Simultaneous measurement of phase retardation and optic axis of a phase compensation film using an axially-symmetric sheared polymer network liquid crystal

Yung-Hsun Wu, Ju-Hyun Lee, Yi-Hsin Lin, Hongwen Ren, and Shin-Tson Wu

College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816
swu@mail.ucf.edu

Abstract: A new method for simultaneously measuring the phase retardation and optic axis of a uniaxial compensation film is demonstrated using an axially-symmetric sheared polymer network liquid crystal (SPNLC). By overlaying a tested compensation film with a calibrated SPNLC cell between crossed polarizers, two dark spots are clearly observed in a CCD image. From the orientation direction and distance of these two spots, the optic axis and phase retardation value of the compensation film can be determined. This method is particularly useful for those optical systems whose optic axis and phase retardation are dynamically changing.

OCIS codes: (230.3720) Liquid-crystal devices; (160.5470) Polymers

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1. Introduction

Phase compensation films have been commonly used for improving the viewing angle and contrast ratio of liquid crystal display devices. For a compensation film, the refractive indices and optic axis need to be specified. Several methods, such as Soleil-Babinet compensator and photoelastic modulator, have been developed for measuring the phase retardation value of a phase compensation film [1-5]. The former is a mechanically adjustable retardation plate using two crystal wedges and the latter is an electrically controllable compensator. By analyzing the modulated signal from photoelastic modulators, we can determine the phase retardation information. The major shortcoming of these methods is that they cannot determine the retardation and optic axis simultaneously.

In this paper, we develop a new method for simultaneous detection of phase retardation and optic axis of a phase compensation film using an axially-symmetric Sheared Polymer Network Liquid Crystal (SPNLC) [6]. The axially-symmetric SPNLC exhibits two unique features: 1) its optic axis is radial in all directions, and 2) its phase retardation has a gradient distribution from center to edges. In experiment, we first characterize the phase retardation profile of our axially-symmetric SPNLC film. Then we overlay a phase compensation film, whose retardation value and optic axis is yet to be determined, on top of our SPNLC film. The transmitted image between crossed polarizers is recorded by a CCD camera. After analyzing the compensation pattern of the CCD image, we can precisely identify the phase retardation value and optic axis of the tested phase compensation film. To demonstrate this powerful technique, we use a quarter-wave plate with an arbitrary axis as an example to illustrate the measurement principles. Excellent agreement between experiment and simulation is obtained. This new method is particularly useful for those optical systems whose optic axis and phase retardation are dynamically changing.

2. Sample fabrication

To prepare an axially-symmetric PNLC cell, we mixed 15 wt % of a photopolymerizable monomer (Norland Optical Adhesive NOA65) in a commercial Merck E7 LC mixture. The mixed LC and monomer was filled in two ITO (indium-tin-oxide) glass substrates with cell gap d~9 μm. In order to polymerize the LC cell, a two-step UV curing process was adopted [7, 8]. After UV curing, we applied an off-axis shearing force to the top substrate, as sketched in Fig. 1, while keeping the bottom glass substrate fixed. This shearing force stretches the entangled polymer networks and suppresses the light scattering completely [7, 8]. If the shearing torque is large enough, the polymer networks begin to contract and form an axially-symmetric pattern owing to the restoring force. The detailed mechanism for forming such radially-symmetric LC patterns is not yet completely understood but is believed to result from the displacement-induced torque as shown in Fig. 1. The applied shearing force is off from the axis of the bottom substrate, as a result, the polymer networks contract and form the axially-symmetric structure.

To control the radial SPNLC patterns, we employed a precise motor motion system (Newport ESP-300) to control the initial acceleration, shearing speed, deceleration, and total shearing distance. The shearing conditions are listed as follows: acceleration =10 mm/s^2, speed =2.5 mm/s, deceleration= -10 mm/s^2, and shearing distance ~150 μm. To prevent the sheared LC directors from relaxing back, the peripherals of the cell were sealed by a UV adhesive. All our measurements were performed using the sealed LC cell. No noticeable performance change was detected before and after the sealing.

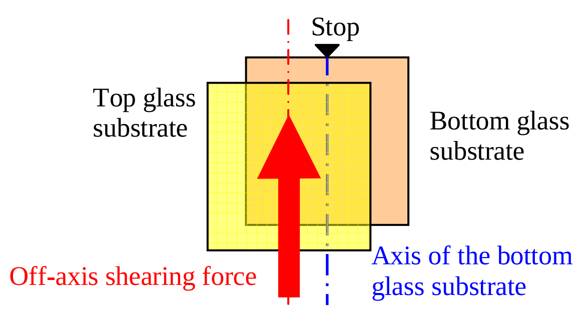


Fig. 1. The illustration of the off-axis shearing of the SPNLC cell

#8443 - $15.00 USD
Received 11 August 2005; revised 25 August 2005; accepted 25 August 2005

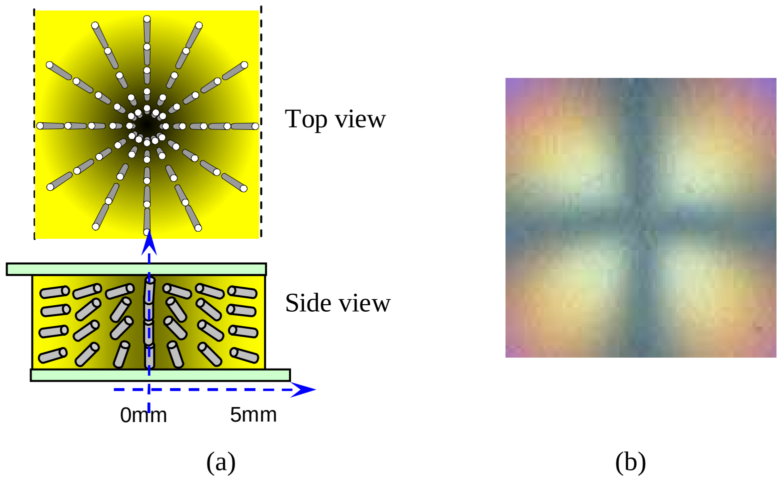


Fig. 2. (a) The LC director profile of a SPNLC layer, and (b) Detected image under crossed polarizers.

Figure 2(a) shows the top and side views of the axially-symmetric SPNLC structure. Polymer network forms a radial structure and constrains the LC directors within a circle [6]. The diameter of the structure is around 10 mm; whose size depends on the fabrication process. The top view of the structure displays a symmetric alignment of LC directors toward the center. The side view of the structure reveals a gradient distribution of the hybrid alignment from the center to the edge of the circle. Figure 2(b) shows the cross-hair pattern while sandwiching axially symmetric SPNLC structure between the crossed polarizers. It is an indirect proof of the axially symmetric structure because the black cross turns while rotating the polarizer and analyzer pairs [6].The axially-symmetric SPNLC exhibits two unique characteristics. First, its optic axis is radial in all directions. Second, its phase retardation has a gradient distribution from center to edges because of the gradient distribution of the liquid crystal alignment. This radial gradient phase plate can be used for measuring the phase retardation and optic axis of an optical phase compensation film.

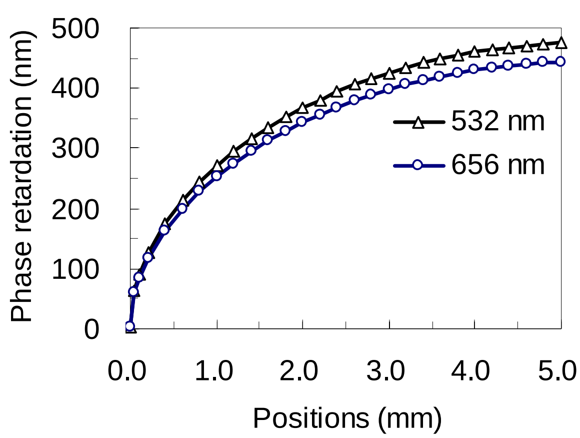


Fig. 3. Phase retardation (dΔn) profile of the axially-symmetric SPNLC layer. Cell gap d=9 μm.

3. Measurement methods and experimental results

To measure the phase retardation, $d\Delta n(\lambda)$, of the sample, we first characterize the phase retardation profile of our axially-symmetric SPNLC film. Figure 3 shows the gradient distribution of the phase retardation from the center to the outer ring of the SPNLC cell at λ=656 nm and 532 nm. The phase retardation increases from 0 at center to 470 nm at the edge of the pattern. The different phase retardation at each position originates from the different LC hybrid alignment. At a given position, the shorter wavelength exhibits a higher phase retardation because of the birefringence dispersion, i.e., $\Delta n(\lambda)$ is higher at a shorter λ [9].

Then we overlay a phase compensation film, whose retardation value and optic axis are yet to be determined, on top of our SPNLC film. Figure 4(a) depicts the experimental setup. To demonstrate this powerful technique, we used a quarter-wave plate with an arbitrary axis as an example. Figure 4(b) shows the concept of our measurement methods. We put our sample and SPNLC film under an optical microscope and took images from a CCD camera. All we need to do is to look for the compensated dark spots of the stacked SPNLC and λ/4 films. Since our SPNLC has continually varying retardation values, we can always find a point that would cancel the phase of our measured object. At the same time, we can also determine the optic axis of the tested object. For example, Fig. 4(b) shows that the slow axis of the SPNLC is compensated with the fast axis of the λ/4 film. After analyzing the CCD image, we obtain the direction of the fast axis of the object under study. Furthermore, we can obtain the phase retardation value of the measured object by comparing the location of the dark spots with respect to the SPNLC phase retardation chart plotted in Fig. 3.

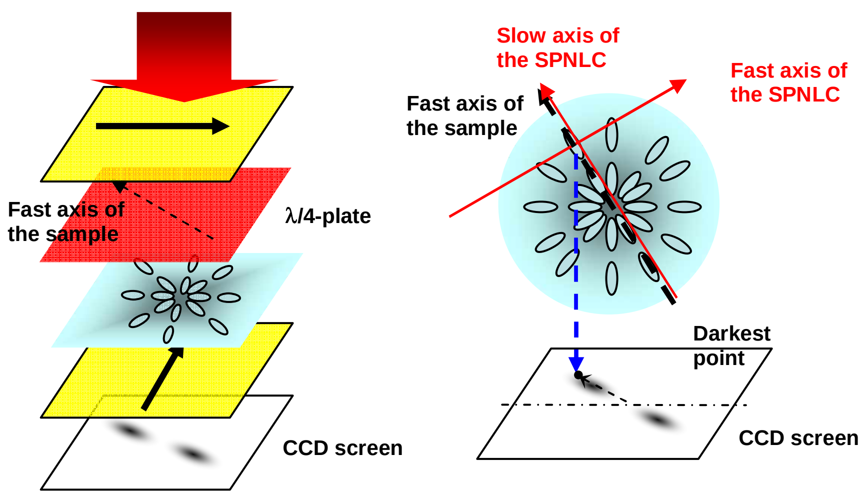
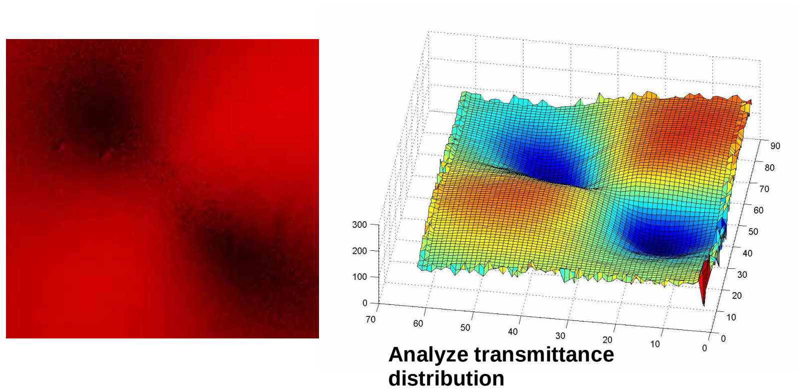


Fig. 4. (a)Measurement setup and (b) illustration of the measurement methods.

Figure 5(a) shows the transmitted image between crossed polarizers, which is recorded by a CCD camera. The employed light source is incoherent white light with a red (λ~656 nm) color filter. We could convert the measured phase compensation pattern of the CCD image to transmittance by a computer program. Figure 5(b) plots the transmittance distribution corresponding to the measured results shown in Fig. 5(a). From Fig. 5(b), there are two transmission minima, represented by the blue color. This is because the alignment of the liquid crystal directors is 180° symmetric. Therefore, there are two completely compensated points in the image.



(a) (b)

Fig. 5. (a) The transmitted image recorded by a CCD camera, and (b) the converted transmittance distribution.

To extract the phase retardation value and optic axis of the compensation film from Fig. 5, we need to find the fast axis and the distance of the transmission minima from the center, as illustrated in Fig. 6(a). From Fig. 6(a), the fast axis (white dashed lines) is at 135° with respect to the horizontal axis. That means the optic axis of the uniaxial compensation film is oriented at 135° with respect to the horizontal axis. Next, we need to determine the $d\Delta n$ value of the compensation film. To do so, we measure the distance of the transmittance minima from the center. From Fig. 6(a), we find that these two dark spots are quite symmetric; their distance to the center is ~399 μm. Next, we need to convert the measured distance to phase retardation from a corresponding phase retardation chart at a selected wavelength. The procedure is shown in Fig. 6(b). Figure 6(b) plots the phase retardation value of the axially-symmetric SPNLC cell we fabricated. At the indicated position, we find the corresponding phase retardation value is 162.1 nm. This is in a very good agreement with the expected quarter-wave plate, whose retardation value is 163.8 nm at λ= 656 nm.

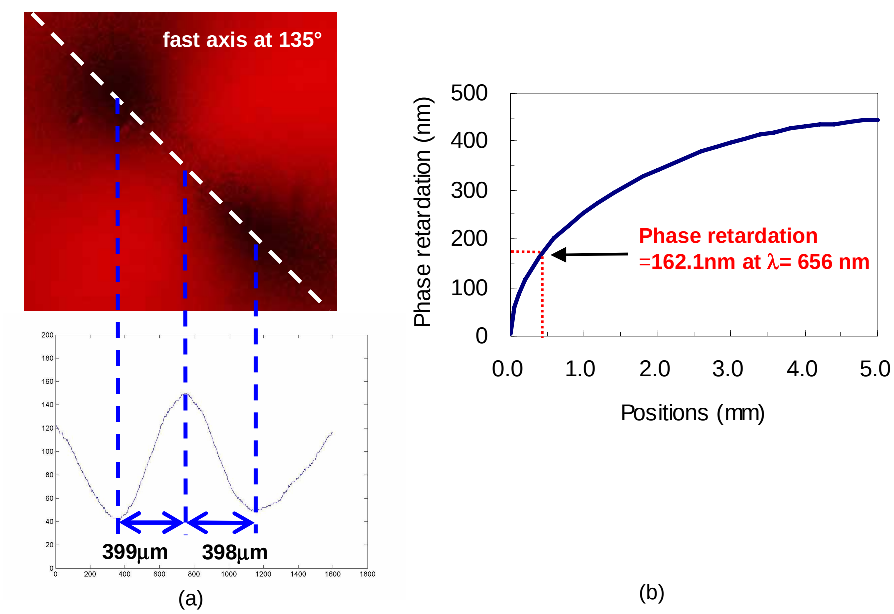


Fig. 6. (a) The relative distance of the two transmission minima recorded by a CCD camera. (b) The corresponding phase retardation of the quarter-wave film.

#8443 - $15.00 USD Received 11 August 2005; revised 25 August 2005; accepted 25 August 2005

4. Discussion

When we overlay a uniaxial film on top of the axially-symmetric SPNLC cell, the phase could be subtractive or additive depending on the optic axis of the uniaxial film. Both phase cancellation and accumulation could lead to the dark spots observed in Fig. 6(a). Phase cancellation occurs when the slow axis of the referenced SPNLC ($\Gamma_{R,slow}$) is parallel to the fast axis of the sampled uniaxial film ($\Gamma_{S,\,fast}$). At the transmission minima, the net phase retardation is zero:

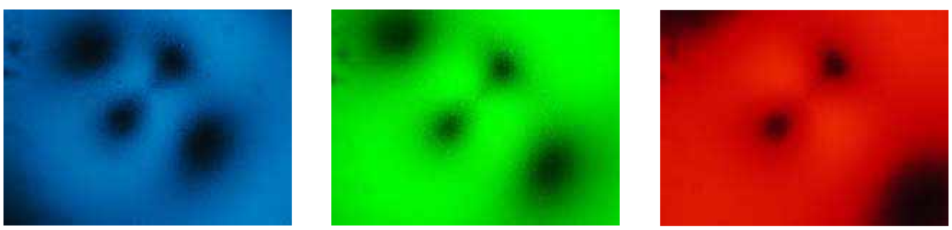
$$\Gamma_{R,slow} - \Gamma_{S,\,fast} = 0 \qquad (1)$$

Therefore, the dark spots represent that the phase retardation of the sample is equal to that of the SPNLC at the wavelength of measurement. The procedures for obtaining the phase retardation of the uniaxial film are illustrated in Fig. 6.

The slow axis of a uniaxial film is 90^{o} with respect to its fast axis. Therefore, in the orthogonal direction the phase of the slow axis of the sampled uniaxial compensation film $\Gamma_{S,slow}$ is additive to the slow axis of the referenced SPNLC cell ($\Gamma_{R,slow}$). When the total phase retardation equals to $m\lambda$ (where m is an integer 1, 2, 3, etc) dark spots appear:

$$\Gamma_{R,slow} + \Gamma_{S,slow} = m\lambda \qquad (2)$$

From Eq. (2), the positions of the dark spots are wavelength dependent. The wavelength information is needed for calculating the phase retardation of the measured sample, $\Gamma_{S,slow}$.



(a) (b) (c)

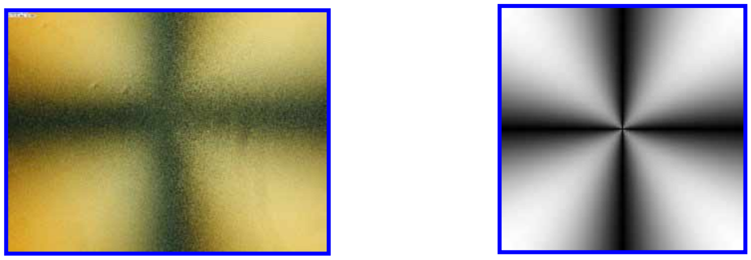
Fig. 7. CCD images taken under three different color filters (a) 486 nm, (b) 532 nm, and (c) 632 nm.

Figure 7 shows the CCD images taken under three different color filters: λ=486 nm, 532 nm and 632 nm. The fast axes in Fig. 7 are along 45° with respect to the horizontal axis. The dark spots locate in the 45° axes present the phase cancellation at the compensated points. They change slightly as the wavelength changes due to the dispersion of the SPNLC film. On the other hand, the dark spots located at the135° axes stand for the phase accumulation at the compensated points. The distance of the dark spots increases noticeably as the wavelength increases from blue, to green, and then to red.

The phase cancellation method is a better and more reliable approach to measure the phase retardation. This is because the result is more straightforward and does not need additional calculation and wavelength information.

Figure 8(a) is a movie showing an example of dynamic image with a rotation of a quarter wave plate under the white light illumination. After analyzing the image data from the movie, we can simultaneously obtain the rotation angles of the optic axis and the phase retardation values. We then constructed a model based on the results obtained in Fig. 8(a). Figure 8(b) is a movie showing the simulated results based on Fig. 8(a). The simulation shows the same trend as the quarter-wave plate rotates from 0° to 135°. The simulation results agree quite well with our experiment.

#8443 - $15.00 USD Received 11 August 2005; revised 25 August 2005; accepted 25 August 2005



(a) (b)

Fig. 8. (a) A movie shows the real dynamic image changes when the quarter-wave plate rotates at different angles (377 KB) (b) The simulation result shows the same trend when we rotate the slow axis of the quarter-wave plate from 0° to 135° (368 KB).

5. Conclusion

We have demonstrated a new method to measure the phase retardation and the optic axis simultaneously using an axially-symmetric SPNLC layer. To prove feasibility, a quarter-wave film is used as an example for demonstrating the measurement procedures. The measured results agree with reality well. This method is particularly attractive for those optical systems whose optic axis and phase retardation are dynamically changing.

Acknowledgments

The authors are indebted to Toppoly Optoelectronics (Taiwan) for the financial support.