the director profile reorients into a pre-switched stressed state, with the director pinned at the chevron interface; this reorientation leads to a corresponding change in transmission. If the field remains, the stress causes the director at the chevron interface to switch at various points, nucleating domains of the opposite WHITE state. Subsequently, these domains grow and coalesce at the expense of the BLACK state. Once the device has completely switched it remains in a new stressed state until the field is removed, whereupon it relaxes to its new WHITE state. If the amplitude (voltage) and time duration of a pulse is insufficient to switch a device fully, domains of the two polarizations coexist in a partially switched state. Since achieving an analogue grey scale is difficult in bistable FLC devices, a possible solution is to control these partial states [4–8].

In general, as the amplitude of an applied voltage pulse is increased, a shorter time duration is required to switch a device completely [9]. Observations have also shown that both the number of nucleated domains and their growth rate increase with increasing voltage [10]. Two types of nucleation mechanism are known to exist in C2 type structures: homogeneously nucleated sites are random and believed to be due to thermal fluctuations in the director profile; in contrast, heterogeneously nucleated sites form repeatedly around defects or spacer beads. Ease of nucleation of the latter dominates over the homogeneous case, especially at weak electric fields; this may be due to local perturbations in the director

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profile, allowing stronger coupling of the polarization vector **P** with the external electric field and hence subsequent nucleation. The rate of growth (or wall velocity) of domains is sensitive to temperature variation and field strength, and the increase in wall velocity at stronger fields is accompanied by a change in domain shape, from the characteristic 'speedboat' faceting at weak driving fields to elliptical domains [10].

In a previous paper the use of a 'three variable' model of FLC switching was discussed [11]. The aims of this approach are two-fold: (i) to include in a model the physical processes of domain formation and evolution in switching; (ii) to ensure that the approach is as computationally simple as possible. In the three variable approach, we model the director orientation inside and outside the evolving domains separately, with a third variable representing the domain area.

In this paper we discuss the extensions/modifications which have to be made to the approach if the response to bi-polar pulses is to be reproduced. Specifically we show that it is necessary to include a non-linear approximation to the elastic stress during reorientation of the director.† This is because of the pinning of the director which occurs at the chevron interface, but is not explicitly included in the three variable approach.

2. Basic three variable approach

As described in the introduction, the switching in FLC devices in the C2 structure takes place through the formation and evolution of domains at the chevron interface. It is this domain formation and evolution process which we wish to reproduce. We do not however wish to model the process explicitly, as this would be rather computationally intensive, and such an approach would not lend itself well to the development of device addressing schemes. To this end we set up a model where the director orientation in any region of the cell is modelled by a single variable. In practice, the director orientation in any region is a function of distance through the thickness of the device, and our variable will represent some average of this. Additionally the director orientation is not uniform over the area of a device, but varies from region to region. Typically, however, there are only two identifiable regions in a switching device: the domains (which generally appear to be identical), and what we term the background, i.e. the regions in which domains have not formed. Thus it is possible to characterize a switching FLC device by the use of three variables:

(i) the 'average' director orientation in the 'background', for which we use the symbol ϕ_b,
(ii) the 'average' director orientation in the domains, for which we use the symbol ϕ_d,
(iii) the ratio of domain area to total device/pixel area, for which we use the symbol a.

In order to model the reorientation we will use a simple equation of the form:

$$-\eta \frac{\partial \phi}{\partial t} = \mathbf{PE} \cos \phi \cos \delta + T \qquad (1)$$

where we have ignored the effects of dielectric anisotropy/biaxiality. This is legitimate for the material used in the devices under investigation—any known anisotropy can be added to equation (1) trivially. Here ϕ is the director orientation (it may be ϕ_b or ϕ_d, depending on the region being modelled), η is the rotational viscosity, **P** the material's spontaneous polarization, **E** the applied electric field and δ the chevron tilt angle. Normally the symbol T is given the meaning of restoring torque due to surface interactions, but we wish to attach a more sophisticated meaning to it, and the majority of this work will be seen to be determining an appropriate empirical form for T. *Here T is used to represent the combined restoring effect of any surface torques present and internal elasticity*. Assuming that the surface and chevron interface anchoring are strong, it is the latter term which dominates in restoring the director orientation to its equilibrium position. In the previous work this was approximated by:

$$T = T_0(\phi - \phi_0) \qquad (2)$$

where ϕ_0 is the equilibrium director orientation, and T_0 is a constant of proportionality which together with the viscosity η controls the rate of director orientation relaxation, with a time constant of $\tau \approx \eta / T_0$. The value of ϕ_0 may be positive or negative depending on whether we are modelling the background or the domains.

In addition to modelling the reorientation of the director in the 'background' and 'domains', it is also necessary to model the formation of domains. As this formation takes place at the chevron cusp, and it has been suggested that this interface behaves as a surface, we use the same reorientation equation (1), but with T now replaced with a simple surface interaction term. We write this in the form:

$$T = T'(\sin 2\phi - 2 \cos \phi_0 \sin \phi) \qquad (3)$$

The intrinsic bistability of equation (3) leads to two stabilized equilibrium positions, which are the average

† Poster 163 in the Program Book of Abstracts of FLC'93 (Tokyo) also introduces an empirical elastic torque term which changes with orientation.

relaxed director orientation angles $+\phi_0$ and $-\phi_0$. So with these equations we can now model the formation of domains, and the director orientation in the background and domain regions. In order completely to represent the switching, however, we also require a model of the domain area evolution. We follow the suggestion of Ishibashi [12] and use the Avrami model. This can be written in the form:

$$a=1-\exp\left\{-N\left(\frac{\sigma}{2}v(t-t_{\mathrm{nuc}})\right)^2\right\} \qquad (4)$$

where a is the fraction of switched area, N is the number of domains which nucleated at time t_{nuc}, σ is a shape factor and v is the domain wall velocity. This can be differentiated to obtain a form for the instantaneous rate of change of area, which together with the common assumptions that the number of nucleated domains is proportional to the applied voltage, and domain wall velocity is proportional to applied voltage, allows a simple form for the domain area evolution. The former of these approximations is reasonable, the latter has been demonstrated when dielectric torques are minimal, as they are here [13].

Finally the net transmission through a device/pixel can be determined from the average of the transmissions through the background and domain regions, weighted by their areas.

Further details of the structure of the three variable approach to modelling switching in FLC devices can be found in reference [11]. This also describes an approach to setting the various constants involved in the theory.

3. Results

Previously the predictions from the three variable theory were compared with simple monopolar pulse driven switching, over a very limited voltage range, and found to be quite successful. If however we wish to use this technique to understand and develop addressing schemes for FLC devices, then we need to consider at least both monopolar and bipolar pulses over a wide voltage range. If the results from this comparison are successful, then we can have some confidence that the method will be suitable for the development and testing of addressing schemes. In order to test this we consider the time to nucleate and time to switch as a function of pulse amplitude for monopolar and bipolar pulses. It is common to plot the time to switch as a function of applied pulse amplitude as a means of characterizing materials and addressing schemes, but we will also be able to consider the time to nucleation, and check that both sets of data are reproduced in our model.

Here a device consisting of a 2 μm thick sample of the ferroelectric liquid crystal ZLI-4655-000 (Merck) in a C2 structure, was placed between crossed polarizers and illuminated with a non-coherent light source. A charge coupled device camera with a $\times 10$ objective connected to a video monitor allowed switching to be observed. The camera was focused on a region free of defects and spacer beads, and the applied switching pulses were derived from an arbitrary waveform generator. If the pulse amplitudes are below the threshold for domain nucleation, or sufficiently large to cause total switching, then no 'flickering' of domains is observed. However, if domains are nucleated and partial switching is taking place, then domains which are present during the switching cycle are seen as a 'flicker' on the monitor. It is thus relatively simple to generate the time/voltage data for both nucleation and total switching.

The results are compared with the three variable theory predictions in figures 1 and 2. Figure 1 shows the t_{nuc} and t_{sw} data and theory for monopolar pulses, and figure 2 shows the data and theory (solid lines) for bipolar pulses. While it is apparent that the comparison in figure 1 is quite reasonable, that in figure 2 for the theory as stated above is totally inadequate. The model, where the parameters were optimized for simple monopolar switching, proves unable to reproduce the bipolar results.

4. Development

It is apparent from the results in figure 2, and from direct observation of transmission through a device as a function of time during switching, that the switching during the second half of a bipolar pulse takes place

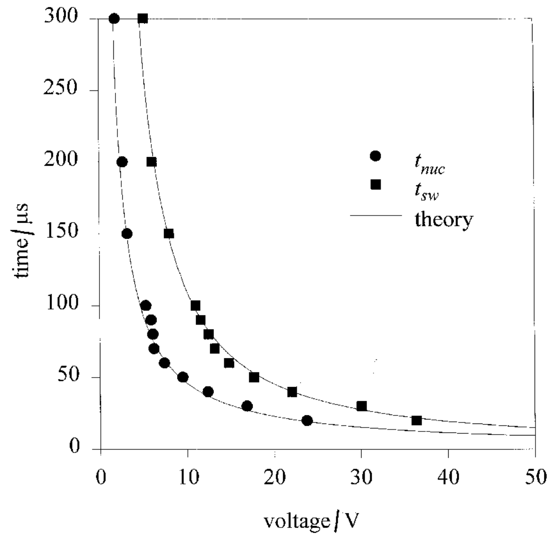

Figure 1. Monopolar switching data and theory showing time to nucleation t_{nuc} and time to switch t_{sw}.

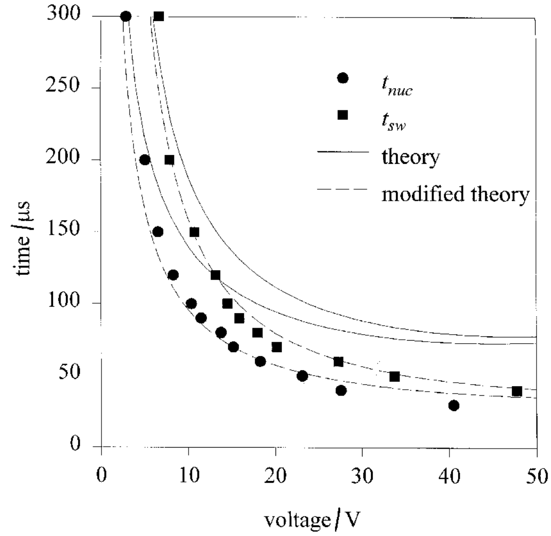

Figure 2. Bipolar switching data and theory showing t_{nuc} and t_{sw} for the original three variable model and improved approach.

much faster than predicted. Why should this be? The relaxation rate after a single monopolar pulse is correct, so the reason must be linked with the dipole torque term. This is extremely small at the beginning of the second half of the bipolar pulse, due to the reorientation during the first half. In the three variable model, the reorientation is limited by the term in equation (2), but this only grows linearly with increasing reorientation, and so with large fields the director will reorient to $\phi \approx \pm \pi/2$, and thus on field reversal the torque will be small. This is a reasonable representation of what is taking place in the bulk of the FLC device; however there will be small regions near the surfaces and chevron interface where the reorientation is limited by the surface/chevron interface anchoring. This can be seen in the so called 'stressed states' which have been discussed before [14]. In these regions the torque will be much larger on field reversal, and therefore lead to a decrease in the switching times. The question then is whether we can in some way represent the effects of this in our three variable approach. Clearly it is not trivial, as these effects are explicitly due to the variation in the director orientation across the thickness of the device, and we wish to approximate this with a single variable.

We will outline here the developments to overcome the above limitations in the three variable approach, making the method more broadly applicable.

(i) The maximum reorientation may simply be limited by restricting the reorientation (symmetrically about $\phi = 0$) using a cut-off angle, ϕ_c. On field reversal from a stressed state, the dipole torque term is then $\mathbf{PE} \cos \phi_c \cos \delta$, and more rapid switching takes place than if ϕ saturates at $\pi/2$. Good agreement with both the monopolar and bipolar t_{nuc} and t_{sw} data is achieved for $|\phi| \leqslant \phi_c = 1{\cdot}1$ radians, without modifying any of the parameters used above. However, inclusion of a cut-off angle results in the transmission being limited discontinuously when ϕ_1 or ϕ_2 equals ϕ_c. This means that transmission/time data are not modelled well, and therefore the approach is unacceptable.

(ii) The discontinuity in the response can be overcome if the limit in reorientation is introduced as a more gradual function, rather than a discontinuous cut-off. This can be obtained by using a non-linear restoring torque term of the form

$$T = T_0 |(\phi - \phi_0)|^{n-1} (\phi - \phi_0) \tag{5}$$

With $n \geqslant 3$ and an appropriate value for T_0, agreement with the bipolar data can be obtained. However, using a restoring torque term of this form (with $n \geqslant 2$) leads to a situation where $\mathrm{d}T/\mathrm{d}\phi \Rightarrow 0$ as $\phi \Rightarrow \phi_0$, and the torque therefore decreases rapidly as ϕ_0 is approached. Relaxation times from stressed states are thus much greater than the typical value of ≈ 1 ms.

(iii) A reasonable progression is to combine such a high order polynomial with the linear term used originally. In so doing the higher polynomial will dominate the restoring torque when the director profile is stressed to a degree where the reorientation from the relaxed state ($\phi = \phi_0$) is significant, limiting the high field reorientation, and allowing the bipolar data to be accurately modelled. Furthermore, when the reorientation tends towards the relaxed state, the significance of the higher order term diminishes, and the restoring torque (and therefore relaxation rate) is effectively determined by the linear term. This then controls the relaxation time. A suitable torque term can be written as

$$T = (\phi - \phi_0)[T_1 |(\phi - \phi_0)|^3 + T_0] \tag{6}$$

(iv) Examination of this term however reveals that we now have the wrong symmetry in the high order terms of the restoring torque. While for small reorientations we expect the restoring torque to be symmetric around $\phi = \phi_0$, the saturation reorientation angle is similar in both directions (as evidenced by the decrease in background/domain contrast at high fields). This means that the high order term we have introduced to limit this saturated switching angle should in fact be symmetric about $\phi = 0$ rather than the relaxed state. In order to express this we break the torque term into three regions, and express it as:

$$
\begin{aligned}
T &= T_0(\phi-\phi_0)+T_1(\phi-\phi_0)^4 && \phi\geqslant\phi_0\\
T &= T_0(\phi-\phi_0) && -\phi_0<\phi<\phi_0\\
T &= T_0(\phi-\phi_0) && \phi\leqslant-\phi_0\\
&\quad + T_1(\phi+\phi_0)|(\phi+\phi_0)|^3
\end{aligned}
\tag{7}
$$

The incorporation of a linear term between the two relaxed state orientations allows the saturation reorientation angles to be limited at similar values for both the domain and background regions.

(v) Finally, in order best to reproduce the variation in contrast between the background and domains at all applied fields we optimize the high order terms in the forward and reverse reorientation directions independently. We believe this is reasonable because the two cases are being reoriented (stressed) from different starting positions. We therefore use for the restoring torque the empirical form

$$
\begin{aligned}
T &= T_0(\phi-\phi_0)+T_2(\phi-\phi_0)^6 && \phi\geqslant\phi_0\\
T &= T_0(\phi-\phi_0) && -\phi_0<\phi<\phi_0\\
T &= T_0(\phi-\phi_0) && \phi\leqslant-\phi_0\\
&\quad + T_1(\phi+\phi_0)|(\phi+\phi_0)|^3
\end{aligned}
\tag{8}
$$

This form allows a good representation of the monopolar and bipolar pulse nucleation and switching time data, while also reproducing the correct domain/background contrast over a range of applied fields.

The fit to the time to nucleation and time to switch as a function of applied pulse amplitude is equal to that shown in figure 1 for monopolar pulses, and is shown in figure 2 by dashed lines for bipolar pulses. Clearly this is now a far more adequate reproduction of the data. We also show in figure 3 the data and theory for switched area as a function of pulse separation, where the pulses are equal in duration and of opposite polarity. For zero pulse separation this is of course a bipolar pulse, whereas if the separation is sufficient for total relaxation to occur between the pulses it reduces to the monopolar case. The good comparison shows that the theory we have developed is useful not only in the cases of switching from a relaxed state (monopolar) and highly stressed state (bipolar), but also in regions between these.

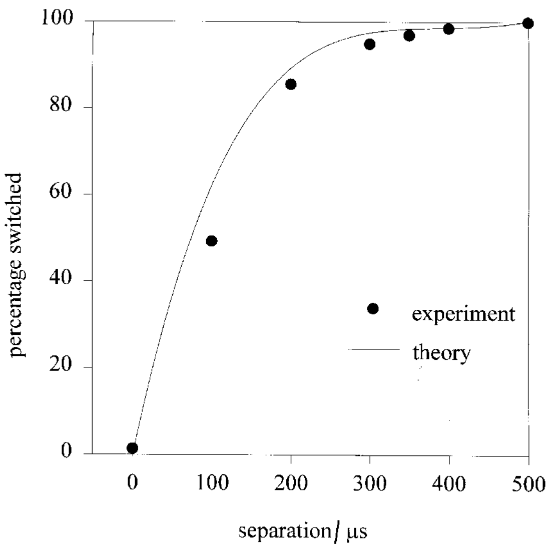

Figure 3. Variation in switched area as a function of separation between opposite polarity pulses, 17 V amplitude and of 50 µs duration.

5. Conclusions

In this paper we have discussed the further development of the three variable approach to modelling switching in ferroelectric liquid crystal devices. In particular we have extended the approach to allow the modelling of both monopolar and bipolar switching, and also the variation in switched area as a function of pulse separation. We have shown that a rather complex empirical form is required for the restoring torque, and it remains to be seen if this ultimately limits the usefulness of the approach. In future work we intend to investigate the use of the developed theory in modelling and designing addressing schemes for FLC displays.

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