

# Polarization-independent and fast-response phase modulators using double-layered liquid crystal gels

Hongwen Ren, Yi-Hsin Lin, and Shin-Tson Wu<sup>a)</sup>

College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816

(Received 2 December 2005; accepted 17 January 2006; published online 10 February 2006)

A polarization-independent phase modulator using two thin homogeneously stratified but orthogonally oriented liquid crystal (LC) gels is demonstrated. In addition to polarization independence and submillisecond response time, the LC gel possesses a much larger phase change and lower operating voltage than the nanosized polymer-dispersed liquid crystal. For a 16  $\mu\text{m}$  transmissive E48 LC gel, the phase shift exceeds  $1\pi$  at  $\lambda=633\text{ nm}$  with an electric field strength of  $\sim 11\text{ V}_{\text{rms}}/\mu\text{m}$ . Potential applications of such a phase modulator for laser beam steering, microlens array, and switchable two- and three-dimensional LC displays are foreseeable. © 2006 American Institute of Physics. [DOI: 10.1063/1.2173248]

Liquid crystal (LC) based phase-only modulation is useful for laser beam steering,<sup>1,2</sup> agile filter,<sup>3</sup> tunable-focus microlens array,<sup>4</sup> and switchable two- (2D) and three-dimensional (3D) displays.<sup>5</sup> Various phase modulation mechanisms have been developed<sup>1,2,6-9</sup> wherein the nanosized polymer-dispersed LC (nano-PDLC) is most promising due to its polarization independence and fast-response time. However, the nano-PDLC has two major drawbacks: Its phase shift is small and its operating voltage is too high ( $>20\text{ V}_{\text{rms}}/\mu\text{m}$ ).<sup>3,9-11</sup> The voltage-biased microsized PDLC is also polarization independent, however, its residual phase is still small ( $\sim 0.1\pi$  at  $\lambda=633\text{ nm}$ ) so that its applications are limited to microphtonic devices, such as tunable-focus microlens array.<sup>8</sup>

In this letter, we demonstrate a phase modulator using two thin stratified LC gels. The two homogeneously aligned gel films are identical, but stacked in orthogonal directions. Because of high LC concentration and uniform molecular alignment, our LC gel possesses a large phase change ( $>1\pi$ ). Meanwhile, because of the relatively high monomer concentration (28 wt %), the formed LC domains are in the submicron range. Therefore, the response time of the LC gel is around 0.5 ms.

In a LC gel, the homogeneously aligned LC is stabilized by dense polymer networks, as shown in Fig. 1(a). The phase shift along  $x$  axis can be expressed as

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

where  $d$  is the cell gap,  $c$  is the LC concentration,  $\lambda$  is the incident wavelength,  $n_e$  and  $n_{\text{eff}}(V)$  are the extraordinary and effective refractive index of the LC, respectively. At  $V \rightarrow \infty$ ,  $n_{\text{eff}} \rightarrow n_o$  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 shown that two orthogonally oriented homogeneous LC layers are polarization independent for phase modulation if the two films are identical.<sup>12</sup> As the voltage

increases, the phase change occurs because of the electric field-induced LC director reorientation. At a very high voltage, the voltage-induced phase shift is reduced to

$$\Delta\delta_{\text{Gel}}(V \rightarrow \infty) = \frac{2\pi dc\Delta n}{\lambda}, \quad (2)$$

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

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

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  $V \rightarrow \infty$ ,  $n_{\text{eff}} \rightarrow n_o$  and the phase shift is reduced to

$$\Delta\delta_{\text{PDLC}}(V \rightarrow \infty) = \frac{2\pi d'c'\Delta n}{3\lambda}. \quad (4)$$

To fairly compare the phase change of the orthogonal LC gel films with the nano-PDLC, let us use the same LC material. To achieve polarization independence, the LC gel needs two orthogonal layers, but nano-PDLC only needs one. Thus,  $d' = 2d$ . However, the LC concentration in the gel is  $2\times$  higher than that in nano-PDLC, i.e.,  $c = 2c'$ . From Eqs. (2) and (4), we find

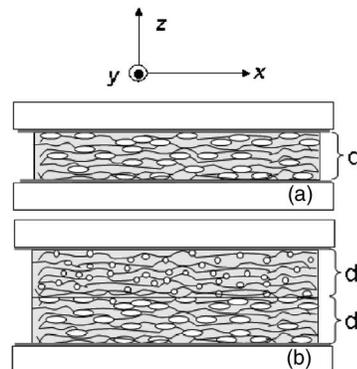


FIG. 1. A homogeneous LC gel: (a) Single layer and (b) double layers.

<sup>a)</sup>Electronic mail: swu@mail.ucf.edu

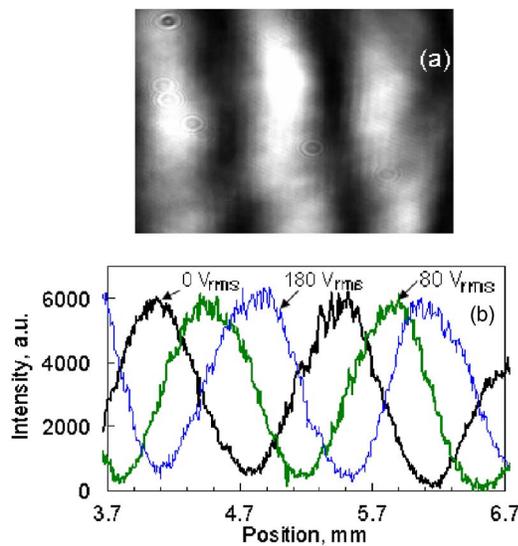


FIG. 2. (a) Interference fringes of the LC gel and (b) intensity profile at different voltages.

$$\frac{\Delta \delta_{\text{Gel}}(V \rightarrow \infty)}{\Delta \delta_{\text{PDLC}}(V \rightarrow \infty)} = 3. \quad (5)$$

From Eq. (5), the phase shift of the LC gel is  $3 \times$  higher than that of a nano-PDLC.

To prepare a LC gel, we mixed 28 wt % of photocurable rodlike LC diacrylate monomer (RM257) in a nematic LC (E48:  $n_o=1.523$ ,  $\Delta n=0.231$  at  $\lambda=589$  nm). The mixture was injected into an empty cell in the nematic state. The inner surfaces of the indium-tin-oxide glass substrates were coated with a thin polyimide layer and then rubbed in antiparallel directions. The filled cell was exposed to an ultraviolet (UV) light ( $\lambda=365$  nm,  $I \sim 10$  mW cm<sup>2</sup>) for 30 min. The cell gap was controlled at  $8 \mu\text{m}$  by spacer balls.

After UV exposure, the cell is highly transparent. To get a gel layer, we cleaved off the top glass substrate. The stratified gel remained on the bottom substrate surface without LC leakage. We examined the LC alignment of the gel layer using a polarized optical microscope. The gel (on the bottom substrate) was placed between crossed polarizers. If the cell rubbing direction was along one of the polarizer's axis, a dark state was obtained. Rotating the gel film by  $45^\circ$ , the brightest state was obtained. These results imply that the LC gel is indeed aligned homogeneous without being damage during cell cleaving.

To obtain a double-layered structure, we cut the LC gel into half and stacked the films together at orthogonal direction and then covered with another top ITO substrate, as shown in Fig. 1(b). We used the Mach-Zehnder interferometer to measure the phase shift of the orthogonal gel cell. An unpolarized He-Ne laser ( $\lambda=633$  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 charge coupled device (CCD) camera (SBIG Model ST-2000XM).

Figure 2(a) shows the recorded interference fringes at  $V=0$ . As the voltage increases, the fringes shift. Figure 2(b) shows the intensity profiles of the fringes at  $V=0$  (black),

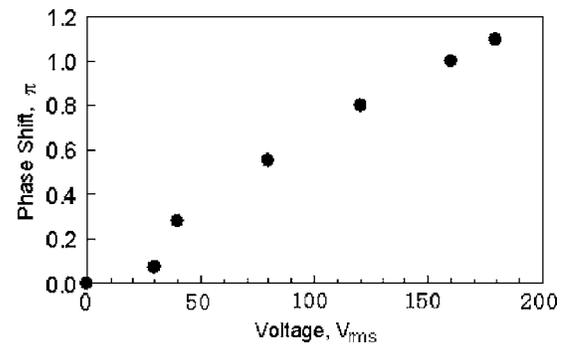


FIG. 3. Measured phase shift of a  $16 \mu\text{m}$  double-layered LC gel at different voltages.

$80 V_{\text{rms}}$  (green), and  $180 V_{\text{rms}}$  (blue), respectively. More than  $1 \pi$  phase shift is observed between 0 and  $180 V_{\text{rms}}$ .

The voltage-dependent phase shift of the  $16 \mu\text{m}$  double-layered LC gel at  $\lambda=633$  nm was plotted in Fig. 3. The threshold voltage is  $\sim 30 V_{\text{rms}}$ . 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  $8 \mu\text{m}$  LC gel which contains  $\sim 80$  wt % E48 should be  $\sim 2\pi$  for a linearly polarized He-Ne laser ( $\lambda=633$  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.

Response time is another 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  $V=100 V_{\text{rms}}$  at 1 kHz was applied to the LC gel cell. Results are shown in Fig. 4. The measured rise time is  $\sim 0.2$  ms and decay time is  $\sim 0.5$  ms at

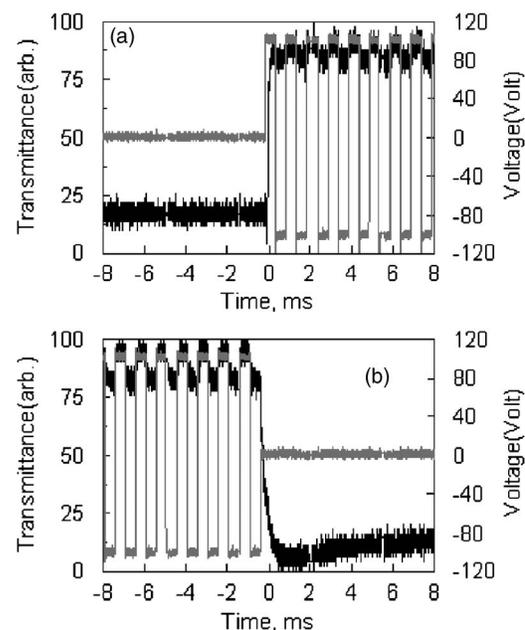


FIG. 4. The measured response time of the  $16 \mu\text{m}$  LC gel between 0 and  $100 V_{\text{rms}}$  bursts ( $f=1$  kHz). (a) Rise time  $\sim 0.2$  ms and (b) decay time  $\sim 0.5$  ms at  $T \sim 22^\circ\text{C}$ . The gray lines in each figure represent the applied voltage and the black lines represent the optical signals.

room temperature ( $\sim 22^\circ\text{C}$ ). 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.

To get a  $2\pi$  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 ( $11 V_{\text{rms}}/\mu\text{m}$ ). To increase phase change, we could use a high  $\Delta n$  LC material<sup>13</sup> while to reduce the operating voltage, we could use a high dielectric anisotropy ( $\Delta\epsilon$ ) LC or optimize the LC and monomer concentration. A high  $\Delta n$  LC also enables a thinner gel to be used which, in turn, helps reduce the operating voltage. A high  $\Delta\epsilon$  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.

In conclusion, we have developed a double-layered LC gel for polarization-independent phase-only modulators. Its phase change at  $\lambda=633\text{ nm}$  reaches more than  $1\pi$  at  $V$

$\sim 11 V_{\text{rms}}/\mu\text{m}$  and its response time is in the submillisecond range. 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.

The authors would like to thank Dr. H. Xianyu for technical assistance.

- <sup>1</sup>R. L. Sutherland, L. V. Natarajan, V. P. Tondiglia, and T. J. Bunning, *Chem. Mater.* **5**, 1533 (1993).
- <sup>2</sup>D. P. Resler, D. S. Hobbs, R. C. Sharp, L. J. Friedman, and T. A. Dorschner, *Opt. Lett.* **21**, 689 (1996).
- <sup>3</sup>S. Matsumoto, K. Hirabayashi, S. Sakata, and T. Hyashi, *IEEE Photonics Technol. Lett.* **11**, 442 (1999).
- <sup>4</sup>H. Ren, Y. H. Fan, and S. T. Wu, *Opt. Lett.* **29**, 1608 (2004).
- <sup>5</sup>W. L. IJzerman, S. T. de Zwart, and T. Dekker, *SID Tech. Digest* **34**, 98 (2005).
- <sup>6</sup>J. S. Patel, *Appl. Phys. Lett.* **58**, 1314 (1991).
- <sup>7</sup>J. L. West, G. Zhang, A. Glushchenko, and Y. Reznikov, *Appl. Phys. Lett.* **86**, 031111 (2005).
- <sup>8</sup>H. Ren, Y. H. Lin, Y. H. Fan, and S. T. Wu, *Appl. Phys. Lett.* **86**, 141110 (2005).
- <sup>9</sup>D. E. Lucchetta, R. Karapinar, A. Manni, and F. Simmoni, *J. Appl. Phys.* **91**, 6060 (2002).
- <sup>10</sup>R. Blacker, K. Lewis, I. Mason, I. Sage, and C. Webb, *Mol. Cryst. Liq. Cryst.* **329**, 799 (1999).
- <sup>11</sup>H. Ren and S. T. Wu, *Appl. Phys. Lett.* **81**, 3537 (2002).
- <sup>12</sup>Y. H. Lin, H. Ren, Y. H. Wu, Y. Zhao, J. Fang, Z. Ge, and S. T. Wu, *Opt. Express* **13**, 8746 (2005).
- <sup>13</sup>S. Gauza, H. Wang, C. H. Wen, S. T. Wu, A. J. Seed, and R. Dąbrowski, *Jpn. J. Appl. Phys., Part 1* **42**, 3463 (2003).