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Polarization-independent phase modulation using a polymer-dispersed liquid crystal

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Polarization-independent phase-only modulation of a polymer-dispersed liquid crystal (PDLC) is demonstrated. In the low voltage region, PDLC is translucent because of light scattering. Once the voltage exceeds a saturation level, PDLC is highly transparent and exhibits phase-only modulation capability. Although the remaining phase is not too large, it is still sufficient for making adaptive microdevices, such as microlens. A tunable-focus microlens for arrays using PDLC is demonstrated. This kind of microlens is scattering free, polarization independent, and has fast response time. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1899749]

Phase-only modulation can be used for tunable grating, prism, lens, and other photonic devices. Homogeneous alignment of liquid crystals (LCs) is commonly used for phase-only modulation,[1] although twisted nematic LC cells also exhibit such capability in the low voltage regime.[2] For phase modulation using a homogeneous cell, the polarization axis (z axis) of the input linearly polarized light (along x axis) is parallel to the LC directors. As the voltage exceeds a threshold, the LC directors are reoriented in the z-x plane. The phase change of the outgoing light varies with voltage as: $\Delta = 2\pi d[n_e(V) - n_o]/\lambda$; where d is the cell gap, $n_{e,o}$ is the refractive index of the extraordinary (or ordinary) ray, and λ is the wavelength. The major advantage of such a homogeneous cell is that a large phase change can be obtained with a relatively low voltage. However, the homogeneous cell is polarization dependent and its response time, which depends on d^2, is typically ~10 ms for a 5 μm cell gap using a high birefringence LC operated at 70 °C.[3]

To achieve polarization-independent phase-only modulation and fast response time, nanosized polymer-dispersed liquid crystal (nano-PDLC) droplets have been explored.[4–9] In a nano-PDLC system, the LC droplets dispersed in the polymer matrix are randomly oriented. Since the LC droplet size is smaller than a visible wavelength, the light scattering is almost completely suppressed and the nano-PDLC acts as a phase retarder in the voltage-off state. As the voltage increases, the LC directors within the droplets are reoriented along the electric field direction and, therefore, induce a phase shift. Because of the small LC concentration (~35%) and random droplets distribution, the available phase change is fairly small. Despite this small phase change, nano-PDLC has potential applications for phase gratings, microprisms, microlens arrays, color filters, and color displays. A critical issue of the nano-PDLC is high operating voltage (~10 V/μm). For a 20 μm cell gap, the required voltage is ~200 V$_{rms}$.

Unlike nano-PDLC, the conventional PDLC[10] has a larger droplet size (~1 μm) and higher LC concentration (~70%). As a result, PDLC exhibits a lower saturation voltage (~2–3 V/μm) than nano-PDLC. However, in the voltage-off state, PDLC strongly scatters visible light because its droplet size is comparable to the wavelength and its average refractive index mismatches with that of polymer matrix. The phase modulation property of PDLC has been investigated previously.[11] It was found that phase shift coexists with light scattering, but depends on the incident light polarization and incident angle. For the normally incident light, PDLC does not possess any phase change when the applied voltage is below the saturation voltage (V_{sat}).

In this letter, we find that the phase-only modulation using PDLC for the normally incident light exists in the high voltage region ($V > V_{sat}$). Moreover, such a phase shift is polarization independent and has fast response time. Although the remaining phase change is not too large, it is still sufficient for making microdevices, such as microprisms and microlens. For feasibility demonstration, we fabricate a two-dimensional tunable-focus microlens arrays using PDLC. In comparison to nano-PDLC, PDLC has a lower operating voltage.

Figure 1 illustrates the phase modulation mechanism of a PDLC. In Fig. 1(a), the LC droplets (or domains) are randomly dispersed in polymer matrix. Because of the refractive index mismatch, light scattering is strong. As the applied voltage increases, the LC directors are reoriented along the electric field direction. As a result, PDLC becomes transparent, as shown in Fig. 1(b). If the voltage is increased further, more LCs in the droplet cavities are reoriented by the electric
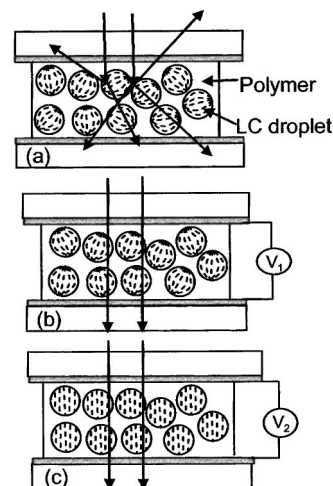

FIG. 1. LC droplet orientations in a PDLC film at (a) $V=0$, (b) V_1, and (c) $V_2 > V_1$.

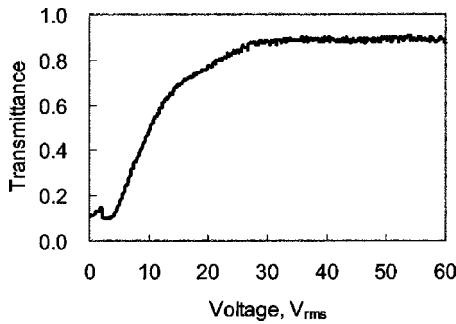[a)]Electronic mail: swu@mail.ucf.edu

FIG. 2. Voltage-dependent transmittance of a PDLC film. $\lambda=633$ nm and cell gap $d=22$ μm.
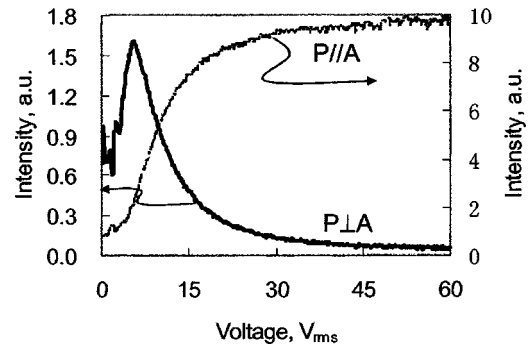

FIG. 3. Voltage-dependent transmittance of a PDLC cell between parallel (right ordinate) and crossed (left ordinate) polarizers. $f=1$ kHz, $\lambda=633$ nm, and cell gap $d=22$ μm.

field, as shown in Fig. 1(c). From Figs. 1(b) and 1(c), phase-only modulation is still available and is independent of polarization for the normally incident light.

To prepare a PDLC cell, we mixed nematic LC E48 ($n_o=1.523$ and $\Delta n=0.231$) with an UV-curable monomer NOA65 (refractive index $n_p=1.524$) at 84:16 wt % ratios. Here, we intentionally used a higher LC concentration in order to obtain a larger phase change at a lower voltage. The conventional PDLC with $\sim$65:35 LC/monomer ratios would work equally well but the required voltage is higher. The LC/monomer mixture was injected into an empty cell whose inner surfaces were coated with a thin indium-tin-oxide (ITO) electrode. The cell gap was measured to be $d=22$ μm. The filled cell was then exposed to UV light ($\lambda \sim 365$ nm and $1-15$ mW/cm^2) at room temperature for 30 min to induce phase separation.

We observed the phase separation morphology of the PDLC sample using a polarized optical microscope. The formed morphology indicates that the LC dispersed in polymer matrix exists as *domains* separated by polymer networks rather than isolated LC *droplets*. This kind of morphology is common for the PDLC system having a high LC concentration.[12]

Next, we measured the transmittance of the PDLC cell using a He–Ne laser ($\lambda=633$ nm) beam. A large area photodiode detector was placed at $\sim$30 cm behind the sample which corresponds to $\sim$2° collection angle. A computer controlled LabVIEW data acquisition system was used for driving the sample and recording the light transmittance.

Figure 2 plots the measured voltage-dependent transmittance of the PDLC sample. At $V=0$, the PDLC sample is translucent so that the transmittance is low. As the voltage increases, the transmittance increases. From Fig. 2, the measured contrast ratio is $\sim$9:1, which is lower than a typical PDLC because of the larger domain size which originates from the higher LC concentration. When the applied voltage exceeds 26 V$_{rms}$, the transmittance remains basically unchanged. We define this voltage as saturation voltage (V_{sat}). At $V>V_{sat}$, the PDLC cell remains highly transparent. For each cell, the saturation voltage could vary because it depends on the cell gap, LC material, and monomer concentration.

To examine whether the PDLC film exhibits a phase-only modulation capability in the high voltage regime, we measured its transmittance at $\lambda=633$ nm between parallel and crossed polarizers. Results are shown in Fig. 3. The transmittance increases for the parallel polarizer configuration, while it decreases gradually for the crossed polarizers in the $V>V_{sat}$ region. These results imply that PDLC can pro-

duce phase-only modulation when the applied voltage is higher than the saturation voltage. Moreover, rotating the sample does not affect the measurement results shown in Fig. 3. This indicates that the phase-only modulation is independent of the incident light polarization. In the high voltage state, the LC directors are basically perpendicular to the substrates, similar to a homeotropic cell. The input linearly polarized light always sees the ordinary refractive index, regardless of its polarization axis. Thus, the phase modulation is independent of the incident light polarization.

From Fig. 3, the saturation voltage of the PDLC sample is $\sim$1.2 V/μm, which is $\sim$10$\times$ lower than that of a nano-PDLC. The phase change (δ) of the PDLC sample can be calculated using the following equation:[13]

$$\delta = 2 \tan^{-1} \sqrt{T_\perp/T_\parallel}, \tag{1}$$

where $T_\perp$ and $T_\parallel$ represent the transmittance at the crossed- and parallel-polarizer configurations, respectively. Figure 4 plots the measured voltage-dependent phase change of the PDLC cell. From 26 to 60 V$_{rms}$, δ decreases gradually because the LC directors inside the droplets continue to be reoriented by the electric field, as schematically shown in Fig. 1(c). Although the phase change is small, it is still sufficient for making microlens arrays. To increase the phase difference, several approaches can be implemented, for instance, to use a high birefringence LC material, increase LC cell gap, or enhance LC concentration.

Response time is a very important parameter for almost every LC device. We measured the PDLC response time using a square voltage burst at $f=1$ kHz between 26 and 55 V$_{rms}$. The measured rise time is $\sim$0.8 ms and decay time $\sim$1.9 ms at room temperature. Such a fast response time results from the high bias voltage effect.[14]
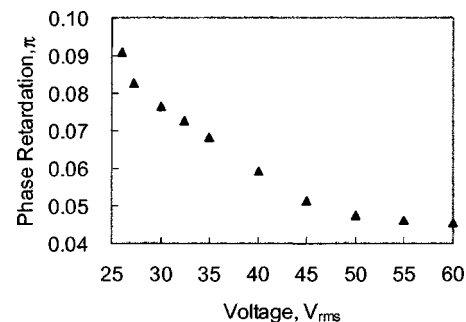

FIG. 4. Measured phase shift of the PDLC cell at different voltages. Cell gap $d=22$ μm.
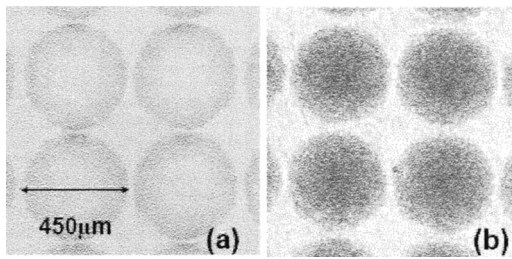
FIG. 5. Microscope photos of (a) concave polymer microlens arrays, and (b) polymer/PDLC microlens arrays.

FIG. 6. Measured CCD images of the 2D microlens arrays at different voltages: (a) $V=0$ (b) $V=70$ V_{rms}, and (c) $V=140$ V_{rms}.

To demonstrate the usefulness of the observed phase change, we fabricated 2D microlens arrays using the PDLC as electro-optic medium. We first used a lamination method to prepare polymer microlens arrays.[15] The polymer material used is NOA65 ($n_p=1.524$). The thickness and diameter of the formed microlens is ~50 and 450 μm, respectively. Afterwards, we filled the polymer microlens array cavities with the NOA65/E48 mixture. The cell was then sealed with a top ITO-glass substrate. Finally, we cured the sealed cell using an UV light. The UV curing condition is the same as mentioned above.

Figure 5(a) and 5(b) show the patterned polymer microlens arrays before and after filling the PDLC material. These two images were taken under a polarized optical microscope. From Fig. 5(a), each circular ring corresponds to a concave lens of ~450 μm diameter and lens pitch ~20 μm. In Fig. 5(b), the filled circular region is translucent due to light scattering.

To characterize the focusing properties of the microlens, we illuminated the lens arrays with a collimated unpolarized He–Ne laser beam. The transmitted light was detected by a CCD camera. Figure 6 shows the images of the focused spots produced by the microlens arrays at different voltages. At $V=0$, the focusing effect is obscured because of strong light scattering. At $V=70$ V_{rms}, the focal spots appear but not very sharp. At $V=140$ V_{rms}, the focus is at image plane. Thus, the light intensity increases noticeably. This result means that the patterned microlens arrays have a tunable focal length in the high voltage regime. If we increase the voltage from 70 to 180 V_{rms}, the focal length is tuned continuously from ~8 to ~12 cm. In principle, if the LC and polymer have a similar ordinary refractive index, the focal length of the polymer/PDLC microlens should reach infinity in the high voltage regime. The focal length of a microlens is dependent on the lens radius, LC birefringence, and lens thickness. If we want to reduce the focal length, we could reduce the lens
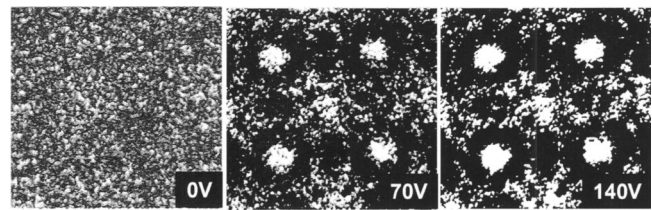
diameter, use a higher birefringence LC, or increase the lens thickness.

In comparison with other tunable LC phase modulators, PDLC exhibits a relatively small phase change. This is because the phase phenomenon only exists in the high voltage regime where the LC orientation is close to the saturation level. However, the phase modulation using PDLC is polarization independent, scattering-free, and has fast response time. The operating voltage is lower than that of a nano-PDLC system. Although the tunable phase shift is small, it is still sufficient for some microdevices.

In conclusion, we have demonstrated the phase modulation capability using a PDLC film which only exists in the high voltage regime. Such a phase modulation is scattering-free, polarization independent, and has fast response time. Although the phase change is small, it is still sufficient for making tunable-focus microlens arrays.

[1]V. Freedericksz and V. Zolina, Trans. Faraday Soc. **29**, 919 (1933).
[2]N. Konforti, E. Marom, and S. T. Wu, Opt. Lett. **13**, 251 (1988).
[3]S. Gauza, H. Wang, C. H. Wen, S. T. Wu, A. J. Seed, and R. Dabrowski, Jpn. J. Appl. Phys., Part 2 **42**, 3463 (2003).
[4]S. Matsumoto, M. Houlbert, T. Hayashi, and K. Kubodera, Appl. Phys. Lett. **69**, 1044 (1996).
[5]L. Vicari, J. Appl. Phys. **81**, 6612 (1997).
[6]T. J. Bunning, L. V. Natarajan, V. P. Tondiglia, G. Dougherty, and R. L. Sutherland, J. Polym. Sci., Part B: Polym. Phys. **35**, 2825 (1997).
[7]H. Ren and S. T. Wu, Appl. Phys. Lett. **81**, 3537 (2002).
[8]D. E. Lucchetta, R. Karapinar, A. Manni, and F. Simoni, J. Appl. Phys. **91**, 6060 (2002).
[9]R. L. Sutherland, V. P. Tondiglia, L. V. Natarajan, T. J. Bunning, and W. W. Adams, Appl. Phys. Lett. **64**, 1074 (1994).
[10]J. W. Doane, N. A. Vaz, B. G. Wu, and S. Zumer, Appl. Phys. Lett. **48**, 269 (1986).
[11]F. Basile, F. Bloisi, L. Vicari, and X. Simoni, Phys. Rev. E **48**, 432 (1993).
[12]P. S. Drzaic, *Liquid Crystals Dispersions* (World Scientific, Singapore, 1995).
[13]S. T. Wu, U. Efron, and L. D. Hess, Appl. Opt. **23**, 3911 (1984).
[14]S. T. Wu and D. K. Yang, *Reflective Liquid Crystal Displays* (Wiley, New York, 2001).
[15]H. Ren, Y. H. Fan, and S. T. Wu, Opt. Lett. **29**, 1608 (2004).