Quantum Dots-enhanced LCD Color and Optical Efficiency

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Abstract

We optimized the emission spectrum of a quantum dot (QD) backlight and achieved ~140% color gamut in CIE 1976 color space. The QD-based LCD not only exhibits a wide color gamut but also improves the optical efficiency. Our systematic photometric analysis provides useful guidelines to further optimize the QD backlight design.

1. Introduction

Liquid crystal display (LCD) has become ubiquitous and indispensable in our daily life. Recently, LCD 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 better color saturation than OLED while keeping high optical efficiency.

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 [2] because the yellow phosphor has a relatively broad emission band. Discrete RGB LEDs can significantly extend the color gamut but they require complicated driving circuitry. Recently, quantum dot (QD) is emerging as a new backlight solution [3]. Several companies are actively engaging into this area, including material providers (QD vision, Nanosys, and 3M) and display manufacturers (Sony, Samsung, and LG) [4-7]. However, a full investigation and systematic performance analysis of QD display is still lacking.

In this paper, we used a blue LED-pumped QD backlight to achieve a very wide color gamut LCD (over 120% AdobeRGB in CIE 1931 color space and 140% AdobeRGB in CIE 1976) and higher system efficiency. Four commonly used LC modes: TN (for notebook computers), FFS (for mobile displays), MVA (for large-screen TVs), and IPS are analyzed. A fundamental tradeoff between color gamut and system efficiency is explained. This systematic photometric analysis establishes an important guideline for further optimizing QD backlight design.

2. Systematic analysis

Figure 1 depicts the optical properties of our green and red QD samples (purchased from Cytodiagnostics). They have core/shell structure, with CdS_xSe_{1-x} as core and ZnS as shell. The emission color can be tuned by changing the composition ratio x of the core material. For a given material, its emission spectrum is determined by the diameter of the QDs. The diameter of QDs can be controlled quite uniformly so that their full width half maximum (FHWM) is ~30 nm [Fig. 1(b)]. QDs exhibit a fairly broad absorption band. By using a blue LED to excite the green/red QD mixture, we can obtain a white light with three distinguished emission bands, and the input spectral power distribution (SPD) can be given as:

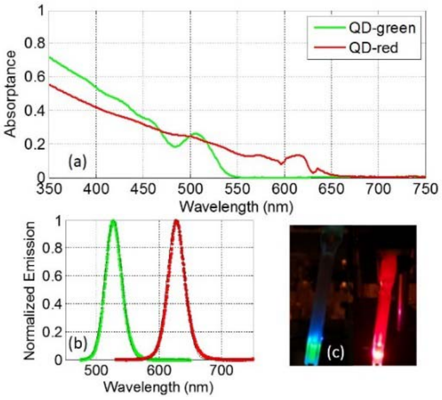

Figure 1. Optical properties of green and red QDs: (a) Absorption spectra, (b) Emission spectra, and (c) A photo of the emitted vivid colors.

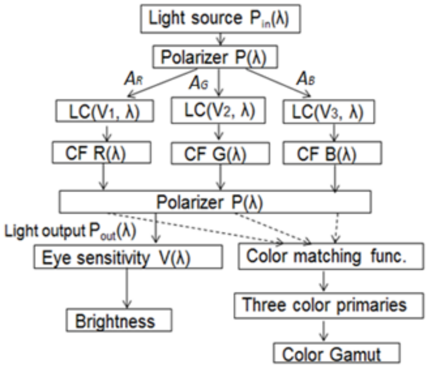

Figure 2. Light flow chart in a typical LCD system.

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

In Eq. (1), S(λ, $\Delta\lambda_i$, 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 the central wavelength, FHWM and relative intensity, respectively.

This tri-color spectrum is suitable for LCD backlight. Figure 2 depicts the light flow chart in a typical LCD panel. The incident light is split into RGB channels 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 lights finally mix together and transmit through the LCD panel with SPD $P_{out}(\lambda)$ written as:

$$\begin{aligned} P_{out}(\lambda) &= P_{out,R}(\lambda) + P_{out,G}(\lambda) + P_{out,B}(\lambda) \\ &= P_{in}(\lambda) P_{pol}(\lambda) R(\lambda) LC(V_1,\lambda) A_R + P_{in}(\lambda) P_{pol} G(\lambda) LC(V_2,\lambda) A_G \\ &+ P_{in}(\lambda) P_{pol} B(\lambda) LC(V_3,\lambda) A_B, \end{aligned} \quad (2)$$

We also define two metrics for evaluating the backlight performance:

1). *Total light efficacy* (*TLE*) defined as

$$TLE = \frac{683\frac{lm}{W_{opt}}\int P_{out}(\lambda)V(\lambda)d\lambda}{\int P_{in}(\lambda)d\lambda}. \qquad (3)$$

This criteria expresses how much input light transmitting 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* defined as [8]:

$$Color\ gamut = \frac{Area\ encicled\ by\ RGB\ primaries}{Area\ defined\ by\ AdobeRGB\ standard}. \qquad (4)$$

It indicates the range of colors that can be faithfully reproduced by the LCD. A backlight with optimal $P_{in}(\lambda)$ should achieve a wide *color gamut* while maintaining a high *TLE*.

To make a fair comparison, we set the white point at D65 (x= 0.312, y=0.329 in CIE1931 color diagram). After knowing the color coordinates of the targeted white light and three primary colors, the relative proportion of each color component (f_r, f_g, f_b) can be determined by solving the color mixing function. The remaining free parameters for each color component are central wavelength and FWHM. In total, there are 3x2=6 free parameters and two metric functions that are subject to maximization:

$$\begin{aligned} Color\ gamut &= F_1(\lambda_b, \Delta\lambda_b, \lambda_g, \Delta\lambda_g, \lambda_r, \Delta\lambda_r), \\ TLE &= F_2(\lambda_b, \Delta\lambda_b, \lambda_g, \Delta\lambda_g, \lambda_r, \Delta\lambda_r). \end{aligned} \qquad (5)$$

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. For such a multi-objective problem, a result that simultaneously satisfies each objective may not exist. Instead, a group of solutions could be obtained; any further improvement of the solution in terms of one objective is likely to be compromised by the degradation of another objective. Such solutions constitute a so-called *Pareto front*. In this paper we choose the particle swarm optimization algorithm as optimization solver to search for *Pareto front* [9-11].

3. Results and discussion

We first analyze fringe field switching LCD with a negative $\Delta\varepsilon$ liquid crystal (n-FFS) [12,13]. This LC mode exhibits several attractive features: high transmittance, wide viewing angle, cell gap insensitivity and single gamma curve. Two separate optimizations are performed in CIE 1931 or CIE 1976 color space and the results are shown in Figs. 3(a) and 3(b), respectively. The performance of four other backlight sources is also included for comparison, including: 1) CCFL; 2) Single-chip white LED with yellow phosphor (1p-LED); 3) Single chip white LED with green and yellow phosphor (2p-LED); 4) Multi-chip RGB LEDs (RGB-LED) [14]. The black curve in Fig. 3(a) represents the *Pareto front* of QD backlight. The QD backlight could vary from low color gamut (80% AdobeRGB) but high TLE (30.2 lm/W) to high color gamut (130% AdobeRGB) 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.

From Fig. 3(a), it is evident that QD backlight has superior performance to conventional backlights. For example, by keeping the same TLE as that of RGB-LEDs, the QD backlight can achieve 121% 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 TLE~29.2 lm/w, which is ~15% higher than that of RGB LEDs (25.3 lm/w).

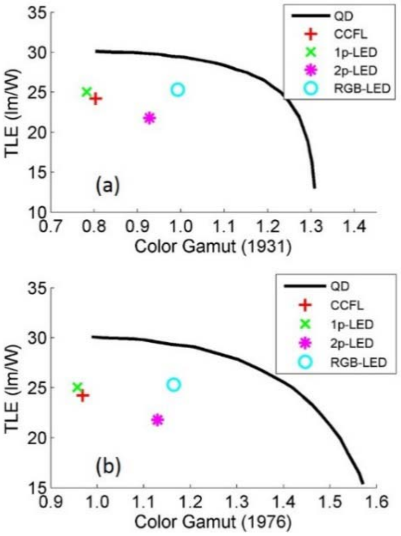

Figure 3. TLE vs. color gamut in (a) CIE 1931, and (b) CIE 1976 color space. LCD mode: n-FFS. Black solid lines represent the Pareto front.

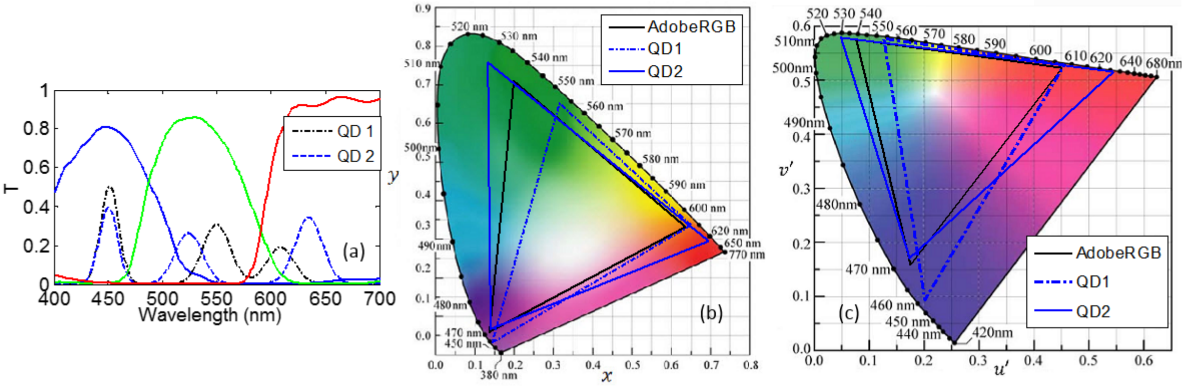

Figure 4. (a) Transmission spectra of color filters and emission spectra of QD1 and QD2, (b) Color gamut in CIE 1931 color space, and (c) Color gamut in CIE 1976 color space.

According to Fig. 3(b), the color gamut defined in CIE 1976 color space is correspondingly higher. By keeping the same TLE 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%).

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 (30.2 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 with a deep red QD, therefore it has significantly larger color gamut (~125%) but with reduced TLE (24.7 lm/W). This explains the fundamental tradeoff between TLE and color gamut. The color gamut of QD backlight almost covers the whole region defined by AdobeRGB, and it can faithfully reproduce most natural colors.

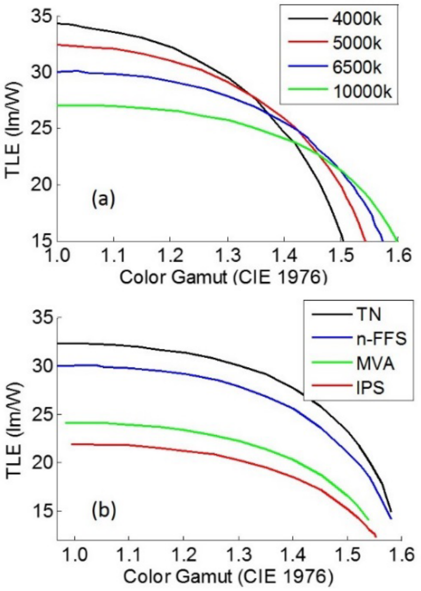

Figure 5. (a) Influence of white point, and (b) Influence of different LC modes.

The selection of white point also affects the performance of backlight, as shown in Fig. 5(a). A lower color temperature white point will result in higher light efficiency but limited color gamut, while a higher color temperature white point will result in a wider color gamut but reduced white point. A proper selection of white point should consider both light efficiency and color gamut.

Finally, we extend our analysis to different LC modes. As shown in Fig. 5(b), for all the four popular LCD modes, QD backlight can produce ~140% color gamut in CIE 1976 color space. A different LC mode mainly affects the light efficiency. The n-FFS mode has much higher light efficiency compared to MVA and IPS. Although its transmission is slightly lower than that of TN (without considering the TFT aperture ratio), it has wide viewing angle and is more robust for touch screen. If we combine QD backlight with n-FFS, we can obtain high transmittance, wide viewing angle, and wide color gamut for touch panels. It will greatly enhance the color performance of mobile displays, such as iPhone and iPad.

4. Conclusion

We demonstrated a QD-enhanced LCD with 140% AdobeRGB color gamut in CIE 1976 color space. QD backlight outperforms conventional backlights in both system efficiency and color gamut. By combining the QD backlight with n-FFS mode, we can achieve high optical efficiency, wide viewing angle, and vivid colors for mobile displays. By integrating QD backlight with blue phase LCD, we can obtain high image quality TVs without image blurs.

5. References

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