Eliminating hotspots in a multi-chip LED array direct backlight system with optimal patterned reflectors for uniform illuminance and minimal system thickness

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Abstract: We propose an optical design process that significantly reduces the time and costs in direct backlight unit (BLU) development. In it, the basic system specifications are derived from the optical characteristics of RGB light-emitting diodes (LEDs) comprising the BLU. The driving currents are estimated to determine the theoretical RGB flux ratio for a desired white point. The number of LEDs needed to produce the target luminance is then calculated from the combined optical efficiencies of the components. Last, an appropriate array configuration is sought based on the illuminance distribution function for meeting the target uniformity. To showcase the design process we built two 42-inch triangular cluster arrays of 40 × 16 LED elements. When a flat reflective sheet was used, the minimum thickness required of the system to satisfy the target uniformity was 30 mm. Introducing a patterned reflective sheet removed hotspots that resulted from reducing the system thickness without the aid of additional optical components. Using an optimized patterned reflective sheet, reduction in system thickness as much as 5 mm was possible.

OCIS codes: (220.2740) Geometric optical design; (220.2945) Illumination design; (220.4830) System design; (230.3670) Light-emitting diodes; (330.1730) Colorimetry.

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1. Introduction

The use of light-emitting diodes (LEDs) has been continuously expanding as part of the trend toward more ecologically friendly technology. For example, the cold-cathode fluorescent lamps (CCFL) used in backlight unit (BLU) systems for large-area liquid crystal displays (LCD) have begun to be replaced by LEDs with favorable characteristics, such as lower power consumption, longer lifetime, higher brightness, larger color gamut, tunable white point, etc. For a direct BLU using direct LED arrays, without a light guide plate below the LCD panel, the image quality and power efficiency can be improved by controlling the local dimming to obtain higher contrast and faster response times [1–3]. However, these benefits can only be achieved if the optical characteristics of the LEDs are properly characterized, which is an expensive repetitive task of finding the optimal initial working conditions for reaching the target performance. Therefore, we propose an optical design process that significantly reduces the time and costs in direct backlight unit (BLU) development. Figure 1 summarized the process. First, in the LED design phase, we analyzed actual LED properties and calculated theoretically the initial input current ratio with respect to the output flux of the RGB chip based on an idealized linear transformation matrix to change the International Commission on Illumination (CIE) RGB space to an XYZ space. However, it should be noted that the driving current ratio of each RGB chip should be compensated considering the actual nonlinear correlation between the input current and the output flux. In the BLU design phase, the total number of LEDs required for a target LCD panel size and luminance is calculated from the output flux of a single LED according to the calibrated current ratio, which depends on the actual optical efficiency of the system. The LEDs are then arranged according to an optimal LED cluster design to allow local dimming control. The minimum position for a uniform illuminance distribution is calculated theoretically to determine the initial thickness of the BLU system. Finally, the geometry of the reflective structure can be optimized based on ray-tracing simulation to improve the nonuniform illuminance distribution caused by the reduction in thickness of the BLU system.

2. Design Process of LED BLU

2.1 Initial input current ratio for a unit LED to obtain a target white point

The radiometric RGB stimulus of a multi-chip LED is expressed with the tristimulus values (R, G, B) in the CIE RGB space, which can be converted to the tristimulus (X, Y, Z) values in the CIE XYZ space of the BLU photometric white stimulus to calculate the color coordinates of (x, y, z). If the output RGB stimulus values for the LED also act linearly with the input currents of each RGB chip, the relationship between the RGB input currents (I_R, I_G, I_B) and output fluxes (P_R, P_G, P_B) can be obtained by the following transformation matrix according to the various objective white color coordinates [4–6].

\[
\begin{bmatrix}
L_R I_R \\
L_G I_G \\
L_B I_B \\
\end{bmatrix} = \begin{bmatrix}
P_R \\
P_G \\
P_B \\
\end{bmatrix} = \frac{1}{y_w} \begin{bmatrix}
y_R & 0 & 0 & x_w \\
0 & y_G & 0 & x_G \\
0 & 0 & y_B & x_B \\
\end{bmatrix}^{-1} \begin{bmatrix}
x_R \\
x_G \\
x_B \\
\end{bmatrix} \begin{bmatrix}
y_R & y_G & y_B \\
0 & 0 & 0 \\
0 & 0 & 0 \\
\end{bmatrix} \begin{bmatrix}
z_R \\
z_G \\
z_B \\
\end{bmatrix},
\]

(1)
where \((x_R, y_R, z_R)\), \((x_G, y_G, z_G)\), and \((x_B, y_B, z_B)\) are the individual color coordinates of the RGB chip and \((x_w, y_w, z_w)\) are the color coordinates of the BLU system target white points. \((L_R, L_G, L_B)\) are the linear luminous coefficients of output fluxes with respect to input driving currents of the RGB chip. However, if the driving RGB current values, based on the flux ratio calculated from Eq. (1) for the input condition, are applied in the actual system, the final white point will be shifted from the target because the relationship between the actual output flux and the input current is not strictly linear [see the case of the green chip in Fig. 2(a)]. Of course, the variation in color coordinates generated by the output flux reduction according to the elevated temperature of each chip, as well as this nonlinear output flux, can be compensated for using color sensors for feedback control of the color coordinates [7,8].

Fig. 2. Optical design process of multi-chip LED by (a) Measured output fluxes of RGB chip with an LED measurement system and compensation of the driving currents, (b) verification of optical properties by input fluxes of 2.52 lm \((P_R)\), 9.85 lm \((P_G)\) and 0.55 lm \((P_B)\) applied to ray-tracing simulation, (c) verification of optical properties by input currents of 25.8 mA \((I_R)\), 23 mA \((I_G)\) and 31.7 mA \((I_B)\) applied to experimental unit LED.

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However, it is crucial to calculate the precise initial driving conditions of LEDs because the total number of LEDs required in the entire BLU system depends on the initial output flux of each LED. Therefore, in this paper, the optical properties of each of the 10 LED RGB chips, including the spectral distribution, color coordinates, and total flux, were measured using an integrating sphere and a color analyzer. The linear current ratio for RGB chips, 0.86:1:1.06 (at \(G = 30\) mA), is based on output fluxes calculated from Eq. (1) and was...
replaced with the actual current ratio, 1.12:1.38, for the color coordinate target white point of (0.253, 0.266, 0.481) by curve fitting the measured nonlinear flux data. This result was then verified by ray-tracing analysis based on input fluxes of 2.52 lm (P_R), 9.85 lm (P_G) and 0.55 lm (P_B) and experiment with compensated input currents of 25.8 mA (I_R), 23 mA (I_G) and 31.7 mA (I_B) as shown in Figs. 2(b) and 2(c).

2.2 Array design of multi-chip LEDs

To calculate the total number of LEDs required in the entire BLU system, the final luminance value of the LCD TV (L_BLU), the transmittance of the LCD panel (T_LCD), the size of the BLU (A_BLU), and the optical efficiency (η_BLU) of the BLU components, such as the diffuser plate, the reflective sheet, and the dual brightness enhancement film(DBEF), should be considered [9,10]. Here, η_BLU can be obtained by measuring the optical properties of the BLU components, and can also be used as a feedback variable to improve the accuracy of the optical simulation results. In particular, for an LED showing Lambertian behavior, where the intensity distribution is a cosine function of the emission angle, the total number of LEDs can be calculated by dividing the total flux required for the entire BLU system into the total flux (Φ_LED) emitted from a single multi-chip LED as follows:

\[ n \approx \frac{\pi \cdot A_{BLU} \cdot L_{BLU}}{T_{LCD} \cdot \eta_{BLU} \cdot \Phi_{LED}}, \quad (2) \]

The target conditions were L_BLU = 300 nit; η_BLU = 1.12, given by the product of the measured optical efficiencies of the reflective sheet (reflectance 0.95), the diffuser plate (transmittance 0.75) and DBEF (luminance increasing rate 1.55); T_LCD=5%; and total flux = 12.92 lm. Therefore, from Eq. (2) and the flux ratio of RGB chips to a single LED for the target white point, 640 LEDs were needed for a 42-inch BLU (0.49 m²). Calculation of the total power consumption of this 640-LED BLU system yielded approximately 178 W. Here, it is also noted that T_LCD can be an important factor to affect decision of BLU specifications. If T_LCD of LCD panel is larger than 5%, the power consumption can decrease for the same number of LEDs due to reduction of total flux required for the BLU system and vice versa, but this causes the LED spacing and initial BLU thickness with uniform illuminance distribution to increase.

| Table 1. M × N array configurations of 640 LEDs for a 42-inch BLU and the radius of the overlapping area |
|--------------------------------------------|
| Array type (MxN) | 16x40 | 20x32 | 32x20 | 40x16 |
|------------------|-------|-------|-------|-------|
| a (mm)           | 58.3  | 46.6  | 29.1  | 23.3  |
| b (mm)           | 12.6  | 15.8  | 25.3  | 31.6  |
| R_triangle (mm)  | 29.8  | 24.6  | 19.3  | 19.6  |
| R_triangle (mm)  | 29.5  | 24.0  | 17.3  | 17.0  |
We chose a triangular cluster array design for the LEDs, as this has better illuminance distribution uniformity than a rectangular cluster of the same thickness with the row and column spacing shown in Fig. 3 because of the reduction in overlapping LED areas. Table 1 shows the spacing between the LEDs for four types of $M \times N$ array configurations and the radius of overlapping area for each cluster type. For this design, we selected a $40 \times 16$ array configuration of triangular clusters with a minimum radius of 17 mm. The illuminance distribution function for an LED array configuration is expressed as the sum of the functions of a single LED. In this design, using Lambertian function LEDs in a triangular cluster formation, the illuminance distribution function can be expressed as:

$$E(x, y, z) = z^3 \sum_{j \in \mathbb{Z}} \sum_{i \in \mathbb{Z}} \left( x - \frac{a(M + 1 - 2j)}{2} \right)^2 + \left( y - \frac{b(N + 1 - 2i)}{2} \right)^2 + z^2 \right)^{3/2}, \quad (3)$$

where $M$ and $N$ are the number of columns and rows, respectively, with $N = \frac{N_+ + N_-}{2}$ in the triangular array. Here, $N$ and $N_+$ are used to define a number of LEDs and the $y$ coordinate of each LED for each column $j$ because the symmetric triangular cluster array has a different number of LEDs with respect to odd and even columns as shown in Fig. 4(a); $z$ is the distance to the diffuser plate; and $a$ and $b$ are the column and row spacing of the triangular, respectively. Therefore, we could easily analyze the illuminance distribution according to the change in distance $\Delta z$ for given values of $M$, $N$, $a$, and $b$.

To derive the minimum thickness of the BLU that meets the uniform illuminance, we used Eq. (3) in the same manner as in Ref [11], that is, we solved $\frac{\partial^2 E}{\partial y^2} = 0$ for thickness $z$ using Sparrow’s criterion. Among the parameters that influence the minimum thickness is the number of LEDs contained in the array. As the array recruits more LEDs, newly-joining LEDs have an additional smoothing effect on the overall illuminance distribution, and consequently the required minimum thickness gradually decreases. For instance, our calculation showed that the minimum thickness was 35.4 mm for a $2 \times 16$ array, which
leveled off to 30 mm as the array size was increased to 40 × 16. Figure 4(b) shows the computed illuminance distribution for the 40 × 16 array at the minimum distance of 30 mm.

3. Illuminance Simulation

The choice of initial input simulation conditions is critical when performing optical simulations based on a Monte Carlo ray-tracing, both to minimize the structural optimization computation time and to obtain accurate, reproducible results, for the analytic illuminance distribution at arbitrary distances using Eq. (3). Therefore, we determined the minimum number of input rays and detector area meshes required to secure an illuminance distribution simulation error of less than 1% when compared with the analytic results of Eq. (3). Figures 5(a) and 5(b) show the illuminance distribution calculated from Eq. (3) and the ray-tracing simulation at $z = 20$ mm for the 144 cm$^2$ area of 45 LEDs shown in Fig. 4(a). In the simulation, the average error with respect to the $x, y$ axes between illuminance patterns could be reduced to less than 1%, as shown in Figs. 5(c) and 5(d), using more than 10 million rays in 61 × 61 meshes. The number of input rays and detector meshes used fulfilled the basic simulation condition of maintaining an equal simulation error for increasing numbers of LEDs.

From Fig. 5, it should be noted that reducing the thickness below the initial value of 30 mm for the slimmer BLU system caused hotspots on vertical positions above LEDs. Of course, the intensity of the hotspot can be weakened by using multiple optical sheets in the upper diffuser plate. As this is hardly a fundamental solution for reducing hotspots, it was necessary to design an optical lens or other structure to uniformly redistribute the rays [12,13]. However, as an additional optical lens inevitably causes optical loss, which decreases the initial output flux of the LED through material absorption, Fresnel reflection, total internal...
reflection etc., the number of LEDs would have to be recalculated and the cluster arrays rearranged. Therefore, to avoid the additional components, we optimized the patterned reflective sheet (>95% reflectance) of triangular shape, as shown in Fig. 6(a), to improve the uniformity distribution by increasing the illuminance between LEDs.

![Illuminance distribution](image)

Fig. 6. (a) Schematic of the reflection characteristics for uniform illuminance redistribution using a patterned reflective sheet structure, (b) sheet structure modeling for the ray-tracing simulation and the 7 illuminance points in the unit triangular cluster used to calculate the average illuminance deviation for the uniformity evaluation.

The average deviation, $E_{deviation}$, was then calculated by substituting the illuminance values at the seven points in the unit triangular cluster shown in Fig. 6(b) in the following equation [14].

$$E_{deviation} = \frac{1}{E_{avg}} \sqrt{\frac{\sum_{k=1}^{7} (E_k - E_{avg})^2}{n}}. \quad (4)$$

where $E_{avg}$, $E_k$, and $n$ are the average illuminance, the illuminance at each detection point, and the total number of detection points, respectively. Based on Eq. (4), the criterion hotspot value for optimizing this reflector was calculated as 0.00767 using illuminance values at $z = 30$ mm and the uniform illuminance distribution derived from Eq. (3). That is, if the average deviation calculated from the ray-tracing simulation results for each condition of the patterned reflective sheet is smaller than the criterion value, the hotspot has been completely removed. In the two cases of $z = 25$ mm and $z = 20$ mm, we computed average deviation as a function of the height ($h$) and width ($w$) of a triangular reflective sheet in 1 mm increments. The ray-tracing simulation was carried out in the ranges of $0 \leq h \leq 24$, $0 < w \leq 18$ at $z = 25$ mm and $0 \leq h \leq 19$, $0 < w \leq 18$ at $z = 20$ mm, respectively. Figure 7 shows the distribution graphs of the calculated average deviations for each case within the variable range of the patterned reflective sheet. The results indicated that the average deviation could be minimized using a patterned reflective sheet around A$_1$ ($h = 5$ mm, $w = 11$ mm at $z = 25$ mm) and B$_1$ ($h = 7$ mm, $w = 12$ mm at $z = 20$ mm).
4. Analysis and Verification

The ray-tracing simulations were performed in detail to determine the final specifications for the patterned reflective sheet. First, as indicated in Fig. 7, the final-initial thickness for a 42-inch BLU system was chosen from the average deviation values of A₁ and B₁. Figure 8 shows the average deviation variation between a flat reflective sheet (points A₀ and B₀ in Fig. 7) and a patterned reflective sheet with a minimum average deviation value (points A₁ and B₁ in Fig. 7) depending on the thickness. With the exception of B₁, with an average deviation of 0.00633, the other points appeared larger than the criterion hotspot value of 0.00767. At a thickness of 20 mm, the hotspot could not be eliminated even with an optimal patterned reflective sheet. Therefore, we selected 25 mm as the final BLU system thickness, with a patterned reflective sheet 11 mm in width and 5 mm in height.
In addition, ray-tracing analysis of the entire system with reflective sheets at the above four points was performed for qualitative verification of the hotspot appearance. Figures 9(a) and 9(b) show the illuminance distribution with an average deviation of 0.0367 when using a flat reflective sheet (condition A₀) and with an average deviation of 0.016 when using the optimal patterned reflective sheet 20 mm thick (condition A₁). Hotspots appeared distinctly in both results because the deviation values were more than twice the criterion value. At a thickness of 25 mm, Fig. 9(c) shows the illuminance distribution with hotspots of 0.0137, when using a flat reflective sheet (condition B₀), but Fig. 9(d) shows the uniform illuminance distribution without hotspots with a value of 0.00633 using an optimal patterned reflective sheet (condition B₁).

**Fig. 9.** Ray-tracing simulations for the illuminance distribution for the entire BLU system with an average deviation value of (a) 0.0367 using a flat reflective sheet (condition A₀: h = 0 mm, w = 0 mm) at z = 20 mm, (b) 0.016 by using an optimal patterned triangular reflective sheet (condition A₁: h = 7 mm, w = 12 mm) at z = 20 mm, (c) 0.0137 using a flat reflective sheet (condition B₀: h = 0 mm, w = 0 mm) at z = 25 mm, and (d) 0.00633 using an optimal patterned triangular reflective sheet (condition B₁: h = 5 mm, w = 11 mm) at z = 25 mm.

**Fig. 10.** The measured illuminance distribution images on diffuser plate of 25-mm-thick BLU system with (a) an average deviation of 0.0148, using a flat reflective sheet (condition B₀: h = 0 mm, w = 0 mm) and (b) an average deviation of 0.0073, using an optimal patterned triangular reflective sheet (condition B₁: h = 5 mm, w = 11 mm) in mold frame of aspect ratio 16:9 with 640 multi-chip LEDs.
In the final phase of this study, we made a direct LED backlight system [see Fig. 10(b)] for a 42-inch LCD TV with mold frame of aspect ratio 16:9, 640 RGGB 4-in-1 multi-chip LEDs (triangular array of 40 × 16 elements) within a highly reflective sheet of flat and triangular shape below a diffuser plate and a dual brightness enhancement film DBEF 3M®. The backlight was built with a 25mm thickness based on simulation result to experimentally verify the optical performance of optimum patterned reflective sheet. Figure 10(a) shows the measured real illuminance distribution image with hotspots of 0.0148 using a flat reflective sheet at a system thickness of 25 mm. However, we verified that the hotspots could be eliminated using an optimal patterned reflective sheet 5 mm in height and 11 mm in width. This configuration yielded the illuminance distribution shown in Fig. 10(b), because the value of 0.0073 is lower than the criterion value of 0.00767, although slightly higher than the simulation result of 0.00633.

5. Conclusions

The current compensation for nonlinear output fluxes in an RGB LED chip plays an important role in determining the required number of LEDs for a direct type BLU system. Therefore, we proposed an accurate and efficient optical design process to determine the optimal initial specifications of a BLU system, such as the total number of LEDs, their array structure, and the minimum BLU thickness that could provide a uniform illuminance distribution. Finally, a 42-inch BLU system was actually fabricated and verified. First, in the LED design phase, the driving current based on the RGB flux ratio of a single LED was calculated from a transformation matrix to meet the target color coordinates and luminance of the BLU system. An array of LED clusters was then designed to decrease the area of overlap among LEDs. Next, the minimum system thickness was derived from the illuminance distribution function to provide best uniformity. Finally, we introduced the structure of the patterned reflective sheet to eliminate hotspots generated by the reduction in thickness. Using the design process, a final BLU system 25 mm thick, consisting of 640 LEDs in a triangular cluster array with an optimal patterned reflective sheet 11 mm in width by 5 mm in height was fabricated to verify the optical performance. It should be noted that hotspots are clearly eliminated as the value of 0.0073 (< the hotspot criterion value of 0.00767). Further studies are currently underway to optimize other shapes of reflective sheets to reduce the thickness of BLU systems.

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