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Polarization-independent liquid crystal phase modulator using a thin polymer-separated double-layered structure

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Abstract: A polarization-independent phase-only liquid crystal (LC) phase modulator using a double-layered structure is demonstrated. Two orthogonal LC layers are separated by two ultra-thin anisotropic polymer films. The anisotropic polymeric films not only separate the LC layers but also provide good molecular alignment. As a result, a polarization-independent phase modulator with 2π phase shift is achieved at $9V_{rms}$ and 8.1π at $40V_{rms}$ using a 12-μm-thick E7 LC layers. This operating voltage is ~10X lower than that using a conventional 0.3-mm-thick glass separator.

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

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1. Introduction

Phase-only modulation [1] plays an important role in adaptive optics, optical cross-connect switching, laser beam steering, and low-cost electro-optic sensor. Several interesting applications using phase modulators have been identified, e.g., tunable-focus lens [2], grating and prism [3], and spatial light modulators [4]. Liquid crystal (LC)-based phase modulators offer several advantages: low cost, light weight, low power consumption and no mechanical moving part. Several LC-based phase modulators have been developed, e.g., homogeneous LC [5], polymer network liquid crystal (PNLC) [6], and sheared polymer network liquid crystal (SPNLC) [7, 8]. The homogenous cell is attractive for its large phase shift and low operation voltage. However, it is polarization dependent and the response time is relatively slow. A PNLC cell significantly reduces the response time but its operating voltage is quite high. To obtain 2π phase change in a transmissive PNLC cell, the required voltage is ~$90V_{rms}$ for a 12 μm E44 cell, which corresponds to ~7 V/μm. To achieve more phase change by increasing cell gap would result in a substantial light scattering and higher voltage. The sheared PNLC cell does not require alignment layers but it needs a shearing force to stress the LC directors and to suppress light scattering. SPNLC also exhibits a fast response but its operating voltage is also high. A common drawback of these three approaches is that they are polarization sensitive. For laser applications, the incident light polarization may not be always parallel to the LC directors to ensure phase-only modulation. Thus, it is highly desirable to develop polarization-independent phase modulators.

Several approaches for obtaining polarization-independent LC phase modulation have been discovered, e.g., the 90^o twisted nematic cell operated at a voltage ~3X higher than the threshold voltage [9, 10], nanoscale polymer-dispersed liquid crystal (nano-PDLC) [11], voltage-biased PDLC [12], and voltage-biased polymer-stabilized cholesteric texture (PSCT) [13]. A common problem of these approaches is that their phase change is relatively small and the operating voltage quite high. Thus, more polarization-independent light modulation mechanisms need to be developed.

In this paper, we demonstrate a polarization-independent LC phase modulator using a double-layered structure with two ultra-thin anisotropic polymer films as cell separators. The double-layered structure has been proposed for guest-host liquid crystal displays (LCDs) more than two decades ago [14-18]. The conventional approach uses a thin glass (~0.3 mm) or Mylar film (~0.1 mm) to separate the two orthogonal LC layers. In the former case, an indium-tin-oxide (ITO) glass substrate is used as a middle substrate. To overcome the electric field shielding effect, both sides of the ITO layers should be pixilated and connected (e.g., via feed-through holes), and then overcoated with a thin polyimide layer which is rubbed in the orthogonal directions to match the LC alignment. This approach is difficult for high resolution devices because of the complicated pixel structures and extra alignment between the passive ITO pixels in the middle substrate and active elements. To reduce the parallax incurred by the middle glass substrate and to enable high resolution, a thin Mylar film can be considered. However, the Mylar film cannot align the LC molecules [18] because the baking temperature of polyimide is higher than the glass transition temperature of the Mylar film. The anisotropic polymer films we developed in this paper are thin and they possess alignment capability. As a result, excellent LC alignment, large phase shift, and low operating voltage are achieved. Using two 12-μm orthogonal E7 LC layers, we obtain 2π phase shift (λ=633 nm) at merely 9 V_{rms} and 8.1π phase shift at 40 V_{rms}. This is by far the polarization-independent LC phase

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modulator ever demonstrated exhibiting the largest phase change at the lowest operating voltage.

2. Structure and mechanism

Figure 1 shows the schematic design of our polarization-independent phase modulator. The cell consists of two glass substrates which are overcoated with thin (~80 nm), mechanically buffed polyimide layers, two anisotropic polymer films, and two LC layers. The top and bottom LC directors are oriented orthogonal to each other. The anisotropic polymer films were peeled off from a UV-induced phase separation of a LC/polymer cell. Such a polymer film is an optically uniaxial film. It has excellent alignment capability [19]. To achieve orthogonal homogeneous LC layers, the principal axes of these two anisotropic polymer films were also arranged to be orthogonal to each other.

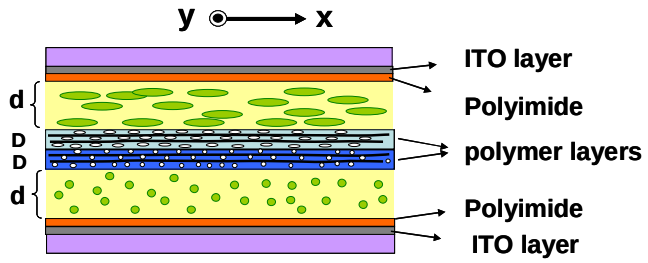

Fig. 1. The structure of a polarization-independent phase modulator.

The polarization-independent mechanism of the double-layered LC device can be proven as follows. Let us assume the electric field of the normal incident light can be expressed as:

$$E_i = A_x \cdot \hat{x} + A_y \cdot \hat{y}\,, \tag{1}$$

where A_x and A_y are two complex numbers, and $\hat{x}$ and $\hat{y}$ are unit vectors along the *x* and *y* axes, as depicted in Fig. 1. When the light traverses through the LC cell (with V=0), the total accumulated phases of the *x* and *y* components are $e^{i\cdot\kappa\cdot(n_e+n_o)\cdot d}$ and $e^{i\cdot\kappa\cdot(n_e+n_o)\cdot d}$, respectively, where the placement of the indices has been ordered to reflect the sequence of materials traversed from top to bottom, κ is the wave vector in the vacuum, *d* is the cell gap of each layer, and n_e and n_o are the extraordinary and ordinary refractive indices of the LC. The output electric field of the light becomes:

$$E_o = A_x \cdot e^{i\cdot\kappa\cdot(n_e+n_o)\cdot d} \cdot \hat{x} + A_y \cdot e^{i\cdot\kappa\cdot(n_e+n_o)\cdot d} \cdot \hat{y} \tag{2}$$

With an applied voltage, the total accumulated phases of the *x* and *y* components become $e^{i\cdot\kappa\cdot n_{eff}(\theta,\psi)\cdot d}$ and $e^{i\cdot\kappa\cdot n_{eff}(\theta,\frac{\pi}{2}+\psi)\cdot d}$, respectively, where $n_{eff}(\theta,\psi)$ is the effective refractive index of the LC, and θ and ψ respectively represent the tilt angle and the twist angle of the LC directors.

Therefore, the electric field of the outgoing light becomes:

$$E_o' = e^{i\cdot\kappa\cdot(n_{eff}(\theta,\psi)+n_{eff}(\theta,\frac{\pi}{2}+\psi))\cdot d} \cdot (A_x \cdot \hat{x} + A_y \cdot \hat{y}) \tag{3}$$

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From Eq. (2) and Eq. (3), the polarization of the output beam remains the same at a given applied voltage. Therefore, our LC device is polarization-independent in all different voltage states. The phase change increases with increasing voltage.

3. Sample fabrication

To fabricate the anisotropic film, we mixed a Merck E7 nematic LC mixture, photo-initiator IRG184, and an LC monomer RM-257 (4-(3-Acryloyloxypropyloxy)-benzoic acid 2-methyl-1,4-phenylene ester) at 19:1:80 wt % ratios. The LC/monomer mixture was injected into a homogeneous cell with 23 μm cell gap which was controlled by the Mylar stripes and then the cell was exposed to a UV light with intensity I = 10 mW/cm^2 for ~30 min at 90 °C. After UV exposure, the two substrates of the homogeneous cell were peeled off and a solidified anisotropic film with 23 μm thickness was obtained. The anisotropic polymer film is fully transparent. We prepared two polymer films with the same thickness (D=23 μm) and stacked them together in orthogonal directions, as Fig. 1 depicts. The LC mixture employed is also E7. The LC was filled to the empty cell by the one-drop-fill method. The cell gap of each LC layer was controlled by a Mylar film to be d~12 μm. The total dimension of our cell is around 25 mm by 25 mm.

4. Experiment and results

Figure 2 shows the surface morphologies of an anisotropic polymer film taken from an atomic force microscope (AFM) (Dimension 3100, Digital Instruments). Silicon nitride cantilever with a normal spring constant of 30 N/m and an apical radius of 20 nm was used. The AFM measurements were performed in tapping mode at a scan rate of 1 Hz in air under ambient conditions. In Fig. 2, the polymer film appears to consist of elongated polymer grains. The elongated polymer grains are oriented at the same direction (marked with an arrow), giving an anisotropic polymer surface. The root-mean-square (RMS) roughness of the surface can be defined as RMS average of height deviations taken from the mean data plane. Then, the RMS roughness of the surface of the anisotropic polymer film is 1.01 nm. The LC molecules were found to be aligned along the elongate direction of the polymer grains in order to minimize free energy. During fabrication process, when we peel off the polymer film from the ITO glass substrates the LC molecules near the surface stay on the glass substrates which leave the anisotropic polymer film with valleys and polymer network structures. The size and the structure of the polymer grains depend on the fabrication conditions.

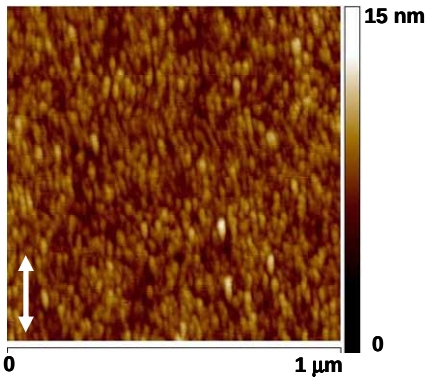

Fig. 2. AFM images of the anisotropic polymer film surface. LC directors are aligned along the arrow. The color bars indicate the height.

To characterize the phase shift of the double-layered LC cell, we used Mach-Zehnder interferometer as depicted in Fig. 3. An unpolarized He-Ne laser (λ=633 nm) was used as a light source. The laser beam was split equally into two arms by a beam splitter. We placed the

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LC cell in one arm. The cell was driven by a square-wave voltage at frequency f=1 kHz. The interference pattern was recorded by a digital video camera (SONY, DCR-HC40). The whole system was built on a floating optical table to avoid any environment-induced fluctuation.

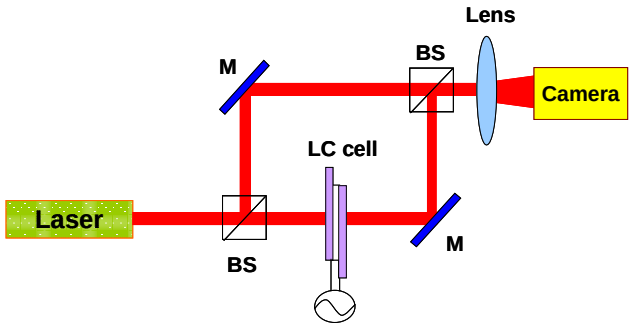

Fig. 3. Mach-Zehnder interferometer for measuring the phase shift. M: dielectric mirror, and BS: beam splitter.

Figure 4(a) is a recorded movie showing the voltage-dependent interference fringes of the double-layered LC cell. The phase shift at V=0 was used as reference. Figure 4(b) plots the interference fringes at three specific voltages: V= 0, 7, and 9 V_{rms}. The phase shift is around 1.06 π between 0 and 7 V_{rms} and around 2 π between 0 and 9 V_{rms}.

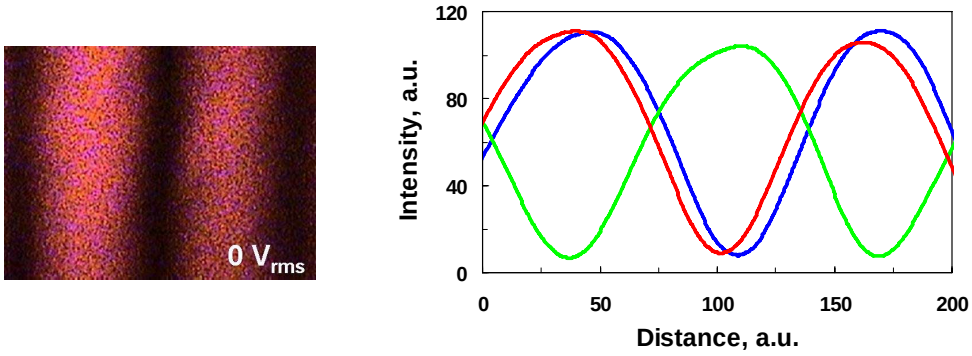

Fig. 4. (a) Interference patterns at various voltages (703 KB) and (b) intensity profiles at 0 (blue), 7 (green) and 9 V_{rms} (red). The two orthogonal LC cells are 12-μm E7 layers. λ=633 nm from an unpolarized He-Ne laser.

Figure 5 plots the measured voltage-dependent phase shift at λ=633 nm of the double-layered E7 LC cell (filled circles). The threshold voltage is ~5 V_{rms}. For reference, the threshold voltage of the single E7 cell without any middle substrate is ~0.95 V_{rms}. The increased threshold voltage is due to the dielectric shielding effect of the middle polymeric layers. In the interferometer, the measured phase shift is referenced to that at V=0. The total phase shift reaches ~8.1π at V=40 V_{rms}. This total phase shift remains the same no matter we placed a polarizer in front of the LC device or rotated the polarizer.

We also performed numerical analysis for the double-layered structure using a 0.3-mm-thick glass separator. Both sides of the glass separator are assumed to be coated with thin polyimide layers and rubbed in orthogonal directions to match with the top and bottom substrates. The simulation results (open circles) are included in Fig. 5 for comparison. The same LC material (E7) and same cell gaps are assumed. The calculated threshold voltage is as high as ~24 V_{rms} because of the electric field shielding effect from the relatively thick glass

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separator. To obtain 8π phase shift, the required voltage is ~600 V_{rms}. Our thin polymeric separators reduce the required operating voltage by nearly 15X.

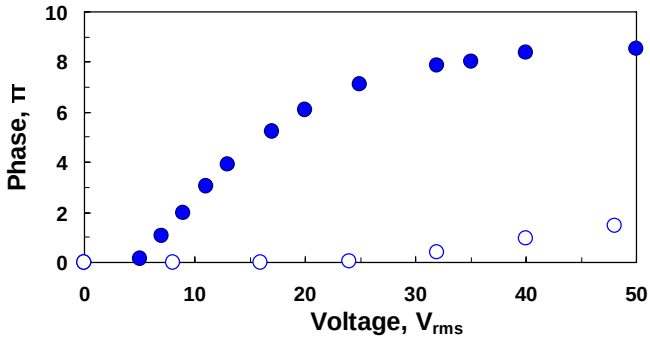

Fig. 5.Voltage-dependent phase shift of the polarization-independent LC phase modulator at λ=633 nm. Filled circles represent the measured data using our anisotropic polymeric films while open circles are the simulated results of the double-layered structure using a 0.3-mm-thick glass separator.

5. Discussion

Theoretically, the phase difference between two arms of the Mach-Zehnder interferometer is:

$$\phi(V) = \kappa \cdot (n_{eff}(\theta,\psi) + n_{eff}(\theta,\frac{\pi}{2}+\psi) - 2) \cdot d + \delta, \quad (4)$$

where $\kappa = 2\pi/\lambda$, λ is the laser wavelength, *d* is the cell gap, and δ is the phase difference contributed by the two anisotropic polymer films, glass substrates, and optical path difference in the air. At V=0, the phase difference between the two arms is

$$\phi(0) = \kappa \cdot (n_e + n_o - 2) \cdot d + \delta, \quad (5)$$

At a very high voltage, all the LC directors are reoriented along the electric field direction except the boundary layers. Under such a circumstance, the effective refractive index becomes

$$n_{eff}(\theta,\psi) = n_{eff}(\theta,\frac{\pi}{2}+\psi) = n_o, \quad (6)$$

And the phase difference between two interferometer arms is as follows:

$$\phi(V >> 0) = \kappa \cdot (2n_o - 2) \cdot d + \delta \quad (7)$$

Therefore, the total phase shift is reduced to the well-known expression:

$$\Delta\phi = \phi(0) - \phi(V >> 0) = (2\pi/\lambda) \cdot d \cdot (n_e - n_o), \quad (8)$$

The birefringence of E7 is $\Delta n = n_e - n_o \approx 0.21$ at λ=633 nm. The calculated total phase shift is ~8π, which is rather close to our measured value (8.1π) at V=40 V_{rms}.

The obtainable phase shift of our double-layered structure is much larger and the operating voltage is much lower than those of nano-PDLC, PDLC, and PSCT [11-13]. To further lower the operating voltage of our double-layered structure, we can reduce the thickness of the anisotropic polymer films, but the tradeoff is that a thinner polymer film may degrade the uniformity of the cell.

The response time of our double-layered LC cell was measured to be ~300 ms at T~23 °C. The slow response time originates from the thick LC layers (d~12 μm) and high viscosity of the E7 LC employed. To reduce response time, a high Δn and low viscosity LC could be used

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[20]. A high Δn LC enables a thinner cell gap to be used which is helpful for reducing response time.

The thickness of polymer film is 23 μm which is larger than that of the LC layer (12 μm). The flexibility and hardness can be controlled by the fabrication process, such as UV curing condition and LC concentration. Although the anisotropic films are thin, their deformation during operation should not be a problem because the films are sandwiched by two glass substrates. Therefore, the mechanical stability of the system is not a concern.

6. Conclusion

In conclusion, we have demonstrated a polarization-independent LC phase modulator using a double-layered structure. The LC directors are orthogonal to each other. Two anisotropic polymer films are used as the cell separators and alignment layers. The total phase shift is ~2π at V=9 V_{rms} and ~8.1π at V=40 V_{rms} at λ=633 nm. Using a thinner cell gap would simultaneously reduce the response time and operating voltage. The key technical challenge is to control the cell gap and uniformity of each LC layer, especially for a large aperture phase modulator. The uniformity of polymer film is relatively easy to obtain and the cell gap can be controlled by using post spacers. Finally, this approach opens a new door for achieving polarization-independent phase modulation.

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