Quantum Dot-Enhanced LCDs with Wide Color Gamut and Broad Angular Luminance Distribution

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Abstract

For public displays, wide viewing angle and good sunlight readability are the key requirements. To achieve these goals, we incorporated a quantum dot enhancement film into the LCD backlight unit while eliminating the crossed prism films. The resultant angular luminance distribution is comparable to that of OLED, and the color gamut is enlarged to ~90% of the Rec. 2020 color space. Meanwhile, new LC mixtures are developed to get fast response at wide working temperature range (-40°C ~ 80°C).

Keywords

Liquid crystal displays (LCDs); Quantum dots; Public display.

1. Introduction

Public display is ubiquitous; it has been widely used for advertisement, entertainment, and information distribution [1]. Different from conventional flat panel displays such as smart phones and TVs, ideally public displays should exhibit broad angular luminance distribution, vivid colors, and high ambient contrast ratio, no matter indoor or outdoor. Several display technologies, including light-emitting diode (LED), organic light-emitting diode (OLED), and liquid crystal display (LCD) have been considered [1]. Currently, LED is a favored choice because of its high brightness and wide color gamut, despite its high power consumption and low resolution density. Similarly, OLED shows superiorities in wide color gamut and broad angular luminance distribution, but its drawbacks are notable as well, like low brightness and short lifetime, especially in some extreme weathers.

On the other hand, LCD (or tiled LCD) has advantages in low power consumption, high resolution, and low cost, but its brightness decreases relatively steeply as the viewing angle increases, and its color gamut is narrow due to the employed white LED backlight. To overcome these problems, here we propose a quantum dot-enhanced LCD with improved device performances to fulfill public display requirements. Firstly in Sec. 2.1, we eliminate the prism films in a conventional LCD backlight unit to achieve broad (comparable to OLED) angular luminance distribution. Then in Sec. 2.2, quantum-dot technology is discussed and employed in LCD backlight to enlarge the color gamut to 90% Rec. 2020. Also, high ambient contrast ratio is obtained. Moreover, in Sec. 2.3 we report new LC mixtures to maintain fast response time even at a low working temperature range (-40°C ~ 80°C).

2. Results

2.1 Wide viewing angle

For public displays, wide viewing angle is a critical requirement, as multiple viewers can enjoy the displays from different angles. Conventionally, several approaches are adopted to improve this property, like multi-domain electrodes or adding compensation films [2]. However, these methods are not adequate for public displays. Recently, Y. Gao, et al. proposed a structure design utilizing a directional backlight combined with an engineered diffusive film (DF) to enhance the viewing angle and obtain OLED-like angular luminance distribution [3]. But the structure configuration is fairly complicated. Here we propose a simple method to get the same performance. The idea is to remove the prism films (also known as brightness enhancement film) from a conventional LCD backlight unit, as Fig. 1 shows.

Figure 1(a) depicts the configuration of a conventional LCD backlight unit, consisting of a light source (e.g. pseudo-white LEDs, or white LED (WLED)), a diffuser plate (DP), two crossed prism films, and a reflective polarizer known as dual brightness enhancement film (DBEF) [4-6]. The emitted light from WLEDs passes through diffuser plate and becomes Lambertian-like distribution. The prism films help boost the normal luminance while reducing the angular luminance width and viewing angle [5]. This approach is useful for single user displays, like smart phones and notebook computers, but less attractive for public displays.

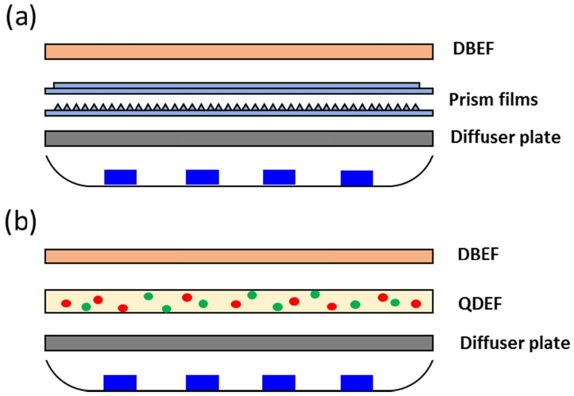

Figure 1. Schematic diagrams of LCD backlight units (a) with prism films, and (b) without prism films.

Figure 1(b) depicts our device structure. We just replace the prism films with a quantum dot enhancement film (QDEF) [7, 8]. Since the emission pattern of quantum dots (QDs) is isotropic, the backlight will remain Lambertian after passing through the diffuser and QDEF.

Figure 2 compares the angular luminance distributions for backlight with and without prism films. Clearly, the angular width without prism films is much wider. Meanwhile, the total efficiency is improved by 37%, because two prism films are removed. For TVs and monitors, only one prism film is employed, in this case, the efficiency improvement is ~15% because only one prism film is removed [6].

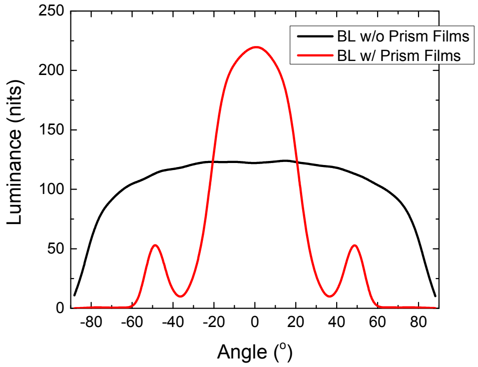

Figure 2. Angular luminance distribution for LCD backlight (a) with two crossed prism films and (b) without prism films.

Then we incorporated this backlight into the whole LCD system to evaluate the output angular luminance distribution. In our calculations, patterned vertical alignment (PVA) LCD [9-11] was employed as an example and the device parameters are listed as follows: electrode width $w = 42\ \mu m$, electrode gap $g = 6$ μm, and cell gap $d = 3.47\ \mu m$. The LC material is ZOC-7003 with $\Delta\varepsilon = -4.4$ and $\Delta n = 0.103$ at λ=550nm. One positive A-plate and one negative C-plate are used as compensation films.

Figure 3 shows the viewing angle dependent luminance for OLED, conventional LCD, and proposed LCD. As expected, OLED exhibits much wider luminance distribution than conventional LCD. For example, the luminance of OLED decreases about 35% at 60°, but for conventional LCD it drops nearly 70% [12]. It makes a big difference for different viewers at normal and oblique angles. However, the proposed LCD has overcome this drawback, showing OLED-like performance.

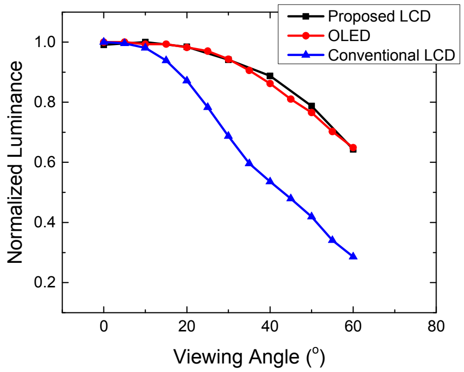

Figure 3. Viewing angle dependent luminance for OLED, conventional LCD, and proposed LCD.

2.2 Large color gamut

Public displays with vivid colors are more attractive. Briefly speaking, light source and color filters are two dominant factors for the final color performance of an LCD. Currently, WLED is commonly used as LCD backlight due to its high efficiency and low cost. Moreover, the transmittance of RGB color filters partially overlap in the blue-green and green-red bands. As a result, the purity of each color is deteriorated greatly, leading to decreased color gamut. To overcome this issue, quantum dot (QD) technology is emerging. The unique property of these nanoparticles is their narrow emission bandwidth; a typical FWHM is around 25nm, which is highly preferred to get saturated colors.

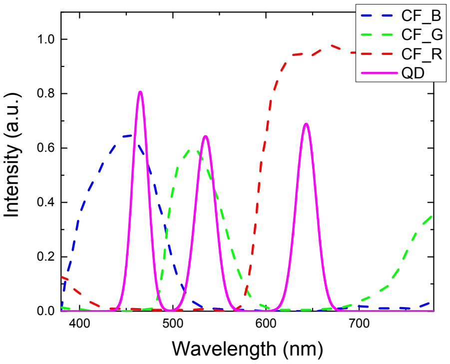

Figure 4. Spectrum for quantum dot-based backlight and R/G/B color filters.

In practical applications, QD chip, QD rail, and QD film have been considered [13, 14]. Each approach has its own merits and demerits. Here, we choose the film type (i.e. QDEF) [Fig. 1(b)] for the backlight system and remove the prism films. Figure 4 depicts the emission spectra of the QDs and RGB color filters. The central wavelengths for green and red QD emissions are 535 nm and 643 nm, respectively.

Figure 5 shows the color gamut for OLED and proposed QD-LCD. As depicted in Fig. 5, QD-LCD can cover 90.2% Rec. 2020 in CIE 1931 color space [15], while for OLED this value is only 76.4%. QD-LCD shows more vivid colors than OLED.

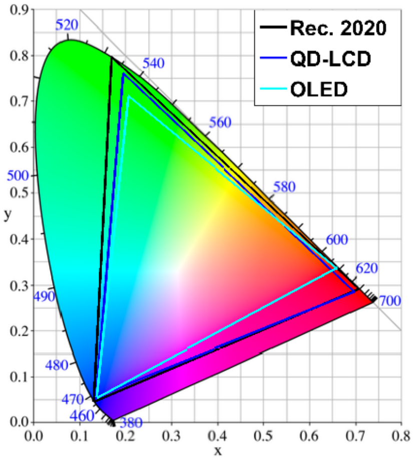

Figure 5. Color gamut for OLED and QD-LCD in CIE 1931 color space.

Another issue for public displays is sunlight readability. As the ambient light flux increases, the displayed image could be washed out [16]. Figure 6(a) depicts the color gamut of QD-enhanced MVA LCD under different ambient light levels. Although the color gamut is reduced from 90% to 70% as the ambient light intensity increases from 0 lux to 2000 lux, it still covers most part of Rec. 2020 and is much better than OLED, as Fig. 6(b) depicts. If we keep increasing the ambient light to 10000 lux or higher (direct sunlight), the color gamut shrinks further, but QD-LCD still covers a portion of Rec. 2020 color space. Moreover, according to a psychophysical phenomenon called Helmholtz-Kohlrausch effect, a highly saturated color appears to be brighter than that with lower saturation, even they have the same luminance [15, 17]. QDs provide saturated light emission and therefore their colors remain more discernable under sunlight.

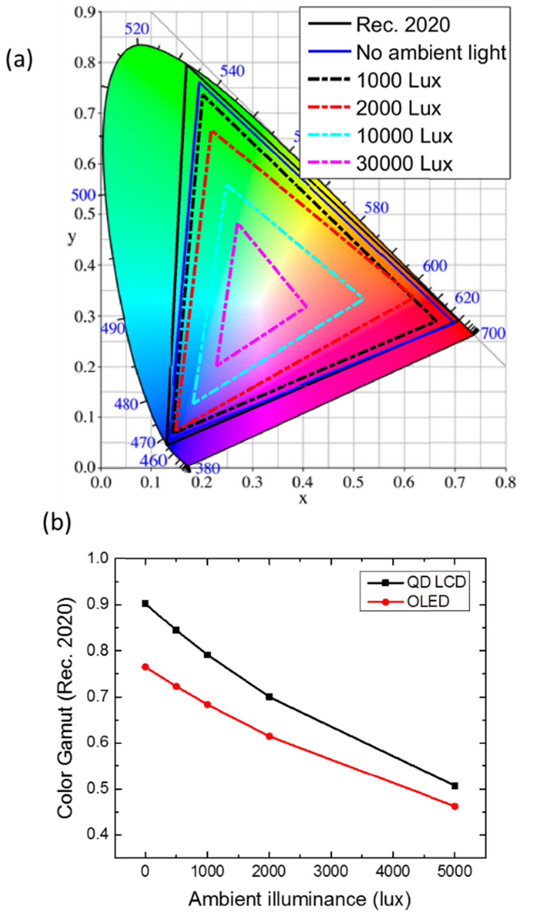

Figure 6. (a) Variation of QD-LCD color gamut at different ambient light levels; the LCD is assumed to have luminance intensity of 500 cd/m^2 and 3% surface reflection; (b) simulated color gamut for OLED and QD-LCD at different ambient illuminance.

2.3 Wide working temperature range

Outdoor public displays should endure extreme environments, such as cold and hot temperatures and UV stability. Although the response time of OLED remains fast at cold temperatures, its lifetime is greatly shortened at high temperatures. On the other hand, the response time of LCD increases exponentially as the temperature decreases. To keep fast response time at low temperatures, we developed an ultra-low viscosity LC mixture with a wide temperature range. Its physical properties are summarized as follows: $\Delta\varepsilon$ = 3.05, Δn = 0.098, rotational viscosity γ_1 = 41.5 mPas, melting point T_m < -40^{o}C and clearing point T_c = 78.8^{o}C [18]. To characterize response time, we measured the visco-elastic constant (γ_1/K_{11}) at different temperatures, because the response time is proportional to $\gamma_1 d^2/(\pi^2 K_{11})$. Results are shown in Fig. 7. From Fig. 7, γ_1/K_{11} remains as small as 15 ms/μm^2 even at –30^{o}C, which corresponds to ~30 ms response time for an IPS LCD (assuming K_{11}~$2K_{22}$) [19]. It is over 8X faster than conventional LC materials.

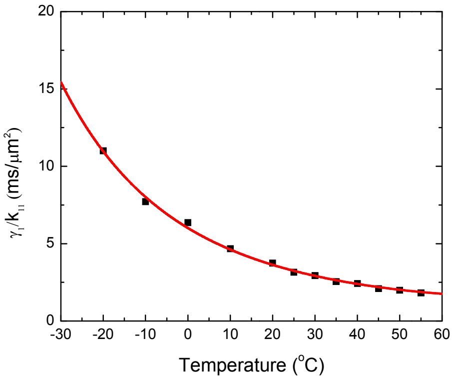

Figure 7. Temperature dependent visco-elastic constant.

3. Discussion

Apart from abovementioned parameters, color shift is another critical issue for public displays. As Fig. 4 shows, the transmittance of RGB color filters partially overlap in the blue-green and green-red bands, which in turn deteriorates the color purities. Meanwhile, the LC transmittance is highly dependent on the incident light angle and wavelength; thus, the observed colors could shift when viewed from different angles. This is called color shift, which is characterized by the distance ($\Delta u'v'$) between two points on the color chart (e.g. CIE 1976). By analysis, color shift is unnoticeable if $\Delta u'v' < 0.02$ [20]. Figure 8 depicts the simulated color shift of QD-enhanced LCD, showing unnoticeable color shift, which is desirable for practical applications.

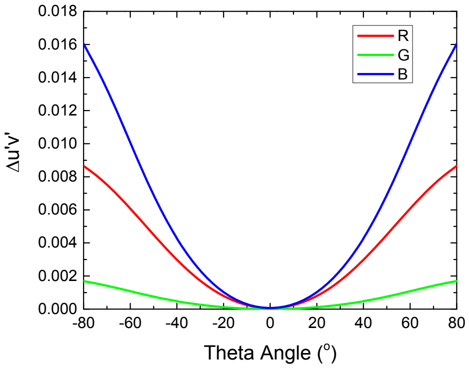

Figure 8. Simulated color shift for QD-LCD.

To reduce the motion blur for moving pictures, fast response time is highly desirable. OLED is self-emissive, and has fast response time (~0.1ms). For our MVA LCD, the calculated gray-to-gray (GTG) rise time is 1.28 ms and decay time is 3.18 ms, as summarized in Table 1. Here, overdrive and undershoot technologies are applied to accelerate the transition processes. Nevertheless, LCD is still over 10 times slower than OLED. If we consider the motion picture response time (MPRT), this gap is narrowed, because thin-film transistor (TFT) sampling and holding effect dominates [21]. For 120 Hz frame rate, OLED shows 6.65ms MPRT, which is only slightly faster than LCD (7.56ms) [22]. Both LCD's and OLED's MPRT will be improved if a higher frame rate (e.g. 240 Hz) is adopted [22]. The major challenge for OLED is that it uses 4-5 TFTs in each pixel. Higher operation rate leads to shorter charging time for TFTs, especially when the resolution increases. On the other hand, the major challenge for LCD is its slower response time.

Table 1. Calculated gray-to-gray response time of our MVA cell (unit: ms)

	Rise time (ms)								
		1	2	3	4	5	6	7	8
Decay time (ms)	1		1.1	1.2	1.4	1.6	1.9	2.2	2.8
	2	5.0		0.4	0.7	1.0	1.3	1.7	2.4
	3	5.2	1.4		0.4	0.6	1.0	1.3	2.2
	4	5.4	2.3	0.9		0.3	0.6	1.1	1.9
	5	5.7	2.9	1.6	0.7		0.4	0.8	1.9
	6	6.0	3.6	2.4	1.4	0.6		0.4	1.7
	7	6.4	4.3	3.1	2.1	1.4	0.7		1.6
	8	7.2	5.2	4.2	3.3	2.7	1.9	1.3	

4. Conclusion

We proposed to replace the prism films with a QDEF in the LCD backlight unit to widen the viewing angle and improve the image quality at high ambient light environments. Also, by employing an ultra-low viscosity LC mixture, fast response is obtained even at extreme temperatures, e.g. -30°C. These properties are highly favorable for public displays.

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