Leaky-wave exploration of two-stage switch-on in a nematic pi-cell

L. Z. Ruan and J. R. Sambles[a)]
Thin Film Photonics Group, School of Physics, University of Exeter, Stocker Road, Exeter, EX4 4QL, United Kingdom

(Received 25 June 2004; accepted 23 August 2004; published online 24 January 2005)

The two-stage switch-on dynamics of a nematic pi-cell are explored in detail using a convergent beam fully-leaky guided mode technique. The cell shows an initial switch-on with a time scale in the range several ms to tens of ms (depending on drive voltage) from the symmetrical H state to a new and semistable H state. It then slowly changes (over several hundred ms) to the final stable asymmetrical H state. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1806544]

Nematic liquid crystals form the basis of the majority of flat screen displays. Much interest has focused on pi-cells,[1–3] in which the director has parallel surface tilts, with liquid crystals of positive dielectric anisotropy. There are three different director states in such cells, a horizontal state, or H state, a twisted vertical state, or T state and a planar vertical state or V state, depending upon the surface tilts and the elastic constants of the material. Under application of an electric field, there are possible transitions between the different states which have been considered in device applications.[3–5]

There exists a very well-accepted theory concerning flow and dynamic effects in nematic liquid crystals which was developed by Ericksen[6,7] and Leslie.[8] in the 1960's, and later simplified by Berreman and van Doorn.[9,10] However, there are only a few detailed experimental confirmations of many of its predictions. Some simple experiments[11,12] have confirmed the theoretically predicted "backflow" in a twisted nematic cell during switch-off by recording an optical "bounce" effect in transmission. However almost all experiments have been based on transmission or reflection observations during switching and as such the optical signal from the liquid crystal cell is an integrated response. Only recently, by using a convergent beam optical guided wave technique[13,14] has the switching process[15,16] in a twisted nematic cell been studied in detail providing convincing detailed evidence of the validity of the Ericksen–Leslie theory. In this present study, a convergent beam system is used to investigate the switch-on dynamics of a pi-cell, finding a two-stage switching process.

The cell is comprised of two low index glass plates ($n=1.5170$ at 632.8 nm), each coated inside by a thin (~50 nm) layer of indium tin oxide (ITO), on top of which are surface aligning layers of rubbed polyimide. The rubbing directions are parallel and the plates are spaced by 5.0 μm beads. A monodomain is obtained by filling the cell with liquid-crystal E7 (Merck) in the isotropic phase and slowly cooling to room temperature.

This cell is inserted between the two glass hemispheres, optical contact being achieved with matching fluid all having the same index as the glass substrates. This complete assembly is placed so that the center of the sample is at the focus of a monochromatic light beam (see Fig. 1). The light beam is collimated into a less-coherent parallel beam of diameter about 5 cm by using one rotating and one fixed diffuser and a beam expander. This beam passes through a polarizer, a horizontal slit aperture, and a pair of converging lenses, being focused to a spot at the center of the cell to be studied. Both reflectivity and transmissivity signals from the cell are recorded, through a second polarizer, by a charge coupled device camera (DALSA).

To obtain data most sensitive to the director profile in the cell, it is set such that the rubbing direction at the surface has an angle of about 45° with the incident plane. In addition, because the angular region of the fully-leaky guided modes which is most sensitive to the director alignment is in the high in-plane wave vector area, the sample is arranged such that the angle between the central axis of the convergent beam and the cell normal is 70°. Choice of input polarizer (*p*, transverse magnetic, or *s*, transverse electric) and output polarizer allows a variety of angle dependent signals to be recorded. Data are fully analyzed for the static guided mode data at 0 V, 2.8 V, and 4.7 V [root-mean-square (10 kHz) voltages], and also for the dynamic switch-on data for 2.8 V and 4.7 V. Figure 2 shows how one of the signals, T_{ss}, varies with time after switch-on of 4.7 V.

It is apparent that in this dynamic process there are two quite different steps, first there is a relatively rapid change to a nearly unchanging semistable state. This state remains for a long time slowly relaxing to a different final state. The fast switch-on time of the first step is about 22 ms for 2.8 V and 7 ms for 4.7 V (Fig. 2), while the time over which the cell remains in the semistable state is about 200 ms for 2.8 V and 300 ms for 4.7 V applied fields. The cell reaches its final state after about 500 ms for 2.8 V and 750 ms for 4.7 V.

Using multilayer optical theory[17] to fit the reflection and transmission data, the full director profile in the cell is obtained at many time steps (~1000 sets of angle dependent data recorded) during the switch-on. From the data taken

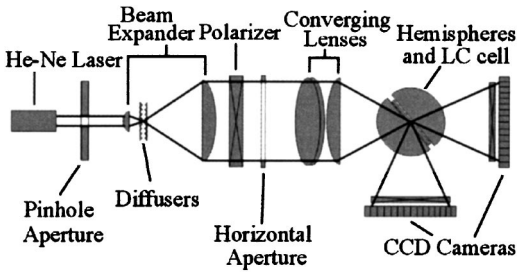

FIG. 1. Schematic of the convergent beam system.

[a)]Electronic mail: j.r.sambles@exeter.ac.uk

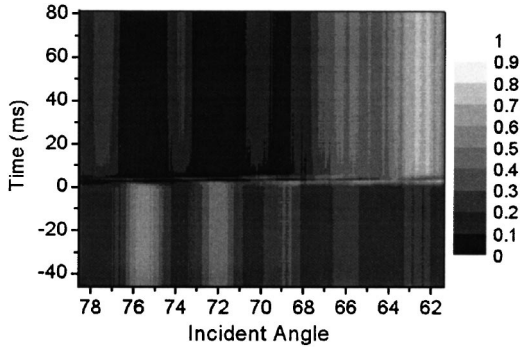

FIG. 2. The dynamic data of T_{ss} after switch-on of 4.7 V.

with no applied field, the optical parameters of the different layers in the cell at 632.8 nm are first found to be as follows. The ITO layers have a thickness of 50 nm with an optical permittivity of $\varepsilon = 3.900 + i0.15$; while the polyimide layers have anisotropic optical permittivities $\varepsilon_o = 2.350 + i0.001$, $\varepsilon_e = 2.800 + i0.001$ with a thickness of 25.0 nm. The optical permittivities of the liquid crystal, E7, are $\varepsilon_o = 2.309 + i0.0001$, $\varepsilon_e = 2.998 + i0.0001$ with the thickness of the liquid-crystal layer being 4.328 μm. There is no director twist through the cell which provides surface tilts of 9.0° on one surface and -9.0° on the other. One of the fitted data sets, T_{ss}, and the director profile which provides a model fit to this data are shown in Fig. 3(a). This original state is a symmetrical H state. A long time after the ac voltage has been applied the director structure in the cell is substantially altered. Based on the Frank–Oseen elasticity theory model, director profiles to fit the final static data taken at 2.8 V and 4.7 V are also found [shown in Fig. 3(b) for 4.7 V]. It is obvious that the long time static state in the applied field is an asymmetrical H state, where the director in the cell center has a large tilt. From these fits, the elastic constants of the liquid crystalline

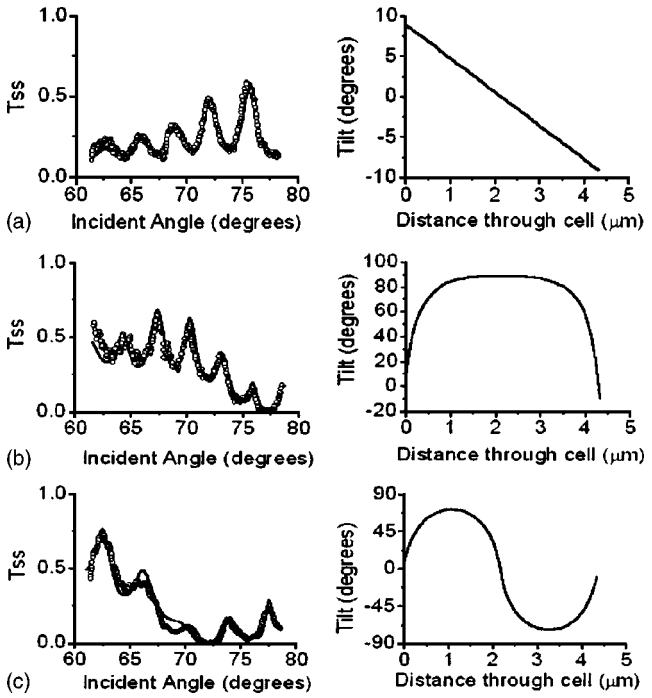

FIG. 3. The experimental data T_{ss} (crosses) with the theoretical fit (solid line) and the director tilt profile for (a) no applied voltage and (b) after a long time (>1 s) at 4.7 V, and (c) in the semistable state (~4 ms) at 4.7 V.

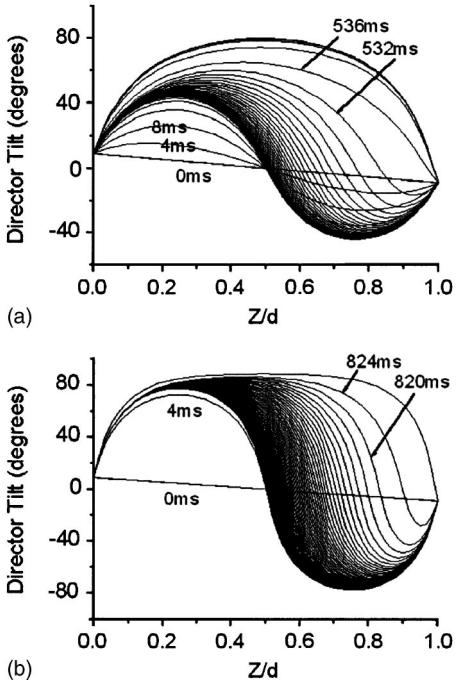

FIG. 4. Dynamic director tilt profile at 4 ms time intervals during switch-on to (a) 2.8 V and (b) 4.7 V.

material are found to be $K_{11} = 1.11 \times 10^{-11}$N and $K_{33} = 1.71 \times 10^{-11}$N, with dielectric permittivities are $\varepsilon_{\parallel} = 19.0$ and $\varepsilon_{\perp} = 5.2$. These values agree well with those supplied by Merck.

Next we turn to the switch-on dynamics in the pi-cell. By using a modeling program (DIMOS) based on the approximation[9,10] to the Ericksen–Leslie hydrodynamic theory,[6–8] a fit is obtained to the data taken in the semistable state. All the physical and structural parameters of the cell are set from the preceding fits to the static data, and the viscosity coefficients are taken from manufacturer's database. From the modeling, it is found that the semistable state is a symmetrical H state. The director profile is shown in figure Fig. 3(c). The director in the cell center is parallel to the cell surface, the largest director tilts occurring near to both sides of the cell. Further there is no director twist through the cell. The largest director tilts found in the cell for applied voltages of 4.7 V and 2.8 V are 72.64° and 44.12°, respectively.

Further modeling of the director tilt profiles during the switch-on process is conducted using the DIMOS modeling package. The results of this modeling are shown in Fig. 4, which clearly shows the two steps switch process. This also confirms that the experiment results are in very good agreement with the Ericksen–Leslie theory.

Energy analysis may be used to explain this dynamic transition. In a liquid-crystal cell, under an applied electric field E the free energy density is given by

$$F = \frac{f(\theta)}{2}\left(\frac{d\theta}{dz}\right)^2 + \frac{g(\theta)}{2}\left(\frac{d\phi}{dz}\right)^2 + \frac{D \cdot E}{8\pi}, \tag{1}$$

where

$$f(\theta) = k_{11}\cos^2\theta + k_{33}\sin^2\theta$$

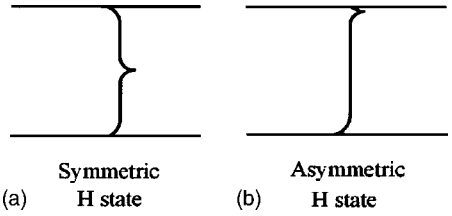

FIG. 5. The boundary layer models in (a) the symmetric H state and (b) the asymmetric H state under an applied field.

$$g(\theta) = (k_{22}\cos^2\theta + k_{33}\sin^2\theta)\cos^2\theta,$$

θ and ϕ are the director tilt (measured from the cell surface) and director twist, respectively, D is the electric displacement. Minimizing gives the equilibrium equation. By using the boundary layer model proposed by Cheng *et al.*,[18] at high fields the director distortion tends to concentrate in thin layers with most of the cell having the director aligned parallel to the field. The two surfaces as largely decoupled, each surface layer has in effect a semi-infinite layer adjacent to it. Supposing ϕ= constant with the boundary conditions $\theta = \pi/2$, $d\theta/dz = 0$ at $z=\infty$ then the equilibrium equation[19] in this boundary layer approximation is

$$\frac{d\theta}{dz} = \frac{\pm(\varepsilon_\parallel/\varepsilon_\perp)^{1/2}\cos\theta}{\xi(1+\gamma\sin^2\theta)^{1/2}(1+k\sin^2\theta)^{1/2}}, \tag{2}$$

where

$$\xi = \left(\frac{\varepsilon_\parallel}{D}\right)\left(\frac{4\pi k_{11}}{\Delta\varepsilon}\right)^{1/2}$$

and

$$\gamma = \frac{\varepsilon_\parallel - \varepsilon_\perp}{\varepsilon_\perp}, \quad k = \frac{k_{33}-k_{11}}{k_{11}}.$$

Thus, the total energy per unit area, including the elastic energy and excess of dielectric energy, for each semi-infinite boundary layer is

$$E(\theta_0,\theta_\infty) = \left(\frac{k_{11}}{\xi}\right)\left(\frac{\varepsilon_\parallel}{\varepsilon_\perp}\right)^{1/2}\int_{\theta_0}^{\theta_\infty}\frac{\cos\theta(1+k\sin^2\theta)^{1/2}d\theta}{(1+\gamma\sin^2\theta)^{1/2}}$$
$$= \left(\frac{k_{11}}{\xi}\right)q(\theta_0,\theta_\infty), \tag{3}$$

where θ_∞ is the value of θ for $z \gg \xi$.

In the asymmetric H state, there are three boundary layers and the total energy per unit area is

$$E_A = E(\theta_{01},\pi/2) + E(0,\pi/2) + E(0,\theta_{02}), \tag{4}$$

according to Eq. (3). Here θ_{01} and θ_{02} are the director tilts on the lower and the upper cell surfaces, respectively. By contrast, in the symmetric H state there are four boundary layers [Fig. 5(a)], and the total energy per unit area is

$$E_S = E(\theta_{01},\pi/2) + 2E(0,\pi/2) + E(\theta_{02},\pi/2),$$
$$= E(\theta_{01},\pi/2) + E(0,\pi/2) + E(0,\theta_{02}) + 2E(\theta_{02},\pi/2),$$
$$= E_A + 2E(\theta_{02},\pi/2). \tag{5}$$

So, the asymmetric H state has a lower energy than the symmetric H state on the basis of this simple model. From this, it is relatively straightforward to explain the experimental results. At the beginning of the switch-on, due to the original symmetric state, the director structure switches rapidly to a symmetric state. It stays in this semistable state for quite a long time there being only distant (and balanced) forces from both walls trying to drive it asymmetric. Ultimately the director gradually transfers to a lower-energy stable state, an asymmetric state. It is generally observed that such pi-cells show multidomains because of this formation of two energetically degenerate asymmetric states. However, it is believed that with the rather high surface pretilt of about 9°, the present cell type does not suffer from this problem, forming instead large monodomains of just one asymmetric state.

In conclusion, using the convergent beam fully-leaky guided mode technique, it has been possible to examine in detail the director switch-on process of a nematic pi-cell. The approximation of Berreman and van Doorn of the Ericksen–Leslie theory of the flow of the director profile in the cell agrees very well with the experimental data. There exists a fast switching process from an original symmetric H state to another symmetric but semistable H state under the application of an electric field. This state may be useful in device applications for it is only after a substantial length of time that it relaxes to the final stable asymmetric H state. The final state, reached after some hundreds of milliseconds, is a single asymmetric state with there being no visible break up of the cell into the two possible types of asymmetric domain often found in such cells.

The authors acknowledge both the Engineering and Physical Sciences Research Council of the UK and QinetiQ for jointly funding this research.

[1] J. Cheng, R. N. Thurston, and D. W. Berreman, J. Appl. Phys. **52**, 2756 (1981).
[2] P. J. Bos and K. R. Beran, Mol. Cryst. Liq. Cryst. **113**, 329 (1984).
[3] M. J. Towler and P. Raynes, SID 00 Digest, 1 (2000).
[4] R. Vatne, P. Johnson, and P. Bos, SID Digest of Technical Papers, 28 (1983).
[5] P. J. Bos, SID Digest of Technical Papers, 30 (1983).
[6] J. L. Ericksen, Arch. Ration. Mech. Anal. **4**, 231 (1960).
[7] J. L. Ericksen, Trans. Soc. Rheol. **5**, 23 (1961).
[8] F. M. Leslie, Q. J. Mech. Appl. Math. **19**, 357 (1966); Arch. Ration. Mech. Anal. **28**, 265 (1968); Advances in Liquid Crystals, edited by G. H. Brown (Academic, New York, 1979), Vol. 4, p. 1.
[9] D. W. Berreman, J. Appl. Phys. **46**, 3746 (1975).
[10] C. Z. van Doorn, J. Appl. Phys. **46**, 3738 (1975).
[11] C. J. Gerritsma, C. Z. van Doorn, and P. van Zanten, Phys. Lett. **48A**, 263 (1974).
[12] F. Nakano, H. Kawakami, H. Morishita, and M. Sato, Jpn. J. Appl. Phys. **19**, 659 (1980).
[13] N. J. Smith and J. R. Sambles, J. Appl. Phys. **85**, 3984 (1999).
[14] F. Yang and J. R. Sambles, J. Opt. Soc. Am. B **10**, 858 (1993).
[15] L. Z. Ruan and J. R. Sambles, J. Appl. Phys. **92**, 4857 (2002).
[16] L. Z. Ruan and J. R. Sambles, Phys. Rev. Lett. **90**, 168701 (2003).
[17] D. Y. K. Ko and J. R. Sambles, J. Opt. Soc. Am. A **5**, 1863 (1988).
[18] J. Cheng, R. N. Thurston, and D. W. Bereman, J. Appl. Phys. **52**, 2756 (1981).
[19] L. Z. Ruan, T. W. Preist, F. Yang, and J. R. Sambles, Liq. Cryst. **13**, 541 (1993).