Prospects of quantum dots-based liquid crystal displays

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ABSTRACT

We report a systematic photometric study of LCD based on quantum dot (QD) backlight, and find the optimal emission spectrum combination in terms of system efficiency and wide color gamut. A QD-based LCD has potential to achieve 120% AdobeRGB color gamut in CIE 1931 and 140% in CIE 1976 color space, while keeping the same energy efficiency as conventional backlights. Moreover, we present a transmissive color display based on voltage-stretchable liquid crystal droplet and quantum dot backlight. This polarizer-free display exhibits highly saturated colors, wide viewing angle and reasonably good contrast ratio. QD backlight allows LCD to display original colors with high fidelity, which makes LCD more competitive to organic LED. The prime time for QD-enhanced LCDs is near.

Keywords: liquid crystal display, quantum dot, dielectric liquid display

1. INTRODUCTION

Liquid-crystal-display (LCD) has become the dominant flat panel display technology. However, conventional LCDs face a ceiling in color performance, at best reaching the sRGB color gamut, or 70% AdobeRGB color gamut. This limitation mainly originates from backlight. Presently, most LCDs use cold cathode fluorescent lamp (CCFL) or single chip white LED (blue LED pumping yellow phosphor) as backlight. Although the blue LED has a narrow bandwidth, the yellow phosphor has a fairly broad emission. As a result, the LCD color is not highly saturated. Since natural objects and cinema are significantly more colorful than LCD TV standard, there is an urgent need for wide color gamut display in order to faithfully reproduce the original colors.

To widen the color gamut, one can employ narrow band color filters (CFs) or light sources. A narrow band CF reduces the transmittance and therefore is not a favorable option. On the light source side, newly developed white LED with green/red phosphor materials has narrower emission bandwidth, but their efficiency is not yet satisfactory [3]. Discrete RGB LEDs can significantly expand the color gamut, but they require complicated and separated driving circuits [4]. Recently, a promising new backlight technology involving quantum dot (QD) is emerging [5-8]. Several companies are actively engaging into this area, including material provider (Nanosys, QD vision, 3M) and TV manufacturers (Samsung, LG, Sony) [9-11]. However, a full investigation and systematic performance analysis of QD display is still lacking.

In this paper, we first optimize the emission spectrum of QD light with multi-objective optimization method, and demonstrate its superior performance to conventional backlights. QD backlight offers a wider color gamut (over 120% AdobeRGB in CIE 1931 color space and 140% AdobeRGB in CIE 1976 color space) and higher system efficiency. A fundamental tradeoff between color gamut and system efficiency is explained. Moreover, we present a transmissive color display based on voltage-stretchable liquid crystal (LC) droplet and quantum dot backlight. QD backlight allows LCD to display images with high fidelity and makes LCD more competitive to organic LED technology. Widespread application of QD enhanced LCD is foreseeable.

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2. QUANTUM DOT ENHANCED LCD

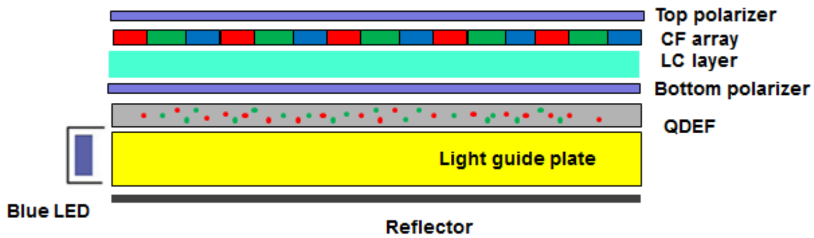

Figure 1. Schematic diagram of a LCD system with QDEF backlight.

Figure 1 is a schematic diagram of a backlight system involving a quantum dot enhancement film (QDEF). The edge-lit blue LED array propagates in the light guide plate and is steered upward to the LCD panel. The green and red QDs in the QDEF absorb part of the blue light and convert it to green and red light respectively. After the blue light passing through the QDEF, it combines with the emitted red and green beams to form a white light with spectral power distribution $P_{in}(\lambda)$, which can be expressed as:

$$P_{in}(\lambda) = f_b S(\lambda, \lambda_b, \Delta\lambda_b) + f_g S(\lambda, \lambda_g, \Delta\lambda_g) + f_r S(\lambda, \lambda_r, \Delta\lambda_r). \quad (1)$$

Where $S(\lambda, \Delta\lambda_i, f_i)$ (i=r,g,b) is the Gaussian function used to fit the emission spectra of blue LED and green/ red QDs, and λ_i, $\Delta\lambda_i$, and f_i represent central wavelength, FHWM and relative intensity respectively.

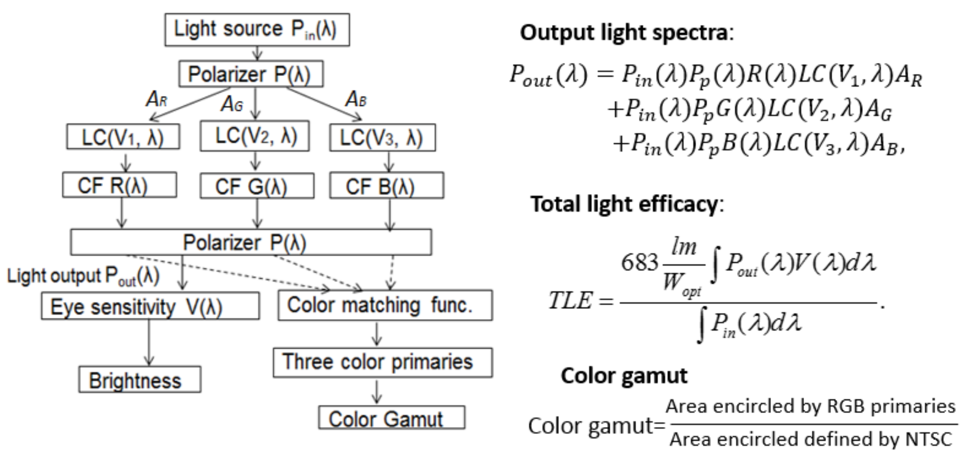

Figure 2. Light flow chart in a typical LCD system.

Figure 2 depicts the light flow chart in a typical LCD panel. The incident light $P_{in}(\lambda)$ is split into three channels: red (R), green (G) and blue (B) corresponding to the color filters. The TFT aperture ratio, LC layer, applied voltage, and color filters jointly determine the optical efficiency and color saturation of a LCD panel. The light finally mix together and transmit out of the LCD panel with SPD $P_{out}(\lambda)$. Two metrics are defined to evaluate the backlight performance: 1) total light efficacy (*TLE*). It expresses how much input light transmit through the LCD panel and finally be converted to the brightness perceived by human eyes. $V(\lambda)$ is the human eye sensitivity function which is centered at λ=550 nm. 2). Color gamut. It indicates the range of colors that can be faithfully reproduced with the LCD display. A backlight with optimal $P_{in}(\lambda)$ should achieve large color gamut while maintain high *TLE*.

We fix the proportion of each color component (f_r, f_g, f_b) to obtain the display white point at D65 (x= 0.312, y=0.329 in CIE1931 color diagram) [11], and optimize the central wavelength and FWHM of each color component to co-maximize the following two objective equations:

$$\begin{aligned} &Color\ gamut = \quad F_1(\lambda_b, \Delta\lambda_b, \lambda_g, \Delta\lambda_g, \lambda_r, \Delta\lambda_r), \\ &TLE = F_2(\lambda_b, \Delta\lambda_b, \lambda_g, \Delta\lambda_g, \lambda_r, \Delta\lambda_r). \end{aligned} \tag{2}$$

For practical considerations, we also set the following constraints: 400 nm < λ_b<500 nm, 500 nm < λ_g< 600 nm, 600 nm < λ_r< 700 nm, 20 nm ≤ $\Delta\lambda_b$≤ 30 nm, 30 nm ≤ $\Delta\lambda_g$,$\Delta\lambda_r$ ≤50 nm. In this paper the particle swarm optimization algorithm is chosen as optimization solver. We found there is no single results that can co-maximize the above two objective functions. Instead, we obtained a group of solutions; improvement one objective is compromised by the degradation of another objective. This group of solutions forms the so-called *Pareto front*.

As an example, we performed the optimization for a twisted nematic (TN) LCD. Two separate optimizations are performed in CIE 1931 or CIE 1976 color space and results are shown in Figs. 3(a) and 3(b), respectively. The performance of conventional backlight sources is also included in the same figure for comparison, including: 1) CCFL; 2) Single-chip white LED with yellow phosphor (1p-LED); 3) Single chip white LED with green and yellow phosphors (2p-LED). 4) Multi-chip RGB LED combination (RGB-LED). Their spectrums are given in Ref. 2 and Ref. 3, respectively. The blue curve in Fig. 3(a) represents the *Pareto front* of QD backlight. The QD backlight could vary from low color gamut (78% NTSC) but high TLE (32.3 lm/W) to high color gamut (125% NTSC) but low TLE (<20 lm/W). The tradeoff between TLE and color gamut is obvious because the gain of one metric results from the loss of the other.

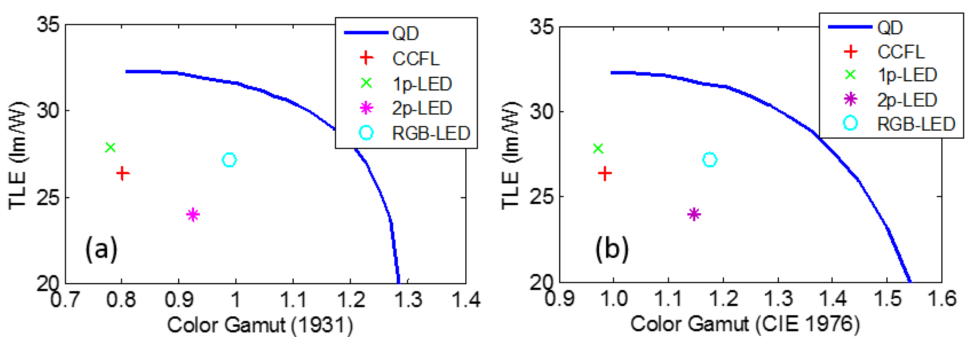

Figure 3. Relationship between TLE and color gamut in (a) CIE 1931 and (b) CIE 1976 color space. LCD mode: TN. Blue solid lines represent the Pareto front.

From Fig. 3(a), it is evident that QD backlight has superior performance to conventional backlights. For example, by keeping the same LER as that of RGB-LEDs, the QD backlight can achieve 118% color gamut, which is much larger than that of any conventional backlight. Similarly, by keeping the same color gamut as RGB-LEDs, the QD backlight can achieve TER~31 lm/w, which is ~13% higher than that of RGB LEDs (27.2 lm/w).

Figure 3(b) shows the *Pareto front* for TER and color gamut defined in CIE 1976 color space. In contrast to the CIE 1931 results shown in Fig. 3(a), the color gamut in CIE 1976 is correspondingly higher. By keeping the same TER as that of RGB LEDs, the QD backlight can achieve >140% color gamut. This is a tremendous improvement compared to conventional backlights. It is also significantly larger than that of commercial OLED color gamut (~100%). QD backlight has advantages in light efficiency and color gamut due to its spectrum design freedom. Unlike conventional backlights whose emission peaks are determined by material properties, QD can readily tune its emission peak via varying particle size/composition. By taking advantage of this design freedom, we can optimize the spectrum to match the transmission peaks of CFs to obtain high light efficiency, and choose appropriate color primaries to encircle a larger area in the CIE color space. Moreover, QD can emit the high purity color, so it naturally has very excellent color reproduction ability for saturate colors.

Figure 4 compares the emission spectra and color primaries of two optimal QD spectral solutions that are lie on the *Pareto front* line in Fig. 3(a). QD1 has emission band relatively close to 550nm where human eye is more sensitive, therefore it has high TLE (32.2 lm/W). But a lot of light emission falls into the overlapped region of red/green color filters leading to reduced color gamut (85%). On the other hand, QD2 has three separated emission peaks matching well with the transmission peaks of color filters. From Fig. 3(a), only a small portion of QD2 emission spectrum falls into the overlapped blue-green region of the color filters. For example, the red color filter transmits the red emission band while totally blocking the blue and green emissions. This leads to highly saturated RGB color primaries and large color gamut (125%). However, the system has low light efficiency (27.2 lm/W) as human eye is less sensitive to deep red and blue. This explains the fundamental tradeoff between TLE and color gamut.

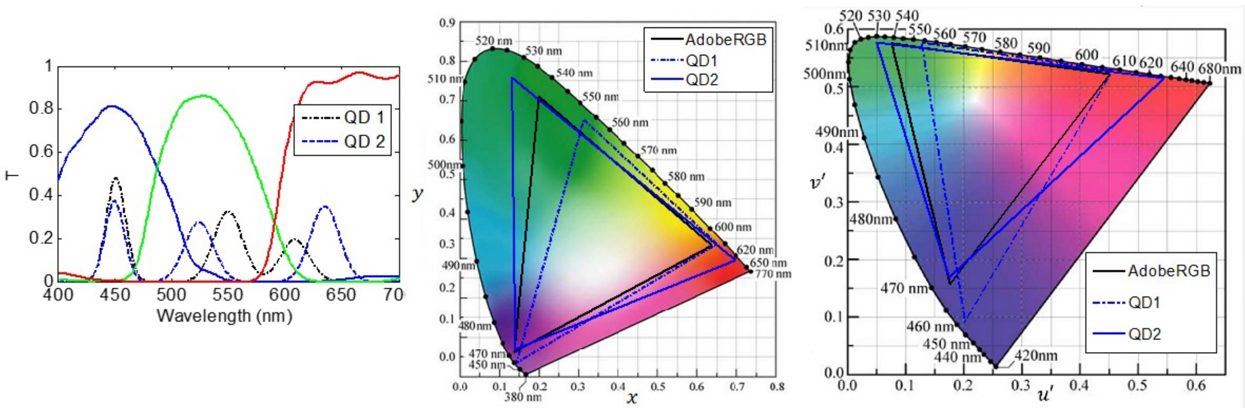

Figure 4. (a) Transmission spectra of color filters and emission spectra of QD1 and QD2; (b) color gamut of QD 1 and QD 2 in CIE 1931; (c) color gamut of QD 1 and QD 2 in CIE 1976.

Next, we investigate the influence of color filters. Figure 5(a) shows the transmission spectra of three commercial color filters. CF1 has the largest transmission peak but it also has significant overlap between the blue-green and red-green filters. To reduce color crosstalk, CF2 and CF3 employ green photoresist with narrower transmission FHWM but their transmittance is sacrificed. LG recently developed CF3 [14] with highly saturated green photoresist (FHWM~65nm). Using narrower CFs can significantly extend the color gamut for conventional light sources. For example, a typical single-chip white LED (1p-LED) with CF1, CF2 and CF3 has color gamut of 97%, 106% and 109%, respectively, but this color improvement is compromised by the reduced system efficiency.

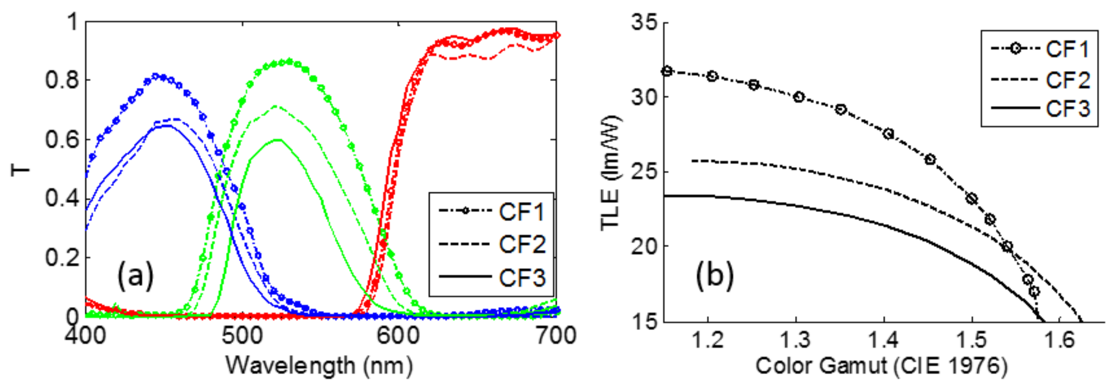

Figure 5. (a) Transmission spectrum of different color filters; (b) *Pareto front* of TLE and color gamut for different color filters.

For comparison, we perform optimization for QD backlight with different color filters and show *Pareto front* results in Fig. 5(b). QD backlight with CF1 has the highest light efficiency and significant color gamut. CF2 and CF3 only slightly improve color gamut while drastically reduce the system light efficiency. Narrow band color filters are not effective for QD backlight, especially when considering the loss in light efficiency. QD backlight itself has very pure emission peaks, and we can further optimize the three emission peaks to match the transmittance of different color filters. Therefore, the system color gamut is less dependent on the color filters. As a result, QD backlight mitigates the color separating requirement for color filters. By using broadband color filters, the cost can be reduced and the system light efficiency improved.

3. COLOR DISPLAY BASED ON LC DROPLET AND QUANTUM DOT

Besides LCD and OLED, novel display based on reconfigurable liquid has some attractive features: no need for polarizer, low power consumption and good sunlight readability [15]. Recently, our group proposed a color display based on voltage-stretchable LC droplet [16,17]. The structure is shown in Fig. 6. 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. 6), on the top of which is a thin hole-patterned Teflon layer (marked as gray in Fig. 6). These holes partially contact with the electrodes, pinning down the position of the droplets. Here we chose a Merck LC mixture ZLI-4389 as droplet; it has a relatively low surface tension (γ~38mN/m) and a large dielectric constant ($\varepsilon_{//}$=56, $\Delta\varepsilon$ =45.6). The LC droplet is doped with 1.2 wt% black dye (S-428, Mitsui Fine Chemicals). At V=0, dye-doped LC droplet shrinks with the smallest surface-to-volume ratio [Fig. 6(a)]. As voltage increases, a nonuniform lateral electric field is generated across the ITO stripes, the droplet is stretched to spread like a film by dielectrophoretic force (Fig. 6(b)). The gray scale is achieved by stretching the droplet to different extent. Upon removing the voltage, the droplet returns to its initial state.

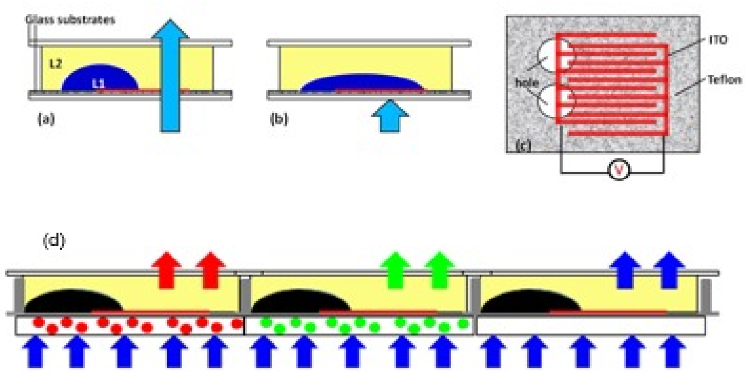

Figure 6. (a) Side-view of the cell structure at V=0, (b) black state at voltage-on state, and (c) layout of the bottom substrate. The dimension of the hole and ITO stripes are not drawn by scale. (d) Color display based on reconfigurable LC droplet and quantum dot backlight.

To realize such a color display, we used LC doped with different dyes [15]. However, organic dyes cannot generate very saturated color and its long term stability remains an issue. Here, we propose an alternative approach as shown in Fig. 6(d). The new display device combines the liquid droplet with a quantum dot backlight. QDs are dispersed in the substrate and pixelated according to the color pixel arrangement. The green and red QDs absorb the incident red light and convert it into green and red colors, while the blue pixels do not have any QD particles so that the incident blue light can transmit through. Those three sub-pixels construct the three color primaries for a color display. The droplet is doped with black dye and acts as a light shutter. At V=0, the droplet shrinks to the side and the cell is transparent, while in a high voltage state the stretched droplet blocks the incident light and the pixel appears dark.

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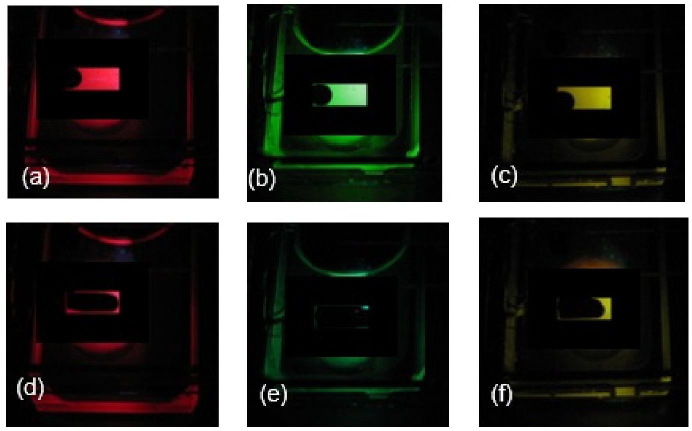

Figure 7. Single color pixel with red, green and yellow QDs at voltage-off state (a,b,c) and voltage-on state (d,e,f).

Figs. 7(a,b,c) show the light transmittance of three single pixels (red, green and yellow) at V=0, while Figs. (d,e,f) show the dark state in a voltage-on state. The measured contrast ratio of each pixel is over 30:1. Clearly, the new device can display high purity colors. Fig. 8(a) depicts the normalized light emission spectrum and Fig. 8(b) plots the color primaries in the CIE 1976 color space. Ideally, the devices can have color gamut of ~136% AdobeRGB. This color gamut is much wider than that of the state-of-the-art liquid display devices [14]. This will be an attractive feature for color E-book and electronic signage. By combining QD backlight with reconfigurable LC droplet, we can obtain a polarizer-free display device with richly saturated colors, wide viewing angle, and reasonably good contrast ratio.

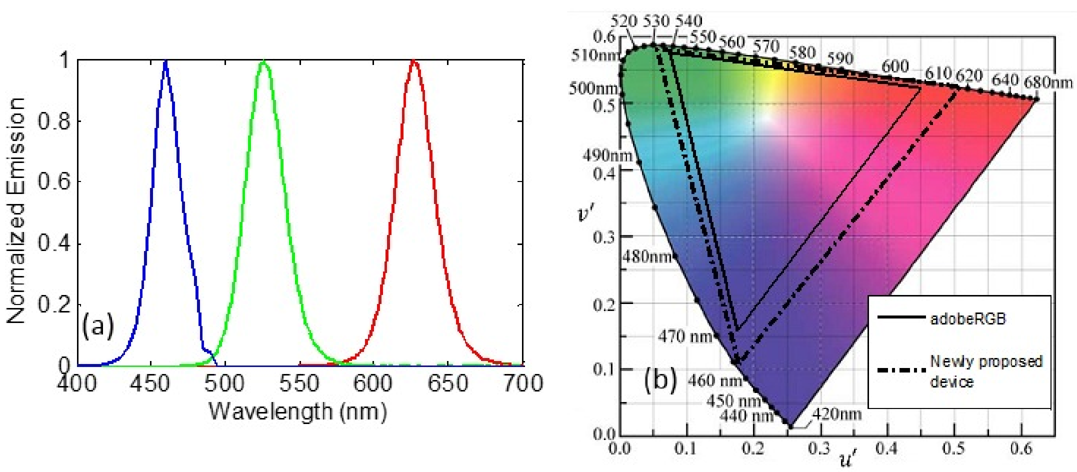

Figure 8. (a) Normalized emission spectra of blue LED and yellow and red QDs; (b) Color primaries in the CIE 1976 color space.

4. CONCLUSION

We have demonstrated a quantum-dot-enhanced LCD, which can have 140% AdobeRGB in CIE 1976 color space. QD backlight outperforms conventional backlight sources in both system efficiency and color gamut. Moreover, we presented a transmissive color display based on voltage-stretchable liquid crystal droplet and quantum dot backlight. This polarizer-free display shows richly saturated colors, wide viewing angle, and ~30:1 contrast ratio. QD backlight allows LCD to display original colors with high fidelity, which makes LCD more competitive to OLED. The prime time for quantum dot enhanced display is near.

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