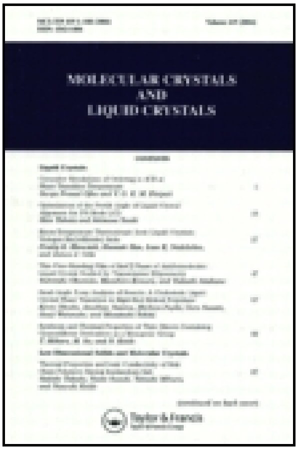

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Modelling Switching and Optics in Ferroelectric Liquid Crystal Microdisplays

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Modelling Switching and Optics in Ferroelectric Liquid Crystal Microdisplays

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Switching in surface stabilised ferroelectric liquid crystal (SSFLC) cells takes place through the formation and evolution of domains, which can grow up to many tens of microns in size. Domain growth can be described by the Avrami model, but this relies on a statistical distribution of the number of nucleated domains, and hence a large number of domains are required for this model to succeed. We discuss the limitations of this model, for example in a micro-display pixel, which is between 10-20 microns in size, and therefore only a few domains exist within each pixel. We also investigated the effects of light scattering during partial switching. Light scattering through domains is modelled using the Finite Difference Time Domain (FDTD) method, and shows good agreement with experimental results.

Keywords: modelling; switching; optics; SSFLCs; domains; scattering

INTRODUCTION

Surface stabilised ferroelectric liquid crystal (SSFLC) structures, which were discovered by Clark and Lagerwall [1] are able to reorient on the application of a DC field due to the coupling between the spontaneous polarisation and the applied electric field. In such devices, a chevron structure generally exists, where smectic layers are tilted with respect to the substrate normal and a cusp forms in the centre of the cell. The chevron structure supports switching between two stable states, which is initiated by the latching of the chevron cusp from one side of the smectic cone to the other.

Under a polarised microscope, this switching process can be observed as follows: the device is initially in a uniform state, say white. Upon field application, black boat-shaped domains can be seen to appear, representing nucleation sites where the directors have already switched to the opposite stable state. These domains can be seen growing from these nucleation sites at the expense of the white background, until they finally coalesce and the whole device can be seen to have switched to the opposite black state. Removal of the field now allows the device to relax into the newly switched state, and the device remains black.

MODELLING OF SWITCHING IN SSFLC CELLS

We have modelled the switching within SSFLCs using what we term the "Three Variable Model in One Dimension" [2]. As its name implies, this model involves three variables: $\phi_1(z)$, the director orientation for the background state through the thickness of the cell; $\phi_2(z)$, the director orientation for the domain state through the thickness of the cell; and **A**, the ratio of the domain area to the total device area. Details of the modelling using these three variables are explained in Ref. [2], and we were able to demonstrate that over a wide range of voltages, this model indeed reproduced the switching characteristics of an SSFLC cell.

Experimentally, we applied a waveform containing a series of monopolar pulses to an SSFLC cell, and noted, for a given pulse amplitude, the pulse width required to give rise to nucleation(t_{nuc}) and total switching(t_{sw}). Figure 1 illustrates the comparison of experimental data to the theoretical fit produced by our model. The shaded region between the t_{nuc} and t_{sw} curves define the partial switching regime, where the cell is in a mixed state of domains and background.

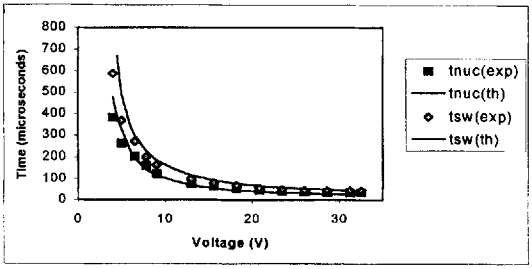

FIGURE 1. Comparison of the modelling of switching characteristics using the "Three Variable Model in One Dimension", with experimental results.

MODELLING DOMAIN GROWTH

In the "Three Variable Model in One Dimension", the growth of the domains was characterised by the Avrami theory [3]. However, the use of the Avrami theory is an approximation which relies on a homogenous distribution of nucleation sites, and is particularly useful for describing a large device area. However, we now consider the limitation to the Avrami theory, where the domain area is comparable to the size of the pixel. The typical size for a microdisplay pixel is 10-20 microns, and during switching there may exist only a few domains within each pixel.

We investigate the progression of the domain growth within a pixel of size 20 microns x 20 microns, using stroboscopic microscopy. A bipolar pulse of a known amplitude is applied to the pixel, and images of the growing domains were captured at regular intervals. The total domain area was then plotted as a function of time. We also simulated the domain growth process by generating domains within an active area of 100 x 100 elements. The nucleation sites were randomly seeded within this area, and the domain wall velocity was set to be proportional to the applied electric field [3].

The experimental results were compared with the predicted domain growth using the statistical simulation described above, and also the predicted domain growth using the Avrami theory. It can be seen from Figure 2 that for a low number of nucleation sites (due to a low applied voltage), the experimental plot is best described by the statistical model (compared to the Avrami model). However, as the number of domains increases, the theoretical curves of the statistical model and the Avrami model increasingly converge.

In microdisplay pixels only a low number of domains may be present, and we see that the description of the domain area growth in this case is best described by the statistical model. As the calculation for the transmission of light is dependent upon the domain area, the right description of the domain area growth is essential for correct modelling of the transient transmitted light through the microdisplay pixel. We also wish to investigate whether there are other factors that affect the transmission of light through the microdisplay pixel, for example the effect of scattering from domain walls.

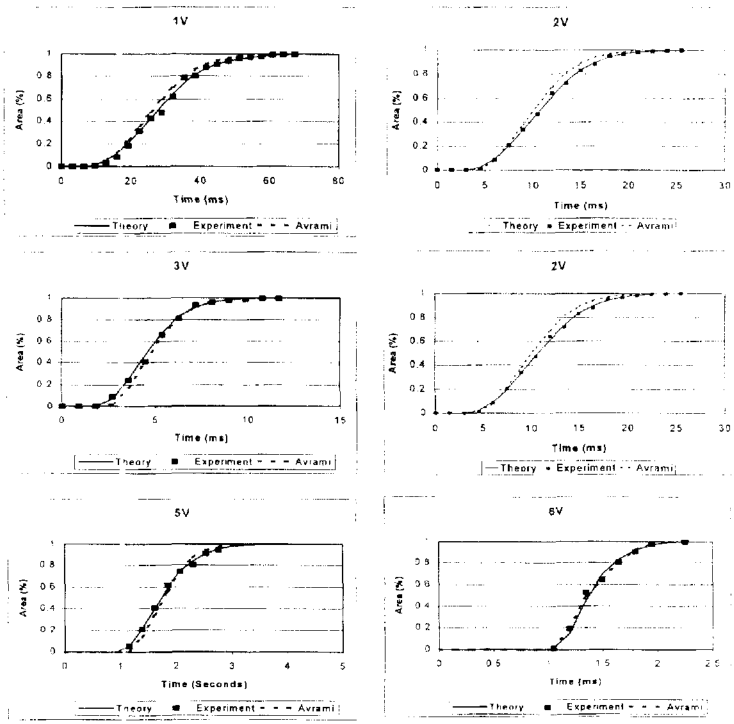

FIGURE 2. Comparison of the experimental area growth within an area of 20 μm x 20 μm, with the theoretical prediction according to the Avrami model and Statistical model.

SCATTERING FROM DOMAIN WALLS

Experiment

The SSFLC cell was placed above the centre of a rotation stage on which was mounted a photodetector. The 2.7 micron thick SSFLC cell was filled with SCE8 material which was in its Smectic C phase at room temperature. Light from an s-polarised laser beam was shone onto the cell at normal incidence. The diameter of the laser beam was 0.8mm, and the divergence of the beam was 1 mrad. The illuminated area was chosen to be free of defects, and the cell was placed in an "equilibrium orientation", i.e. where the transmission levels for the two opposite stable states were equivalent. The cell was forced into a mixed switched state, upon the application of a waveform which contained a series of DC-balanced monopolar pulses. These monopolar pulses were of an amplitude which were sufficient to partially switch certain parts of the cell into the opposite stable state via domain formation, but were insufficient to totally switch the whole cell to the opposite stable state. This partially switched state was determined by observing the transmission response of the cell through crossed polarisers. By visual inspection, we could observe a significant increase in scattering intensity in the partial switching regime, and we attribute this scattering phenomenon to the presence of the multi-domain structure.

It was found that the scattering pattern was strongest when an analyser was placed perpendicular to the input polariser, indicating that the light scattered by the domain structure was highly depolarised. Figure 3. (a) shows the straight-through transmission response of polarised light through the cell at equilibrium position, and Figure 3. (b) shows the scattering response at 4° off the normal axis.

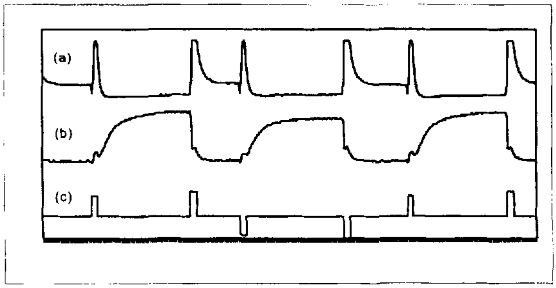

Figure 3. (a) Straight through transmission for a cell in its equilibrium position. (b) Scattering due to the partial switching pulse. (c) Plot of applied waveform.

We measured the level of scattering due to monopolar pulses of different pulse widths and amplitudes by placing a photodetector at 4° off the normal axis. Figure 4 shows the plot of scattering intensity as a function of applied voltage. This plot shows that the cell exhibits the maximum scattering during the partial switching regime, with the scattering intensity increasing with increasing voltage amplitude. This partial switching regime corresponds to the shaded region in Figure 1 and may be modelled by the "Three Variable Model in One Dimension".

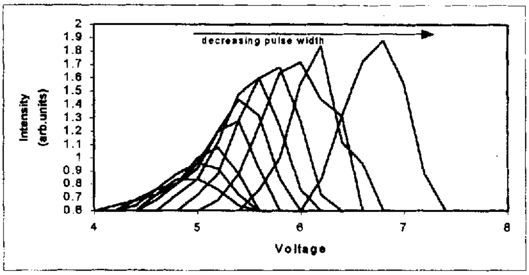

FIGURE 4. A plot of the intensity of scattered light as a function of voltage and pulse width.

An angular scan of the scattered light due to the domains in this partially switched state was obtained, by scanning the photodetector using the rotation stage. We obtained the angular scattering profiles due to monopolar pulses of different pulse widths and amplitudes, and compared them with the angular scattering profile for an unswitched cell, as shown in Figure 5. We confirm our previous observation that the amount of scattering in a partial switching regime is significantly greater than in the non-switching case; and increases with applied voltage. We also note that the scattering angles increased as the pulse amplitude was increased.

We also obtained stroboscopic images of these partially switched states for the recorded pulse widths and amplitudes, in order to measure the size of the domains produced. It is found that the typical domain sizes range from 10 microns for an applied voltage of 4.7 V, to 4 microns for an applied voltage of 6.3 V.

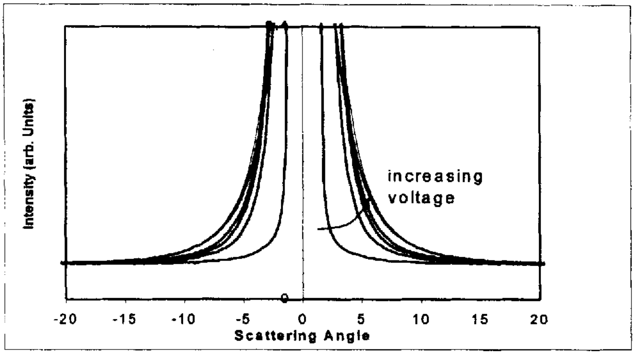

Figure 5. The scattered light intensity as a function of scattering angle.

THEORETICAL MODELLING OF LIGHT PROPAGATION THROUGH DOMAIN STRUCTURES

To analyse the propagation of light through domain structures, including walls in a rigorous and consistent way, the finite-difference time-domain (FDTD) method was chosen. The FDTD method is a purely numerical method providing an explicit solution to Maxwell's equations in both time and space. The mathematical and numerical details of the FDTD method in solving light propagation in FLCs can be found in Ref. [4]. The use of the FDTD method to investigate light propagation problems in liquid crystals is relatively new [5][6][7], but it has significant advantages over the more conventional Berreman method when the distortions within the liquid crystal director profile are of the scale of the propagating optical wavelength in more than one dimension.

The director profile through a region of an SSFLC cell containing a single background/domain interface is obtained, by solving a continuum model using a simple relaxation routine. Light propagation through this region was studied by applying the FDTD method. The FLC material is considered to be uniaxial, with an ordinary refractive index n_{ord}=1.486 and extraordinary refractive index n_{ext}=1.646. These refractive indices are used in conjunction with the twist/tilt director profiles obtained from the continuum model to evaluate the dielectric tensor variation within the SSFLC. Glass plates having a refractive index n_{glass}=1.5 provided support for the FLC material. The cell was oriented at an equilibrium position between crossed polarisers, i.e. both the background and domain transmission levels were equivalent. The variation of intensity across this region is shown in Figure 6, where the position of the domain wall is indicated by a very distinct dip in intensity. It is important to note the oscillations in intensity close to the wall structure which are due to scattered light from the wall. This would be missed by more conventional (Berreman) approaches.

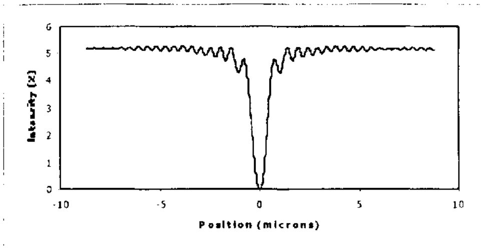

FIGURE 6. Variation of intensity across a background/domain interface.

In order to simulate a realistic profile of domain distribution within the sampled area, we generated a random sequence of domain walls. We then obtained, using a Fourier Transform method, the intensity spectrum due to this sequence, as a function of the scattered angle. The angular distribution of this spectrum compares well with the experimental results of the angular scan of scattered light due to the partially switched cell.

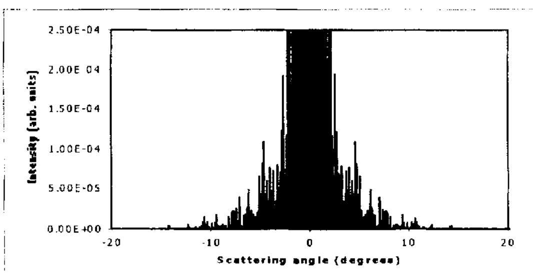

FIGURE 7. The intensity spectrum through a partially switched region that consists of a random distribution of domains and background.

CONCLUSION

Due to its small size, the modelling of switching and optics of an FLC microdisplay pixel is different from a normal large area display pixel. We have shown that the growth rate of the domains within these pixels may be described successfully by a statistical model. We also modelled the optics of domain structures in SSFLCs using the FDTD method. This approach is necessary due to the fact that the distortion of the liquid crystal director profile (due to domain walls) is of the scale of the propagating optical wavelength. Using this method, we have obtained a theoretical prediction of the scattering due to domain walls, which shows considerable agreement with our experimental results.

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