Transmissive liquid crystal cell parameters measurement by spectroscopic ellipsometry

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A powerful method for liquid crystal (LC) cell twist angle and retardation measurement is presented. This method is based on the spectroscopic ellipsometry. By varying the polarizer and analyzer angles only, a transmission spectrum containing null transmission at some particular wavelengths can be obtained. Analytical equations derived bases on a polarization analysis of twisted birefringent layers are then solved to give all the LC cell parameters. In general, the twist angle, twist sense, retardation, and the rubbing direction can all be determined. Measurement results on commercial liquid crystal display panels are presented. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1332800]

I. INTRODUCTION

Liquid crystal displays (LCD) are widely used. Large panels of over 14 in. diagonal are commonly used in notebook computers, while smaller displays of sizes less than one square inch are used in portable electronic devices. For all LC displays, there are two very important parameters that affect their optical properties. They are the liquid crystal molecule twist angle ϕ and the LC retardation value (the cell gap times the LC birefringence). The 90°-twisted nematic (TN) mode with retardation of about 0.5 μm (first minimum) or 1.0 μm (second minimum) is the most common LCD. The 180°–240° supertwisted nematic (STN) modes with retardation of about 0.8 μm are also widely used in mobile electronic communication devices.

In the manufacturing as well as the development of LCD, there is a constant need for an accurate measurement of the twist angle and retardation value of the LC cells. Such data during the manufacturing process can also help to eliminate bad LC cells and improve production yield. While the cell gap of empty cells can easily be determined by optical interference techniques, the same is not true for filled LC cells where the optics is considerably more complex. Several methods have been proposed in the past. They all fall into the categories of single wavelength[1–7] and spectral methods.[8,9] One major disadvantage of the single wavelength method is that they cannot measure empty cell gap. Furthermore, all these methods are inherently unable to treat the wavelength dispersion of the LC molecules.

Most commercial products use the spectral method to determine the LC retardation value. We have previously introduced a spectral method where the twist angle as well as the retardation of any unknown LC cell can be determined. Inoue *et al.* discussed a method, which is similar to the one we proposed. However, in the Inoue method, the LC twist angle and the rubbing orientation of the LC directors have to be known in advance. In our method, the rubbing directions of the LC cell can be determined by the measurement technique. Moreover, in most cases, the wavelength dispersion of the LC birefringence can also be taken into account. This method is applicable to both transmissive and reflective LC cells. In this article, we shall present details on the operation principles of this new spectroscopic method, which is based on a new representation of a generalized twisted nematic LC cell. We shall also concentrate mainly on transmissive LC cells cases. The case of reflective LC cells, such as silicon based microdisplays, will be discussed in a separate publication.

II. THEORETICAL BACKGROUND

A. Polarization rotation states

In general, the optical transmission and reflection of a twisted nematic cell depends on four parameters: ϕ, $d\Delta n$, α, and γ. Here ϕ is the twist angle, d is the LC cell thickness, Δn is the birefringence of the LC material, α and γ are the polarizer and analyzer angles relative to the input director of the LC cell (Fig. 1). The LC cell $d\Delta n$ value can be represented by the angle δ, which is equal to $\pi d\Delta n/\lambda$, where λ is the wavelength of light. In any measurement of the LC cell, $(\phi,d\Delta n)$ are the intrinsic parameters to be determined, and α, γ can be changed at will. By varying α and γ, null transmission at certain wavelengths can be obtained and then by solving appropriate equations, the values of $(\phi,d\Delta n)$ can be uniquely determined.

For any general twisted nematic LC cell, given a linearly polarized input light, the output polarization is in general elliptically polarized. However, under certain conditions of (α,ϕ,δ), the output polarization can be exactly linearly or circularly polarized. These conditions can be derived using the Jones matrix method.[10] For the simple configuration shown in Fig. 1, the transmission is given by

$$T=\left|(\cos\ \phi\ \sin\ \gamma)M\begin{pmatrix}\cos\ \alpha\\ \sin\ \alpha\end{pmatrix}\right|^2, \tag{1}$$

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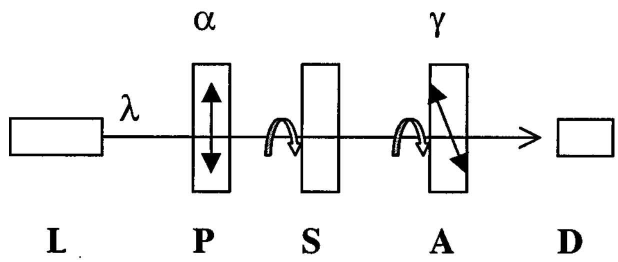

FIG. 1. Setup for transmissive LC cell measurement. L is the light source, P is the polarizer, S is the sample LCD, A is the analyzer and D is the detector. It is a standard PSA configuration. α and γ are, respectively, the polarizer and analyzer angles relative to the input LC director orientation.

where M is the Jones matrix of a twisted nematic LC layer.[10] Using the given standard expression for M, Eq. (1) yields[11]

$$T=\left[\cos\beta\cos(\phi-\gamma+\alpha)+\frac{\phi}{\beta}\sin\beta\sin(\phi-\gamma+\alpha)\right]^2+\frac{\delta^2}{\beta^2}\sin^2\beta\cos^2(\phi-\gamma-\alpha), \tag{2}$$

where $\beta^2=\delta^2+\phi^2$. From Eq. (2), it can be seen easily that if $\sin\beta=0$, $T=\cos^2(\phi-\gamma+\alpha)$. Thus $T=1$ if $\gamma=\phi+\alpha\pm m\pi$. This is the first linear output solution (LP1). If $\sin\beta\neq 0$, then Eq. (2) gives

$$\cos^2(\phi-\gamma-\alpha)=0, \tag{3}$$

and

$$\cos\beta\cos(\phi-\gamma+\alpha)+\frac{\phi}{\beta}\sin\phi\sin(\phi-\gamma+\alpha)=0. \tag{4}$$

Equation (3) requires $\gamma=\phi-\alpha\pm\pi/2$. Substituting this result into Eq. (4) gives

$$\frac{\phi}{\beta}\tan\beta=\tan 2\alpha. \tag{5}$$

This is the second linear polarization output solution (LP2). Thus there are two distinct conditions for a linearly polarized output, given a linearly polarized input at angle α. They are given by the following conditions.

LP1:

$$\delta=\sqrt{N^2\pi^2-\phi^2}, \tag{6a}$$

$$\gamma=\phi+\alpha\pm m\pi. \tag{6b}$$

LP2:

$$\frac{\phi}{\beta}\tan\beta=\tan 2\alpha, \tag{7a}$$

$$\gamma=\phi-\alpha\pm m\pi, \tag{7b}$$

where $N=1,2,3\ldots$ and $m=0,1,2,\ldots$.

Alternative derivations of Eqs. (6) and (7) that are based on the Mueller matrix and the polarization state concept can also be found in our previous reports.[9,12] Physically, it has been proven before that a uniformly twisted LC cell behaves as a combination of a polarization rotator and a retardation plate.[13] The LP1 solution simply corresponds to the case where the ''equivalent retardation plate'' has a full-wave retardation, which is the same as no retardation. The LP2 solution corresponds to the case where the input light polarization is along the principal axis of the ''equivalent retardation plate.'' Hence for the LP1 solution, the input polarizer angle α is irrelevant in calculating ϕ and δ. However, for the LP2 solution, α has to be a certain value, given by Eq. (7a), in order for linearly polarized output to occur. It is interesting to note that for the LP1 solution, from Eq. (6b), the LC cell behaves as a pure polarization rotator and the output polarization is simply equal to the input polarization plus the twist angle of the LC cell. This actually is a generalization of the time-honored waveguiding mode for a LCD. The various values of N corresponds to the first and second Mauguin minimum, etc.

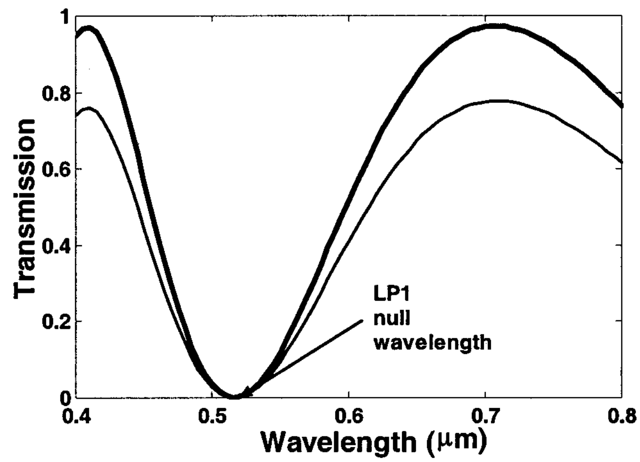

FIG. 2. Thick curve represents an LP1 null transmission curve for a $d\Delta n=1.0\ \mu$m, $\phi=90°$ TN cell with $\alpha=40°$. Thin curve corresponds to a $+10°$ rotation of the LC cell. The null wavelength remains at the same characteristic wavelength regardless of the rotation of the LC cell.

B. LC cell parameter extraction

The LP1 solution can be used to obtain the unknown parameter (ϕ,δ) of the LC cell as follows. For a given LC cell with fixed (ϕ,δ) values, there are always some wavelengths, λ^*s, such that Eq. (6a) holds. In that case, there will be some direction for the output analyzer angle such that Eq. (6b) is satisfied. If one rotates the output analyzer by an additional 90°, then the transmission at that λ^* will be zero, or a null. Furthermore, under such conditions, the transmissions at these characteristic wavelengths λ^*s should be independent of α as shown in Fig. 2. It is because that from Eq. (6b), as long as $\gamma-\alpha$ is fixed, the LP1 condition is satisfied, regardless of the absolute value of α.

Thus, experimentally, it is easy to identify these characteristic wavelengths. One would obtain the null transmission spectrum by changing γ. To verify that the null wavelengths are indeed the characteristic wavelengths corresponding to LP1 solutions, one can simply rotate the LC cell (thus changing α) while keeping the input polarizer and output analyzer fixed. If the null wavelengths remain unchanged, it is a characteristic wavelength. Once this is established, the α, γ, and λ^* values can be used to deduce the values of ϕ and $d\Delta n$ according to Eq. (6).

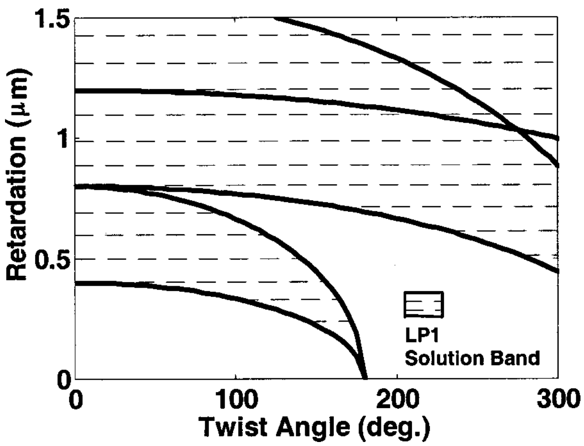

FIG. 3. LP1 solution band. Note that all common TN and STN displays are within the hatched area.

In order to find the characteristic wavelengths, a broadband light source is required. In other words, a single wavelength laser source is not appropriate for obtaining LC cell parameters when using the LP1 solution. Figure 3 shows the solution band of the LP1 solution in the 400–800 nm spectral range. The solution band is defined as the range of $(\phi,\ d\Delta n)$ values where there is at least one null characteristic wavelength within the experimentally convenient range of 400–800 nm. It should be noted that all the common TN and STN modes are within the solution band. That means the present method can be used to determine the optical parameters of all common LCDs.

Let us now consider the LP2 solution. For any given LC cell, there should exist many solutions of (λ,α) such that Eq. (7a) holds. The output light is linear polarized at $\phi-\alpha$ as indicated in Eq. (7b). An analyzer with its passing axis oriented at $\gamma=\phi-\alpha\pm\pi/2$ will produce a null transmission, similar to the case of the LP1 solutions. One very important difference between the LP1 and LP2 solutions is that the null λ that satisfies Eq. (7a) is dependent on the input polarizer angle α. This situation is illustrated in Fig. 4. This is not the case for the LP1 solutions however (Fig. 2). Thus experimentally, it is a simple matter to distinguish between the null wavelengths that are due to LP1 or LP2 solutions.

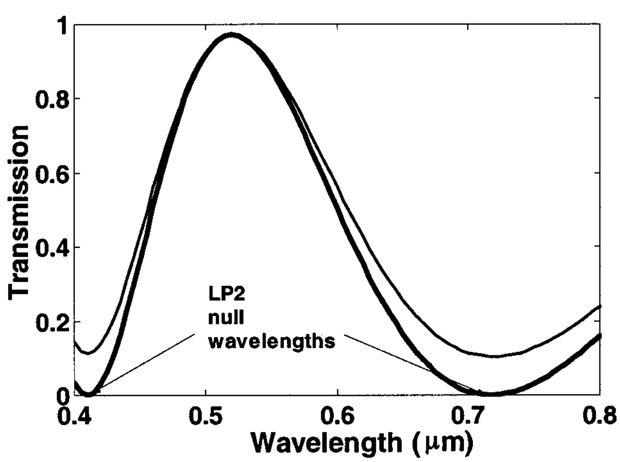

FIG. 4. Shift of the LP2 null wavelength when the input polarizer angle is changed. The same LC cell parameters as in Fig. 2 are used. The original input polarizer angle is 40° and the thin curve corresponds to a +10° rotation of the LC cell. No null transmission is obtained for the shifted curve.

Since one can always find an input polarizer orientation α such that Eq. (7a) holds for a given wavelength, thus the LP2 solution is well suited for measurements using a laser light source. If the twist angle is known in advance, then the retardation value of the LC cell can be determined directly from the α value. This will be discussed further in a future publication. In this article, we shall employ mainly the LP1 solutions for obtaining the important parameters for the unknown LC cell.

Finally, let us mention a special configuration of the experimental setup that is particularly useful. When the input polarizer angle α equals to 45°, Eq. (7a) reduces to a much simpler form, which is quite similar to Eq. (6a):

$$d\Delta n=\lambda\sqrt{(N-0.5)^2-(\phi/\pi)^2}. \tag{8}$$

If the output analyzer is oriented at $\phi-\alpha$, the LP2 solutions will produce unity transmission at some λ, while the LP1 solutions will produce a null at the characteristic wavelengths λ^*. It is easy to show that the transmission curve is represented by $T(\lambda)=\sin^2(\beta)$. It is also easy to show that the 50% transmission wavelength is represented by Eq. (9):

$$d\Delta n=\lambda\sqrt{(N/2-0.25)^2-(\phi/\pi)^2} \tag{9}$$

where

$$N=1,2,3,\ldots\ .$$

These special solutions are very useful in determining the rubbing direction and the birefringence dispersion characteristics of the LC cell.

Equations (6a), (8), and (9) are of the same form. We can combine them in a single equation:

$$d\Delta n=\lambda\sqrt{M^2-(\phi/\pi)^2}. \tag{10}$$

A measured transmission spectrum may contain all the wavelengths corresponding to LP1, T_{50}, and LP2 solutions. For successive LP1, T_{50}, and LP2 solutions, the value of M increased by 0.25 counting from the long wavelength side. Figure 5 illustrates the transmission curve for the case of a 240° STN cell. It shows the LP1 solution, T_{50} solution, and the LP2 solution, respectively. The M values are 2, 2.25, and 2.5, respectively.

III. EXPERIMENTAL DETERMINATION OF LC CELL PARAMETERS

With the theoretical foundation given above, it is possible to discuss the measurement of the various LC cell parameters using Eqs. (6)–(10).

A. Twist angle

According to Eq. (6b), for a LP1 solution, the angle between the polarizer and analyzer is fixed and has the following relation. γ is the analyzer angle responsible for a LP1 null transmission:

$$\phi=(\gamma-\alpha)\pm m\pi\pm\pi/2. \tag{11}$$

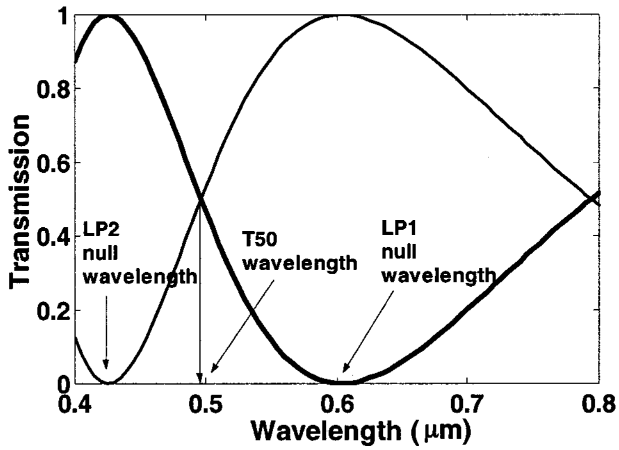

FIG. 5. LP1 and LP2 null transmission curves for a 240° STN cell with a retardation of 0.9 μm. The input polarizer angle is 45°. The T_{50} wavelength is determined by finding the wavelength corresponds to a half maximum transmission.

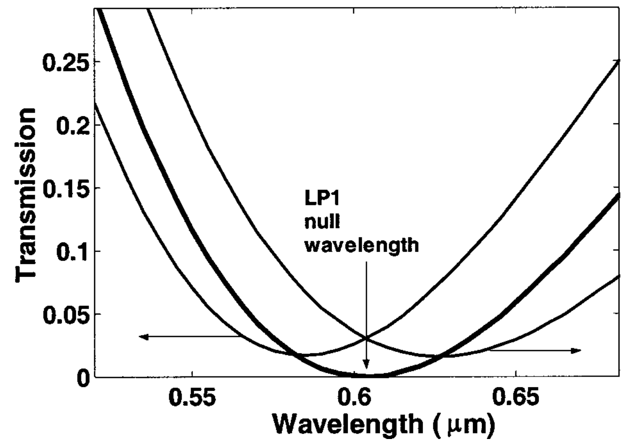

FIG. 6. Shifting of the LP1 null transmission curve for an additional analyzer rotation. The same STN cell parameters is used as in Fig. 5. The $+10°$ analyzer rotation curve is on the right. The $-10°$ analyzer rotation curve is on the left-hand side. The STN cell has a right-handed twist.

Thus the twist angle is determined by Eq. (11). In practice, there is always more than one possible solution. The ambiguity of the solution can be removed by knowing the twist sense of the LC cell or if an estimated twist value is known in advance. For example if $(\gamma-\alpha)=30°$, then there are two sets of solution for left and right twist LC cell. For left twist, the solution is $-60°$ or $-240°$. For right twist, the solution is 120° or 300°. If the twist sense is determined, then there remains only two possible solutions that differs by 180°. These two solutions can be resolved by comparing the retardation values deduced and a simulated transmission curve. Very often, an approximate value is known in advance, therefore it is not necessary to compare with a simulated curve to determine the final solution.

It is important to note that for LC samples where the twist angle is completely unknown, one can only use the LP1 solution to obtain the twist angle. For the LP2 solution, the angle relation, Eq. (7b) can be written in the form

$$\phi=(\gamma-\alpha)+2\alpha\pm m\pi\pm\pi/2. \tag{12}$$

Since the twist angle of Eq. (12) depends not only on the difference between the polarizer–analyzer angle $(\gamma-\alpha)$, but also on the absolute polarizer angle α, therefore without knowing the rubbing direction, LP2 null transmission alone cannot be used to determine the twist angle.

B. Twist sense

The twist sense (handedness) of an unknown LC cell can be determined using the approach discussed here as well. The handedness of the LC director twist is related to the shifting of the measured transmission spectrum to longer or shorter wavelengths. Experimentally, after obtaining a LP1 null transmission, the analyzer can be rotated further to the right (clockwise) and the transmission spectrum is monitored at the same time. If the spectrum shifts to the right (longer wavelength), then the LC cell has a right twist, and vice versa. This fact is depicted in Fig. 6 for a typical 240° STN cell. This can be proved vigorously by considering the slope of the transmission curves at the characteristic wavelength.[16]

C. Rubbing direction

The rubbing direction on the LC cell can be obtained for an unknown cell if we assume strong surface anchoring. In other words, the rubbing direction on the glass surface is equal to the liquid crystal surface director orientation, which is usually the case for all commercial LC cells where the alignment is carried out by rubbing a polyimide film. It has been pointed out in Sec. II that the LP1 solution is independent of the input polarizer angle α. Thus it is not possible to determine the rubbing direction by using the LP1 solution alone. However, if we can find both LP1 and LP2 solutions for the same LC cell, the rubbing directions can be uniquely determined using the formulas derived. Subtracting Eq. (6b) by Eq. (7b), one obtains

$$\gamma_1-\gamma_2=2\alpha, \tag{13}$$

where γ_1 and γ_2 are the LP1 and LP2 null transmission analyzer angles, respectively. Equation (13) gives therefore the direction of the input director of the LC cell (as the bisector of the γ_1 and γ_2 directions).

For the special case of α equals to 45°, γ_1 is perpendicular to γ_2. In practice, it is preferable to determine the rubbing direction by using α=45°. In order to obtain the α=45° condition, one can use the following procedures: (i) obtain a LP1 solution by rotating the analyzer; (ii) rotate the analyzer by 90°, (iii) rotate the LC cell until a LP2 null transmission is observed. At this point, the polarizer is at ±45° to the input director.

D. Retardation

The retardation value is the product of the cell gap thickness and the LC material birefringence $(d\Delta n)$. In general Δn is wavelength dependent. This wavelength dispersion can be measured for some LC samples where there are more than one null wavelengths. In the simplest case, the wavelength dispersion of $\Delta n(\lambda)$ can be approximated by the Cauchy formula using the one-band model[14]

$$\Delta n(\lambda)=A+B/\lambda^2+C/\lambda^4. \tag{14}$$

TABLE I. Measured data from a sample STN cell. Two null wavelengths and one T_{50} wavelength were obtained. The cell gap is 4.76 μm.

Solution type	Wavelength (nm)	Retardation (nm)	Birefringence
LP1	549	812.9	0.1708
T_{50}	483	871.4	0.1831
LP2	440	927.4	0.1948

TABLE II. Birefringence data for liquid crystal ZLI-5300-100 obtained from the sample STN cell as compared with the Merck data.

	450 (nm)	550 (nm)	650 (nm)
Merck data	0.1879	0.1708	0.1610
Measured data	0.1917	0.1706	0.1594
Difference	+2.02%	−0.12%	−0.99%

The Cauchy coefficients A, B, and C in Eq. (14) are to be determined. In general, for most liquid crystals, the retardation value decreases as the wavelength increases.

In practice, if one can have both the LP1 and LP2 solutions, then the T_{50} solution can also be found. Thus one can determine at least three retardation values at three different wavelengths, which are obtained by Eqs. (6a), (8), and (9). Equation (14) can then be solved to obtain the Cauchy coefficients. However, if only one LP1 solution is obtained, as the case for first minimum TN cells, only the LP1 solution exists and the dispersion of Δn cannot be determined.

IV. ILLUSTRATION: STN SAMPLE

A STN display was examined by the described spectroscopic ellipsometry method described above. The procedures given in the above section were used to obtain the null characteristic wavelengths. In this case both the LP1 and LP2 solutions were obtained. The results are listed in Table I. The analyzer angle $(\gamma-\alpha)$ corresponds to the LP1 null spectrum was 28°. Using the procedure discussed in Sec. III A, it was determined that the cell has a left-handed twist of 242°. The designed cell gap for this sample STN is 4.76 μm.

Since there are three wavelengths where the birefringence values can be determined, it is possible to obtain the Cauchy coefficients for this sample. The resulting dispersion characteristic is shown in Fig. 7. The null wavelengths and T_{50} wavelength obtained fit very well to the one-band Cauchy dispersion model. The LC material used in this sample was ZLI-5300-100 from Merck. The dispersion curve plotted according to data from Merck (Hong Kong) is also provided for comparison. It is observed that the measured values have a slightly larger dispersion and the average deviation from the Merck data is about 1%–2%. This deviation is explained by the fact that the null wavelengths obtained are all closer to the shorter wavelength end and the dispersion in this region tends to be higher. Table II lists some representative birefringence values for both the Merck data and our experimental data.

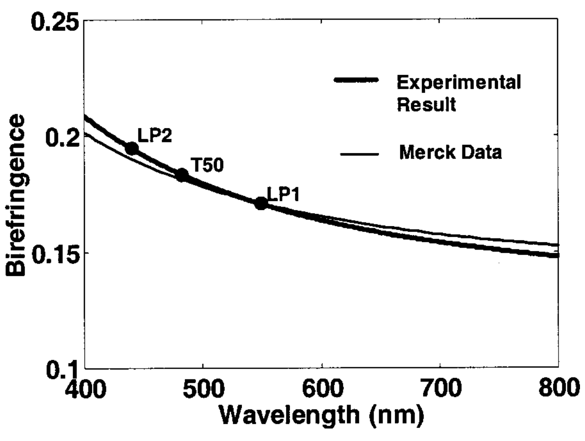

FIG. 7. Measurement results for the STN cell. Thick line shows the experimental birefringence dispersion curve. The three wavelengths obtained from LP1, LP2, and T_{50} fit the Cauchy dispersion model very well. Thin line is the dispersion curve plotted using data from Merck.

In the above calculations, two factors that decrease the effective birefringence are considered. First, an average tilt angle of 8° is considered; second, a 1% decrease of birefringence due to the slightly higher measurement temperature[15] than 20 °C is considered. The effect of the average tilt angle is calculated according to Eq. (15):

$$\Delta n_{\mathrm{eff}}=\frac{n_e}{\sqrt{1+w\ \sin^2\theta}}-n_0, \tag{15}$$

where w is $(n_e/n_0)^2-1$ and θ is the average tilt angle. n_e and n_0 are the extraordinary and ordinary refractive index of the LC material, respectively.

V. CONCLUSIONS

We have introduced a new spectroscopic ellipsometry method for liquid crystal display twist angle and retardation measurement. This method is based on the discovery of the various polarization preserving modes, namely the LP1 and LP2 modes for a transmittive LC cell. By obtaining the null transmission wavelengths with proper polarizer and analyzer positions, the twist angle, twist sense, retardation, and rubbing directions of an unknown transmissive cell can be determined totally, without any *a priori* knowledge of the LC cell. If the birefringence of the LC molecule is known, then one can make use of the measured retardation to obtain the cell gap of the filled LC cell.

This method can also be extended to include the measurement of reflective cell retardation, which will be covered in another publication. The experimental setup using this spectroscopic ellipsometry method is quite simple and can be easily adopted to be carried out in a commercial microscope. All methods discussed give reasonably accurate and repeatable measurement results.

ACKNOWLEDGMENTS

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