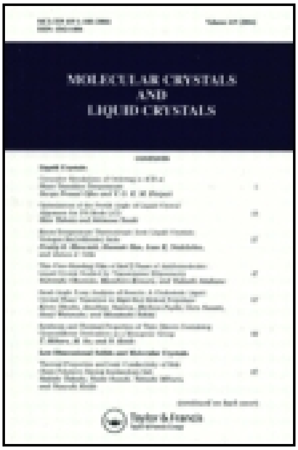

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Nonlinear Birefringence in Electrically Biased Hybrid Aligned Nematics

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Nonlinear Birefringence in Electrically Biased Hybrid Aligned Nematics

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The laser induced nonlinear birefringence in electrically biased hybrid aligned nematics is investigated. It is either enhanced or suppressed by the quasi-static electric field depending on the sign of the dielectric anisotropy of the nematics. An analytical solution is obtained for small distortion. The experimental results is in good agreement with theoretical prediction.

Keywords: HAN, nonlinear birefringence, electrical bias

I. INTRODUCTION

It is well known that with the presentation of external field the molecules in a nematic liquid crystal cell (NLC) will orient themselves toward the minimum energy configuration. This is referred to as the Freedericksz transition (FT). There usually exists a threshold field for this transition. However, the threshold is absent for the hybrid aligned nematic cell[1] (HAN). It is formed when the two glass walls of a nematic sample are treated to induced, respectively, homeotropic and planar orientation. The HAN cell is recently receiving a growth of interest due mainly to its potential application in displays[2,3] and nonlinear optics. Nevertheless, up to our knowledge so far, the birefringence studies of HAN cell are limited in single field (electric[2,3] or optical[4,5] field) effect.

From our previous work, it is known that the optically induced birefringence in a homeotropically aligned MBBA cell can be enhanced by a quasi-static electric field.[6] The biased electric field plays an important role in nonlinear optical phenomena of NLC. For example, the first order F.T. and optical bistability can be induced by applying an electric field.[7] The degenerate four wave mixing is crucially influenced by the biased electric field, too.[8]

In this paper, the birefringence controlled byelectric and/or optical fields is studied for HAN cell for NLC of either positive or negative dielectric anisotropy. The continuum theory is used in the derivation for field-induced molecular reorientation angles and birefringence. The phase retardation which is measured by Ho's high-resolution birefringence measurement method is proportional to laser intensity and the square of the applied quasi-static electric voltage in agreement with the theoretical prediction in the small distortion regime. The bend elastic constants are determined for 5CB and MBBA. The thermal effect due to laser heating is discussed.

II. THEORY

Consider a HAN film of thickness d with the geometry depicted in Figure 1. Its unpertured director $\hat{n}_0$ making an angle $\theta_0(z)$ with the z-axis. The quasi-static electric potential V (1 kHz) is applied on the electrodes coated on the inner faces of the substrates. The incident linearly polarized light beam is in the (x, z) plane with the wave vector $\vec{k}$ making an angle β with the z axis. Under the action of the applied fields, the local director $\hat{n}(z)$ orients itself to the angle $\theta(z)$ with the z-axis. Thus $n_x = \sin\theta(z)$, $n_y = 0$ and $n_z = \cos\theta(z)$.

The reorientation angle of the director, $\theta(z)$, can be calculated as usual by minimizing the total free energy $\mathbf{F} = \int \mathbf{f}\, dV$, where the free energy density $\mathbf{f}$ is given by[10]

$$\mathbf{f} = \frac{K_{33}}{2}(1 - K\sin^2\theta)\left(\frac{\partial\theta_d}{\partial z}\right)^2 - \frac{D_z^2}{8\pi\varepsilon_{//}(1 - W\sin^2\theta)} - \frac{I}{c}\frac{n_o}{\sqrt{1 - u\sin^2(\theta + \beta)}} \quad (1)$$

where $K \equiv 1 - K_{11}/K_{33}$, $u = 1 - n_o^2/n_e^2$, $W = 1 - \varepsilon_{\perp}/\varepsilon_{//}$; D_z is the z component of the electric displacement, I is the optical intensity and c is the velocity of light in vacuum ; K_{11}, K_{33} are splay and bend elastic constants, respectively.

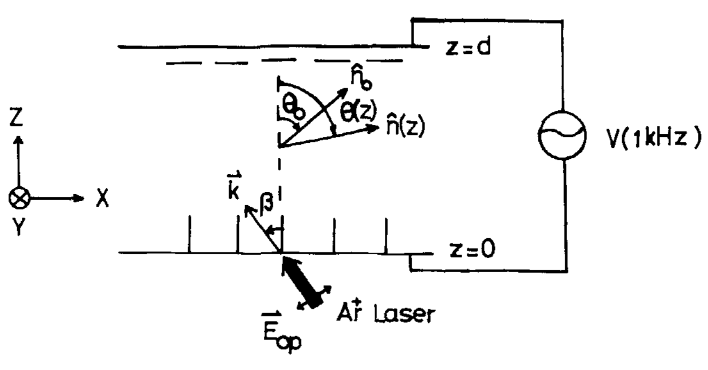

FIGURE 1 Configuration for a hybrid aligned nematic liquid crystal under the action of a quasi-static electric field and a light beam.

This minimization procedure yields the Euler-Lagrange equation, which can be rewritten as

$$(1 - K\sin^2\theta)\left(\frac{\partial\theta_d}{\partial z}\right)^2 + f(I, Dz; \theta) = A^2 \tag{2}$$

where

$$f(I, Dz; \theta) = \frac{2In_0}{\sqrt{1 - u\sin^2(\theta + \beta)}} - \frac{D_z^2}{8\pi\varepsilon_{//}(1 - W\sin^2\theta)}$$

with the boundary condition $\theta(0) = 0$ and $\theta(d) = \pi/2$, integration of Equation (2) yields

$$\int_0^{\theta(z)} \left[\frac{1 - K\sin^2\theta'}{A^2 - f(I, Dz; \theta')}\right]^{1/2} d\theta' = z \tag{3}$$

The constant A can be found from

$$\int_0^{\pi/2} \left[\frac{1 - K\sin^2\theta'}{A^2 - f(I, Dz; \theta')}\right]^{1/2} d\theta' = d$$

knowing $V = \int_0^d E_z\, dz$ and $E_z = Dz/\varepsilon_{//}(1 - W\sin^2\theta)$ from Equation (2) one can obtain

$$\frac{V}{Dz} = \int_0^{\pi/2} \frac{1}{\varepsilon_{//}(1 - W\sin^2\theta)} \left[\frac{1 - K\sin^2\theta}{A^2 - f(I, Dz; \theta)}\right]^{1/2} d\theta \tag{4}$$

Typically, using Equation (2), (3), and (4), $\theta(z)$ can be solved by numerical method. However, under the one constant approximation ($K_{11} = K_{22} = K_{33}$), we let

$$\theta(z) = \theta_0 + \theta_d \sin(\pi z/d) \tag{5}$$

Since the Euler-Lagrange equation yields $\theta_0 \cong \pi z/2d$ for absence of external fields, put this trial solution into Equation (1) and minimize the total free energy F with respect to θ_d, $\partial F/\partial\theta_d = 0$, yields

$$\theta_d \approx \frac{\dfrac{In_0ud}{4c}\cos 2\beta - \dfrac{\varepsilon_{//}V^2W}{4\pi d(2 + W)^2}}{2\left[\dfrac{K_{33}\pi^2}{4d} + \dfrac{2In_oud}{3\pi c}\sin\beta - \dfrac{\varepsilon_{//}V^2W^2}{4\pi d(2 + W)^3}\right]} \tag{6}$$

for $u/2\sin^2 u(\theta + \beta) << 1$; $W\sin^2\theta << 1$ and $\theta_d << 1$.

In the case of normal incidence, $\beta = 0$, and $\varepsilon_{//}V^2W^2/4\pi d(2 + W)^3 << K_{33}\pi^2/4d$, θ_d becomes

$$\theta_d \approx \frac{n_o u}{2cK_{33}\pi^2} d^2 I - \frac{\varepsilon_{//}W}{2K_{33}\pi^3(2 + W)^2} V^2 + \frac{n_o u \varepsilon_{//} W^2}{2K_{33}^2\pi^5 c(2 + W)^3} d^2V^2I \quad (7)$$

The laser beam with wavelength λ should have extraordinary component experience an extra induced phase retardation that that of its ordinary component with an amount of

$$\Delta\delta \approx \frac{n_o u n_{op} u_p^2}{4ck_{33}\pi\lambda} d^3 I - \frac{n_{op}u_p\ \varepsilon_{//}W}{4K_{33}\pi\lambda(2 + W)^2} dV^2 + \frac{n_o u n_{op} u_p^2 \varepsilon_{//} W^2}{4K_{33}^2\pi^4 c(2 + W)^3\lambda} d^3V^2I \quad (8)$$

where n_{op}, n_{ep} are the index for probe beam and $u_p = 1 - n_{op}^2/n_{ep}^2$.

III. EXPERIMENTAL

The HAN cells used in the experiment are arranged with two parallel indium tin oxide coated glass plates separated by mylar spacers (75 ~ 250 μm). Homeotropic orientation is obtained by DMOAP coating on the electrode. Planar alignment is achieved by rubbing after PVA coating. Nematic MBBA and 5CB are used, as typical materials of opposite dielectric anisotropy.

A block diagram of our experimental apparatus is shown in Figure 2. A quasi-static electric field at 1kHz is applied normal to the glass plates. An Ar^+ laser beam (at 5145Å) is incident normally on the cell with its polarization along the easy direction of the first plate. The field-induced birefringence is measured with a He-Ne probe laser by using a modulation technique originally devised by Lim and Ho.[9]

Briefly, the probe beam is split and the main measurement beam passes through a rotating polaroid before being detected by photo diode A. The projection of E_{0p}

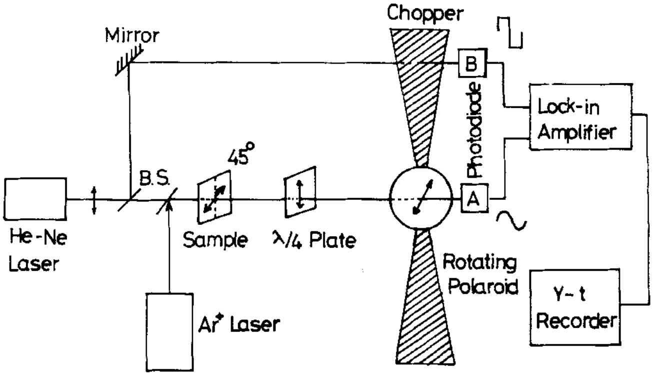

FIGURE 2 Block diagram of the experimental setup.

on the same plane is at an angle of 45° to the probe laser polarization direction. The axis of the $\lambda/4$ plate is aligned with the probe laser polarization direction. A polaroid is mounted at the end of the open shaft of a synchronous motor. The shaft of the motor also carries a chopper which intercepts the reference beam. The phase difference between the signals from the photodiodes is measured with lock in amplifier as a phase meter.

IV. EXPERIMENTAL RESULTS

The birefringence measurement results are shown in Figures 3, 4 and Figures 5, 6 for MBBA and 5CB, respectively. Figures 3 and 5 show the laser beam intensity dependence of phase retardation difference ($\Delta\delta$) of the E-ray and O-ray of the probe beam after passing through the sample film for two samples of different thickness with and without biased voltage. Figures 4(a) and 6(a) show the electric field controlled birefringence (ECB) for samples of different thickness. Figures 4(b) and 6(b) are the replots of Figures 4(a) and 6(a), respectively. The linear retardation of $\Delta\delta$ versus laser intensity I and the square of the voltage V is obvious as shown in Figures 3, 4(b), 5 and 6(b). The discrepancy in the high field regime for the 262µm MBBA sample with $0.5V$ biased voltage shown in Figure 3 will be discussed in next section.

V. DISCUSSION AND CONCLUSION

It is obvious to find from Figure 4 that the electric field induced birefringence is positive for MBBA which exhibits a negative dielectric anisotropy. However, as

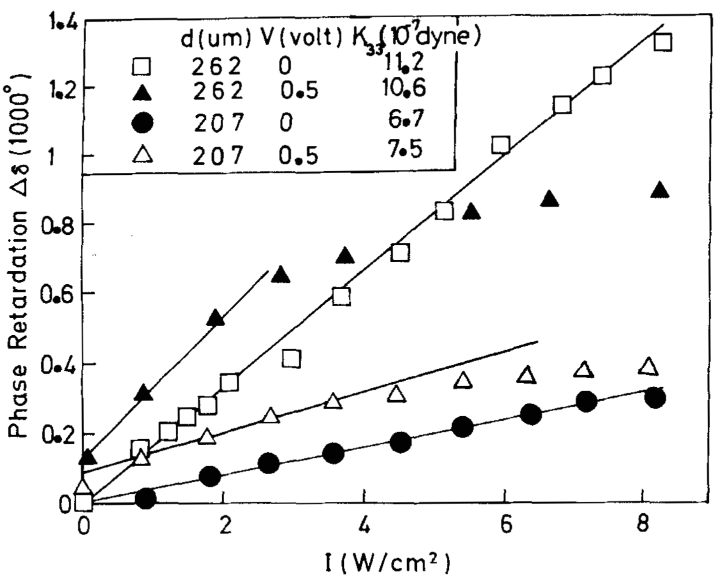

FIGURE 3 Induced birefringence versus pumping laser intensity for MBBA. The straight lines are the least square fitting results.

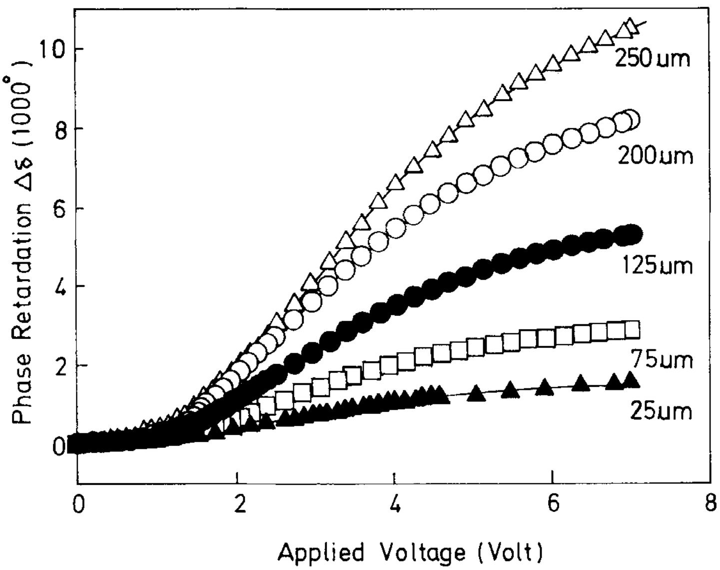

FIGURE 4(a) Induced birefringence versus biased voltage for MBBA. The solid curves are drawn freehand as a guide to the eye.

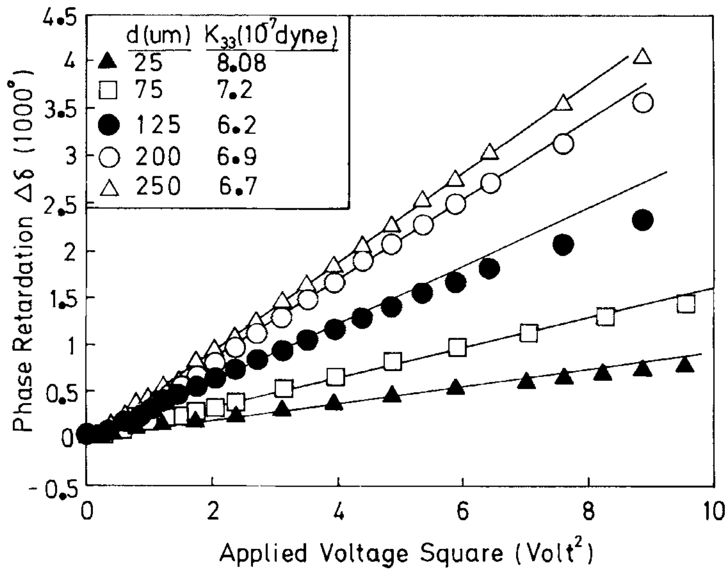

FIGURE 4(b) Induced birefringence versus the square of biased voltage for MBBA. The straight lines are the least square fitting results.

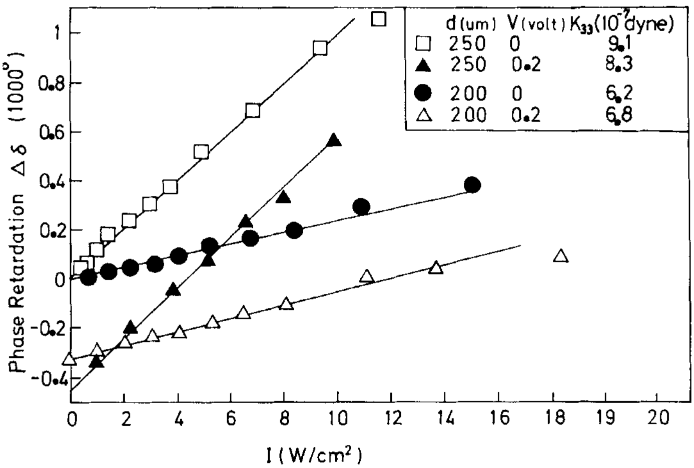

FIGURE 5 Induced birefringence versus pumping laser intensity for 5CB. The straight lines are the least square fitting results.

shown in Figure 5, it is negative for 5CB with a positive dielectric anisotropy. The phase retardation difference is proportional to the biased voltage in agreement with the prediction of Equation (8). The slope of the Equation (8) can be found from the least square fitting straight lines in Figures 4(b) and 6(b). Putting the physical parameters $n_o \approx n_{op} = 1.56(1.52)$; $n_e \approx n_{ep} = 1.78(1.68)$, $\varepsilon_{//} = 4.9(18.0)$ and $\varepsilon_{\perp} = 5.4(7.0)$ for MBBA (5CB), one can easily obtain k_{33} for each sample film. The linear relation for induced phase retardation difference $\Delta\delta$ versus the intensity I for weak laser beam is shown in Figures 3 and 5. The effect of biased electric field on laser induced birefringence is unambiguous. The electric field does either enhance or suppress the induced phase retardation for MBBa or 5CB, respectively as predicted from Equation (8). Again using the known values of physical parameters and the slopes of the least square fitting line, the bend elastic constants can be obtained. The average value of k_{33} obtained from Figures 3 and 4(b) is 8.0 $\times$ 10^{-7} dyne for MBBA, which is close to 7.5 $\times$ 10^{-7} dyne as reported.[11] The average value of k_{33} obtained from Figures 5 and 6(b) is 7.9 $\times$ 10^{-7} dyne for 5CB, which is close to 7.5 $\times$ 10^{-7} dyne found in the literature.[12]

The discrepancy of data for MBBA with 0.5 volts biased voltage in higher intensity regime on Figure 3 can be explained by thermal effect.[13] In general,[13] the rate of change of index with respect to temperature $\Delta n_e/\Delta T$ is negative while $\Delta n_o/\Delta T$ is positive. In other words, $\Delta n = n_e - n_o$ decreases as temperature increases. Consequently, thermal effect is significant for MBBA for two reasons. First, MBBA is sensitive to Ar^+ laser as the thermal effect is considered. Second, $|\Delta n_e/\Delta T| \approx 5$ $|\Delta n_o/\Delta T|$ for MBBA. That is when the orientation angle θ is small, the suppression of phase retardation is negligible. However, when θ is large, the suppression becomes significant. In particular, the orientation angle of HAN is much larger than of the homeotropically aligned cell. Therefore with a biased voltage of 0.5 volts brings the molecular angle even larger such that n_{eff} is closer to n_e. In this case the suppression becomes observable.

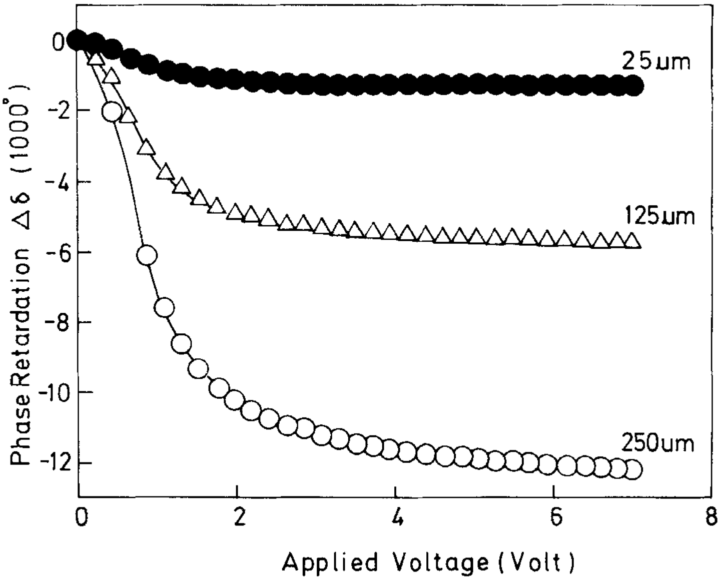

FIGURE 6(a) Induced birefringence versus biased voltage for 5CB. The solid curves are drawn freehand as a guide to the eye.

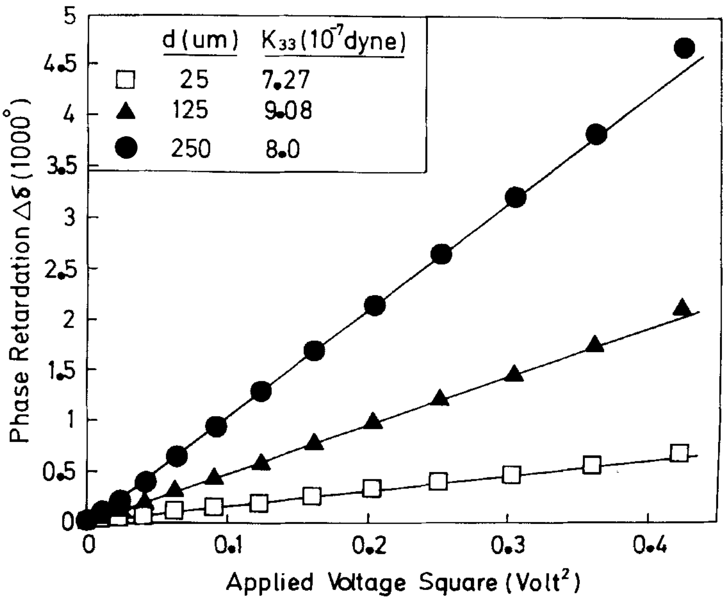

FIGURE 6(b) Induced birefringence versus the square of biased voltage for 5CB. The straight lines are the least square fitting results.

In conclusion, the laser induced nonlinear birefringence in a hybrid aligned nematic cell is either enhanced or suppressed by the quasi-static field depending on the sign of the dielectric anisotropy of the nematic. For small distortion, the phase retardation difference due to molecular reorientation is proportional to the pumping laser intensity and to the square of the applied voltage. The thermal effect is significant for electric field biased cell of MBBA.

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