Is Quantum-Dot LCD Ready for Prime Time?

(*invited paper*)

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***Abstract*— Quantum dots (QDs) backlight brings several advantages to LCDs, including wider color gamut, higher light efficiency, enhanced ambient contrast ratio, and over 100X smaller color shift. The prime time for QD-enhanced LCDs is around the corner.**

Liquid crystal display (LCD) has become ubiquitous and indispensable in our daily life. Recently, it faces strong competition from organic light emitting diode (OLED). Each technology has its own pros and cons. For examples, LCD has advantages in low cost, power consumption, and high resolution density, but OLED is superior in response time, vivid colors, contrast ratio (in dark ambient), thin profile and flexibility. To achieve microsecond response time, blue phase LCD is emerging [1]. The next urgent need for LCD is to achieve comparable or superior color saturation to OLED while keeping high optical efficiency.

Much effort has been devoted to improve LCD color performance. Presently, the majority of LCDs use single chip white LED (blue LED plus yellow phosphor) as backlight. Its color gamut is ~75% of AdobeRGB standard due to the broad emission band of yellow phosphor. Narrowband green and red phosphor materials are under development but they still have low efficiency. Discrete RGB LEDs can significantly extend the color gamut but they require complicated driving circuitry.

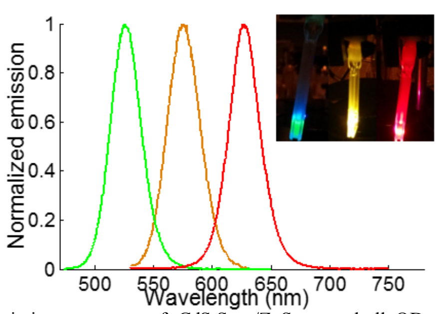

Fig.1: Emission spectrum of CdS$_x$Se$_{1-x}$/ZnS core shell QDs. Emission spectrum is tuned by varying the material composition or particle size. Inset photo shows the emission color when QDs is excited by a 459nm blue LED.

Recently, quantum dot (QD) is emerging as a new backlight source. QDs are nanoparticle with diameter around 5~20nm. Resulting from the size quantization effect, QD exhibits several attractive features: high quantum efficiency, broad absorption band, narrow emission linewidth, and controllable emission peak. As shown in Fig.1, the QD samples emit highly saturated colors with full width half maximum (FHWM) ~30 nm. More amazingly, for a given material the individual emission spectrum can be tuned from green to red via varying QD size/composition. By using a blue LED to excite the green/red QD mixture, a white light spectrum with three distinguished emission bands can be obtained and be customengineered for 'smart' backlighting.

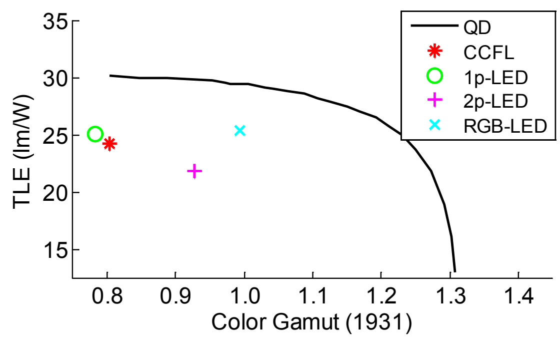

Fig. 2: Performance of QD backlight and various conventional backlights, including 1) CCFL; 2) Single-chip white LED with yellow phosphor (1p-LED); 3). Single chip white LED with green and red phosphors (2p-LED). 4) Multi-chip RGB LEDs (RGB-LED).

To take advantage of spectrum design freedom, we performed a systematic modelling for LCD backlight and searched for the optimal spectrum. An ideal backlight should provide wide color gamut while maintain high light efficiency. Fig. 2 depicts the performance of QD backlight in terms of these two objectives. Instead of finding one QD spectrum that simultaneously satisfies both objectives, we found a series of solutions. Moreover, increasing light efficiency is compromised by the degradation of color gamut, and vice versa. To improve light efficiency, the three emission peaks should be all close to 550 nm, where human eye is most sensitive. These two requirements are mutually exclusive and set the fundamental tradeoff between light efficiency and color gamut. Depending on different application needs and display requirements, we can have different weight ratio on the two criteria and pick up a proper solution. It is evident that QD backlight has superior performance to those conventional backlights. For example, by keeping the same color gamut as that of RGB-LEDs, the QD backlight shows ~15% higher efficiency. More strikingly, by keeping the same light efficiency the QD backlight can achieve 118% AdobeRGB color gamut, which is significantly wider than that of commercial OLED (color gamut ~100%). QD backlight boosts the color performance of LCDs at an affordable cost.

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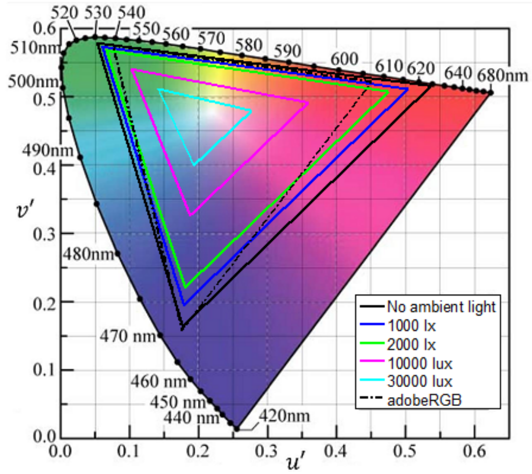

Fig. 3: Variation of display color gamut at different ambient light levels. The LCD is assumed to have luminance intensity of 500cd/m^2 and 5% surface reflection.

QD backlight also offers improved sunlight readability, which is an important issue for mobile displays. As the ambient light flux increases, the displayed image could be washed out. The reflected ambient light degrades color characteristics because a portion of the reflected light is also seen as noise by the observer. The reduced color gamut deteriorates image quality. Fig. 2 depicts the color gamut of QD-enhanced LCD under different ambient light levels. Although the color gamut is reduced from 130% to 95% as the ambient light intensity increases from 0 to 2000 lux (outdoor daylight in heavy shade), it still covers most AdobeRGB color region and the image quality can be preserved. Moreover, according to a psychophysical phenomenon called Helmholtz-Kohlrausch effect, the highly saturated colors appear to be brighter than those with lower saturation, even they have the same luminance. QDs provide saturated light emission and therefore the colors remain more discernable under sunlight.

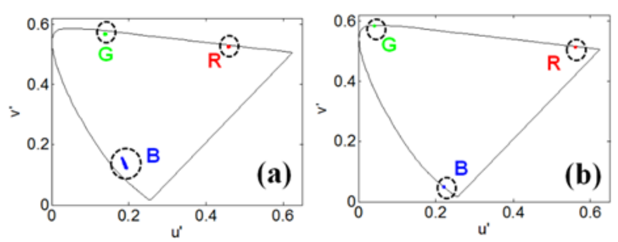

Fig. 4: Simulated color shift of RGB primaries in the film-compensated FFS at 70° incident angle: (a) n-FFS using white LED, (b) n-FFS using QD-LED ($\Delta\lambda$ =10 nm).

Moreover, QD backlight helps to suppress color shift, as shown in Fig. 4. In comparison with white LED, QD-LED shows more than 100X better angular color uniformity. This much weaker color shift originates from the narrower spectral bandwidth and less spectral overlapping of the QD-LED backlight.

In summary, QD backlight adds several advantages to LCDs: 1) Their narrow emission spectra lead to vivid colors and large color gamut (~120% in CIE 1931 and ~140% in CIE 1976). 2) The LCD system light efficiency can be improved by ~15% by optimizing QD emission spectrum to match the color filters. 3) QD backlight mitigates color separating requirement of color filters. By using broadband color filters, the cost can be reduced and the optical efficiency improved. 4) QD spectrum can be readily designed for different application needs, such as achieving different white point. In fact, QD backlight can also be integrated with multi-color primary technique to further improve display performance [6]. 4) QD backlight enhances the image quality under ambient light illumination. 5) QD backlight greatly suppresses color shift and therefore it enhances the LCD's viewing angle property. We can combine QD backlight with n-FFS mode to achieve high optical efficiency, wide viewing angle, and vivid colors for mobile displays [8]. We can also integrate QD backlight with blue phase LCD [1] to obtain crisp TV pictures without image blurs. The prime time for QD-enhanced LCDs is around the corner.

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