Quantum Dot LCDs for Rec. 2020

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Abstract:

We optimize the optical efficiency and color gamut simultaneously to realize Rec. 2020 for photoluminescence quantum dot (QD) LCDs. Our results indicate that we can achieve 97% of the Rec. 2020 color gamut while maintaining a reasonably high optical efficiency for both FFS and MVA LCDs by properly selecting QD wavelengths and slightly modifying the transmission spectra of the employed color filters.

Keywords: Quantum dot, color gamut, optical efficiency.

1. Objective and Background

The Rec. 2020 standard for ultra-high-definition (UHD) TVs has a wide color gamut that can faithfully reproduce almost all the natural object colors [1-2]. The three primary colors of Rec. 2020 are located on the border of the CIE 1931 and CIE 1976 color spaces, indicating that such a wide color gamut can only be realized by laser displays [1-2]. However, because of the problem of speckle, laser displays are still not ready for mass production. To achieve such a wide color gamut, QD is a strong candidate because of its narrow and tunable emission spectra [3-9]. Here we use the Pareto front analysis [4] to optimize the color gamut coverage and optical efficiency simultaneously for the PL QD-enhanced LCD. Results indicate that with photoluminescence (PL) QDs we can easily achieve over 90% of Rec. 2020 coverage with commercially available color filters while maintaining a high optical efficiency. For PL, the optical efficiency can be evaluated as [1, 4, and 5]:

$$TLE = \frac{K_m \int S_{out}(\lambda)V(\lambda)d\lambda}{\int S_{in}(\lambda)d\lambda} \qquad (1)$$

Here *TLE* is the total light efficiency; $S_{in}(\lambda)$ and $S_{out}(\lambda)$ are the spectra power density (SPD) of the backlight and the output spectra, respectively. $V(\lambda)$ is the standard luminosity function, and K_m=683 lm/W is the luminous efficacy of radiation (*LER*) of the ideal monochromatic 555-nm source. Eq. (1) takes the transmittance of the LC module and the color filters (CFs) into consideration.

Another advantage of QD is small color shift [1] because of its narrow PL spectra (10-30 nm). In this paper we extend our study to the combined white light and compare the results for QD-enhanced LCD with different LC modes. Also, we have compared the results for QD LCD with red and green phosphors embedded LCD and the results show that if QDs can be incorporated into blue LED chip to form a white LED, QDs will have wider color gamut and higher optical efficiency than red and green phosphors.

2. QD-enhanced LCDs

For the QD-enhanced LCDs, their optical efficiency and color gamut is a combination of the input light source, the transmittance of the LC module and the CFs. In our analysis, the light source is blue LED with green and red QDs, and two LC modes: n-FFS and MVA are analyzed. As for the color filters, we first use two commercially available CFs shown in Fig. 1(a), here CF1 is used mainly in TVs because of its relatively large transmittance. However, the crosstalk of CF1 is also more severe compared with CF2. For commercial QDs, the linewidth is usually between 20~30 nm and we assume that the linewidth of the RGB color are all 20nm. By optimizing the central wavelength of the RGB spectra, the Pareto front of the QD-enhanced LCDs are shown in Fig. 1(b). Here the color gamut coverage is calculated under CIE 1931.

From Fig. 1(b) we can tell that when the linewidth of the red and green QDs and blue LED is fixed, the largest color gamut that LCDs can achieve is determined by the CFs, and at the same time the n-FFS mode is more efficient than the MVA mode because of the higher transmittance [10-12]. However, difference LC modes do not have much impact on the color gamut. The optimal output light spectra for the two color filters are shown in Fig. 1(c), and the corresponding color gamut are illustrated in Fig. 1(d). Also, the optimized values for the two CFs are shown in Table 1.

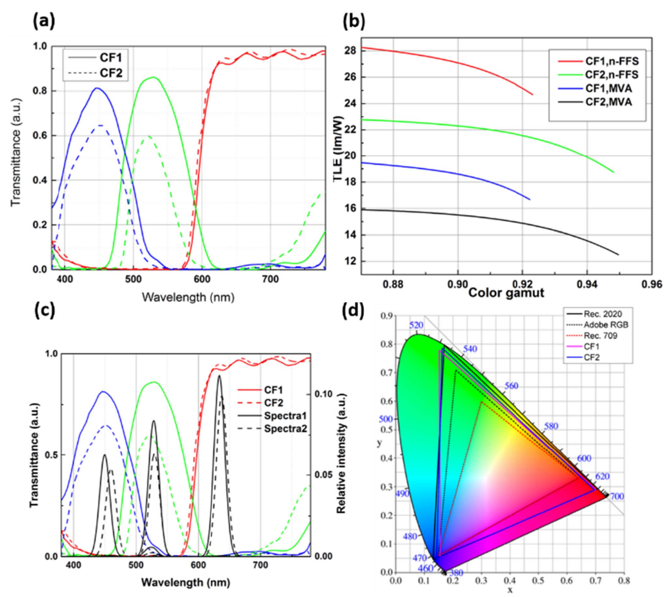

Figure 1. (a) The transmittance of two color filters; (b) the Pareto front of the QD-LCDs with different LC mode and color filters; (c) the transmittance and the corresponding optimized output spectra for the two color filters; and (d) the simulated color gamut for the two optimized output spectra.

Table 1. Optimized values of the two wide color gamut n-FFS LCDs with CF1 and CF2, respectively.

CF type	TLE (lm/W)	Color Gamut
CF1	24.6	92.3%
CF2	18.7	94.8%

There are two approaches to further improve the color gamut of the QD-LCDs: shrinking the linewidth of the light source or re-designing the CFs. For the first approach, even if we can reduce the linewidth of the RGB colors to 10nm, which is still not commercially available, the color gamut improvement is insignificant because of the crosstalk between different CFs, as can be seen from Table 2, even with 10nm RGB colors, for CF1 we can only achieve 94.1% of Rec. 2020. Such result is even smaller than the case where 20 nm RGB colors are used with CF2, which is shown in Fig. 1(b) and Table 1, indicating that redesigning the CFs is more vital for a wide color gamut.

Table 2. Optimized values of two wide color gamut MVA LCDs with 10-nm-linewidth primary colors for CF1 and CF2, respectively.

CF type	TLE (lm/W)	Color Gamut
CF1	17.6	94.1%
CF2	13.3	96.0%

As for the second approach, we have re-designed the color filters [1, 7] by reducing the crosstalk between different color channels, as is shown in Fig. 2(a). And the resultant widest color gamut is shown in Fig. 2(b).

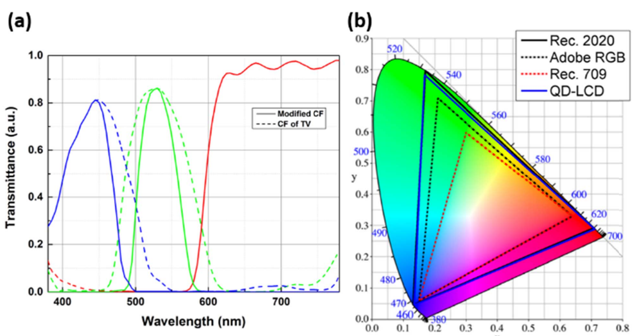

Figure 2. (a) The transmittance of our modified CFs based on the CFs for TV and (b) Simulated color triangle of the wide color gamut QD-LCD (MVA mode).

For this configuration, the parameters for the optimized display is shown in Table 3. From Table 3 we can see that with the optimized CFs, the best color gamut we can get is larger than 97%.

Table 3. System parameters of the widest color gamut we can get with the modified color filters, for both MVA and n-FFS modes.

LC mode		MVA	n-FFS
Central Wavelength (nm)	Red	637.8	638.3
	Green	530.9	530.5
	Blue	469.1	467.6
TLE (lm/W)		12.1	18.3
Color Gamut		97.6%	97.5%

3. Color shift of QD LCD

Color shift at an off-axis angle is a critical issue. For a QD-LCD, the angular performance is primarily determined by the birefringence of the LC material [10-12]. Here we demonstrate that with two wide-view LC modes: 1) two-domain (2D) n-FFS for smart phones and 2) 4D MVA for TVs. From Figs. 3(a)-(b), the color shift of each RGB primary color is rather small and the blue has the largest color shift. For the worst scenario, the color shift (Δu'v') of the blue color stays below 0.01 at 80° viewing angle. This means at large viewing angles, the color gamut will not shrink and remain the same. However, for the white color, the color shift is much larger because of the birefringence dispersion of the LC material. A possible solution is to use color mixing films to mitigate the color shift [1]. Even so, the color shift of QD-LCD is still better than contemporary LCD with white LED [1].

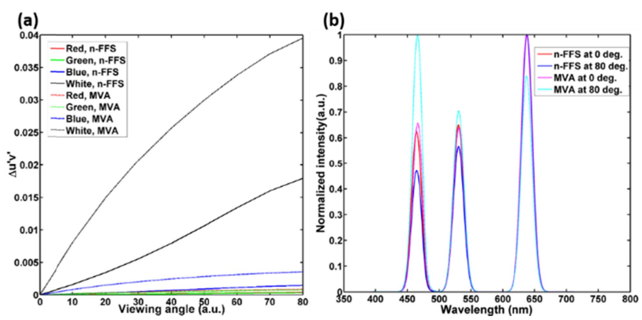

Figure 3. (a) Color shift of QD-LCDs for 2D n-FFS and 4D MVA, and (b) the normalized output spectra of the QD-LCD at different viewing angle.

4. Comparison with red and green phosphors embedded LCD

Besides QDs, two-phosphor LEDs (2p-LED, i.e. blue LED pumping red and green phosphors) have also attracted much attention because of their excellent reliability and low cost. Figure 4(a) shows the emission spectra of such a 2p-LED [13]. From Fig. 4(a), the green and red emission spectra are relatively broad as compared to quantum dots. Our simulation results in Fig. 9(b) show that for this 2p-LED backlit LCD system with the color filters designed for TV (CF1), it covers 90% of the Adobe RGB and 67% of the Rec. 2020, and the TLE is 21.7 lm/W for the n-FFS mode and 15.6 lm/W for the MVA mode. Compared with the results in Fig. 1 and Table 1, we find that it is less efficient than QD-LCD. Therefore, we conclude that theoretically QD offers wider color gamut and higher optical efficiency than 2p-LED. However, contemporary red and green phosphors can be deposited on top of the blue LED chip to form a white LED [1, 10], whereas for red and green QDs, it is still not mature to place them on the blue LED chip [1,5-7] because of the material reliability issue. The "on edge" and "film" approaches for QDs are not as efficient as the white LED with 2p phosphors because of the longer optical path.

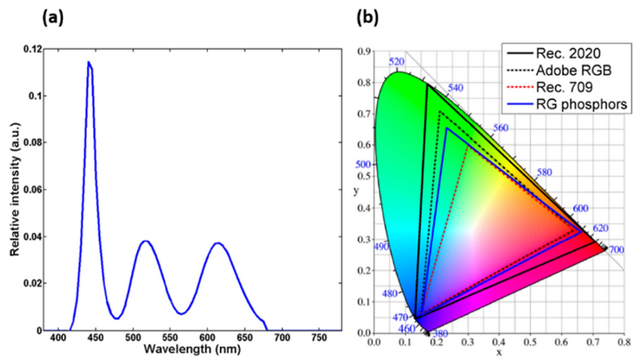

Figure 4. (a) The spectra of the RG phosphor embedded LCD and (b) its color triangle.

5. Conclusion

With our analysis on the color gamut and optical efficiency of PL QD-LCDs, we have proven that QDs can easily reproduce more than 97% of the Rec. 2020 color gamut, which means Rec. 2020 color gamut is no longer exclusive to laser display. QD is a great candidate for realizing high efficiency and wide color gamut displays. Also, we have analyzed the color shift of QD displays and the results indicate that QD-based displays have negligible color shift for the primary colors. The comparison between QD-LCD and red and green phosphors embedded LCD indicates that the QD-LCD will eventually be more efficient and have wider color gamut than 2p-LED embedded LCD.

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7. References

[1] R. Zhu, Z. Luo, H. Chen, Y. Dong and S.-T. Wu, "Realizing Rec. 2020 color gamut with quantum dot displays," Opt. Express **23**(18), 23680-23693 (2015).

[2] K. Masaoka, Y. Nishida, and M. Sugawara, "Designing display primaries with currently available light sources for UHDTV wide-gamut system colorimetry," Opt. Express **22**(16), 19069-19077 (2014).

[3] R. Zhu, Z. Luo and S.-T. Wu, "Light extraction analysis and enhancement in a quantum dot light emitting diode," Opt. Express **22**(S7), A1783-A1798 (2014).

[4] Z. Luo, D. Xu, and S.-T. Wu, "Emerging quantum-dots-enhanced LCDs," J. Display Technol. **10**(7), 526–539 (2014).

[5] Z. Luo, Y. Chen, and S.-T. Wu, "Wide color gamut LCD with a quantum dot backlight," Opt. Express **21**(22), 26269–26284 (2013).

[6] J. Chen, S. Gensler, J. Hartlove, J. Yurek, E. Lee, J. Thielen, J. Van Derlofske, J. Hillis, G. Benoit, J. Tibbit, and A. Lathrop, "Quantum Dots: Optimizing LCD Systems to Achieve Rec. 2020 Color Performance," SID Symp. Dig. Tech. Pap. **46**(1), 173-175 (2015).

[7] J. S. Steckel, J. Ho, C. Hamilton, C. Breen, W. Liu, P. Allen, J. Xi, and S. Coe-Sullivan, "12.1: Invited Paper: Quantum Dots: The Ultimate Down-Conversion Material for LCD Displays," SID Symp. Dig. Tech. Pap. **45**(1), 130-133 (2014).

[8] B. S. Mashford, M. Stevenson, Z. Popovic, C. Hamilton, Z. Zhou, C. Breen, J. Steckel, V. Bulovic, M. Bawendi, S. Coe-Sullivan and P. T. Kazlas, "High-efficiency quantum-dot light-emitting devices with enhanced charge injection," Nat. Photonics **7**, 407-412 (2013)

[9] H. Shen, W. Cao, N. T. Shewmon, C. Yang, L. S. Li, and J. Xue, "High-Efficiency, Low Turn-on Voltage Blue-Violet Quantum-Dot-Based Light-Emitting Diodes," Nano Lett. **15**(2), 1211-1216 (2015).

[10] M. Schadt, "Milestone in the History of Field-Effect Liquid Crystal Displays and Materials," Jpn. J. Appl. Phys. **48**(3S2), 03B001 (2009)

[11] A. Takeda, S. Kataoka, T. Sasaki, H. Chida, H. Tsuda, K. Ohmuro, T. Sasabayashi, Y. Koike and K. Okamoto, "A super-high-image-quality multi-domain vertical alignment LCD by new rubbing-less technology", SID Symp. Dig. Tech. Pap. **29**(1), 1077-1080 (1998).

[12] S. H. Lee, S. L. Lee, and H. Y. Kim, "Electro-optic characteristics and switching principle of a nematic liquid crystal cell controlled by fringe-field switching", Appl. Phys. Lett. **73**(20), 2881-2883 (1998).

[13] Y. Ito, T. Hori, H. Tani, Y. Ueno, T. Kusunoki, H. Nomura, and H. Kondo, "59.1: A Backlight System with a Phosphor Sheet Providing both Wider Color Gamut and Higher Efficiency," SID Symp. Dig. Tech. Pap. **44**(1), 816-819 (2013).