Reflective Direct-View Displays Using a Dye-Doped Dual-Frequency Liquid Crystal Gel

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***Abstract*—A high-contrast, fast-response, and polarizer-free reflective display using a dye-doped dual-frequency liquid crystal gel is demonstrated. The high contrast ratio originates from the combination of light scattering from the microdomain polymer gel and absorption from the black dyes. The fast response is due to the frequency modulation of the dual-frequency liquid crystal.**

***Index Terms*—Dual frequency liquid crystal gel, fast response time, guest–host (GH) reflective display, high contrast ratio, polarization-independent.**

I. INTRODUCTION

GUEST–HOST liquid crystal displays (GH LCD) exhibit high brightness and a wideviewing angle because they do not require any polarizer [1], [2]. Several device configurations such as Cole-Kashnow cell [3], White-Taylor cell [4] or double orthogonal cells [5]–[7] have been proposed for achieving polarization independence. A typical reflectance of the GH LCD is ~50%, but the contrast ratio is only ~5:1. The low contrast ratio is limited by the dichroic ratio (typically ~10:1) of the employed dyes. To enhance contrast ratio, one could increase the LC cell gap or dye concentration, however, the tradeoff is the decreased reflectance.

Besides absorption, light scattering is another mechanism which is independent of polarization. The commonly known example is polymer-dispersed liquid crystal (PDLC) [8], [9]. However, the light scattering state is not a black state; rather, it is a translucent state. For a high contrast display, a good black state is required. To achieve a black state, a few percent of black dyes are added and a ~10:1 contrast ratio is demonstrated using a PDLC in a twisted cell [10]. The response time of such a guest-host PDLC is about 20–30 ms, depending on the cell gap and LC and dye materials employed.

To improve response time and light scattering efficiency, our group has developed a polarization independent dual-frequency liquid crystal (DFLC) gel [11]. The gel is also a light scattering device. Two important features of the DFLC gel are fast response time and high contrast ratio. This gel has been used for high speed photonic devices. But for displays, we need a good black state, high contrast ratio, and wide viewing angle.

In this paper, we demonstrate a new GH LCD using a dye-doped DFLC gel to realize polarizer-free fast response, and high contrast reflective display. This is a normally white display utilizing both light scattering and absorption effects. In the voltage-off state, the gel exhibits ~50% reflectance. At ~30 $V_{\rm rms}$, a good black state is observed. The device contrast ratio as high as ~150:1 is obtained. The response time is ~6 ms.

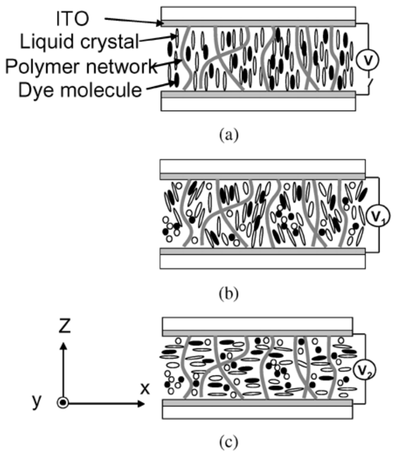

Fig. 1. Schematic representation of the operating principle. (a) Voltage-off state, (b) voltage-on state at $\rm f > f_c$, and (c) voltage-on state at $\rm f > f_c$ and $\rm V_2 > V_1$.

II. EXPERIMENT

To fabricate DFLC gel, we first prepare a DFLC mixture consisting of some biphenyl esters and lateral difluoro tolanes. The formulated DFLC mixture has following physical properties: birefringence $\Delta n = 0.267$ (at $\lambda = 633$ nm. $T = 21$ °C), crossover frequency $f_c = 10$ kHz, and dielectric anisotropy $\Delta\varepsilon = 7.72$ at $f = 1$ kHz and $\Delta\varepsilon = -3.51$ at $f = 50$ kHz. We mixed the DFLC, a diacrylate monomer (bisphenol-A-dimethacrylate), and the dichroic dye S428 (Mitsui Chemicals Inc.) at 90:5:5 wt% ratios. The mixture was injected into an empty cell whose inner surfaces were coated with a thin indium-tin-oxide (ITO) electrode. The cell gap is $d = 5$ μm. The filled cell was irradiated by a UV light ($\lambda \sim 365$ nm, $\rm I \sim 15$ mW/cm^2) at room temperature for one hour with a biased voltage ~40 $\rm V_{rms}$ ($f = 1$ kHz). The formed chain-like polymer networks are along the electric field direction because the LC directors are aligned perpendicular to the glass substrates during the UV curing process, as shown in Fig. 1(a).

At $\rm V = 0$, the cell does not scatter light and the absorption is rather weak because the dye molecules are aligned perpendicular to the substrates, as shown in Fig. 1(a). Therefore, the

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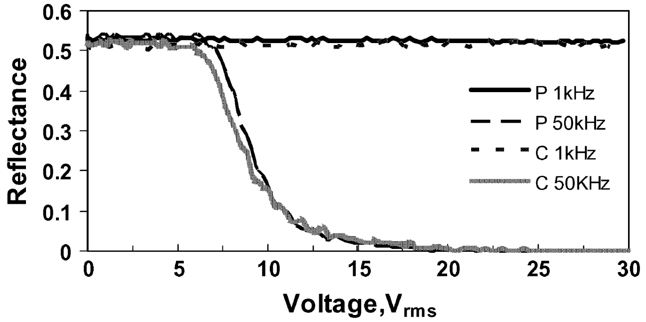


Fig. 2. Voltage-dependent reflectance of dye-doped DFLC gel. P and C's polarizations of the incident light are orthogonal.

display has the highest reflectance. This is known as the normally-white mode. When the applied high-frequency $(\mathrm{f} > \mathrm{f_c})$ voltage exceeds a threshold, the LC directors and dye molecules are tilted away from the electric field because the LC has a negative $\Delta\varepsilon$. Under such a circumstance, the gel is switched into micron-sized domain structure. The titled direction is random because the substrates do not have any alignment treatment, as depicted in Fig. 1(b). As a result, the reflectance is reduced due to light scattering of the gel and absorption of the dyes. As the applied voltage increases further, the liquid crystals and dye molecules are reoriented in the x-y plane, as shown in Fig. 1(c), so that light scattering and dye absorption efficiency reach their maxima and the display appears black.

To measure the reflectance of the dye-doped DFLC gel, ideally we should use an unpolarized white light. The dye we employed appears black, but when dissolved in the gel system it appears dark red. Its cutoff wavelength was measured to be ~650 nm. That means it has some light leakage in the red spectral region. Therefore, we used a linearly polarized green diode laser ($\lambda = 532$ nm) for characterizing the device performances. A dielectric mirror was put behind the cell so that the laser beam passed through the cell twice. A large area photodiode detector was placed at ~40 cm behind the sample which corresponds to ~1.5° Collection angle. A computer controlled LabVIEW data acquisition system was used for driving the sample and recording the light reflectance.

III. RESULTS AND DISCUSSIONS

Fig. 2 plots the voltage-dependant reflectance of the dye-doped DFLC gel. The reflectance is normalized to that of a pure DFLC cell with the same cell gap. At $f = 1$ kHz, the applied voltage cannot reorient the dye-doped DFLC gel because the LC directors are in homeotropic structure and $\Delta\varepsilon$ is negative. At $f = 50$ kHz, the reflectance remains higher than 50% in the low voltage regime and decreases gradually as $V > V_{\mathrm{th}}$. For the 5-μm gel, $V_{\mathrm{th}} \sim 7\ V_{\mathrm{rms}}$. At $V = 30\ V_{\mathrm{rms}}$, the measured contrast ratio for the green laser beam is as high as 150:1.

For a scattering device, the contrast ratio is dependent on the distance of the detector from the sample. In a handheld reflective display, a comfortable viewing distance is about 20–25 cm. To mimic this condition, we shortened the detecting distance from 40 to 20 cm and the measured contrast ratio is still 120:1. This result indicates that our gel has a very strong scattering property. The scattered light diverges quite fast.

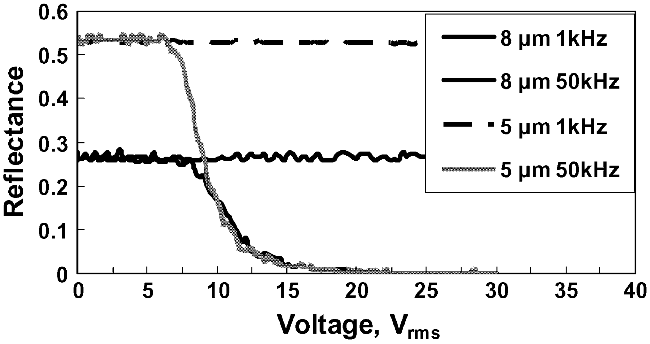


Fig. 3. Voltage-dependent reflectance of dye-doped DFLC gel with different cell gaps. Dye and polymer concentrations are kept at 5 wt%.

To verify that the gel is indeed polarization independent, we rotated the cell by 90° and repeated the voltage-dependant reflectance curves. Results are plotted in Fig. 2, where P and C's polarization of the incident light are orthogonal to the LC cell. From Fig. 2, the P and C curves almost overlap each other. That means our dye-doped DFLC gel is polarization independent. The contrast ratio (CR) is defined as the ratio of reflectance at $\mathrm{V} = 30\ \mathrm{V_{rms}}$ and 0. The CR is ~150 at $f = 50$ kHz and the maximum reflectance is ~50%.

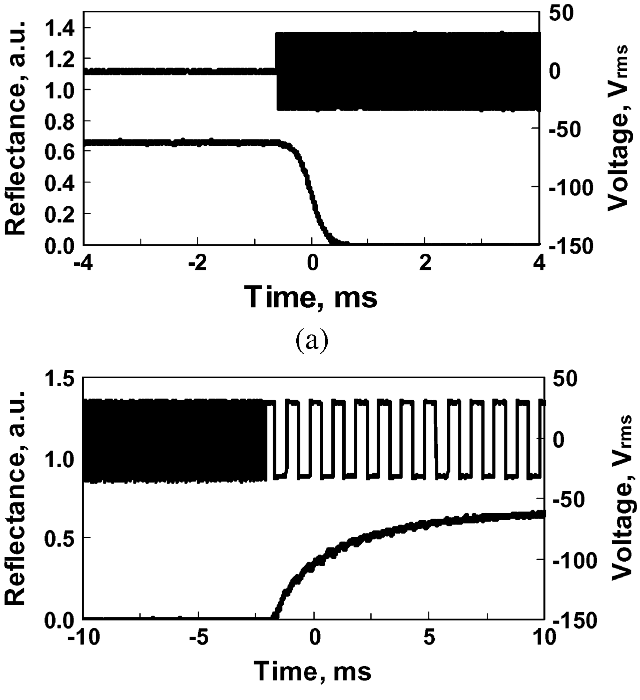
In our sample, the dark state voltage is still high $(\sim 30\ V_{\mathrm{rms}})$ and it can be reduced by using a higher $\Delta\varepsilon$ DFLC material, thinner cell gap, or lower monomer concentration. The contrast ratio can be further improved by increasing the cell gap, monomer concentration, or dye concentration. However, increasing dye concentration would reduce display reflectance and lead to a slower response time, increasing polymer concentration would cause a higher operating voltage, and increasing cell gap would increase the operating voltage, reduce the voltage-off state reflectance, and lengthen the response time.

Fig. 3 shows the voltage-dependant reflectance of a 5-μm and 8-μm cells. In both cells, the LC host and dye and polymer concentrations are kept the same. As the cell gap increases from 5 to 8 μm, the bright-state reflectance decreases from 52% to 28% when a high-frequency voltage is applied. Although the contrast ratio is improved, the bright state reflectance is greatly sacrificed. Thus, this approach is not worth taking.

Response time is another important issue for guest-host displays. The dye molecules are usually bulky and have a large viscosity. Moreover, guest-host displays do not use any polarizer so that their governing response time equations are different from those with polarizers. As a result, a typical response time of a guest-host display is around 50 ms. Detailed values depend on the dye concentration and cell gap.

The response time of our dye-doped DFLC gel is fast. Fig. 4 shows the measured response times of the 5-μm gel. If we switch the applied voltage from 0 to 30 V_{rms} at 50 kHz frequencies, the rise time is 1 ms and decay time is 10 ms. If we fix the voltage at 30 V_{rms} while switching the frequency between 1 kHz and 50 kHz, the rise time is reduced to ~0.55 ms and decay time to ~5.78 ms, as shown in Fig. 4(a) and (b). Fast response time is a key feature of the DFLC materials.

To prove principle, we fabricated a segmented reflective display using the dye-doped DFLC gel. Fig. 5 shows a sample



(a)

(b)

Fig. 4. Measured response time of a 5-μm dye-doped DFLC gel at $V = 30\ \mathrm{V_{rms}}$. The upper traces show the dual-frequency (50 kHz and 1 kHz) addressing and lower traces show the corresponding optical signals. (a) $\mathrm{Rise\ time} = 0.55$ ms and (b) $\mathrm{decay\ time} = 5.78$ ms. $\lambda = 532$ nm.

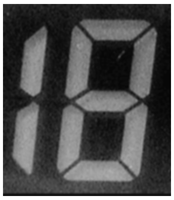


Fig. 5. A device of the dye-doped DFLC reflective display. A diffusive reflector is laminated to the back of the bottom glass substrate. In the white segments, the ITO electrodes were etched away so that $\mathrm{V} = 0$. $\mathrm{Cell\ gap} = 7\ \mu$m.

using a 7-μm dye-doped DFLC gel. To avoid specular reflection, we laminated a diffusive reflector on the backside of the bottom glass substrate in order to widen the viewing angle. The bright segments represent the areas without ITO electrodes. Since no voltage was applied, these segments appear white. The dark areas represent the ITO electrodes with $V = 30\ V_{\mathrm{rms}}$ at $f = 50$ kHz.

IV. CONCLUSION

We have demonstrated a polarizer-free, high contrast, and fast response new reflective GH LCD using a dye-doped DFLC gel. The fabrication process is relatively simple as compared to the double cell GH LCD. The reflectance reaches ~50% and the contrast >100:1. The response times are fast (0.55-ms rise and 5.8-ms decay) when using the dual-frequency addressing method. Since it does not require any polarizer, the viewing angle is wide. This new reflective GH LCD is attractive for handheld displays. To make color displays, pixilated color filters should be implemented.

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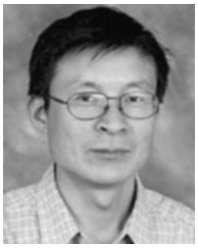

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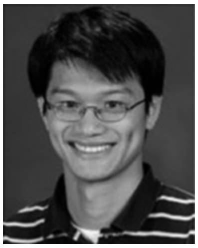

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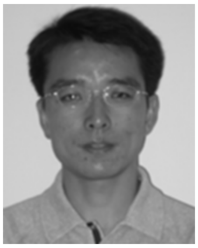

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