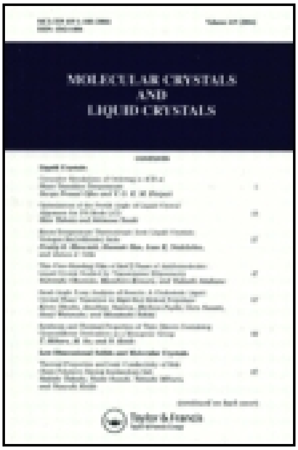

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Evaluation of the Refractive Indices and their Wavelength Dispersion of Liquid Crystal by using Renormalized Transmission Ellipsometry

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EVALUATION OF THE REFRACTIVE INDICES AND THEIR WAVELENGTH DISPERSION OF LIQUID CRYSTAL BY USING RENORMALIZED TRANSMISSION ELLIPSOMETRY

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Renormalized Transmission Ellipsometry (RTE) was applied to a precise measurement of anisotropic refractive indices of nematic liquid crystals. It is quite important for the evaluation to use a monodomain cell with high quality. To realize the good alignment, the alignment film was coated. In this study, the influence of the alignment film thickness and its refractive indices on the accuracy of the measurement is reported. From the numerical analysis and several experiments, it is shown that if $n_e(\lambda) > n_o(\lambda) \approx n_{glass}(\lambda)$ is satisfied and $n_{glass}(\lambda)$ is nearly equal to $n_{al}(\lambda)$, the evaluated results of $n_o(\lambda)$ and $n_e(\lambda)$ are not influenced by the film thickness d_{al}. From the results, RTE can be the powerfull tool to measure $n_o(\lambda)$ and of $n_e(\lambda)$ for the LC substances with easy operation.

Keywords: alignment film; birefringence; ellipsometry; nematic liquid crystal; refractive index

INTRODUCTION

To determine the wavelength (λ) dispersion of anisotropic refractive indices for ordinary- and extraordinary ray (viz. $n_{\mathrm{o}}(\lambda)$ and $n_{\mathrm{e}}(\lambda)$) within the visible wavelength range is one of the important issue to develop a more refined Liquid Crystal Display (LCD) devices. We proposed a method to determine $n_{\mathrm{o}}(\lambda)$ and $n_{\mathrm{e}}(\lambda)$ by using renormalized transmission ellipsometry (RTE) [1]. The advantage of RTE is not only a simple experimental procedure but also the adaptability for a conventional sandwich-typed LCD sample cell. Furthermore RTE can provide a sample information such as

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the cell thickness (d) and the twist angle (Φ_t) of Twisted Nematic LCDs. In our early demonstration, $n_o(\lambda)$, $n_e(\lambda)$, d, Φ_t of samples filled with 4-pentyl-4′-cyanobiphenyl (5CB) were successfully determined. In case of the LC substances where the birefringence is fairly small, however, high refractive index glass plate as an LCD substrates should be chosen. In Secondary report [2], a numerical solution of such shortcoming was proposed and reliable results for ZLI-4792 (Merck) were shown.

In our preliminary experiments, for simplying the numerical procedure, the alignment film was omitted under such assumption that $n_e(\lambda) > n_o(\lambda) = n_{glass}(\lambda)$. The surface of the glass substrates without coating the alignment films was directly processed by rubbing treatment. However, since the measured results was influenced by the condition of the surface alignment, the alignment film is required to make the surface alignment beautiful. In this paper we discuss about the influence of the thickness and refractive indices of the alignment film on the accuracy of the evaluation results for determining the refractive indices of the LC substances.

NUMERICAL ANALYSIS

Figure 1 shows the schematic model of the LC cell and the optical path for the transmission ellipsometry. Even in case of homogeneous LCD cell, the director at the upper substrate ($\vec{n}_{upper}$) and the lower substrate ($\vec{n}_{lower}$) are not always parallel because of a fabrication error. The angle between the projection of $\vec{n}_{upper}$ and $\vec{n}_{lower}$ onto the $x-y$ plane is called 'twist

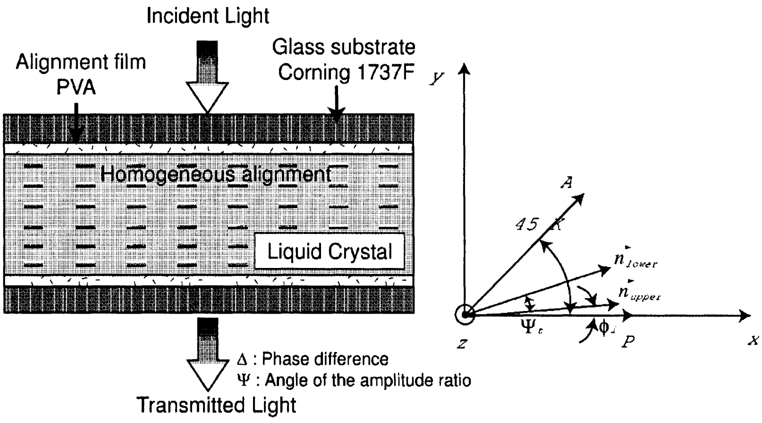


FIGURE 1 Schematic model of the LC cell and its Cartesian local coordinate system.

angle,' and here we define ϕ_t. The angle between $\overrightarrow{n}_{\text{upper}}$ and the p-polarized light is defined by ϕ_i. Generally speaking for the ellipsometry measurement, polarization state of the outgoing- light from a subject is expressed by means of the ellipsometric parameters such as the phase difference Δ and the angle of amplitude ratio $\boldsymbol{\Psi}$. To analyze Δ and $\boldsymbol{\Psi}$, a numerical expression called Jones matrix method is widely used. The Jones matrix connects the two modes of the incident and the emergent electromagnetic plane waves with respect to the Cartesian laboratory coordinate system (one is the p-polarized light whose electric field vector is parallel to the plane of incident, the other is s- polarized light whose electric field vector is perpendicular to it). In case of the transmission ellipsometry, the transmission Jones matrix of the sample $\boldsymbol{J}_{\text{SM}}$ is generally given by

$$\boldsymbol{J}_{\text{SM}} = \begin{bmatrix} \rho_{\text{pp}} & \rho_{\text{ps}} \\ \rho_{\text{sp}} & \rho_{\text{ss}} \end{bmatrix}, \tag{1}$$

where the matrix element ρ_{ij} $(i,j = \text{p}, \text{s})$ denotes a transmission coefficients for the incident light with j polarization state into the transmitted light with i polarization state. Here, we redefine the transmission coefficients as follows;

$$\begin{cases} \rho_{\text{p}} \equiv \rho_{\text{pp}} + \rho_{\text{sp}} \\ \rho_{\text{s}} \equiv \rho_{\text{ps}} + \rho_{\text{ss}} \end{cases}, \tag{2}$$

where, ρ_{p} (or ρ_{s}) means the amplitude of total emergent electromagnetic plane waves by the p-polarized (or s-polarized) incident light proceeding into the subject. Again the ratio of transmission is described as

$$\frac{\rho_{\text{p}}}{\rho_{\text{s}}} = \tan\boldsymbol{\Psi} \exp(i\Delta). \tag{3}$$

By following this simple redefinition, as a result, conventional measurement setup of standard ellipsometry can be applicable to anisotropic medium, and Δ and $\boldsymbol{\Psi}$ can be interpreted by the same manner as the standard ellipsometry,

$$\begin{cases} \Delta = \Delta_{\text{p}} - \Delta_{\text{s}} = \arg\left(\frac{\rho_{\text{p}}}{\rho_{\text{s}}}\right), \\ \boldsymbol{\Psi} = \tan^{-1}\left(\frac{|\rho_{\text{p}}|}{|\rho_{\text{s}}|}\right). \end{cases} \tag{4}$$

We named this numerical analysis as 'renormalized ellipsometry.' The characteristics curves of $\Delta(\lambda)$ and $\boldsymbol{\Psi}(\lambda)$ for the incident light with the wavelength λ are quite sensitive to the *condition* of the cell such as the cell gap d, ϕ_t, ϕ_i and $n_o(\lambda)$ and $n_e(\lambda)$ of the LC sample. Theoretically, based on an appropriate assumption for such condition of the LC cell, $\Delta(\lambda)$ and $\boldsymbol{\Psi}(\lambda)$

can be simulated by using computer. Then, by fitting the experimentally measured $\Delta(\lambda)$ and $\Psi(\lambda)$ with the simulation and finding the distinctive features of the curves, d, ϕ_t, ϕ_i and $n_o(\lambda)$ and $n_e(\lambda)$ can be determined.

EXPERIMENTAL

The nematic LC substance was filled in a conventional sandwich type cell, as illustrated in Figure 1. The glass substrate was Corning-1737F (Corning). In order to realize a homogeneous alignment of LC layer, the surface of the glass substrates were pre-rubbed in an antiparallel direction. The nominal cell gap is 10.0 μm. Before filling LC substance, the cell gap d_{empty} was measured by conventional monochrometer. After filling the LC substance, beautiful alignment was observed under the polarized microscope. PVA was used as alignment film. The nematic liquid crystal substances used in this experiment were 4-pentyl-4′-cyanobiphenyl (5CB), and MLC-2051 (Merck). In our experiments Δ and Ψ were measured by the polarization modulated spectroscopic ellipsometer (PMSE) (M-150, JASCO., co.) equipped with a photoelastic modulator [3]. Measured wavelength λ was ranging 350 nm–750 nm. Measurements were carried out at 25°C. Beforehand, thickness of the alignment film d_{al}, refractive index of the glass $n_{glass}(\lambda)$ and refractive indices $n_{al}(\lambda)$ was measured by the conventional reflection ellipsometry. $n_{glass}(\lambda)$ and $n_{al}(\lambda)$ were expressed by the Cauchy's equation as follows,

$$n(\lambda) = \alpha_0 + \frac{\alpha_1}{\lambda^2} + \frac{\alpha_2}{\lambda^4} + \frac{\alpha_3}{\lambda^6}, \tag{5}$$

where α_i are the ith Cauchy's coefficients. Tables 1 and 2 show the results of the measurements.

TABLE 1 Thickness of Alignment Film:PVA and their Concentrations

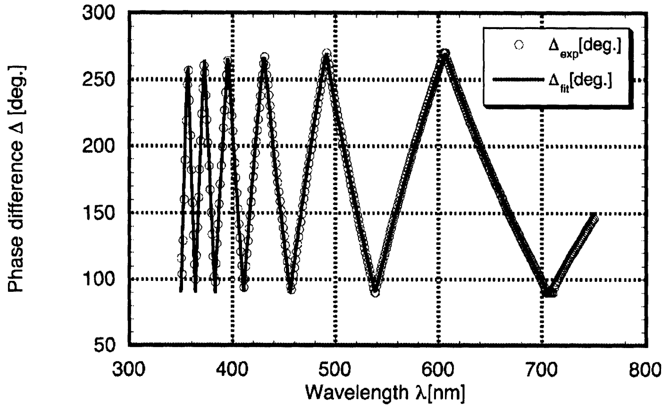
Concentrations of solutions	Thickness d_{al} [nm]
2.0 wt%	45.8
0.5 wt% (Corning)	4.25
0.5 wt% (FD60)	10.73

TABLE 2 Cauchy' Coefficients for $n_{al}(\lambda)$:PVA

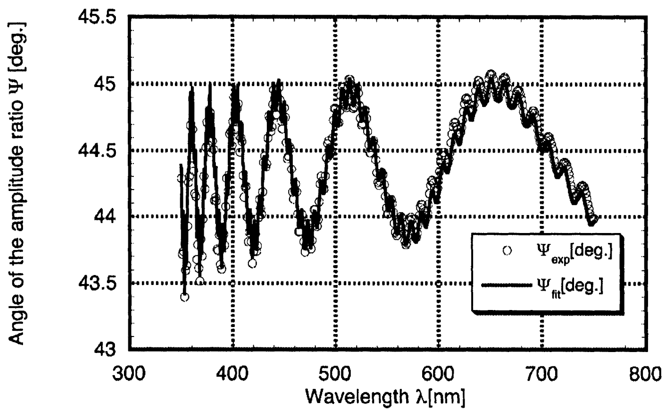
α_0	α_2	α_4
1.5324	1.9908×10^{-2}	5.8022×10^{-3}

RESULTS AND DISCUSSIONS

$n_e(\lambda)$ and $n_o(\lambda)$ for 5CB with $d_{al} = 10\,[\mathrm{nm}]$ PVA alignment film were evaluated. Figure 2 shows experimental results and numerical fitting curves of the phase difference $\Delta(\lambda)$ (Figure 2(a)) and $\Psi(\lambda)$ (Figure 2(b)). In regard to the numerical fitting procedure, it is noteworthy to point out that we did not take the existence of the alignment film into consideration in the numerical fitting.



(a) Phase difference $\Delta(\lambda)$



(b) Angle of the amplitude ratio $\Psi(\lambda)$

FIGURE 2 Experimental result and numerical fitting curves of the phase difference (a) $\Delta(\lambda)$ and (b) $\Psi(\lambda)$ for 5CB.

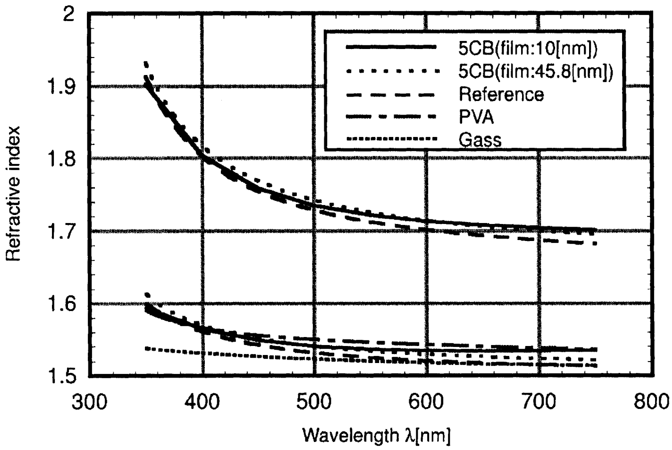


FIGURE 3 Wavelength dispersion of anisotropic refractive indices 5CB, where the thickness of PVA $d_{\mathrm{al}} = 10$ [nm] and $d_{\mathrm{al}} = 45.8 =$ [nm] respectively.

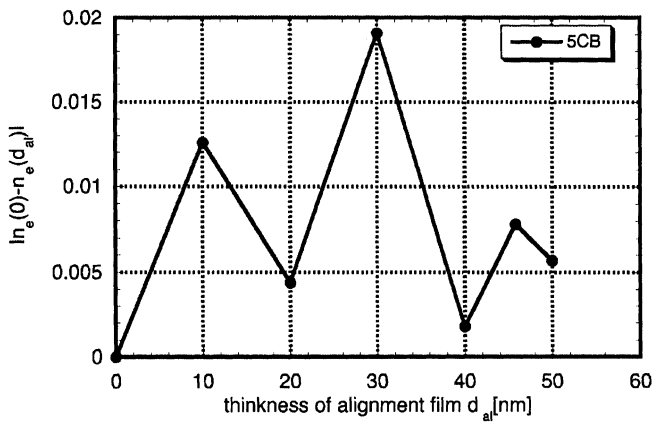


FIGURE 4 Estimated results of refractive index n_{e} at 589.0 [nm] with PVA film (thickness d_{al}[nm]):5CB.

Figure 3 shows the resultant $n_{\mathrm{e}}(\lambda)$ and $n_{\mathrm{o}}(\lambda)$ of 5CB with $d_{\mathrm{al}} = 10$ [nm] and $d_{\mathrm{al}} = 45.8[nm]$ PVA alignment films respectively. The refractive indices of the alignment film $n_{\mathrm{al}}(\lambda)$ and glass $n_{\mathrm{glass}}(\lambda)$ are also depicted. S.T. Wu *et al.* [4] have reported that $n_{\mathrm{o}}(\lambda)$ and $n_{\mathrm{e}}(\lambda)$ of 5CB by using the Talbot-Rayleigh refractmeter, which is also depicted in Figure 3. These results suggest that the measured refractive indices are in good agreement with the data in the reference. To confirm the influence of the film thickness on

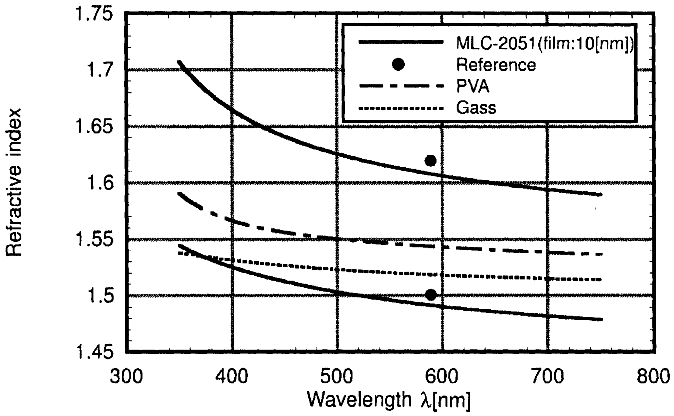


FIGURE 5 Wavelength dispersion of anisotropic refractive indices:MLC-2051 with 10 [nm] film thickness PVA.

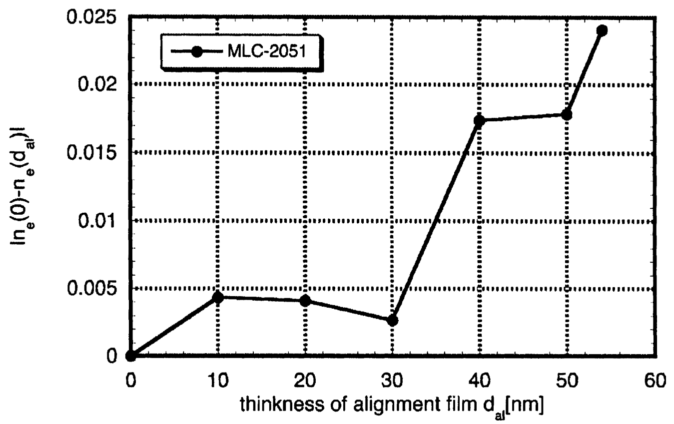


FIGURE 6 Estimated results of refractive index n_e at 589.0 [nm] with PVA film (thickness d_{al} [nm]):MLC-2051.

the evaluation result, numerical simulation were carried out. Firstly, $\Delta(\lambda)$ and $\Psi(\lambda)$ were simulated by substituting the obtained results such as d, $\phi_i, \phi_t, n_e(\lambda)$ and $n_o(\lambda)$, where the 4×4 matrix for the alignment film was taken into account, and the thickness of the alignment film was varied toward 55 [nm]. Then, $n_e(\lambda)$ and $n_o(\lambda)$ were reproduced by substituting the simulated $\Delta(\lambda)$ and $\Psi(\lambda)$ into our analysis where the alignment film was omitted as we mentioned above. Figure 4 shows the deviation of the refractive index evaluated by this method at $\lambda = 589.0$ [nm] from the assumed value. It suggests there is not clear dependence between the thickness of the alignment film and the refractive index evaluated by this method. Because of $n_{\mathrm{o}}(\lambda) \approx n_{\mathrm{glass}}(\lambda) \approx n_{\mathrm{al}}(\lambda)$ as shown in Figure 3, the multiple reflection of the extraordinary ray occurs at the interference between the LC substance and the alignment film.

As same as 5CB evaluation, $n_{\mathrm{e}}(\lambda)$ and $n_{\mathrm{o}}(\lambda)$ for MLC-2051 with $d_{\mathrm{al}} = 10$ [nm] PVA alignment film were evaluated as shown in Figure 5. Figure 5 also shows the reference measured by the Abbe refractmeter. In case where the thickness of alignment film $d_{\mathrm{al}} = 45.8$[nm], however, results of $n_{\mathrm{o}}(\lambda)$ and $n_{\mathrm{e}}(\lambda)$ could not be obtained. This reason was interpreted as follows;

As a prerequisite such as $n_{\mathrm{e}}(\lambda) > n_{\mathrm{o}}(\lambda) \approx n_{\mathrm{glass}}(\lambda)$ can not be satisfied at all as shown in Figure 5, the multiple interference between the alignment film and LC substance interrupts an object interference between the glass and LC substance. To verify such interpretation, numerical simulation was carried out as shown in Figure 6. From these simulation, it seems that the effect of the alignment film is negligible if the thickness of the alignment film is relatively thin(e.g. $d_{\mathrm{al}} \leq 30$[nm]).

CONCLUSION

Renormalized transmission ellipsometry was proposed to determine the continuous dispersion of the anisotropic refractive indices $n_{\mathrm{o}}(\lambda)$ and $n_{\mathrm{e}}(\lambda)$ with adopting the alignment film. To measure the $n_{\mathrm{o}}(\lambda)$ and $n_{\mathrm{e}}(\lambda)$ of the LC substances precisely, $n_{\mathrm{al}}(\lambda)$ of the alignment fillm is preferable to almost same as $n_{\mathrm{glass}}(\lambda)$ and/or $n_{\mathrm{o}}(\lambda)$. If $n_{\mathrm{e}}(\lambda) > n_{\mathrm{o}}(\lambda) \approx n_{\mathrm{glass}}(\lambda)$ is satisfied and $n_{\mathrm{glass}}(\lambda)$ is nearly equal to $n_{\mathrm{al}}(\lambda)$, the evaluated results of $n_{\mathrm{o}}(\lambda)$ and $n_{\mathrm{e}}(\lambda)$ are not governed by the film thickness d_{al}. Even if this condition is not satisfied, when the film thickness d_{al} is sufficiently thin, appropriate $n_{\mathrm{o}}(\lambda)$ and $n_{\mathrm{e}}(\lambda)$ of the several LC substances can be evaluated by this proposed method.

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