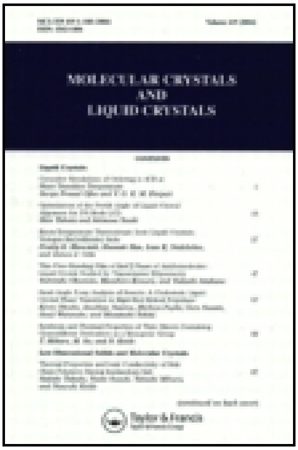

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A NEW MEASUREMENT METHOD FOR STOKES PARAMETERS USING A WEDGE-SHAPED LC DEVICE

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A new optical measurement method for Stokes parameters using a wedge-shaped (WS) liquid crystal (LC) device is reported for characterizing optical elements such as LC display devices, where the WS LC device is used for one-dimensional modulation of a transmitted light through an optical element. The method is very simple and reliable and does not use any mechanical parts, so it is very useful for measuring Stokes parameters of arbitrarily polarized light.

Keywords: liquid crystal device; optical measurement; Stokes parameters

INTRODUCTION

Stokes parameters, which represent a polarized state of light, are very useful for evaluating the optical properties of optically anisotropic mediums such as retardation films and liquid crystal displays (LCDs). This is because the Stokes parameters can be plotted on a Poincare sphere, and the polarized state plotted on the sphere can be easily imaged. Until now, several methods for measuring Stokes parameters have been proposed [1–3], and these methods have been shown to be powerful tools for characterizing various optical elements.

In this study, we report a new measurement method for Stokes parameters that uses a wedge-shaped (WS) LC device. In order to clarify the usefulness of the method, we present some measurement results of Stokes parameters of a light transmitted through various optical elements.

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MEASUREMENT PRINCIPLE OF STOKES PARAMETERS

Figure 1 shows the optical arrangement for measuring Stokes parameters using a WS LC device [4]. When a collimated light beam of wavelength λ with a polarized state of (S_0, S_1, S_2, S_3) is incident into the WS LC device, the polarized state of the light beam is modulated along the x axis due to the variation of the optical retardation along the direction in the WS LC device, where the LC director of the device is uniformly aligned along the y axis. Therefore, the polarized state of the incident light into the WS LC device is modulated along the x axis. By using an analyzer, the one-dimensionally modulated light profile is converted to a one-dimensionally modulated intensity profile, which is finally detected by a linear image sensor. From a simple Jones matrix calculation, the intensity profile I(x) is written as

$$I(x) = \frac{1}{2}\{S_0 + S_1\cos(2\varphi) + \sin(2\varphi)[S_2\cos(\Delta(x)) - S_3\sin(\Delta(x))]\}, \quad (1)$$

where $\Delta(x) = 2\pi\Delta nd(x)/\lambda$ is an optical retardation of the WS LC device at position x, which is proportional to the channel number of a linear image sensor, and φ is the angle of the transmission axis of the analyzer from the x axis. The Equation (1) is also rewritten by using the channel number N as

$$I(N) = \frac{1}{2}\{S_0 + S_1\cos(2\varphi) + \sin(2\varphi)[S_2\cos(\Delta(N)) - S_3\sin(\Delta(N))]\}. \quad (2)$$

Therefore, if we know the optical retardation profile Δ(N) of the WS LC device as a function of the channel number N, the Stokes parameters

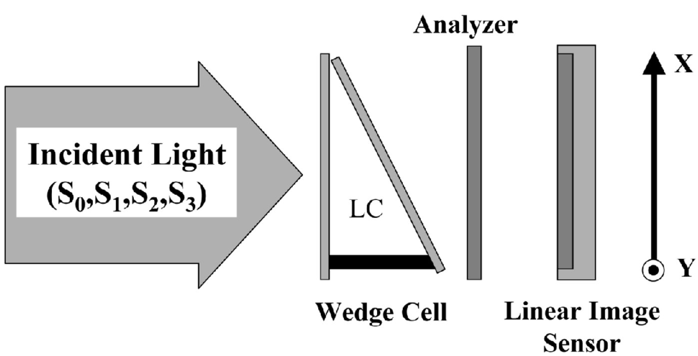

FIGURE 1 Basic arrangement for measuring Stokes parameters using a WS LC device.

(S_0, S_1, S_2, S_3) of the incident light are determined by comparing the measured light intensity profile with the theoretical Equation (2).

EXPERIMENTAL

Figure 2 shows an optical setup for measuring Stokes parameters. An LED light source with a center wavelength λ of 633 nm ($\Delta\lambda = 20$ nm) was incident into a plastic optical fiber (1) with a diameter of 1 mm, and then the light from the fiber was collimated by a lens (2). The collimated light beam was then linearly polarized by a rotatable polarizer (3) and was incident into a sample (4), in which the polarized state of the transmitted light was varied by the optical anisotropy of the sample. The beam size of the transmitted light with the polarized state of (S_0, S_1, S_2, S_3) was then expanded by using a beam expander (5), and the light beam was incident into a WS LC device (6), after which the one-dimensionally modulated light was transmitted through the rotatable analyzer (7) and the intensity profile of the light was detected with the linear image sensor (8). The LC used for the WS LC device, in which we used a glass substrate size of $40 \times 30 \times 1.5\,\text{mm}^3$ and a spacer film of $12\,\mu$m, was ZLI-4792 with $\Delta n \sim 0.09$. The linear image sensor consisting of 1024 photodiode arrays had a resolution of 12 bits. Here it should be noted that the angle φ of the polarized axis of the analyzer (7) is very important to determine all the Stokes parameters. In this study, the angle was set to be 112.5° from the x axis, so the intensity profile I(N) on the linear image sensor can be rewritten as

$$I(N) = \frac{S_0}{2}\left\{1 - \frac{1}{\sqrt{2}}s_1 - \frac{1}{\sqrt{2}}[s_2\cos(\Delta(N)) - s_3\sin(\Delta(N))]\right\}, \qquad (3)$$

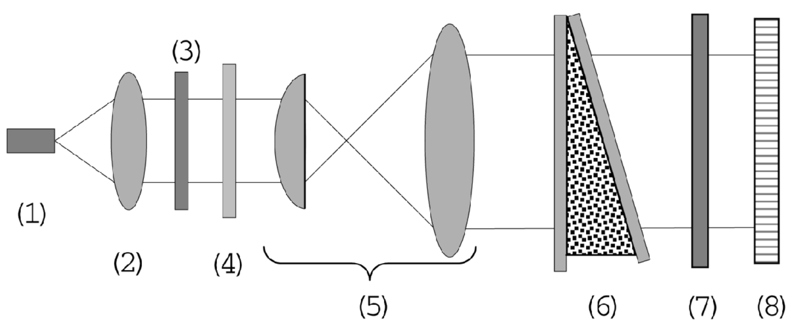

FIGURE 2 Optical setup for measuring Stokes parameters.

where s_i (i = 1, 2, 3) represents a normalized Stokes parameter and is defined as $s_i = S_i/S_0$, and, as mentioned above, N represents the channel number of a linear image sensor.

Before measuring the Stokes parameters of a sample, a one-dimensional retardation profile of Δnd(N) for the WS LC device is needed. For this purpose, a light with a known polarized state $(s_1,s_2,s_3) = (0, 1, 0)$ was incident into the WS LC device, and the resultant intensity profile was measured. Using Equation (2), the intensity profile I(N) is written as

$$I(N) = \frac{S_0}{2}\{1 - \cos(\Delta(N))\}, \quad (4)$$

where the transmission axis of the analyzer was set to be 135°.

In Figure 3 we show the estimated profile of Δnd(N), where the quadratic variation of the optical retardation along the x axis was assumed. From the result, we obtained the following Δnd(N) profile of the WS LC device used:

$$\Delta nd = 4.1 \times 10^{-7}\, N^2 - 1.4 \times 10^{-3}\, N + 1.25. \quad (5)$$

For determining the Stokes parameters from an intensity profile, we used a limited channel range from 150 to 850. Even in this channel range,

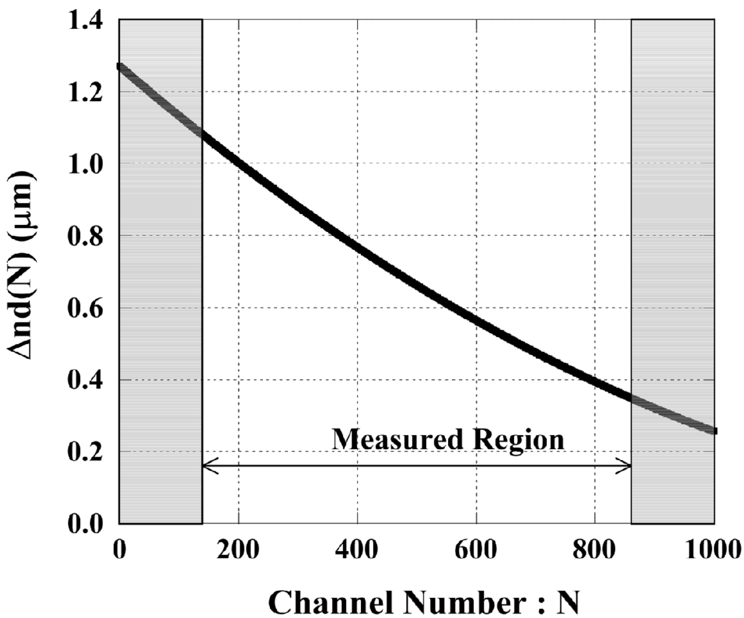

FIGURE 3 Retardation profile of the WS LC device used in this study.

sufficient one-dimensional (x axis) modulation of more than λ (633 nm) can be achieved for incident light polarization to the WS LC device.

RESULTS AND DISCUSSION

Residual Birefringence Correction of an Optical System

Figure 4 shows an example of a measured intensity profile (solid line) with a theoretical fitting (dotted curve), where a linearly polarized incident light with the polarization direction along x axis was used, and the profile is normalized by the light intensity (S_0) of incident light. From this result it is clear that the fitting is rather good, and the normalized Stokes parameters of $(s_1,s_2,s_3) = (0.49,\ 0.87,\ 0.08)$ are derived using this fitting procedure. It should be pointed out here that the subtraction of the background level of the light intensity profile is very important to obtain reliable values of Stokes parameters.

In order to confirm the performance of the present method, a variation of the Stokes parameters as a function of the rotation angle of a polarizer was measured (Figure 5), where the angle of a zero position corresponds to

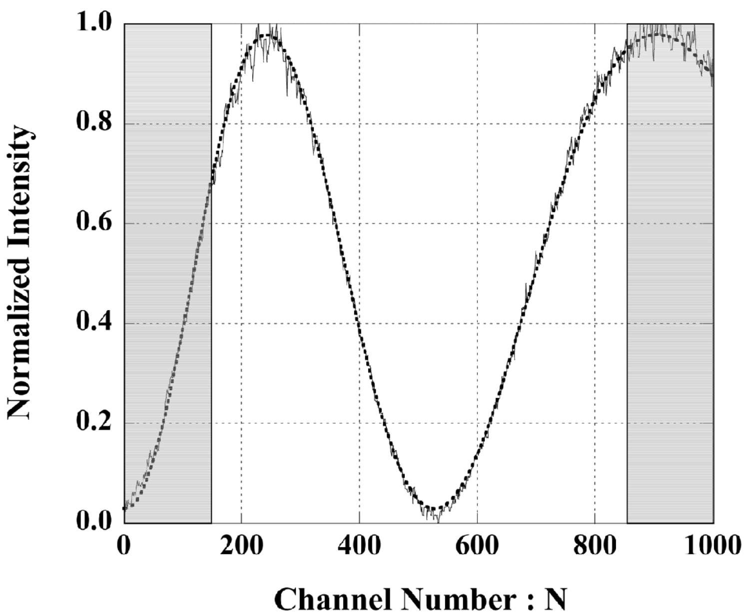

FIGURE 4 Intensity profile of a polarized light detected on a linear image sensor. The dotted curve represents best-fit results using Equation (3).

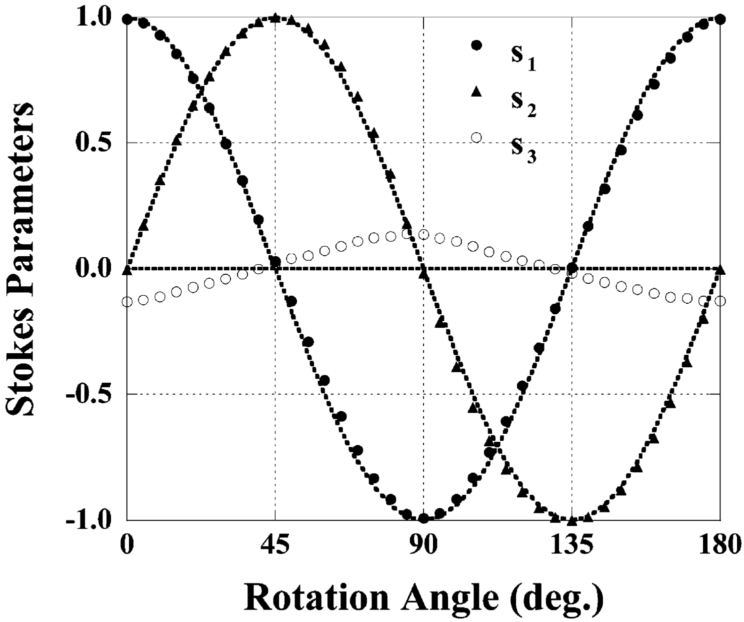

FIGURE 5 Variations of Stokes parameters as a function of the rotation angle of a polarizer.

light polarized along the x axis. From a simple theoretical consideration, the variation of the Stokes parameters is written as

$$(\mathrm{s}_1, \mathrm{s}_2, \mathrm{s}_3) = (\cos\theta, \sin\theta, 0), \tag{6}$$

where θ represents the rotation angle of the polarizer. Regarding s_1 and s_2, the experimental results are well represented by the theoretical curves, but for s_3 the value should be zero, regardless of the rotation angle. This difference indicates that, in passing through the optical system, a linearly polarized light is converted into a somewhat elliptically polarized light, and this may be due to the residual birefringence of some optical components used in the system. To compensate for this residual birefringent effect from the experimental results, we modified the theoretical intensity equation I(N) by taking the effect into account in which an imaginary birefringent plate with optical axis ϕ and retardation δ is inserted in front of the WS LC device. The fitting results using the modified theoretical equation are shown in Figure 6, where the values of $\phi = 53°$ and $\delta = 13.2\,\mathrm{nm}$ were used. These corrected results clear demonstrate the reliability of the present method for measuring the Stokes parameters.

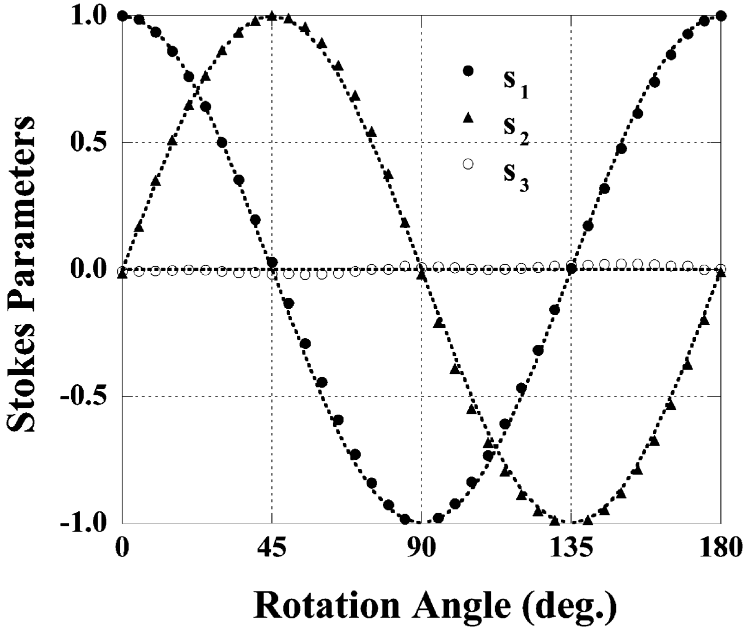

FIGURE 6 Corrected results of the variations of Stokes parameters shown in Figure 5. The corrections are done by assuming a residual birefringence in a measurement optical system.

A Stokes Parameter Measurement for LC Samples

In order to apply the present method to estimate the polarized state (Stokes parameters) of a light transmitted through an LC sample, we used two types of LC cells; one was a plane-aligned LC cell and the other a twisted nematic (TN) cell.

Shown in Figure 7 are variations of the Stokes parameters as a function of an applied voltage for a plane-aligned cell, where a polarizer axis of the optical system was set at zero (x axis), and the slow axis of the LC cell was 45° with respect to the x axis. We used ZLI-4792 as the LC material, and the cell thickness was 7.8 μm. At zero applied voltage the polarized state of the transmitted light is a left-handed elliptical polarization with its long principal axis along the x axis, amd above the threshold voltage of about 1.5 V the LC directors start to be aligned along the electric field direction. As the applied voltage is further increased, the polarized states vary from a linearly polarized state along the x axis at 2 V to a right-handed circularly polarized state at 2.5 V. Then the polarized state finally becomes an almost left-handed circularly polarized state at 5 V through a linear polarized state

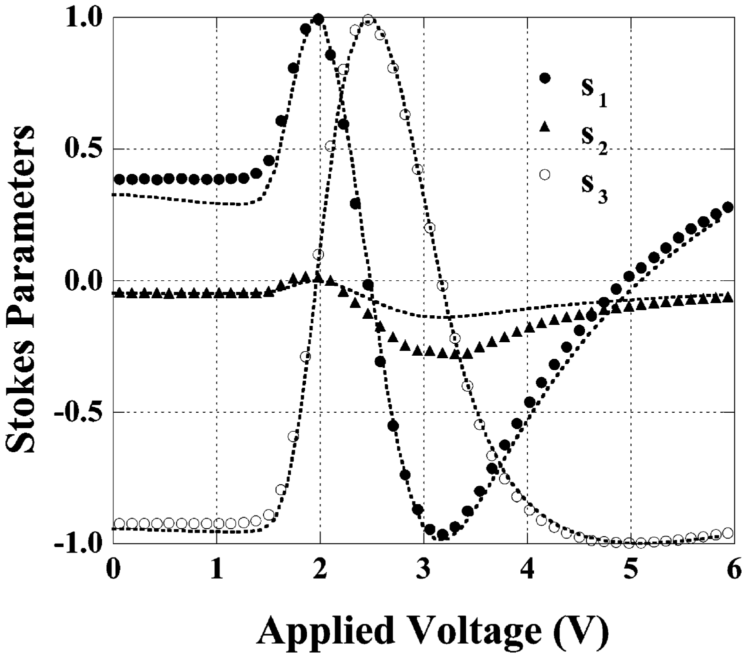

FIGURE 7 Applied voltage dependence of Stokes parameters for a plane-aligned LC sample.

along the *y* axis. These variations in the polarization state were also confirmed by the experimental results (dotted lines) using a photoelastic modulator as shown in Figure 7. From a theoretical viewpoint, s_2 should become zero, but the experimental results indicate a finite value of s_2. This may be due to misalignment in the optical system and the existence of some twist deformation in the LC sample used.

Figure 8 shows an applied voltage dependence of the Stokes parameters of the transmitted light through a TN cell, where the LC material used was also ZLI-4792 and the cell thickness was 5.1 μm with a twist angle of 90°. An incident light to the cell was linearly polarized with the polarization direction coinciding with the entrance director direction of the cell (*x* axis). Closed circles, closed triangles, and open circles, respectively, represent experimental results for s_1, s_2, and s_3, and dotted lines are best-fitted simulated curves using the 2×2 Jones matrix method. As seen in this figure, the experimental points are well represented by the simulated results with reasonable cell parameters (twist angle of 87° and cell thickness of 4.5 μm), and thus this measurement method for Stokes parameters is very useful for characterizing LCDs.

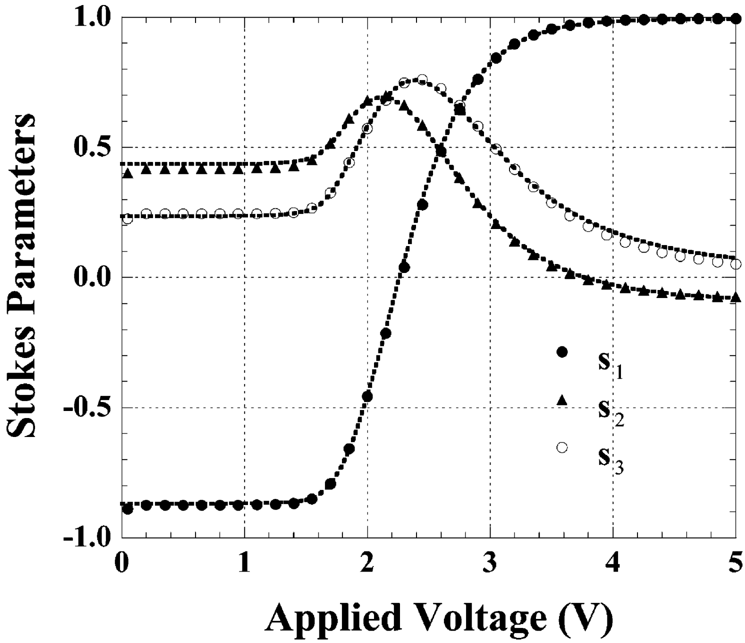

FIGURE 8 Variations of Stokes parameters for a twisted nematic LC sample as a function of an applied voltage.

CONCLUSIONS

A new optical measurement method for Stokes parameters using a wedge-shaped liquid crystal device was reported for characterizing the optical properties of optically anisotropic devices such as LC display devices. We presented several experimental results to demonstrate the usefulness of the method. From the results, we showed that the present method was very simple and reliable, thus it is very useful for measuring Stokes parameters.

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