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# Multi-Dimensional Switching and Low-Dimensional Modelling in Ferroelectric Liquid Crystals

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The switching mechanism in ferroelectric liquid crystals takes place through domain formation and evolution, and therefore can be considered as a multi-dimensional process with variation in the director orientation over the area of a switched region as well as with time. It has become commonplace to model the switching using very simple low-dimensional models which do not allow for this. We discuss why these appear to be quite successful, and how the modelling fits in with reality. It is seen that at reasonable switching voltages low-dimensional modelling works well in correctly predicting the time to domain nucleation. At higher voltages this nucleation time dominates and therefore the model is reasonable in this regime.

*Keywords: Ferroelectric liquid crystal, domains, switching*

## INTRODUCTION

Interest in ferroelectric liquid crystals has evolved largely due to their potential for applications in display devices,[1] and this interest continues even though nematic liquid crystal display technology is now well developed. There are a number of reasons for the continuing interest in these materials: (i) the switching mechanism in ferroelectric liquid crystal devices is intrinsically bistable (at least in the ideal case), this potentially allows large passively addressed displays to be constructed; (ii) the switching process in these materials is faster than that available in nematics which has sparked interest in sequential colour etc. (iii) the nature of the optical switching mechanism employed in ferroelectric liquid crystal devices leads to a wider viewing angle which is important in many display applications. However even though there has been considerable global research effort in ferroelectric liquid crystals there are still a very limited number of commercial devices available. This is because of a combination of factors including difficulty in obtaining well controlled alignment and the complexity of director structures which form.[2]

## MODELLING AND REALITY

One area where there is continuing development in ferroelectric liquid crystal research is the modelling of switching processes in devices. This is clearly a very important topic

for practical device development, but is difficult to tackle because of the complexity involved. Full continuum theory for ferroelectric liquid crystals is under development, but is not yet at a stage where it can be usefully employed in modelling real devices.[3,4] Because of this difficulty various models have evolved in order to explain the switching processes, and for use in the prediction of structures in development of devices prior to fabrication. These models have been what could be termed low-dimensional, involving either the assumption of a uniform director profile in the device[5] (zero-dimensional in space), or allowing for variation in the profile across the thickness of the device only[6] (one-dimensional in space). The former simple zero-dimensional model has been that most commonly applied in switching studies. Models such as this may include a number of factors, and can generally be written in the form:

$$\eta \frac{d\phi}{dt} = T_p + T_k + T_e \tag{1}$$

where the left hand side is the viscous torque and the right hand side represents the applied torques. Within this $T_p$ is the torque due to interaction between the spontaneous polarization and externally applied field, $T_k$ is the restoring torque due to surface interaction and $T_e$ is the dielectric torque due to dielectric anisotropy and biaxiality.[7,8] These can be written as:

$$T_p = -P_s E \cos\delta \sin\phi \tag{2.1}$$

$$T_k = T' \cos\phi (\sin\phi_0 - \sin\phi) \tag{2.2}$$

$$T_e = \varepsilon_0 \partial\varepsilon E^2 \cos^2\delta \cos\phi \sin\phi \tag{2.3}$$

where $P_s$ is the ferroelectric liquid crystal spontaneous polarization, $E$ is the applied switching field, $\delta$ is the smectic layer tilt angle, $\phi$ is the azimuthal angle of molecular director measured around the cone of allowed director orientations, $T'$ is a surface restoring torque, $\phi_0$ is the relaxed director azimuthal angle and $\partial\varepsilon$ is the dielectric biaxiality term.[7] This set of equations can be further modified to allow for effects such as ionic content of devices, but has generally been applied as above.

This type of modelling has been used by Towler *et al.*[9] and Jones *et al.*[10] to investigate the effects of dielectric biaxiality in ferroelectric liquid crystal switching, and by Maltese *et al.*[11] to model switching in response to various addressing wave forms. In these cases (and others) this modelling proved quite successful. In the dielectric biaxiality studies it was shown that the model could reproduce the minimum switching time voltage, where switching is defined as latching the ferroelectric liquid crystal device between states. In Maltese's work the model was not only used to demonstrate switching for well known addressing schemes but was also used successfully to develop new fast addressing schemes. Thus it is generally seen that this zero-dimensional modelling of switching in ferroelectric liquid crystal devices is very useful. This is however not how real devices switch.

In a real ferroelectric liquid crystal device the switching generally takes place through the formation and evolution of domains; it is therefore a multi-dimensional

process. This has been investigated by a number of workers,[12,13] and the process is seen to vary depending on the precise construction of the device. In devices with the commonly used C2 structure in the smectic layering[14] the switching takes place as follows.[15] On field application the director begins to rotate around the smectic cone in response to the dipole interaction, this takes place in the bulk of the liquid crystal layer but not in the centre of the device where the director is pinned at the chevron interface. After a certain time the internal elastic stresses balance the field torque terms and an equilibrium is reached. Although the reorientation in this state can be considerable, if the field is removed the device will still relax back to the original state. At about the point when equilibrium is reached domains appear. These occur when the pinned point at the chevron interface switches to the opposite state. The domains then evolve until they cover the entire device and the ferroelectric liquid crystal layer is switched into the opposite state. Removal of the field now allows the device to relax into the switched state. The switching takes place through this process over a wide voltage range (at least 2 orders of magnitude), although it is possible that a uniform bulk switching process takes over at higher voltages. Switching through the formation and evolution of domains is somewhat different from that predicted in the zero-dimensional models, which are therefore clearly incorrect for moderate driving voltages. The question as to why this type of modelling is reasonably useful is therefore raised.

## ILLUSTRATION

The fundamental differences between the results of the modelling and those obtained in practice can be demonstrated by considering the transmission/time curves during switching for each case, where the device is placed between crossed polarizers in the conventional way. Modelling based on the theory as presented by Maltese *et al.*[11] is illustrated in Figure 1. The liquid crystal parameters are chosen to be representative of the device studied experimentally, with appropriate smectic layer tilt angle, relaxed director orientation and relaxation time. In order to study switching in a simple way the device model is addressed with a single pulse of fixed duration but with variable amplitude. Two regimes are evident in this case. One where the pulse is below a critical height and latching into the opposite state does not occur (Figure 1a). In this regime the director begins to reorient in response to the field application but relaxes back to its original state when the field is removed. In the second regime (above a critical pulse height) latching into the opposite state does occur (Figure 1b–f). In these cases sufficient reorientation has taken place during the field application for the director to be beyond a position where the surface restoring torque moves it into the second stable state when the field is removed. These predictions are clearly consistent with the nature of the model used, and indeed may be what we would initially intuitively expect to see for a real ferroelectric liquid crystal device.

In Figure 2 we show the results of similar single pulse addressing for a real device. This device contains the ferroelectric liquid crystal material ZLI4655 (Merck Ltd.) and has a C2 structure[14] induced through a small tilt in the surface alignment. In this case there are three regimes of interest. Below a certain critical amplitude ($V_{nuc}$) the device behaves similarly to the model in that reorientation takes place during the field

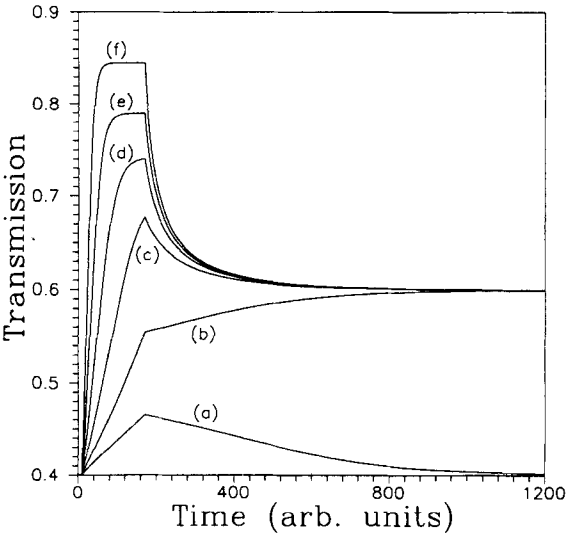


FIGURE 1 Plot of transmission as a function of time for the zero-dimensional theoretical model. The curves are for a range of arbitrary pulse amplitudes and illustrate that (i) latching into the switched state is always clean, and (ii) latching occurs if the director rotates beyond the mid position. Pulse amplitudes are in the sequence: (a) $V =$ V', (b) $V = 2$ V', (c) $V = 4$ V', (d) $V = 8$ V', (e) $V = 16$ V' and (f) $V = 32$ V'.

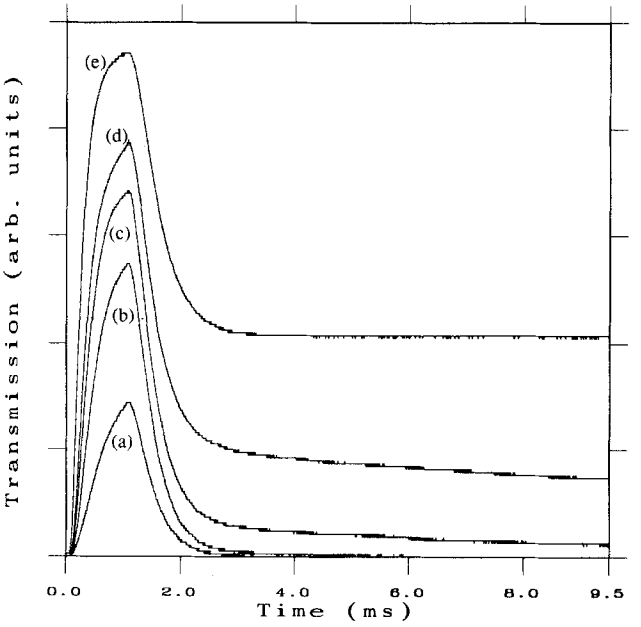


FIGURE 2 Plot of transmission as a function of time for a real device, again with various pulse amplitudes. These are: (a) $V = 1.0$ V, (b) $V = 2.0$ V, (c) $V = 3.0$ V, (d) $V = 4.0$ V, (e) $V = 10$ V. Note here that (i) latching into the switched state is not clean as there are various multi domain states which can occur (e.g. (d)), and (ii) the director can move well past the mid position and still return to the pre switched state when the field is removed (e.g. (b)).

application, but the device relaxes back to its original state when the field is removed (Figure 2a, b). Also above a certain higher critical voltage ($V_{sw}$) the device is latched into the opposite state (Figure 2e). There is however also in practice a third region between $V_{nuc}$ and $V_{sw}$ where partial switching takes place (Figure 2c, d). In this regime the domain switching process described above is partially complete; i.e. domains have nucleated and begun to evolve, but have not covered the entire device area during the applied switching pulse. Therefore when the field is removed there are regions in both the original and the switched states, resulting in a net transmission between the two. There are other important differences which are highlighted by comparison of Figures 1 and 2. For example in the modelling case (Figure 1) the director always latches into the opposite state if it moves beyond the half way point. This is clearly not the case in practice (Figure 2). In a real device the latching depends on whether the director at the chevron interface has switched, and this does not always occur just because there is significant bulk director reorientation. Indeed the director profile can reorientate into an extremely stressed state before this occurs, resulting in very little contrast between the background and domains during switching. This leads to a situation where for all switching pulses the transmission/time curves follow a similar form while the field is applied, with a large part of the change in transmission being due to the director moving elastically into the stressed states. Such a form is clearly not followed in the simple modelling, as can be seen in Figure 1. In the model the elastic torques help the switching once the director has moved part way in the reorientation process, leading to more rapid reorientation in these cases. Thus these comparisons illustrate the differences between the theory and practice, but do not directly serve to suggest why the theory works reasonably well in many situations.[9-11]

We therefore wish to consider where the model fits in with real switching and why it proves useful in practice. If bulk switching were the correct mechanism at higher voltages, we may expect the zero-dimensional model to work well in this regime, as at this point any stress in the material (i.e., profile change) could be absorbed into the other parameters. However as this is apparently not correct (i.e., domain switching takes place at all moderate voltages[15]) we cannot expect correct results beyond the point of domain nucleation. We are therefore interested in comparing the performance of the model with a real device up to and after domain nucleation. In order to do this we will examine the times for nucleation and switching in the experimental work. This will allow us to evaluate how the model fits in, as it would be expected to work well for the time up to domain nucleation during field application where the director profiles are uniform over the entire pixel, but of course cannot describe the regime where domains are evolving and would therefore not be expected to predict the correct transmission/time form during and after field application.

## RESULTS

The time to nucleation ($t_{nuc}$) and time to switch ($t_{sw}$) are shown for various illustrative pulse amplitudes in Table 1. These data were obtained using a stroboscopic polarizing microscope, where a switching pulse was applied to the device and images of the switching process were taken at the end of the pulse. The pulse duration was then varied

TABLE I

Illustrative data for the time to nucleation ($t_{nuc}$) and the total switching time ($t_{sw}$) for the device considered here

| Applied pulse (V) | Nucleation time (ms) | Switching time (ms) |
|---|---|---|
| 1 | 2.5 | 43 |
| 2 | 0.8 | 10 |
| 3 | 0.42 | 5.5 |
| 4 | 0.29 | 2.5 |
| 5 | 0.23 | 1.25 |
| 6 | 0.18 | — |
| 7 | 0.16 | — |
| 8 | 0.14 | 0.4 |
| 9 | 0.12 | 0.33 |
| 10 | 0.11 | 0.27 |
| 13 | ~0.085 | ~0.185 |

in order to determine the length of pulse required to just cause nucleation and length of pulse to just cause complete switching. These data are difficult to obtain at higher voltages because the background/domain contrast becomes very low, although the device does apparently still switch through domain formation and evolution. We are therefore restricted to modest pulse amplitudes in this study. The time between $t_{nuc}$ and $t_{sw}$ is the regime of domain evolution, and if a pulse of duration $t_{pulse}$ such that $t_{nuc} < t_{pulse} < t_{sw}$ is applied a partially switched state occurs.[16]

Firstly it is interesting to consider the nucleation time. Recall that the nucleation and subsequent domain switching take place at the point that reorientation into a pre-switching stressed state is complete, and that for most reasonable voltages this state is very similar to the final switched state. This has been discussed before,[15] and leads to a situation where the contrast between the stressed background and evolving domain is very small, because most reorientation has occurred before domain formation. We might therefore expect the time to nucleation to follow closely the simple predicted time from the modelling. Now for the moderate voltage regime considered in the data above the dielectric term in the theory is small and can be neglected. In addition the relaxation time for the device is ~2 ms. As this is due to the bulk distortion and surface torque terms which are all covered by the single elastic term in the model this can also be neglected for switching times $\ll$ 2 ms. This leaves just the polarization torque term, and solution for this leads to the well known result of $t_{sw} \propto 1/V$ or $Vt_{sw}$ = constant. We plot in Figure 3 both $Vt_{nuc}$ and $Vt_{sw}$ from our data as a function of voltage. As expected there is a reasonable range over which $Vt_{nuc}$ has converged to a constant value.

This result is interesting, demonstrating that the model works well in what might be termed the elastic regime, but does not demonstrate why in practice the model is useful generally. However we also show in Figure 3 a plot of $(t_{sw} - t_{nuc})/t_{nuc}$ against $V$. This represents the variation in the time for domain growth in comparison with the nucleation time for varying switching voltages. The change of this with voltage is fitted empirically and roughly follows a $(t_{sw} - t_{nuc})/t_{nuc} \propto 1/V$ form. Time of domain evolution depends on domain wall velocity and number of nucleation sites, both of

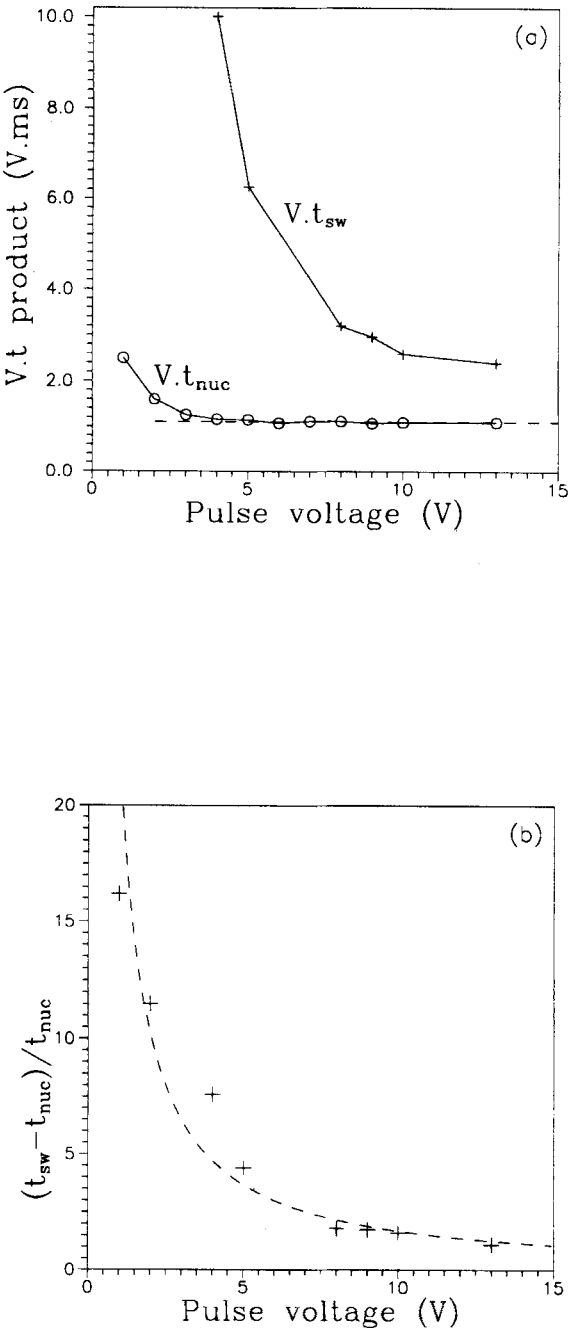


FIGURE 3 Plots of (a) $V \cdot t_{nuc}$ and $V \cdot t_{sw}$, and (b) $(t_{sw} - t_{nuc})/t_{nuc}$ against voltage for switching in a ferroelectric liquid crystal device. Note that $V \cdot t_{nuc}$ is approximately constant over a reasonable range of applied voltage pulse amplitudes (as indicated in (a) by the dashed line), and that $(t_{sw} - t_{nuc})/t_{nuc}$ approximately follows a $1/V$ form (shown in (b) by the dashed line), indicating that the relative time of domain evolution compared with time to nucleation decreases as the applied voltage increases.

which are voltage dependent. Also domain walls can become pinned during evolution. As the nucleation sites and wall pinning vary from cell to cell there is some variation in the domain evolution time, although the observed trend appears to be general. This indicates that although the switching takes place through the formation and evolution of domains over a wide range of voltages, at higher voltages the time of domain growth becomes small in comparison with the time of nucleation. As the zero-dimensional modelling is reasonable for the pre-nucleation period we therefore can see that it will become useful when $t_{nuc} > t_{sw} - t_{nuc}$. For the device investigated here this occurs for pulses $> \sim 10$ V in amplitude.

## CONCLUSIONS

We can see that simple zero-dimensional modelling reproduces the time to nucleation well. The time to switching is however not well reproduced for smaller voltages, but the model works quite well at larger voltages. This is because at voltages $< \sim 10$ V the domain evolution to latching time is greater than the nucleation time, but for voltages $> \sim 10$ V the evolution to latching time is less than the nucleation time. Even in this case it is probable that the viscosity constant generally used in the modelling, which is itself derived from switching measurements, is in fact not the true value but is in effect adjusted to compensate for the time of domain evolution. This would then allow the modelling to predict latching reasonably well, even though the theoretical mechanism is incorrect.

Thus the modelling works not because a collective switching mechanism takes over at higher voltages (although this can appear to be the case as the background-domain contrast becomes low), but because the bulk reorientation time becomes greater than the domain evolution time. (It is for this reason that $t_{nuc}$ versus voltage curves vary smoothly with increasing voltage, rather than showing a transition where bulk switching might take over.)

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