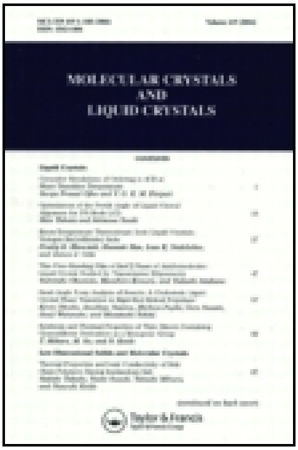

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Electro-Optics of the Hybrid Nematic Cell

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Electro-Optics of the Hybrid Nematic Cell†

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The first experimental data on the electro-optical properties of a hybrid aligned nematic cell submitted to an electric field are reported. Our theoretical treatment accounts for the observed behavior under an A.C. field, whereas the agreement in the D.C. case is not very good. This anomalous behavior can be explained by taking into account the flexoelectric characteristics of the examined cell. We show that, at small fields, the flexoelectric effect plays the role of changing the anchoring energy for the planar alignment.

INTRODUCTION

The hybrid aligned nematic (HAN) cell is recently receiving a growth of interest due mainly to its potential application in displays[1,2] and non-linear optics.[3,4] It is formed when the two glass walls of a nematic sample are treated to induce, respectively, homeotropic and planar orientations. The configuration is stable only for cells of sufficient thickness,[5] otherwise the stable configuration is homogeneous or homeotropic depending on the anisotropy of the surface anchoring energy.[6] This cell shows very peculiar optical properties, for example

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a high non-linear birefringence due to the molecular reorientation[4] induced by an intense light field.[3]

To realize displays based on the flexoelectric effect Durand's group[7,8] studied the HAN cell submitted to a D.C. field normal to the deformation plane. Their main results are that the polarization plane of the light can be rotated by an angle which is proportional to the applied electric field. Moreover the same group[9] was able to measure the flexoelectric coefficients by applying a D.C. field parallel both to the cell glass walls and to the deformation plane. On the other hand Matsumoto *et al.*[1] considered the HAN cell in a A.C. field parallel to the deformation plane and perpendicular to the glass boundaries. The principal feature in this situation is the absence of a threshold field for the electrooptical effects.

In this paper we study, both theoretically and experimentally, the optical properties of a HAN cell under D.C. and A.C. electric fields in the geometry of Reference 1. We calculate the molecular distribution as a function of the applied field by means of standard techniques, using as parameters the dielectric and elastic anisotropies; then we evaluate the birefringence behavior of the system and the transmitted light intensity between crossed polarizers. We report also some experimental data for HAN cells as a function of the slab thickness (6–15 μm), using liquid crystal materials of opposite dielectric anisotropy. A good agreement is achieved for A.C. fields between experiment and theory, if only the dielectric contribution to the total free energy is taken into account. On the other hand the flexoelectric contribution must be added to justify the experimental D.C. results.

EXPERIMENTAL

The HAN cells used in the experiments are arranged with two parallel tin oxide-coated glass plates (1 and 2) separated by mylar spacers (6–15 μm). Homeotropic orientation on electrode 1 is obtained with a silane surface coupling agent (ODS-E by Chisso Corp.), planar alignment on electrode 2 by deposition of a polymer thin film from a 0.25% solution of formvar in dichloroethane.

Nematic MBBA (from Riedel De Haen Ag.) and K15 (from BDH) are used, as typical materials of opposite dielectric anisotropy.

The observations are carried out at room temperature between crossed nicol polarisers, using a polarizing microscope Reichert Zetopan equipped with a halogen microlamp and a green filter. The light beam is incident normally on the cells. The phase shift induced in the extraordinary ray is measured by detecting the transmitted light intensity when the angle between the deformation and the polarization planes is $\pi/4$ (see Figure 1). The intensity variations of the transmissions are detected by a photodiode and registered with a recorder. Measurements are performed using a 500 Hz A.C. sinewave or a 10 V power source for the D.C. experiments. Accuracy in both

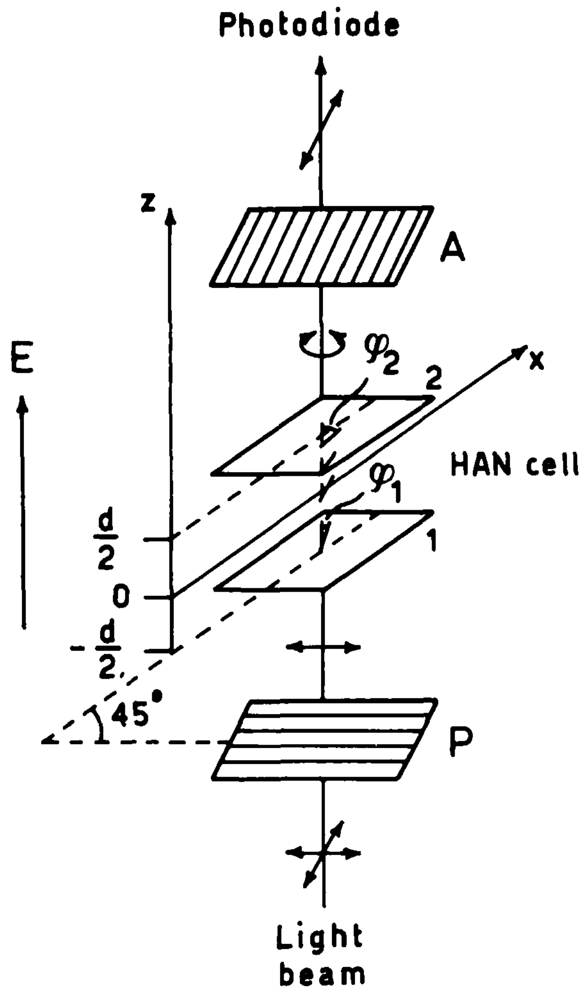

FIGURE 1 Schematic representation of the experimental arrangement (ϕ_1 and ϕ_2 are the angles between the nematic director $\hat{n}$ and $\hat{z}$ at the boundaries).

cases is not less than ± 0.005 V; the rate of increasing of the applied voltage is 0.05 V/min.

Experimental results in A.C. field for MBBA and K15 ($d = 6$ μm) are shown in Figure 2 (a and b); Figure 2a also indicates the theoretical curve derived using the physical parameters of MBBA[10] (see theory and discussion below). No threshold field can be detected, for either material, in the electro-optical effect, which varies continuously between zero and 4 V showing a maximum and a minimum in this range for MBBA and two maxima for K15.

The results in D.C. fields shown in Figures 3 and 4 (for MBBA cells of different thicknesses and a 6 μm cell of K15, respectively) reveal the nonappearance of any effect before about 1.5 V, so that only a maximum or a minimum can be identified.

THEORY AND DISCUSSION

As is well known, the stable configuration of the nematic director, under an external applied field, can be derived by minimizing the total free energy per unit surface area. If only the dielectric contribution is taken into account for the coupling between deformation and field, after trivial calculations[11] we get to the following first integral of the Lagrange-Euler equation

$$(1 - k \sin^2\phi)\left(\frac{\partial\phi}{\partial z}\right)^2 + \frac{\epsilon_a E^2}{4\pi k_{33}} \sin^2\phi = c^2, \tag{1}$$

where $k = 1 - k_{11}/k_{33}$ is the elastic anisotropy, ϕ the angle between the nematic director $\hat{\mathbf{n}}$ and $\hat{\mathbf{z}}$, k_{11} and k_{33} the Frank elastic constants of splay and bend, ϵ_a the dielectric anisotropy and c^2 an integration constant. By standard methods the tilt angle is found to be

$$\int_{\phi_1}^{\phi(z)} \left[\frac{1 - k \sin^2\phi}{c^2 - \dfrac{\epsilon_a}{4\pi k_{33}} |E|^2 \sin^2\phi}\right]^{1/2} d\phi = z + \frac{d}{2} \tag{2}$$

where $\phi_1 = \phi(-d/2)$ and $\phi_2 = \phi(d/2)$ are determined by the boundary conditions connected to finite anchoring energies.

Consequently the optical phase shift between the ordinary and the

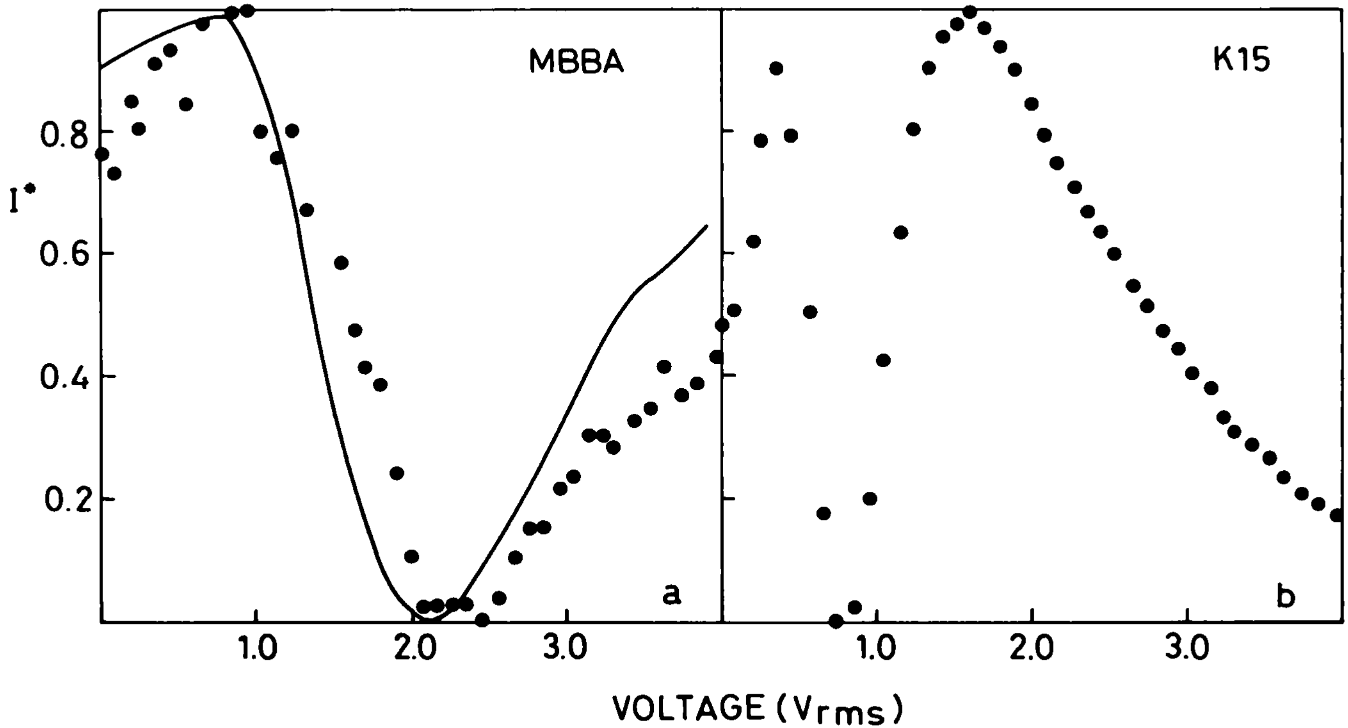

FIGURE 2 Intensity of the transmitted light (normalized as $(I - I\ \mathrm{min})/(I\ \mathrm{max} - I\ \mathrm{min})$) under A.C. voltages at 500 Hz for (a) MBBA $d = 6\ \mu m$ (the solid curve is calculated) and for (b) K15 $d = 6\ \mu m$.

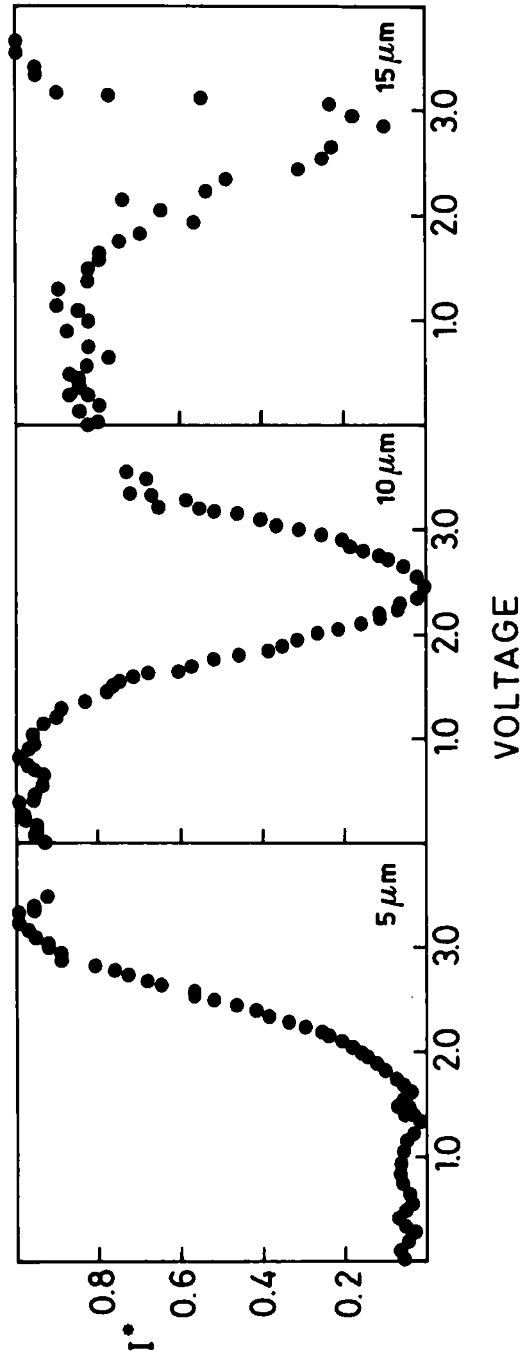

FIGURE 3 Experimental transmission curves in D.C. fields. MBBA cells of different thicknesses.

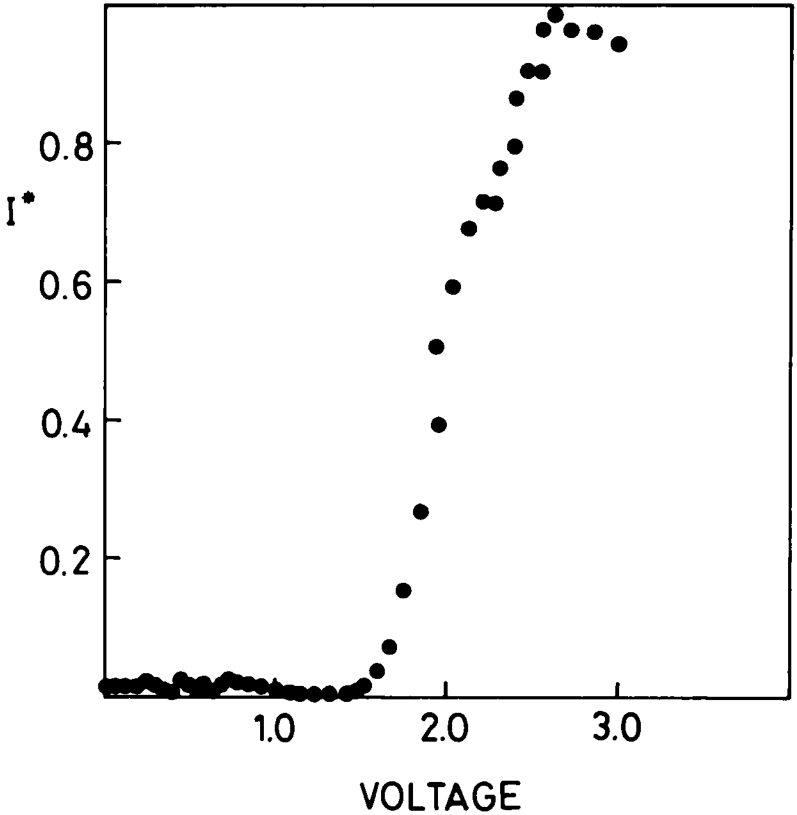

FIGURE 4 Transmission I^* versus applied D.C. voltage for a 6 μm cell of K15.

extraordinary rays is

$$\delta = \frac{2\pi}{\lambda} \int_{-d/2}^{d/2} \Delta n_{eff}(z)\, dz \tag{3}$$

or, by changing the integration independent variables, the equivalent form

$$\delta = \frac{2\pi}{\lambda} \int_{\phi_1}^{\phi_2} \Delta n_{eff}(\phi) \frac{dz}{d\phi}\, d\phi \tag{4}$$

where λ is the wave-length of the incident light and Δn_{eff} the difference between the refractive indices $n(\phi)$ and $n_\perp$. The phase shift vs the applied field, derived for MBBA cells of different thickness, is given in Figure 5.

The intensity of the transmitted light between crossed polarizers, in our geometry, can be written as

$$I = I_0 \sin^2 \frac{\delta}{2} \tag{5}$$

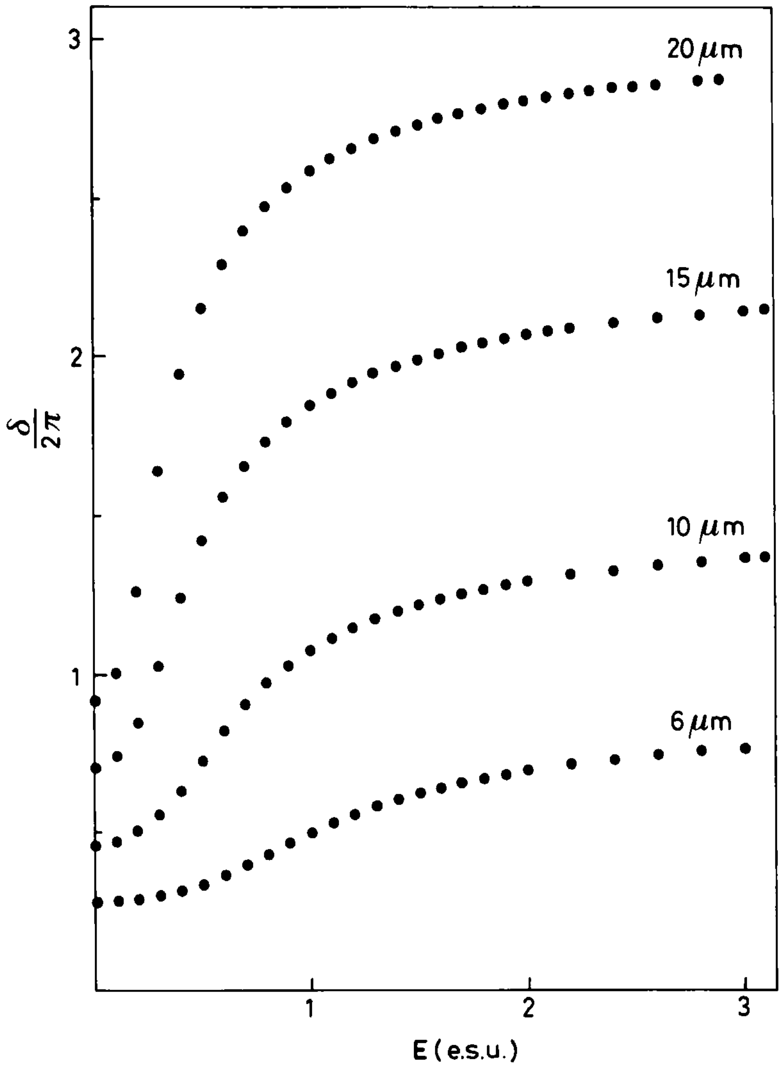

FIGURE 5 Phase shift dependence on the applied field calculated for MBBA samples of different d.

with I_0 intensity of the incident light. The transmission curves for MBBA cells of different d, shown in Figure 6 as a function of the applied voltage, are derived from Eq. 4 using Eq. 5.

The comparison between the calculated intensity and the A.C. field experiments is reported in Figure 2a as an example. It is easy to observe how the agreement is satisfying in this case. On the contrary, the situation is quite different in D.C. fields, where the agreement between experimental points and calculated transmission curves can be achieved only at high voltages (>1.5 V). In this paper we do not develop a full theoretical treatment of this problem, neither do we present a curve fit of the results and calculations. We wish only to discuss the possible role of the flexoelectric effect in this situation.

If we consider a very small field the dielectric contribution to the free energy becomes negligible. In this situation the volume free energy density is found to be

$$F_v = F_{elast} + F_{flexo} \tag{6}$$

if the flexoelectric effect is present and as in D.C. case. The F_{elast} term is composed of a true elastic contribution of the type

$$\frac{1}{2} k_{33} (1 - k \sin^2\phi) \left(\frac{d\phi}{dz}\right)^2 \tag{7}$$

and a contribution connected to a back electric effect coming from the flexoelectric polarization

$$2\pi \frac{(e_{11} + e_{33})^2}{\epsilon_\parallel} \frac{\cos^2\phi \sin^2\phi}{\left(1 - \frac{\epsilon_a}{\epsilon_\parallel} \sin^2\phi\right)} \left(\frac{d\phi}{dz}\right)^2 \tag{8}$$

as derived by Deuling,[12] where e_{11} and e_{33} are the flexoelectric coefficients and $\epsilon_\parallel$, ϵ_a the dielectric characteristics. The back electric field acts only to change slightly the elastic constants. Considering the order of magnitude of the contributions involved, we can neglect the last term in F_{elast}.

The second term in Eq. 6 represents the direct flexoelectric effect[13]

$$F_{flexo} = \vec{\mathbf{E}} \cdot \vec{\mathbf{P}} = -\vec{\mathbf{E}}(e_{11}\, \vec{\mathbf{n}}\, \mathbf{div}\, \vec{\mathbf{n}} - e_{33}\, \vec{\mathbf{n}}\, \mathbf{x}\, \mathbf{rot}\, \vec{\mathbf{n}}) \tag{9}$$

where $\vec{\mathbf{P}}$ is the flexoelectric polarization. In our case where the de-

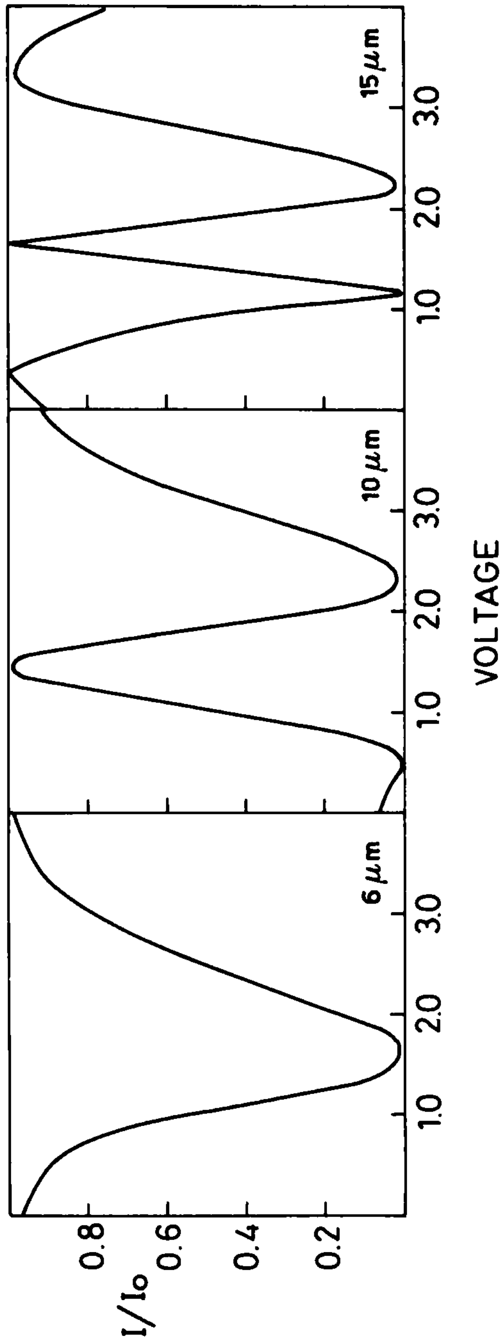

FIGURE 6 Calculated transmission curves for HAN cells of MBBA of 6, 10 and 15 μm thicknesses.

formation is contained in a plane, Eq. 9 simplifies to

$$F_{flexo} = -\vec{\mathbf{E}}(z) \cdot \vec{\mathbf{P}}_z = -\frac{1}{4}\bar{e}\,E\frac{d}{dz}(\cos 2\phi) \tag{10}$$

with $\bar{e} = (e_{11} + e_{33})$. Therefore F_{flexo} only gives a surface contribution.

In order to gain an estimation of the influence of flexoelectricity, we simplify the problem by assuming: i) one constant approximation ($k = 0$, $k_{11} = k_{33} = \bar{k}$); ii) strong anchoring on the homeotropic plate (assured by silane treatment[14]) and iii) that the dielectric contribution to the free energy is very small at low fields. Under these assumptions the Lagrange equation gives

$$\phi(z) = \frac{\phi_2}{d}\left(z + \frac{d}{2}\right), \tag{11}$$

where ϕ_2 is determined by minimizing the total free energy

$$\mathrm{F}(\phi_2) = \frac{\bar{k}}{2d}\Phi_2^2 + \frac{1}{4}\bar{e}\,E(1 - \cos 2\phi_2) + \frac{W_2}{2}\cos^2\phi_2 \tag{12}$$

obtained by substituting Eq. 11 in Eq. 7 and integrating over the sample thickness. W_2 is the anchoring energy on surface 2. Eq. 12 is deduced on the assumption that the anchoring energy is only due to dispersion forces.[15,16] Minimization of Eq. 12 gives

$$2\phi_2 = \frac{d}{k}(W_2 - \bar{e}\,E)\sin 2\phi_2 \tag{13}$$

This expression shows that the flexoelectric effect produces only a variation of the surface energy.

When a D.C. field is applied its effect depends on the polarity. Two configurations are possible, the first in which the external and the flexoelectric fields are parallel, the second in which they are antiparallel. In the former case the anchoring energy is lowered; consequently for low fields the homeotropic configuration is favoured by the flexoelectric effect, whereas the planar one is favoured by the dielectric effect.[17] The two competing effects are compensated, so the transmission intensity is almost constant until the dielectric term dominates. In the latter case the free energy is increased and the deformation phenomenon should be amplified but the charge injec-

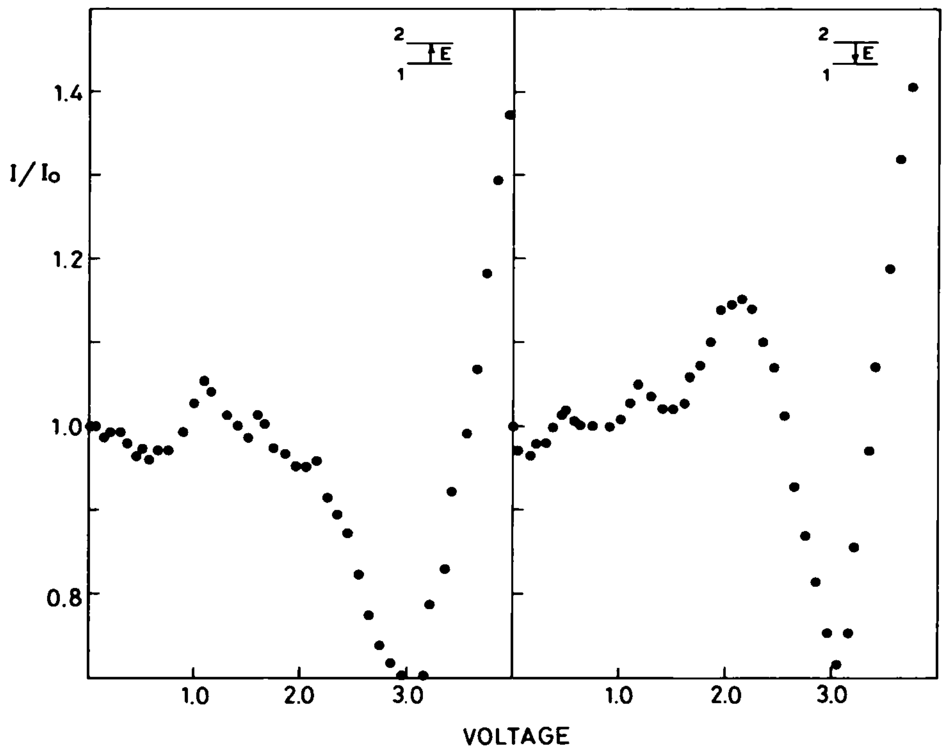

FIGURE 7 Experimental plots of the transmitted light intensity, normalized to the intensity of the incident light, for a 6 μm cell of MBBA. D.C. voltage; opposite field polarity.

tion could mask it. Qualitatively we can see such an effect in Figure 7, where two transmission curves with opposite field polarity are presented.

CONCLUSIONS

We report electro-optical behaviour of HAN cells both under applied A.C. and D.C. fields. Under A.C. fields the main contribution to the molecular reorientation, because of a coupling between the electric field and the deformation, comes from a dielectric term. On the contrary in the D.C. case the same dielectric contribution only becomes relevant at higher fields, since at lower fields a flexoelectric term is dominant.

A more quantitative comparison between the experimental and calculated curves derived that includes the flexoelectric term in the free energy expression is in progress. Experimental results under low frequency fields and controlled charge injection will be reported elsewhere.

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