

## BIREFRINGENCE MEASUREMENT ON THE LIQUID CRYSTAL BY PHASE MODULATION TECHNIQUE

Kang Ho YOON\*, O Ok PARK\*\* and Jong-Duk KIM

Department of Chemical Engineering, Korea Advanced Institute of Science and Technology, Seoul 130-650, Korea

(Received 5 February 1989 • accepted 17 April 1989)

**Abstract**—A convenient and accurate technique for measuring the birefringence of liquid crystal (LC) is developed. The birefringence of LC was obtained with only one experimental run by using phase modulation technique, which is an expansion of PMFB (Phase Modulated Flow Birefringence) technique developed elsewhere [1]. The basic principle of the method is based on the determination of the phase differences which occur when a phase modulated monochromatic polarized light propagates through a medium with an anisotropic refractive index. Birefringence measurements with red light (wavelength: 0.6328  $\mu\text{m}$ ) for commercial liquid crystal material (Merck, ZLI 3201-000) are reported.

### INTRODUCTION

The magnitude and wavelength dependence of the birefringence  $\Delta n$  of liquid crystals (LCs) are of fundamental interest and are key parameters which affect the operation of liquid crystal based electro-optic devices. Several techniques [2-6] have been developed for evaluating the birefringences of liquid crystals in the visible spectral region. The conventional interference technique [2] developed for birefringence measurements in the visible region has several particularly disadvantageous features. First, it only provides relative birefringence values, and in order to determine the absolute birefringence  $\Delta n$ , two independent measurements are necessary. It is also difficult to measure continuous birefringence data even over a narrow spectral range by this method.

A voltage-dependent transmission technique [3,4] has also been used to measure the birefringence of liquid crystals at single wavelength in the visible spectral region. However, in the implementation of this technique only one polarization component of the transmitted light was measured and, therefore, a portion of the total phase shift  $\delta$  was not accounted for. The accuracy of the method decreases significantly as the phase shift induced by the liquid crystal becomes smaller [4].

The voltage-dependent optical transmission tech-

nique [7] is to determine the total phase differences induced by a liquid crystal retardation plate in two different optical arrays. To determine the absolute birefringence  $\Delta n$  in this method, two independent measurements are necessary. Experimental errors may occur in two independent experimental measurements.

In this work we report an improved technique to determine the absolute birefringence with one experimental run. The novelty and value of this method is in the use of PEM (Photoelastic Modulator) to determine the absolute birefringence accurately and conveniently through the one experimental run. Details of the method are described in Sec. III.

### PRINCIPLE OF MEASUREMENT

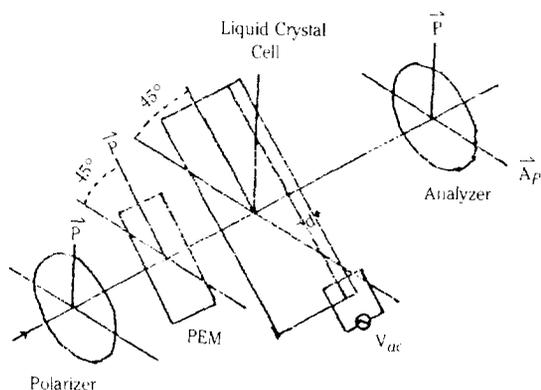
Nematic liquid crystals consist of rodlike molecules which on the average line up parallel to the preferred direction specified by the vector  $\mathbf{L}$ . When a polarized monochromatic lightwave propagates through a homogeneously aligned LC cell with its polarization axis  $\mathbf{p}$  at an angle of  $45^\circ$  to  $\mathbf{L}$ , the extraordinary and ordinary rays in the outgoing light will experience a phase difference  $\delta$ :

$$\delta = \frac{2\pi d \Delta n}{\lambda} \sin^2 \theta \quad (1)$$

where  $d$  is the LC layer thickness,  $\Delta n$  ( $n_e - n_o$ ) is the birefringence of the LC,  $\lambda$  is the wavelength, and  $\theta$  is an angle between the light propagation direction and

\* Current address: Sumsung General Chemicals Co., Ltd.

To whom all correspondence should be addressed.



**Fig. 1. Schematic diagram of optical configuration for liquid crystal birefringence measurement.**

the cell plate containing LC.

Generally, the pretilt angle ( $90^\circ - \theta$ ) of the LC is small ( $< 5^\circ$ ) and Eq. (1) reduces to  $\delta = 2\pi d \Delta n / \lambda$ . When the LC cell is placed between a analyzer and PEM as shown in Fig. 1, the transmitted intensity can be calculated by using Jones calculus [8]. The mathematical derivation is similar to the case reported in other paper [9] so that we omit the detailed procedure here.

$$I_{dc} = 1 + J_0(A) [\cos 4\phi \sin^2 \delta - \cos^2(\delta/2)] \quad (2)$$

$$I_\omega = 2 \sin \delta (2 \cos^2 \phi - 1) J_1(A) \quad (3)$$

$$I_{2\omega} = 2 J_2(A) [\cos 4\phi \sin^2(\delta/2) - \cos^2(\delta/2)] \quad (4)$$

where  $\phi$  is orientation angle of the sample.

Here PEM produces a sinusoidal phase such as  $\delta_m = A \sin \omega t$ .  $\omega$  is a resonance frequency of PEM and  $t$  is time. The details can be seen elsewhere [1,9].

If the sample was homogeneous and perfectly aligned, we can assume  $\phi = 0$ . Since  $J_0(A)$  is adjusted by changing the amplitude of the PEM, the setting of the PEM controller can be chosen such that the dc signal given in eq. (2) will not have any dependence on the optical anisotropy of the sample. In other word, it is possible to make  $J_0(A)$  equal to zero. Then

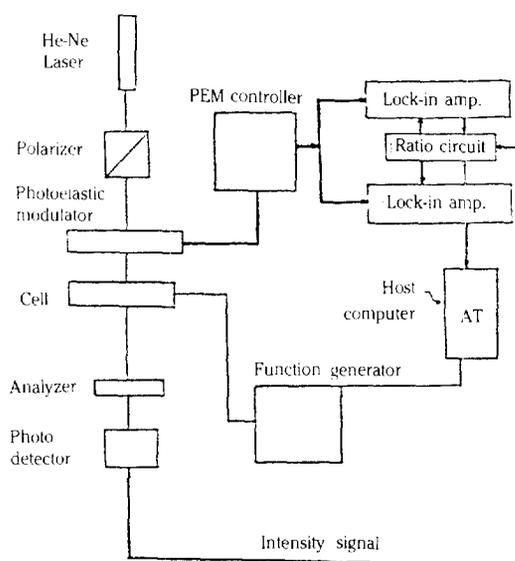
$$I_{dc} = 1 \quad (5)$$

$$\sin \delta = I_\omega / 2 J_1(A) \quad (6)$$

$$\cos \delta = -I_{2\omega} / 2 J_2(A) \quad (7)$$

Eq. (6) and (7) reduce to

$$\delta = N\pi + \tan^{-1} \left( \frac{-I_\omega J_2(A)}{I_{2\omega} J_1(A)} \right), N = 0, 1, 2, \dots \quad (8)$$



**Fig. 2. Schematic representation of the experimental arrangement.**

## EXPERIMENTAL

As shown in Fig. 2, we have incorporated the capability of signal processing in the experiment to determine the birefringence of the sample. The light intensity detected at the photodiode is converted to the voltaic output and goes into the input port in pre-amplifier. The output, full intensity signal is fed into two lock-in Amplifiers (Stanford Research System, Inc. SR510), 1f and 2f. They are both sent the same reference frequency signal from the PEM controller and phase reference of the 1f and 2f amplifier are set to  $0^\circ$  and  $90^\circ$ , respectively. Then the output signals from two lock-in Amplifiers are fed back to the ratio circuit. The information to be extracted from the signal includes the mean intensity  $I_{dc}$  and the first harmonic component  $I_\omega$ .  $I_{dc}$  is easily obtained from low pass filter. And the analog ratio circuits provide two ratio components  $R_\omega (I_\omega / I_{dc})$  and  $R_{2\omega} (I_{2\omega} / I_{dc})$ . These analog ratio signals are converted to the corresponding digitized signals by the A/D converter with 13 bit resolution. A digitization is performed in about 1 ms. These digitized signals are then read by the IBM/AT via the serial asynchronous data communication (RS-232C). Here, the lock-in Amp. (1f) is DCE and RS-232C port on computer (COM1: port on IBM/AT) is DTE and RS-232C communication are made at 9600 baud, no parity, two stop bits.

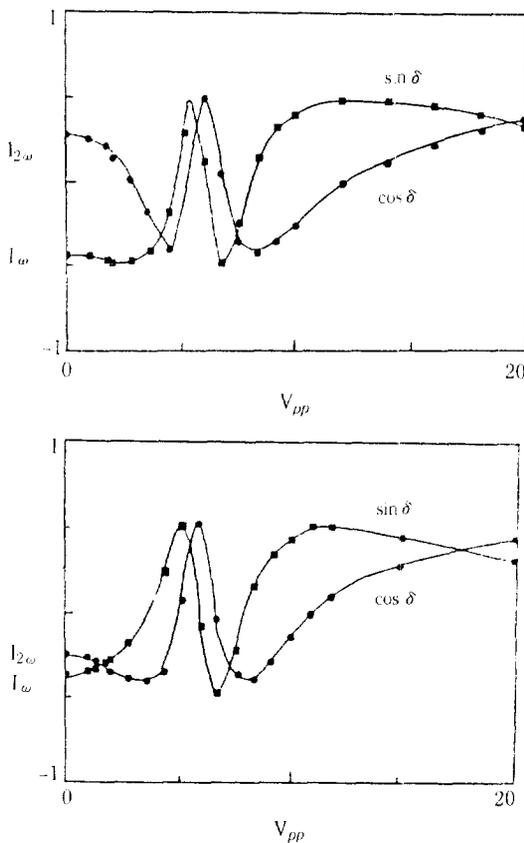


Fig. 3. Retardation as a function of the applied voltage. Frequency is 1 KHz. The sample is ZLI 3201-000; (a) 8  $\mu\text{m}$  cell, (b) 9  $\mu\text{m}$  cell.

## RESULT AND DISCUSSION

As shown in Fig. 3,  $I_\omega$  and  $I_{2\omega}$  go through maxima and minima as the applied voltage increases and they approach limiting values in the high voltage region. The reason for this behavior is that the LC molecules are reoriented by the applied electric field. Initially, with  $V = 0$ , the pencil-shaped LC molecules cause the LC cell to behave as a phase retardation plate. Above the limiting voltage, virtually all the molecules are reoriented by the electric field so that the liquid crystal director  $\mathbf{L}$  is perpendicular to the plane of polarization of the incident light. This molecular reorientation effectively removes the original optical anisotropy of the cell, and no phase difference between the ordinary and extraordinary rays is observed at high voltages. When the applied voltage is reduced by a small amount, partial relaxation of the liquid crystal molecules toward their original parallel orientation occurs,

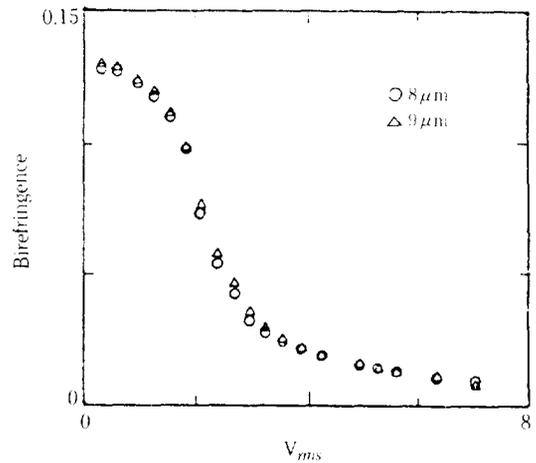


Fig. 4. Voltage dependent birefringence of ZLI 3201-000 liquid crystal.

and a small optical anisotropy is produced. The first intersection in Fig. 3(a) (starting from the high voltage end) where  $\sin \delta = \cos \delta$  is identified with an absolute phase retardation  $\delta$  of  $\pi/4$ , since precise phase shift for any applied voltage range is calculated from Eq. (8). At second crossing point  $\delta$  is  $5\pi/4$ . Following this procedure the total phase difference produced by this cell is given by Eq. (8) with  $\frac{13}{4} \pi$  ( $N = 3$ ) this value of  $\delta$  can then be used to calculate the birefringence to obtain  $\Delta n = \delta \lambda / 2\pi d = 0.1307$  for 8  $\mu\text{m}$  cell, with  $\lambda = 0.6328 \mu\text{m}$  and  $T = 26^\circ\text{C}$ . Similarly, we obtain  $\Delta n = 0.1291$  from data shown in Fig. 3(b) for 9  $\mu\text{m}$  cell. The dependence of LC effective birefringence on voltage can also be calculated from the data shown in Fig. 3(a) and (b) by using Eq. (8). The results are shown in Fig. 4 for both 8  $\mu\text{m}$  and 9  $\mu\text{m}$  cell. These data for two different cell thickness agree well. We can conclude the method developed here is accurate.

In Fig. 4 birefringence decreases linearly as the voltage exceeds the Freedericksz transition threshold and the rate of decrease is less in the high voltage region owing to the balance between surface torque and external field-induced torque [10]. From Fig. 4, we find that the threshold voltage,  $V_{th} = 0.8 V_{ms}$ , where  $\Delta n$  first begins to decrease. The threshold voltage for a homogeneous liquid crystal cell is given by [4]

$$V_{th} = \pi \left[ \frac{K_{11}}{\epsilon_o \Delta \epsilon} \right]^{1/2} \quad (9)$$

where  $K_{11}$  is splay elastic constant and  $\Delta \epsilon$  is dielectric anisotropy.

We obtain that the value of  $K_{11} = 10.7$  and  $\epsilon_o = 12.267$  from literature information (Merck). By substituting the value of  $K_{11}$  on Eq.(9), we can calculate the

dielectric anisotropy. We compute  $\Delta\epsilon = 14.65$ , while a reported value of  $\Delta\epsilon$  is 16.4 from the supplier. The small deviation between the reported value and our calculated one is due to the absence of the information for the temperature dependence of  $K_{11}$  and frequency dependence of  $\Delta\epsilon$ .

### CONCLUDING REMARKS

A phase modulated technique was developed to measure the birefringence of liquid crystals at discrete wavelength (0.6328  $\mu\text{m}$ ). This technique developed here for measuring the birefringence of LC is proved accurate and convenient. The unique feature of this technique is that it is useful for the automation of birefringence measurement of LC by using computer-aided phase modulation technique.

### ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support of Samsung Electron Devices Co., Ltd.

### NOMENCLATURE

$d$  : cell thickness  
 $\mathbf{L}$  : director of the LC molecules  
 $\mathbf{p}$  : polarization axis  
 $I_{dc}$  : mean intensity signal  
 $I_{\omega}$  : intensity of the first harmonic component  
 $I_{2\omega}$  : intensity of the second harmonic component  
 $J_0(A)$  : Bessel function of the first kind of order 0  
 $J_1(A)$  : Bessel function of the first kind of order 1  
 $J_2(A)$  : Bessel function of the first kind of order 2

$R_{\omega}$  : ratio signal intensity with first harmonic component  
 $R_{2\omega}$  : ratio signal intensity with second harmonic component

### Greek Letters

$\delta$  : retardance  
 $\lambda$  : wave length  
 $\theta$  : tilt angle  
 $\phi$  : orientation angle of liquid crystal  
 $\Delta n$  : birefringence

### REFERENCES

1. Frattini, P.L.: Ph.D. Thesis, Stanford Univ., 1986.
2. Chang, R.: *Mater. Res. Bull.*, **7**, 267 (1982); *Mol. Cryst. Liq. Cryst.*, **38**, 77 (1977).
3. Soref, R.A. and Rafuse, M.J.: *J. Appl. Phys.*, **43**, 2029 (1972).
4. Haase, W. and Potzsch, D.: *Mol. Cryst. Liq. Cryst.*, **38**, 77 (1977).
5. Hanson, E.G. and Shen, Y.R.: *Mol. Cryst. Liq. Cryst.*, **36**, 193 (1976).
6. Miraldi, E. and Oldano, C.: *Appl. Opt.*, **21**, 4163 (1982).
7. Wu, S.T. and Efron, U.: *Appl. Opt.*, **23**, 3911 (1984).
8. William, A.S.: Polarized Light, Harvard Univ. Press, 1972.
9. Park, O.O., Hwang, C.I. and Lim, T.J.: *Korean J. of Chem. Eng.*, **6**, 23 (1989).
10. de Gennes, P.G.: The Physics of Liquid Crystals, Clarendon, Oxford, 1974.