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Citation: *Applied Physics Letters* **94**, 143504 (2009); doi: 10.1063/1.3111790

View online: <http://dx.doi.org/10.1063/1.3111790>

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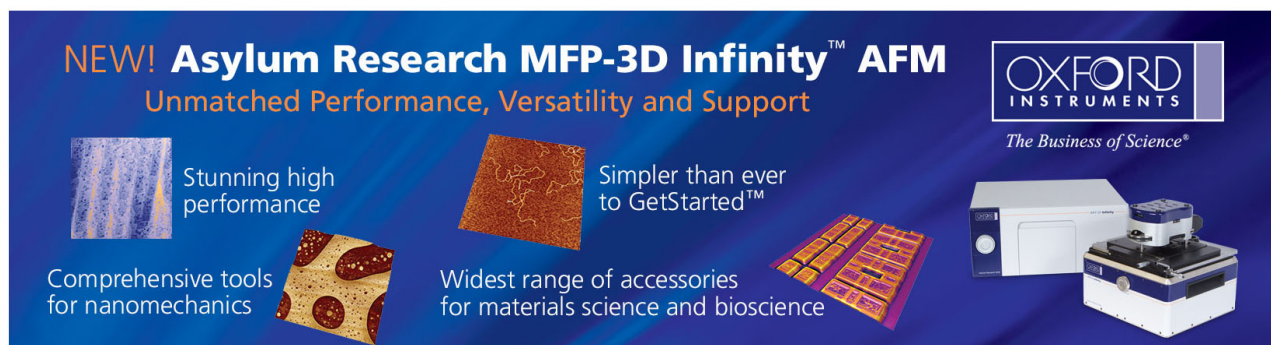
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A polarizer-free three step switch using distinct dye-doped liquid crystal gels

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(Received 26 February 2009; accepted 7 March 2009; published online 9 April 2009)

A polarizer-free three step switch using distinct dye-doped liquid crystal (LC) gels is demonstrated in reflective mode. By controlling the spatial distribution of the density of polymer networks, the distinct dye-doped LC gels can produce multiple states: bright, dark, and information states without patterning indium-tin oxide. The multiple states are generated by adapting different polymer network density in different display regions. The dark state is due to the combination of scattering and absorption. It can be further extended for a four step switch. The potential applications are decorative displays, electrically tunable iris, and electrically tunable low pass or high pass filter.

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Liquid crystal (LC) based photonic devices are widely used in light modulated applications including amplitude modulation and phase modulation.¹ Most of LC devices suffer a low optical efficiency ($\sim 3\%$) due to employing two polarizers. Therefore, it is highly desirable to develop polarizer-free LC devices.^{1,2} Polarizer-free guest-host liquid crystal displays have been studied for years.³⁻⁷ Recently, we have demonstrated a polarizer-free flexible electro-optical switch using dye-doped LC gels.⁸⁻¹² To further realize a display with multipixels, the substrate is patterned by pixilated indium-tin oxide (ITO) in general. However, the involved fabrication and driving are complicated. It also causes problems especially in the fabrication process of flexible displays, such as chemical stability of plastic substrates, failure of ITO under tension, and so on.¹³ In order to achieve a simple and easy process for flexible displays, we can develop a multiple-step switch using dye-doped LC gels without patterning ITO layers. Moreover, the switch should provide extra information states besides voltage-on and voltage-off states for the applications of the decorative displays within a simple driving and manufacturing process.

In this letter, we demonstrate a polarizer-free three step switch using distinct dye-doped LC gels in reflective mode. The distinct dye-doped LC gels can display information by the spatial distribution of polymer network density without patterned ITO layers. The different regions of polymer network densities have different threshold voltages but similar bright and dark states. The distinct dye-doped LC gel is transparent (or in bright state) at $0 V_{\text{rms}}$ and opaque (or in dark state) at $30 V_{\text{rms}}$. At $9 V_{\text{rms}}$, it shows the colored pattern (or information) because of distinct polymer networks. The response time is ~ 10 ms and contrast ratio is $\sim 200:1$. We can also extend the concept for a polarizer-free four step switch. The potential applications are for decorative displays, electrically tunable diaphragm, and electrically tunable low pass or high pass filter.

Figure 1 illustrates the operating principles of a polarizer-free three step switch using distinct dye-doped LC gels. The structure consists of ITO glass substrates, vertical alignment layer without rubbing treatment, a diffusive

reflector, negative LCs, dichroic dye molecules, and the distinct distribution of polymer networks, which divide the cell into two parts, the low density of polymer networks (LDPN) and the high density of polymer networks (HDPN), as shown in Fig. 1(a). Without an applied voltage ($V=0$), polymer networks, LC, and dye molecules are aligned vertically; hence, the cell does not scatter light and the absorption is weak. The cell has high polarization-independent reflectance. When V_1 is larger than the threshold voltage in LDPN (V_{th1}), the LC directors are reoriented first and then bring dye molecules to rotate accordingly due to weak anchoring energy provided by LDPN; meanwhile, the LC directors remain vertically aligned in HDPN, as shown in Fig. 1(b). The reflectance then reduces in LDPN region due to the increases, the scattering, and absorption, while the reflectance remains high in HDPN region. Furthermore, all the LC directors and dye molecules in LDPN have the same tilt angle within random orientations, which originate from the alignment layer without rubbing treatment.¹⁴ The reflectance in LDPN is polarization independent. When the applied voltage is larger than the threshold voltage V_{th2} ($>V_1$) of HDPN, the LC directors in HDPN begin to reorient by the electric fields and then the reflectance in this region decreases as well. When the applied voltage V_2 is much larger than V_{th2} , the negative LCs and dye molecules in both regions are reoriented randomly in the

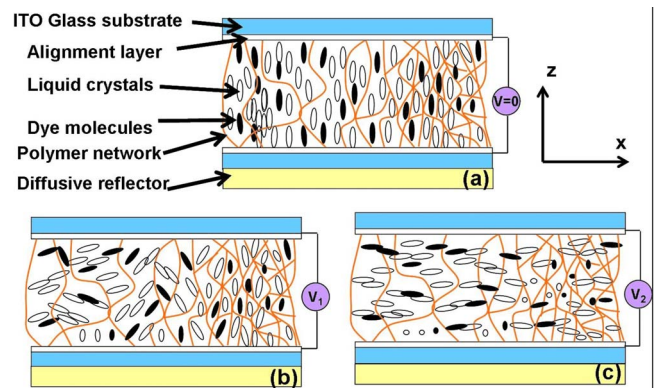


FIG. 1. (Color online) Schematic structure and operating principles of distinct dye-doped LC gels at (a) $V=0$, (b) V_1 , and (c) V_2 ($V_2 > V_1$).

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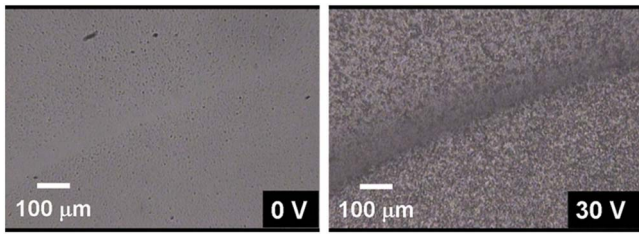


FIG. 2. (Color online) The microscopic images of distinct dye-doped LC gels at 0 V_{rms} and 30 V_{rms} .

x - y plane, as shown in Fig. 1(c). Thus, both regions appear polarization-independent dark state.

To prepare a cell of distinct dye-doped LC gels, we mixed nematic LC ZLI-4788 (Merck, $n_e=1.6567$, $\Delta n=0.1647$ at $\lambda=589$ nm and $\Delta\epsilon=-5.7$ at $f=1$ kHz) with an UV-curable diacrylate monomer and a dichroic dye S428 (Mitsui, Japan) at 90:5:5 wt % ratios. The fabrication process is similar to dye-doped LC gels.^{11,12} In order to generate distinct distribution of polymer networks, two-step UV curing process was applied. First, one region of the cell with filled mixtures was exposed to an UV light ($\lambda\sim 365$ nm) with UV intensity 1.37 mW/cm² at 10 °C for 1.5 h to generate HDPN. After that, the other region of the cell was irradiated by the UV light with lower UV intensity 0.73 mW/cm² at 20 °C for another 1.5 h to develop LDPN. The higher curing intensity of UV light and lower curing temperature results in HDPN.^{11,12,15} The cell gap was 5 μm . The three step switch can be a flexible switch by replacing substrates.¹³ To demonstrate the concept, we use glass substrates in this paper.

Figure 2 shows the morphologies of the distinct dye-doped LC gels observing under an optical microscope without a polarizer. In Fig. 2, LDPN is in the upper left area and HDPN is in the lower right area. The cell shows a good bright state in both regions at 0 V_{rms} due to the vertically aligned polymer networks, LC, and dye molecules. At 30 V_{rms} , it shows the different and fine domain textures of the polymer networks in two regions separated by a discontinuous line. Because of the interaction between monomer and some components of dye,¹¹ the distinct dye-doped LC gel is reddish at 30 V_{rms} . The reddish problem can be improved by employing another dye and polymer composite materials.

To measure electro-optical properties, we adopted laser-based reflectance measurement.^{11,12} An unpolarized green He-Ne laser ($\lambda=543.5$ nm, Melles Griot, Model 05-LGR-173) was used as a light source instead of a white light source. The reflectance is normalized to that of a pure LC cell with the same cell gap. Figure 3(a) plots the measured voltage-dependant reflectance of the sample for HDPN and LDPN when the voltage is ramped up. The threshold voltages in HDPN and LDPN are 5.42 and 4.62 V_{rms} , respectively. At $V=0$, the reflectance in HDPN and LDPN are 50.2% and 49.2%, respectively. The contrast ratio (CR) is defined as a reflectance ratio of 0 to 30 V_{rms} . The CRs in both regions are $\sim 200:1$ under laser-based measurement. When we use an integrating sphere (DMS803, product of the AUTRONIC-MELCHERS GmbH) under a white light source, the CRs in both regions are $\sim 3:1$. Typically CR for newspaper under the same measurement is $\sim 5:1$. Improving the scattering state and dichroic ratio of dye can further im-

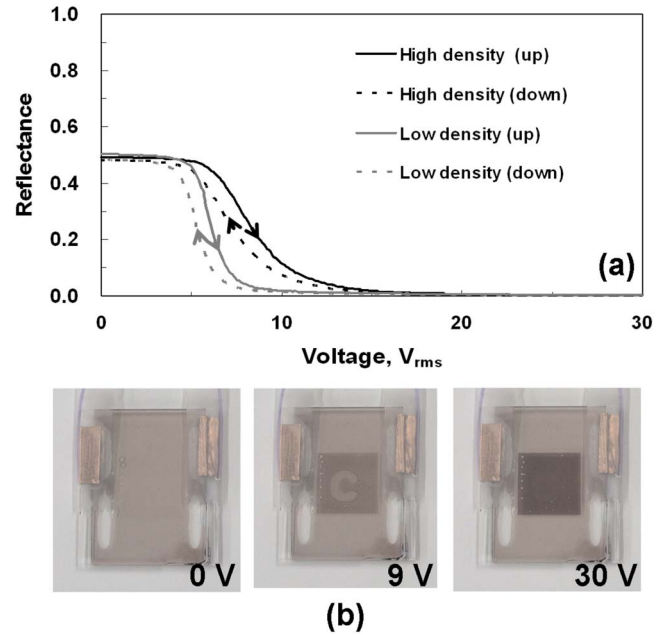


FIG. 3. (Color online) (a) Voltage-dependent reflectance of the three step switch with increasing voltage (solid line) and decreasing voltage (dotted line) for the high and low density of polymer networks. (b) Images of the three step switch (enhanced online) [URL: <http://dx.doi.org/10.1063/1.3111790.1>]. A white paper was used as a diffusive reflector.

prove the CR. The response time (rise time plus decay time) is 11 ms in LDPN and ~ 9 ms in HDPN by using 30 V_{rms} squared pulses with time duration 500 ms at $f=1$ kHz. The HDPN results in the stronger anchoring force between the LC and polymer networks; therefore, the threshold voltage is higher and response time is faster.¹⁶ To demonstrate the image of the three step switch, we patterned the distinct dye-doped LC gels with a photomask of a “C” pattern without patterning the ITO layer, as shown in Fig. 3(b). The cell can show three switching states: bright state at $V=0$, information state at 9 V_{rms} , and dark state at 30 V_{rms} .

The reflectance in HDPN (R_{high}) and in LDPN (R_{low}) can be expressed as a function of tilt angle θ of LC directors with respect to x -axis (in Fig. 1),^{17,18}

$$R_{\text{high}}(\theta) \approx e^{-2d \times [\alpha_1(\theta) + \beta_1(\theta)]}, \quad (1)$$

$$R_{\text{low}}(\theta) \approx e^{-2d \times [\alpha_2(\theta) + \beta_2(\theta)]}, \quad (2)$$

where d is the cell gap, $\alpha_1(\theta)$ and $\alpha_2(\theta)$ are the averaged absorption coefficients, and $\beta_1(\theta)$ and $\beta_2(\theta)$ are the average scattering coefficients. The averaged absorption can be expressed in Eq. (3),

$$\alpha_i(\theta) = \rho \times \frac{\alpha_{\text{eff}}(\theta) + \alpha_{\perp}}{2}, \quad i = 1, 2, \quad (3)$$

where ρ is dye concentration and α_{\perp} is the absorption coefficient for the polarization of incident light perpendicular to the principal axis of the dye molecule. The effective absorption coefficient $\alpha_{\text{eff}}(\theta)$ of the dye molecules can be expressed as:

$$\alpha_{\text{eff}}(\theta) = \frac{\alpha_{\parallel} \times \alpha_{\perp}}{\sqrt{\alpha_{\parallel} \times \sin^2 \theta + \alpha_{\perp} \times \cos^2 \theta}}, \quad (4)$$

where α_{\parallel} is the parallel absorption coefficient. At $V=0$, θ is near $\pi/2$; consequently, $\alpha_1(\theta) \approx \alpha_2(\theta)$ approximately equals

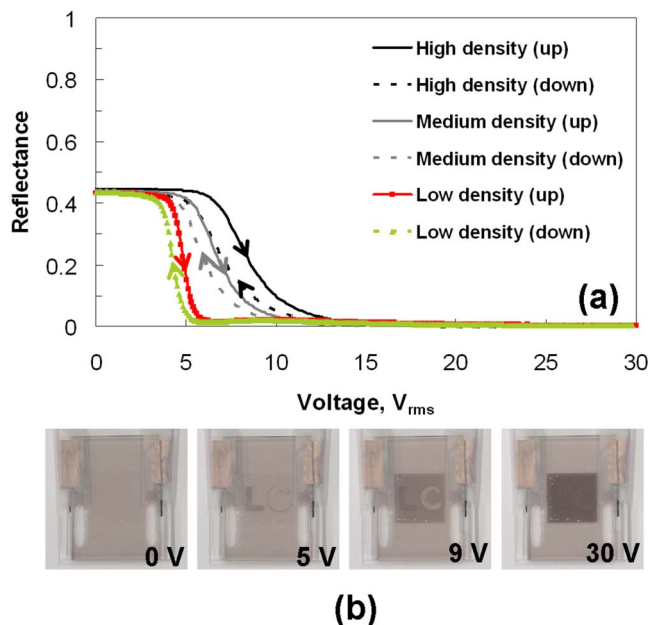


FIG. 4. (Color online) Voltage-dependent reflectance of the four step switch with increasing voltage (solid line) and decreasing voltage (dotted line) for the high, medium, and low density of polymer networks. (b) Images of the four step switch (enhanced online). [URL: <http://dx.doi.org/10.1063/1.3111790.2>] A white paper was used as a diffusive reflector.

to $\rho \times \alpha_{\perp}$ and $\beta_1(\theta) \approx \beta_2(\theta)$ equals to 0 because of the vertically alignment of LC directors, dye molecules, and polymer networks. Therefore, $R_{\text{high}}(\theta) \approx R_{\text{low}}(\theta) \sim 63\%$ after we calculated by $\rho=0.05$ and $\alpha_{\perp}=0.926 \mu\text{m}^{-1}$. However, the measured reflectance ($\sim 50\%$) is lower than 63%. That is because of the imperfection of vertical alignment of LC, dye, and polymer networks, which is limited by the order parameter of dye molecules and the structure of the monomer without a rodlike central core. At $V_2 (\gg V_{\text{th1}}$ and V_{th2}) in Fig. 1(c), $\alpha_1(\theta=0) \approx \alpha_2(\theta=0) \approx \rho \times (\alpha_{\perp} + \alpha_{\parallel})/2$ is around $0.319 \mu\text{m}^{-1}$ since measured α_{\parallel} is $11.83 \mu\text{m}^{-1}$. Moreover, the scattering is stronger in HDPN due to smaller domains and the mismatch of refractive indices, i.e., $\beta_1(\theta=0) > \beta_2(\theta=0)$; therefore, theoretically $R_{\text{high}}(\theta=0)$ is lower than $R_{\text{low}}(\theta=0)$, which also means higher CR in HDPN. However, CRs in both regions are similar in our experiment. Owing to the strong anchoring energy in HDPN, LC directors and dye molecules are not totally aligned along x - y plane, which means $\theta \neq 0^\circ$ at $30 V_{\text{rms}}$; hence, absorption and scattering are not as high as we expect in HDPN. At V_1 [in Fig. 1(b)], $\theta_1 > \theta_2$ due to the different anchoring strengths in two regions. Thus, $\alpha_1(\theta_1) < \alpha_2(\theta_2)$. So does $\beta_1(\theta_1) < \beta_2(\theta_2)$. Therefore, $R_{\text{high}}(\theta_1)$ is larger than $R_{\text{low}}(\theta_2)$ at V_1 .

Furthermore, we can extend the distinct dye-doped LC gels for making a four step switch. Figures 4(a) and 4(b) show the measured voltage-dependant reflectance and the images of the four step switch with a ramped-up voltage. To fabricate polymer networks with three different densities, the UV curing intensities were 0.73 mW/cm^2 at 10°C (black line), 0.35 mW/cm^2 at 10°C (gray line), and 0.73 mW/cm^2 at 30°C (red line). The three regions have a similar reflectance at $V=0$ ($\sim 44\%$), similar response time ($\sim 10 \text{ ms}$), but different threshold voltages and CRs. The

threshold voltages in high, medium, and low densities of polymer networks are 5.9, 4.8, and $3.9 V_{\text{rms}}$, accordingly. The CRs are 450:1, 450:1, and 200:1 at high density, medium density, and low density. The cell was patterned with “LC” pattern. The cell shows four switching states: bright state at $V=0$, two information states at 5 and $9 V_{\text{rms}}$, and dark state at $30 V_{\text{rms}}$, as shown in Fig. 4(b).

The distinct dye-doped LC gels also show the hysteresis when the voltage is ramped up (solid line) and down (dotted line) as shown in Figs. 3(a) and 4(a). Without patterning ITO layer, the voltage is applied to different density regions simultaneously. Thus, the sample can still be operated as a three step or a four step switch as long as the electro-optical curves in different density regions are distinguishable no matter ramped-up voltages or ramped-down voltages.

In conclusion, we have demonstrated polarizer-free multiple switches including a three step switch and a four step switch using distinct dye-doped LC gels. The distinct dye-doped LC gels can display information by the spatial distribution of polymer network densities without patterned ITO layer. The advantages of such polarizer-free switches are (1) polarizer-free, (2) simple fabrication without ITO patterning, and (3) simple driving. However, the issues we have to overcome are high driving voltages, low resolution, nonblack colors, and long term stability of dye molecules due to photobleach. This concept can also be extended for making a polarizer-free multiple switch. The potential applications are decorative displays, electrically tunable iris, and electrically tunable low pass or high pass filter.

The authors are indebted to Dr. Yan-Rung Lin, Dr. Shie-Chang Jeng, and Dr. Chi-Chang Liao (EOL/ITRI, Taiwan) for discussions. This work is supported by National Science Council (NSC) in Taiwan under Project No. 96-2112-M-009-019-MY2.

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