Quantum Dots Enhanced Vivid Color Liquid Displays

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Abstract

We demonstrated two types of dielectrophoretic liquid displays with patterned quantum dots array for achieving highly saturated colors. These polarizer-free liquid displays offer high transmittance, wide view, modest response time and contrast ratio, and vivid colors. They are promising candidates for e-book and mobile display applications.

1. Introduction

Liquid display is attractive for applications where power consumption is a major concern. Various liquid displays [1-5] have been developed, such as electrophoretic, electrowetting, and electrofluidic, but all of them have limited color performance. Some devices use dye-doped liquid or color filter array to generate color [2, 4]. Both dyes and color filters have a fairly broad absorption/transmission band and the display device has very limited color gamut. Moreover, these approaches are not energy efficient because only a portion of the backlight can pass through the dyes/color filters. To broaden the application of liquid displays, there is urgent need to enhance the color performance while keeping high optical efficiency.

In this paper, we propose two types of dielectrophoretic liquid display and enhance its color performance with patterned quantum dots (QDs) [6-10]. QDs not only provide wide color gamut (136% AdobeRGB), but also greatly reduce optical loss in color filters by pre-converting the light to desired colors. Our devices demonstrate several advantages: low power consumption, wide viewing angle, acceptable response time and contrast ratio, and vivid colors. They are promising candidates for E-books or mobile displays.

2. Liquid display based on voltage stretchable droplet

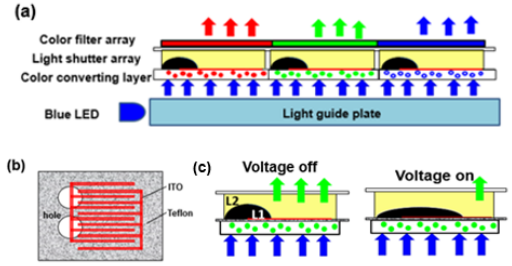

Figure 1. (a).Side view of our proposed color display based on reconfigurable LC droplet and quantum dot backlight. (b).top view and layout of the bottom substrate. (c).Illustration of single pixel at voltage off (bright) and voltage on (black) state.

The first type of liquid display is based on voltage stretchable droplet. Its structure is shown in Fig. 1(a). It consists of blue LED, light guide plate (LGP), color converting layer, light shutter array, and color filter array. In the color converting layer, the closed circles represent the patterned green/red QDs while the open circles represent scattering particles. When the blue light passes through the color conversion layer, QDs absorb some blue light and reemit as green and red. The scattering particles in the blue pixels diffuse the blue light to balance the light distribution of each color. Finally, the color filter array blocks the unabsorbed blue light in the green/red pixels to guarantee color purity. Since most of the light is already converted into the proper color, the absorption loss in the color filters is negligible.

The light shutter array modulates the transmittance of each color pixel. Fig. 1(b) shows layout of the bottom substrate. The substrate is first coated with interdigitated-stripe indium tin oxide (ITO) electrodes with 10-μm width and 10-μm gap, and then coated with a hole-patterned Teflon layer. These holes are used to pin down the liquid droplet at voltage-off state.

Fig. 1(c) explains the mechanism of our proposed liquid display. The droplet (L1) and the surrounding liquid (L2) are sealed between two glass substrates. These two liquids are immiscible with each other and match well in density. In experiment, we chose Merck LC mixture ZLI-4389 as L1. It has high dielectric constant ($\varepsilon_{//}$=56 and $\Delta\varepsilon$=45.6), and relatively low surface tension (γ~38 mN/m). This high dielectric constant is beneficial for low driving voltage and low surface tension is favorable for fast response time. ZLI-4389 is also doped with 1.7% black dye S428 (Mitsui, Japan) in order to function as a light shutter. L2 is silicone oil (ε~2.9, γ~21 mN/m). In the voltage-off state, the L1 droplets stay within the holes and the light can freely pass through. When applying a voltage on the bottom electrodes, a nonuniform lateral electric field is generated across the ITO stripes. This fringing field reorients the LC molecules on the droplet border. As a result, the dielectric constant of the LC on the border is increases to $\varepsilon_{//}$=56, which is much larger than that of the silicone oil (ε~2.9). Under such circumstance, a DEP force is generated on the dielectric liquid-liquid interface:

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

Where ε_0, ε_1, and ε_2 represent the permittivity of free space, L1, and L2, respectively, and E denotes the electric field on the curved droplet. This dielectric force is exerted on the liquid interface to deform the interface profile. The LC droplet can be stretched along the stripe electrodes to blocks the incident light and modulate the grey level. After removing the voltage, the droplet will quickly return to its initial state due to interfacial tension.

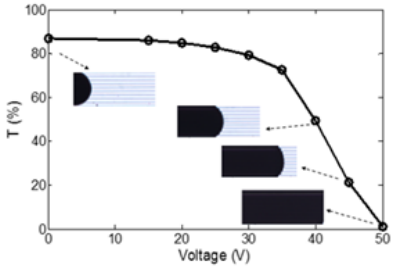

Figure 2. Measured VT curve (The insets show the microscopic photos of a single pixel under different voltages).

Fig. 2 shows the voltage-dependent transmittance (VT) curve of a single pixel device; the insets show the droplet deformation under different voltages. At V=0, the droplet shrinks to a small area and the pixel has a reasonably high transmittance (~86%). As voltage increases, the droplet is stretched along the stripe electrodes. At 40 V_{rms}, the LC droplet covers ~50% of the pixel. At 50 V_{rms}, the droplet is stretched by ~4X and it covers the whole pixel area. The contrast ratio between bright state and dark state is about 100:1.

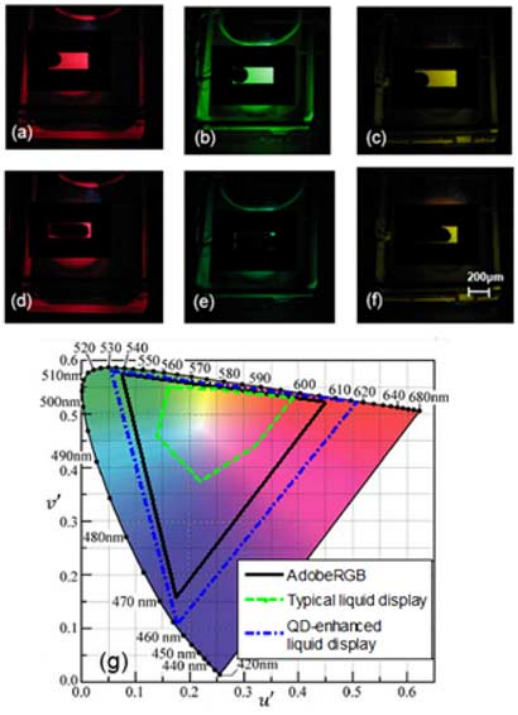

Figure 3. Single color pixel with red, green and yellow QDs at (a-c) voltage-off state and (d-f) voltage-on state (50V_{rms}). (g). Color primaries in the CIE 1976 color space.

To obtain vivid color, we patterned the QD suspension beneath the liquid shutter array. The QD suspensions have core-shell structure, with CdS_xSe_{1-x} as core and ZnS as shell. The particle size is between 5.5 nm and 6.5 nm. The QD samples can emit color from green to red by varying the composition ratio *x* of the core material [6-7]. Fig.3(a-f) shows the color pixels with red, green and yellow QDs. These pixels display brilliant colors at voltage off state and excellent dark state after applying voltage. The light emitted from QD has high color purity with full width at half maximum (FWHM) ~20~30 nm. In comparison, the transmission/absorption FHWM of dyes/color filters is around 80~150nm. Fig. 3(g) plots of the color primaries in the CIE 1976 color space. A typical liquid display with color dyes (green dashed lines) can only covers 35.3% AdobeRGB, which means it has a very limited color reproduction capability [2]. In comparison. The blue dash-dot line shows the color primaries our QD-enhanced liquid display. Its color gamut is ~136% AdobeRGB, which is even wider than that of a typical LCD (70%~80%) and OLED (100%~110%).

The response time of our liquid display depends on the droplet's size and traveling distance. For an 180um diameter size droplet, with 60 V_{rms} the measured expanding and recovering time is 84.5 ms and 116 ms, respectively. The typical sub-pixel size of LCD is 80-μm*240-μm. If we can reduce our droplet size to 80 μm and stretch 3X, then the estimated expanding and recovering time would be ~25ms and ~35ms, respectively. Although this response time is still insufficient for video rate operation, it is acceptable for E-book applications.

3. Liquid display based on variable circular iris

To obtain faster response time, we also propose another liquid display based on variable circular iris and its structure is shown in Fig.4 (a). For device fabrication, we first mixed NOA65 (Norland Optical Adhesive 65, γ~40 mN/m) with 2% Sudan black dye and made a polymer film by spin coating. The polymer film was exposed by UV light through a photomask, and then rinsed off with ethanol to generate a hole-pattern. We then peeled off the film and tightly stacked it onto another glass substrate, which was already coated with ITO electrode and a thin Teflon layer. The hole-pattern film acts as the polymer wall in each pixels to pinning down the liquid droplet at voltage-off state. The liquid droplet used in this experiment is the also LC mixture ZLI-4389 with 1.7% black dye S428.

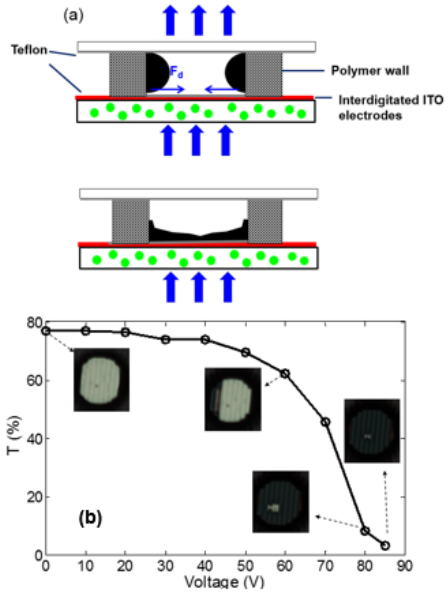

Figure 4. (a).Illustration of single pixel at voltage off (bright) and voltage on (black) state. (b). Measured VT curve.

Fig. 4(b) shows the measured VT curve of a single pixel device. At V=0, the filled LC droplet concentrated as a ring along the polymer wall due to the de-wetting properties of Teflon on the substrate. These LC droplets occupy ~23% of the aperture so the pixel's transmittance is 77%. After applying a voltage, fringing field is generated across the ITO stripes, and the generated DEP force deforms the LC droplet. Because of the large contact area between the LC droplet and the polymer, the required voltage should be larger than a threshold value in order to overcome the friction and stretch the LC droplets. At ~70V_{rms}, almost half of the pixel aperture is covered by the black LC droplet. The induced aperture is not circular because the electrode is one dimensional and dielectric force exerted on the LC ring is asymmetrical. At V~85V_{rms}, LC droplet covers most of the

aperture and the transmittance is ~3%. The contrast ratio between the bright and dark states is 25.7:1. This contrast ratio can be enhanced by increasing the concentration of black dye.

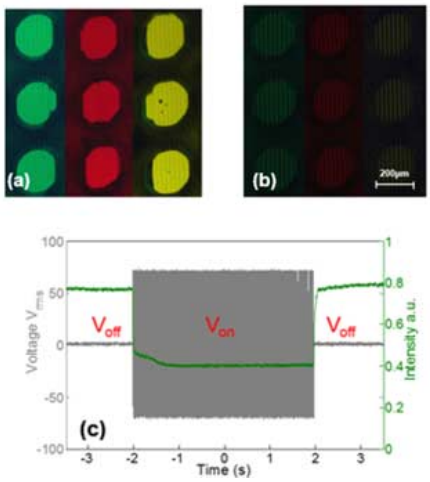

Figure 5. Single color pixel with red, green and yellow QDs at (a) voltage-off state and (b) voltage-on state (100Vrms). (c). Dynamic response of a single pixel.

Fig. 5(a,b) shows the color pixels with red, green and yellow QDs. These pixels exhibit vivid colors in the voltage-off state, and appear reasonably dark in the voltage-on state. In this ring-shape device configuration, the liquid droplet is stretched along all the directions so that its required travel distance is shorter to fully cover the pixel. As a result, the display device has a much faster response time. Fig. 5(c) shows dynamic response of a single pixel. With 60 V_{rms}, the stretching and recovering time is ~11.7 ms and ~14.8 ms, respectively. Such a fast response time is attractive for mobile display applications.

Sunlight readability, which depends on the relative value of surface reflection and display brightness, is highly desirable for mobile displays and E-books. Our proposed liquid displays do not require any polarizer and has low absorption in the color filters, therefore the device appear brighter and more vivid under the same backlight power. Moreover, recently green/red QDs with separated excitation and emission spectra have been reported [7]. With proper color filter design, we can minimize the ambient light effect and achieve a decent ambient contrast ratio.

4. Conclusion

We have experimentally demonstrated two types of QD-enhanced electrophoretic liquid displays. The first type liquid display has a relatively low driving voltage and good contrast ratio (100:1), while the second liquid display has faster response time (<20ms). They are intended for different applications.

Overall, QD-enhanced dielectrophoretic liquid displays exhibit several attractive features: vivid colors, high transmittance, wide view, and modest response time and contrast ratio. They are promising candidates for e-books and mobile displays.

5. References

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