

# Liquid Crystal-based Linear Polarization Rotation and Restoration

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## ABSTRACT

*Precise polarization control based on twisted-nematic liquid crystals (TNLCs) has been proposed. We introduce a linear polarization restorer based on dynamic linear polarization rotator using a 90°-TNLC cell. By varying the applied voltages for different incident polarization directions, the precise restoration of any incident linearly polarized lights to a specified orientation is achieved.*

## 1 Introduction

The manipulation of light polarization plays a fundamental role in modern optics, including imaging systems, optical communication, liquid crystal (LC) display, and laser technologies. In practical environments, the polarization state of transmitted light is influenced by various external factors, such as birefringence, magnetic fields, and total internal reflection [1-2]. Conventional waveplates are commonly used to modulate polarization states by their optical phase retardation, which are limited by their fixed design and dispersion effects [3-4]. Twisted-nematic LCs (TNLCs) are often used to modify the polarization state of output light which enables the rotation of output light [5]. According to Mauguin's condition, if the cell gap of the TNLC cell is sufficiently thick, the output light of the polarization state maintains good linear polarization for the cases of 0° and 90° of  $\beta$ -angle, defined as the angle made by the incident light linear polarization and the LC director of the first LC layer. However, TNLCs satisfying Mauguin's condition cannot maintain linear polarization rotation with the variation of the applied voltage.

Recently, we proposed a new class of continuous adjustable linear polarization rotation using a 90°-TNLC cell, where dynamic linear polarization rotation with a high degree of linear polarization (DoLP) is achieved [6-7]. To maintain high DoLP during dynamic variation, it is crucial to select the LC cell thickness  $d$ , optical anisotropy  $\Delta n$ , and incident wavelength  $\lambda$  to satisfy the specific condition  $d\Delta n/\lambda$  to be in the range between 1.27 and 1.7. Here, we introduce linear polarization restorer based on the proposed dynamic linear polarization rotator, which is controlled by applying AC voltage [8]. Highly efficient restoration with a low threshold voltage, low operating voltage, a narrow operational voltage range is realized. Moreover, the device exhibits around 80% light transmittance, demonstrating the advantage of low optical

loss. These advancements fully show the application potential in spatial light modulator, fiber optics, and materials with optical activity.

## 2. Experimental procedure

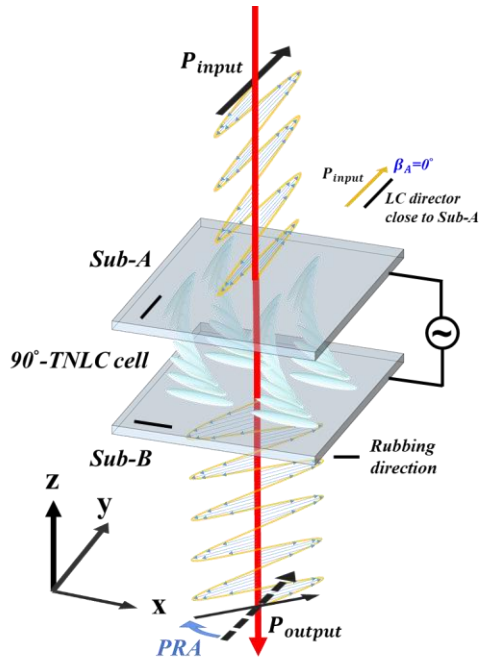
In this study, nematic LC (E7) with positive dielectric anisotropy was adopted. In the fabrication of cells, two indium tin oxide-coated glass substrates were initially coated with polyimide (PI) films and then treated with rubbing treatment in orthogonal directions. Subsequently, the substrates were assembled to form an empty cell with a uniform gap of about 5  $\mu\text{m}$  through precision spacers. Afterward, the LC mixture was uniformly injected into the empty cell. In the experiment, the polarization rotation angle (PRA), polarization restoration rotation angle (PRRA) and DoLP were measured using a He-Ne laser ( $\lambda=632.8$  nm). To prove that the output light is linearly polarized, the DoLP value, defined as  $=(I_{max}-I_{min})/(I_{max}+I_{min})$ , where  $I_{max}$  and  $I_{min}$  are the maximum and minimum polarized intensities, can be evaluated. The simulation was utilized by 1D-DIMOS software to analyze the experimental results.

Moreover, we implemented two sequential setups for the measurement of polarization rotation and restoration, respectively. The rotation setup precisely characterized the relationship between the applied electric stimuli and the resulting PRAs, and the restoration setup verified the device's ability to restore incoming linear polarized light at different polarization direction to a required output direction.

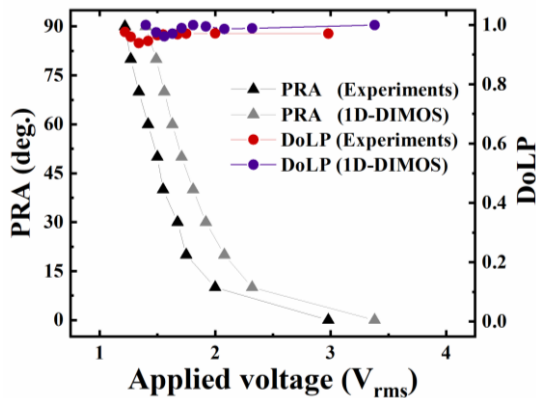
## 3. Results and discussion

Fig. 1 shows the schematic of the optical properties of dynamic linear polarization rotation based on a thin 90°-TNLC cell that is controlled by the applied electric stimuli. This device provides a continuous linear polarization rotation, consistently reaching a high level of DoLP value ( $>0.9$ ). Notably, the  $\beta_A$ -angle is defined as the angle of the incident linearly polarized light's polarization direction and the LC director close to substrate A (Sub-A). The  $\beta_A$ -angle is set at 0°, and it propagates along the -z direction. Fig. 2 shows the PRA and the DoLP of the output beams versus the applied voltage, demonstrating continuously electro-tunable properties of linear polarization rotation of output beams when linearly polarized light propagates through the thin 90°-TNLC cell. The PRA of linearly polarized light varies continuously from 90° to 0° as the

applied voltage increases, and the DoLP maintains a value higher than 0.9. Moreover, we examined the polarization rotation property using simulation, where the simulated data shows that DoLP values are greater than 0.95 in all modulation cases, indicating a great linear polarization performance. Within the PRA range of 80°–60°, a subtle reduction in DoLP was observed. Notably, both experimental and simulated results exhibited significant quality of output linear polarization. Furthermore, the low threshold and operating voltages and the narrow operational voltage range indicate considerable advantages for practical application.



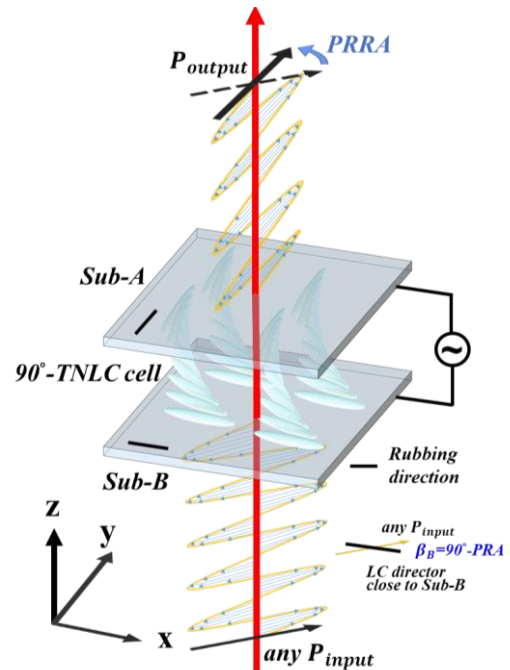
**Fig. 1.** Schematics of linear polarization rotation based on a 90°-TNLC cell.



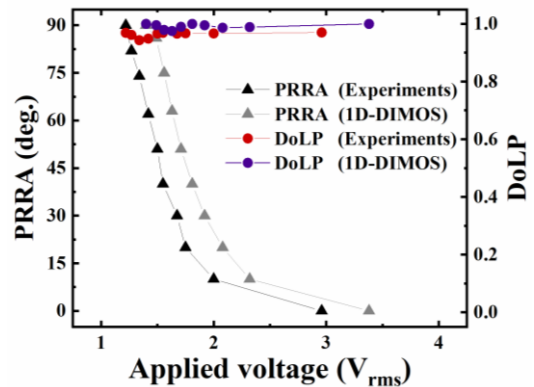
**Fig. 2.** PRA and DoLP as functions of the applied voltage for light transmitting through a 90°-TNLC cell, with a  $\beta_A$ -angle set at 0°.

Based on the principle of light reversibility, when the linearly polarized light is incident from substrate B (Sub-B) at any linear polarization direction and propagates along

the +z direction, the polarization direction of output light is theoretical to be adjusted to a required direction by applying the appropriate electric stimuli, as shown in Fig. 3. The desired direction (along the x-axis) is identical to the polarization direction of incident linearly polarized light shown in Fig. 1. Notably, the  $\beta_B$ -angle is defined as the angle of the incident linearly polarized light's polarization direction and the LC director close to substrate B (Sub-B), and the  $\beta_B$ -angle shown in Fig. 3 is considered to be 90° minus the PRA shown in Fig. 1.



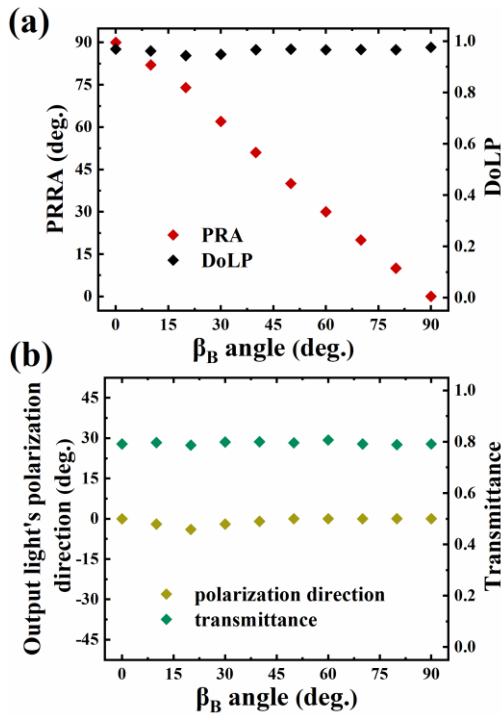
**Fig. 3.** Schematics of linear polarization restoration based on a 90°-TNLC cell.



**Fig. 4.** PRRA and DoLP as functions of the applied voltage through a 90°-TNLC cell for linear polarization restoration with variable  $\beta_B$ -angles.

Fig. 4 fully demonstrates the polarization restoration characteristics utilizing a 90°-TNLC cell. Different  $\beta_B$ -angle were set according to the corresponding PRAs measured in Fig. 2. As shown in Fig. 4, the PRRA of output light varies from 90° to 0° with a high DoLP value (>0.94) as the applied electric stimuli increases. These

results exhibit the remarkable optical performance of the designed system, demonstrating a precise and electro-tunable modulation of linearly polarized light from a deviant polarization direction to a desired orientation.



**Fig. 5.** Experimental results for the 90°-TNLC cell: (a) PRRA and DoLP as functions of the  $\beta_B$ -angle. (b) Polarization direction and transmittance as functions of the  $\beta_B$ -angle. The linearly polarized light is incident on Sub-B.

To further clarify the polarization restoration performance, we investigated the optical behavior of the device across various  $\beta_B$ -angles, as shown in Figs. 5(a) and 5(b). Figure 5(a) illustrates how the restoration of linear polarization varies with different  $\beta_B$ -angles when linearly polarized light is incident from Sub-B along the +z direction. The PRRA was found to decrease linearly as the  $\beta_B$ -angle increased, which consistently maintained DoLP exceeding 0.94. This finding demonstrating an exceptional quality for output linearly polarized light, where the strong relationship between PRRA and the  $\beta_B$ -angles highlights the robust behavior in linear polarization restoration of the device. Figure 5(b) further strengthens these results, indicating that the polarization direction of the output light remains near 0° that is close to the polarization direction of the incident linearly polarized light. Notably, the transmittance of the 90°-TNLC cell is around 80 %, exhibiting a low light loss which is benefit for practical application.

#### 4. Conclusions

Here, we introduced a linear polarization restorer using a proposed dynamic linear polarization rotator based on

90°-TNLCs. The device enables precise restoration of incident linearly polarized light with any polarization directions to a desired direction through applied AC electric stimuli. Both experimental and simulation results demonstrate accurate polarization restoration with a stably high DoLP (>0.94). The device exhibits a low threshold voltage, low operating voltage, and simple optical setup. Moreover, ~80 % of transmittance is observed, thereby minimizing light loss. These advantages make this device promising for applications in the modulation of linearly polarized light, including fiber optics, spatial light modulators, and polarization-selective photonics.

#### 5. Acknowledgments

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