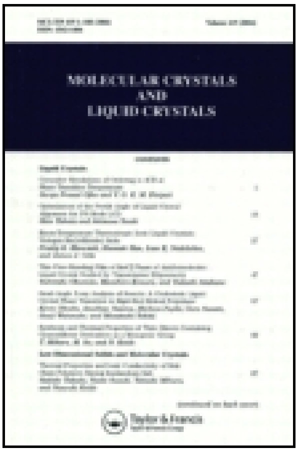

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Improved Method for the Dispersion of Refractive Indices Based on Transmission Spectroscopic Ellipsometry

K. Goda [a], M. Kimura [a] & T. Akahane [a]

[a] Department of Electrical Engineering, Faculty of Engineering, Nagaoka University of Technology, Nagaoka, Niigata, Japan

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Improved Method for the Dispersion of Refractive Indices Based on Transmission Spectroscopic Ellipsometry

K. GODA, M. KIMURA, AND T. AKAHANE

Department of Electrical Engineering, Faculty of Engineering, Nagaoka University of Technology, Nagaoka, Niigata, Japan

In our previous study, we have proposed a novel analysis method to determine the dispersion of refractive indices based on the plural incidence renormalized transmission spectroscopic ellipsometry. This method was, however, applicable only to the homogeneous cell. In this paper, we introduce the improved method to determine the wavelength dispersion of refractive indices by using the twisted nematic cell as well as by the homogeneous cell. Numerically calculated refractive indices of ordinary and extraordinary rays were in good agreement with the refractive indices experimentally measured by the Abbe Refractometer.

Keywords Berreman's 4×4 matrix method; Cauchy equation; ellipsometry; Jones matrix method; refractive index

1. Introduction

Refractive index of nematic liquid crystal (NLC) substance is one of most important parameter to determine the performance of liquid crystal displays (LCDs). Generally, refractive index of NLC was measured by employing Abbe Refractometer [1]. However, it is not easy to obtain the continuous wavelength dispersion of NLC. Besides, the observer sometimes suffers from eye fatigue. Therefore, some another automatically measurement method is still expected. To resolve these problems, many approaches have been demonstrated by means of Ellipsometer [2–6]. Previously, we presented the determination method for the continuous wavelength dispersion of refractive indices of ordinary and extraordinary rays (viz. $n_e(\lambda)$ and $n_o(\lambda)$) based on the Jones matrix method and the Berreman's 4×4 matrix method [7]. However, this method was applicable only to the homogeneous cell, because, the tentative cell gap $d_{tent.}$ was estimated by the retardation of LC layer. In case of twisted nematic (TN) cell, measured retardation does not coincide with that of homogeneous cell. To extend our analysis so as to determine $d_{tent.}$ of TN cell, we introduced Jones matrix method into calculation of $d_{tent.}$. In this paper, we

Address correspondence to K. Goda, Department of Electrical Engineering, Faculty of Engineering, Nagaoka University of Technology, 1603-1 Kamitomioka, Nagaoka, Niigata 940-2188, Japan. Tel.: +81-258-47-9540; Fax: +81-258-47-9500; E-mail: goda@stn.nagaokaut.ac.jp

propose the improved method for the determination of continuous wavelength dispersion of refractive indices of NLC.

2. Renormalized Transmission Spectroscopic Ellipsometry

Figure 1 shows an illustration of the spectroscopic ellipsometer equipped with photoelastic modulator (PMSE) [8,9] (M-150, JASCO. Co.). PMSE was composed of the polarizer, the photo elastic modulator (PEM) and the analyzer. In the Cartesian principal coordinate, the passing axis of polarizer was set parallel to the x axis. The modulation axis of PEM and the passing axis of analyzer were also set 45 degrees with respect to x axis. The director of entrance plane of sample was set to be parallel to the y axis.

Generally, Jones matrix of the optical anisotropic material such as LC J_{SM} was represented by

$$J_{SM} = \begin{bmatrix} \rho_{pp} & \rho_{ps} \\ \rho_{sp} & \rho_{ss} \end{bmatrix}, \tag{1}$$

where the matirx elemet ρ_{ij} $(i,j = p,s)$ denotes transmission coefficinents for the transition of incident light with the j polarization state into transmitted light with the i polarazation state. Okutani *et al.* Proposed the basic theory of renormalized elipsometry (RE) [10]. By following this concept, we define the transmission coefficients ρ_p and ρ_s as

$$\begin{cases} \rho_p = \rho_{pp} + \rho_{sp} \\ \rho_s = \rho_{ps} + \rho_{ss} \end{cases}. \tag{2}$$

The ratio of transmission coefficients is described as

$$\frac{\rho_p}{\rho_s} = \tan\Psi \exp(i\Delta). \tag{3}$$

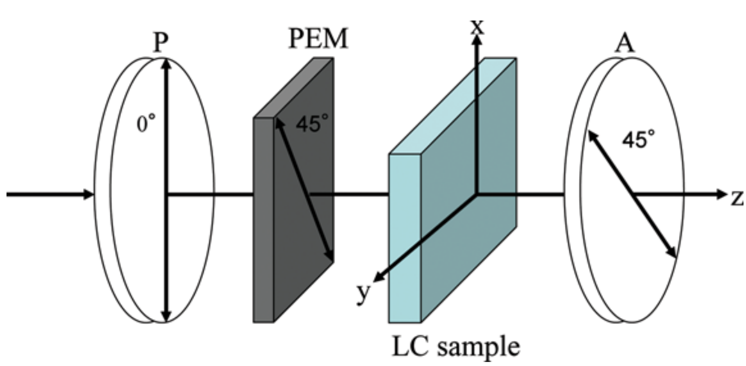

Figure 1. The optical arrangement of the spectroscopic ellipsometer with photoelastic modulator. (Figure appears in color online.)

By following this simple definition, the conventional standard ellipsometer for isotropic medium can be applicable to anisotropic media, and the phase difference Δ and the angle of amplitude ratio Ψ can be interpreted in the same manner as standard ellipsometry. The characteristic curves of $\Delta(\lambda)$ and $\Psi(\lambda)$ for incident light with the wavelength λ are quite sensitive to the parameters such as the cell gap d, the twisted angle of LC director between upper and lower substrates φ_t, the rotation angle between y axis and LC director of entrance plane φ_i and $n_e(\lambda)$ and $n_o(\lambda)$ of LC sample. The fitting error F between experimental measured values and theoretical values is defined as

$$F = \sqrt{\frac{\sum^N \left(\Delta_{fit} - \Delta_{\exp}\right)^2 + W \sum^N \left(\Psi_{fit} - \Psi_{\exp}\right)^2}{N_\Delta + WN_\Psi}}, \tag{4}$$

where N_Δ is number of data of Δ, N_Ψ is number of data of Ψ and W is weight factor of Δ to Ψ. Δ_{fit}, Δ_{exp}, Ψ_{fit} and Ψ_{exp} are also represent calculation value and measurement value of Δ and Ψ, respectively. Here, we set $W = 1000$ in total analysis procedure. By minimizing F, the appropreate values of fitting parameters are obtained, simultaneously [11].

3. Experiments

In this experiment, polyvinylalcohol (PVA) alignment film was employed. PVA was spin-coated on the upper and lower glass substrates, and then baked at 180°C for 60 min. Indium tin oxide (ITO) film as an electrode is not necessary in our experiment. In order to realize the homogeneous and the 85° TN cell, the surface of the alignment film coated on the substrates were rubbed, then conventional sandwich-type cell was fabricated so as to make intersection angle of rubbing direction at the upper and lower substrates 180 degrees (homogeneous cell) or 95 degrees (85°TN cell), respectively. Before filling the NLC substance, the cell gap d_{empty} was measured by employing the polarization microscope based on multiple beam interference (MBI) method. Table 1 shows measurement results of refractive indices of NLC substances ZLI-4792 ($\Delta\varepsilon > 0$) and MLC-2037 ($\Delta\varepsilon < 0$) (Merck Ltd.) at $\lambda = 480$, 546, 589 and 656 nm by means of Abbe Refractometer (DR-M2 1410, Atago Co.). The measurement of refractive indices were carried out at 25°C. LC substances were filled into the cell at isotropic phase, and then cool down at room temperature. The observed texture of the NLC sample was uniform planar alignment under the polarized microscope.

Table 1. Measured values of refractive indices of ZLI-4792 and MLC-2037 by means of Abbe Refractometer

	λ [nm]	480	546	589	656
ZLI-4792	n_e	1.584	1.575	1.571	1.567
	n_o	1.485	1.480	1.477	1.475
MLC-2037	n_e	1.564	1.540	1.537	1.534
	n_o	1.478	1.475	1.473	1.470

4. Results and Discussion

The proposed method consists of three measurement steps. The step 1 is for the determination of $d_{tent.}$ which is based on the Jones Matrix method [12]. The step 2 is for the determination of the anisotropic refractive indices which is also based on the Jones matrix method. The step 3 is for the determination of continuous wavelength dispersion of $n_e(\lambda)$ and $n_o(\lambda)$ which is based on the Berreman's 4×4 matrix method [13]. From above-mentioned three steps, the continuous wavelength dispersion of $n_e(\lambda)$ and $n_o(\lambda)$ are obtained. Here, description of $n_e(\lambda)$ and $n_o(\lambda)$ were employing extended Cauchy Eq. [14],

$$\begin{cases} n_e(\lambda) = \alpha_0 + \frac{\alpha_2}{\lambda^2} + \frac{\alpha_4}{\lambda^4} \\ n_o(\lambda) = \beta_0 + \frac{\beta_2}{\lambda^2} + \frac{\beta_4}{\lambda^4} \end{cases}, \tag{5}$$

where α_i and β_i are the i_{th} Cauchy coefficients (λ is the wavelength in micron).

Firstly, $d_{tent.}$ was determined by the Jones matrix method. Let us consider the transmission coefficients of TN cell. When the light beam was propagated in the TN cell, total phase difference (viz. retardation) was defined by

$$\chi = \sqrt{\phi_t^2 + \left(\frac{\Gamma}{2}\right)^2} = \sqrt{\phi_t^2 + \left(\frac{\pi(n_e(\lambda) - n_o(\lambda))\Delta h}{\lambda}\right)^2}, \tag{6}$$

where φ_t is twisted angle between each slabs, Γ is retardation at the each slab, $n_e(\lambda)$ and $n_o(\lambda)$ are refractive index of ordinary and extraordinary rays at arbitrary wavelength, Δh is thickness of slab and λ is wavelength in nanometer. Form Eq. (1), the transmission coefficients on TN cell are expressed as

$$\begin{cases} \rho_{pp} = \frac{\phi_t \sin\chi \sin\phi_t}{\chi} + \cos\chi\cos\phi_t + i\frac{\pi\Delta n}{\lambda\phi_t^2}\frac{\sin\chi\cos\phi_t}{\chi} \\ \rho_{ps} = \frac{\phi_t \sin\chi \cos\phi_t}{\chi} - \cos\chi\sin\phi_t + i\frac{\pi\Delta n}{\lambda\phi_t^2}\frac{\sin\chi\sin\phi_t}{\chi} \\ \rho_{sp} = -\frac{\phi_t \sin\chi \cos\phi_t}{\chi} + \cos\chi\sin\phi_t + i\frac{\pi\Delta n}{\lambda\phi_t^2}\frac{\sin\chi\sin\phi_t}{\chi} \\ \rho_{ss} = \frac{\phi_t \sin\chi \sin\phi_t}{\chi} + \cos\chi\cos\phi_t - i\frac{\pi\Delta n}{\lambda\phi_t^2}\frac{\sin\chi\cos\phi_t}{\chi} \end{cases}. \tag{7}$$

Substituting φ_t, $n_e(\lambda)$, $n_o(\lambda)$ and λ into Eq. (7), the theoretically calculated Δ is computed where φ_t was assumed the intersection angle of rubbing direction at the upper and lower substrates. Figure 2(a) shows calculated results of fitting error $F_{tent.}$ between the measured Δ and the theoretical Δ of ZLI-4792. Also, Figure 2(b) shows $F_{tent.}$ of MLC-2037. Here black line represent homogeneous cell and green line represent 85° TN cell, respectively. The measurement were carried out at $\lambda = 589$ nm and $\lambda = 656$ nm. As a consequence, minima of $F_{tent.}$ were obtained. The cell gap 15.4 µm at homogeneous cell (ZLI-4792) was assumed as $d_{tent.}$, because the actual d_{empty} measured by MBI method was about 14.9 µm. In the same manner, 14.9, 16.4 and 15.0 µm were determined for homogeneous cell (MLC-2037) and TN cell (ZLI-4792 and MLC-2037), respectively.

Secondly, the anisotropic refractive indices were simulated by the Jones matrix method. In this step 2, Δ and Ψ were measured at normal incidence by means of PMSE. The measurement wavelengths were ranging from 400 to 750 nm in 1 nm

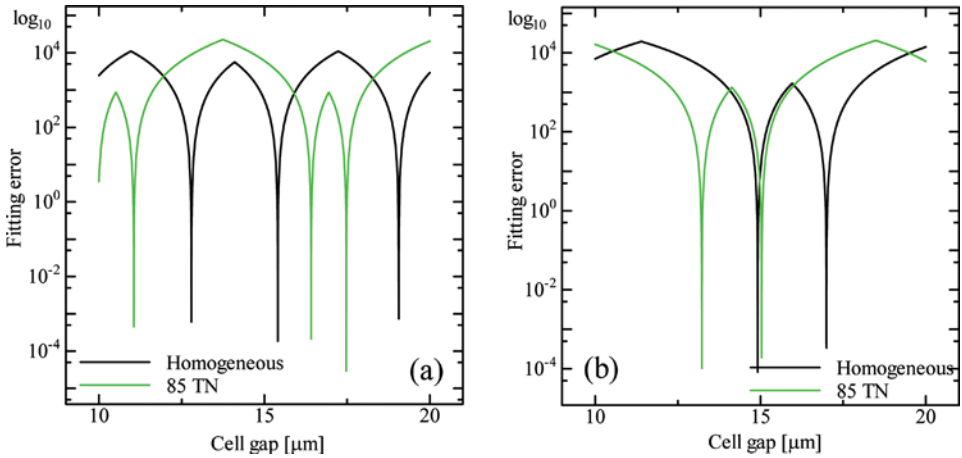

Figure 2. Fitting error between measured value of Δ and theoretical value of Δ. (a) ZLI-4792 for homogeneous and 85° TN mode. (b) MLC-2037 for homogeneous and 85° TN mode. (Figure appears in color online.)

step. Determined $d_{tent.}$ at step 1 was fixed in this simulation. The fitting parameters are φ_t, φ_i and Cauchy coefficients of the anisotropic refractive indices. As for the initial values, it was assumed that φ_t was intersection angle of rubbing direction at

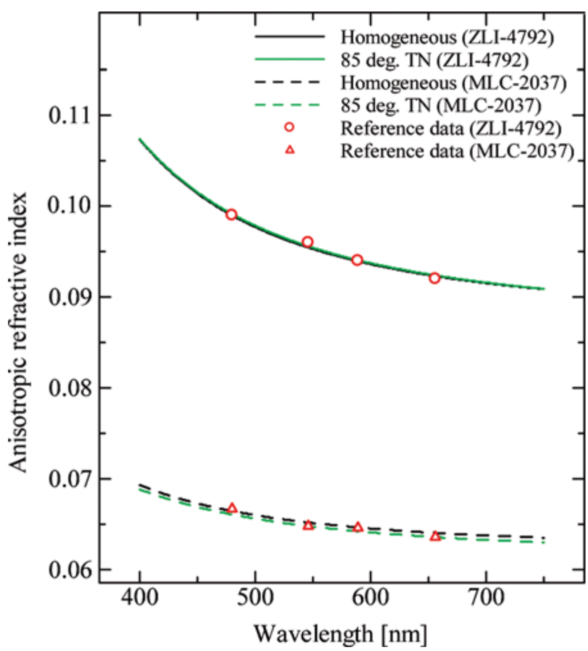

Figure 3. Fitting results of the anisotropic refractive indices. Black and green lines are ZLI-4792 and dashed lines of black and green color are MLC-2037. The open circle and triangle are measured values of the anisotropic refractive indices by means of Abbe Refractometer.

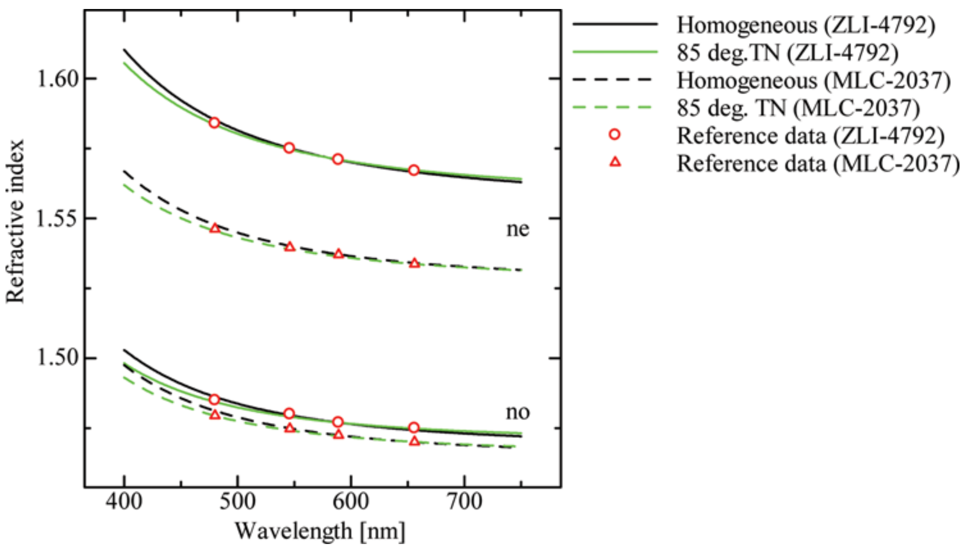

Figure 4. Calculated results of refractive indices of ordinary and extraordinary rays. Black and green lines are ZLI-4792 and dashed lines of black and green color are MLC-2037. The open circle and triangle are measured values by means of Abbe Refractometer.

the upper and lower substrate and φ_i was zero. The initial values of Cauchy coefficients of the anisotropic refractive indices were calculated by the measured values by means of Abbe Refractometer, as follows: $\beta_0 = 0.094$, $\beta_2 = 0.0$ and $\beta_4 = 0.0$ at ZLI-4792 and $\beta_0 = 0.065$, $\beta_2 = 0.0$ and $\beta_4 = 0.0$ at MLC-2037. The simulated results are shown in Fig. 3. The simulated anisotropic refractive indices were in accordance with the measured values of refractive indices by means of Abbe Refractometer.

Finally, the continuous wavelength dispersion of refractive indices of ordinary and extraordinary rays were simulated by the Berreman's 4×4 matrix method. Δ and Ψ were measured at 45 degree incidence by means of PMSE. The fitting parameters were genuine cell gap d, φ_t, φ_i and Cauchy coefficients of refractive index of ordinary ray. The initial values of Cauchy coefficients of refractive indices of ordinary ray were substituted as follows: β_0 is refractive index at wavelength in step 1, $\beta_2 = 0.0$ and $\beta_4 = 0.0$. The refractive index of ordinary ray at wavelength in step 1 is set to be in accordance with the value which is measured by Abbe Refractometer as the reference. The simulated results of $n_e(\lambda)$ and $n_o(\lambda)$ are shown in Fig. 4. A good agreement between measured values by means of Abbe Refractometer and simulation values were obtained. However, the calculated refractive indices at short wavelength have difference with the measured refractive indices. In our analysis, the effect of alignment film is neglected, because, the alignment film is significantly thin compare with LC layer. Therefore, we thought that the alignment film may be affect the simulated results of $n_e(\lambda)$ and $n_o(\lambda)$.

5. Conclusions

We proposed an improved method for determining the wavelength dispersion of refractive indices of ordinary and extraordinary rays. By employing the Jones matrix method when the tentative cell gap is determined, this method becomes applicable not only to the homogeneous but also the TN cell. A good agreement between the determined wavelength dispersion and the measured values by means of Abbe Refractometer were confirmed.

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