Journal of the Optical Society of Korea, Vol. 3, No. 1, March 1999, pp. 23-26

Simple polarimetric method for electro-optic coefficients

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(Received November 30, 1998)

A simple technique to measure electro-optic coefficients has been developed. It is based on rotating analyzer polarimetry. With a coaxial configuration of the optically active polarizing devices, the synchronously digitized signals are Fourier analyzed to quantitatively determine the elliptical polarization of light and, hence, the electric field induced birefringence. This technique has the advantage that it does not require waveguiding, and since it is improved from the crossed polarizer method it measures the phase retardation directly. It has been applied for the precise determination of electro-optic coefficients of uniaxial $LiNbO_3$ single crystals. The excellent agreement with reported values confirms its usefulness toward accurate characterization of electro-optic coefficients of unknown specimens.

I. INTRODUCTION

For the application of nonlinear optical materials to electro-optic (EO) devices, an accurate characterization of the EO effect is crucial. Several experimental methods have been developed for the determination of EO coefficients [1–4]. The majority are based on the measurement of the light intensity modulation propagated from the EO modulation of the refractive index via the polarization state variation of the traveling beam. Thus the electric field-induced phase retardation across the light path in the material can be measured. To accomplish this, many conventional methods rely on waveguiding. From the measurement of the synchronous mode angles and their variation, for prism-coupled waveguide excitations, the Pockels coefficients can be determined [2]. In the Mach-Zehnder interferometer scheme, the light modulation inside the nonlinear optical film, across which the modulating field is applied, is related to the EO coefficients [3]. Simple techniques without making use of the waveguide have been reported also. The light intensity modulation is measured either in the reflection mode [1] or in the transmission mode [4] with a proper arrangement of the compensator and fixed crossed polarizers. These have been used to get the EO coefficients. Meanwhile, the technique to detect a polarization state using a rotating analyzer has been developed and widely applied to ellipsometry [5]. Since the rotating analyzer technique enables one to measure the ellipticity angle and the azimuth angle of an elliptically polarized light quite accurately, it has been applied to the measurement of the Faraday rotation, the magneto-optical Kerr effect, and birefringence induced by the ferroelastic monoclinic-tetragonal phase transition in $BiVO_4$ [6–8]. This technique is very simple in design and easy to operate. It is also versatile so that it can be applied to a variety of fields, but its application has not been extended to the determination of the electric field induced birefringence of nonlinear optical materials. In this article, we report the application of the rotating analyzer polarimetric technique to the measurement of the EO coefficients of $LiNbO_3$ single crystals.

II. ROTATING ANALYZER POLARIMETER AND DETERMINATION OF RETARDING PHASE ANGLE

The schematic of the measuring system is shown in Fig. 1 and the rotating analyzer module is shown in Fig. 2. Samples were prepared either for a longitudinal configuration, where a single test layer was sand-

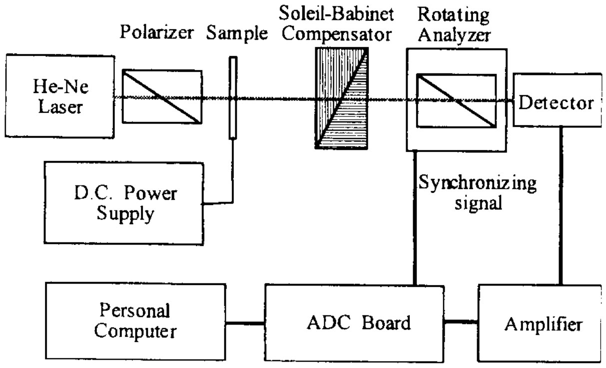

FIG. 1. The schematic of an electro-optic effect measuring system.

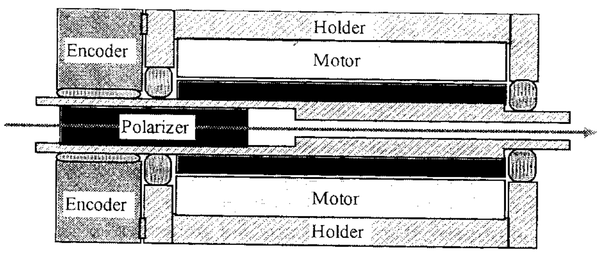

FIG. 2. The schematic of the rotating analyzer module.

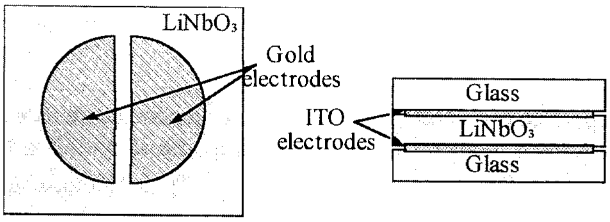

FIG. 3. The electrode configurations for a transverse (a) and for a longitudinal (b) application of DC electric fields.

wiched between a pair of plane-parallel, transparent electrodes or for a transverse configuration, where the metal electrodes with 5-mm-gap were deposited on one side of a test layer. The schematic of the electrode configurations appears in Fig. 3. A He-Ne laser was used as the light source. For active polarizing devices, laser quality Glan-Thompson polarizers were used as polarizers and a Soleil-Babinet compensator was used as the phase retarder. A brushless, hollow type DC motor drove the rotating analyzer, where a hole-type micro-encoder was mounted in a coaxial configuration. The light falling on the Si-diode photo-detector was analog-to-digital converted synchronous with the trigger signal from the coaxial micro-encoder.

The explicit expression of electric field induced birefringence can be derived with the help of Jones matrix formalism, where the electric field of light falling on a detector can be written as follows.

$$E(t) = E_0(1 \;\; 0)\cdot \mathbf{R}(A-C)\cdot \mathbf{T}_C \cdot \mathbf{R}(C)\cdot \mathbf{T}_S \cdot \mathbf{R}(-P)\cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix} \qquad (1)$$

Here A, C and P are the azimuth angles of the analyzer, the compensator and the polarizer, respectively. The angles are measured with respect to the semi-major axis of the sample indicatrix (y-axis for the x-cut $E = E_z$, x-axis for the y-cut $E = E_z$ and for the y-cut $E = E_y$, and 45^o with respect to x-axis for the z-cut $E = E_x$) of the uniaxial $LiNbO_3$ crystals. $\mathbf{R}(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$ is the rotation matrix, and $\mathbf{T}_C$ and $\mathbf{T}_S$ are the transfer matrix of the Soleil-Babinet compensator and the sample, respectively. The explicit expressions of these transfer matrices are $\mathbf{T}_C = T_{0C}\begin{pmatrix} 1 & 0 \\ 0 & e^{-i\delta} \end{pmatrix}$ and $\mathbf{T}_S = T_{0S}\begin{pmatrix} 1 & 0 \\ 0 & e^{-i\Gamma} \end{pmatrix}$, where δ and Γ are the retarding phase angle of compensator and sample, respectively. The phase angle of the sample can be regarded as the sum of two terms like $\Gamma = \Gamma_0 + \delta\Gamma$, where Γ_0 comes from the intrinsic birefringence of sample and $\delta\Gamma$ from the electric-field-induced birefringence. The induced birefringence includes linear (Pockels) and quadratic (Kerr) effects. The intensity of light has a simple and compact expression when $|C| = |P| = \pi/4$.

$$I = I_0(1 + \alpha\cos 2\omega t + \beta\sin 2\omega t) \qquad (2)$$

where $\alpha = Sgn(C)Sgn(P)\cos\Gamma$ and $\beta = -Sgn(P)\sin\delta\sin\Gamma$. Here $Sgn(x) = x/|x|$ means the sign of x, and ω is the angular frequency of the rotating analyzer. The analyzer offset is calibrated such that $A - C = \omega t$. When δ is an odd integer multiple of $\pi/2$ then $|\sin\delta| = 1$ and $\sqrt{\alpha^2+\beta^2} = 1$, and the reflected light is linearly polarized. Then, the phase angle of the sample is

$$\Gamma = (-1)^{n+1} Sgn(C)\tan^{-1}(\beta/\alpha). \qquad (3)$$

The absolute value of the right hand side of Eq. (3), on the other hand, is the same as the azimuth angle of linearly polarized light, which can be measured quite accurately by rotating analyzer polarimetry. The precision of rotating analyzer polarimetry is known to be better than a hundredth of a degree [5]. When δ is an even integer multiple of $\pi/2$, then $\beta = 0$ and $|\alpha| = |\cos\Gamma| \leq 1$. Hence the light on the detector is elliptically polarized, and although one can determine the phase angle from the ellipticity measurement, since $\cos\Gamma$ is stationary to Γ variation around $\Gamma = 0$, the precision is not comparable to the former case when δ is an odd multiple of $\pi/2$.

Let (α, β) and (α_0, β_0) be the Fourier coefficients in Eq. (2) with and without electric field, respectively. Then adopting the condition of $\delta = n\pi + \pi/2$, the retarding phase angle induced by the applied electric field is given by Eq. (4).

TABLE 1. Electo-optic properties and four dominant phase retardation angles in uniaxial $LiNbO_3$ single crystal for a few applied fields.

Type of cutting (applied field)	Index ellipsoid	Phase
x-cut $\begin{pmatrix} E_x = E_y = 0 \\ E_z = E \end{pmatrix}$	$\left(\frac{1}{n_o^2}+r_{13}E\right)y^2+\left(\frac{1}{n_e^2}+r_{33}E\right)z^2=1$	$\delta\Gamma = -\frac{2\pi l}{\lambda}\left[\frac{1}{2}(n_e^3 r_{33}-n_o^3 r_{13})E\right]$
y-cut $\begin{pmatrix} E_x = E_y = 0 \\ E_z = E \end{pmatrix}$	$\left(\frac{1}{n_o^2}+r_{13}E\right)x^2+\left(\frac{1}{n_e^2}+r_{33}E\right)z^2=1$	$\delta\Gamma = -\frac{2\pi l}{\lambda}\left[\frac{1}{2}(n_e^3 r_{33}-n_o^3 r_{13})E\right]$
y-cut $\begin{pmatrix} E_x = E_z = 0 \\ E_y = E \end{pmatrix}$	$\left(\frac{1}{n_o^2}-r_{22}E\right)x^2+\left(\frac{1}{n_e^2}\right)z^2=1$	$\delta\Gamma = \frac{2\pi l}{\lambda}\left[-\frac{1}{2}n_o^3 r_{22}E\right]$
z-cut $\begin{pmatrix} E_y = E_z = 0 \\ E_x = E \end{pmatrix}$	$\left(\frac{1}{n_o^2}\right)x^2+\left(\frac{1}{n_o^2}\right)y^2-2xyr_{22}E=1$	$\delta\Gamma = \frac{2\pi l}{\lambda}\left[n_o^3 r_{22}E\right]$

$$\delta\Gamma = (-1)^{n+1}Sgn(C)\tan^{-1}\left(\frac{\beta}{\alpha}\right) - (-1)^{n+1}Sgn(C)\tan^{-1}\left(\frac{\beta_0}{\alpha_0}\right) \quad (4)$$

The four Fourier coefficients $(\alpha, \beta, \alpha_0, \beta_0)$ can be obtained from the intensity data versus analyzer angle [5,6].

This rotating analyzer polarimetry has been applied to the measurement of the electric-field-induced birefringence of uniaxial $LiNbO_3$ crystals whose Pockels coefficients are well known. The relation between retarding phase angles and EO properties of $LiNbO_3$ crystals with electric fields along x, y, and z (c-axis) directions are summarized in Table 1.

III. ELECTRO-OPTIC COEFFICIENTS OF LINBO$_3$ SINGLE CRYSTAL AND DISCUSSIONS

We prepared 1 mm-thick plates of x-, y-, and z-cut $LiNbO_3$ single crystal as test samples. For the longitudinal configuration (y-cut, $E = E_y$), the sample was sandwiched between two glass substrates, which are precoated with indium tin oxide (ITO) electrodes. For the transverse configurations, 3000-Å-thick gold electrodes with a 5-mm gap were deposited in vacuum as shown in Fig. 3(a) on one side of $LiNbO_3$ plate to obtain a uniform electric field [9]. The analyzer was driven at the angular speed of 33 Hz.

Fig. 4 shows the measured phase retardation for the configurations in Table 1. The linear behavior of retardation angles versus applied electric field is clearly observed. When an electric field is applied along the transverse z-direction, both data of x-cut and y-cut specimens nicely overlap on each other. The EO coefficients determined from the slopes of the best fit

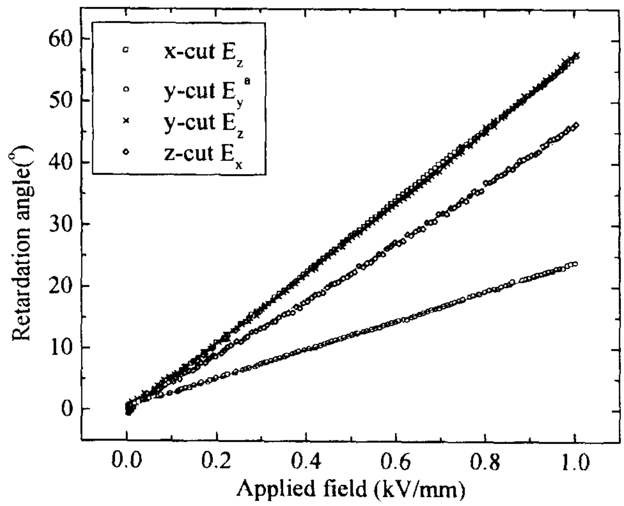

FIG. 4. Measured retardation angles of uniaxial $LiNbO_3$ single crystal versus applied electric field.

TABLE 2. Linear electo-optic coefficients of $LiNbO_3$ at $\lambda = 0.633\mu m$ determined in the present research, agree quite well with the previously reported values

EO coefficient	Type of cutting x-cut	y-cut	z-cut	reported value[10]
r_{22} (pm/V)	-	6.86	6.5	6.81
$\frac{1}{2}[(n_e^3 r_{33} - n_o^3 r_{13}]$ (pm/V)	98.8	99.7	-	95

straight lines in Fig. 4 are compared with the previously reported values and are summarized in Table 2. The agreement with literature values is quite excellent. The difference is less than 5%, comparable to the magnitude of relative error in measuring electrode gap distance.

Each data point in Fig. 4 was averaged over 10 analyzer rotations. By increasing the number of rotations, say by N times, random error will be reduced by $1/\sqrt{N}$, which can be easily achieved with the present system of automatic control and measurement. At present, it takes about 4 seconds to average over 100 rotations. Based on the observed linearity in Fig. 4, it is expected that this rotating analyzer polarimetry can be readily applied to measure the electro-optic effect of very thin nonlinear polymer films whose phase retardation angle would be a few tenths of degree.

IV. CONCLUDING SUMMARY

In summary, a rotating analyzer polarimetric method has been developed and was applied to the characterization of electric-field-induced birefringence and hence to the determination of electro-optic coefficients. This technique, with its computer-assisted data collection and manipulation, enables one to measure the phase retardation quickly and accurately. Also, since it measures the phase retardation directly, the result is model independent. With its rugged design and automatic, high-speed operation in data collection, precision can be improved easily by increasing the number averaged over. When applied to uniaxial $LiNbO_3$ single crystal, the measured electro-optic coefficients agreed quite tightly to the literature values. This technique is believed useful for the measurement of small birefringence like that due to the electro-optic effect of very thin optically nonlinear polymer films.

REFERENCES

[1] C. C. Teng and H. T. Man, Appl. Phys. Lett. **56**, 1734 (1990).

[2] W. H. G. Horsthuis and G. J. M. Krijnen, Appl. Phys. Lett. **55**, 616 (1989).

[3] K. D. Singer, M. G. Kuzyk, W. R. Holland, J. E. Sohn, S. J. Lalama, R. B. Comizzoli, H. E. Katz, and M. L. Schilling, Appl. Phys. Lett. **53**, 1800 (1988).

[4] C. P. J. M. van der Vorst, and C. J. M. van Rheede, SPIE **1337**, 246 (1990).

[5] D.E. Aspnes, J. Opt. Soc. Am. **64**, 812 (1974); W. Budde, Applied Optics **1**(3), 201 (1962).

[6] S.Y. Kim, Y.H. Won, and H.N. Kim, J. Appl. Phys. **67**, 7026 (1990).

[7] S.Y. Kim, H.G. Lee, and Y.H. Won, SPIE **2873**, 45 (1996); H.G. Lee, Y.H. Won, G.S. Lee, Appl. Phys. Lett. **68**, 3072 (1996).

[8] I.G. Wood and A.M. Glazer, J. Appl. Crystal. **13**, 217 (1980).

[9] M. De Sario, A. D'Orazio, V. Petruzzelli, SPIE **1274**, 38 (1990).

[10] E.H. Turner, Appl. Phys. Lett. **8**, 303 (1966).