

Wider Color Gamut and Lower Deep-Blue Luminance Requirement Enabled by an Extra Light-Blue Pixel in the QLED Display

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Abstract

The inferior stability of blue quantum-dot light-emitting diodes (QLEDs) hinders their practical application. In this study, we propose enhancing QLED performance and stability by adding a light-blue (L) pixel to the traditional Red-Green-Blue (RGB) display panel. Our simulations show that the RGLB panel design, featuring an L pixel with a wavelength of 489 nm, expands the color gamut by 1.186 times, requiring only 6.49% of the luminance of deep-blue pixel compared to the RGB design.

Author Keywords

quantum-dot light-emitting diodes; RGLB panel design; color gamut; luminance of deep-blue pixel;

1. Introduction

With the continuous advancement of quantum-dot light-emitting diodes (QLEDs) display technology, the limited lifetime of blue pixels has become a key factor that restricts the sustainability of display performance and the long-term durability of QLED devices [1-3]. Blue quantum-dots (QDs) with longer wavelengths exhibit greater stability compared to those with shorter wavelengths [4], resulting in a significant improvement in the lifetime of the corresponding QLED devices. To address the issue of the relatively short lifespan of blue pixels, this study proposes an innovative solution by introducing a new pixel situated between blue and green within the existing red-green-blue (R/G/B) pixel structure. The stability of this new pixel should surpass that of traditional blue pixels, thereby alleviating the emission load on the blue pixels and extending their lifespan. The selection of this fourth pixel not only needs to consider its impact on the color gamut but also its potential to optimize the overall display longevity, aiming to enhance color reproduction while improving the long-term stability of blue pixels. In this study, simulation analysis is employed to identify the optimal wavelength for the fourth pixel under ideal conditions, where it is assumed that the areas of all subpixels are equal.

However, the addition of this fourth pixel requires corresponding adjustments at the circuit level, such as additional driving circuits involving thin-film transistors (TFTs) and the use of a Black Matrix to prevent optical crosstalk, ensuring color accuracy and display clarity. This design, however, inevitably affects the aperture ratio, or the proportion of the display panel that is available for light emission. A reduction in the aperture ratio will directly lead to a decrease in light transmission, thereby impacting the overall display brightness, particularly the optimization of blue pixel brightness. Such considerations must be included within the evaluation scope to more precisely balance the trade-off between brightness optimization and lifespan extension, providing a theoretical foundation and design strategy for the development of efficient and durable display technologies.

2. Optimization of the Color Gamut & Deep-Blue Light Load using white light synthesis

As shown in Figure 1, for the three-pixel design, a maximum coverage of 74% in CIE 1931 can be obtained; and for a four-pixel

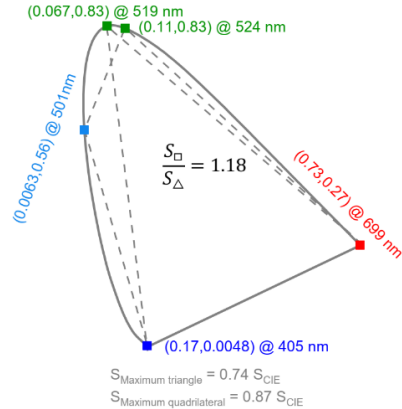


Figure 1. The maximum color coverages achieved by three pixels and four pixels in the CIE1931 chart.

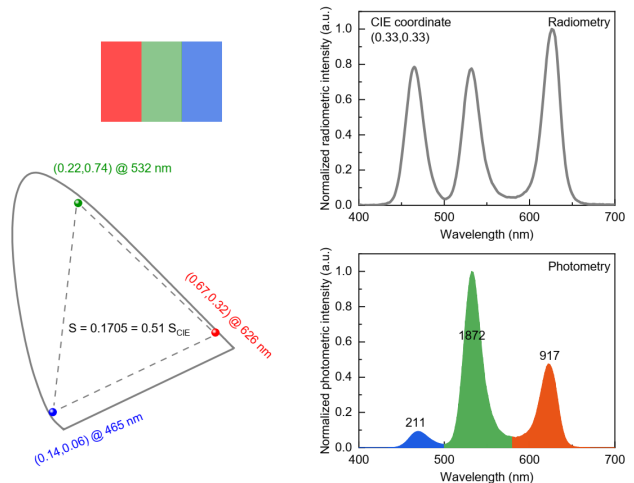


Figure 2. Three-pixel design simulated using the RGB spectra of the CdSe-based QLEDs.

design, 87% coverage will be achieved, which is the maximum among the designs and 1.18 times that of the three-pixel design.

Since the colors obtained on the CIE contour line all correspond to monochromatic light, in real situations, it is difficult for the R/G/B pixels to meet such demanding spectral conditions. Given that QLED has a relatively narrow full width at half maximum of the emission spectrum^[5], it possesses better color purity and corresponds to a larger color gamut area. Therefore, the spectra corresponding to the existing R/G/B QLEDs in the laboratory, with center wavelengths of 630 nm, 532 nm, and 467 nm, respectively, are utilized for further analysis and calculation.

The actual luminance requirement in a display panel is calculated using the following equation.

$$L_v(\lambda) = \frac{I_e(0^\circ)(\lambda) \cdot K_m \cdot V(\lambda)}{A} \quad (1)$$

Where L_v represents the luminance (cd/m^2); $I_e(0^\circ)$, the radiant intensity in the forward direction (W/sr); K_m , the maximum luminous efficacy corresponding to the wavelength of 555 nm (683 lm/W); V , the standard spectral luminous efficiency function; and A , and the emission area (m^2).

Therefore, in the case of white light such as 1000 cd/m^2 , the initial luminance for the blue lifetime testing standard is not exactly 1000 cd/m^2 . Since it is an important parameter in lifetime measurement, we should accurately calculate the actual luminance requirements of the R/G/B sub-pixels in the display panel through the above-mentioned formula. We consider the areas of each of the R/G/B sub-pixels to be the same. Under such circumstances, for a three-pixel design, only 51% color coverage will be obtained and a 211 cd/m^2 luminance is required for a deep-blue QLED in a 1000 cd/m^2 white emission, as shown in Figure 2.

To reduce the luminance of the original blue light pixels and expand the color gamut, a new pixel point is introduced. Due to the fact that it is only an approximate calculation, its spectrum is obtained by translating the spectrum of the CdSe-based QLED with a central wavelength of 465 nm. Through MATLAB, each point on its CIE locus is traversed and calculated, thus obtaining the new color gamut and the situation of 1000 cd/m^2 white light synthesis.

As shown in Figure 3, for a four-pixel design, when the color gamut is expanded to a large extent, the performance in sharing the luminance of the original blue pixels is mediocre. When the required luminance of the original blue pixels is relatively small, at this time, the central wavelength of the new pixel is close to that of the original blue pixel, which is equivalent to doubling its area. But there is almost no increase in the color gamut in this situation. Therefore, taking into consideration both the color gamut and deep-blue luminance requirement, a light-blue QLED with a 482 nm wavelength is utilized as the fourth pixel, resulting in a 56% color coverage of the CIE 1931 chart and a 152 cd/m^2 luminance requirement for a deep-blue QLED in a 1000 cd/m^2 white emission. However, considering practical scenarios, the introduction of the fourth subpixel will result in a decrease in the aperture ratio. If the original aperture ratio is 80%, and after the addition of the fourth pixel, the aperture ratio decreases to 70%, and according to formula (3), the required luminance for the deep-blue QLED is inversely proportional to its aperture ratio. Assuming that

$$152 \times \frac{80\%}{70\%} = 174 \text{ cd/m}^2 \quad (2)$$

Thus, it is evident that during the synthesis of white light, with the introduction of the fourth pixel, the initial color gamut can be extended to 1.1 times of its original size, and the luminance demanded by the original blue pixels will decline by 17.5%, demonstrating a significant improvement in performance.

3. Optimization of the Color Gamut & Deep-Blue Light Load using randomly selected pictures

Due to the fact that the daily display includes not only white but also a variety of other colors, considering only the white balance situation with a four-pixel approach is highly limited.

By analyzing a large number of pictures to obtain the color and brightness distributions of pixel point, we can calculate the average usage of blue light through weighted calculation. Therefore, we employ Python to process over 5,000 images, extracting the RGB values (0-255) of each pixel. And then we convert the images into HSV format to extract the corresponding luminance (i.e., the V channel) for each pixel.

Due to the large color gamut of Adobe RGB and its similarity to the color gamut of QLED, it is adopted for calculation and analysis in this study. Before converting RGB to CIE coordinates, the RGB values must first undergo gamma correction using the following formula, which is typically performed using the following formula for each RGB component (R/G/B):

$$C_{corrected} = \begin{cases} \frac{C}{12.92}, & \text{if } C \leq 0.04045 \\ \left(\frac{C+0.055}{1.055}\right)^{2.4}, & \text{if } C > 0.04045 \end{cases} \quad (3)$$

where C represents the original RGB component (in the range of 0 to 1), and $C_{corrected}$ is the gamma-corrected value.

Substitute the linear RGB values into the Adobe RGB - to - XYZ conversion matrix to calculate X, Y, and Z in the XYZ color space. The standard conversion matrix from Adobe RGB to XYZ is as follows:

The Adobe RGB to XYZ conversion matrix is:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.5767309 & 0.1855540 & 0.1881852 \\ 0.2973769 & 0.6273491 & 0.0752741 \\ 0.0270343 & 0.0706872 & 0.9911085 \end{bmatrix} \begin{bmatrix} R_{linear} \\ G_{linear} \\ B_{linear} \end{bmatrix} \quad (4)$$

Where:

$\begin{bmatrix} R_{linear} \\ G_{linear} \\ B_{linear} \end{bmatrix}$ are the linear RGB values (after gamma correction).

$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$ are the resulting XYZ values.

After converting from RGB to XYZ, the CIE 1931 xy chromaticity coordinates can be obtained using the following formulas:

$$x = \frac{X}{X+Y+Z} \quad y = \frac{Y}{X+Y+Z} \quad (5)$$

Where X, Y and Z are the XYZ values. The x and y coordinates represent the chromaticity in the CIE 1931 color space.

Each color corresponds to a CIE coordinate, and the brightness of each pixel is weighted to the number of occurrences of its corresponding color. Finally, through normalization, the color usage

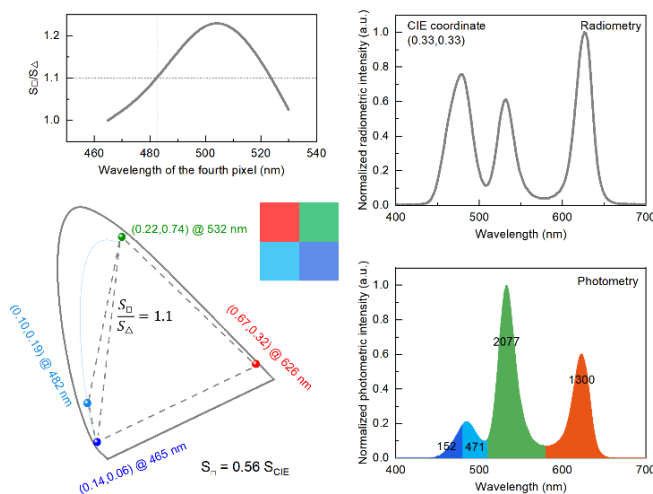


Figure 3. The four-pixel design.

all subpixels have equal areas, the required luminance can be calculated as:

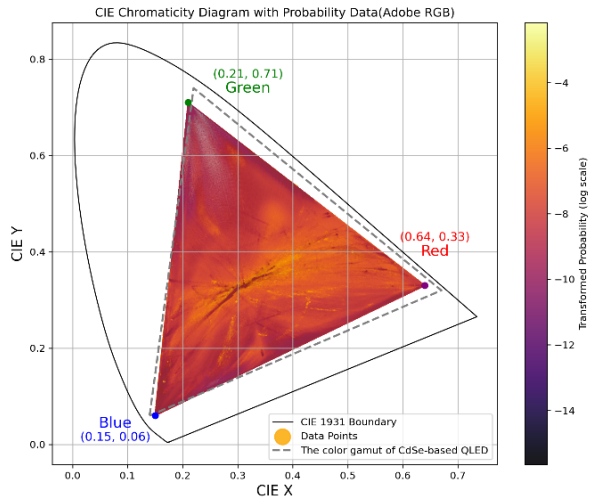


Figure 4. The frequency distribution of colors in daily displays weighted by luminance.

probability distribution within the Adobe RGB color gamut under typical display conditions can be obtained, as shown in Figure 4. We can observe that the predominantly appearing colors are almost all around the center of the color gamut, that is, near the white light.

Next, a fourth pixel is introduced to explore the optimization of the color gamut and the brightness of the original blue pixel under actual display conditions. Since the study is conducted based on the Adobe RGB color gamut rather than the QLED color gamut, the spectrum of the fourth pixel is approximated using a Gaussian distribution, with a half-width at half-maximum (HWHM) of 30 nm, and the central wavelength is varied between 400 nm and 535 nm.

By conducting simulation analysis, the results depicted in Figure 5 can be obtained. After introducing the fourth pixel, the color of the intersection area in the figure can be represented using only the R/G pixels and the light-blue pixel of the fourth one, without relying on the original deep blue pixel. In this study, we evaluate the required brightness of the blue light in everyday displays using a weighted approach (The weighted intersection area represents the contribution of the fourth pixel to deep-blue luminance alleviation). Considering that the area of each sub-pixel is the same and there is a change in the aperture ratio, the effective area of the deep - blue pixel should change from $80\% \times \frac{1}{3}$ to $70\% \times \frac{1}{4}$. Therefore, the optimized required brightness of the deep - blue pixel should be multiplied by $(80\% \times \frac{1}{3}) / (70\% \times \frac{1}{4})$, which has been implemented in the simulation code. Therefore, with the introduction of the fourth pixel, the color gamut can be increased by up to 32.69%, while the average brightness required for blue light only decreases by 6.22%. However, when the average brightness required for the original blue pixel is reduced by 99.00%, the color gamut increases by only 4.33%. In this case, the center wavelength of the fourth pixel is very close to that of the original blue pixel, making it unstable with a shorter lifespan, which would significantly affect the expected improvement in pixel longevity.

As shown in Figure 6, considering both the color gamut and the luminance requirement for the deep-blue pixel, the fourth pixel with a center wavelength of 489 nm achieves the best optimization, improving the color gamut by 18.61% while reducing the average brightness required for blue light by 93.51%. Since the brightness required for the fourth pixel is 14.4 times that required for the original blue pixel and the lifetime of the 486 nm quantum dots far exceeds that of 465 nm quantum dots by a factor of 15^[5], the introduction of this light blue /fourth pixel is able to significantly

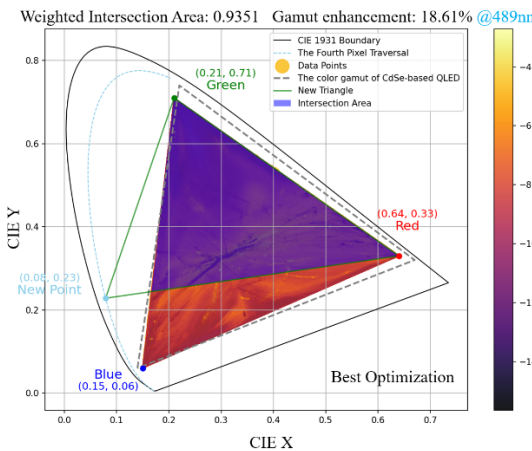
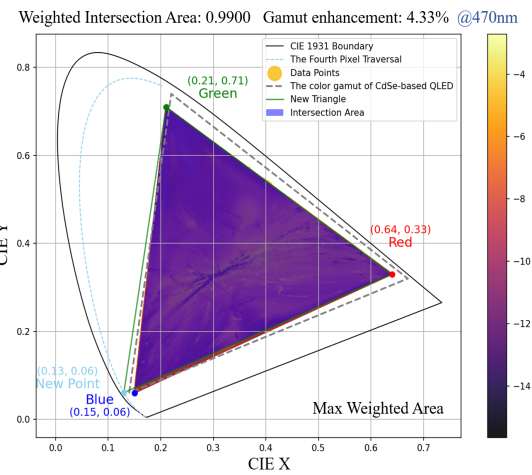
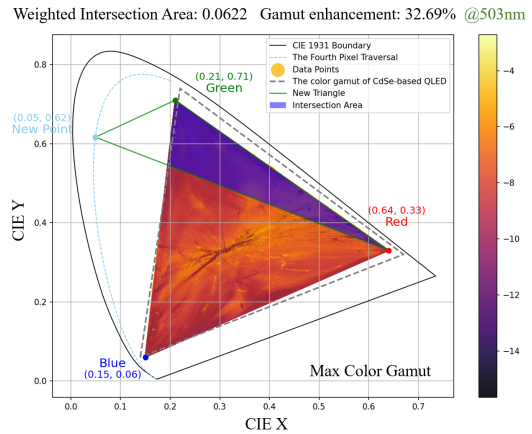


Figure 5. The optimization effect of four pixels in daily display

alleviate the brightness pressure on the original deep blue pixel, thus extending the overall pixel lifespan. The specific data of the above three cases can be found in Table 1.

The optimal fourth pixel wavelength of 482 nm, as mentioned in the previous context of synthesized white light, in this case, the color gamut is expanded by 13.73% and the average brightness required for the original dark blue pixel is reduced by 96.97%, indicating a more efficient sharing of blue light intensity. However, considering both the color gamut and luminance

Table 1. Optimization status of the fourth pixel corresponding to different central wavelengths.

Optimization	CIE coordinates of the fourth new point	Wavelength	Color gamut expansion	Deep-blue luminance alleviation
Max color gamut	(0.05, 0.62)	503 nm	32.69%	0.0622
Max weighted area	(0.13, 0.06)	470 nm	4.33%	0.9900
Best optimization	(0.079, 0.23)	489 nm	18.61%	0.9351

optimization comprehensively, we still conclude that the fourth pixel with a central wavelength of 489 nm yields the best overall optimization.

4. Discussion and Conclusion

This study explores an innovative solution to the persistent issue of blue QLED instability by introducing a light-blue pixel in the RGB panel design. The findings indicate that adding a light-blue QLED with a wavelength of 489 nm results in significant benefits for display performance, most notably an expansion of the color gamut by 1.186 times and a significant reduction in the original deep-blue luminance requirement (down to 6.49%). This improvement not only offers a broader color spectrum but also enhances the overall display longevity by alleviating the emission load on the blue pixels, thus prolonging their lifespan. The addition of the extra light-blue pixel demonstrates the potential for achieving a more efficient and durable QLED display.

Moreover, this study rigorously considers the impacts of introducing the fourth sub-pixel on the aperture ratio and the area of the sub-pixels. The effective area of each pixel will change from $80\% \times \frac{1}{3}$ to $70\% \times \frac{1}{4}$.

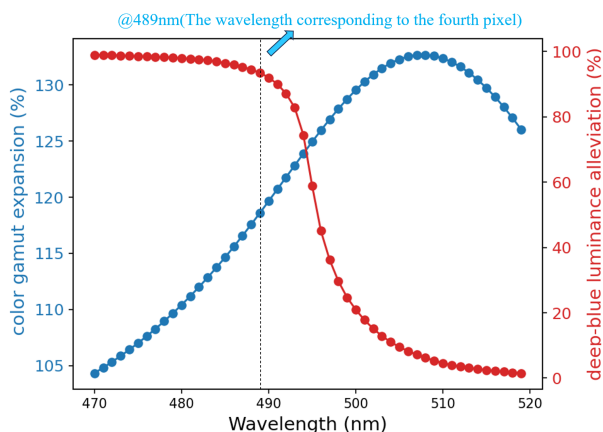


Figure 6. Relationship diagram between the wavelength of the fourth pixel, color gamut expansion, and deep-blue luminance alleviation.

Although the analysis is based on the Adobe RGB color gamut, it closely overlaps with the color gamut corresponding to the center wavelengths of 630 nm, 532 nm, and 467 nm for the R/G/B QDs used in the laboratory. This strong overlap makes the results highly relevant and practical for QLED display applications.

In conclusion, the introduction of a light-blue pixel into QLED panels offers a viable pathway to expanding the color gamut and enhancing the stability of blue pixels. The proposed strategy, with further refinement and optimization, holds great potential for advancing the efficiency and durability of next-generation QLED displays.

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6. References

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