P-131: Polarization Independent and Fast Response Phase Modulators Using Orthogonally Orientated Liquid Crystal Gels

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Abstract

A polarization independent phase modulator using two ultra-thin homogeneously stratified liquid crystal gels is demonstrated. In addition to the polarization independence and submillisecond response time, our liquid crystal gel possesses a much larger phase change and lower operating voltage than the nanosized polymer-dispersed liquid crystal.

1. Introduction

Polarization independent and fast response nematic liquid crystal (NLC) phase modulators are particularly useful for laser beam steering, tunable microlens array, agile filter, and even switchable 2D/3D displays. Various phase modulators have been developed [1-6] wherein the nano-sized polymer-dispersed liquid crystal (nano-PDLC) is most promising due to its polarization independence and fast response time. However, nano-PDLC has a small phase shift and too high operating voltage (>20 $V_{rms}/\mu m$). The voltage-biased conventional PDLC is also polarization independent [6], however, its residual phase is too small (~0.1π). So far, PDLC based phase modulators are still impractical for photonics applications.

In this paper, we demonstrate a phase modulator using double-layered liquid crystal (LC) gels. The two homogeneously aligned gel films are identical, but stacked in orthogonally oriented directions. Due to the high LC concentration and uniform molecular alignment, our LC gel possesses a large phase change (>1π) at a relatively low voltage. Because of the relatively high monomer concentration (28%), the formed LC domains are in the submicron range. Therefore, the response time of the LC gel is very fast (around ~0.5 ms).

2. Basic theory and experiment

In a LC gel, homogeneous LC is stabilized by polymer networks, as shown in Fig. 1(a). The phase shift along x-axis can be expressed as

$$\Delta\delta_{Gel}(V) = \frac{2\pi dc[n_e - n_{eff}(V)]}{\lambda} \tag{1}$$

where *d* is the cell gap, *c* is the LC concentration, λ is the incident light wavelength, n_e and n_{eff} (V) are the extraordinary and effective refractive index of the LC, respectively. At $V\to\infty$, $n_{eff} \to n_o$, where n_o is the ordinary refractive index of LC. From Fig. 1(a), the homogeneous LC gel is polarization dependent. To make it polarization independent, we stack two identical homogeneous LC gels in the orthogonal directions, as shown in Fig. 1(b).

It has been proven that two orthogonally oriented homogeneous LC layers are polarization independent for phase modulation if the two films are identical [7]. As the voltage increases, the phase change occurs because of the LC director reorientation. At a very high voltage, the voltage-induced phase shift is reduced to:

$$\Delta\delta_{Gel}(V \to \infty) = \frac{2\pi dc\Delta n}{\lambda} \tag{2}$$

where $\Delta n = n_e - n_o$. In comparison, the LC droplets in a PDLC cell are almost randomly orientated. Thus, the phase shift is

$$\Delta\delta_{PDLC}(V) = \frac{2\pi d'c'[\bar{n} - n_{eff}(V)]}{\lambda} \tag{3}$$

where $\bar{n} = (2n_o + n_e)/3$ is the average refractive index of the LC at V=0, ***d′*** and ***c′*** are the cell gap and LC concentration, respectively. At $V\to\infty$, $n_{eff} \to n_o$ and the phase shift is reduced to

$$\Delta\delta_{PDLC}(V \to \infty) = \frac{2\pi d'c'\Delta n}{3\lambda} \tag{4}$$

To fairly compare the phase change of the orthogonal LC gel films vs. the nano-PDLC, let us use the same LC material. To achieve polarization independence, LC gel needs two layers, but nano-PDLC only needs one, i.e., d′=2d. However, the LC concentration in the gel is **2X** higher than that in nano-PDLC, i.e., c=2c′. From Eq. (2) and Eq. (4), the phase shift of the LC gel is **3X** higher than that of nano-PDLC.

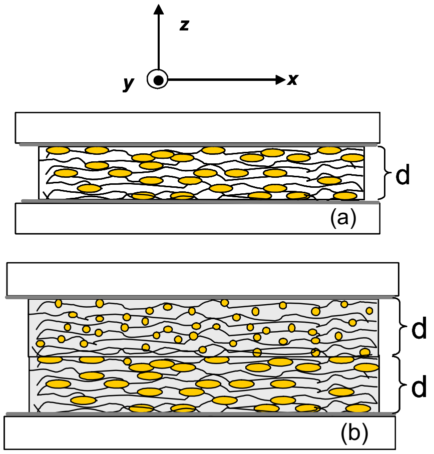

Fig. 1. Homogeneous LC gel: (a) single layer and (b) double layers oriented at orthogonal directions.

To prepare a LC gel, we mixed 28 wt% of UV curable rod-like LC monomer (RM257) in a nematic LC (E48: n_o=1.523, Δn=0.231). The mixture was injected into an empty cell in the nematic state. The inner surfaces of the ITO glass substrates were coated with a thin polyimide layer and then rubbed in antiparallel directions. The filled cell was exposed to UV light (λ=365 nm, I~10 mW/cm^2) for 30 min. The cell gap was controlled at 8 μm.

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3 Results and Discussion

After UV exposure, the cell is highly transparent. To get a gel layer, we cleaved the cell. The stratified gel remained on one substrate surface without LC leakage. We first examined the LC alignment of the gel layer using a polarized optical microscope. The gel film was placed between crossed polarizers. If the cell rubbing direction was along one of the polarizer's axis, a dark state was obtained, as shown in Fig. 2(a). Rotating the gel film by 45°, the brightest state was obtained, as shown in Fig. 2(b). These results imply that the LC gel possesses homogeneous alignment without damage during cell cleaving.

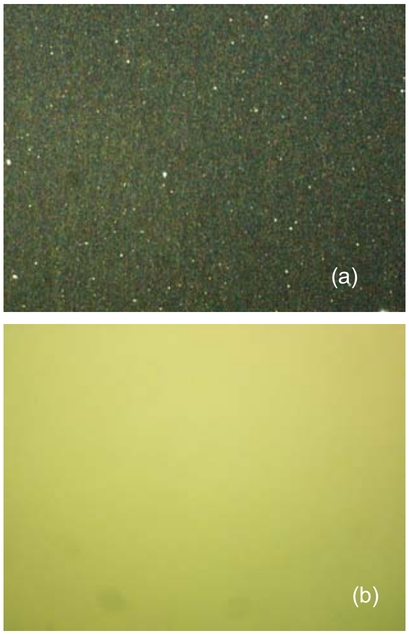

Fig. 2. Microscope images of an 8-µm LC gel between crossed polarizers: (a) dark state and (b) bright state.

To obtain a double-layered structure, we cut the LC gel in half and stacked the films together at orthogonal direction in an ITO cell, as shown in Fig. 1(b). We used the Mach-Zehnder interferometer to measure the phase shift of the orthogonal gel cell [7]. An unpolarized He-Ne laser (λ=633 nm) beam was split equally into two arms by a beam splitter. The two beams were then recombined again. In the beam overlapping region, several parallel interference fringes occur. The stacked gel was placed in one arm. When an ac voltage (f=1 kHz) was applied to the LC gel, the interference fringes moved as recorded by a digital CCD camera (SBIG Model ST-2000XM).

Figure 3 shows the intensity profiles of the interference fringes at different voltages. As the applied voltage increases, the intensity profile shifts to the right direction. Comparing with the voltage at V=0, the voltage at 180 V_{rms} can cause more than 1π phase shift.

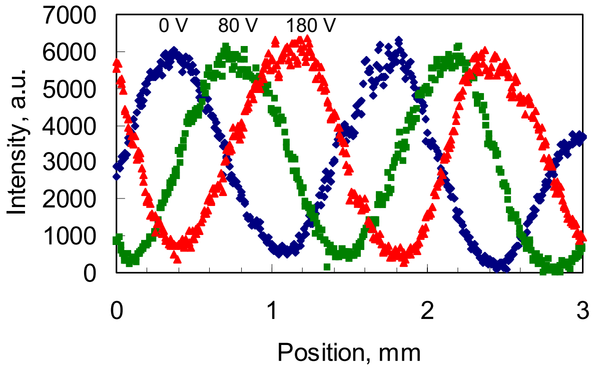

Fig. 3. Intensity profile of interference stripes at different voltages measured from the Mach-Zehnder interferometer. λ=633 nm.

The voltage-dependent phase shift of the 16-µm double-layered LC gel at λ=633 nm is plotted in Fig. 4. The threshold voltage is ~30 V_{rms}. This high threshold originates from the dense polymer networks. Beyond this threshold, the phase change increases almost linearly with the applied voltage. The estimated total phase change from an 8-µm LC gel which contains ~80 wt% E48 should be ~2π for a linearly polarized He-Ne laser (λ=633 nm). Therefore, our applied voltage has not reached the saturation regime. In comparison to a nano-PDLC, our LC gel possesses a much larger phase shift at a lower operating voltage because of the higher LC concentration and directional stratification.

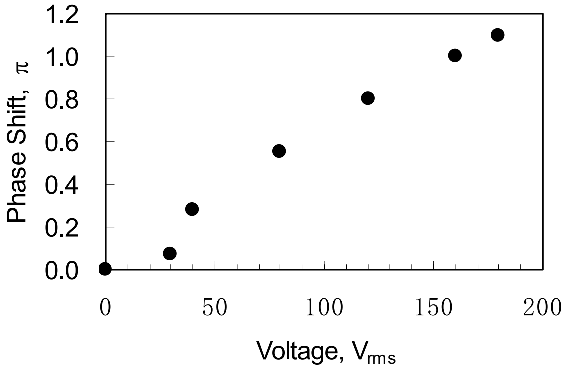

Fig. 4. Voltage-dependent phase shift of a 16-µm double-layered LC gel. λ=633 nm.

Response time is an important parameter for a LC-based phase modulator. To measure the response time of the LC gel, we used a photodiode detector instead of CCD camera to receive the transmitted beam. A diaphragm was put right before the detector. At V=0, no light passes through the diaphragm. A square voltage V=100 V_{rms} at 1 kHz was applied to the LC gel cell. Results are shown in Fig. 5. The measured rise time is ~0.2 ms and decay time is ~0.5 ms at room temperature (~22°C). Such a fast response time results from the small LC domain sizes and polymer stabilization. Due to the relatively high monomer concentration (28 wt%), the formed polymer networks are quite dense so that the formed LC domains are in submicron size. Similar to a nano-PDLC, the contact interfaces between the polymer networks and the LC molecules are large. As a result, the anchoring force of polymer networks exerting on the LC is very strong. This is the primary reason for the observed fast response time and high threshold voltage.

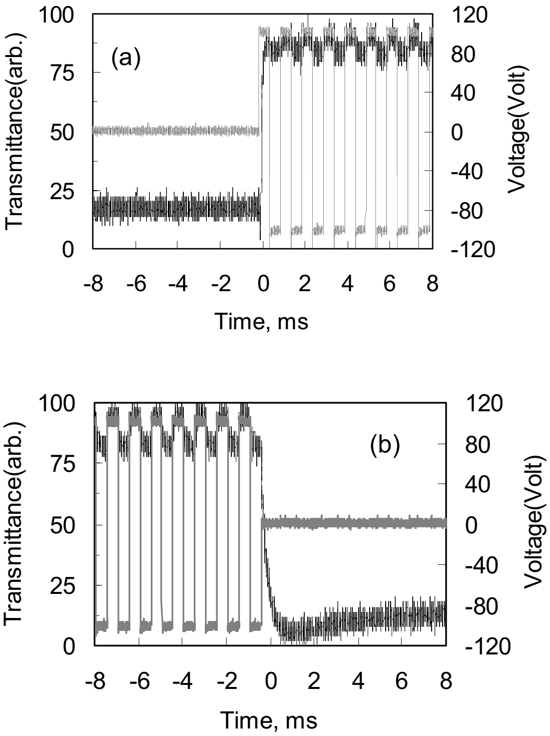

Fig. 5. The response time of the LC gel between 0 and 100 V_{rms} bursts (f=1 kHz). (a) Rise time ~0.2 ms and (b) decay time ~0.5 ms at room temperature. The gray lines in each figure represent the applied voltage and the black lines represent the optical signals.

To get a 2π phase change for laser beam steering and other photonic applications, we could operate the LC gel in reflective mode without increasing the operating voltage. For practical applications, the operating voltage of our LC gel is still very high. To increase phase change, we could use a high Δn LC material [8] while to reduce the operating voltage we could use a high dielectric anisotropy (Δε) LC or optimize the LC and monomer concentration. A high Δn LC also enables a thinner gel to be used which, in turn, helps reduce the operating voltage. A high Δε LC lowers the threshold and the operating voltages simultaneously. Increasing the LC concentration would boost the phase change and reduce the operating voltage. However, the gel may become too soft to stand alone. Moreover, its response time will increase.

4. Conclusion

A double-layered LC gel for polarization independent phase-only modulators has been demonstrated. For a 16 μm-cell gap LC gel, the tunable phase shift at λ=633 nm can reach more than 1π at V~11 V_{rms}/μm and its response time is ~0.5ms. By enhancing LC concentration further, the operating voltage will be reduced and the phase shift will be increased. Potential applications of this polarization independent LC gel for laser beam steering, microlens array, agile filter, and switchable 2D/3D liquid crystal displays are emphasized.

5. Acknowledgements

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6. References

[1] J. S. Patel, “Polarization insensitive tunable liquid crystal etalon filter”, Appl. Phys. Lett. Vol. 59, 1314-1316, 1991.

[2] R. L. Sutherland, L. V. Natarajan, V. P. Tondiglia, and T. J. Bunning, “Bragg gratings in an acrylate polymer consisting of periodic polymer-dispersed liquid-crystal planes” Chem. Mater. Vol. 5, pp1533-1538, 1993.

[3] D. P. Resler, D. S. Hobbs, R.C. Sharp, L. J. Friedman, and T. A. Dorschner, “high-efficiency liquid-crystal optical phased-array beam steering”, Opt. Lett. Vol. 21, pp 689-691,1996.

[4] D. E. Lucchetta, R. Karapinar, A. Manni, and F. Simoni, “Phase-only modulation by nanosized polymer-dispersed liquid crystals”, J. Appl. Phys. Vol. 91, pp 6060-6065, 2002.

[5] J. L. West, G. Zhang, A. Glushchenko, and Y. Reznikov, “Fast birefringent mode stressed liquid crystal”, Appl. Phys. Lett. Vol. 86, 031111, 2005.

[6] H. Ren, Y. H. Lin, Y. H. Fan, and S. T. Wu, “Polarization-independent phase modulation using a polymer-dispersed liquid crystal”, Appl. Phys. Lett. Vol. 86, 141110, 2005.

[7] Y. H. Lin, H. Ren, Y. H. Wu, Y. Zhao, J. Fang, Z. Ge, and S. T. Wu, “Polarization-independent liquid crystal phase modulator using a thin polymer-separated double-layered structure”, Opt. Express Vol. 13, pp 8746-8752, 2005.

[8] S. Gauza, H. Wang, C. H. Wen, S. T. Wu, A. J. Seed, and R. Dabrowski, “High Birefringence Isothiocyanato Tolane Liquid Crystals” Jpn. J. Appl. Phys., Part 1 Vol. 42, pp 3463-3466, 2003.