Continuously Electronically Controlled Linear Polarization Rotator

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ABSTRACT

Dynamic polarization control based on twisted-nematic liquid crystal (TNLC) has widely developed in display. Here, we propose a thin 90° TNLC cells that enable the unique feature of electrotunable linear polarization rotation with high degree of linear polarization. Our work extends to designing tandem 180° TNLC devices, demonstrating linear polarization rotation regardless of incident light's polarization.

1 Introduction

The manipulation of light polarization is crucial for expanding the scope of optical applications, including optical communication, imaging, and light-matter interaction. Traditionally, waveplates are commonly used to modulate light polarization. However, their limitations lead to challenges in designing compact, efficient, and integrative optical devices. To tackle these concerns, liquid crystals (LCs) are combined with polarizers to control polarization in electrically operated optical devices such as LC displays. However, polarization rotator based on LC waveplates highly depends on the operating wavelength, as it frequently leads to phase retardation in LC medium. The half-waveplate retarder is the most commonly used type of polarization rotator. The operation of waveplates disperses polarization rotation, which is entirely chromatic when performed at various wavelengths. To resolve this concern, researchers have proposed achromatic polarization rotators by combining multiple waveplates, but it has limitations [1].

Twisted nematic liquid crystals are widely used to modify the polarization state of output light due to their spiral configuration, which enables the rotation of output light through the superposition of the phase of each LC layer. According to Mauguin's condition, if the cell gap of the TN-LC cell is sufficiently thick, the output light of the polarization state maintains linear polarization in 0° or 90° β angle, where β angle defines as the angle between the incident light linear polarization and the LC director of the first LC layer. Furthermore, the polarization rotation fitting the Mauguin condition is wavelength-independent, making it highly advantageous for applications of LC displays. However, TN-LC does not continuously maintain linearly polarized rotation when an electric field is applied onto the LC cell, significantly limiting its application.

Here, we propose a new class of continuously electronically controlled linear polarization rotator using thin 90° TN-LC cell. The polarization rotation angles (PRAs) of output linearly polarized light electrically tunes from 0° to 90°, and the values of degree of linear polarization (DoLP) remains higher than 0.95. Low driving voltage and small cell gap are the advantage of this linear polarization rotator. Furthermore, we extend our research to examine utilizing tandem 180° TNLC cells, performing the characteristic of β-independence and omni-directional PRAs. This advancement fully show the application potential in spatial light modulator and flat-top beam shaper.

2. Experimental procedure

In this study, the nematic LC (E7) with positive dielectric anisotropy was adopted. A polyimide (PI) film was coated onto indium–tin–oxide (ITO) layer on the inner glass substrates. The LC mixture was uniformly injected into the empty cell at thickness of 5 μm. To establish tandem 180° TNLC, two 90° TNLC cells with 5 μm cell gap were then employed. In the experiment, the PRA and DoLP of 90° TNLC cell and tandem 180° TNLC cells were measured using a He-Ne laser at 632.8 nm. To prove that the output light is linearly polarized, the DoLP can be evaluated as follows: DoLP=$(I_{max}-I_{min})/(I_{max}+I_{min})$, where I_{max} and I_{min} are the maximum and minimum polarized intensities. The simulation was utilized by 1D-DIMOS software to analyze the experimental results.

3. Results and discussion

Fig 1(a) shows the PRA and the DoLP of the output beams versus the applied voltage, demonstrating electrotunable property of output beam's linear polarization rotation when linearly polarized light propagates through the thin 90° TNLC cell. However, 90° TNLC with 5 μm thickness does not meet Mauguin's condition. Therefore, the output light is not entirely linear polarization without any applied voltage. When the applied voltage exceeds 1.3 V, the polarization condition shifts to nearly linear polarization. The direction of linearly polarized light rotates continuously from 94° to 0° as the applied voltage increases, and the DoLP maintains a value higher than 0.9. Moreover, we examine the polarization rotation property using simulation, as shown in fig 1(b). The simulated data shows that DoLP values are greater than 0.95 in all modulation cases, indicating a significant linear polarization level. Fig 1(c) shows the experimental images of the linear polarization rotation observed through an azimuthally symmetric dye-doped LC (AS-DdLC) cell, which is adopted as a polarization detector [2]. Each photographs exhibits a two-lobed pattern, depicting the relationship between the polarized transmittance of AS-DdLC and polarization state of output light transmitting through 90° TNLC cell (according to Malus' Law). The PRA is equal to the angle at which the polarized transmittance reaches its maximum value. The pattern rotates counterclockwise from 90° to 0° as applied electric field increases, shown as fig 1(c).

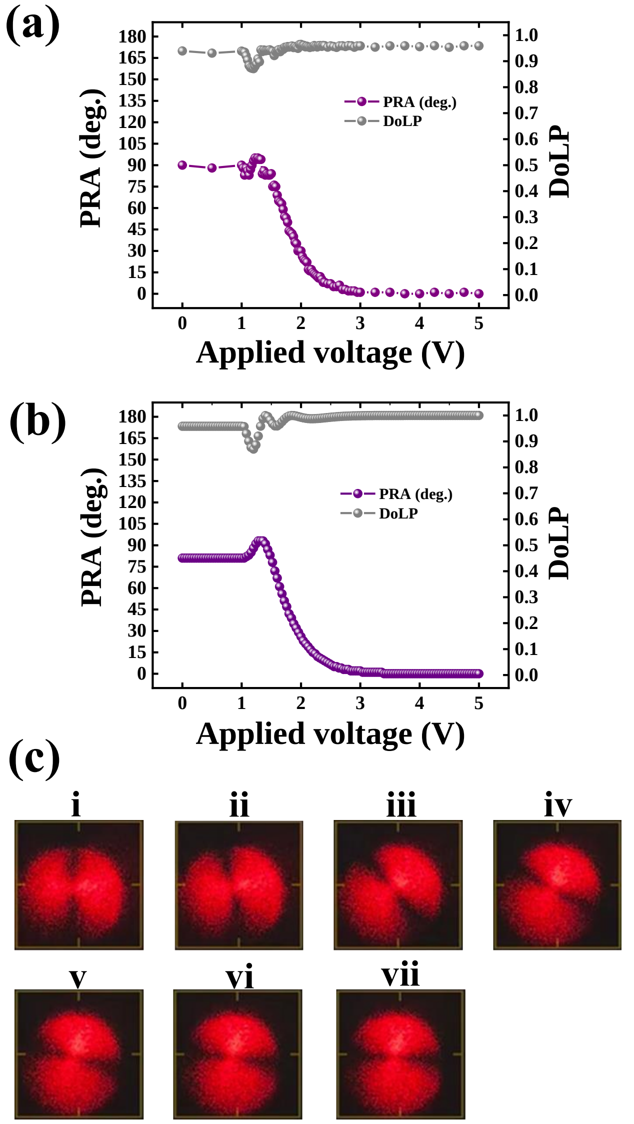


Fig.1. PRA and DoLP as functions of applied voltage determined by (a) experimental measurement using a 90° TNLC cell and (b) modeling using 1D-DIMOS software. (c) Photographs showing output light propagating through the 90° TNLC cell for different applied voltages, as determined by an azimuthally symmetric dye-doped liquid crystal cell. The voltages applied onto the 90° TNLC cell are (i) 1.3 V, (ii) 1.5 V, (iii) 1.7 V, (iv) 1.9 V, (v) 2.1 V, (vi) 2.3 V, and (vii) 2.5 V, respectively.

Electric stimuli change the polarization state of output light because of the alignment changing of LCs, leading to a change in phase retardation. A specific range of dΔn/λ can produce extreme linear polarization rotation. To discuss the contribution of dΔn/λ, we employed the LC simulation software, 1D-DIMOS, to display the LC directors' configuration under different applied voltages. We further decompose the LC orientation into the twist and tilt angles components, shown in Fig 2(a) and (b). When light passes through an LC cell, the twist angles primarily determine the direction where the polarization shifts and tilt angles dominate the contribution of phase retardation, which determines the polarization state. The alignment of LCs at the boundary is not influenced when the voltage is applied because of the strong surface anchoring, which is sufficient to balance the force contributed by the applied electric field. By contrast, as surface force less impacts LCs at the near center location, the alignment of LCs is more easily orientated than at the edge position.

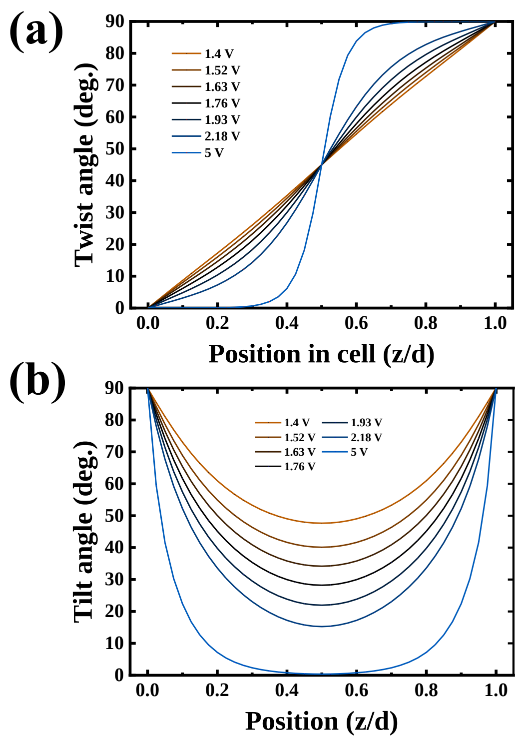


Fig.2. (a) Tilt and (b) twist angles as position functions in a 90° TNLC cell with various electrical stimuli.

Based on simulated LC's alignment data (fig. 2), we provide in-depth discussions into the relationship between dΔn/λ and DoLP by Jones Calculus, as shown in fig 3(a). In fig 3(a), the starting voltage value is set to be 0 V. The results of DoLP is higher than 0.95 when the range of dΔn/λ is within the geographical region from 1.27 to 1.7. Consequently, when dΔn/λ falls within the range of 1.27 to 1.7, the electrotunable property of linear polarization rotator is achieved. The simulated result of DoLP reaches the maximum average value of 0.98 when dΔn/λ equals 1.49, shown in fig 3(b). The value of DoLP is reduced to less than 0.95 during linear polarization rotation if the value of dΔn/λ is beyond the aforementioned range. We also investigated linear polarization rotation when dΔn/λ is 1.6 with different wavelengths, optical anisotropy, and cell gaps (fig 3(c)). The results indicate that linear polarization rotation occurs across any wavelengths when dΔn/λ ranges between 1.27 and 1.7, regardless of the specific values of each parameter. This finding is expected to be beneficial for practical applications.

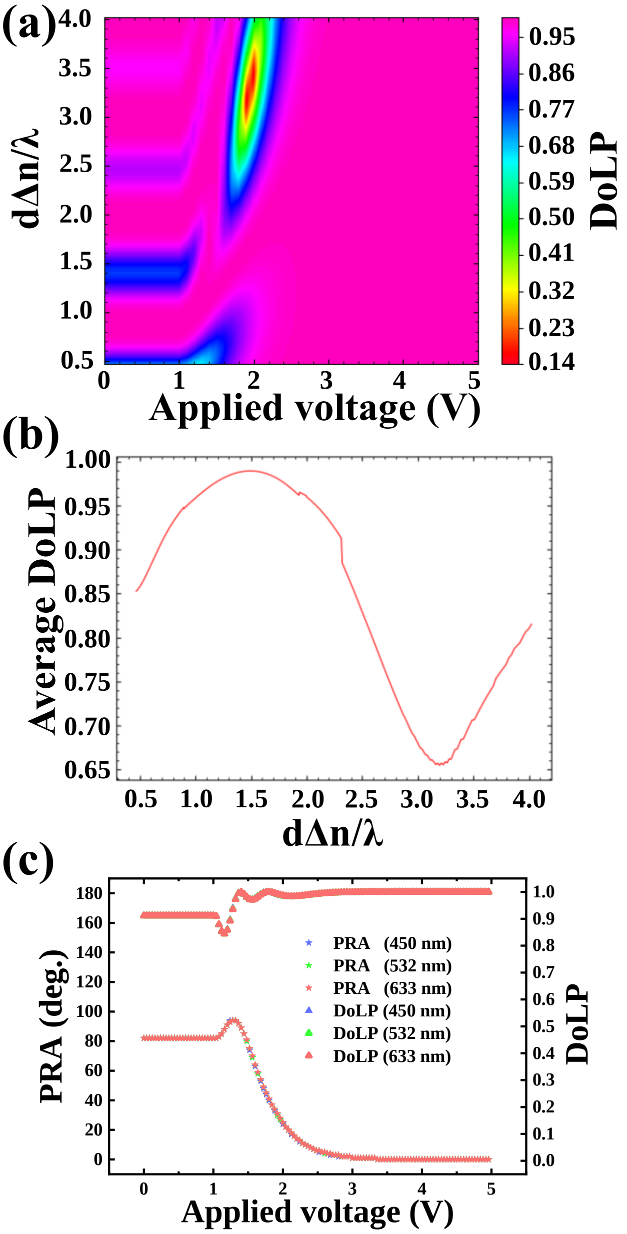
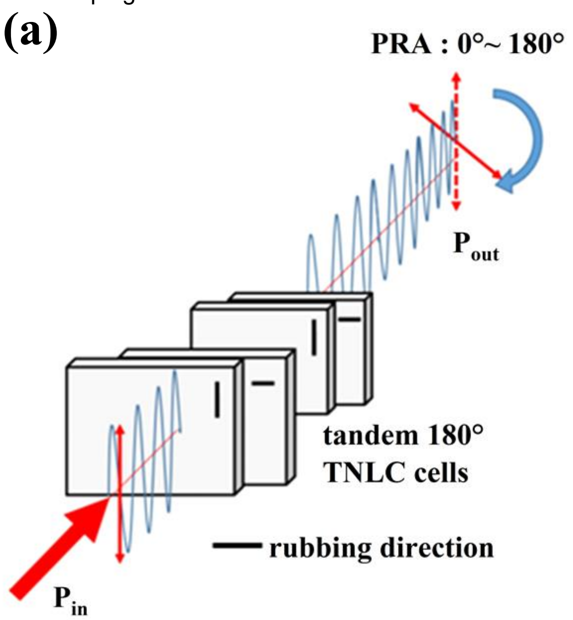


Fig.3. (a) DoLP relation diagrams using dΔn/λ with different applied voltages. (b) Average DoLP during the PVA changing from 90° to 0°(c) PRA and DoLP as functions of applied voltage using 1D-DIMOS software and a thin 90° TNLC cell. We used three different wavelengths: 450, 532, and 633 nm, and the dΔn/λ parameter was set at 1.6.

To optimize the linear polarization rotator for the application, we extended our research to examine the tandem 180° TNLC [3]. It performs β-independence properties at different polarization direction of incident light, as shown in fig 4. Fig 4(a) shows the schematic of the linear polarization rotator based on tandem 180° TNLC cell, depicting the continuous shift of PRAs from 180° to 0° via the variation of applied voltages. The results of omni-directional linear polarization rotator are shown in experiments (fig 3(b)) and simulations (fig 3(c)). The various β angles indicate that the direction of linearly polarized input light does not affect the output light's polarization state, demonstrating the β-independent property of the linear polarization rotator. The values of PRAs and DoLP differ without an applied field because the cell gap fails to meet Gooch–Tarry's conditions. Except for the region between 1.56 and 1.7 V, the data show that the PRAs of different β angles are identical. Due to experimental error, PRAs slightly vary when applying relatively high voltage. However, the DoLP of all PRAs remains above 0.9, indicating the property of linear polarization rotation. As we extend this polarization rotation property into 2D-space application, the omni-directional characteristic of the output light and the β-independence of the incident light's polarization direction fully show the potential in spatial light modulator and beam shaping.



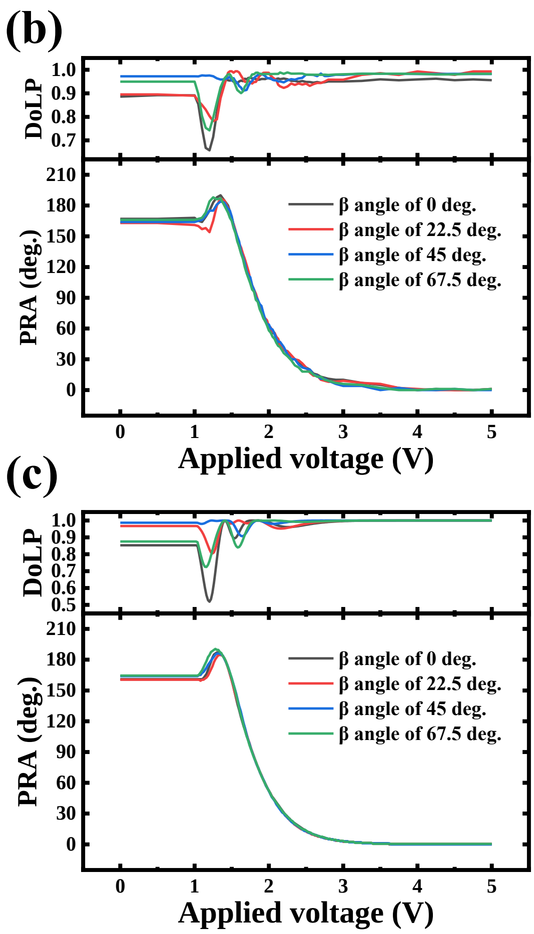


Fig.4. (a) Schematic of the tandem 180° TNLC cell. PRA and DoLP are functions of applied voltage by (b) experimental measurement and (c) simulation of 1D-DIMOS software employing tandem 180° TNLC cells with four different β angles.

4. Conclusions

We realized a new class of continuously electronically controlled linear polarization rotator using a thin 90° TNLC cell. This linear polarization rotator facilitates continuous rotation of the output light's linear polarization from 90° to 0° within a dΔn/λ range from 1.27 to 1.7, maintaining the DoLP higher than 0.95 during the variation of the applied voltages. We extends the application of polarization in tandem 180° TNLC, offering linear polarization rotation insensitive to the polarization direction of incident light and achieving any output polarization direction (0°–360°). The dynamic tunability of linear polarization rotation demonstrates the potential applications of 2D-space in beam shaping and polarization-only SLM-based linearly polarized vector field.

5. Acknowledgments

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