A bistable polarizer-free electro-optical switch using a droplet manipulation on a liquid crystal and polymer composite film

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Abstract: A bistable, polarizer-free, and reflective electro-optical switch based on a droplet manipulation on a liquid crystal and polymer composite film (LCPCF) is demonstrated. A color droplet on LCPCF can be manipulated by a wettability gradient owning to the distribution of LC directors anchored among the polymer grains on LCPCF. The contrast ratio is around 8:1 in a reflective mode. The potential applications of droplet manipulation are electronic papers and reflective displays.

OCIS codes: (230.3720) Liquid-crystal devices; (160.5470) Polymers.

References and links

1. D. K. Yang, and S. T. Wu, *Fundamental of Liquid Crystal Devices*, (England: Wiley, 2006).
2. D. K. Yang, "Review of operating principle and performance of polarizer-free reflective liquid-crystal displays," J. Soc. Inf. Disp. **16**(1), 117–124 (2008).
3. Y. H. Lin, H. Ren, and S. T. Wu, "High Contrast Polymer-Dispersed Liquid Crystal in a 90° twisted cell," Appl. Phys. Lett. **84**(20), 4083–4085 (2004).
4. Y. H. Lin, H. Ren, Y. H. Wu, X. Liang, and S. T. Wu, "Pinning effect on the phase separation dynamics of thin polymer-dispersed liquid crystals," Opt. Express **13**(2), 468–474 (2005).
5. Y. H. Lin, J. M. Yang, Y. R. Lin, S. C. Jeng, and C. C. Liao, "A polarizer-free flexible and reflective electrooptical switch using dye-doped liquid crystal gels," Opt. Express **16**(3), 1777–1785 (2008).
6. Y. H. Lin, and C. M. Yang, "A polarizer-free three step switch using distinct dye-doped liquid crystal gels," Appl. Phys. Lett. **94**(14), 143504 (2009).
7. Y. H. Lin, H. C. Lin, and J. M. Yang, "A polarizer-free electro-optical switch using dye-doped liquid crystal gels," Materials **2**(4), 1662–1673 (2009).
8. R. A. Hayes, and B. J. Feenstra, "Video-speed electronic paper based on electrowetting," Nature **425**(6956), 383–385 (2003).
9. M. K. Chaudhury, and G. M. Whitesides, "How to make water run uphill," Science **256**(5063), 1539–1541 (1992).
10. S. L. Gras, T. Mahmud, G. Rosengarten, A. Mitchell, and K. Kalantar-Zadeh, "Intelligent control of surface hydrophobicity," ChemPhysChem **8**(14), 2036–2050 (2007).
11. J. Lahann, S. Mitragotri, T. N. Tran, H. Kaido, J. Sundaram, I. S. Choi, S. Hoffer, G. A. Somorjai, and R. Langer, "A reversibly switching surface," Science **299**(5605), 371–374 (2003).
12. Y. H. Lin, H. Ren, Y. H. Wu, S. T. Wu, Y. Zhao, J. Fang, and H. C. Lin, "Electrically tunable wettability of liquid crystal/polymer composite films," Opt. Express **16**(22), 17591–17598 (2008).
13. H. Ren, S. T. Wu, and Y. H. Lin, "In situ observation of fringing-field-induced phase separation in a liquid-crystal-monomer mixture," Phys. Rev. Lett. **100**(11), 117801 (2008).
14. 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 **13**(22), 8746–8752 (2005).
15. Y. H. Lin, H. Ren, S. Gauza, Y. H. Wu, and S. T. Wu, "Single-substrate IPS-LCD using an anisotropic polymer film," Proc. SPIE **5936**, 59360O (2005).
16. Y. H. Lin, H. Ren, S. Gauza, Y. H. Wu, Y. Zhao, J. Fang, and S. T. Wu, "IPS-LCD using a glass substrate and an anisotropic polymer film," J. Display Technology **2**(1), 21–25 (2006).
17. P. De Gennes, F. Brochard-Wyart, and D. Quere, *Capillarity and Wetting Phenomena Drops, Bubbles, Pearls, Waves* (Springer-Verlag, Berlin, 2004)

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1. Introduction

Liquid crystal displays (LCD) require at least one polarizer; as a result, the optical efficiency and viewing angle are limited by polarizers [1]. In order to increase optical efficiency, many approaches of polarizer-free LCDs are developed, such as Guest-Host LCDs based on light absorption [2], Cholesteric LCDs based on Bragg reflection [2], and dye-doped LC-polymer systems based on both effects of light scattering and light absorption [2–7]. Hayes et. al. demonstrated a non-LC type displays based on a stretch of a color droplet on a basis of electrowetting effect [8]. However, unavoidable Joule's heating is a common issue for dielectrophoresis (DEP) or electrowetting in fluidic-based devices. The alternative way to manipulation the droplet is to utilize switchable surface. The droplet can be manipulated on a switchable surface within a wettability gradient by utilizing spatial changes in molecular conformation of a self-assembled monolayer (SAM) under external stimuli [9–11]. However, a fluidic drop usually refuses to move toward more hydrophilic regions on the SAM-based switchable surfaces because the weak chemical gradient cannot overcome the hysteresis of the surface. Moreover, the fabrication of SAM is complicated and costly, especially for large areas. Based on phase separation in liquid crystal and polymer complex system, we recently developed a switchable surface, a liquid crystal and polymer composite film (LCPCF) whose wettability is electrically tunable by controlling the orientation of LC molecules anchored among the polymer grains [12,13]. LCPCFs can also be used for the applications of liquid lenses [12], a double-layered LC phase modulators [14], a single-substrate in-plane switching (IPS) liquid crystal displays [15,16].

In this paper, we demonstrate a reflective, bistable, and polarizer-free electro-optical switch using a droplet manipulation on the LCPCF. A droplet manipulation on LCPCF is demonstrated by an electrically controlled wettability gradient of LCPCF resulting from the spatially reorientation of liquid crystal directors. A droplet on the LCPCF is then driven by a net force because of the imbalanced Young's forces on the opposite sides of the droplet edges. The contrast ratio of such the electro-optical switch is about 8:1 in reflective mode and response time is around 500 ms in average. The applications are electronic papers and reflective displays.

2. Sample preparation and operating principle

To fabricate LCPCF, we mixed a nematic LC mixture E7 (Merck) and a liquid crystalline monomer (4-(3-Acryloyloxypropyloxy)-benzoic acid 2- methyl-1, 4-phenylene ester) at 70:30 wt % ratios. The mixtures were then filled into an empty cell with a gap of 12 μm. Such an empty cell consists of a glass top substrate and a patterned ITO bottom glass substrate. The top substrate of the cell was overcoated with a thin polyimide (PI) layer and then mechanically buffed at the direction of 20° with respect to the electrode strips. After filling, the cell was exposed to a UV light with intensity I = 10 mW/cm^2 for ~30 min at 70 °C. After phase separation and photo-polymerization, the top glass substrate was peeled off by a thermal-releasing process. A solidified LCPCF was obtained with 12 μm thickness and 30 nm root-mean-squared roughnesses. The different concentration of LCPCF affects the surface morphologies of LCPCF and the performance of electrically tunable wettability. The lower LC concentration of LCPCF results in the smaller LC domains of LCPCF. As a result, the driving voltage is higher and also the tunable wettability is also smaller. When the LC concentration of LCPCF is too high, the polymer networks are not strong enough to support LC. The LCPCF turns out fluidic material with high viscosity, not a film-like material. The roughness of LCPCF is larger when the LC concentration is higher.

The LCPCF surface including polymer grains and liquid crystal directors anchored among the polymer grains is exaggeratedly illustrated in Fig. 1. Without applying voltage, the LC directors anchored the polymer grains are aligned along y-direction, as shown in the right region in Fig. 1. Under an applied AC voltage (f =1 kHz), LC directors are reoriented along the electric fields, as shown in the left region in Fig. 1. The LCPCF is more hydrophobic in the right region in Fig. 1 (at 0 V_{rms}) because the phenyl rings of the E7 LC directors are more

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parallel to the surface of the LCPCF (x-y plane) due to strong anchoring force of polymer grains. On the other hand, the LCPCF is more hydrophilic in the left region in Fig. 1 (in a high voltage state) because of the field-induced uneven tilts on the cyano terminal groups of the E7 LC directors near the edges of the fringe electric fields. The fluidic drop in Fig. 1 is then experience a net Young's force to move toward left or more hydrophilic region. The net Young's force (F) of the droplet owning to the difference of contact angles can be expressed as [9,17]:

$$F = \pi \times r \times \gamma_{LV} (\cos(\theta_L) - \cos(\theta_R)), \quad (1)$$

where γ_{LV} represents the surface tension (i.e., energy per unit surface) of the liquid–vapor interface, and r is the radius of the drop. θ_R and θ_L stand for the local contact angles on the right and on the left of the droplet, respectively.

Based on the droplet movement, we can realize an electro-optical switch, as shown in Figs. 2(a), 2(b) and 2(c). The two regions of the interdigitated chevron electrodes were patterned identically. The ITO electrodes on the glass substrate were etched with interdigitated chevron patterns, shown as the zigzag electrodes in Figs. 2(a), 2(b) and 2(c). The zigzag ITO strips have corner angles of 150°. The width and gap of the electrode strips are 4 μm and 14 μm, respectively. The distance (B) between two regions is 1.5 mm and the width (A) of each region is 1.5 mm. Patterned ITO (indium tin oxide) electrodes provide fringe electric fields to reorient LC directors on LCPCF. When two regions are at V=0, the contact angles on both sides of the droplet are the same, as shown in Fig. 2(a). When we apply a voltage in the left interdigitated region, the left region of LCPCF is more hydrophilic because of the tilts of LC directors anchored to the polymer grains, so the droplet experiences a net Young's force to move toward the left, as depicted in Fig. 2(b). When the voltage is turned off, the droplet contracts and then stays in the left region, as shown in Fig. 2(c). By using a reflective diffuser on the bottom of the glass substrate, dropping a colored droplet and placing a black matrix with an aperture on the top of the colored droplet, we can realize the concept of an electro-optical switch which is polarizer-free, color-filter-free, and bistable. We used the red fluid, dye-doped ethylene glycol, in the experiments.

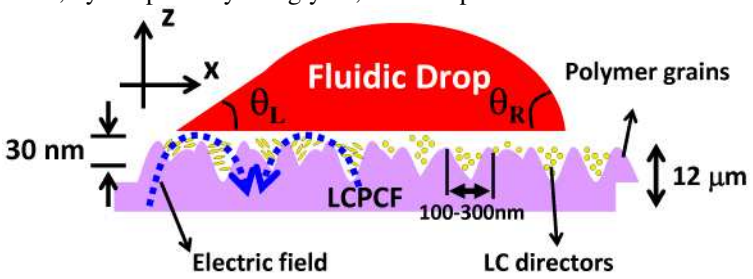

Fig. 1. The operating principles of droplet movement on LCPCF.

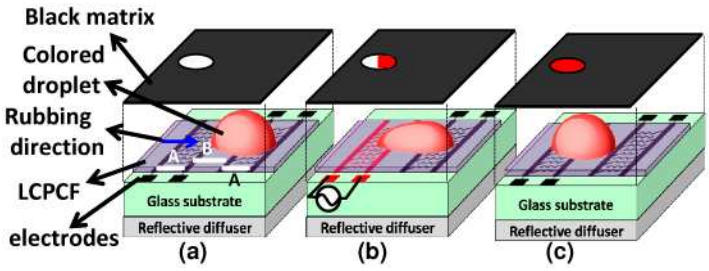

Fig. 2. The operating principles of a polarizer-free bistable electro-optical switch using the movement of a colored droplet on the LCPCF at (a) voltage-off state, (b) voltage-on state on the left electrode region. (c)After the voltage is turned off, the droplet contracts and then stops moving. A and B are 1.5 mm.

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3. Experiment and results

To observe the surface morphology, we removed LC of LCPCF by hexane. The photograph of Scanning Electron Microscopy (SEM) of LCPCF is shown in Fig. 3. In Fig. 3, polymer grains are observed on the LCPCF. LC directors are anchored among the polymer grains. The root-mean squared roughness of LCPCF measured by AFM is around 30 nm. The LC domains are around 100-300 nm. To observe the droplet motion on LCPCF, we dropped a water droplet of 3μL on LCPCF under crossed polarizers, as shown in Figs. 4 (a) and 4(b). In Fig. 4(a), the droplet was placed on LCPCF. Two electrode regions consisting of a lot of zigzag ITO electrodes are beneath the LCPCF. At voltage-off state (V=0), the LCPCF is dark and that indicates the LC directors anchored the polymer grains are aligned along the transmissive axis of the polarizer (P). The alignments of LC directors under water and under air are the same due to strong anchoring energy of polymer grains. The light leakage along the circumference of the droplet is because of the incident light is refracted by the curved water-air interface; as a result, the polarization of light is no longer at a normally incidence. When we apply pulsed voltages on the right region in Fig. 4(b), the right region turns out brighter because of the orientation of LC directors. The tilt of LC directors along the edge of fringing field results in more hydrophilic in the right region; therefore, the droplet moves toward the right region, as shown in Fig. 4(b). After manipulating the water droplet several times, we did not observe that the LC is extracted by the water droplet. The high voltage applied to the LCPCF did not affect the droplet due to the large thickness of the LCPCF [12].

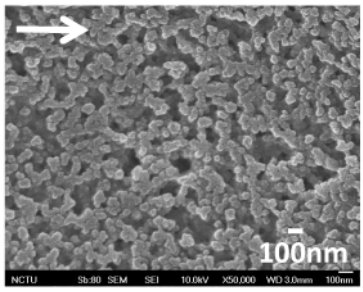

Fig. 3. The SEM photograph of LCPCF. The white arrow indicates the rubbing direction during the fabrication process.

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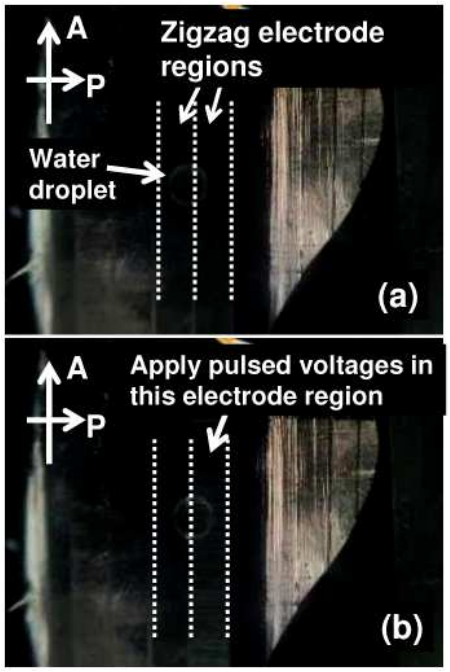

Fig. 4. The droplet motion on LCPCF under crossed polarizers (a) without driving voltages. (b)The droplet moves toward the right electrode region, when we apply pulsed voltages (250 V_{rms}) on the right region of zigzag-electrodes. P: polarizer. A: analyzer. The rubbing direction during fabrication process is parallel to P.

To observe the droplet manipulation of a dye-doped ethylene glycol on LCPCF under an inhomogeneously spatial distribution of LC reorientations induced by fringing electric fields, we recorded the dynamics of the droplet by a CCD camera (JAI CV-M30) with a frame rate of 360 fields/sec and measured the contact angles of the droplet with time by contact angle measurement (FTA 1000 Analyzer System). A drop of dye-doped ethylene glycol of 3μl was dropped on the LCPCF surface. We then applied 250 V_{rms} square pulses (f = 1 kHz) to the left region of the electrodes shown in Fig. 2(b) for a time duration of 600 ms. Figures 5 (a), 5(b) and 5(c) show the measured results. The photos of the droplet dynamics at various times are shown in Fig. 5(a). The related contact angles on both sides of the droplet with time in Fig. 5(a) are shown in Fig. 5(b). As one can see, the contact angles on both sides are the same at V= 0. When we turned on the pulsed voltages in the left region divided by a dotted line in Fig. 5(a) at 0.4 sec, the contact angle on the left (~49.5^o) is smaller than that on the right (~61.2^o). The left region turns out more hydrophilic due to the reorientation of the LC directors. Between 0.40 sec and 0.45 sec, the contact angle on the left is smaller than that on the right, as shown in Fig. 5(c). After 0.46 sec, the water droplet slides toward the smaller contact angle on the left. When the voltage is turned off at 1.1 sec, the LCPCF is more hydrophobic and the droplet contracts with high contact angles on both sides. The droplet stays in the same location after the voltage is off. The droplet moves again when we turn on the voltage at 1.7 sec again. The reason why we used periodic electric fields is mainly to overcome the LCPCF's hysteresis and keep the droplet moving forward. The hysteresis of LCPCF, the difference between advancing (~64.3^o) and receding angle (~52.0 ^{o}), is ~12.3^o. The translation distance of center of mass (CM) of the droplet as a function of time under pulsed voltages is shown in Fig. 5(d).We can see that the droplet translates and contracts by turns; therefore, the CM of the droplet moves forward straightly and backward slightly by turns.

The images of the top view of the droplet translation are shown in Fig. 6 (a) and 6(b). A white paper was used as a diffusive reflector. The white paper was also drawn with four

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rectangles to indicate the regions of zig-zag electrodes on the glass substrate. When LCPCF was applied pulsed voltages on the electrode number "4", the droplet moved to the number "4". After that, the droplet moved to the left as the LCPCF was applied pulsed voltages on the electrode number "2". By controlled the applied voltages on the electrode number "4" and "2", the droplet can be manipulated back and forth.

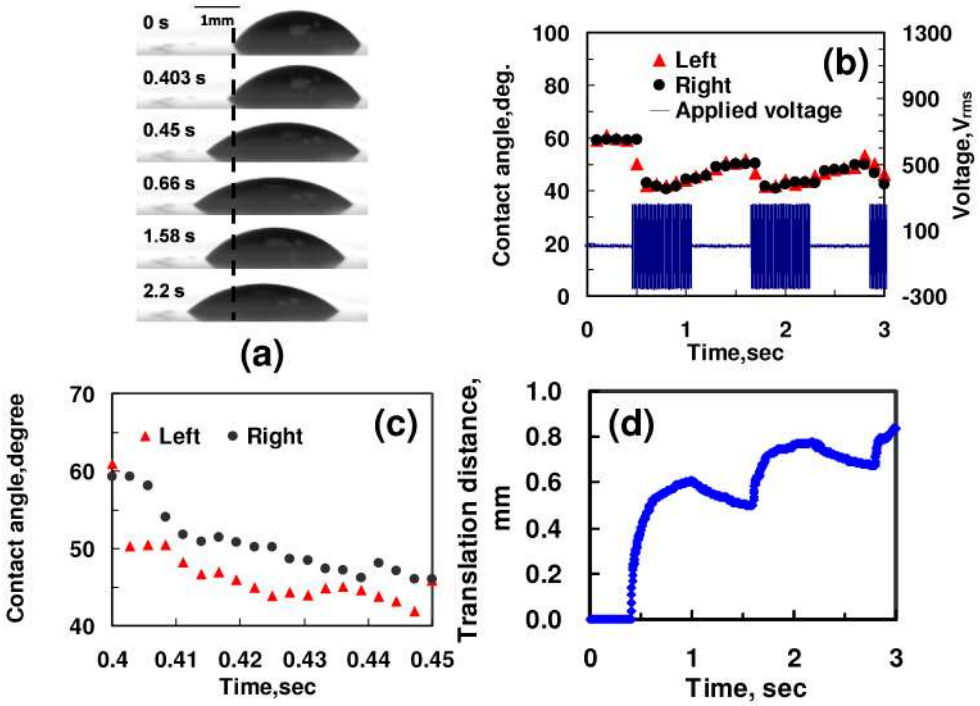

Fig. 5. (a) The photos of the droplet manipulation at different times. (Media 1, 690 KB)(b) The contact angle on the left and right of the droplet as a function of time under a squared pulsed voltage (250 V_{rms}) with 600 ms time duration. (c) The contact angle as a function of time in (b) between 0.4 sec and 0.45 sec. (d) The translation distance (black line) of center of mass of the droplet as a function of time under pulsed voltages (blue line). The droplet volume was 3 μL.

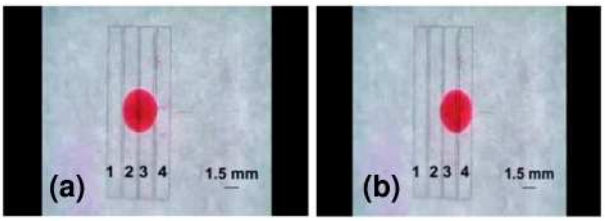

Fig. 6. The color droplet translate from (a)the left to (b)the right when we apply pulsed voltages on the electrode number "4".(Media 2, 1585 KB) A white paper was used as a diffusive reflector. The paper was drawn with four rectangles to indicate the regions of zig-zag electrodes.

To realize the electro-optical switch using droplet manipulation on LCPCF, we place a black matrix with a circular opening (or aperture) with a diameter of 300 μm on the top of the droplet. The structure is illustrated in Fig. 2 (a). The experimental images are shown in Fig. 7(b).The corresponding locations of electrodes, the droplet, and the aperture in Fig. 7(b) are depicted in Fig. 7(a). When the lower electrode region was applied voltage, the droplet moved from the initial upper region to the lower region. The aperture was then filled with red gradually. The red droplet then stayed in the aperture region even though we turned off the

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voltage. When we turned on the voltage of the upper region, the droplet translated back to the upper region and then stays. Thus, the red pixel turned out white back gradually. The time-dependent percentage of the white area in Fig. 7(b) is shown in Fig. 7 (c). The response time was around 400 ms from white (W) to red (R) and around 600 ms from R to W. The reason why the response time from R to W is slower than that from W to R is because the net force results from the advancing edge of the droplet which drags the receding edge of the droplet. We also measured the transmission spectrum by a spectrometer (Ocean Optics USB 2000). We defined the contrast ratio (CR) is the transmittance ratio of white-state (without the droplet in the aperture) to red-state (the droplet is fully colored the aperture). The contrast ratio as function of wavelength is shown in Fig. 7(d). The contrast ratio at wavelength of 630 nm is ~ 2.8:1 in the transmissive mode and ~8:1 in the reflective mode. Increasing dye concentration can improve the CR, but the tradeoff is the slower response time. As to the response time, the response time depends on the translation velocity of the droplet and the aperture size of aperture. Reducing the aperture size can improve the response time. Reducing the thickness of LCPCF can also improve the response time and reduce the driving voltage. The small pixel size is preferred for realizing a high resolution display. However, a small droplet size would slow down the speed of a drop because of increasing surface tension.

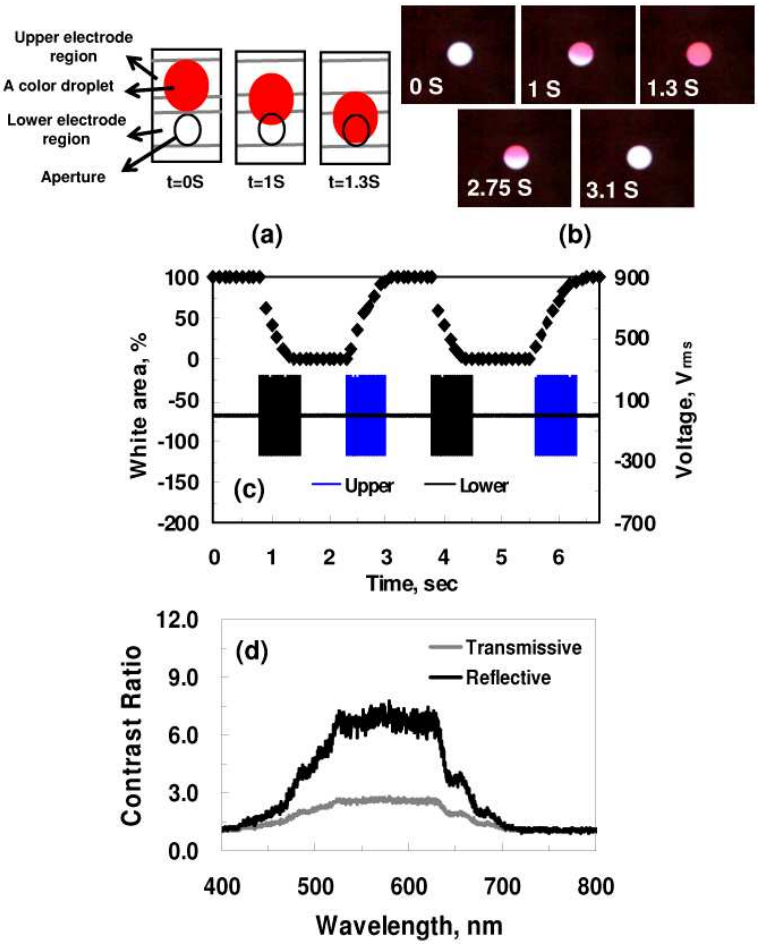

Fig. 7. (a) The illustration of (b) a reflective, polarizer-free, and bistable electro-optical switch using colored droplet movement on the LCPCF at different time. (Media 3, 1391 KB) (c) The percentage of white area as a function of time under an applied pulsed voltage on the lower or the upper region of electrodes in (a). (d) A contrast ratio of the polarizer-free electro-optical switch as a function of wavelength in the transmissive mode and the reflective mode.

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According to Eq. (1), the net force of the droplet is calculated as~28.5 μN as γ_{LV} is ~45 mN/m. The contact angle (θ') as a function of applied voltage (V_{rms}) in the LCPCF can be expressed as [12]:

$$\cos[\theta'(V_{rms})] = f_{lc} \cdot \cos(\theta_{lc}(V_{rms})) + f_P \cdot \cos(\theta_P), \quad (2)$$

where f_{lc} and f_p are the fractions of LC and polymer grains for the inherent contact angles θ_{lc} and θ_P. In the experiments, f_{lc} and f_p which are determined by concentrations are 0.7 and 0.3, respectively. θ_P is 33°. θ'(250 V) and θ'(0 V) are 49.5° and 61.2°, respectively. Therefore, (θ_{lc}(250V)- θ_{lc}(0V)) is around 15.44° which results from the orientation of LC directors.

5. Conclusion

In conclusion, a reflective, polarizer-free and bistable electro-optical switch based on droplet manipulation on LCPCF is demonstrated. The droplet can be manipulated because of the electrically tunable wettability gradient of LCPCF which is adjusted by the orientation of liquid crystal directors anchored among the polymer grains. For long term operation, the alignment of LC on the top of LCPCF layer may be disordered due to the fluidic droplet contacts to LC directly. To place the bistable electro-optical switch both horizontally and perpendicularly, we can use two fluids, one is colored and the other is colorless, under a cover glass substrate for packaging. To obtain a color display, we can use three color fluids, such as red, blue and green fluids in three pixels. For achieving a good display performance, the contrast ratio and response time must be improved by properly designing the pixel size, the droplet size, and the electrodes. Other potential applications of LCPCF are liquid lenses, bio-sensors, and microfluidic devices.

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