

A polarization-independent liquid crystal phase modulation using polymer-network liquid crystal with orthogonal alignment layers

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ABSTRACT

A polarization-independent liquid crystal (LC) phase modulation using polymer-network liquid crystals with orthogonal alignments layers (T-PNLC) is demonstrated. T-PNLC consists of three layers. LC directors in the two layers near glass substrates are orthogonal to each other. In the middle layer, LC directors are perpendicular to the glass substrate. The advantages of such T-PNLC include polarizer-free, larger phase shift ($\sim 0.4\pi$ rad) than the residual phase type ($< 0.05\pi$ rad), and low operating voltage ($< 30V_{\text{rms}}$). It does not require bias voltage for avoiding scattering because the refractive index of liquid crystals matches that of polymers. The phase shift of T-PNLC is affected by the cell gap and the curing voltages. The potential applications are laser beam steering, spatial light modulators and electrically tunable micro-lens arrays.

Keywords: Liquid-crystal devices; Phase modulators; Polarization independent phase modulators.

1. INTRODUCTION

Electrically tunable liquid crystal (LC) phase-only modulations are important in many applications, such as laser beam steering¹, tunable focus lenses²⁻⁶, electrically tunable gratings and prisms⁷, and spatial light modulators⁸. To obtain high optical efficiency, four main types of polarization independent LC phase modulator have been demonstrated.⁹⁻¹⁷ They are the residual phase type⁹⁻¹², the double-layered type^{9,13-14}, the mixed type which is the combination of the residual phase type and the double-layered type¹⁵, and the type which is based on the optical isotropy induced by Kerr effect of BP-LC¹⁶. In those four types of LC phase modulations, the double-layered type has the largest phase shift. However, it is difficult to fabricate a LC cell with two separated LC layers and the response time of such structure is slow ($\sim 200\text{ms}$). For improving the response time, a 90° twisted dual-frequency liquid crystals (T-DFLC) with an in-cell

double-layered structure was proposed¹⁷. However, it requires the bias voltage ($>5.5V_{rms}$) to achieve polarization independent and the unavoidable heating effect of dual-frequency liquid crystals hinders the practical applications. It is very important to realize an electrically tunable liquid crystal phase-only modulation with polarizer free, low driving voltages, a large phase shift, easy fabrication process, and no bias voltages.

In this paper, a polarization-independent liquid crystal phase modulation using polymer-network liquid crystal with orthogonal alignment layers (T-PNLC) is demonstrated. We applied a vertical electric field during the polymerization process. After polymerization process, the orientations of LC directors are confined to the rubbing directions in the regions near the alignment layers. In the region far from the alignment layers or the bulk region, LC directors are perpendicular to the glass substrate and contribute no phase shift. As a result, T-PNLC is polarization independent. We do not need to apply any bias voltages. Therefore, the operating voltage is low ($<30V_{rms}$) and phase shift is larger ($\sim 0.4\pi$ rad). The phase shift of T-PNLC is affected by the cell gap and the curing voltages. The potential applications are laser beam steering, spatial light modulators and electrically tunable micro-lens arrays.

2. OPERATING MECHANISM

The structure and operating principles of the polarization independent LC phase modulation using T-PNLC is illustrated in Figure 1(a) and 1(b). The structure consists of two ITO glass substrates, two alignment layers, LC directors located in the domains surrounding by polymer networks which are perpendicular to the glass substrates. The polymer networks are made of polymer grains. The rubbing directions of two alignment layers are orthogonal to each other (i.e. x- and y-directions). As a result, without applied voltage, LC directors in the region near the alignment layers are also orthogonal to each other. The effective thickness of two LC layers near two alignment layers is d_1 . The effective thickness of the bulk region of T-PNLC is d_2 . Therefore, $(2d_1+d_2)$ equals to the cell gap (d). The LC directors in the bulk region are parallel to z-direction, as shown in Figure 1(a).

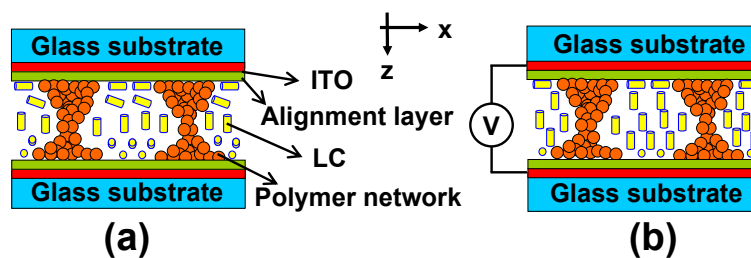


Figure 1 : Structure and operating principles of T-PNLC. (a) Without applied voltage, LC directors near two alignment layers are orthogonal to each other, and LC directors in the bulk region are parallel to z-direction. (b) As applied voltage increases, LC directors near two alignment layers are reoriented by the electric field and then perpendicular to the alignment layers.¹⁸

We can consider a randomly polarized light incident to T-PNLC at a normal angle. The unpolarized light can be decomposed into two linear eigen-modes, x and y linearly polarized lights. The electric field of the incident light can be written as¹⁵

$$\vec{E}_{inout}(\vec{r}, t) \sim \sum_j [a_j(\vec{r}, t) \times (A_{0x}(\vec{r}, t) \times \hat{x} + A_{0y}(\vec{r}, t) \times \hat{y})]_j, \quad (1)$$

where $A_{0x}(\vec{r}, t)$ and $A_{0y}(\vec{r}, t)$ are two complex numbers that are functions of the position (\vec{r}) and the time (t). The coefficient $a_j(\vec{r}, t)$ is a complex weighting factor for the j th component, and $(A_{0x}(\vec{r}, t) \times \hat{x} + A_{0y}(\vec{r}, t) \times \hat{y})$ represents the polarization state of the j th component. The total accumulated phase (δ) of the x and y components of the polarization of the incident light is attributed to two parts. One is the two regions near the alignments layers. The phase modulation is similar to the double-layered type of phase modulations. As a result, the phase of the two eigen-polarizations is $(k \times n_1(\theta) \times d_1 + k \times n_o(\theta) \times d_1)$, where k is a wave number, $n_1(\theta)$ is the effective refractive index depending on the tilt angle θ , and n_o is the ordinary refractive index of LC materials. The other part is the bulk region of T-PNLC. The LC director in the bulk region is always parallel to z-direction. Thus, the accumulated phase is a constant: $k \times n_o \times d_2$. The total accumulated phase can be expressed

$$\delta = k \times n_1(\theta) \times d_1 + k \times n_o \times d_2 + k \times n_o \times d_1. \quad (2)$$

After incident light passes through a T-PNLC cell, the electric field of the output light is

$$\begin{aligned} & \vec{E}_{output}(\vec{r}, t) \\ &= \sum_j \{ a_j(\vec{r}, t) \times [e^{i \times (k \times n_1(\theta) \times d_1 + k \times n_o \times d_2 + k \times n_o \times d_1)} \times A_{0x}(\vec{r}, t) \times \hat{x} + e^{i \times (k \times n_o \times d_1 + k \times n_o \times d_2 + k \times n_1(\theta) \times d_1)} \times A_{0y}(\vec{r}, t) \times \hat{y}]_j \}. \end{aligned} \quad (3)$$

We can arrange Eq. (3), and it can be represented as

$$\vec{E}_{output}(\vec{r}, t) = e^{i \times (k \times n_1(\theta) \times d_1 + k \times n_o \times d_2 + k \times n_o \times d_1)} \times \vec{E}_{input}(\vec{r}, t). \quad (4)$$

In Eq. (4), the polarization state is the same between output and input light. The only difference is the phase shift. Therefore, T-PNLC is polarization independent. At $V=0$, we assume LC directors near the alignment layers have a pretilt angle θ_p , as shown in Figure 1(a). As the applied voltage increase, the LC directors are reoriented along the z-direction. When we apply a high voltage, the LC directors are perpendicular to the glass substrates except the LC directors very closed to

two alignment layers, as shown in Figure 1(b). The difference of the phase shift ($\Delta\delta$) between high voltage and 0 is

$$\Delta\delta = k \times [(n_1(\theta_p) - n_o) \times d_1]. \quad (5)$$

Therefore, by operating different applied voltage to T-PNLC, we can realize a polarization independent phase modulation.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 T-PNLC under different curing voltages

The detailed fabrication process of T-PNLC was proposed¹⁸. For testing the T-PNLC with different curing voltages, we prepared the samples with an identical cell gap of $5.6\mu\text{m}$ and applied different curing voltages. To understand the orientation of LC directors of the sample after photo-polymerization, we observed the samples under two crossed polarizers. Figure 2(a) and Figure 2(b) show the images of the samples with a curing voltage (V_c) of 0 V_{rms} and 2V_{rms} , respectively. In Figure 2(a), the sample is bright when the rubbing directions of the sample are parallel to the transmissive axis of the polarizer and analyzer. The T-PNLC with a curing voltage of 0V_{rms} acts as a TN cell. It should be operated at high voltages to achieve polarization independent phase modulation. When the curing voltage is larger than 2V_{rms} , the sample is dark under crossed polarizers. This means the LC directors in the sample are almost perpendicular to the alignment layers.

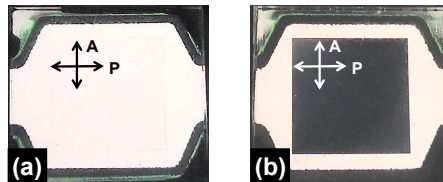


Figure 2 : The images of T-PNLC observed under two crossed polarizers. P and A are the transmissive axes of the polarizer and the analyzer. (a) The curing voltage is 0. (b) The curing voltage is 2V_{rms} .

To measure the electro-optical properties of the T-PNLC samples, we measured the transmittance of the T-PNLC samples under applied voltages. Figure 3 shows the transmittance as a function of an applied voltage. We also measured the transmittance of the pure LC sample for calibrating and comparing the transmittance. In Figure 3, when $V_c=0$, the transmittance varies with an increase of an applied voltage because of the refractive index mismatch between the LC and polymer networks. When curing voltage is larger than 2V_{rms} , the transmittance of T-PNLC remains similar and the scattering of T-PNLC is less than 10%.

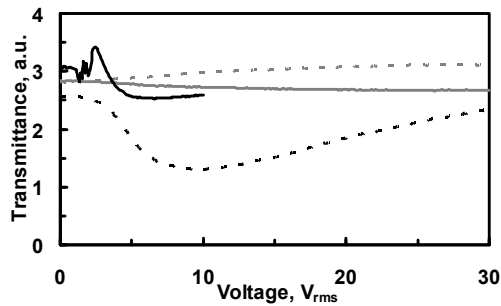


Figure 3 : Transmittance as a function of voltage for pure LC cell (black solid line), T-PNLC at $V_c=0V_{rms}$ (black dotted line), T-PNLC at $V_c=2V_{rms}$ (gray dotted line), and T-PNLC at $V_c=8V_{rms}$ (gray line).

To measure the phase shifts of T-PNLC samples, we adopted a Mach-Zehnder interferometer using an unpolarized He-Ne laser ($\lambda=633\text{nm}$). Figure 4 shows the phase shift of T-PNLC as a function of an applied voltage. The phase shift decreases from 0.37π radians to 0.1π radians when the curing voltage of T-PNLC increases from $2V_{rms}$ to $8V_{rms}$ because high curing voltages causes high pretilt angles of LC directors. This can be proved by measuring and analyzing the optical phase shift of T-PNLC at the oblique incidence of transverse magnetic wave¹⁸.

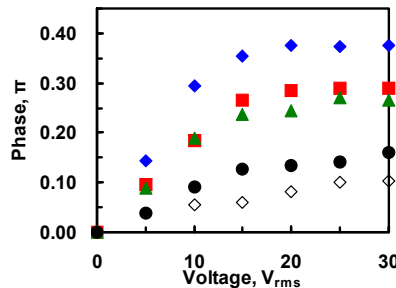


Figure 4 : Phase shift as a function of voltage for T-PNLC at $V_c=2V_{rms}$ (blue solid diamonds), T-PNLC at $V_c=2.5V_{rms}$ (red solid squares), T-PNLC at $V_c=3V_{rms}$ (green solid triangles), T-PNLC at $V_c=4V_{rms}$ (black solid circles) and T-PNLC at $V_c=8V_{rms}$ (black hollow diamonds).

The curing voltage also affects the response time of The T-PNLC. Figure 5 shows the response time (i.e the sum of the rise time and fall time) of T-PNLC as a function of a curing voltage. The response time of T-PNLC for $V_c>2V_{rms}$ is smaller than 6 ms and the response time of T-PNLC for $V_c=0V_{rms}$ is around 20 ms. The response time of T-PNLC for $V_c>2V_{rms}$ is faster than the response time of T-PNLC for $V_c=0V_{rms}$ because the LC layers near alignment layers are separated by the middle LC layer and the effective thickness of the regions d_1 is smaller than cell gap d . The response time is faster when the thickness of the LC layer is thinner.

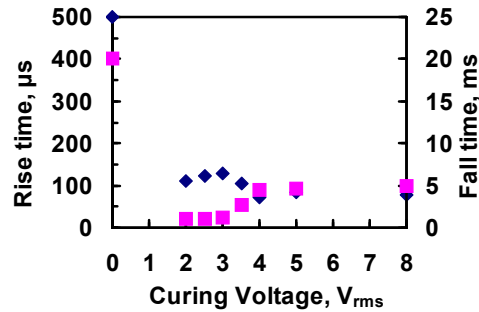


Figure 5: Rise time (blue diamonds) and fall time (pink squares) of T-PNLC as a function of the curing voltage.

3.2 T-PNLC with different cell gaps

For testing the T-PNLC with different cell gap, we prepared the samples with a same curing voltage $2.5 V_{rms}$ and two different LC cell gap: $5\mu m$ and $7\mu m$. We also measured the transmittance of the T-PNLC under applied voltages to see the electro-optical properties of T-PNLC samples with different cell gaps. Figure 6 shows the transmittance as a function of an applied voltage. The transmittance of T-PNLC is similar with different applied voltages. In Figure 6, the transmittance decreases when cell gap of T-PNLC increases. However, the scattering of T-PNLC is still less than 10% when the cell gap is $7\mu m$.

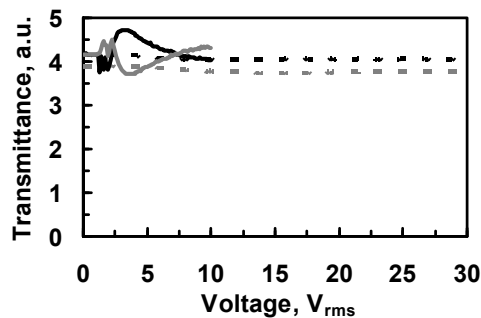


Figure 6 : Transmittance as a function of voltage for pure LC cell with cell gap $5\mu m$ (black line), pure LC cell with cell gap $7\mu m$ (gray line), T-PNLC with cell gap $5\mu m$ (black and dotted line), and T-PNLC with cell gap $7\mu m$ (gray and dotted line).

The phase shift of T-PNLC as a function of an applied voltage with different cell gaps is shown in Figure 7. The phase shift of T-PNLC with the cell gap of $5\mu m$ is around 0.25π radians and the phase shift of T-PNLC with the cell gap of $7\mu m$ is around 0.4π radians. The phase shift increases when the cell gap of T-PNLC increases. However, when the curing voltage is fixed, the thicker cell gap of T-PNLC causes more serious scattering effect. For obtaining a large phase shift, the cell gap and the curing voltage of T-PNLC should be adjusted and optimized.

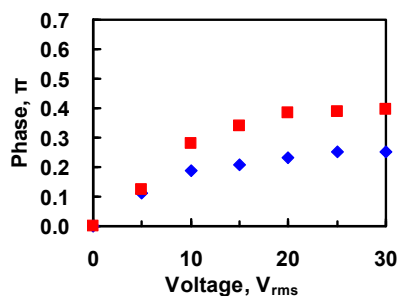


Figure 7 : The phase shift as a function of voltage for T-PNLC with the cell gap of $5\mu\text{m}$ (blue diamonds) and T-PNLC with the cell gap of $7\mu\text{m}$ (red squares).

4. CONCLUSION

A polarization-independent liquid crystal (LC) phase modulation using T-PNLC is demonstrated. The mechanism of T-PNLC belongs to the double-layered type. The three sub-layers structure in T-PNLC should be preserved with high curing voltage. The T-PNLC with curing voltage $0V_{rms}$ acts as a TN cell and should be applied very high voltages to achieve polarization independent and to avoid scattering. The phase shift of T-PNLC depends on the curing voltages and cell gaps. The phase shift of T-PNLC is 0.4π radians when the curing voltage is $2.5 V_{rms}$ and the cell gap is $7\mu\text{m}$. To further enlarge the phase shift, we can enlarge the cell gap and choose the proper curing voltages. The potential applications are spatial light modulators, laser beam steering, and micro-lens arrays.

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