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A polarization independent liquid crystal phase modulation adopting surface pinning effect of polymer dispersed liquid crystals

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A polarization-independent liquid crystal (LC) phase modulation using the surface pinning effect of polymer dispersed liquid crystals (SP-PDLC) is demonstrated. In the bulk region of the SP-PDLC, the orientations of LC directors are randomly dispersed; thus, any polarization of incident light experiences the same averaged refractive index. In the regions near glass substrates, the LC droplets are pinned. The orientations of top and bottom droplets are orthogonal. Two eigen-polarizations of an incident light experience the same phase shift. As a result, the SP-PDLC is polarization independent. Polarizer-free microlens arrays of SP-PDLC are also demonstrated. The SP-PDLC has potential for application in spatial light modulators, laser beam steering, and electrically tunable microprisms. © *2011 American Institute of Physics*. [doi:10.1063/1.3666053]

I. INTRODUCTION

Liquid crystal (LC) phase-only modulations are useful for laser beam steering,[1] tunable focus lenses,[2] electrically tunable gratings and prisms,[3] and spatial light modulators.[4] The advantages of LC phase modulators are their low cost, light weight, low power consumption, and electrical controllability without mechanical moving parts. However, the use of polarizers greatly reduces the optical efficiency. Therefore, the development of a polarization independent LC phase modulator is necessary.[5–7] Two main types of polarization independent LC phase modulators have been demonstrated. One is the residual phase type of LC phase modulations.[5,6] The orientations of LC directors are randomly dispersed. As a result, any polarization of incident light experiences the same averaged refractive index, which is related to the same phase shift. However, the residual phase type suffers from a relatively small phase change. To enhance the phase change while maintaining polarization independence, a double-layered type of LC phase modulations is demonstrated.[5,7] The structure is based on two homogeneous LC layers with orthogonal rubbing directions. Each LC layer modulates one of the eigen-polarizations of an incident light. As a result, two eigen-polarizations of an incident light experience the same phase shift. Recently, the polarization independent phase modulation of polymer-stabilized blue phase liquid crystals (PSBP-LC) has been investigated as well, based on the optical isotropy of blue phase liquid crystals.[8] However, the stability of materials and the temperature range of PSBP-LC limited the applications. In the current work, we aim to develop a different type of polarization independent LC phase modulator by mixing the residual phase type and the double-layered type. In 2005, the surface pinning effect of polymer dispersed liquid crystals (SP-PDLC), which can determine the morphologies of polymer dispersed liquid crystals, was studied.[9] The LC droplets are pinned near glass substrates and at random in the bulk region. Adding dye in to SP-PDLC can enable a high contrast polarizer-free display.[10] Up to now, no related phase investigation of SP-PDLC has been studied. Here, we demonstrate a polarization independent LC phase modulation based on SP-PDLC. The mechanism of such a LC phase modulation includes the residual phase type of LC phase modulation in the bulk region and the double-layered type of LC phase modulation in two layers near the glass substrates. The measured phase shift is around 0.28 rad. Polarizer-free LC microlens arrays using SP-PDLC are also demonstrated.

II. STRUCTURE AND OPERATING PRINCIPLES

Figures 1(a) and 1(b) illustrate the structure and operating principles of the phase modulation using SP-PDLC. In Fig. 1(a), the LC droplets near the substrates are pinned owing to the surface pinning effect,[9,10] and the orientations of LC directors are along the rubbing directions (y direction of the top alignment layer and x direction of the bottom alignment layer). In the bulk region of Fig. 1(a), the averaged orientations of the rest of the LC droplets are randomly dispersed in the polymer matrix. Without an applied voltage ($V = 0$), the SP-PDLC cell scatters the incoming light due to the refractive mismatch between polymer and liquid crystals, as shown in Fig. 1(a). As the applied voltage increases, LC directors are reoriented along the direction of the electric field (z direction), as shown in Fig. 1(b). As a result, scattering decreases and the SP-PDLC cell becomes more transparent. When the voltage exceeds the saturation voltage (V_s), the SP-PDLC is scatter-free and it is switched into a pure phase modulation that is polarization independent.

In the pure phase region ($V > V_s$), the mechanism of the polarization-independent phase modulation of SP-PDLC can be proven as follows. Let us consider a randomly polarized and quasi-monochromatic light incident to a sample at a normal angle. The electric field of the incident light consists of randomly polarized lights, and each polarized light can be

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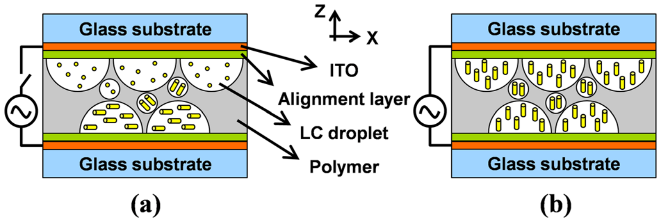

FIG. 1. (Color online) The structure and operating principles of SP-PDLC at (a) V = 0 and (b) V > V_s.

decomposed as x- and y-linearly polarized lights. The electric field of the incident light can be written as

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

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). $A_{0x}(\vec{r},t)$ and $A_{0y}(\vec{r},t)$ satisfy the following relationship: $A_{0x}(\vec{r},t)^2 + A_{0y}(\vec{r},t)^2 = 1$. The coefficient $a_j(\vec{r},t)$ is a complex weighting factor for the jth component, and $(A_{0x}(\vec{r},t) \times \hat{x} + A_{0y}(\vec{r},t) \times \hat{y})_j$ represents the polarization state of the jth component. When the incoming light passes through the SP-PDLC cell along the +z direction in Fig. 1(a), the x and y components of the polarization of the incident light accumulate phases. The total accumulated phase (δ) is attributed to two parts. First, the orientations of LC droplets near the top and bottom glass substrates are orthogonal to each other at V = 0. The phase modulation is similar to the double-layered type of phase modulations.[5,7] Thus, the phase of the two eigen-polarizations (x and y linear polarizations) is $(k \times n_{eff}(\theta,\psi+\pi/2) \times d_1 + k \times n_{eff}(\theta,\psi) \times d_1)$, where k is a wave number ($k = 2\pi/\lambda$), d_1 is the radius of the droplet pinned on the glass substrate, and $n_{eff}(\theta,\psi)$ is the effective refractive index depending on the tilt angle θ with respect to the z direction and the twist angle ψ of LC directors with respect to the x direction. $n_{eff}(\theta,\psi)$ satisfies the following relation when $\psi = 0$:

$$\frac{1}{n_{eff}^2(\theta,0)} = \frac{\sin^2(\theta)}{n_e^2} + \frac{\cos^2(\theta)}{n_o^2}, \quad (2)$$

and $n_{eff}(\theta,\psi) = n_o$ with arbitrary θ when $\psi = \pi/2$ radians. Second, LC droplets in the middle layer are randomly dispersed; therefore, it is similar to the residual phase type of phase modulations.[5,6] The phase is $(k \times n_{ave}(\theta) \times d_2)$, where d_2 is the diameter of the droplet in the middle layer of SP-PDLC as depicted in Fig. 1, and the averaged refractive $n_{ave}(\theta)$ depending on the tilt angle θ of LC directors is $(n_{eff}(\theta,0) + n_o)/2$. Thus, the total accumulated phase (δ) can be expressed as

$$\delta = k \times n_{eff}(\theta,\psi+\pi/2) \times d_1 + k \times n_{ave}(\theta) \times d_2 + k \times n_{eff}(\theta,\psi) \times d_1, \quad (3)$$

where $\psi = 0$ and $\pi/2$ radians for the x and y components of the polarization of the incident light, respectively. After light passes through a SP-PDLC cell, the electric field of the output light is

$$\vec{E}_{output}(\vec{r},t) = \sum_j \{a_j(\vec{r},t)[e^{i\times(k\times n_{eff}(\theta,\psi)\times d_1 + k\times n_{ave}(\theta)\times d_2 + k\times n_{eff}(\theta,\psi+\pi/2)\times d_1)} \times A_{0x}(\vec{r},t)\times\hat{x} + e^{i\times(k\times n_{eff}(\theta,\psi+\pi/2)\times d_1 + k\times n_{ave}(\theta)\times d_2 + k\times n_{eff}(\theta,\psi)\times d_1)} \times A_{0y}(\vec{r},t)\times\hat{y}]_j\}. \quad (4)$$

We can rearrange Eq. (4), and it can be expressed as

$$\vec{E}_{output}(\vec{r},t) = e^{i\times(k\times n_{eff}(\theta,\psi+\pi/2)\times d_1 + k\times n_{ave}(\theta)\times d_2 + k\times n_{eff}(\theta,\psi)\times d_1)} \times \vec{E}_{input}(\vec{r},t). \quad (5)$$

In Eq. (5), the only difference between output and input lights is the phase shift. Therefore, SP-PDLC is polarization independent.

III. EXPERIMENTS AND DISCUSSIONS

To prepare a SP-PDLC sample, we mixed UV-curable monomer NOA65 ($n_p = 1.524$) in a nematic LC host (E48, $\Delta n = 0.231$ at $\lambda = 589$ nm) at 30:70 wt. % ratios. We injected the LC/monomer mixture into an empty cell with an inner surface coated with indium-tin-oxide (ITO) and polyimide that was mechanically buffered in orthogonal directions in the isotropic state at T = 70 °C. The cell gap was 7.7 μm. The cell then exposed UV light with an intensity I = 60 mW/cm^2 for 15 min at T = 20 °C. We observed the phase separation morphology of the SP-PDLC sample under a polarizing optical microscope (POM) and a scanning electron microscope (SEM) as shown in Figs. 2(a) and 2(b). In Fig. 2(a), the morphology of the SP-PDLC is uniform due to the surface pinning effect.[9,10] In Fig. 2(b), the side view of the SP-PDLC cell shows three layers. The thickness (or droplet size) near the top and bottom substrate is around 3 μm, and the thickness in the middle layer is around 1 μm. The droplet size or layer thickness can be adjusted by changing the curing temperature and UV curing intensity.

Next, we measured the transmittance of the SP-PDLC cell. The light source was an unpolarized He-Ne laser (JDSU, model 1122, $\lambda = 633$ nm). A large area photodiode detector (New Focus, model 2031) was placed ~30 cm behind the SP-PDLC cell, corresponding to a ~2° collection angle. A computer controlled LABVIEW data acquisition system was used to apply the voltage to the sample and record

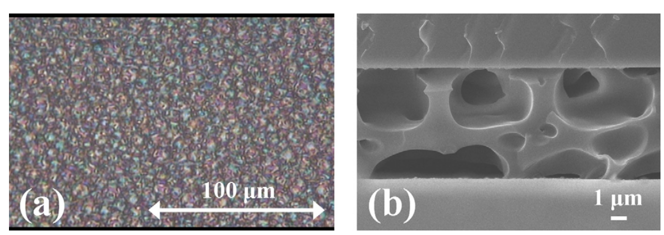

FIG. 2. (Color online) (a) The top view POM morphology and (b) SEM side view image of SP-PDLC.

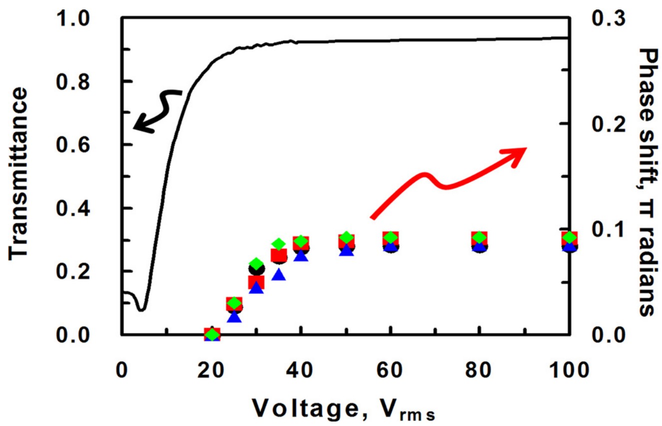

FIG. 3. (Color online) Voltage-dependent transmittance of SP-PDLC and voltage-dependent phase shift at rotational angles of the polarizer: 0° (red squares), 45° (blue triangles), and 90° (green diamonds). Black dots represent instances when no polarizer was used.

the transmittance at the same time. Figure 3 shows the measured transmittance as a function of an applied voltage. At $V = 0$, the SP-PDLC has low transmittance because of scattering. When the voltage increases, the transmittance increases. The transmittance is high and remains almost unchanged after $V > 20\ V_{rms}$. We define this voltage as the saturation voltage (V_s). When $V > V_s$, SP-PDLC is operated as a pure phase modulator.

In order to measure the phase as $V > V_s$, we adopted a Mach-Zehnder interferometer. An unpolarized He-Ne laser (JDSU, model 1122, $\lambda = 633$ nm) was split equally into two arms by a beam splitter, and then the two beams were re-combined again by the other beam splitter. The interference fringes can be observed when two beams overlap. Our sample was put in one arm of the interferometer. The fringes were recorded by a digital camera (SONY, DCR-HC40). By recording the shifted fringes between the high voltage and the saturation voltage, we can obtain the phase shift of the SP-PDLC cell. The saturation voltage is defined as the voltage at a transmittance of 85% due to the clear interference fringes when the voltage is larger than the saturation voltage. Figure 3 shows the phase shift as a function of an applied voltage as $V > V_s$. The total phase shift between 20 and 40 V_{rms} is around 0.09 π or 0.28 rad. In fact, the interference patterns were smeared at $V < V_s$ due to the scattering of SP-PDLC. In order to examine the polarization dependency, we measured the phase shift as we put a polarizer in front of the laser and rotated the polarizer. The phase shifts are almost the same at the different polarizations of the incident light, as shown in Fig. 3. That means SP-PDLC has pure phase modulation and is polarization independent as well. The total response time (rise time plus decay time) is around 12 ms when the SP-PDLC is given a square burst at f = 1 kHz between 0 and 40 V_{rms} and around 3.8 ms when the voltage is switched between 20 and 40 V_{rms}. The fast response is because of the bias voltage effect and polymer networks.[11]

From Eq. (3), the total accumulated phases at V_s and at high voltage ($V \gg V_s$) for any polarized light can be expressed as in Eq. (6) and Eq. (7).

$$\delta(V_S) = k \times n_{eff}(\theta) \times d_1 + k \times n_{ave}(\theta) \times d_2 + k \times n_o \times d_1 \quad (6)$$

$$\delta(V \gg V_S) = k \times n_o \times d_1 + k \times n_o \times d_2 + k \times n_o \times d_1 \quad (7)$$

From Eqs. (6) and (7), the total phase shift ($\Delta\delta$) between V and V_s, defined as $\Delta\delta \equiv \delta(V \gg V_s) - \delta(V_s)$, turns out to be

$$|\Delta\delta| = k \times (n_{eff}(\theta) - n_o) \times d_1 + k \times (n_{ave}(\theta) - n_o) \times d_2. \quad (8)$$

In our experiments, $n_o = 1.523$, $n_e = 1.754$, $d_1 \sim 3\ \mu$m, and $d_2 \sim 1\ \mu$m. The values of d_1 and d_2 are obtained from Fig. 2(b). The SP-PDLC cell is transparent when $n_{ave} - n_o < 0.005$.[11] The value of $n_{ave} - n_o$ equals $(n_{eff}(\theta, 0) - n_o)/2$, and then the calculated θ is around $\sim 13°$ according to Eq. (2). The calculated $\Delta\delta$ is then $\sim 0.106\ \pi$ radians, close to the measured result of 0.09 π radians. The phase shift of SP-PDLC ($\sim 0.1\ \pi$ radians) is larger than that of the residual phase type ($\sim 0.016\ \pi$ radians with an 8 μm cell gap) and smaller than that of the double layered type ($\sim 5\ \pi$ radians with an 8 μm cell gap).[5–7] To enlarge the phase shift, we can enlarge the domain size and cell gap. However, the polarization dependency increases as the domain size gets too large. The surface pinning effect decreases when the cell gap is large.

To demonstrate a two-dimensional (2D) microlens arrays using SP-PDLC as an electro-optics medium, we prepared microlens arrays consisting of one ITO glass substrate, one glass substrate coating with an aluminum layer into which were etched hole-patterns 130 mm in diameter, and SP-PDLC, as shown in Fig. 4(a).[12] The distance between hole-patterns was 120 mm. The cell gap was 8 mm. In order to characterize the focusing properties, a collimated unpolarized light at $\lambda = 532$ nm was used to illuminate the SP-PDLC microlens arrays. The transmitted light was recorded by a charge-coupled device (CCD). The light intensities of a sub-microlens of SP-PDLC microlens arrays at different voltages are shown in Fig. 4(b). The CCD was placed 3 cm from the sample. The intensity in Fig. 4(b)

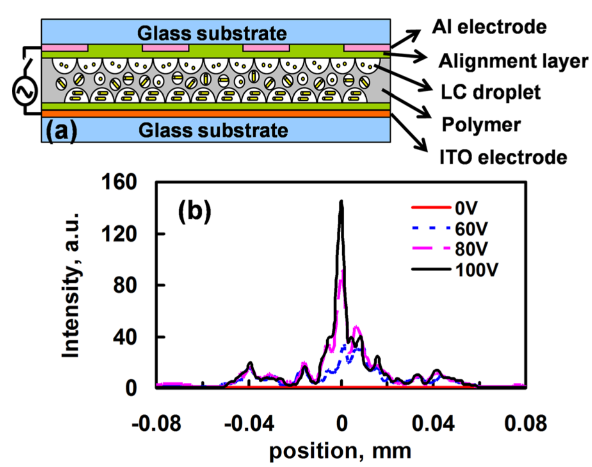

FIG. 4. (Color online) (a) The structure of SP-PDLC microlens arrays. (b) The light intensity of a sub-microlens of SP-PDLC microlens arrays as a function of position at different voltages.

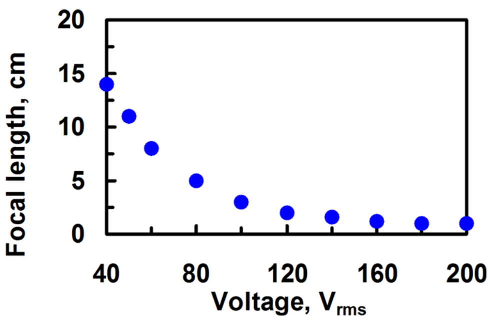

FIG. 5. (Color online) The voltage-dependent focal length of SP-PDLC microlens arrays.

increases with the voltage. SP-PDLC microlens arrays showed clear focal spots at 100 V_{rms}. When we applied different voltages, the position of the CCD was changed so as to obtain a clear focal spot, and we recorded the distance between the CCD and the sample as the measured focal length. The measured focal length as a function of voltage is plotted in Fig. 5. When the applied voltage is less than 40 V, the SP-PDLC microlens arrays are in the scattering state and are out of focus. As the applied voltage exceeds 40 V, the SP-PDLC microlens arrays become transmitted and focus the light. The tunable focal length was measured from ~14 cm at 40 V_{rms} to ~1 cm at 200 V_{rms}. When we placed a polarizer in front of the microlens arrays, the measured focal length did not change with the rotation of the polarizer. Thus, the focal length of SP-PDLC microlens arrays is electrically tunable, and SP-PDLC microlens arrays are polarization independent. To reduce the voltage, the droplet size can be increased and the dielectric constant of the polymer can be enlarged.

IV. CONCLUSION

We have demonstrated a polarization-independent LC phase modulation using SP-PDLC, as well as the microlens arrays. The mechanism of polarization independence of the SP-PDLC phase modulation is a mixture of LC phase modulations that is a combination of two well-known types, the residual phase type LC phase modulations in the bulk region and the double-layered type LC phase modulation near two substrates. The microlens arrays of SP-PDLC are in the scattering state at $0 < V < 40\ V_{rms}$ and in the pure phase state at $V > 40\ V_{rms}$. The focusing properties are polarization independent. The focal length is electrically tunable from 14 cm to 1 cm. Such a polarization independent LC phase modulation is important in many applications, such as spatial light modulators, laser beam steering, e-lens, and microprisms.

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