Quantum Dot Enabled High Color Gamut LCDs

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Abstract

Quantum dots are a new generation of phosphor material that have high photon conversion efficiency, narrow spectral line-widths and can be continuously tuned in their emission wavelengths. Since 2013, quantum dots have been adopted by the consumer electronics industry into LCDs to significantly increase their color performance. Compared to the OLED solution, quantum dot LCDs have higher energy efficiency, larger color gamut, longer lifetime, and are offered at a fraction of the cost of OLED panels. In this paper, we demonstrate that quantum-dot based LCDs can achieve more than 90% coverage of the ultra-wide color gamut, Rec. 2020, which is the new color standard for UHDTV.

Keywords: quantum dot, LCD, high color gamut, Rec. 2020.

1. Introduction

The next wave of market push for TVs is Ultra-High Definition (UHD). The increase in resolution from high definition (i.e., 1080p) to 4K (i.e., 2160p) is perhaps the most well known benefit of UHD but there is much more to this new broadcast specification. Higher dynamatic range and higher color gamut are also important parts of the UHD specification and these new features may bring more perceptible benefits to users in terms of an improved viewing experience than improved resolution alone.

LCD TVs are already moving towards direct-back-lit systems using LED arrays in the back light. These direct-lit TVs use local dimming to control the intensities of the individual LEDs based on the display content to greatly improve the dynamic range of LCDs. To bring higher color gamut to TVs, especially Rec. 2020 which is the UHDTV color standard, remains a serious challenge.

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In LCDs, the limitation to color gamut comes from the back light. The dominant back light technology for LCDs today is based on white LEDs. These white LEDs use blue LED chips combined with Ce-doped YAG, which is a broad-band yellow phosphor [1]. This yellow phosphor has low spectral weights in green and red. The three primary colors -- red, green, and blue -- are generated by using red, green, and blue color filters in the liquid crystal panel within each pixel [2]. The transmission coefficients of a typical set of color filters are shown in Figure 1. To make high color gamut displays using these white LEDs, the color filters have to have much narrower transmission band-widths. As a result, the transmisivity of the LC panels will be much reduced, which leads to poor power efficiency. In practice, LCDs using white LEDs can meet the Rec. 709 color gamut standard (also known as sRGB), which is the current HDTV broadcast standard for color gamut [3]. For higher color gamut standards, such as Adobe-RGB [4] displays used by graphics designers and professional photographers, RGB LEDs have been used. LCDs based on RGB LEDs have very limited market share because of low power

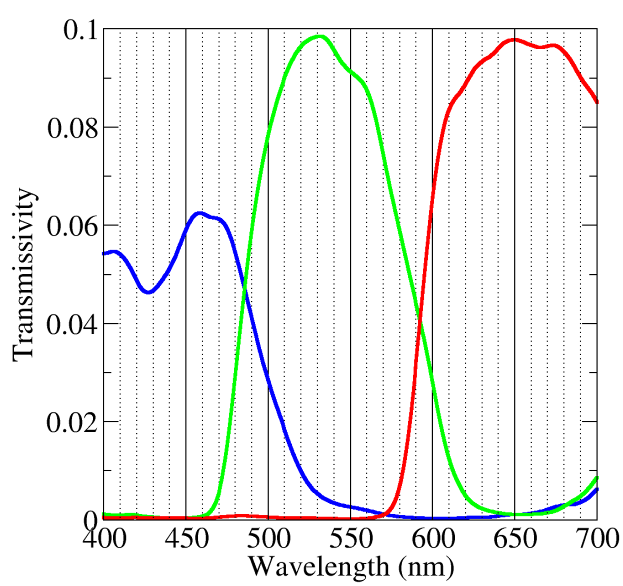

Figure 1: Blue, green, and red color filter transmission coefficients of a typical Rec.709 LCD display.

efficiency (green LEDs have much lower power efficiency than blue and red LEDs [1]) and high system costs. Recently, new RG phosphors have been introduced [5] in some mobile displays to increase color gamut. However, some of these phophors are phosfluoresent and cannot match the high refresh rates needed for local dimming in LCD TVs. In addition, some of these new phosphors still have lifetime issues.

Quantum dots are a new class of phosphor material with high photon conversion efficiencies and narrow emission line-widths (in the low 30nm) [6]. Quantum dots are semiconductor nanocrystals that are typically synthesized via high temperature solution processes. By varying the size of these nanocrystals, different emission wavelengths can be obtained due to the quantum-confinement effect [6]. Over the last few years, quantum dot efficiencies and lifetimes have steadily improved to meet the requirements of display applications. In addition, low cost packaging solutions have been developed to protect the quantum dots from being oxidized by the ambient environment. In particular, quantum dot films are made by embedding quantum dots into a polymer matrix sandwiched between two barrier films [7]. These quantum dot films are flexible and are manufactured by a roll-to-roll process. Quantum dots of two different colors are embedded in these films – green and red. When excited by a blue LED light source, the green and red quantum dots absorb part of the excitation and conver the high-energy blue photons to lower energy green and red photons. The blue, green, and red photons combine to become the new white light source for the LCDs.

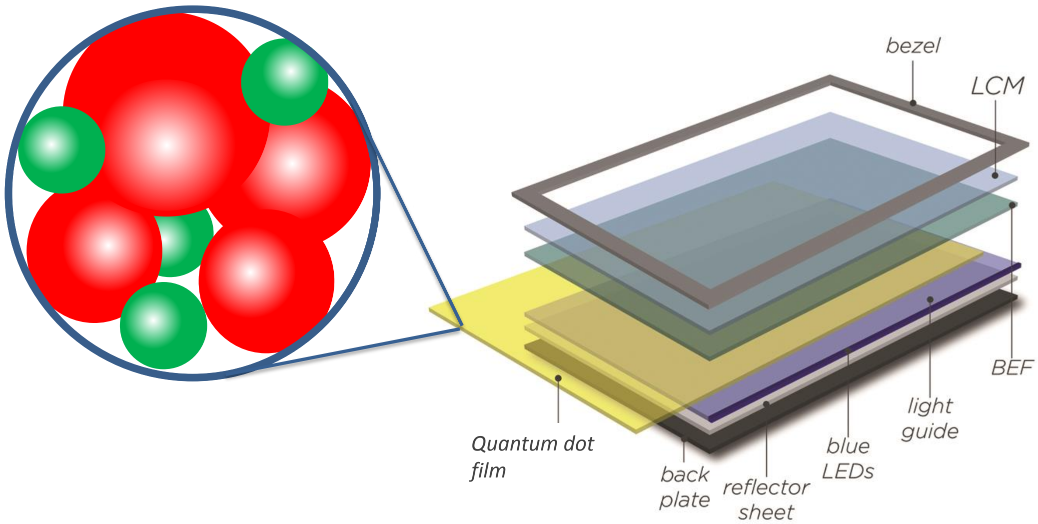

Figure 2: Schematic structure of an edge-lit LCD display with quantum dot film.

Since 2013, quantum dots have seen market adoption in tablets, notebook computers, and televisions. In the case of tablets, quantum dots enabled an accurate Rec. 709 display while improving the power efficiency of the backlight by 20% [8]. In notebooks and TVs, quantum dots delivered high color gamuts that cover both Adobe-RGB and DCI-P3 color standards [9].

The ultra-high color gamut standard Rec. 2020 was originally defined for laser-based projectors, where the color primaries are on the color locus of the cie diagram [10]. Because of the deeply saturated color coordinates, Rec. 2020 is beyond the capabilities of OLEDs. Is Rec. 2020 color standard reachable for consumer displays or is it only for high-end laser-based projection systems? In this paper, we will explore the capability using quantum dots in LCDs to reach the ultra-high color gamut of Rec. 2020.

2. Results

To demonstrate quantum dots' capability for higher color gamut in LCDs, we retrofitted two off-the-shelf displays: (1) a 65-inch direct-lit 4K LED TV and (2) a 13-inch edge-lit 1080p

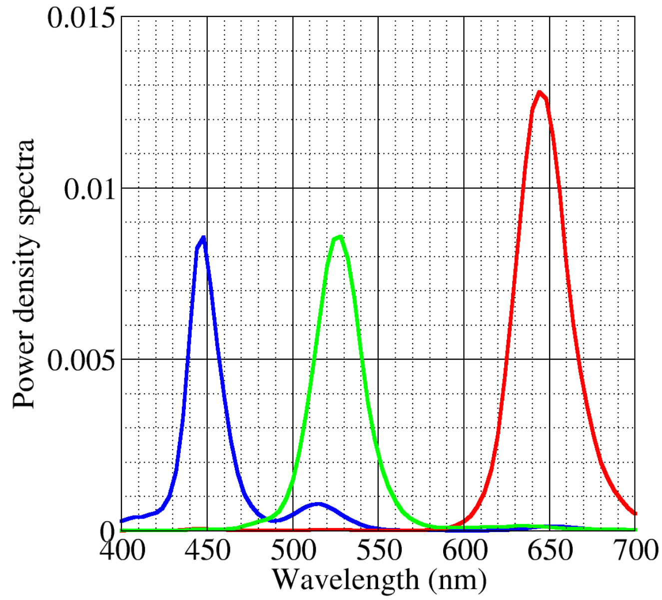

Figure 3: Power density spectra of the 3 primary colors from a demo LCD using QDEF for Rec. 2020 color gamut.

ultrabook. Both the original panels are standard Rec. 709 displays and use white LEDs for the backlight. In the 65-inch direct-lit TV, we replaced the white LEDs with blue LEDs and inserted the quantum dot film between the diffuser plate and the prism sheet. In the 13-inch ultrabook, we replaced the white LEDs with blue LEDs and replaced the bottom diffuser with a quantum dot film. Compared to the existing LCD products on the market with quantum dot films (that were intended for ~100% NTSC color gamut), the new quantum dot films used here have quantum dots with different green and red wavelengths that are chosen for Rec.2020. The green and red peak wavelengths are 525nm and 644nm, respectively. The power density spectra of the blue, green, and red primaries measured on the 13-inch display are shown in Figure 3. The spectra of the 65-inch TV are very similar and not shown here. Note that the red spectrum has pronouncedly higher intensity than the blue and green spectra. This is because of the low photopic response of the human eye at such long red wavelengths [1]. To achieve the target

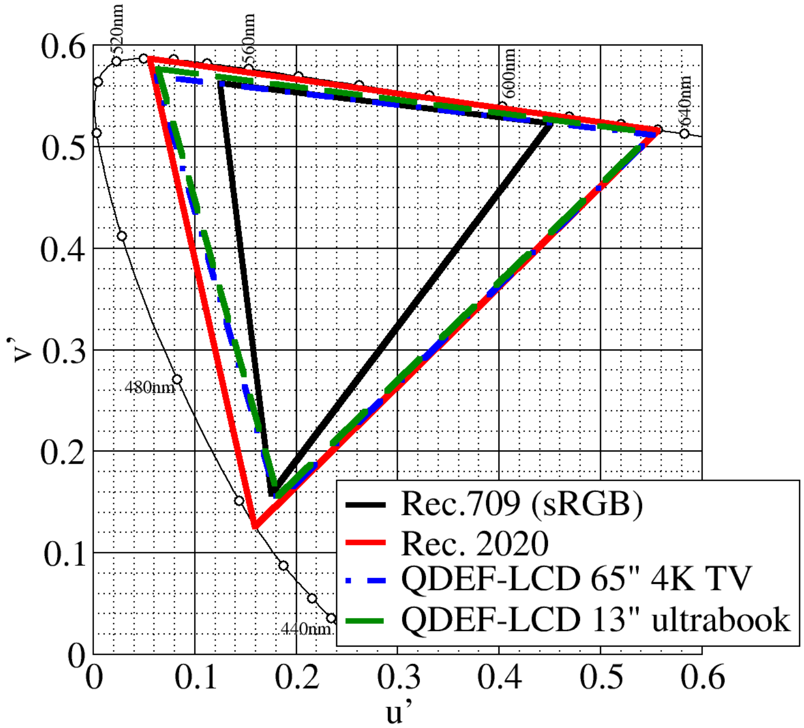

Figure 4: 1976 cie diagram of two LCD demos using quantum dot films, Rec. 709 and Rec. 2020 color standards. The color gamut of both demos covers 90% of Rec. 2020 color space.

color temperature for the white point on the panel (typically 6,500K), a bigger fraction of the total photons needs to be allocated to red.

The color gamut of both retrofitted demos is at 133% of NTSC (measured in cie 1976 [11]) and cover 90% of the Rec. 2020 standard, as shown in Figure 4. In particular, the red and green primaries of the demos are very close to those of the Rec. 2020 color standards, all within 0.02 in u' and v'. The primary that is further off from the color standard is the blue, which is off by less than 0.03.

The reason the blue primary has the largest deviation from the Rec.2020 standard can be understood from the power density spectra shown in Figure 3. The blue spectrum, in particular, has its primary peak at the blue LED wavelength close to 445nm. In addition, the blue spectrum has a satellite peak at close to 520nm. This is the result of the green peak in the backlight leaking through the blue color filter on the liquid crystal panel. As can be seen from the color filter transmission spectra in Figure 1, the blue color filter does not completely cut off beyond 500nm and still has significant transmission at around 525nm where the green peak needs to be for Rec.2020. It is this color leakage that limits the coverage of Rec. 2020 to around 90%. The blue color filters used today are designed for Rec. 709 and for white LEDs where the yellow peak (around 560nm) is further separated from the blue peak [1]. The leakage of the yellow peak through the blue color filter is not significant, especially for the lower requirement of Rec.709. For Rec. 2020, however, the green peak needs to be at much shorter wavelengths to hit the green color primary target. In this case, the green leakage through the blue color filter is more pronounced especially for the target of a deeper blue primary.

To further improve Rec.2020 coverage, changes in the color filters are necessary. The transmission coefficients of a theoretically constructed set of color filters is shown in Figure 5.

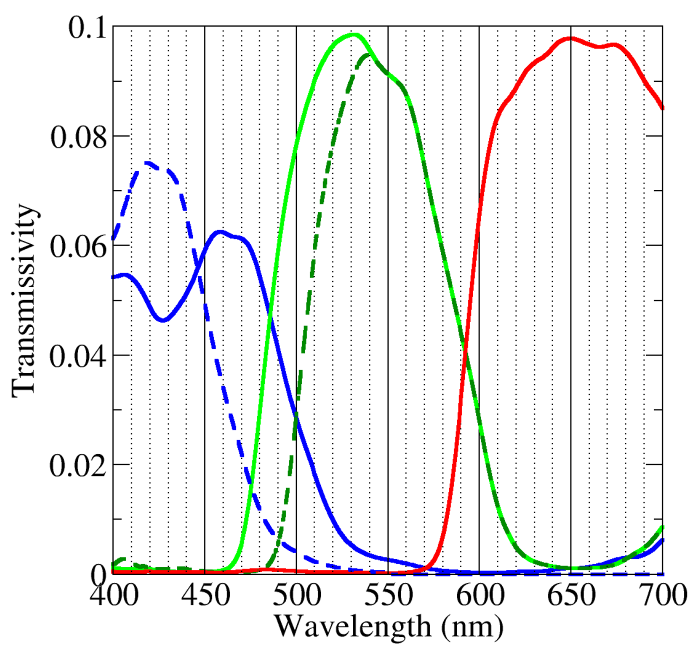

Figure 5: Solid lines: existing color filter transmission coefficients. Dashed lines: proposed color filter transmission coefficients for QD-LCD with Rec.2020 color gamut. The red color filter transmission coefficients are the same.

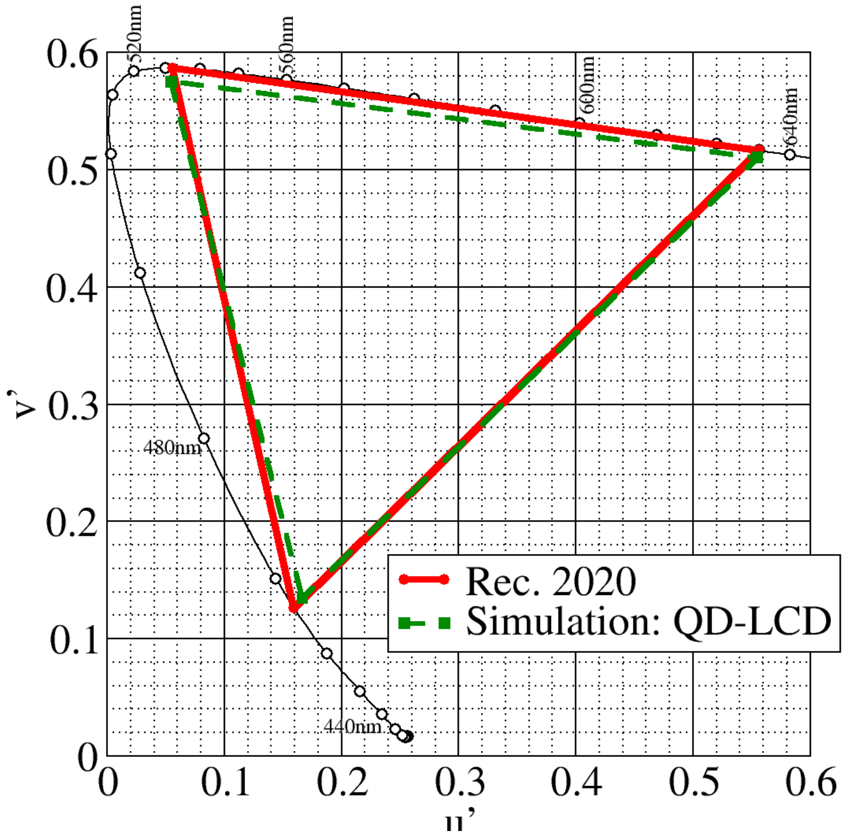

Figure 6: 1976 cie diagram with Rec.2020 and simulated QD-LCD with proposed color filter transmission coefficients plotted in Figure 5. The simulated QD-LCD covers 95% of Rec.2020 color space.

Instead of having large spectral overlaps in the blue-green spectral region for the existing color filters, the proposed blue and green color filters are spectrally separated to more effectively filter out the blue and green peaks. The red color filter can remain unchanged. Numerical simulations using this proposed set of color filters show that a 95% coverage of the Rec.2020 can be realized in LCDs (see Figure 6).

3. Conclusions

By combining quantum dot films with today's standard LCD panels, ultra-high color gamut displays have been demonstrated. In both the two demos built, a 65-inch direct-lit 4K TV and a

13-inch edge-lit ultrabook, 90% coverage of the Rec. 2020 color standard is achieved. This represents a ~70% increase in the color space compared to today's Rec.709 color standard. If the color filters can be optimized to better separate the blue and green peaks, a 95+% Rec. 2020 coverage is feasible. Quantum dot films thus offer a practical and ready-to-implement solution for UHD LCD-TVs to drastically expand the color gamut and, when combined with high resolution and local dimming, bring true-to-life viewing experience to the end users.

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