Color Displays Based on Voltage-Stretchable Liquid Crystal Droplet

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***Abstract*—In this paper, we demonstrate a transmissive color display based on voltage-stretchable liquid crystal (LC) droplet. The gray scale is induced by stretching a dye-doped LC droplet from a small circular visible area to different extent through dielectrophoretic force. This polarization-insensitive liquid display shows a relatively low operating voltage, fast response, wide viewing angle and good contrast ratio. Both transmissive and reflective mode can be configured.**

***Index Terms*—Voltage-stretchable LC droplet, dielectrophoretic force, color display.**

I. INTRODUCTION

DIELECTROPHORETIC (DEP) effect is an attractive approach for adaptive liquid devices, e.g., adaptive lenses [1]–[5], beam steers [6], tunable irises [7], and optical attenuators [8]–[11]. Different from an electro-wetting device using oil and salty water [12], in a typical DEP device, the two employed liquids are non-conductive [1]–[11]. Thus the DEP devices can bear a high operating voltage while keeping low power consumption. At the same time, electrolysis, Joule heating, and microbubbles can be suppressed, which always appear in an electrowetting device due to the transportation of the free electric charges and the alternating electric fields [1].

Recently, a transmissive color display based on DEP-induced light channel was demonstrated [10]. At $V = 0$, the incident light is absorbed by the black liquid, resulting in a dark state. As the voltage increases, the droplet dome touches the top substrate and becomes flat, a dielectric effect-induced light channel is open and the beam is transmitted. While the voltage is removed, the droplet recovers to its original spherical shape. This polarization-independent liquid display shows a reasonably fast response. However, the contrast ratio is only ∼10:1. To achieve a wide viewing angle and high optical efficiency, an extra turning film and a microlens array are required in the integration with a conventional edge-lit backlight. Besides, it only works in transmisisve mode.

In this paper, we demonstrate a single-pixel color display based on voltage-stretchable LC droplet. By choosing proper liquid materials, the dye-doped droplet shrinks with the smallest surface-to-volume ratio at $V = 0$. As $V = 0$ increases, the droplet is stretched to spread like a film by DEP force. The gray scale is achieved by stretching the droplet to different extent. Upon removing the voltage, the droplet returns to its initial state. Such a display does not need any polarizer and color filters. It shows wide viewing angle, good contrast ratio and large aperture ratio, as well as easy integration with the edge-lit backlight. Both transmissive and reflective modes can be configured. The relatively low operating voltage and reasonably fast transition speed make it promising for mobile displays.

II. OPERATION PRINCIPLES

Fig. 1(a) shows the side-view structure of our proposed device. The droplet (L1) and the surrounding liquid (L2) are sandwiched between two glass substrates. The inner surface of the bottom substrate is coated with interdigitated-stripe indium–tin–oxide (ITO) electrodes (marked as red in Fig. 1), on the top of which is a thin hole-patterned Teflon layer (marked as gray in Fig. 1). These holes partially contact with the electrodes, pinning down the position of the droplets [see Fig. 1(c)].

For most liquids with low surface tensions, their dielectric constants are usually very small ($\varepsilon \sim 5$). While for the liquids with a large dielectric constant (such as water $\varepsilon \sim 80$ and glycerol $\varepsilon \sim 47$), their surface tensions are usually very high (over 60 mN/m) at room temperature. To largely stretch the droplet under a low operating voltage, L1 should have a relatively low surface tension (γ) and a large dielectric constant [11]. Here we chose a Merck LC mixture ZLI-4389. Its properties are listed as follows: $\varepsilon_{//} = 56, \Delta\varepsilon = 45.6, \gamma \sim 38$ mN/m, $\langle n \rangle \sim 1.58$, and $\rho \sim 0.98$ g/m^3. L2 is silicone oil ($\varepsilon \sim 2.9, \gamma \sim 21$ mN/m, $n \sim 1.4$, and $\rho \sim 0.97$ g/cm^3). These two liquids are immiscible with each other and match well in density. The cell gap was controlled by spacers, and the periphery was sealed by glue. At $V = 0$, the LC droplet shrinks with the smallest surface-to-volume ratio, and only occupies a small area, as Fig. 1(a) shows. When a voltage is applied to the bottom electrodes, a nonuniform lateral electric field is generated across the ITO stripes. The dielectric force, which is generated via interaction between electric field and the surface polarization induced on the dielectric liquid-liquid interface, is exerted on the liquid interface to deform the interface profile [13]. According to Kelvin's theory, it can be expressed as [14]

$$F_d = \frac{1}{2}\varepsilon_0(\varepsilon_1 - \varepsilon_2)\nabla(E \cdot E) \qquad (1)$$

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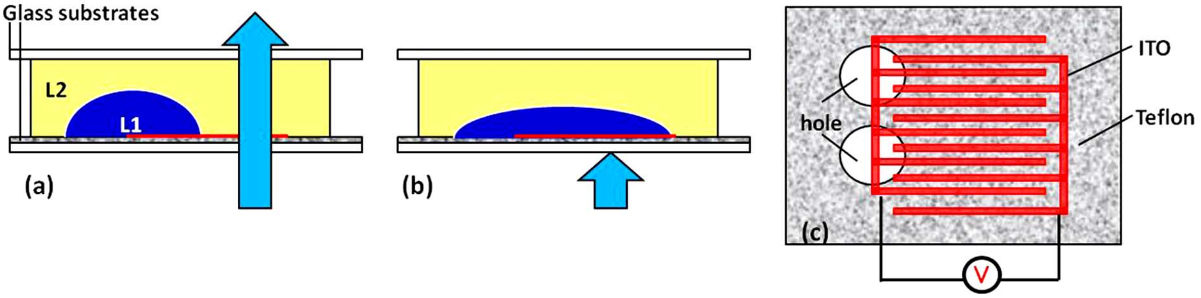

Fig. 1. (a) Sideview of the cell structure at V-off, (b) black state at V-on, and (c) layout of the bottom substrate. The dimension of the hole and ITO stripes are not drawn by scale.

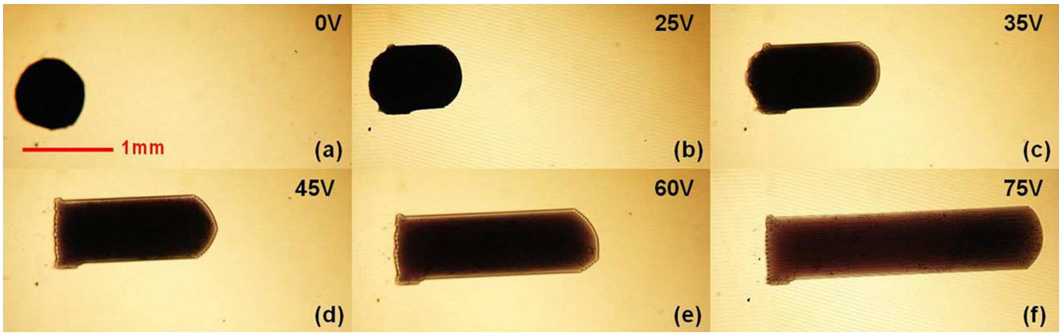

Fig. 2. Droplet deformation (black pixel switch) at various voltages.

where $\varepsilon_0, \varepsilon_1$, and ε_2 represent the permittivity of free space, $L-1$, and $L-2$, respectively, and E denotes the electric field on the curved droplet. Since the LC molecules on the droplet border are reoriented by the fringing field, the dielectric constant of the LC on the border is close to $\varepsilon_{//} = 56$, which is much larger than that of the silicone oil. Therefore, the droplet border bears the strongest dielectric force along the ITO stripe direction. When the voltage is high enough, in order to reach a new balance among the interfacial tension, friction force from the hole surface and the generated dielectric force, the LC droplet will be stretched outward along the stripes, partially blocking the incident light. If the droplet is further stretched to totally block the incident light, a black state is achieved, as shown in Fig. 1(b). When the voltage is removed, the droplet will quickly return to its original state because of interfacial tension.

III. RESULTS AND DISCUSSIONS

A. Black Pixel Switch

To prove concept, we fabricated a droplet cell with the structure shown in Fig. 1(a). The LC droplet was doped with 1.2 wt% black dye (S-428, Mitsui Fine Chemicals). The droplet aperture (the diameter of the droplet's touching area on the bottom substrate) is ≈800 μm and the cell gap was ≈420 μm. The droplet initially does not appear circular because the hole patterned on the Teflon layer is not in perfect circular shape.

Fig. 2 shows the droplet deformations as well as the pixel switch at various voltages. At $V = 0$, the droplet shrinks to a small area. As the voltage is gradually increased to 25 $V_{\rm rms}$, the droplet begins to stretch along the stripe electrodes. At $V = 35$ $V_{\rm rms}$, the deformation becomes more noticeable, and goes further with the increased voltage. Compared to the original black area at $V = 0$, the black dispersion is stretched by ≈3× at $V = 60$ $V_{\rm rms}$, and ≈4.5× at $V = 75$ $V_{\rm rms}$, respectively. In a practical display, we have to design the pixel and initial droplet size to achieve a suitable aperture ratio. For example, if the final dark state is that shown in Fig. 2(e), then the aperture ratio is 67%. The aperture ratio can be further enlarged by increasing the voltage to further stretch the droplet. However, this will reduce the residual droplet volume in the hole. Then if we suddenly turn off the high operating voltage on an extremely stretched droplet, the friction between the droplet and the surrounding liquid begins to play a key role in the recovering process. As a result, the residual droplet may be lifted off from the hole and no longer returns to its original state.

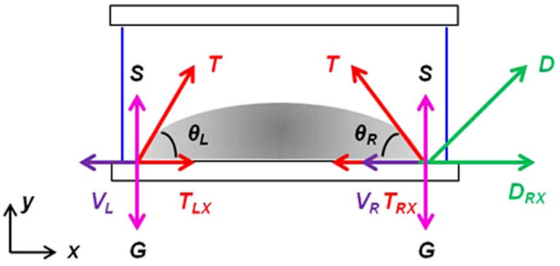

Fig. 3. Dielectric force, interfacial tension and viscosity friction analysis.

In our experiments, we find that at $V < 35$ $V_{\rm rms}$, the rest part of the LC droplet (no embedded electrodes beneath) stays still, while at $V > 35$ $V_{\rm rms}$, it begins to move along with the stretched part (embedded electrodes beneath) in the hole area, as Fig. 2(c) shows. The detailed explanation about the droplet movement is given as follows. When a small LC droplet is dispensed in the patterned hole, it exhibits a nearly spherical shape and a

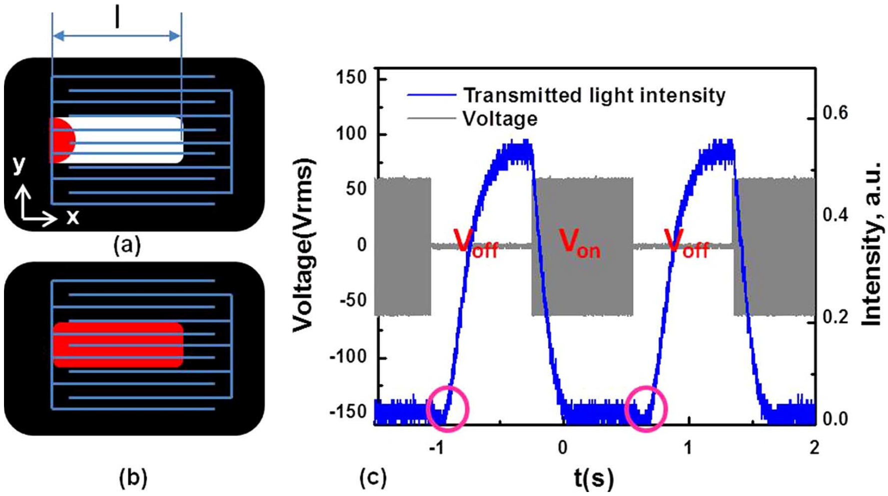

Fig. 4. Measurement of the switching time.

large contact angle on the bottom substrate. Under an operating voltage, the forces exerted on a small group of LC molecules near droplet border are shown in Fig. 3. The molecules, which are close to the left edge of the liquid-liquid interface, experience the gravity (G) and supporting force (S), viscosity friction (V) and the surface tension (T) [13]. For the molecules close to the right edge of the liquid-liquid interface, besides the four forces mentioned above, they also experience the dielectric force (D), which is perpendicular to the interface between $L1$ and $L2$, orienting in outward direction. But only D_{RX} (the horizontal component of the dielectric force on the molecules near the right edge) will deform the droplet. T_{RX} (T_{LX}) is the horizontal component of the interfacial tension on the molecules near the right (left) edge; $V_R(V_L)$ is the viscosity friction on the molecules near the right(left) edge; θ_R, θ_L is the contact angle of the right(left) edge on the bottom substrate. When $D_{RX} > T_{RX} + V_R$, the molecules near the right edge begin to move along the ITO stripe direction, expanding the droplet surface and decreasing its contact angle (θ_R, θ_L) on the bottom substrate. As a result, T_{LX} will increase accordingly. When it is large enough to overcome the viscosity friction $(T_{LX} > V_L)$, the rest part of the droplet will start to move forward.

The switching time was measured by monitoring the time-dependent transmitted light intensity in a dark room. The expanding (recovering) time is defined as the time needed from the initial (stretched) shape to a stretched (initial) shape. Usually, a droplet stretched to a longer distance leads to a longer expanding and recovering time. Here we measured the switching time when the droplet was stretched to $\sim 3\times$ at 60 $V_{\rm rms}$. Since the droplet aperture ($\approx$800 μm) is small, it cannot block the beam (in x-direction) even when it is extremely stretched. Therefore, we add a special black mask on the top substrate of the cell, in which only the area where the droplet travels through is transparent, as shown in Fig. 4(a)–(b).

At $V = 0$, a collimated and expanded He-Ne beam passes through with the highest transmittance $\approx$74.6%. At 60 $V_{\rm rms}$ (500 Hz) burst, the stretched droplet covers the whole transparent area, and the transmittance reaches the minimum $\approx$0.88%. The contrast ratio is $\approx$83:1. The expanding and recovering time were measured as 260 ms and 500 ms, respectively, as shown in Fig. 4(c). The corresponding travel speeds are estimated to be $\sim$6.1 mm/s and $\sim$3.2 mm/s. respectively. Such results are comparable to electrofluidic displays ($\sim$2.65 mm/s) [15]. The short delay in the transmitted light intensity (the curve in the pink circle) may result from the size mismatch between the black mask and the stretched droplet. The length of the stretched droplet may be slightly longer than that of the transmitted area of the black mask (1). The cycle driving with two periods shows that the LC droplet returns to its original state quite well.

Due to the facility limitation in our lab, the smallest droplet (or the smallest hole pattern on the Teflon layer) we can fabricate is $\approx$500 μm. Since a typical sub-pixel size of LCD is $\sim$240 μm$*$ 80 μm, an 80-μm-aperture LC droplet would cover the whole sub-pixel when it is stretched to $3\times$. Under the same travel speeds, the expanding and recovering time would be reduced to $\sim$26 ms and $\sim$50 ms. To work in a reflective mode, a mirror was added as the reflector to the bottom substrate and the reflectance was measured to be $\sim$60% (without AR coating).

B. Color Pixels

We also demonstrated a red and blue pixel switch for color displays. In a conventional transmissive color liquid crystal display (LCD), the color is displayed by the embedded color filters [16]. The optical efficiency is only $\sim$30%. To achieve color filter free, we adopted dye-doped LC droplets [17], [18]. They are doped with 1.5 wt% blue dye (M-137, Mitsui Toatsu Dyes) and 1.2 wt% red dye (Oklahoma dyes C10) respectively. Their aperture is $\approx$500 μm, and the cell gap is $\approx$400 μm. At $V = 0$, the two droplets have the smallest surface-to-volume ratio [see Fig. 5(a)]. They show a dark color due to the strong absorption from the thick LC layer. As the voltage increases, they are gradually stretched, and the dispersion at 35 $V_{\rm rms}$ and 50 $V_{\rm rms}$ are shown in Fig. 5(b)–(c), respectively. The color becomes brighter when the thickness of the LC layer is gradually reduced by stretching.

Due to the molecular structure difference in doped dyes, the blue and red droplets have slightly different stretches at the

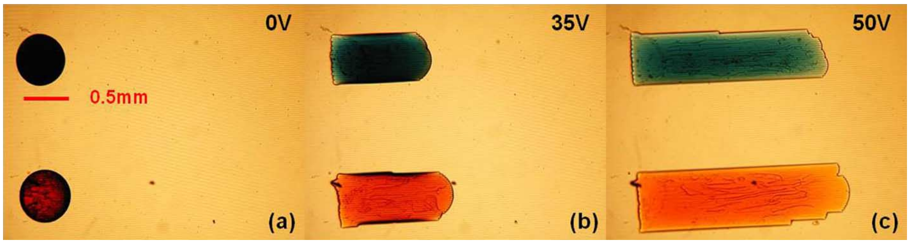

Fig. 5. Droplet deformation (blue and red pixels) at various voltages.

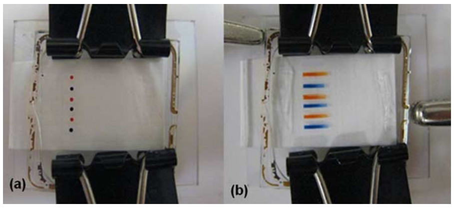

Fig. 6. 1×6 droplet array switching.

same applied voltage. Even for one droplet, it is not uniformly stretched along the stripe direction. Because some dyes are not very well dissolved in the LC, some residual dye clusters form bumpers on the bottom substrate. Besides, a uniform Teflon coating is critically needed in order to achieve a uniform droplet stretching.

Compared to the above-mentioned black droplet, these two colored droplets with smaller apertures need a lower voltage to achieve similar aperture ratio. The operating voltage for an 80-μm-aperture LC droplet will be even lower.

C. 1×6 Array Switch

We also demonstrated a 1×6 colored droplet array. The droplet aperture is $\approx$500 μm, and the cell gap is $\approx$400 μm. A top view of the cell at $V = 0$ is shown in Fig. 6(a), and the switching at 50 V_{rms} is shown in Fig. 6(b). In practical application, a large-scale droplet array is required. These droplets should be separated by a patterned grid (such as black matrices) to avoid the crosstalk. How to fabricate a uniform hole-array on a thin Teflon layer as well as dispensing uniform droplets into the holes is still a challenge.

D. Discussion

From the above experimental results, the selected ZLI-4389 material plays a key role in our device. Such a LC material exhibits a high dielectric constant and medium surface tension. Therefore, the droplet can be largely stretched by a relative low voltage. Otherwise, the droplet deformation will be very limited even under a very high voltage [4]–[7], [19]. In our device, the electric field penetration depth is quite small (less than 10 μm at the highest voltage), and most LC in its bulk is randomly orientated. In this case, the device is polarization insensitive. To further decrease the operating voltage, interdigitated ITO electrodes with a smaller electrode gap can be considered. To further enlarge the aperture ratio, a zigzag striped electrode can be adopted, thus the droplet will be stretched in both elongated and sidewise directions [11]. The contrast ratio depends on the thickness of the area covered by LC and the dye concentration. A higher dye concentration will lead to a larger absorption even though the stretched LC layer is thin. The response time is governed by the liquid interfacial tension, flow viscosity, as well as travel distance. Surrounding liquid with low viscosity helps to improve the travel speed.

IV. CONCLUSION

We have demonstrated a single-pixel color (black, red, blue) display based on voltage-stretchable LC droplet, and investigated its electro-optical properties. For the cell with an 800-μm-aperture droplet and 420-μm-gap, it has a $\sim$67% aperture ratio and $\sim$83:1 contrast ratio at 60 V_{rms} (500 Hz). The corresponding travel speeds are estimated to be $\sim$6.1 mm/s and $\sim$3.2 mm/s. respectively. A simple 1×6 color pixel array was also demonstrated. Increasing dye concentration would improve contrast ratio but the transmittance is sacrificed. The operating voltage can be lowered by using interdigitated ITO electrodes with a smaller striped gap. And aperture ratio can be enlarged by a zigzag striped electrode. Surrounding liquid with low viscosity helps to improve the travel speed. To achieve a full color display, we need to adopt green dopant that is dissolvable in the LC droplet but immiscible with the surrounding liquid.

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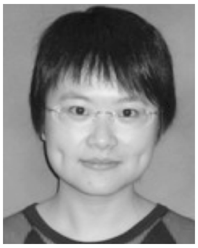

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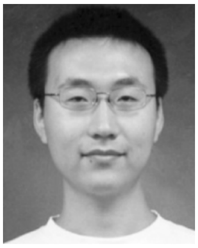

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