

## High contrast polymer-dispersed liquid crystal in a 90° twisted cell

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A polymer-dispersed liquid crystal confined in a 90° twisted cell (T-PDLC) is demonstrated. In comparison to a conventional PDLC, the T-PDLC is also polarization independent while exhibiting a higher contrast ratio. Potential applications of the T-PDLC are in polarizer-free reflective display and light switch. A black and white segmented-alphabet reflective display using a dye-doped T-PDLC is demonstrated. © 2004 American Institute of Physics. [DOI: 10.1063/1.1753052]

Polymer dispersed liquid crystal (PDLC) which does not require a polarizer is a promising electro-optic material for displays,<sup>1,2</sup> light switches,<sup>3–8</sup> and tunable-focus lens.<sup>9</sup> Usually, PDLC consists of micron-sized LC droplets dispersed in a polymer matrix. The droplets are randomly distributed in the polymer matrix and their sizes are close to the visible wavelengths. As a result, light scattering which originates from the refractive index mismatch between the LC droplets and polymer matrix is strong. A normal mode PDLC is translucent in the voltage-off state. As the applied voltage increases, the LC directors within the droplets are gradually reoriented by the electric field. If the LC ordinary refractive index matches well with the refractive index of the polymer matrix, the film becomes transparent. Depending upon the applications, PDLC can be prepared with different polymer concentrations, typically in the 30–65 wt % range. The LC inside the droplets has many contact surfaces with polymer matrix, thus, the operating voltage is relatively high ( $\sim 5 V_{\text{rms}}/\mu\text{m}$ ). Reducing cell gap or polymer concentration would lower the operating voltage, however, the contrast ratio is reduced accordingly. There is an urgent need to develop a low voltage PDLC while maintaining high contrast ratio.

In this letter, we demonstrate a polymer-dispersed liquid crystal confined in a 90° twisted cell (abbreviated as T-PDLC) which exhibits a higher contrast ratio than a conventional PDLC. Unlike the traditional PDLC cell, our polyimide-buffed substrates are rubbed in orthogonal directions, similar to a 90° twisted nematic cell. Due to the larger refractive index mismatch, the T-PDLC not only preserves the advantage of polarization independence but also exhibits a higher light scattering efficiency.

In experiment, we mixed UV-curable monomer NOA65 in a nematic LC host (E48,  $\Delta n = 0.231$  at  $\lambda = 589$  nm). The concentration of NOA65 is in the 15%–50% range. The LC/monomer mixture was injected into an empty 90° twisted cell in the isotropic state. The pretilt angle of the LC cell is  $\sim 3^\circ$  and the cell gaps are  $d = 6.5$  and  $8 \mu\text{m}$ . For comparison, a conventional PDLC cell, i.e., the indium-tin-oxide (ITO) glass substrates without alignment layer, was also prepared under the same conditions ( $d = 8 \mu\text{m}$ ). In our experiments, the UV exposure intensity is  $I = 60 \text{ mW}/\text{cm}^2$  and curing time for both cells is 15 min at  $T = 20^\circ\text{C}$ .

The electro-optic properties of the PDLC and T-PDLC

cells were studied by measuring the transmittance of an unpolarized He–Ne laser beam ( $\lambda = 633$  nm) at normal incidence. The photodiode detector was placed at  $\sim 20$  cm behind the sample; the corresponding collection angle is  $\pm 1^\circ$ . The voltage dependent transmittance curves were recorded by the LabVIEW data acquisition system. The response time was measured using a digital phosphor oscilloscope.

Figures 1(a) and 1(b) show the morphologies of the  $8 \mu\text{m}$  PDLC and T-PDLC cells, respectively, observed from a polarized optical microscope in the voltage-off state. The polymer concentration ( $c$ ) is 30% for both cells. From Figs. 1(a) and 1(b), we find that the liquid crystal droplets in the T-PDLC cell are smaller and more uniformly distributed than those in the PDLC cell. In the voltage-off state, these oriented droplets nearby the surface alignment layers enhance the light scattering efficiency because of the enlarged refractive index mismatch between the LC droplets and polymer matrix. Therefore, to achieve the same light scattering level the required T-PDLC layer is thinner than that of a PDLC.

To evaluate the contrast ratios of the T-PDLC and PDLC cells, we measured their voltage-dependent transmittance. To calibrate the substrate reflection losses, the transmittance of a homogeneous cell filled with E48 LC mixture is defined as unity. Figure 2(a) compares the voltage dependent transmittance of an  $8 \mu\text{m}$  PDLC (gray line) and a  $6.5 \mu\text{m}$  T-PDLC (dark line) cells at the same polymer concentration ( $c = 40\%$ ). The T-PDLC cell has a better dark state at  $V = 0$  and slightly higher transmittance in the voltage-on state than PDLC. Thus, T-PDLC exhibits a higher contrast ratio than the PDLC even though its cell gap is thinner than that of

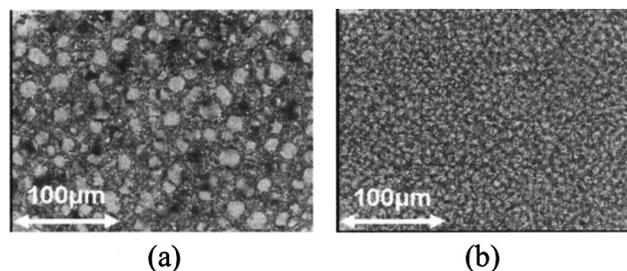


FIG. 1. Phase separation morphologies of (a) PDLC and (b) T-PDLC observed from a polarized optical microscope. NOA65:E48 = 30:70. Both devices have same cell gap  $d \sim 8 \mu\text{m}$ . The T-PDLC has an  $\sim 1.5\times$  smaller and more uniform droplet size than PDLC.

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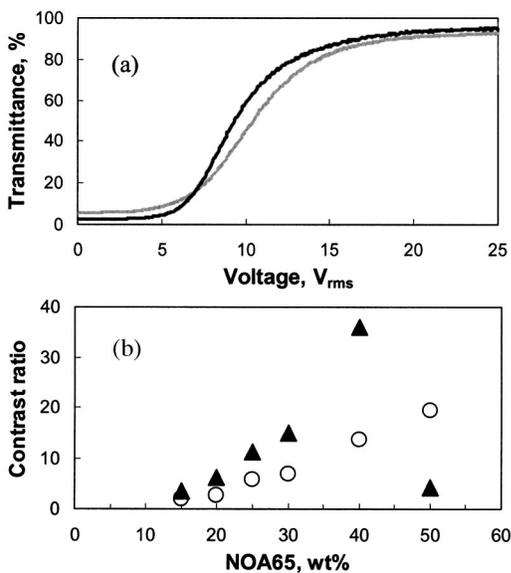


FIG. 2. (a) Voltage-dependent transmittance of T-PDLC (dark line) and PDLC (gray line). LC/polymer mixture: NOA65:E48=40:60;  $\lambda = 633$  nm; (b) polymer concentration effect on device contrast ratio. Triangles are for the 6.5  $\mu\text{m}$  T-PDLC cell and circles are for the 8  $\mu\text{m}$  PDLC cell.

PDLC. To understand this phenomenon, we need to consider the surface alignment effect.

The physical mechanism responsible for the observed smaller droplets and more uniform size distribution in T-PDLC, as shown in Fig. 1(b), is believed to originate from the surface anchoring effect of the buffed polyimide surfaces. The strong surface anchoring energy prevents LC droplets from growing and aggregating with the surrounding droplets during phase separation process. As a result, T-PDLC exhibits a smaller droplet and more uniform droplet distribution than PDLC under the same polymer concentration and UV exposure conditions. The better droplet uniformity helps to enhance light scattering efficiency when the droplet size is comparable to the wavelength. In Fig. 1(b), the droplet size is  $\sim 2$   $\mu\text{m}$ . A 6–7  $\mu\text{m}$  cell gap would contain roughly 3 droplets in each crosssection.

In a T-PDLC, the LC molecules inside the droplets near the substrates present orthogonal orientation. In the bulk, the LC droplets are randomly distributed. Therefore, its light scattering behavior in the voltage-off state is also independent of polarization, similar to a PDLC. In the low voltage regime, the T-PDLC cell exhibits a better dark state than PDLC, as shown in Fig. 2(a). The saturation voltage of both cells occurs at  $\sim 20$  V<sub>rms</sub>. Thus, we compare the contrast ratio at  $V = 20$  V<sub>rms</sub>, i.e.,  $CR = T(V = 20)/T(V = 0)$ . From Fig. 2(a), T-PDLC exhibits a higher contrast ratio than PDLC.

In addition to surface alignment, polymer concentration also plays an important role in affecting the device contrast ratio. We have varied the polymer concentration from 15% to 50%. In both T-PDLC and PDLC cells, the droplet size decreases as the polymer concentration increases. In the same polymer concentration, the droplet size of T-PDLC is roughly  $\sim 1.5\times$  smaller than that of PDLC. Therefore, the optimal polymer concentration for maximizing light scattering (i.e., droplet size is comparable to the laser wavelength) for T-PDLC and PDLC is different. For T-PDLC, the optimal

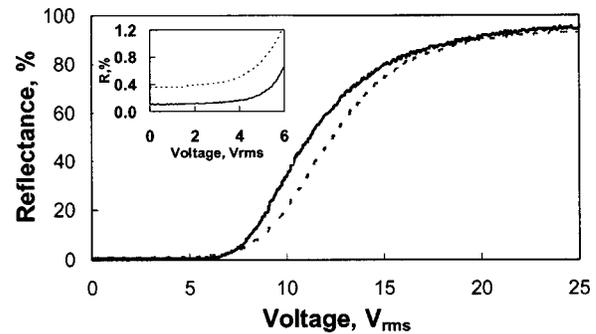


FIG. 3. Voltage dependent reflectance of T-PDLC (solid line;  $d = 6.5$   $\mu\text{m}$ ) and PDLC (dashed lines;  $d = 8$   $\mu\text{m}$ ). The inset shows the magnified scale for comparing the dark state.

polymer concentration would be lower than that for PDLC.

Figure 2(b) shows the polymer concentration dependent contrast ratio (measured at  $V = 20$  V<sub>rms</sub>) for T-PDLC (triangles) and PDLC (circles). From Fig. 2(b), as the polymer concentration increases, the contrast ratios for both T-PDLC and PDLC cells increase almost linearly but at different slopes. For the 6.5  $\mu\text{m}$  T-PDLC, the optimal polymer concentration occurs at  $c \sim 40\%$  where the contrast ratio reaches  $\sim 35:1$ . At  $c = 50\%$ , the droplet size becomes much smaller than the He–Ne laser wavelength. Moreover, the influence of surface anchoring to these tiny droplets is no longer significant. As a result, the contrast ratio decreases sharply. On the other hand, for the 8  $\mu\text{m}$  PDLC at  $c = 50\%$  its droplet size is still  $\sim 1.5\times$  larger than that of T-PDLC so that the light scattering remains significant. Its optimal polymer concentration should occur at a higher level. Increasing cell gap would improve the contrast ratio for both T-PDLC and PDLC at the expense of increased voltage. Increasing curing temperature<sup>10</sup> is another option for improving contrast ratio. However, the response time becomes slower.

The response time of the transmissive T-PDLC and PDLC cells was measured at room temperature using 20 V<sub>rms</sub> square pulses. In general, the PDLC response time depends on the LC viscosity, droplet size and shape, and the ratio of the applied voltage over threshold voltage.<sup>11</sup> For the 6.5- $\mu\text{m}$ -thick T-PDLC cell ( $c = 40\%$ ), the measured rise time (10%–90%) is  $\sim 5$  ms and decay time (90%–10%) is  $\sim 10$  ms. In contrast, the 40% PDLC has 7.6 ms rise time and 21 ms decay time. The faster response time of T-PDLC originates from its smaller droplet sizes. To further improve switching speed, we could reduce the droplet size by increasing the polymer concentration or use a lower viscosity LC. However, smaller droplet sizes require a higher operating voltage. Holographic PDLC is such an example.<sup>4</sup>

In Fig. 2, the contrast ratio of the thin transmissive T-PDLC and PDLC cells is insufficient for display or light switch applications. To enhance contrast ratio, a thicker LC layer or reflective mode operation can be considered. A thicker PDLC layer would result in a higher operating voltage. For the interest of keeping operating voltage low, reflective mode is preferred. In a reflective device, the incident light traverses the LC layer twice so that its contrast ratio is increased by a quadratic function.<sup>12</sup>

Figure 3 depicts the voltage-dependent reflectance of the T-PDLC (solid line) and PDLC (dashed lines) cells with  $c = 40\%$ . The cell gap for the T-PDLC and PDLC is 6.5 and

8.0  $\mu\text{m}$ , respectively. In principle, the reflector should be imbedded in the inner side of the cell in order to avoid parallax.<sup>13</sup> For proving concept, we simply placed a dielectric mirror behind the transmissive cell. To avoid overlapping, the reflected unpolarized He–Ne laser beam was deviated from the incident beam by  $\sim 4^\circ$ . The collection angle of the photodiode detector remains at  $\pm 1^\circ$ . The inlet in Fig. 3 shows the magnified dark state reflectance. Apparently, T-PDLC exhibits a better dark state than PDLC, although its cell gap is thinner. At  $V \sim 20 V_{\text{rms}}$ , the measured contrast ratio of the PDLC cell is  $\sim 250:1$ . For T-PDLC, the measured contrast ratio is  $\sim 900:1$ , which is not too far off from the square of 35:1 (the contrast ratio of the transmissive mode). Indeed, double pass significantly improves the device contrast ratio.

The dark state of a light scattering-based display is translucent, rather than black. To realize a black and white display, we added an  $\sim 2$  wt% black dye to the  $c=40\%$  T-PDLC cell. The cell gap is  $d \sim 6.7 \mu\text{m}$ . The bottom ITO electrode was etched into a segmented number “8.” The T-PDLC cell preparation process remains the same. For demonstration purpose, we placed a piece of white paper behind the bottom substrate to serve as a diffusive reflector. Figure 4 shows the displayed image at  $V=20 V_{\text{rms}}$ . The on-state T-PDLC is highly transparent so that the reflected image appears white. Since the display does not require a polarizer, the viewing angle is wide and the display is bright under room light condition. The display contrast ratio was measured to be  $\sim 10:1$ , limited by the dichroic ratio of the employed dye molecules. The doped 2% dye molecules slightly increase the switching time. Further increasing the dye concentration would enhance the display contrast ratio at the tradeoffs of lower bright state reflectance and slower response time.

In conclusion, the T-PDLC exhibits a more efficient light scattering than the conventional PDLC. The formed droplets are smaller and more uniform. A reflective black and white display using 2% dye-doped T-PDLC shows a reasonably good contrast ratio. The required operating voltage is still too

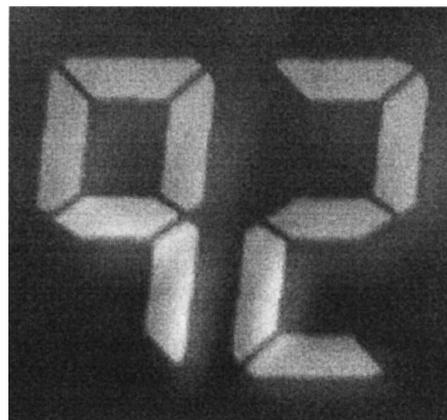


FIG. 4. Displayed image using a dye-doped T-PDLC reflective display. Black dye concentration: 2%, LC/polymer mixture: NOA65:E48=40:60,  $d=6.7 \mu\text{m}$ , and  $V=20 V_{\text{rms}}$ . A white paper was placed behind the bottom substrate to act as a diffusive reflector.

high to be used for active matrix display. To avoid image flickering for active matrix display, the employed LC mixture should have a high resistivity.

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