Mol. Cryst. Liq. Cryst., Vol. 401, pp. 67/[181]–73/[187], 2003
Copyright © Taylor & Francis Inc.
ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421400390243183

FULLY-LEAKY GUIDED MODE MEASUREMENT OF THE FLEXOELECTRIC CONSTANT $(e_{11}+e_{33})$ OF A NEMATIC LIQUID CRYSTAL

S. A. Jewell and J. R. Sambles
Thin Film Photonics Group, School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, U.K.

The response to applied voltages of the director profile within an E7-filled Hybrid Aligned Nematic liquid crystal cell has been determined by using the optical wave-guide method known as the Fully-Leaky Guided Mode Technique. Data was collected with applied AC and DC voltages and the measured director profiles were compared with model profiles generated through a minimisation-of-free-energy routine. The sum of the splay and bend flexoelectric coefficients $(e_{11}+e_{33})$ *of E7 was measured as* $1.5\times10^{-11}\,\mathrm{Cm}^{-1}$*. Results also show the presence of a DC offset voltage of* $+0.64\,\mathrm{V}$ *in the cell.*

Keywords: HAN cell; Flexoelectric effect; Fully-leaky guided mode technique

INTRODUCTION

When liquid crystal molecules possessing a shape polarity are constrained to a splay, twist or bend geometry, an internal DC field is produced due to the charge distribution across the molecules. This field will in turn distort the director profile within the cell. The magnitude of this field, and hence the distortion is dependent upon the magnitude and sign of the flexoelectric coefficient of the material [1].

A liquid crystal cell with a Hybrid Aligned Nematic (HAN) geometry (i.e. homeotropic alignment on one surface and homogeneous on the other) produces strong splay and bend deformations in the director profile. When a DC field is applied in forward or reverse bias across the cell, the internal flexoelectric field will either enhance or reduce the applied field, and the director profile will respond accordingly. The HAN geometry is therefore particularly suited to measuring the flexoelectric coefficient of a liquid crystal material. The geometry is also of interest commercially as it forms one of the two bistable states in a Zenithal Bistable Device.

In this study, the flexoelectric coefficient of E7 has been measured by determining the response of the director in a HAN cell to applied DC fields. In order to determine the subtle changes in director profile under applied fields, the highly sensitive fully-leaky guided mode optical wave-guide technique has been used. The profiles produced have then been compared with those generated by a free-energy minimization model.

THEORY

For a HAN cell with no twist and an applied AC field along the z axis (perpendicular to the substrate), the total free-energy density of the system is given by:

$$G=\int_0^d\left[\frac{1}{2}\left(K_{11}\cos^2\theta+K_{33}\sin^2\theta\right)\left(\frac{d\theta}{dz}\right)^2+\frac{1}{2}\varepsilon_0\left(\varepsilon_e\sin^2\theta+\varepsilon_o\cos^2\theta\right)E_z^{\,2}\right]dz, \tag{1}$$

where θ is the tilt angle measured from the substrate, E_z is the rms value of the applied field, K_{11} and K_{33} are the splay and bend elastic constants, and ε_e and ε_o are the extra-ordinary and ordinary dielectric constants . Minimising this expression using the Euler-Lagrange method [4,5] leads to the two differential equations:

$$-\left(\frac{dV}{dz}\right)\varepsilon_0\left(\varepsilon_e\cos^2\theta+\varepsilon_o\sin^2\theta\right)=D_z=A, \tag{2}$$

$$\left(K_{11}\cos^2\theta+K_{33}\sin^2\theta\right)\left(\frac{d\theta}{dz}\right)^2-\frac{D_z^2}{\varepsilon_0\left(\varepsilon_e\sin^2\theta+\varepsilon_o\cos^2\theta\right)}=B, \tag{3}$$

where V is the applied AC rms voltage, D_z is the displacement current along the z axis and A and B are constants of integration. Combining expressions (2) and (3) gives an expression for V:

$$V=-\int_{\theta_0}^{\theta_d}\left[\frac{\left(K_{11}\cos^2\theta+K_{33}\sin^2\theta\right)}{B\left[\varepsilon_0\left(\varepsilon_e\sin^2\theta+\varepsilon_o\cos^2\theta\right)+1\right]}\right]^{\frac{1}{2}}d\theta, \tag{4}$$

where θ_0 and θ_d are the tilt angles at the homogeneous and homeotropic surfaces respectively. By varying B until the value of the integral is equal to the applied voltage, the tilt profile can be determined.

The authors would like to acknowledge the financial support from the Engineering and Physical Sciences Research Council, and Hewlett-Packard laboratories, Bristol.

When a DC voltage is applied across the cell, the flexoelectric contribution to the free energy must also be considered. For the twist-free HAN cell geometry, the flexoelectric polarisation, P_f, is given by,

$$P_f = \frac{(e_{11} + e_{33})}{2} \sin 2\theta \left(\frac{d\theta}{dz}\right), \tag{5}$$

where e_{11} and e_{33} are the splay and bend elastic constants. The total energy density becomes:

$$G = \int_0^d \left[\frac{1}{2}\left(K_{11}\cos^2\theta + K_{33}\sin^2\theta\right)\left(\frac{d\theta}{dz}\right)^2 + \frac{1}{2}\varepsilon_0\left(\varepsilon_e \sin^2\theta + \varepsilon_o \cos^2\theta\right)E_z^{\,2} + P_f E_z\right] dz. \tag{6}$$

By minimising the expression as before, and combining the resulting differential equations, the expression for the applied DC voltage becomes:

$$V = -\int_{\theta_0}^{\theta_s} \frac{(e_{11} + e_{33})\sin 2\theta}{2\varepsilon_0\left(\varepsilon_e \sin^2\theta + \varepsilon_o \cos^2\theta\right)} d\theta - \int_{\theta_0}^{\theta_s} \left[\frac{\left(K_{11}\cos^2\theta + K_{33}\sin^2\theta\right) + \dfrac{(e_{11} + e_{33})^2 \sin^2 2\theta}{4\varepsilon_0\left(\varepsilon_e \sin^2\theta + \varepsilon_o \cos^2\theta\right)}}{C\left[\varepsilon_0\left(\varepsilon_e \sin^2\theta + \varepsilon_o \cos^2\theta\right) + 1\right]}\right]^{\frac{1}{2}} d\theta. \tag{7}$$

By varying C, the tilt profile can be determined in the same way as for the AC case.

EXPERIMENT

A HAN cell containing E7 (Merck BL001) was constructed from two ITO-coated, low index (n = 1.52) glass substrates. One surface was treated with 23 nm of SiO_x evaporated at a 60° angle to provide homogeneous alignment. The other ITO surface was treated with a surface layer of Octadecyltrimethoxysilane to produce homeotropic alignment. The cell was constructed using 3 µm beads, in a UV setting glue, as spacers, and sealed with an epoxy resin to prevent contamination (Figure 1). The cell was shorted and mounted at a 45° azimuthal angle between two low index (n = 1.52) 60° prisms as shown in Figure 2. This is the fully-leaky guided mode (FLGM) geometry [4,5]. Transmitted and reflected optical intensity versus angle of incidence data was collected for TM and TE polarisation conserving and converting signals. Data collection was repeated with 10 kHz sinusoidal AC rms voltages of 0.5 V, 1.0 V and 1.5 V applied across the cell.

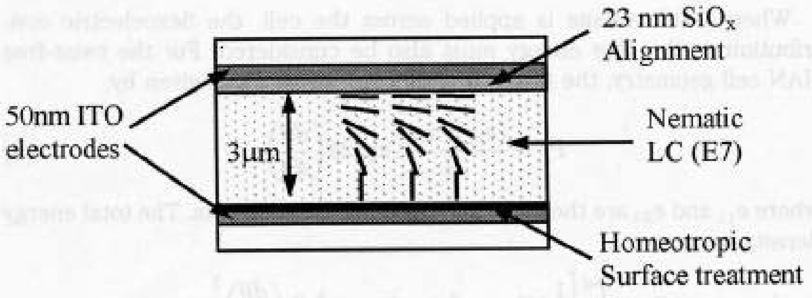

FIGURE 1 Schematic diagram of a Hybrid Aligned Nematic cell.

The influence of an applied DC voltage in forward and reverse bias was determined by collecting FLGM data with voltages of ± 0.5 V, ± 1.0 V and ± 1.5 V applied across the cell. To prevent ion generation and electrolytic decomposition of the liquid crystal a pulsed DC method was used, as shown in Figure 3. The optical response of the transmission detector was monitored over the duration of the pulses with an oscilloscope. This signal remained steady after the initial dynamic response of the director to the applied DC voltages, indicating that the ion concentration within the cell was negligible.

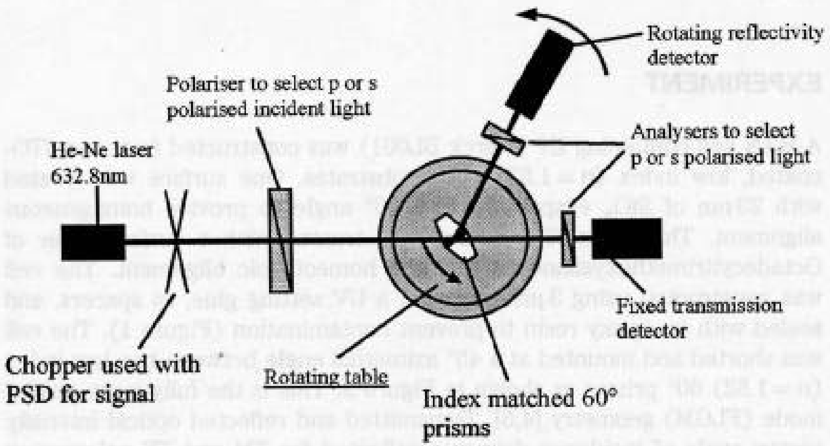

FIGURE 2 Schematic diagram of the fully-leaky guided mode experiment layout.

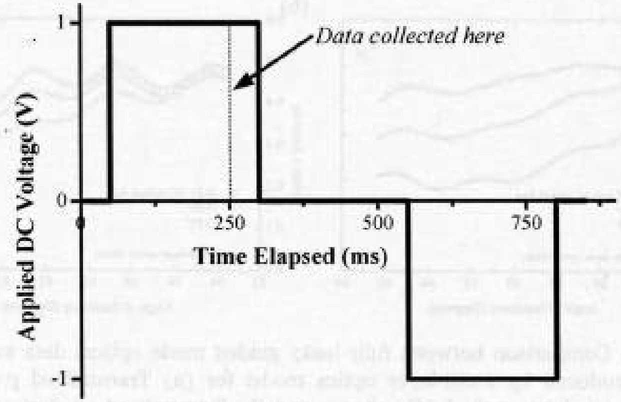

FIGURE 3 Pulsed DC data collection method for forward bias.

The optical data was compared to theoretical data produced from a multilayer optics modelling program, and the refractive indices, absorption and thickness of the optical layers were used as fitting parameters. The tilt profile within the LC layer was modelled as a third order rational bezier function. First the 0 V data was fitted, and the non-liquid crystal parameters were then held constant for the subsequent voltage dependent datasets.

RESULTS AND DISCUSSION

Examples of the fitted FLGM data are shown in Figure 4. As predicted by the free-energy minimisation model, the AC, forward bias DC and reverse bias DC director profiles showed clear differences in the distortion produced in the tilt profile. Model tilt profiles were generated using a free-energy minimisation program. For the AC case, to a first approximation, only elastic and dielectric contributions were considered. Rigid surface anchoring was assumed, and the elastic, dielectric and applied voltage values were varied to produce a tilt profile corresponding to the measured profile. For the 0 V and DC voltage data the flexoelectric energy term was also included in the calculation and the flexoelectric constant was allowed to vary.

A good fit to the measured AC tilt profiles could only be obtained by using the well-documented values for the elastic and dielectric constants of E7 and increasing the applied AC voltage by ≈ 0.1 V in each case (Figure 5(a)). However, In the DC cases, neither forward nor reverse bias could be fitted by simply adjusting the flexoelectric constant of the E7 whilst

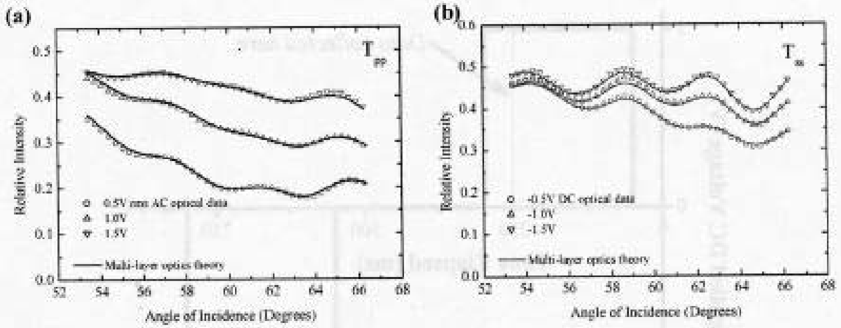

FIGURE 4 Comparison between fully-leaky guided mode optical data and model response produced by multi-layer optics model for (a) Transmitted p-polarised conserving signal for applied AC voltages and (b) Transmitted s-polarised conserving signal for positive applied DC voltages.

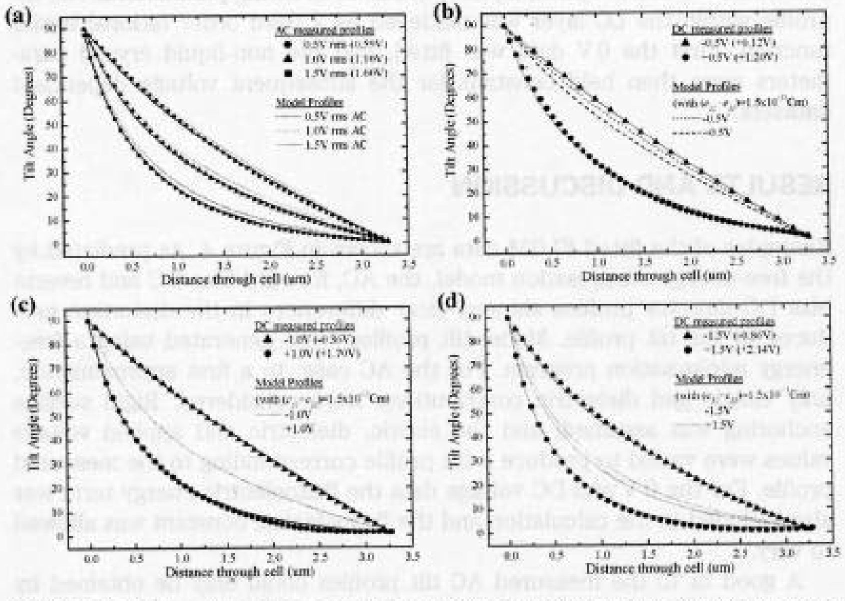

FIGURE 5 Tilt profiles produced by the multi-layer optics model, predicted model tilt profiles for each applied voltage and fitted tilt profiles (with DC offsets) for (a) Applied AC rms voltages and (b), (c) and (d), applied DC voltages in forward and reverse bias.

the applied DC voltage was held constant. When compared to the model profiles produced, the measured profiles implied that the measured distortion was due to the presence of an additional DC voltage enhancing the positive voltage and reducing the negative. This also accounts for the slight discrepancy in the AC voltage tilt-profile fit.

By adjusting the applied DC voltages in the tilt profile model and comparing the results with the measured tilt profiles (Fig. 5(b), (c) and (d)), the magnitude of the offset voltage was determined as $+0.64 \pm 0.04\,\mathrm{V}$, and the flexoelectric coefficient was found to be $1.5 \pm 0.3 \times 10^{-11}\,\mathrm{Cm}^{-1}$. This value of the flexoelectric coefficient is the same magnitude as those determined for similar nematic materials [6].

The most likely source of the internal field is surface polarisation, although further experiments are being performed to establish which surface is producing the offset.

CONCLUSIONS

The flexoelectric effect in a HAN cell has been observed, using the fully-leaky guided mode technique. The flexoelectric coefficient of E7 has been measured as $1.5 \pm 0.3 \times 10^{-11}\,\mathrm{Cm}^{-1}$, and this compares well with values for similar materials. However, the tilt profile measurements have suggested that a DC offset of $+0.64 \pm 0.04\,\mathrm{V}$ is present in the cell. This is thought to be due to surface polarisation.

REFERENCES

[1] Meyer, R. B. (1968). *Phys. Rev. Lett.*, *22*, 918.
[2] Yang, F. & Sambles, J. R. (1999). *J. Opt. Soc. Am.*, ***B16***, No.3.
[3] Yang, F. & Sambles, J. R. (1993). *Liq. Cryst.*, *13*, 1.
[4] Thurston, R. N. & Berreman, D. W. (1981). *J. Appl. Phys.*, *52*, 508.
[5] Ponti, S., Ziherl, P., Ferrero, C., & Zumer, S. (1999). *Liq. Cryst.*, *26*, 1171.
[6] Mazulla, A., Ciuchi, F., & Sambles, J. R. (2001). *Phys. Rev. E.*, *64*, 021708.