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Dynamic processes in ferroelectric liquid crystal filled cells

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The switching process in a ferroelectric liquid crystal cell is of great interest. The precise way in which the optic tensor structure reorientates during switching between states is, however, difficult to determine. Here we consider the use of guided modes and surface plasmon-polaritons as techniques for the investigation of this. It is seen that because of the nature of the dynamic processes the guided mode data is inconclusive, but surface plasmon-polariton data show the surface reorientation mechanism.

1. Introduction

Ferroelectric liquid crystal materials have very interesting characteristics in terms of alignment properties and switching mechanisms. The ferroelectric material is a smectic liquid crystal, the molecules lying in a layered structure with a layer thickness of about one molecular length. The structure generally present in a thin cell ($\sim$2–4 μm thick) of ferroelectric liquid crystal includes a chevron in the smectic layering [1]. This is illustrated in figure 1, and has interesting implications for the mechanisms which operate in such a cell. Firstly it implies as illustrated, that for a uniaxial system the director (or more correctly the optic tensor major axis) is basically uniform throughout the cell in a completely switched state. This assumes that the surface alignment is such that the director lies parallel to the surfaces. It is also possible to form half splayed states, where half of the structure is uniform and the other half is splayed [2, 3], and these may prove useful in future practical devices [4]. This uniform relaxed state of the ferroelectric liquid crystal has been shown to be correct by the use of guided modes in a liquid crystal cell [5]. It has also been discovered that some materials together with suitable surface alignments can form a structure with uniformly varying twist in each half of the cell [6].

Of further interest is the switching mechanism (dynamic process) which takes place in a cell. It has been shown that under a forward bias DC field the ferroelectric liquid crystal distorts within the chevron structure of the smectic layers [7], but how does the switching process work under a reverse bias field? This process has been investigated using microscopic techniques [4], and also compared with theory, assuming a simple one elastic and one viscosity coefficient approximation for the liquid crystal layer [8]. It has been possible to model the director movement within the chevron structure on the assumption that the chevron cusp is an internal interface [2]. Here we seek to investigate the ferroelectric liquid crystal switching process using guided modes and surface plasmon-polariton techniques.

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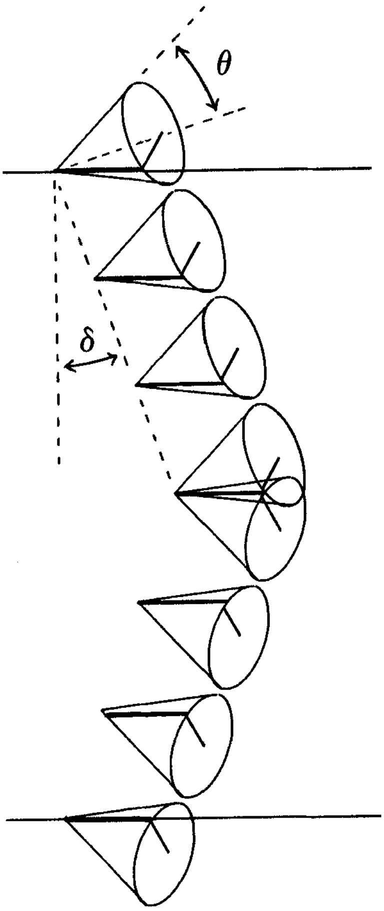

Figure 1. Schematic illustration of the structure present in a thin ferroelectric liquid crystal cell, the so-called chevron structure. In this the smectic layers are tilted by a characteristic angle δ, and the director is tilted by the smectic cone angle θ. In the relaxed state, the director lies parallel to the cell surface.

2. Method

Guided mode and surface plasmon-polariton techniques used for ferroelectric liquid crystal alignment investigation have been fully described elsewhere [9], and only a brief outline is given here. The cell is formed between glass pyramids which are coated with silver films approximately 45 nm thick. These provide reflective surfaces and so wave guide modes can propagate in the cell. They are also of optimum thickness to allow coupling to surface plasmon-polaritons on the silver surface. A layer of SiO about 20 nm thick is evaporated at 60° to the surface normal onto the silver films to provide low surface tilt alignment surfaces for the liquid crystal. The cell is assembled with a gap of about 3·5 μm and filled with the BDH material SCE3 in the isotropic phase. This is slowly cooled to the S_C^* phase at room temperature to provide a well-aligned sample. Guided modes and surface plasmon-polaritons can then be excited by light incident through one of the glass pyramids.

Data are recorded as the reflectivity signal from the cell and this is measured as a function of angle of incidence. This shows the excitation of guided modes and a surface plasmon-polariton as dips in the reflectivity, fitting theory to this allows the cell to be characterized. Those guided modes propagating in the bulk of the ferroelectric liquid crystal layer give information on the bulk alignment, while the surface plasmon-polariton which is localized at the silver surface leads to information on the near surface alignment properties of the liquid crystal. Voltages can then be applied to the cell and the effects of switching are revealed as changes in the reflectivity data.

3. Results

First the possibility of taking data during switching using a stroboscopic method is considered. We apply a slow AC signal across the cell, which causes the liquid crystal layer to switch between the two stable states. Data taking is then synchronized with this applied signal. In this way the reflectivity against angle of incidence data are taken in such a way that the reflectivity curve obtained is at a fixed voltage point during the switching process. It is then possible to examine this as representative of a fixed sampling point within the dynamic process. The changes in the guided mode structure seen should then tell us about the bulk reorientation mechanism. Data taken for an SCE3 cell at room temperature with p-polarized light during the switching process as the 0 V point is crossed are shown in figure 2. This is compared with the relaxed 0 V static state in the figure. The signal applied was ±5 V at a frequency of 0·1 Hz.

Clearly the data taken during switching are a bit of a mess! There are no sharp guided modes as would be hoped for, and as are seen in the relaxed state data. The form of the reflectivity curve is not reproduced for any reasonable model of the optic tensor profile in the cell. It indicates that the structure being sampled is in fact not quasi-static. So as the field is cycled, and data taking synchronized at a particular point, the structure is not identical for each cycle. The reason for this is quite apparent as the slow switching mechanism in a ferroelectric liquid crystal cell is known not to be uniform [10, 11]. The switching process actually consists of a complicated domain nucleation and growth mechanism. As this process occurs the movement of domain walls within the cell and across the probe beam lead to poor resonant guided modes and complicated, inconclusive data. It is thus seen that this technique of stroboscopic data taking, with slow cycling field application, is not good for investigation of the bulk switching process in a ferroelectric liquid crystal cell.

An alternative way to take data in order to examine dynamic processes is to fix the probe beam angle and follow the resulting reflectivity as a function of the applied voltage during switching. In this way the process can be followed, and data for a single cycle examined, thus overcoming the difficulty of different situations between cycles. The surface plasmon-polariton has its largest E field component perpendicular to the silver surface at which it is propagating, thus it is most sensitive to the tilt of the optic axis of the liquid crystal out of the surface plane during the switching process. Rotation of the optic axis out of the plane of light propagation, even if it remains parallel to the cell surfaces, will also perturb the surface plasmon-polariton excitation angle, but to a lesser degree. Thus the surface plasmon-polariton can be used to examine the surface reorientation process taking place. Data taken in this way in the surface plasmon-polariton region of the p-polarized reflectivity curve, with a cell rotated such that the optic axis in the relaxed state after application of a negative voltage pulse is parallel with the plane of light propagation are shown in figure 3. The data are taken at a fixed angle to the side of the surface plasmon-polariton minimum, at a point where the

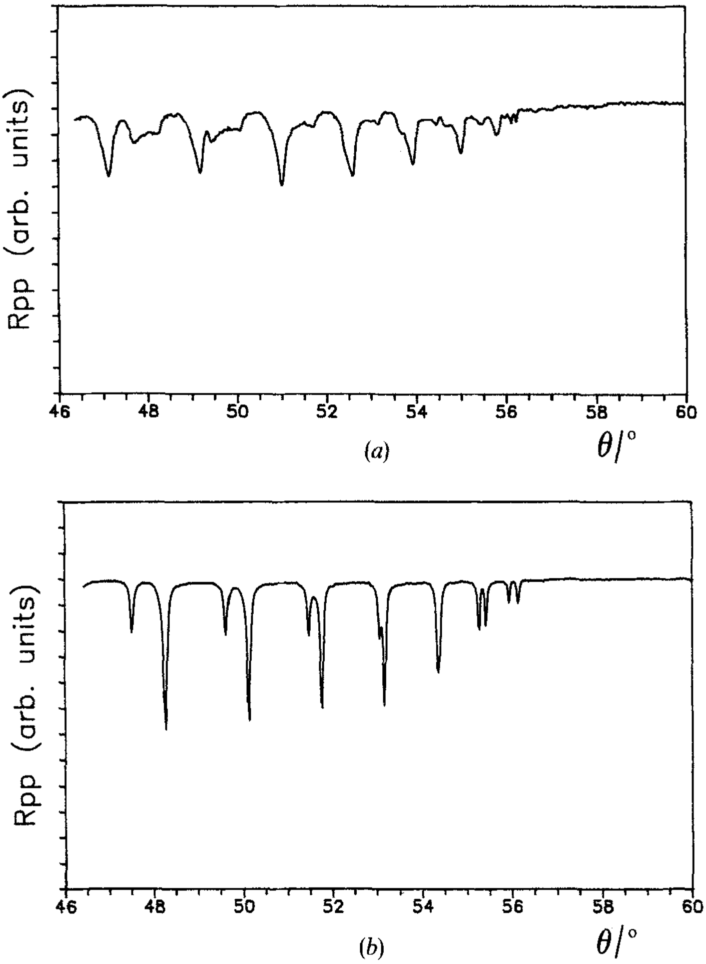

Figure 2. (*a*) Stroboscopically taken data, during the switching process at 0 V. This is for an SCE3 filled cell at room temperature. It is compared with normal data taken for the relaxed state (*b*), clearly the stroboscopic data is rather poor due to domain growth/nucleation processes.

reflectivity differential $\partial R/\partial \theta$ is large, thus changes in the ideal coupling angle are observed as changes in the reflectivity signal.

These data clearly show the switching features, and are much easier to interpret than the stroboscopic data of figure 2. We can understand it in terms of the near surface reorientation of the optic axis (director) of the liquid crystal during switching. With reference to figure 4 which illustrates the switching taking place, at point A the ferroelectric liquid crystal is in the relaxed state after a positive applied field and the optic axis lies on the surface of the cell, but twisted out of the plane of light propagation as set-up, the surface plasmon-polariton is thus at a minimum angle of excitation. When the field starts to become negative, even for a small bias, a switching process occurs, then at point B the optic axis has rotated around the cone, towards the opposite switched state, and as the optic axis is now more parallel to the plane of light propagation the surface plasmon-polariton moves to higher angles, and a decrease in

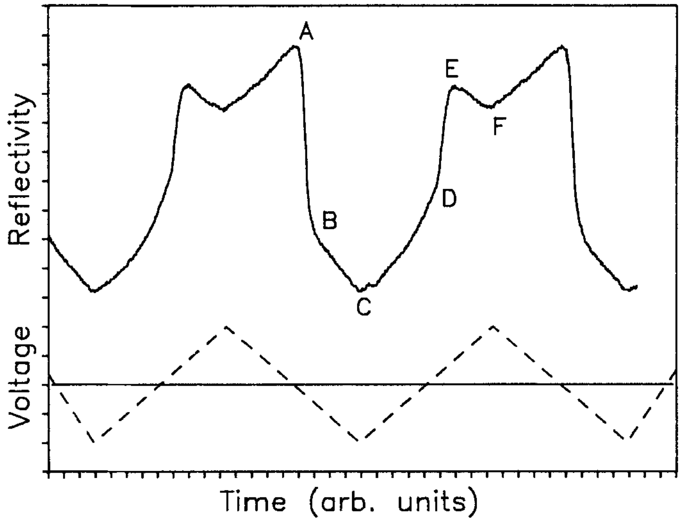

Figure 3. Data taken at a fixed angle just to the right of the surface plasmon-polariton reflectivity minimum during switching of a SCE3 cell. The cell is aligned so that the optic axis lies parallel to the plane of light propagation after a negative voltage pulse across the cell. The data are scaled to fit the graph, actual changes in reflectivity are quite small, being about 2–5 per cent. Points labelled A to F correspond to the points shown in figure 4. A dashed line shows the applied field corresponding to the data, it is a ±5 V triangular wave of 0·1 Hz.

reflected intensity is seen. At point C where there is a negative bias of 5 V the optic axis is in the opposite switched state. Here the optic axis is still nearly parallel to the plane of light propagation, but is tilted out of the surface plane, causing the largest perturbation on the surface plasmon-polariton minimum, and a corresponding large effect on the reflectivity measured here. At point D the optic axis is now switched in the second relaxed state, the optic axis then lies parallel to the cell surfaces and parallel to the plane of light propagation. At point E the optic axis, under the forward biased field has rotated again to the original side of the cone, this is again a state with low tilt but large twist out of the plane of light propagation, leading to a lower surface plasmon-polariton excitation angle and increase in reflectivity. At point F the optic tensor is under maximum forward bias, introducing tilt into the system and again reducing the reflectivity due to a reverse shift in the surface plasmon-polariton minimum. When this field drops to zero, the optic tensor relaxes to the original position, and the reflectivity curve returns to point A. Note that the reflectivity curve is not mirrored at points C and F (the maximum switched states), this is because the points B and E are delayed due to the switching process. There may also be additional effects due to an asymmetry in the switching if the two switched states are not equally stable.

So the near surface switching process can be traced out using the surface plasmon-polariton in this way. It should however be remembered that the surface plasmon-polariton field penetration depth is about 0·3 μm, and hence this is not the true surface process, but a weighted average of the mechanism within the field penetration depth. This is, however, useful and the transition between points such as A and B in figure 3 shows the speed of the surface switching even under small bias fields.

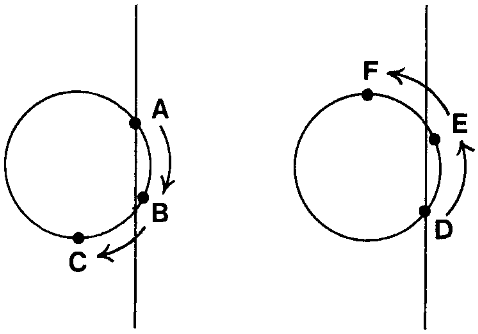

Figure 4. Schematic illustration of the characteristic points observed during the switching process near the surface of a cell. The points labelled A to F show the end projection of the optic axis on the smectic cone at a cell surface (see figure 1), and correspond to the points labelled on the reflectivity against voltage curve shown in figure 3. Alignment of the cell is such that point D corresponds to when the optic axis lies parallel to the plane of light propagation.

4. Summary of dynamic processes

We have seen that taking data stroboscopically in the guided mode region of the reflectivity curve is inconclusive due to the domain growth/nucleation process involved in switching in ferroelectric liquid crystal cells. This could be overcome if data could be taken very rapidly, using perhaps pulsed laser and array detector techniques. Then data could be taken for the optic tensor reorientation within a domain during switching, or possibly for very rapid switching processes a simple switching mechanism may take over. Work of this nature will be undertaken in the near future.

Data taken near the surface plasmon-polariton minimum during switching has been seen to illustrate well the switching process near the surface of the ferroelectric liquid crystal cell. This can be explained quite simply in terms of the reorientation of the optic axis within the cell chevron structure, without the need for a full model of the switching process. It may, however, be useful to compare with such modelling in a quantitative way.

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