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Stressed states in domain switching of ferroelectric liquid crystal devices

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In this paper we show that the director profile of a low pre-tilt surface stabilized ferroelectric liquid crystal passes through quasi-static stressed states during domain switching under direct drive conditions. Using polarized stroboscopic microscopy, we have observed two quasi-static transmission levels during a domain switching transition from dark to light. This is a result of the directors reorienting into stressed profiles both before and after the chevron interface has switched. By modelling the interaction between the elastic forces and the torque from the applied field, we have determined these voltage dependent director profiles and, by calculating their corresponding transmissivities, have shown very good agreement with the experimentally observed values.

1. Introduction

Since the discovery of ferroelectricity in liquid crystals in 1975 by Meyer *et al.* [1], and the subsequent demonstration of the device potential of surface stabilized ferroelectric liquid crystals (SSFLCs) in 1980 by Clark and Lagerwall [2], such materials have been studied extensively in order to understand their physics for use in practical applications. A particular area where liquid crystals have made a great impact is display technology, and although nematic liquid crystal displays are well developed, SSFLC displays can still compete, as they provide a wider viewing angle, faster switching times and can potentially consume less power, with passive addressing schemes by taking advantage of their memory states. In order to compete with the flat panel displays already on the market however, SSFLCs must be able to exhibit grey scale, as the two memory states are normally arranged to appear 'white' and 'black'. One solution to this problem is to find a way to control the formation of ferroelectric domains during switching [3, 4]. As the domains are normally just a few microns in size, the human eye will average the bright and dark areas and see a grey level. Switching from one state to the other in a FLC normally occurs via domain formation and growth, and therefore a fuller understanding of this type of switching is necessary not only for the production of grey scales but also for all device development.

When Handschy and Clark first used polarized stroboscopic microscopy to observe domain switching in 1982, they identified several key aspects [5]. As the applied amplitude of the switching pulse was increased, they observed a faster change in extinction angle, a greater number of domains nucleating sooner and growing faster, and a decrease in contrast between the domains and the background. The change in extinction angle was interpreted as a continuous reorientation of the directors in the

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centre of the cell, while the surfaces remained in their original positions. Domain switching then occurred when the surface anchoring energy was overcome. Ouchi *et al.*, discussed the disclinations at domain boundaries, and proposed several types of internal disclination loop to describe these boundary structures within smectic layers perpendicular to the cell surfaces [6]. The discovery of the chevron structure in the smectic layering [7] has led to a fuller understanding of the structure of the disclinations, and the previous models of the director profile in the smectic layering have been modified to take this into account [8]. Zuang *et al.*, have directly determined the director profile of the domains in various states for planar and high surface tilt chevron SSFLCs, using visible polarized light transmission spectra measurements [9]. This method provides direct information on the director profiles and has shown that for near planar surface alignment, the domain switching occurs at the chevron interface. In addition, the relaxed state structures for planar and high surface tilt cells have been determined by the excitation of guided optic modes in a FLC layer [10, 11].

In this work, the state of the director profile across the cell during the domain switching process is studied. This is observed under square wave direct drive conditions at the point of field reversal. Once steady states in domain evolution are observed, comparison between measured and predicted transmissivities for a model of the director structure allows the true states to be determined.

The cell used here is $2\,\mu$m thick and is filled with the FLC material ZLI 4655 (E. Merck) which has a spontaneous polarization of $7\,\mathrm{nC\,cm^{-2}}$. Before assembly, the cell surfaces were treated to produce a near planar low surface pre-tilt (around 2°), resulting in the chevron structure in the smectic layering and a director profile where the director at the top surface is constrained to lie approximately in the surface alignment direction and at the top of the smectic cone (defined here as $\phi \approx 0°$), while the director at the bottom surface is similarly aligned and constrained to the bottom of the smectic cone ($\phi \approx 180°$). If the director orientation is assumed to rotate smoothly from the surfaces to the chevron interface, where it is pinned at one of two positions, then a triangular director profile [12] results. The actual profile present may be more complex [11], but this model proves adequate here.

2. Experimental technique

The growth of domains during a switching sequence was monitored using polarized stroboscopic microscopy. A charge coupled device camera connected to a computer frame store is used to obtain an image of the cell (placed between crossed polarizers) that has been magnified by a × 10 microscope objective. Illumination of the cell comes from a spark flash lamp that has less than $1\,\mu$s duration. The delay between a positive to negative transition in the applied switching signal and the firing of the flash is controlled with an accuracy of $\sim 1\,\mu$s. Before data were taken, the cell was adjusted in order to find a uniform defect free area for study, and the orientation set to obtain maximum extinction from a fully switched state (which is assumed to occur when a constant $+5$ V is applied). In order to express the data in terms of true (absolute) transmissivities, values of minimum and maximum transmission were obtained by replacing the cell with a glass plate and measuring the transmission through both crossed and parallel polarizers. Also, the variation in intensity of the flash lamp from shot to shot was monitored, and this information used to normalize the data.

A 4 Hz square wave was applied to the cell and the images were taken once the domain evolution was consistent from cycle to cycle. An image processing package was then used to obtain useful data from the raw images. For example, calculating a histogram of the intensity distribution in the image is useful in determining the different intensities of the background and domain regions. If either region occupies a significant proportion of the observed area and the contrast is large enough, the histogram will exhibit two peaks, each peak occurring at the average intensity of a region. By extracting the average intensity of each region separately, we can compare their development with time and determine if a proposed director profile will produce the same transmissivity. A cross-section of the data may also be extracted by sampling the image on a particular line. In this way, we can more closely monitor nucleation and growth of a domain in any given direction. This information may then be used to supplement the histogram data which only gives the distribution of the entire domain and background intensities.

3. Results

During the switching sequence, we observed the nucleation and growth of boat-shaped domains which is consistent with what others have seen [3–6, 8, 9, 13–15]. A typical histogram of the intensity distribution determined from an image with both domain and background regions is shown in figure 1. The first peak occurs at the average intensity of the background region and similarly the second peak occurs at the average intensity of the domain region. An integral around these peaks is a measure of the approximate area each region possesses. This information would allow the study of the growth in size of domains [13]; however we are only concerned with the intensities of the separate regions. It should be noted that separation between the two regions seen in figure 1 (i.e. the domain contrast) is sufficiently large to determine the two intensities directly from this plot. When the domain contrast is low, however, the intensity distribution around the peaks overlaps significantly and the two intensities cannot be distinguished easily. Low contrast occurs both at higher voltages (> ~ 5 V p–p) and when domains first nucleate. In these cases. data are obtained by finding a threshold below which all the background region falls. By removing all of these values,

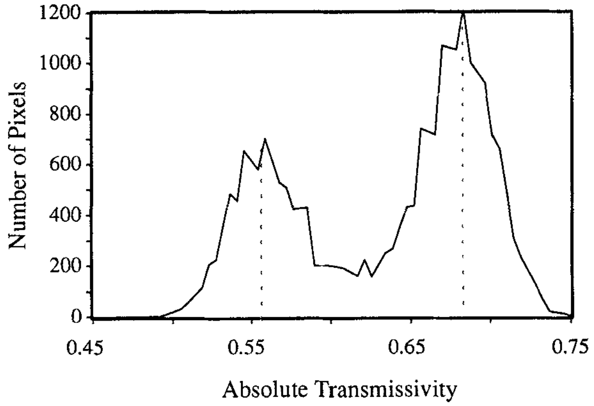

Figure 1. Histogram of intensity distribution in an image containing both domains and background regions. The image was taken 3 ms after field reversal from + 1·4 V to − 1·4 V (during a transition from dark to light). The first peak occurs at the average intensity of the background regions and the second peak occurs at the average intensity of the domain regions (these two intensities also appear as the 3 ms data in figure 2 (*b*)). Note that the second peak is larger because, at this time, the domains are occupying a greater proportion of the observed area.

a new histogram of the image will give a peak at the average domain intensity. These techniques allow the extraction of background and domain intensities at various times.

The transmission as a function of time from the beginning of the switching sequence for the two regions is plotted for three different applied peak to peak voltages in figure 2. Note that in all three cases, the entire area begins to increase its transmission before domains appear. Once the domains nucleate and grow, the background intensity seems to stop increasing, while the domain intensity appears to continue increasing on the same curve. Eventually, the domains fully coalesce and the background disappears (in figure 2 (*a*) the time-scale is not extended far enough to observe this). A plot of average transmission over the entire area will show a fast response to the initial increase of the entire area and a slow response corresponding to the domains nucleating and growing, while the background remains at a constant level. A similar average optical response has been noted before [6].

It is interesting to note that in the two higher voltage cases, the background intensity reaches a value which is over half the final intensity. Initially it might be thought that if the director has switched by over half way, then it would continue to move into the opposite state rather than switch via domain growth. Due to the pinning at the chevron interface of the smectic layering however, stressed states can occur where the bulk director has significant reorientation, but the region near the chevron kink has not switched. As the applied voltage is increased, the pre-chevron-switched stressed state becomes closer to the director profile of the post-chevron-switched stressed state. Therefore, the contrast between the two regions decreases as seen in figure 2, and previously observed by Handschy and Clark [5]. Even though the director profile in the pre-chevron-switched stressed state is close to the fully switched position, the profile will relax back to the original state upon removal of the driving voltage. If, however, the driving voltage is applied for longer, the profile will remain stressed and switching at the chevron interface will occur. A domain nucleation at, or a domain wall movement over, a point is therefore an indication that the chevron interface is switching.

In order to analyse more closely what happens to the director profile during domain formation, a cross-section was taken which passes through two domain nucleation points and runs parallel to the bows of the boat shaped domains. The cross-section at six different times during domain formation is shown in figure 3. Several characteristics of domain growth can be noted from this figure. The background intensity does not rise during domain nucleation and growth, indicating that a quasi-static director profile has been reached. At the domain nucleation point, however, the intensity continues to increase until it reaches a maximum level. Once this level is achieved, the domain wall moves outward, while the maximum level remains constant, here indicating a quasi-static director profile in the domains.

These quasi-static stressed states are voltage dependent and we can calculate the steady state director profile for various applied fields by solving the following equation:

$$K\nabla^2\phi + PE\cos\phi\cos\delta = 0$$

where K is the bulk elastic constant, ϕ is the director rotation angle (as defined in [6]), P is the polarization, E is the applied field, and δ is the smectic layer tilt angle. (The dielectric term has been dropped as the applied fields are not large.) This equation was solved using a finite difference method (as a diffusion equation [16]), starting from an initial relaxed state where $\phi = 0°$ and $180°$ at the top and bottom surfaces, respectively, and varies linearly across the cell until it reaches $\phi = \cos^{-1}(\tan\delta\cot\theta)$ at the chevron

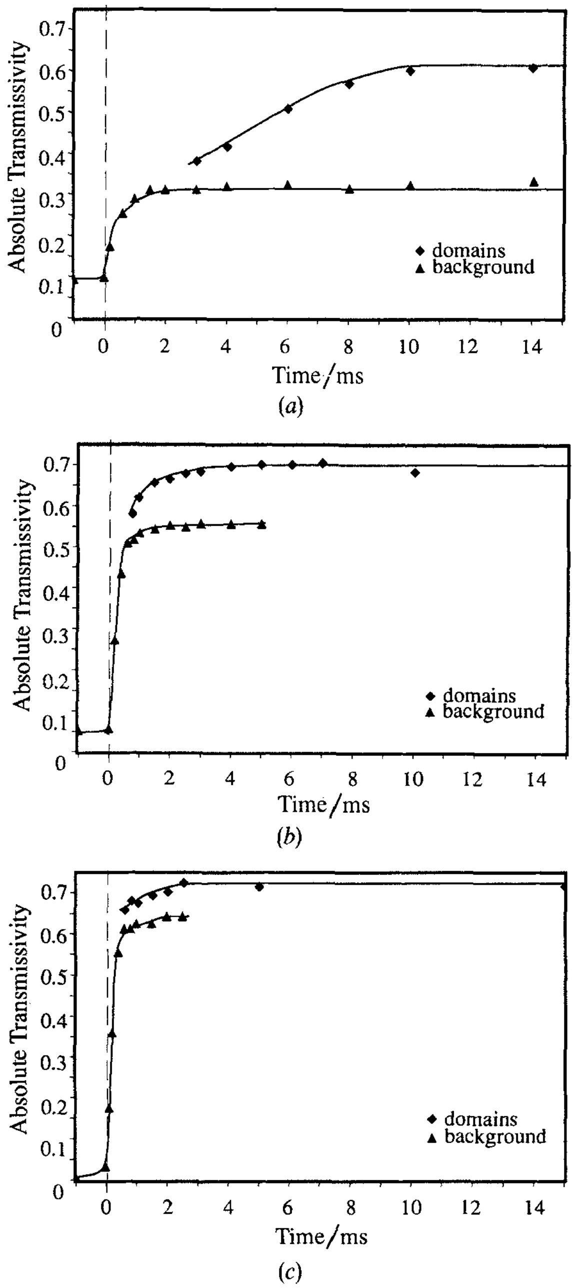

Figure 2. Plots of the rise in transmissivity for the background regions and domain regions as a function of time where the applied voltages are (*a*) 0·95 V p–p, (*b*) 2·8 V p–p and (*c*) 4·95 V p–p. The intensities at each time were obtained through histogram extractions similar to figure 1. At $t = -1$ ms, the applied voltage is still positive and field reversal occurs at $t = 0$ ms. The vertical scale is extended to 0·75, which corresponds to the transmissivity of the maximum stressed state (obtained when +5 V is applied to the cell).

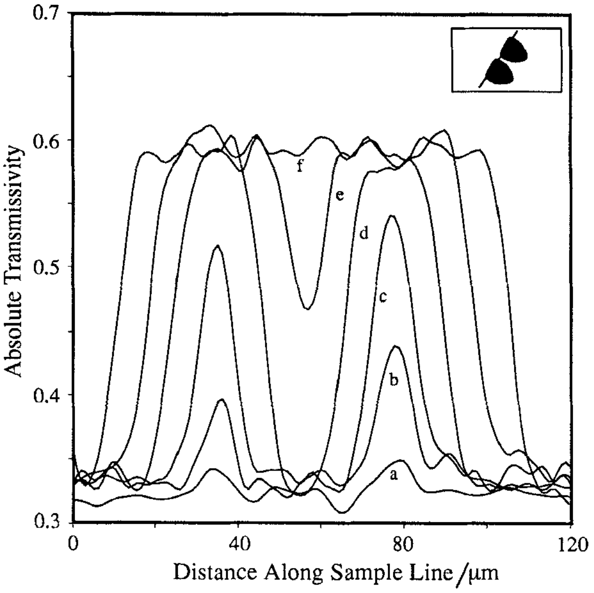

Figure 3. Transmissivity cross sections that intersect two domain nucleation points and run parallel to the bows of the boat shaped domains (as illustrated by the schematic inset). The applied voltage is 0·95 V p–p and the cross-sections were taken at (*a*) 3 ms (*b*) 4 ms (*c*) 6 ms (*d*) 10 ms (*e*) 14 ms (*f*) 22 ms. Note that once domain nucleation begins, the background intensity remains constant, and once the domain walls begin to grow outward, the domain intensity also remains constant.

interface (where θ is the cone angle). In order to perform the calculation, the left-hand side of the equation is set equal to $\gamma(\partial\phi/\partial t)$ (where γ is viscosity) and ϕ is calculated iteratively until $\partial\phi/\partial t = 0$. The elastic constant K is an unknown parameter and was modified to scale the theory to the correct voltages. Plots of ϕ across the sample for the pre-chevron-switched and post-chevron-switched stressed states at the three applied voltages of figure 2 are shown in figure 4. Note that the difference between the pre- and post-chevron-switched profiles decreases at higher voltages, which is consistent with the observed decrease in domain contrast. By calculating the transmission between crossed polarizers for these director profiles (as an average over wavelengths 425–600 nm, to allow for the output spectrum of the flash lamp), we can make comparisons with the experimentally measured transmissivities. The director profiles were calculated for the 'opposite voltage' post-chevron-switched (i.e., before field reversal), the pre-chevron-switched, and the post-chevron-switched stressed states over a range of voltages from 0 V–10 V p–p. Transmissions through these three director profiles at a number of voltages were calculated and are plotted in figure 5. The corresponding experimental values plotted in figure 5 are measures of the transmission of the 'black' state, the maximum transmission that the background reaches (pre-chevron-switched stressed state), and the transmission of the 'white' (post-chevron-switched stressed) state. Note that the two transmission values at zero voltage correspond to the two relaxed states, while the two transmission values approached as the voltage reaches 10 V p–p and beyond correspond to the maximum stressed post-chevron-switched states (i.e. $\phi \approx \pm\pi/2$). The comparison between experiment and theory is very good and demonstrates that the observed quasi-static transmissivities during switching are in

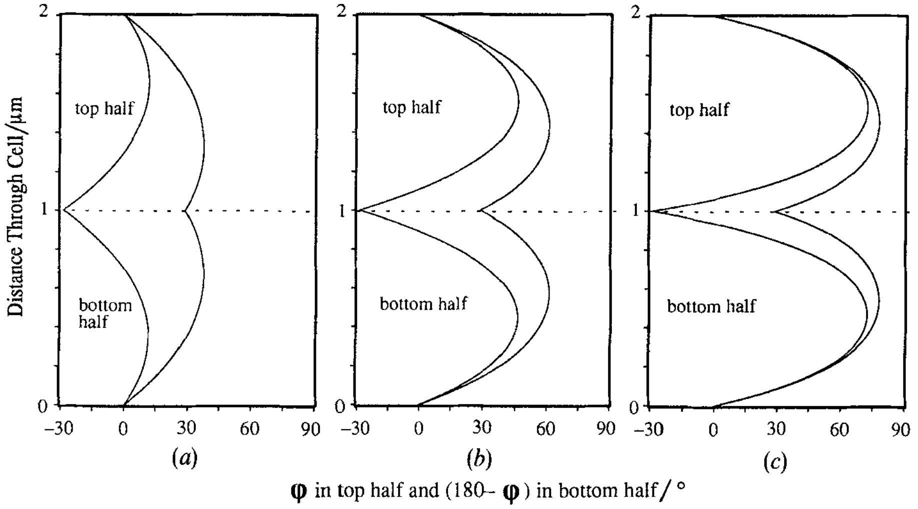

Figure 4. Plots of the variation of ϕ across the cell in the pre- and post-chevron-switched stressed states for applied voltages of (*a*) 0·95 V p–p, (*b*) 2·8 V p–p and (*c*) 4·95 V p–p as calculated from the equation. In order better to visualize the symmetry in the cell, ϕ is plotted in the top half and 180° – ϕ is plotted in the bottom half. Note that the difference between the two profiles decreases as the applied voltage is increased.

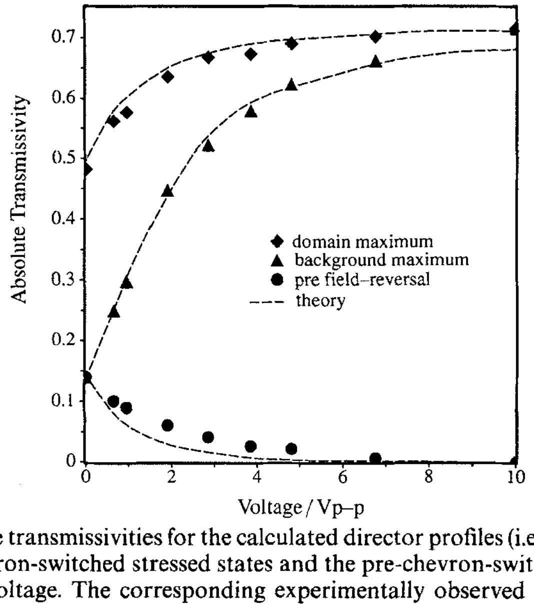

Figure 5. Plots of the transmissivities for the calculated director profiles (i.e. as in figure 4) for the two post-chevron-switched stressed states and the pre-chevron-switched stressed state as functions of voltage. The corresponding experimentally observed transmissivities were measured before field reversal ('black' state), at the maximum domain intensity ('white' state), and the maximum background intensity (pre-domain-forming stressed state) and are also plotted at several voltages.

fact due to voltage dependent stressed states in the director profile. The value of the elastic constant K obtained from fitting the theory to the data was $0{\cdot}4 \times 10^{-11}$ N, which is reasonable.

4. Conclusions

We have observed quasi-static transmission levels during a directly addressed domain switching transition in a SSFLC cell. These levels correspond to stressed states of the director profile before field reversal, before chevron switching, and after chevron switching. Starting from the dark state, a field reversal causes a uniform increase in the transmission of the entire area. This transmission rise was observed to reach a voltage dependent level and is a result of the bulk directors rotating around the cone until a stressed state is reached which balances the applied voltage. The director profile will remain in the pre-chevron-switched stressed state until either the voltage is removed, causing a relaxation back to the unswitched state, or (if the voltage is continued) the chevron interface switches. After the chevron interface switches, there is freedom for the directors to rotate further until elastic interactions again balance the applied voltage. The director profiles in these pre- and post-chevron-switched quasi-static stressed states have been modelled and their corresponding transmissivities calculated, showing very good agreement with the experimentally observed values.

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