Ferroelectrics, 310: 79–85, 2004

ISSN: 0015-0193 print / 1563-5112 online
DOI: 10.1080/00150190490510393

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Observation of Switching in Tri-Stable Antiferroelectric Cells

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(Received in final form August 29, 2003)

An optical convergent beam system has been used to characterise a tri-stable antiferroelectric cell and to observe the complex director reorientation process when a 200 ms dc pulse of ±50 V is applied. The optical permittivities and director structure are measured for all three states, along with the layer tilt of the tilted-bookshelf structure formed, and from these results the cone angle at 74.9°C is calculated to be 35.9 (±0.2)°. The dynamic behaviour of the cell during the application of the pulse has also been analysed qualitatively. On application of a high voltage the cell switches in less than 1 ms to a ferroelectric state. However, on removal of the voltage, the cell rapidly (<1 ms) switches to the reverse ferroelectric state before relaxing back to the 0V anticlinic alignment over several seconds.

Keywords Antiferroelectric; waveguide; cone angle; switching

PACS numbers: 61.30.−v; 77.84Nh; 78.20.Fm

Introduction

Antiferroelectric liquid crystals are regarded as having great potential for use in display applications due to their fast switching properties and ability to form three stable states [1–3]. In addition 45° cone angle orthoconic antiferroelectrics give a high contrast uniaxial zero volt state [1, 2]. To allow these materials to be used to their full advantage, a good understanding of their optical and physical properties is required. In particular, the behaviour of a thin layer (<5 μm) of such a material when confined between two homogeneously aligning substrates (similar to the structure of a conventional nematic display device) is of particular interest.

For many years, optical waveguide characterization techniques have been used to determine the director structure and optical properties in liquid crystal cells containing a wide range of nematic and smectic materials [4–6]. The technique involves collecting transmitted and reflected optical intensity versus angle-of-incidence data from a liquid crystal cell index-matched between two prisms. This optical data is then fitted to yielding the director profile and optical properties of the cell using a multilayer optics model based on a 4×4 Berreman matrix [7]. The latest characterisation method developed uses this technique in a convergent beam arrangement with a CCD camera capable of capturing data in the sub-millisecond timescale, allowing the dynamics of liquid crystal cells to be studied in great detail [8–11]. This method is also ideally suited to studying the effect of applied voltages

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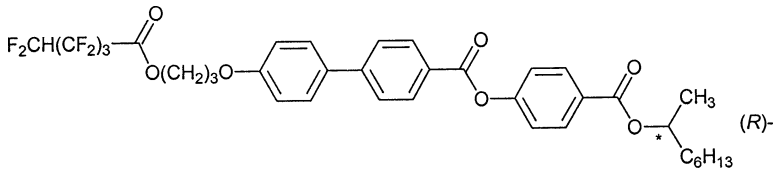

FIGURE 1 The structure of the antiferroelectric material AH56.

on an antiferroelectric-filled cell, as it allows the response of the cell and its switching properties when an applied dc pulse is applied to be analysed.

By measuring the optical properties of an antiferroelectric cell in all three stable states, as well as during the transition between them, a wealth of detailed information including the optical biaxiality, director alignment, layer structure and cone angle of the material can be obtained.

Experiment

A 5 μm thick cell was constructed from ITO coated ordinary (n = 1.518) index glass substrates. Both substrates were spin-coated with polyimide and then baked. One surface was then rubbed to provide directed homogeneous alignment. The other was left unrubbed to allow non-directed homogeneous alignment to limit the constraints on the director structure. The cell was spaced using 5 μm beads in UV setting glue, and filled with the liquid crystal (AH56, (Fig. 1)) in the isotropic phase (95°C). It was then slowly cooled into the antiferroelectric phase with a voltage of +50 V held across the cell to allow a monodomain to form.

The cell was index-matched between two low-index glass hemispheres, contained within an insulating over and mounted at the centre of an optical convergent beam system (Fig. 2). It was then heated into the isotropic phase (95°C) and then cooled into the antiferroeletric phase (74.9°C) in-situ. The data-capture system was triggered to collect optical intensity versus angle-of-incidence data on a 0.3 ms timescale whilst a single pulse of +50 V of 200 ms duration was applied to the cell over a 5 s period to allow the response and relaxation of the cell to be recorded. This was repeated for all combinations of polarisation conserving and converting data in transmission and reflection, and the whole process was repeated again using a pulse of −50 V.

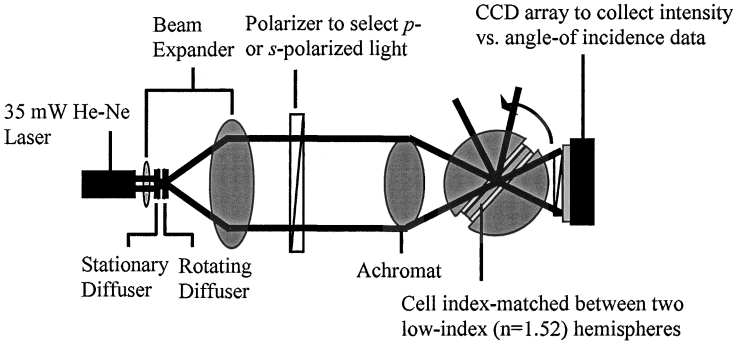

FIGURE 2 Schematic diagram of the optical convergent-beam experiment.

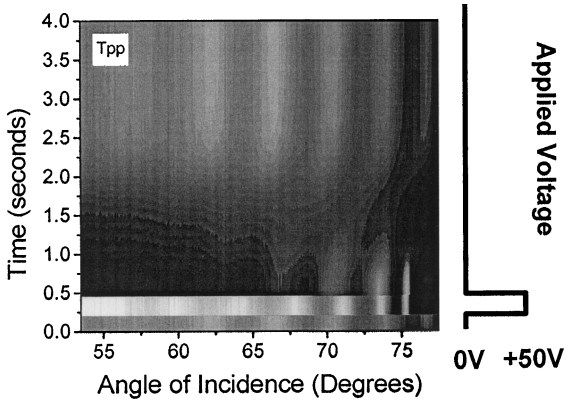

FIGURE 3 An example of the optical intensity versus angle-of-incidence data collected for *p-p* conserving transmitted light during and after the application of a +50 V dc pulse of 200 ms duration. Low intensity is shown as a dark pixel, and high intensity as white.

Results

An example of the variation of optical intensity versus angle-of-incidence data with time, collected during the application of the pulse is shown in Fig. 3. To determine the static properties of the cell, the lines of optical data for the conserving and converting data corresponding to the equilibrium situation at 0 V, +50 V and −50 V during the pulse application were extracted. The datasets corresponding to each of the voltages were then fitted to using the optical permitivity, absorption and thickness of the ITO, polyimide and liquid crystal as fitting parameters, along with the director profile of the liquid crystal.

In the case of the applied voltages the liquid crystal was modelled, to a first approximation, as uniaxial and homogeneously aligned. A selection of the resulting fits are shown in Fig. 4. The measured optical permittivities of the material, along with the orientation of the principal director at ±50 V are shown in Table 1. The results show that at both voltages, the director lies approximately parallel ot the substrate, with an angle of 74.2° between the two azimuths. This indicates the formation of two ferroelectric structures with the director alignment at the two different voltages lying on opposite sides of a cone, due to coupling between the spontaneous polarisation of the material and the applied field.

At 0 V, the structure of the liquid crystal layer is more complex, and it was not possible to fit to the data using a simple uniaxial optical model. The anticlinic layering associated with

TABLE 1 Values for the real part of the optical permittivity of AH56 produced by a least-squares fitting to the optical intensity versus angle-of-incidence data collected at applied voltages of ± 50 V dc, and at 0 V with the cell shorted. The Euler angles ϕ (azimuthal twist) and θ (director tilt) used to define the director orientation are also given (in all cases, the value of the rotational angle was 0°).

	ε_x (±0.001)	ε_y (±0.001)	ε_z (±0.001)	ϕ_F (±0.3)°	θ_F (±0.3)°
+50 V	2.166	—	−2.719	9.1	93.2
−50 V	2.168	—	−2.709	−64.1	89.0
	ε_1 (±0.001)	ε_2 (±0.001)	ε_3 (±0.001)	ϕ_{AF} (±0.3)°	θ_{AF} (±0.3)°
0 V	2.350	2.235	2.525	−27.4	−4.7

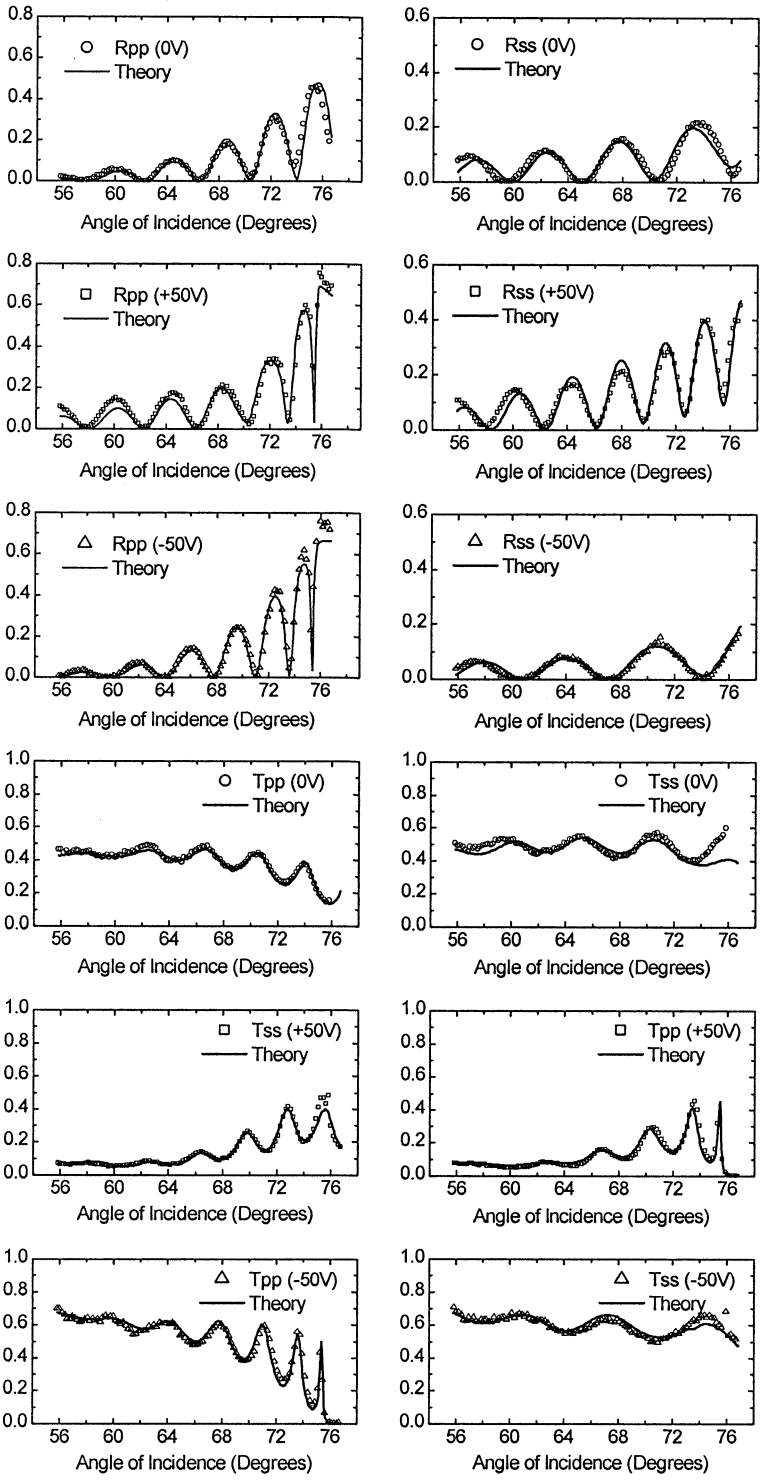

FIGURE 4 Measured (symbols) and modelled (solid line) optical intensity versus angle-of-incidence data for the polarization conserving case (p- to p- and s- to s-) collected in reflection and transmission for the 0 V, +50 V and −50 V states.

the antiferroelectric structure at 0 V requires a biaxial optical model to fit to the optical data. A reasonable fit was obtained by considering the liquid crystal layer, to a first approximation, as being a uniformly aligned biaxial slab (Fig. 4). At the higher angles of incidence, where the data is more sensitive to the alignment at the surface of the cell, the agreement between data and theory is relatively poor. This suggests that the uniform alignment is valid for the bulk of the cell, but at the surface there is a region, possibly influenced by the pretilts associated with the polyimide used, where the structure is more complex. The measured permittivities at 0 V and the orientation of the principal director are shown in Table 1. The azimuthal orientation of the director in the bulk is at an angle of $\approx 27^\circ$ to the rubbing direction, and this is further evidence of surface alignment effects in the cell. The tilt of the optical tensor measured at 0 V is equal to the layer tilt of the structure, indicating that the material forms a tilted bookshelf structure with the layer normal at -4.7° to the substrate.

The measured optical permittivities at 0 V (ε_1, ε_2 and ε_3) are related to those measured in the applied voltage ferroelectric state (ε_x and ε_z) by the dielectric tensor[12]:

$$\varepsilon_{AF} = \begin{pmatrix} \varepsilon_x \cos^2\theta_c + \varepsilon_z \sin^2\theta_c & 0 & 0 \\ 0 & \varepsilon_y & 0 \\ 0 & 0 & \varepsilon_x \sin^2\theta_c + \varepsilon_z \cos^2\theta_c \end{pmatrix} \tag{1}$$

where θ_c is the cone-angle. This tensor is the result of averaging the contributions from alternating layers. The permittivities measured in the antiferroelectric state correspond to those measured at ± 50 V by the expressions:

$$\varepsilon_1 = \varepsilon_x \cos^2\theta_c + \varepsilon_z \sin^2\theta_c \tag{2}$$

$$\varepsilon_2 = \varepsilon_y \tag{3}$$

$$\varepsilon_3 = \varepsilon_x \sin^2\theta_c + \varepsilon_z \cos^2\theta_c \tag{4}$$

Using the value for ε_1, ε_x and ε_z in Table 1 in conjunction with Eq. (2) gives the measured cone angle as $\theta_c = 35.3\,(\pm 0.5)^\circ$. Similarly, using the measured value of ε_3 with Eq. (3) gives $\theta_c = 36.4\,(\pm 0.5)^\circ$. Previous measurements made on the material using optical microscopy whilst switching a 5 μm cell with a field of 15 V μm^{-1} gave the cone angle as $35.6\,(\pm 0.3)^\circ$, which is in excellent agreement with the cone angles calculated here.

Qualitative analysis of the optical data collected as a function of time gives an indication of the switching process that occurs when a high voltage pulse is applied to the cell. It is clear from Fig. 3 that when +50 V (which exceeds the threshold voltage of the cell) is applied the response of the director is extremely rapid with a stable configuration reached in <1 ms. The director then remains in this state throughout the duration of the application of the +50 V voltage. On removal of the applied field, the director immediately (<1 ms) switches to a different configuration, as indicated by the rapid change in the optical data, and remains in this state for ≈50 ms, before slowly relaxing into the original 0 V configuration. A similar but reverse process (but with different optical intensity versus angle-of-incidence data) was seen when a −50 V pulse was used.

Closer examination of this data shows that the optical data collected for each polarization dataset during the application of +50 V coincides exactly with the data corresponding to the configuration of the cell immediately after −50 V is removed. The opposite is also true, with the data collected with −50 V applied coinciding perfectly with the data corresponding to the cell immediately after the removal of +50 V (Fig. 5). This indicates that on removal of the high voltage, the cell switches from one ferroelectric state to the other

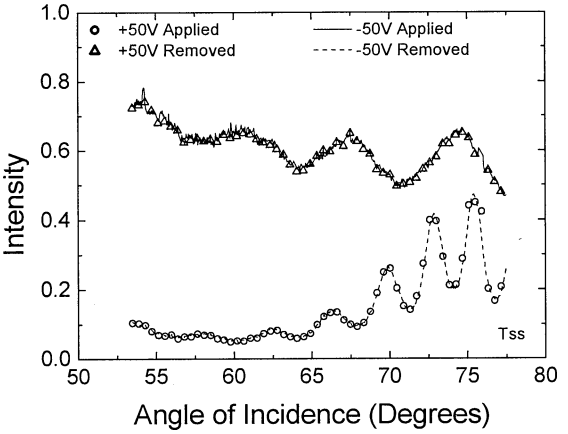

FIGURE 5 Comparison between optical data collected during the application of ±50 V and the optical response immediately after removal of the pulses.

before relaxing back to the 0 V state over several seconds. The mechanism for this switching has to arise from an almost completely canceling internal field generated in the cell by the alignment of the material under an applied voltage [13, 14]. On removal of the external field, the internal field is unopposed and is of sufficient strength to exceed the cell's threshold voltage, and drive it into the opposite ferroelectric state.

Conclusion

The static and dynamic properties of an antiferroelectric liquid crystal have been characterised using the highly sensitive optical convergent beam technique. By fitting to optical intensity versus angle-of-incidence data collected with ±50 V and 0 V applied across the cell, the optical permittivities and director structure of the material in the three stable states has been determined. The material is found to form a tilted bookshelf structure with two different ferroelectric alignments forming at the two applied voltages. In both cases the cell is modelled as a uniaxial slab with the director aligned approximately parallel to the substrate, with the azimuthal orientations differing by 73.2° between the two voltages. At 0 V an anticlinic structure formed, which required a biaxial model to specify the director structure. From this fitting, the layer tilt angle was measured as −4.7° and the cone angle of the material was calculated as 35.3 (±0.5)° and 36.4 (±0.5)°, which was in good agreement with optical microscopy results.

Qualitative analysis of the switching process indicates that the response time of the cell to an applied voltage above the threshold of the material is <3 ms, and the cell remains in a stable ferroelectric state throughout the duration of the applied voltage. On removal of the voltage, the cell rapidly switches to the opposite ferroelectric structure, due to the presence of a strong internal field, and then relaxes back to the 0 V state over a period of several seconds.

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