**Explore Luminance Attenuation and Optical Crosstalk of RGB Mini Light-Emitting Diode via Microscopic Hyperspectral Imaging**

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**ABSTRACT** In this article, we experimentally and quantitatively investigate the luminance attenuation for red, green, and blue mini light-emitting diodes (LEDs), and the optical crosstalk in the RGB mini-LED array under different working currents via the microscopic hyperspectral imaging technique. The evaluation metrics of luminance attenuation for one single mini-LED subpixel and luminance influence among all three colored mini-LEDs are well defined to quantitatively describe the optical crosstalk among three mini-LED subpixels in the array. We also compare the size-dependent behaviors of luminance attenuation for blue and green mini-LEDs with an emission peak of about 465 nm and 529 nm, respectively. The minimum pixel pitch of blue and green mini-LEDs with different chip sizes is obtained through optical simulation based on LightTools software, so that the optical crosstalk can be reduced. Finally, we believe that this study could provide a useful guidance for selecting suitable working current conditions while driving the mini-LED display with suitable pixel size and pixel pitch to reduce both the optical and color crosstalk in the mini-LED display.

**INDEX TERMS** Mini-LED, microscopic hyperspectral imaging, optical crosstalk, luminance attenuation.

## I. INTRODUCTION

In 2000, Jin *et al.* first proposed a theory of micro light-emitting diode (micro-LED) technology [1]. Compared with the liquid crystal display (LCD) and organic LED (OLED) display, the outstanding advantages of micro-LED displays mostly lie in low power consumption, low-cost, high resolution, high reliability, and so on [1]. The power consumption of micro-LED display is only 10% of LCD and 50% of OLED [2], [3]. Therefore, the micro-LED displays own extensive application prospects in the field of portable and wearable devices, visible light communication (VLC), and augment reality/virtual reality (AR/VR) devices [4], [5], possessing extensive practical significance and commercial value.

In general, an ideal micro-LED display requires that each emitting pixel in the display can be individually lit up, and would not affect other surrounding pixels. However, the emitting light coming from epitaxial layer in the micro-LEDs would propagate to the sides of sapphire substrate and epitaxial layer in the form of optical waveguide, causing the optical crosstalk and resulting in abnormal images in the micro-LED display. Recently, more and more researches have focused on addressing the optical crosstalk in the micro-LED display [6], [7], [8], [9]. Among them, Li *et al.* have published a work of in-depth study on the optical crosstalk of micro-LEDs [6]. In their works, they replaced the transparent substrate materials with the opaque Si substrate, which can eliminate the light coming from the side of substrates, thereby reducing the optical crosstalk. However, the light stemming from the side of epitaxial layers still exists, and the simple use of opaque Si substrate cannot authentically and fully eliminate the optical crosstalk. Lin *et al.* employed the
photoresist (PR)-defined mold with a blocking wall for the crosstalk reduction for quantum-dot-based micro-LEDs during the aerosol jet printing process [7]. Gou et al. proposed a solution by setting up a reflective barrier around micro-LEDs, namely by the funnel tube array, to eliminate the color crosstalk [8]. Hsiang et al. proposed a patterned cholesteric liquid crystal polymer film as a self-assembled Bragg reflector to enhance the optical performances of a color-conversion micro-LED display and to reduce the optical crosstalk in the micro-LED display [9]. Although many current works on optical crosstalk have been done, the size-dependent and current-dependent optical crosstalk of RGB micro-LED or mini-LED displays remain unknown till now. Therefore, this paper aims to explore the luminance attenuation of RGB mini-LEDs and optical crosstalk in the RGB mini-LED array under various electrical currents and with various pixel sizes.

II. EXPERIMENTAL

A. SAMPLE AND EXPERIMENTAL SETUP

The used sample under test in this current experiment are red (R), green (G), and blue (B) mini-LED with a chip size of 100 µm x 200 µm, and a RGB mini-LED array composed of these three types of mini-LED chips, while the spacing between each mini-LED chip is about 70 µm. Here, the advanced microscopic hyper-spectral imaging technique is adopted to test the luminous and color performances of mini-LEDs. This method is introduced in detail in our groups’ previous works [10], [11]. The experimental setup in this study mainly contains a hyperspectral imager (GaiaFieldF-V10) and a metallographic microscope (MSHOT-TZTM1000). The samples under test are driven by a precise source/measure unit (B2912A, Keysight Technologies). The temperature of samples is controlled by an equipment of TECSource-5305 (Arroyo Instruments Corp.).

B. LUMINANCE ANALYSES OF RED, GREEN, AND BLUE MINI-LEDS

The emission spectra of red, green, and blue mini-LEDs are shown in Fig. 1(a), in which the peak wavelength of red mini-LED is about 629 nm and the full-width at half maximum (FWHM) is 15.5 nm; the green mini-LED has a peak wavelength of about 530 nm and a FWHM of 30.7 nm; and the blue mini-LED owns a peak wavelength of about 465 nm and a FWHM of 19.3 nm, respectively.

Through experiments, as clearly shown in Fig. 1(b), the external quantum efficiency (EQE) reaches a maximum at 6.0 mA (30 A/cm²) for red mini-LEDs, 0.6 mA (3 A/cm²) for green mini-LEDs, and 1.0 mA (5 A/cm²) for blue mini-LEDs, respectively. The relationship between the average luminance $L_B$ for blue, $L_G$ for green, and $L_R$ for red, respectively) and electrical current density ($J$) is shown in Fig. 1(c). The linear relationship between them can be found from Fig. 1(c) with the coefficient of determination ($R^2$) all above 0.99, indicating excellent linear fittings. In addition, through a comparison, we also observe that the green mini-LED varies faster with $J$ than the other two (blue and red) mini-LEDs. Under the same $J$, the green mini-LED appears to be the brightest among three mini-LEDs due to that the visual sense of human eyes is the most sensitive to green color among three mini-LEDs for the reason that the Commission Internationale de l’Eclairage (CIE) photopic sensitivity curve is peaked at around 555 nm. Therefore, the linear relationship, with relevant coefficients and $R^2$ values, for three mini-LEDs can be respectively expressed by

$$L_B = 37817 \times J, R^2 = 0.9991$$
$$L_G = 174796 \times J, R^2 = 0.9956$$
$$L_R = 71952 \times J, R^2 = 0.9996.$$  

(1)

In order to analyze the luminance attenuation of red, green, and blue mini-LEDs with the distance from the center of mini-LED chips, we tested the luminance distribution of red, green and blue mini-LEDs at different electrical current densities. Because at relatively large current densities, the luminance attenuation gap among RGB mini-LEDs is not large enough, and at the same time, operating at the current density with higher EQE can save more power consumption, so according to normalized EQE presented in Fig. 1(a), the current density ranges for red, green, and blue mini-LEDs are selected as 0.25-45 A/cm², 0.25-10 A/cm², and 0.25-20 A/cm², respectively.

Here, for convenience, we define a parameter $x$ as the position from the edge of the long side of mini-LEDs, so $x = 0$ represents at the edge of mini-LEDs, as obviously shown in the inset of Fig. 2(a). It can be observed that when $x$ is greater than a certain value, the luminance of mini-LED remains at a constant value and would not change or change slightly with the distance $x$. At this moment, we define this distance as luminance attenuation length ($L_{att}$)
of mini-LEDs, and the normalized value maintained at this unchanged luminance is defined as a parameter called as luminance attenuation index \( A \). According to such definition, the larger \( L_{\text{at}} \) and \( A \), the farther the luminance of mini-LEDs spreads towards both sides of mini-LEDs, resulting in more serious optical crosstalk. The value of \( A \) for red (R), green (G), and blue (B) mini-LEDs exhibits a power function relationship with electrical current density, and all fitting coefficients \( (R^2) \) are greater than 0.99, expressed by

\[
\begin{align*}
A_G &= 0.1151 \times J^{-0.778}, \quad R^2 = 0.9952 \\
A_B &= 0.0325 \times J^{-0.936}, \quad R^2 = 0.9983 \\
A_R &= 0.1303 \times J^{-1.66}, \quad R^2 = 0.9906. 
\end{align*}
\]  
(2)

We notice that the luminance attenuation index \( A \) of the mini-LEDs decreases as \( J \) increases, as shown in Fig. 2(d). This fact is attributed to that, as \( J \) increases, the current crowding effect becomes more remarkable, and it aggravates the local overheating and local non-radiative recombination occurring in the sidewalls of mini-LEDs [12], both of which would lower the optical efficiency in the sidewalls, thus reducing the value of \( A \) for the mini-LEDs. However, \( L_{\text{at}} \) of mini-LEDs with three colors does not change much with the increase of \( J \), and \( L_{\text{at}} \) of green mini-LEDs is the longest, about 20 \( \mu \text{m} \), while \( L_{\text{at}} \) of red mini-LEDs is the shortest, about 16 \( \mu \text{m} \). Likewise, \( L_{\text{at}} \) of blue mini-LEDs is about 18 \( \mu \text{m} \). The equation (2) indicates that when driving current density exceeds a certain value, \( A \) of red mini-LEDs is the smallest among three colors, due to that the light with longer wavelength is more easily absorbed during the air propagation [13]. However, under the condition of low electrical current density, \( A \) of red mini-LEDs is larger than that of green mini-LEDs, due to that the light-emitting area of red mini-LEDs is smaller than that of green mini-LEDs, and the side light-emitting area accounts for much larger proportion for red mini-LEDs. Therefore, at relatively low luminance, \( A \) of green mini-LEDs is the smallest. As the current density increases, red mini-LEDs have shown the most obvious change in \( A \), whereas green ones have the smallest change. This is because as \( J \) increases, the peak wavelength of red mini-LEDs is red-shifted mainly due to the self-heating effects, which intensify the attenuation of light during the propagation process, so that \( A_R \) in red mini-LEDs decreases the fastest among three colors. But the peak wavelengths of green and blue mini-LEDs are primarily blue-shifted due to the Quantum Confined Stark Effect (QCSE) coulomb shielding which reduces the attenuation of light during the propagation. At the same time, the QCSE of green mini-LEDs is stronger than that of blue mini-LEDs due to different contents in InGaN/GaN materials, so \( A_G \) decreases the slowest among three colors [14].

In addition, we perform an experimental study on the size-dependent luminance attenuation of blue mini-LEDs (with an emission peak wavelength about 465 nm) and green ones (about 529 nm). Three blue mini-LEDs are denoted as Nos. B1, B2, and B3, respectively, while three green mini-LEDs are denoted as Nos. G1, G2, and G3, respectively, with different pixel sizes, with their relevant parameters (such as length and width) shown in Fig. 3. At the same current density, whether it is a blue mini-LED or a green one, the smallest No. 3 (B3 and G3) mini-LED has the slowest luminance attenuation, and has the largest \( L_{\text{at}} \) and \( A \). This fact implies that the smaller the size, the more uniform the luminance distribution, which is in coincidence with previous reports [15]. Moreover, the side area of No. 3 mini-LED accounts for the largest proportion of overall light-emitting area, and its sides emit most light. Besides, \( A \) of blue and green mini-LEDs with different sizes decreases with the increase of \( J \), and the decaying speed of \( A \) becomes smaller at larger \( J \), as obviously shown in Fig. 3.
C. LUMINANCE ANALYSES AND SIMULATION OF RGB MINI-LED ARRAY

The positions of red, green, and blue mini-LED chips in the RGB mini-LED array are clearly shown in Fig. 4(g), where blue mini-LED is located at 100 µm, green mini-LED is located at 270 µm, and red mini-LED is located at 440 µm, respectively. Figures 4(a) and 4(b) demonstrate the luminance distribution of RGB mini-LED array at different positions when blue mini-LED is lit alone. It can be obviously noted from the figure that when blue mini-LED is lit alone, the luminance of the entire RGB mini-LED array at the edge position (200 µm) of blue mini-LED decreases rapidly, then increases at the position of green mini-LED (270 µm), but decreases rapidly at the edge of green mini-LED (370 µm), and finally the luminance decreases slowly, then stays the same.

Figures 4(c) and 4(d) depict the luminance distribution of RGB mini-LEDs at different positions when green mini-LED is lit alone. It can also be seen that when green mini-LED is lit alone, the luminance decreases on both sides. But it increases at the position of blue and red mini-LEDs. This phenomenon also occurs when red mini-LED is lit alone, where the luminance increases at the position of green mini-LED, as shown in Figs. 4(e) and 4(f). This is mainly because the light absorbs and reflects at the nearby mini-LED position during the light propagation process, but it has almost no effect or little effect after a certain distance. For example, when the blue mini-LED is lit alone, the luminance at the green mini-LED position increases, but the luminance at the position of red mini-LED is still slowly decreasing.

To quantitatively characterize the degree of increase in luminance for an RGB mini-LED array at its adjacent unlit chips, we introduce a luminance reflectance index (R), which is defined as

\[ R = \frac{L_s}{L} \]  \hspace{1cm} (3)

where \( L \) is the luminance of the lit chip and \( L_s \) is the luminance of the unlit chip in the RGB mini-LED array. (a) For example, when the blue mini-LED is lit alone, \( L \) is the luminance of blue mini-LED, and \( L_s \) is the luminance at the position of green mini-LED, and thus luminance reflectance index is written by \( R_B \) (at the position of green mini-LED). (b) While green mini-LED is lit alone, the luminance reflectance index is written by \( R_{G+} \) (at the position of red mini-LED) and \( R_{G-} \) (at the position of blue mini-LED). (c) When the red mini-LED is lit alone, the luminance reflectance index is written by \( R_R \) (at the position of green mini-LED). Because red mini-LED is far away from blue mini-LED, the luminance does not rise at its position, so it would not be discussed here. When three mini-LEDs in the RGB mini-LED array are individually lit, the corresponding relationship between \( R \) and \( J \) is shown in Fig. 4(h), from which \( R \) value of red, green and blue mini-LEDs also has a power function relationship with \( J \), and the fitting coefficient \( R^2 \) is greater than 0.99, as

\[ R_B = 0.1037 \times J^{-0.851}, \quad R^2 = 0.9995 \]
\[ R_{G+} = 0.0263 \times J^{-0.749}, \quad R^2 = 0.9901 \]
\[ R_{G-} = 0.0304 \times J^{-0.715}, \quad R^2 = 0.9902 \]
\[ R_R = 0.0957 \times J^{-1.199}, \quad R^2 = 0.9995 \]  \hspace{1cm} (4)

It can be seen from Fig. 4(h) that \( R \) of red, green, and blue mini-LEDs decreases with increasing \( J \), which is consistent with the phenomenon in a single red, green, and blue mini-LED. Moreover, we found that \( A \) of a single mini-LED is larger than \( R \) of RGB mini-LED array under the same current density, which means that if other mini-LEDs are placed next to a mini-LED, it will absorb parts of the light from them and affect its own luminance diffusion. When the current density is greater than 0.5 A/cm² and less than 10 A/cm², under the same \( J \), \( R \) of blue mini-LED is the largest, whereas \( R \) of the positive electrode side of green mini-LED is the smallest. It means that, under the same current density, when the green mini-LED is lit alone in the RGB mini-LED array, it has the least impact on the

FIGURE 4. The luminance distribution of the RGB mini-LED array at different positions under different current densities: (a) and (b) the blue mini-LED is lit alone; (c) and (d) the green mini-LED is lit alone; (e) and (f) the red mini-LED is lit alone; (b), (d), and (f) an enlarged view of the rectangle in (a), (c), and (e). (g) The schematic diagram of the location of RGB mini-LED array. (h) The luminance reflection index (\( R \)) of red, green, and blue mini-LEDs versus \( J \).
mini-LEDs on both sides, especially the mini-LEDs on the side of the positive electrode. In addition, $R$ of red mini-LED changes the most obviously with $J$. When the current density is greater than 10 A/cm$^2$, $R$ of red mini-LED seems to be smallest, also derived from equation (4).

Next, we turn on red, green, and blue mini-LEDs in the RGB mini-LED array at the same time, and then analyze the impact among three mini-LEDs. In order to evaluate the degree of color crosstalk among them, we define an evaluation metric as chromatic aberration ($\Delta E$), and it is expressed by

$$\Delta E = \sqrt{\Delta u^2 + \Delta v^2} = \sqrt{\left(u - u_0\right)^2 + \left(v - v_0\right)^2}$$

where $u$ and $v$ refer to the chromaticity coordinates in the CIE 1976 color space when three mini-LEDs are turned on at the same time, and $u_0$ and $v_0$ are the chromaticity coordinates when they are lit individually. Figure 5(a) shows the variation of $\Delta E$ with $J$ for three colored mini-LEDs. From it, we can see that, with the increasing current density, the $\Delta E$ drops slightly for blue and red mini-LEDs, but increases slightly for green mini-LEDs.

For describing the optical crosstalk, we also introduce another evaluation metric as $C$, for evaluating the influence of one mini-LED on another one in the luminance. For example, $C_{G-B}$ is the luminance influence of green (G) mini-LED on blue (B) one. When only the blue mini-LED is turned on, its luminance in the green wavelength part ($503 \text{nm} < \text{wavelength} < 594 \text{nm}$) is defined as $L_g$. When the blue and green mini-LEDs are turned on simultaneously, it appears to be $L_g'$, and then we have $L_g' > L_g$. Therefore, $C_{G-B}$ as a positive value can be expressed by

$$C_{G-B} = \frac{L_g' - L_g}{L_B} = \frac{L_g' - L_g}{L_G} \times \frac{L_G}{L_B}$$

where $L_B$ is the average luminance for blue mini-LED when three mini-LEDs are lit at the same time in the RGB mini-LED array, $L_G$ is the average luminance for green mini-LED when three mini-LEDs are lit at the same time. The wavelength ranges of blue and red parts are 425 nm-502 nm and 595 nm-675 nm, respectively. Similar to the definition of $C_{G-B}$, other parameters describing the luminance influence, such as $C_{G-R}$ (green on red), $C_{R-G}$ (red on green), $C_{R-B}$ (red on blue), $C_{B-G}$ (blue on green), and $C_{B-R}$ (blue on red), can be defined in the same way.

It can be known from (6) that the value of $C$ is determined by two parts, one is $R$, and the other is the luminance ratio of one mini-LED to the other. Figures 5(b)-(d) show the variance of $C$ with increasing working current densities. From the above analysis, under the same current density, the luminance of green mini-LED appears to be greater than red and blue ones. Therefore, the luminance influence of green to red (blue) are larger than red (blue) to green, that is $C_{G-R} > C_{R-G}$ and $C_{G-B} > C_{B-G}$, for instance, as depicted in Figs. 5(b)-(d). In addition, $C_{R-G} > C_{B-G}$ is attributed to that the luminance ratio of $L_R/L_G$ is higher than $L_B/L_G$ (Fig. 1(d)), as well as that red mini-LED is on the positive side of green mini-LED, where $R_G$ is smaller than $R_{G-}$.

At this moment, it is worth noting that, as the current density increases, $C$ drops, except that $C_{R-B}$ slightly increases. This is because as the current increases, $R$ of mini-LEDs decreases, and at the same time $L_G/L_R$, $L_C/L_B$, and $L_B/L_R$ also decrease, so $C_{G-R}$, $C_{G-R}$, and $C_{B-R}$ decreases, too. At the same time, red mini-LEDs and blue ones are far apart, and $C$ between them is almost negligible.

Through above experiments, we know that if one of the mini-LEDs in the RGB mini-LED array is lit, the light will reflect on the unlit mini-LED next to it within a certain distance, so that the luminance will increase slightly at this position. The resolution of RGB mini-LED displays is negatively related to the pixel pitch, so we use LightTools software based on Monte Carlo ray tracing to perform an optical simulation on blue and green mini-LEDs with the above three sizes as representatives to find out a more suitable pixel pitch, as shown in Fig. 6(a). Here, we set the pixel pitch of 10 $\mu$m - 150 $\mu$m, and then tested the luminance reflection index of $R$. The specific results are shown in Figs. 6(b)-(d). It can be seen from the figure that with the increase of pixel pitch, $R$ decreases, and then remains unchanged. This result is in well consistent with the phenomenon existing in above experiments. Therefore, this distance is what we need to maintain the display resolution and ensure no or little light reflection, thereby reducing the influence of optical crosstalk.

In addition, from the simulation results, we found that when the pixel pitch of No. 1 mini-LED is larger than 100 $\mu$m, the No. 2 mini-LED is larger than 120 $\mu$m, and the No. 3 mini-LED is larger than 130 $\mu$m, then optical reflections from other mini-LEDs can be basically ignored.

III. CONCLUSION

In this paper, we carry out a study on luminance attenuation of RGB mini-LEDs and RGB mini-LED array under various
currents densities. The luminance attenuation index (A) and luminance reflect index (R) are proposed to quantitatively describe the luminance attenuation for mini-LEDs. We also compare the luminance attenuation index for blue and green mini-LEDs with different chip sizes. Finally, we conclude that larger sizes and higher electrical currents are beneficial for reducing optical crosstalk. However, higher electrical currents will introduce more heating and lower the device efficiency, thereby, thermal management is very much needed. In addition, larger size of mini-LED will decrease the resolution of display. Therefore, suitable current and suitable pixel size and pitch are both required for achieving high-performance mini-LED display. In addition, the luminance attenuation length \( L_{\text{att}} \) in this paper can also be combined by using black photoresist (PR) mold to reduce the optical crosstalk. The PR mold can be set to be separate the LED from each other referring to the \( L_{\text{att}} \) length suggested from this work, which not only ensures the least optical attenuation, but also reduces the optical crosstalk in the microscopic display.

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