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A Novel Optical Measurement Method for the Determination of LC Pretilt Angle without a Restriction of Pretilt Magnitude and a Cell Gap of LC

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Abstract To measure a pretilt angle in liquid crystal cells, a crystal rotation method is commonly used because of its advantages such as high precision, short measurement time and small measurement area. The method, however, has the restrictions on measurable pretilt range and available cell thickness; pretilt in the range of about 16~60 degrees cannot be measured and the cell thickness should be larger than about 10μm. We developed a new pretilt measurement method without the restrictions of cell condition. In our new method, a pretilt angle is determined from a specific polarization direction of incident light, for which either ordinary or extraordinary wave is excited inside the cell. This method permits us to easily and accurately measure the pretilt angle in full range of 0-90 degrees.

key words: *liquid crystal, pretilt angle, measurement method, optical measurement, crystal rotation method*

Introduction

Liquid crystal (abbreviated by) molecule alignment has a marked influence on the optical characteristic of liquid crystal display (LCDs). The orientation of a LC molecule at an interface can be described by an azimuthal angle in plane of the surface and by a polar angle away from the surface. The azimuthal angle can be measured easily,[1)] but the measurement of the polar angle, so-called pretilt angle, is more complicated.

This LC pretilt angle also has a remarkable influence on the electro-optical properties of LC cells[2,3)] Hence, it is necessary to measure accurately the pretilt angle in full range of 0°~90°. At present, the following four methods for measuring pretilt have been reported: crystal rotation method,[4)] capacitance measurement method,[5)] magnetic null method[5)] and ATR method[6)].

Among them, the crystal rotation method is widely used because precise measurement is rapidly obtained. This method, however, can not be applied to the cell with any pretilt angle in the range of about 16°~60°; for a pretilt angle within

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the range, there is not the corresponding incident angle to render a extremum retardation because of the refraction of light at boundary surface. Moreover, in the case of thin LC cells about less than 10μm, the pretilt angle measured by the method can contain a significant error because the change of retardation magnitude due to the variation of incident angle is very small. Also this method requires the high uniformity of cell gap. To solve these problems, we developed a new method, a pretilt angle can be obtained by selecting a polarization direction of incident light to render the excitation of either ordinary or extraordinary wave inside the LC cell.

In this paper, we describe the principle of the new method without the restrictions on measurable pretilt range and available cell thickness. Moreover, we will discuss the validity of the polarizer rotation method (PRM) by calculation and experimental result.

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Measurement principle of New Method

The configuration of our measurement system is shown Figure 1. A homogeneously LC cell with a pretilt angle is put between a polarizer and an analyzer. For convenience' sake, let's choose a right handed *xyz* coordinate system, where *x*-axis and *z*-axis indicate vertical direction and light propagation direction, respectively. The polarizer and the analyzer lying in *x-y* plane are rotated, and the LC cell is tilted from *x-y* plane at a certain angle θ which is the incident angle

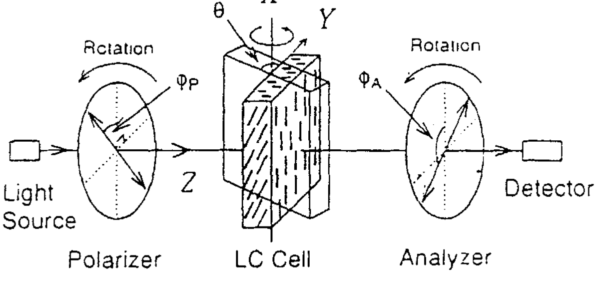

Figure 1. Schematic diagram of new pretilt measurement system

of light, where the rubbing direction (parallel to *x* axis) of the cell parallels to the vertical direction.

Using extended Jones matrix representation,[7,8] the electric field amplitudes of *s*-wave and *p*-wave, A_s' and A_p' of the light passing through the LC cell are connected with those of incident light, A_s and A_p as follows:

$$\begin{bmatrix} A_s' \\ A_p' \end{bmatrix} = \begin{bmatrix} t_s' & 0 \\ 0 & t_p' \end{bmatrix} \begin{bmatrix} t_{os} & t_{es} \\ t_{op} & t_{ep} \end{bmatrix} \begin{bmatrix} e^{-ikozd} & 0 \\ 0 & e^{-ikezd} \end{bmatrix} \begin{bmatrix} t_{so} & t_{po} \\ t_{se} & t_{pe} \end{bmatrix} \begin{bmatrix} t_s & 0 \\ 0 & t_p \end{bmatrix} \begin{bmatrix} A_s \\ A_p \end{bmatrix} \tag{1}$$

Here, t_s and t_p or t_s' and t_p' are the transmittance coefficients when light progress

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from air to glass or from glass to air. Also, t_{so}, t_{po}, t_{se} and t_{pe} are the transmission coefficients of light progressing from glass to LC layer to glass, where the subscripts o and e indicate the ordinary (o-) and extraordinary (e-) waves inside the LC layer, respectively. On the other hand, $e^{-ik_{oz}d}$ and $e^{-ik_{ez}d}$ represent the phase retardation of o-wave and e-wave inside the LC layer, respectively. The wave vectors' z-components, k_{oz} and k_{ez} of o-wave and e-wave are respectively expressed by

$$k_{oz} = \sqrt{\left(\frac{\omega}{c}\right)^2 n_o^{\,2} - \beta^2} \tag{2}$$

$$k_{ez} = \sqrt{\left(\frac{\omega}{c}\right)^2 n_e'^{\,2} - \beta^2} \tag{3}$$

with

$$\beta = \left(\frac{\omega}{c}\right) \cdot \sin\theta \tag{4}$$

$$n_e' = \sqrt{\frac{n_o^{\,2} n_e^{\,2} + \left(n_e^{\,2} - n_o^{\,2}\right)\sin^2\alpha \cdot \sin\theta}{n_o^{\,2}\cos^2\alpha + n_e^{\,2}\sin^2\alpha}} \tag{5}$$

where n_o, n_e, α and θ are ordinary, extraordinary refractive indices of light, the pretilt angle of the cell and the incident angle of light, respectively.

From eq.(1), the electric field amplitudes, C_o and C_e of the o-wave and e-wave inside the LC layer are given by

$$\begin{bmatrix} C_o \\ C_e \end{bmatrix} = \begin{bmatrix} t_{so} & t_{po} \\ t_{se} & t_{pe} \end{bmatrix} \begin{bmatrix} t_s & 0 \\ 0 & t_p \end{bmatrix} \begin{bmatrix} A_s \\ A_p \end{bmatrix} \tag{6}$$

When only either o-wave or e-wave is exited in the LC layer, the light propagating through the LC layer does not undergo any birefrigence, so that the transmitted light results in a linearly polarized one. It is obvious that the o-wave excitation or the e-wave excitation is determined by the polarization direction of a incident light; when the polarizer angle ϕ_{po} or ϕ_{pe}, the light inside the LC layer becomes an o-wave or e-wave, respectively.

We consider the o-wave excitation case, where C_e=0. From eq. (6), we obtain

$$\tan\phi_{po} = \left(\frac{A_p}{A_s}\right)_{Ce=o} = -\frac{t_s t_{se}}{t_p t_{pe}} \tag{7}$$

$$\tan\phi_{po} = \frac{n_g\cos\theta + \sqrt{1-(\sin\theta/n_g)^2}}{\cos\theta + \sqrt{n_g^2 - \sin^2\theta}} \cdot \frac{n_o^2\sqrt{1-(\sin\theta/n_g)^2} + n_g\sqrt{n_o^2 - \sin^2\theta}}{\left(\sqrt{n_g^2 - \sin^2\theta} + \sqrt{n_o^2 - \sin^2\theta}\right)\sin\theta} \cdot \frac{1}{\tan\alpha} \quad (8)$$

In the case of C_e=0, the electric field amplitudes, A_s' and A_p' of a transmitted light becomes

$$\begin{bmatrix} A_s' \\ A_p' \end{bmatrix} = C_o\, e^{-ikozd} \begin{bmatrix} t_s' & t_{os} \\ t_p' & t_{op} \end{bmatrix} \quad (9)$$

This transmitted light, of course, is linearly polarized so that we can adjust the polarizing direction of analyzer to obtain zero-transmission at a detector. Let denote the analyzer angle in this case by ϕ_{AO}, then

$$\tan\phi_{Ao} = -\left.\frac{A_s'}{A_p'}\right|_{Ce=0} = -\frac{t_s' t_{os}}{t_p' t_{op}} \quad (10)$$

After some mathematical manipulation similar to the proceeding ones, we obtain

$$\tan\phi_{Ao} = -\frac{n_g\cos\theta + \sqrt{1-(\sin\theta/n_g)^2}}{\cos\theta + \sqrt{n_g^2 - \sin^2\theta}} \cdot \frac{\left\{n_o^2\sqrt{1-(\sin\theta/n_g)^2} + n_g\sqrt{n_e'^2 - \sin^2\theta}\right\}\sin\theta}{n_o^2\left(\sqrt{n_g^2 - \sin^2\theta} + \sqrt{n_e'^2 - \sin^2\theta}\right)} \cdot \tan\alpha \quad (11)$$

The polarizer angle ϕ_{Po} for an ordinary wave excitation inside the LC layer and the corresponding analyzer angle ϕ_{AO} for zero-transmission as a function of pretilt angle a with a parameter of incident angle θ are repeatively plotted in Figure 2. It is seen from the figures that any pretilt angle in the range of 0°~90° can be determined by the polarizer angle or the analyzer angle for which the transmittance is measured as zero (actually minimum).

Experimental verification of PRM

For a known cell with a pretilt angle 15.7 degrees that was obtained by an improved crystal rotation method,[9,10] we measured the transmittance with simultaneously rotating the polarizer and analyzer while conserving $\phi_A - \phi_P = \phi_{Ao} - \phi_{Po}$ which was calculated by equations (8)~(11). And we theoretically calculated the transmittance as a function of polarizer angle ϕ_P to compare with the measured one. Here the incident angle θ and refractive indices n_o, n_e of liquid crystal used are θ=50.0°, n_o=1.512 and n_e=1.693. As shown in Figure 3, the measured points are very well fitted by the calculated curve. It conforms the validity of our method from the viewpoint of measurement principle and theory.

To directly evaluate the validity of our method, we measured, by the two methods, the pretilt angles of various cells in the measurable range of the crystal rotation method, and compared the differently measured values.

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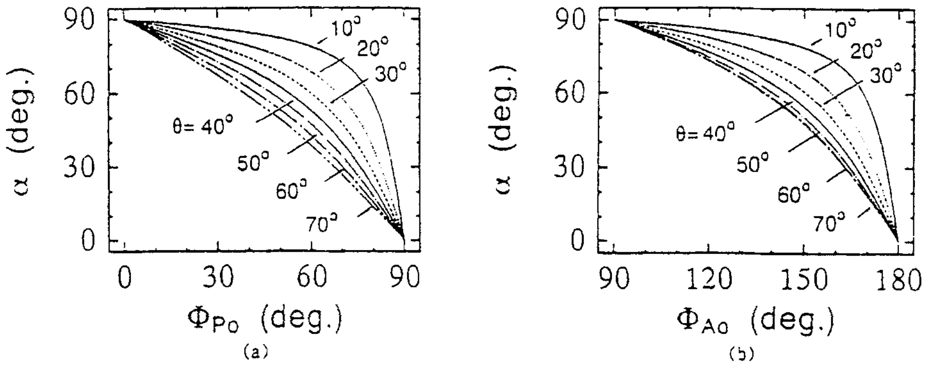

Figure 2. Relation between pretilt angle α and corresponding angles, (a) polarizer angle Φ_{Po} and (b)analyzer angle Φ_{Ao}, with a parameter of incident angle θ for the minimum transmittance.

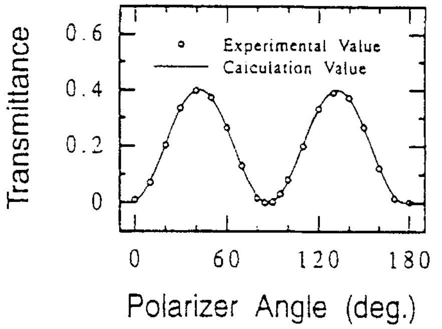

Figure 3. Comparison of the measured and calculated transmittance as a function of polarizer angle

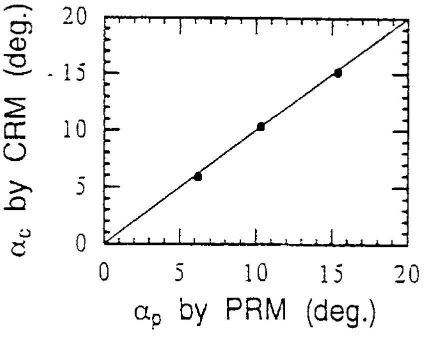

Figure 4. comparison of the pretilt angles measured by different two methods (αc: improved crystal rotation method, αp:polarizer rotation method)

The results are shown in Figure 4. It is seen that the differently measured values are agreed with each other within the measurement error.

Discussion

While in crystal rotation method a liquid crystal cell is rotated, but in our polarizer rotation method a polarizer and an analyzer are rotated during the measurement of a transmittance. And a pretilt angle is determined by a transmittance minimum point in our method by a symmetric transmittance point in crystal rotation method. As the results of the differences in measurement methods, our method has the advantages of full measurable range and cell gap independency for the measurement of pretilts in comparison with crystal rotation method. In addition, there is another noticeable point in our method that the reflections on various boundary surfaces of liquid crystal cells are taken into consideration.

Moreover, the pretilt angle of LC cell might be measured within the error of 0.1° for the case of small (~10^{-6}) ΔT which is available when high quality polarizers, e.g. Glan-Thomson, and a PM tube detector are used.

Conclusions

We have developed for the first time a new optical method(PRM) which can accurately measure a LC pretilt angle without the dependence of a cell gap thickness, and a restriction of pretilt magnitude and a cell gap uniformity.
The measured pretilt error in our method might be less than 0.1 degree in full range when available high quality polarizer are used.

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