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Two new measurement methods for determining TN structure

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A TN structure is characterized by a twist angle (Θ) and a Δnd value, where Δn is the refractive index anisotropy value of a liquid crystal material and d is the TN cell gap value. Two new methods for measuring these values have been proposed. One is to determine only the Δnd value by rotating the TN cell for a known Θ value. The other is to determine the Δnd value and the Θ value by rotating the analyser. After analysing these measurement methods, the Δnd value, or the Δnd value and Θ can be determined graphically. These methods can easily be applied to automatic measurement systems.

1. Introduction

Liquid crystal displays (LCDs) with a twisted nematic (TN) structure are widely used. The optical characteristics of the TN structure were determined by the refractive index anisotropy of the liquid crystal material (Δn), the cell gap (d), and the twisted angle (Θ). Of these three factors, the product value Δnd is important for display panel uniformity and the twisted angle effects the contrast ratio of LCDs.

There are two issues concerning the determination of these two values. One, the Δnd issue, is how to determine the Δnd value for a known twisted angle value. The other, the Δnd–Θ issue, is how to individually determine both values. Δnd and Θ.

For the Δnd issue, the rotating analyser method has been proposed [1]. However, the rubbing directions of the LCDs must be known beforehand. Another measurement method proposed by Lien [2] includes a phase compensation procedure. However, that method includes a manual adjustment procedure and so is not suitable for automatic measurement.

For the Δnd–Θ issue, Lien [3] proposed a similar method with phase compensation procedures. In this case, a complicated iteration procedure and a manual adjustment procedure are needed, and so is also unsuitable for automatic measurement.

Here, two new measurement methods are presented, one can be applied to the Δnd issue and the other to the Δnd–Θ issue. These methods can easily be applied to automatic operation.

2. The general expressions of the measurement system

In our measurement methods, as shown in figure 1, an objective TN cell is set between a polarizer and analyser. Following a Jones matrix calculation approach, the polarization state and the various optical elements correspond, respectively, to a 2×1 vector and a 2×2 matrix [4, 5]. The polarizer in figure 1 has a simple well-known matrix form. A TN cell has the unitary matrix form shown by Lien and the TN cell rotated by x degrees around the ray axis in figure 1 is represented by that unitary matrix transformed by a rotation matrix. In the same way, the analyser rotated by y degrees in figure 1 has the transformed form of the polarizer matrix. Based on the above matrix forms, the polarization state transmitted from the analyser in figure 1 can be described as

$$\begin{bmatrix} E_x^{\text{out}} \\ E_y^{\text{out}} \end{bmatrix} = \begin{bmatrix} \cos y & \sin y \\ -\sin y & \cos y \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \cos y & -\sin y \\ \sin y & \cos y \end{bmatrix} \times \begin{bmatrix} \cos x & \sin x \\ -\sin x & \cos x \end{bmatrix} \begin{bmatrix} a & b \\ -b^* & a^* \end{bmatrix} \times \begin{bmatrix} \cos x & -\sin x \\ \sin x & \cos x \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} E_x^{\text{in}} \\ E_y^{\text{in}} \end{bmatrix},$$

where the 2×1 vector on the right corresponds to the polarization state of the incident light and a matrix with

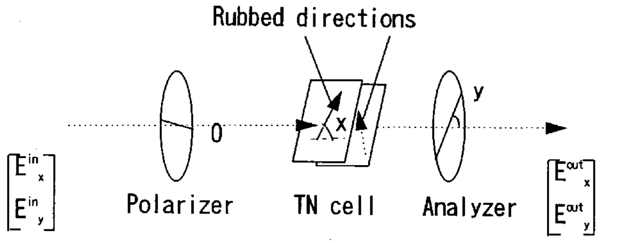

Figure 1. Optical configuration for the measurement methods.

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a, b and their complex conjugate forms (a^* and b^*) to the TN cell. Following Lien's expression and neglecting a small pretilt angle in the TN cell, a and b can be expressed as

$$a=\frac{\sin\Theta\sin\{\Theta(1+u^2)^{1/2}\}}{(1+u^2)^{1/2}}+\cos\Theta\cos\{\Theta(1+u^2)^{1/2}\}+\frac{iu\cos\Theta\sin\{\Theta(1+u^2)^{1/2}\}}{(1+u^2)^{1/2}},$$

$$b=\frac{\cos\Theta\sin\{\Theta(1+u^2)^{1/2}\}}{(1+u^2)^{1/2}}-\sin\Theta\cos\{\Theta(1+u^2)^{1/2}\}+\frac{iu\sin\Theta\sin\{\Theta(1+u^2)^{1/2}\}}{(1+u^2)^{1/2}},$$

and

$$u=\frac{\pi\Delta nd}{\lambda\Theta},$$

where λ is the incident light wavelength [6].

The transmission intensity T emitted from the analyser can be calculated from the expression

$$T=\frac{1}{2}(|E_x^{\mathrm{out}}|^2+|E_y^{\mathrm{out}}|^2).$$

After a slightly complicated calculation, the ordered expression,

$$T=T_{\mathrm{o}}(y,\Theta,u)+T_{\cos}(y,\Theta,u)\cos 4x+T_{\sin}(y,\Theta,u)\sin 4x \tag{1}$$

can be obtained, where

$$T_{\mathrm{o}}(y,\Theta,u)=\frac{u^2}{4(1+u^2)}\sin^2(1+u^2)^{1/2}\Theta+\frac{1}{2}\left[\cos(1+u^2)^{1/2}\Theta\cos(\Theta+y)+\frac{1}{(1+u^2)^{1/2}}\sin(1+u^2)^{1/2}\Theta\sin(\Theta+y)\right]^2,$$

$$T_{\cos}(y,\Theta,u)=\frac{u^2}{4(1+u^2)}\sin^2(1+u^2)^{1/2}\Theta\cos 2(\Theta+y)$$

and

$$T_{\sin}(y,\Theta,u)=\frac{u^2}{4(1+u^2)}\sin^2(1+u^2)^{1/2}\Theta\sin 2(\Theta+y).$$

The above expression (1) can be rewritten into the form:

$$T=\frac{1}{2}[f\cos(\Theta-2x+y)]^2+\frac{1}{2}[g\cos(\Theta+y)+h\sin(\Theta+y)]^2 \tag{2}$$

where

$$f=\frac{u}{(1+u^2)^{1/2}}\sin(1+u^2)^{1/2}\Theta,$$

$$g=\cos(1+u^2)^{1/2}\Theta,$$

and

$$h=\frac{1}{(1+u^2)^{1/2}}\sin(1+u^2)^{1/2}\Theta.$$

Equations (1) and (2) are the basic expressions for our measurement methods.

3. The simple method for determining the cell gap

The method proposed in this section is how to estimate Δnd in a TN cell, given the twist angle. The TN cell is set in an arbitrary azimuthal direction between crossed polarizers. In this case, expression (1) can be reduced to

$$T=T_{\mathrm{o}}(\pi/2,\Theta,u)+T_{\cos}(\pi/2,\Theta,u)\cos 4x+T_{\sin}(\pi/2,\Theta,u)\sin 4x. \tag{3}$$

The rubbing directions of the TN cell are not known before measurement so the cell angle origin ($x=0$) in expression (3) is not known, and this expression cannot be compared with measured data. After rewriting (3), the following expression is obtained:

$$T=T_{\mathrm{o}}(\pi/2,\Theta,u)+[T_{\sin}(\pi/2,\Theta,u)^2+T_{\cos}(\pi/2,\Theta,u)^2]^{1/2}\sin(4x+\phi) \tag{4}$$

Expression (4) indicates that the transmission T consists of a constant component and a variable component. The ratio between these components can easily be derived from measured data. Comparing the derived ratio with the ratio calculated from expression (4), the value u is easily obtained.

4. Examples for 90° TN cells

In this section the twist angle is restricted to 90°, the most important range for LCD applications. In this case, expression (3) is simplified to

$$T=I_{\mathrm{o}}+I_{\cos}\cos 4x, \tag{5}$$

where

$$I_{\mathrm{o}}=T_{\mathrm{o}}(\pi/2,\pi/2,u)=\frac{u^2}{4(1+u^2)}\sin^2(1+u^2)^{1/2}\Theta+\frac{1}{2}\cos^2(1+u^2)^{1/2}\Theta \tag{6}$$

and

$$I_{\cos}=T_{\cos}(\pi/2,\pi/2,u)=\frac{u^2}{4(1+u^2)}\sin^2(1+u^2)^{1/2}\Theta. \tag{7}$$

Figure 2 shows examples calculated from expression (5) for several cell gap values for the condition $\lambda=550$ nm, $\Theta=90°$, and $\Delta n=0{\cdot}1$. Figure 3 shows the relationship between the calculated ratio (I_{cos}/I_O) and the cell gap value. The minimum value condition in figure 3 corresponds to the well-known first minimum condition.

Several causes introduce estimation errors into the above method. To take an example, misaligned polarizers introduce an estimation error into the Δnd value. This influence can be estimated from expression (1), and that result is presented in Appendix 1. In practice, however, misalignment of the cell rotation axis is a more serious

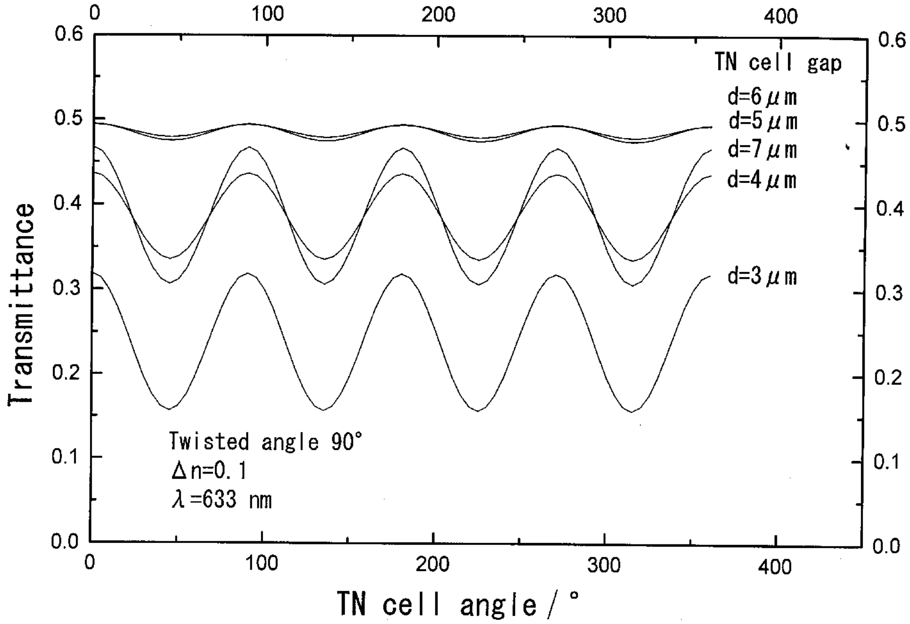

Figure 2. Calculated TN transmittance dependence on the TN cell angle for several gap values under the conditions ($\Delta n=0{\cdot}1$, $\Theta=90°$ and $\lambda=550$ nm).

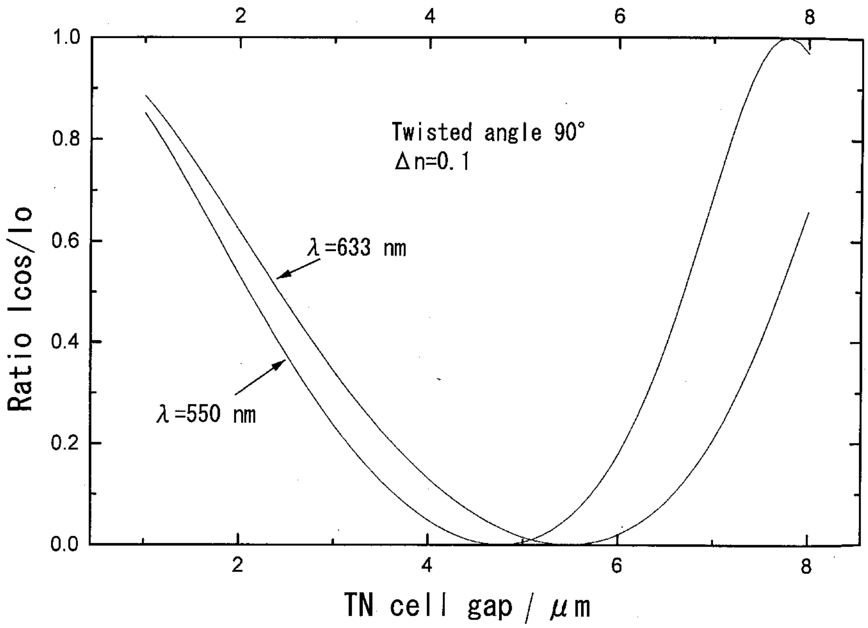

Figure 3. Calculated ratio I_{cos}/I_o dependence on TN cell gap value under the condition ($\lambda=550$ nm or 630 nm, $\Theta=90°$ and $\Delta n=0.1$).

problem. If the cell rotation axis is not parallel to the ray axis, the cell angular dependence introduces an asymmetrical signal in a cell rotation cycle. By observing the movement of a light spot reflected from the cell surface during a cell rotation, this misalignment can be corrected. Even after elimination of this misalignment, if the cell rotation axis is not aligned with the ray axis, the cell non-uniformity introduces an asymmetrical signal. This misalignment can be corrected with a position-sensor.

To confirm our simple measurement method, several 90° TN cells with transparent electrodes and alignment layers were fabricated and filled with a nematic liquid crystal material with a known Δn value. Three gap measurement methods were examined; visible light spectra measurement before filling with the liquid crystal material, capacitance measurement of the filled cell, and our proposed method. The estimation results are shown in the table. The third column values coincide with the second column values to within 2 per cent. Compared with these two columns, the first column values are overestimated by 10 per cent. This disagreement is believed to be due to the multilayer structures of the electrodes and alignment layers on the two substrates disturbing the interference spectra.

5. Rotatory analyser method for determining Δnd and Θ

While the above method is simple, the twist angle must be known beforehand. In this section, a method for determining Δnd and Θ, without any information before the measurement, is explained, referring to figure 1 and expression (2).

At the first stage of this measurement, for the parallel polarizers ($y=0$), the TN cell is fixed at either the angle of maximum transmittance ($x_{\max}$), or the angle of minimum transmittance ($x_{\min}$). From expression (2), these conditions correspond to $\Theta-2x_{\max}=n\pi$ and $\Theta-2x_{\min}=\pi/2(2n-1)$. In the former case, the TN cell is fixed at the angle $x=x_{\max}$ and a sequence of transmittance data is measured during an analyser rotation cycle. In this case, the expression (2) can be rewritten as

$$\begin{aligned}T&=f^2\cos^2(n\pi+y)+[g\cos(\Theta+y)+h\sin(\Theta+y)]^2\\&=f^2\cos^2 y+[g\cos(\Theta+y)+h\sin(\Theta+y)]^2\\&=T_o+T_c\cos 2y+T_s\sin 2y \qquad (8)\end{aligned}$$

where

$$T_o=\frac{1}{2}(f^2+g^2+h^2),$$

$$T_s=gh\cos 2\Theta-\frac{1}{2}(g^2-h^2)\sin 2\Theta$$

and

$$T_c=\frac{1}{2}(g^2-h^2)\cos 2\Theta+gh\sin 2\Theta+\frac{1}{2}f^2.$$

Analysing measured transmittance values, two ratio values (T_c/T_o and T_s/T_o) can be determined. Using these ratio values, Δnd and Θ can be determined. The simplest method is to plot the two ratio values derived from measurement results on a calculated $T_c/T_o-T_s/T_o$ plane. This plotted example is shown in the next section.

6. Estimation results near 90° twisting

In the above method, the cell angle misalignment at the first stage is expected to cause a serious error because this angle alignment shows no extinction. This influence is estimated in Appendix 2. Adding to this effect, in practical cases, a misaligned cell rotation axis can cause a serious error.

To examine the above method, several TN cells with three twist angles (84°, 90°, and 96°) were fabricated, using a known Δn liquid crystal material and known spacers. These twist values are chosen by the crossing angles of the rubbed directions on the top and bottom substrates. The above measurement procedures were carried out, using a HeNe laser and stepping motors. The obtained data were analysed with discrete Fourier analysis. The Fourier components correspond to T_o, T_s and T_c in expression (8).

Figure 4 shows several calculated constant Δnd curves and constant Θ curves on the $T_c/T_o-T_s/T_o$ plane. Several measured values for the three TN cells are also plotted on figure 4. These results show that the twist angle can be determined to within ± 1 degree and the gap value to within 0·1 μm.

Table. Estimated gap values from visible light spectra for empty cells, capacitance measurement for filled cells, and the newly proposed measurement.

Cell no.	Visible light spectra measurement	Capacitance measurement	Newly proposed measurement
TN1	5·2	4·8	4·8
TN2	5·0	4·8	4·8
TN3	5·1	4·7	4·8
TN4	5·0	4·7	4·8
TN5	5·1	4·6	4·7

7. Conclusions

Two new methods have been presented. One is for determining the Δnd of TN cells and the other for determining Δnd and twist angle. In these methods, the values can be determined by a graphical method. These

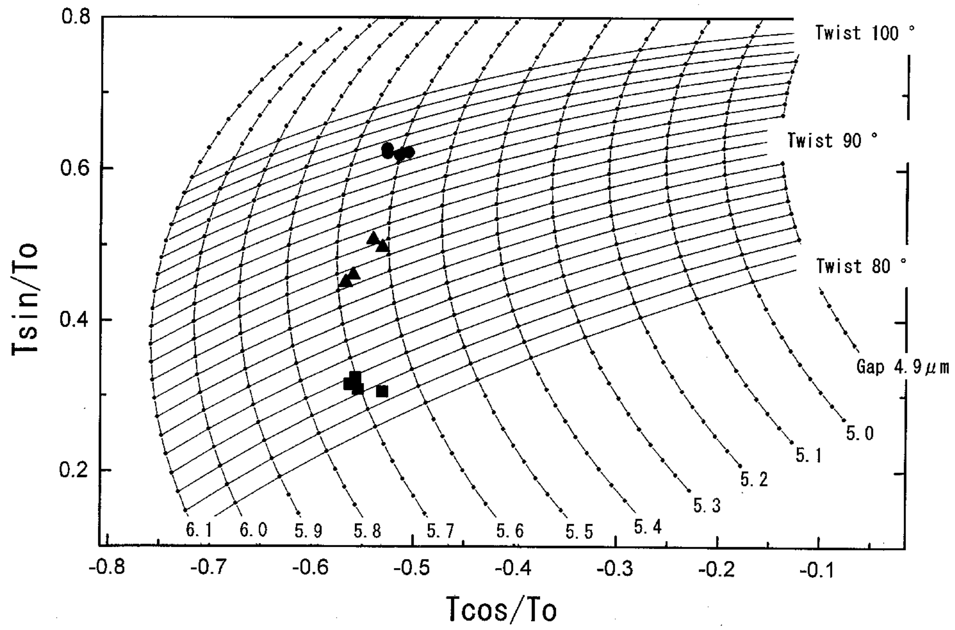

Figure 4. Several calculated constant Δnd curves and constant Θ curves on a $T_c T_o - T_s/T_o$ plane and several points obtained from measuring the TN cells which have three designed twisted angles, 84° (■), 90° (▲), and 96° (●).

methods are easily applied to an automatic measurement system.

Appendix 1

A Δnd error caused by misaligned polarizer and analyser under 90° twisted cases is estimated in this appendix. Let the analyser angle y deviate from 90° by $\varepsilon°$. In this case, the expression (3) can be expanded to the first order of ε and the following form

$$T = T_o(\pi/2+\varepsilon, \pi/2, u) + T_{\cos}(\pi/2+\varepsilon, \pi/2, u)\cos 4x + T_{\sin}(\pi/2+\varepsilon, \pi/2, u)\sin 4x,$$

can be obtained, where

$$T_o(\pi/2+\varepsilon, \pi/2, u) \approx I_o + \frac{\varepsilon}{(1+u^2)^{1/2}}\sin\left(\frac{\pi}{2}(1+u^2)^{1/2}\right) \times \cos\left(\frac{\pi}{2}(1+u^2)^{1/2}\right),$$

$$T_{\cos}(\pi/2+\varepsilon, \pi/2, u) \approx I_{\cos},$$

and

$$T_{\sin}(\pi/2+\varepsilon, \pi/2, u) \approx \varepsilon\frac{u^2}{2(1+u^2)}\sin^2(1+u^2)^{1/2}\Theta.$$

In this case, instead of the true ratio value $(I_{\cos}/I_o)$, the ratio value

$$\frac{(T_{\cos}^2 + T_{\sin}^2)^{1/2}}{T_o} \approx \frac{I_{\cos}}{I_o} + \delta\left(\frac{I_{\cos}}{I_o}\right),$$

where

$$\delta\left(\frac{I_{\cos}}{I_o}\right) = -\varepsilon\frac{\sin(1+u^2)^{1/2}\Theta\cos(1+u^2)^{1/2}\Theta}{I_o(1+u^2)},$$

is measured. The second term in the right-hand side means a ratio estimation error. The Δnd estimation is influenced by this error. This influence can be estimated by the form

$$\delta(\Delta nd) = \frac{\lambda\Theta}{\pi}\delta u = \frac{\lambda\Theta}{\pi}\frac{1}{\left(\dfrac{\partial(I_{\cos}/I_o)}{\partial u}\right)}\delta(I_{\cos}/I_o) = -\varepsilon\frac{\lambda\Theta}{\pi} \times \frac{2u(1+u^2)\sin^2\Theta(1+u^2)^{1/2}}{2\Theta u^2 + 2\Theta u^4 + (1+u^2)^{1/2}\sin 2\Theta(1+u^2)^{1/2}}. \quad (9)$$

Figure 5 shows the numerical estimation of the above expression under the conditions ($\Theta = 90°$, $\lambda = 550$ nm, $\varepsilon = 1°$). Figure 5 shows the misaligned polarizers by 1° introduces an estimation error of less than 0·01 except the region with Δnd less than 0·2.

Appendix 2

Errors in gap value and twisted angle estimation which TN cell misalignment introduces are estimated in this appendix. The TN cell angle is misaligned by ε

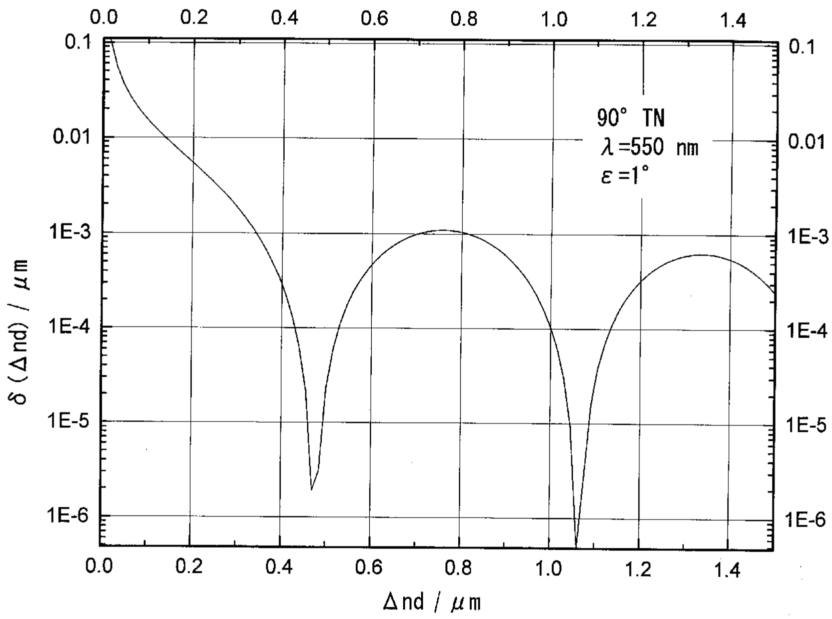

Figure 5. A numerical estimation result based on expression (9) in the case of $\Theta = 90°$, $\lambda = 550$ nm and $\varepsilon = 1°$.

degrees. In this case,

$$T = f^2 \cos^2 (n\pi + 2\varepsilon + y) + [g \cos (\Theta + y) + h \sin (\Theta + y)]^2 = T_o + T_c \cos 2y + T_s' \sin 2y,$$

where

$$T_s' = T_s - 2\varepsilon f^2.$$

The above expression shows this misalignment influences only the T_s/T_o value

$$\delta\left(\frac{T_s}{T_o}\right) = 2\varepsilon \frac{f^2}{T_o} = 4\varepsilon \frac{u^2 \sin^2 \Theta (1 + u^2)^{1/2}}{1 + u^2}. \quad (10)$$

To estimate the error in the case of nearly 90° twist, the Θ in the above expression can be replaced by 90°. Figure 6 shows the calculated examples of the above

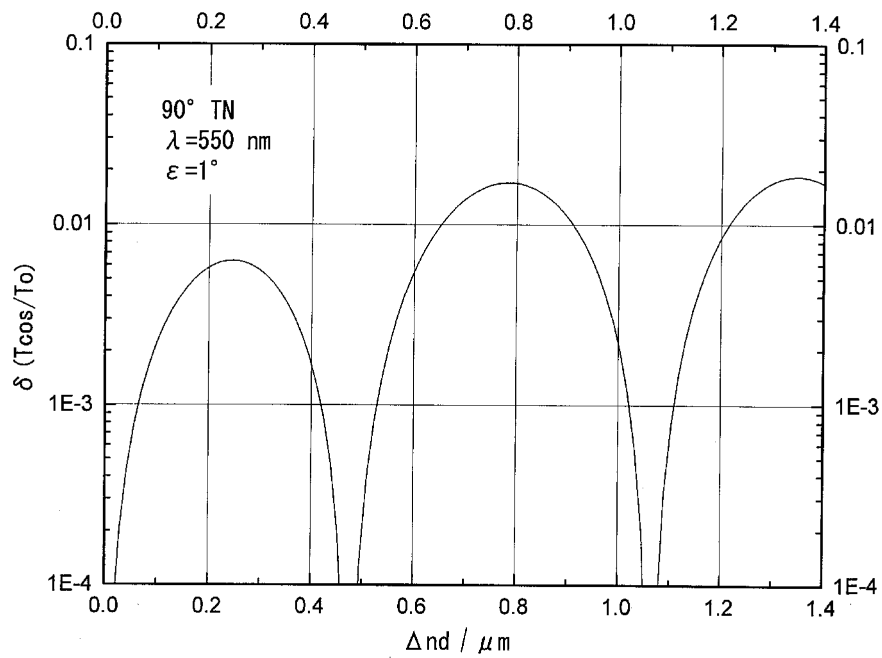

Figure 6. A numerical estimation result of expression (10) in the case of $\Theta = 90°$, $\lambda = 550$ nm and $\varepsilon = 1°$.

expression under the condition ($\Theta = 90°$, $\lambda = 550$ nm, and $\varepsilon = 1°$). Figure 6 shows that the misalignment of the TN cell by 1° introduces an estimation error of less than 0·02. Combining this result and figure 4, it is clarified that this error disturbs mainly twisted angle estimation and its amount is less than 1° in the estimation.

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