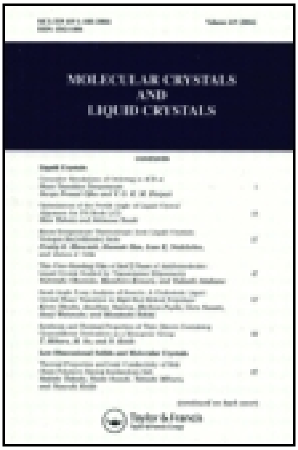

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Determination of the Birefringence, the Twist Angle and the Thickness of the Nematic Liquid Crystal Sample by Renormalized Transmission Ellipsometry

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The birefringence, the twist angle and the thickness of the nematic liquid crystal sample were determined by means of the renormalized transmission ellipsometry. It was proposed that conventional sandwich-type cell is applicable to this ellipsometry measurement and the simplified numerical fitting procedure based on the 4 × 4 matrix method can provide the dispersion of the ordinary and the extraordinary refractive indices. The resolution of the twist angle and cell thickness measurement reaches to 0.05 deg. and 0.05 μm, respectively.

Keywords: birefringence; twist angle; ellipsometry; nematic liquid crystal

Introduction

Evaluation of the principal properties, such as the ordinary and the extraordinary refractive indices, the twist angle and the thickness of the nematic liquid crystal sample, is one of the most important issue to characterize the LCD. Up to now, several techniques to evaluate these principal properties have been proposed, where these properties can be evaluated separately by using proper measurement method with optimized sample structure. In other words, we need to prepare some different kinds of samples to evaluate in each principal properties. No measurement method which provides several principal properties at once has been established yet.

An optical technique called ellipsometry is a potential tool to analyze the principal properties of LCD. Because, as we know, LCD is exactly the device which makes use of the optical polarization. On the other hand, ellipsometry is well-established instrument as a high sensitive analyzer for a dielectric medium. As same as the other dielectric medium, evaluation of the state of polarization in terms of ellipsometric parameters must be quite effective for analyzing the characteristics of LC. Actually, Woollam's group proposed a method to measure the birefringence by using ellipsometry. [1] This method named generalized transmission ellipsometry is quite excellent, while several diagonal and nondiagonal polarization coefficients might be required to be measured precisely. On the other hand Tadokoro *et al* also demonstrated the time-resolved analysis of the bulk and/or surface director reorientation of the nematic liquid crystal experimentally by using the ellipsomerty. [2]

Analytic expressions for 4 $\times$ 4 matrix method [3] would predict that the measured ellipsometric parameters can give the ordinary and the extraordinary refractive indices, the twist angle and the thickness of the sample by the numerical fitting procedure. In this paper we demonstrate more simplified numerical procedure named 'renormalized transmission ellipsometry.'

Experimental

The nematic liquid crystal substance used in this experiment was 4-pentyl-4'-cyanobiphenyl (5CB), which was filled in a conventional sandwich type cell, whose inner surfaces of the two glass substrates were covered with indium thin oxide (ITO) films and polyimide alignment films, as shown in Fig.1. In order to realize the homogeneous or twisted alignment of LC layer, the surface of the polyimide alignment films were pre-rubbed in an antiparallel or cross direction.

The nominal gap d between the two glass substrate are 2.0, 5.0 or 10.0 μm. After filling the LC substance, beautiful alignment was observed under the polarized microscope.

In the ellipsometry measurement, generally, the amplitude transmissivities of the p-polarized and s-polarized light are denoted as

$$\tau_{p,s} = \rho_{p,s} e^{i\Delta_{p,s}}, \tag{1}$$

and ellipsometric parameters such as the phase difference angle Δ and the relative amplitude ratio Ψ are defined by

$$\Delta = \Delta_p - \Delta_s \tag{2}$$

$$\tan\Psi = \rho_p/\rho_s. \tag{3}$$

In our experiments Δ and Ψ were measured by the polarization modulated spectroscopic ellipsometer (PMSE) (M-150, JASCO., co.) equipped with a photoelastic modulator [4]. The optical plane including the incident ray is in keeping with the $x - z$ plane, where the incidence ray was set normal to the sample cell. The optical axis of the polarizer is parallel to the x axis. The optical retarded axis of the PEM and the analyzer was set to be 45° from the x in the x-y plane. The sample cell was placed so that the director at the alignent surface of the top (incident side) of the glass substrate may be set parallel to the x axis.

Theory

Figure 1 shows the schematic model of the LC cell and the optical path for the transmission ellipsometry. The cell consists of the stacks of glass plates, ITO films, alignment films and liquid crystal substance. The numerical analysis can be performed by means of the 4 × 4 matrix method which automatically takes the multiple reflection and multiple interference at the ITO, alignment films and LC layer into account. It is noteworthy to point out that the 4 × 4 matrix method is not applicable to the glass substrate used in our experiment. Because the glass substrate used is sufficiently thick comparing to the wavelength of the incident light and the ununiformity of the thickness over the glass substrate is more than the wavelength. Therefore the multiple interference inside the glass substrate can not be exhibited whereas the multiple reflection still exists.

As a result, at the air-glass interface and at the glass-ITO interface the optical transmission and reflection was estimated by means of the Fresnel's equation.

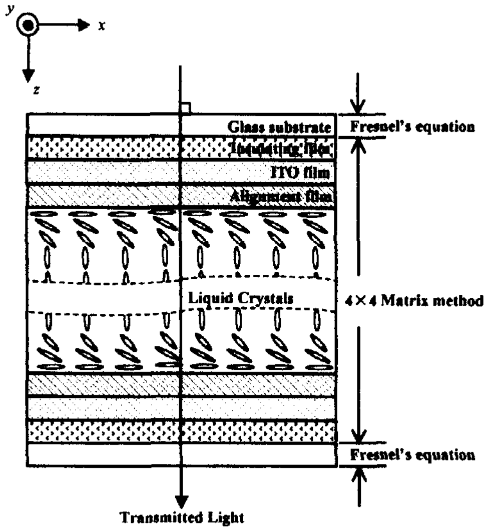

Figure 1: The schematic model of the NLC cell and the geometry of the transmission ellipsometry.

Following these concept mentioned above, the numerical analysis corresponding to the practical sample cell can provide the optical intensity of the transmitted light. Here we describe the theoretical expression for the optical state of polarization.

If the subject is an isotropic medium, the non-diagonal elements which represent the conversion of p- and s- polarized light into s- and p- polarized light are $r_{ps} = r_{sp} = 0$ (say standard ellipsometry). However, in case of the LC cell, r_{ps} and/or r_{sp} are not always zero. As Schubert *et al.* [1] described the analytic expressions of the generalized ellipsometry for the NLC cell, several experimental geometry and precise measurement would be required to determine the birefringence and twist angle of the TN-LCD. In other words, it requires a tremendous labor to determine these four of the amplitude transmissivities.

Corresponding to the geometry of our experimental setup, here we consider the amplitude transmissivities

$$\begin{cases} t_{\mathrm{pp}} + t_{\mathrm{sp}} = t_{\mathrm{p}} \\ t_{\mathrm{ps}} + t_{\mathrm{ss}} = t_{\mathrm{s}} \end{cases}, \tag{4}$$

and the amplitude transmissivities was redefined as

$$\begin{cases} t_{\mathrm{p}} = \rho_{\mathrm{p}} e^{i\Delta_{\mathrm{p}}} \\ t_{\mathrm{s}} = \rho_{\mathrm{s}} e^{i\Delta_{\mathrm{s}}} \end{cases}. \tag{5}$$

By following this simplification, as a result, conventional measurement setup of standard ellipsometry for isotropic medium can be applicable to anisotropic medium, and Δ and Ψ can be interpreted by the same manner as the standard ellipsometry. We named this numerical analysis as 'renormalized ellipsometry.' In order to reproduce the experimental measurement of Δ and Ψ, the renormalized amplitude transmissivities of numerical calculation based on the 4×4 matrix method was also taken into account.

Results and Discussions

Determination for the dispersion of birefringence

Figure 2 shows the experimental results of the ellipsometric parameters Δ and Ψ for homogeneous sample cell, where the nominal cell thickness d is 5μm and the temperature of the cell was 25 C°. As shown in Fig.1, characteristic jagged curves against the incident wavelength λ was found both in Δ and Ψ measurements. It is found that the small amplitude in the big jagged curves of Ψ corresponds to the multiple reflection between the two substrates and NLC layer, which was caused by a difference of the refractive indices between the glass substrate and n_e. It is noteworthy to point out that the dispersion of the refractive index of glass substrate (BK7) is almost as

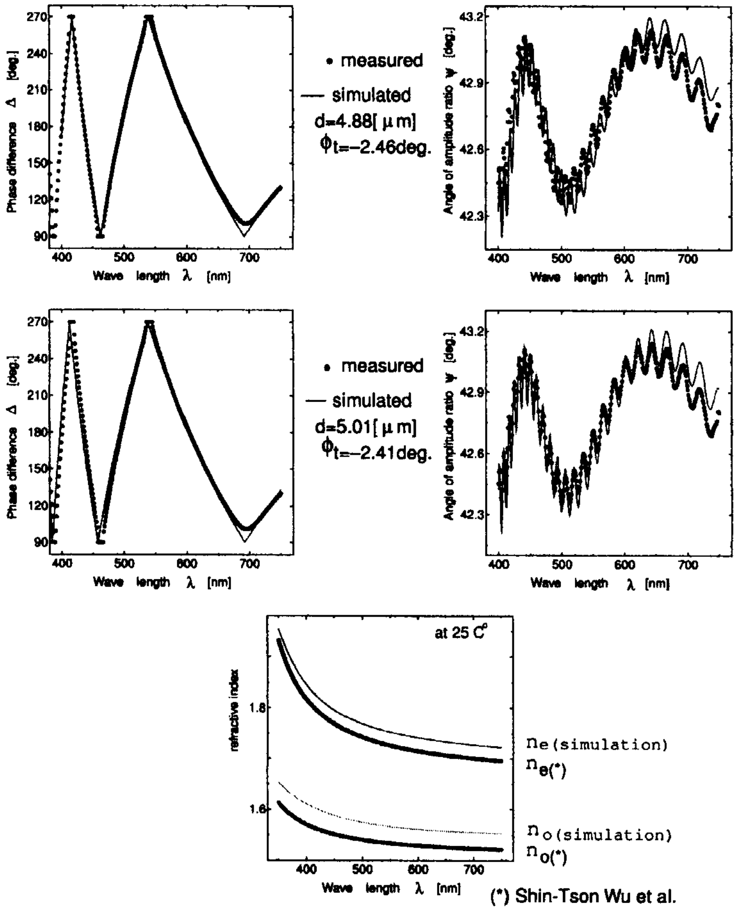

Figure 2: Experimental results of the Δ and Ψ for homogeneous NLC cells. Numerical results of the birefringence was also shown.

same as that of n_o of 5CB, therefore no multiple reflection between the glass substrates and n_o can be found. In other words, dispersion of n_e can be determined by estimating the small amplitude in the Ψ curve. From the simple equation of the multiple reflection,

$$n_e(\lambda)d = \frac{m}{2}\lambda, \qquad (m : integer) \tag{6}$$

dispersion of n_e can be determined as shown in Fig.2.

The phase difference Δ corresponds to the optical parameter so called reterdation. The reterdation of NLC layer is much larger than that of other optical constituent such as the substrate, ITO and alignment film, therefore Δ was considered to be equal to the reterdation of NLC layer,

$$\Delta = \frac{2\pi(n_e - n_o)d}{\lambda}. \tag{7}$$

Calculated n_o was also shown in Fig.2. Comparing to the experimental data published in literature [5], it suggests that our experimental determination is quite reasonable. It is quite beneficial that the continuous dispersion of n_e and n_o can be easily obtained by using conventional sandwich type cell.

Determination for twist angle and cell thickness

Figure 3 shows the experimental results of the ellipsometric parameters Δ and Ψ for TN sample cell, where the nominal cell thickness is 2μm (Fig.3(a)), 5μm (Fig.3(b)) and 10μm (Fig.3(c)), respectively. Characteristic jagged curves against the incident wavelength λ were also found in Fig.3. Solid lines in Fig.3 are obtained from the numerical fitting calculated by 4 $\times$ 4 matrix method. It is proposed that the numerical simulations exhibit quantitative agreement with the experimental results, and it was found that the resolution of the twist angle and cell thickness measurement reaches to 0.05 deg. and 0.05 μm, respectively.

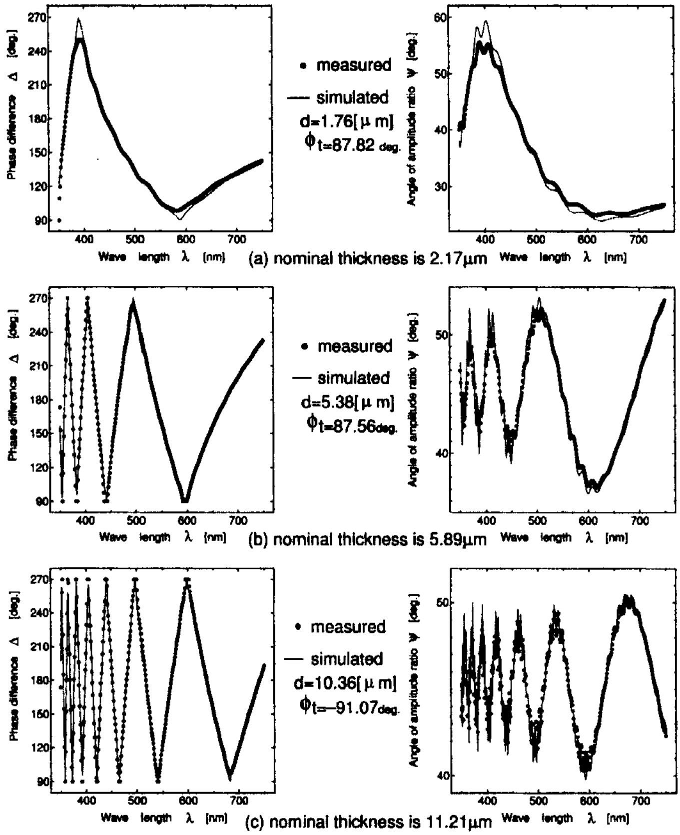

Figure 3: Experimental results of the Δ and Ψ for TN-LC cells. Solid lines are numerical fitting curves.

Conclusion

The optical characteristics of NLC cells were investigated by means of the renormalized transmission ellipsometry. It is proposed that the numerical simulations of the ellipsometric parameters exhibit a quantitative agreement with our experimental measurement. The dispersion of the birefringence of NLC, the twist angle and the cell thickness of the TN-LC cell were easily determined without using samples of any special purpose. The ellipsometry has a great potential to determine the NLC parameters as well as the conventional dielectric mediums.

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