Color uniformity enhancement for COB WLEDs using a remote phosphor film with two freeform surfaces

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Abstract: The color uniformity (CU) of chip-on-board (COB) white light emitting diodes (WLEDs) has been improved by using remote phosphor films with two freeform surfaces (TFS-RPFs). The finite-difference time-domain (FDTD), Monte Carlo ray-tracing, and color-thickness feedback (CTFB) methods were used to design the TFS-RPFs: the blue light distribution of COB WLEDs is greatly affected by the angular thickness distribution of TFS-RPFs, and a high CU can be achieved iteratively. The directional inconsistency of incident and emergent blue light, scattering effect of TFS-RPFs, and illumination characteristics of the COB source were also investigated. COB WLEDs containing optimized TFS-RPFs achieved high CU with a decrease of 26.2% in maximum CCT deviation; thus, TFS-RPFs can improve the CU of COB WLEDs.

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1. Introduction

One of the most important techniques to generate white light in white light-emitting diodes (WLEDs) is using blue LED chips to excite phosphor. As the luminous flux (LF) of WLEDs has already far exceeded traditional lighting sources and has satisfied the demands of most applications [1], the color uniformity (CU) [2] has now become a more outstanding concern, especially for agricultural and medical applications. Phosphor layers (PLs) are critical for the
CU of WLEDs because of the inelastic collision occurring between photons and phosphor, which can be adjusted to balance spatial distributions of blue and converted light by the amount of down-conversion events and scattering effect [3]. Compared with dispensing PLs (DPLs) [4] and conformal PLs (CPLs) [5], remote PLs (RPLs) [6] are able to achieve a high light output efficiency (LE) because of the reduction in the absorption loss of back-scattered light [7]. However, it is challenging to balance the color distributions for WLEDs with RPL structures owing to insufficient blue light scattering [8]. Combining RPLs with special optical elements, such as micro-cone patterned films [9], distributed Bragg reflectors [10], and light-recycling dichroic filters [11], can improve the CU by utilizing their scattering or reflecting effect to fully mix different colors of light. However, this will introduce inevitable increases of interface loss and absorption loss. In addition, RPL structures [12–15] have also been designed to achieve high CU; the geometry, area, and location are adjusted to balance the color distributions by deflecting the propagation direction of the blue light to modify the number of blue photons in a particular direction. This is a low-cost and effective approach to improve CU. However, all of these studies focusing on RPLs are based on discrete components constructed with a single LED chip. The components required to output a high LF are combined by a complex surface-mounting process, which leads to multiple shadow patterns [16] in the illumination area. This has limited the further use of RPL structures in lighting applications. Chip-on-board (COB) WLEDs can solve such problems by using only one source produced by an LED chip array, but have not been widely considered previously.

Presently, optimization in DPLs structures is still an major approach to improve the CU of COB WLEDs [17, 18]. However, the thermal reliability of PLs inside COB lead-frames is significantly worse owing to the great amount of heat generated by hundreds of chips flowing to the PLs, which can even cause phosphor quenching and silicone carbonization [19]. The remote structure can also effectively overcome this issue because an isolated layer with low thermal conductive is inserted between the RPLs and chips [20]. However, it is more difficult to design and manufacture RPLs for COB WLEDs with a high CU, compared with discrete components with a single point source. The extended source in COB WLEDs shows more complicated lighting distributions in the near-field [21] where blue photons interact with RPLs, causing great difficulties in balancing color distributions by the structure design of the RPLs. On the other hand, the depth-width ratio of COB lead-frames is much smaller than discrete components; thus, it is difficult to manufacture RPLs with special structures such as curved shapes [22]. Hence, effective design and simple manufacturability is expected for remote phosphor architectures on COB WLEDs with excellent CU. Phosphor films (PFs) have advantages of easy manufacture, low cost, and flexible integration with COB WLEDs, which is a promising approach for WLEDs applications [23, 24]. However, the traditional PFs with two regular planar surfaces [25–27] have not realized their potential advantages on the CU improvement for COB WLEDs; complicated micro-structures and additional processes are still necessary when optimizing the CU for COB WLEDs.

In this paper, we have proposed a method for modeling remote phosphor films with two freeform surfaces (TFS-RPFs) and investigated the effect of TFS-RPFs on the CU of COB WLEDs. Finally, optimized TFS-RPFs with thicknesses of 0.12 – 0.98 mm were fabricated and assembled into COB WLEDs, and the CCT deviation was measured and discussed.

### 2. Method for TFS-RPFs modeling

#### 2.1 Optical properties of TFS-RPFs

The Monte Carlo ray-tracing method [28] has been widely used when studying light propagation into PFs where the down-conversion and scattering events occur owing to the great number of phosphor particles. The absorption coefficient $\mu_{\text{abs}}$, scattering coefficient $\mu_{\text{scat}}$, and scattering phase function $p$ are used to characterize the optical properties of TFS-RPFs in the bulk scattering model [29], which has the forms [30, 31]
\[
\mu_{\text{abs}}(\lambda) = \frac{c}{\bar{m}} C_{\text{abs}}(\lambda), \quad (1)
\]

\[
\mu_{\text{sca}}(\lambda) = \frac{c}{\bar{m}} C_{\text{sca}}(\lambda), \quad \text{and} \quad (2)
\]

\[
p(\lambda, \theta, \phi) = \frac{\int p_D(\lambda, \theta, \phi) C_{\text{sca}, D}(\lambda) n(D)dD}{\int C_{\text{sca}, D}(\lambda) n(D)dD}, \quad (3)
\]

where \(n(D)\) is the phosphor particle size distribution function, \(c\) is the phosphor concentration (g/cm\(^3\)), \(p_D(\lambda, \theta, \phi)\) and \(C_{\text{sca}, D}\) are the scattering phase function and the scattering cross-section of the phosphor with particle size \(D\), respectively, and \(\bar{C}_{\text{abs}}(\lambda)\), \(\bar{C}_{\text{sca}}(\lambda)\), and \(\bar{m}\) are the absorption, scattering cross-section, and the particle mass of the phosphor integrated over \(n(D)\), respectively. These three parameters take on the following forms

\[
\bar{C}_{\text{abs}}(\lambda) = \frac{\int C_{\text{abs}, D}(\lambda) n(D)dD}{\int n(D)dD}, \quad (4)
\]

\[
\bar{C}_{\text{sca}}(\lambda) = \frac{\int C_{\text{sca}, D}(\lambda) n(D)dD}{\int n(D)dD}, \quad \text{and} \quad (5)
\]

\[
\bar{m} = \frac{\int m(D) n(D)dD}{\int n(D)dD}, \quad (6)
\]

where \(C_{\text{abs}, D}(\lambda)\) and \(m(D)\) are the absorption cross-section and mass of the phosphor with particle size \(D\), respectively. Furthermore, the \(C_{\text{sca}, D}\), \(C_{\text{abs}, D}(\lambda)\), and \(p_D(\lambda, \theta, \phi)\) can be written as follows [32, 33]

\[
C_{\text{sca}, D}(\lambda) = \frac{P_{\text{sca}}(\lambda)}{I_{\text{inc}}(\lambda)}, \quad (7)
\]

\[
C_{\text{abs}, D}(\lambda) = \frac{P_{\text{abs}}(\lambda)}{I_{\text{inc}}(\lambda)}, \quad \text{and} \quad (8)
\]

\[
p_D(\lambda, \theta, \phi) = \frac{P_{\text{inc}}(\lambda, \theta, \phi)}{I_{\text{inc}}(\lambda)}, \quad (9)
\]

where \(I_{\text{inc}}(\lambda)\) is the irradiance of the source propagation into the phosphor particles, \(P_{\text{sca}}(\lambda)\) and \(P_{\text{abs}}(\lambda)\) are the total power scattered and absorbed by phosphor particles, respectively, and \(P_{\text{inc}}(\lambda, \theta, \phi)\) is the far-field scattering power distribution. Here, we introduced the finite-difference time-domain (FDTD) method [34] to solve the scattered electromagnetic field of phosphor particles in order to obtain these three parameters, and the detailed simulation setup is shown in the following.
We proposed a color-thickness feedback (CTFB) method to calculate the geometry of TFS-RPFs in order to obtain a high CU for COB WLEDs. The principle of the CTFB method is shown in Fig. 1. The aim is to balance the blue light output power, \( P_B \), from the LEDs, with the yellow light output power, \( P_Y \), from the RPFs, at various viewing angles \( \theta \) and obtain the target color. Increasing the thickness of the RPF unit could lead to a color with less proportion of blue light, and thus become yellowish; contrarily, it could lead to a color with more proportion of blue light, and thus become bluish. Therefore, the geometry of the TFS-RPFs can be determined by its angular thickness \( t(\theta) \) distribution, which is in turn determined by the output color of COB WLEDs. The critical point of the CTFB method is understanding how to use the color deviation (the deviation of \( P_Y/P_B \)) to adjust the thickness of the TFS-RPFs. Firstly, we define \( CDC_n(\theta) \) as the color deviation coefficient at the \( n \)th feedback iteration process, as per [35]

\[
CDC_n(\theta) = \frac{TC}{YBR_{n-1}(\theta)},
\]

where \( TC \) is the target color that is a constant; \( YBR_{n-1}(\theta) \) is the angular ratio distribution of \( P_{Y_{n-1}} / P_{B_{n-1}} \) at the \((n-1)\)th feedback iteration process, which characterizes the color of WLEDs and was achieved by the Monte Carlo ray-tracing method; and \( \theta \) is the viewing angle. Obviously, a higher (lower) \( CDC_n(\theta) \) means that the \( P_{B_{n-1}}(\theta) \) is also relatively higher (lower), leading to a more serious deviation of the \( YBR_{n-1} \) at each \( \theta \) from the \( TC \); when the \( CDC_n(\theta) \) is equal to 1, it means that the \( YBR_{n-1} \) at each \( \theta \) becomes the \( TC \), thus achieving a high \( CU \) for WLEDs. Subsequently, the \( CDC_n(\theta) \) is used to adjust the thickness of TFS-RPFs in order to make the \( YBR_n \) at each \( \theta \) all tend to the constant \( TC \).

Then, it is necessary to establish the relation between the \( CDC_n(\theta) \) and \( t(\theta) \) of the TFS-RPFs. For simplicity, the calculation method is based on the 2D COB WLED model as shown in Fig. 2(a). The parameters are defined as follows: \( r \) is the symmetric line radius between the inner and outside freeform surfaces of the TFS-RPF, and is set as a constant; \( \alpha \) is the emission angle of blue rays emitting from the COB lighting surface; \( \beta \) is the incident angle of blue rays propagating into the TFS-RPF inside surface; and \( I_{xz-uw} \) indicates the emission direction of blue rays emitting from the point \((x, z)\) of the COB lighting surface to the point \((u, w)\) of the TFS-RPF inside surface. Regardless of the scattering effect, most blue rays can reach the detector with their initial emission direction, and can also potentially reach the same
point \((i,k)\) of the detector with different \(l_{xz-uw}\), which determines the value of the \(PB(\theta)\). However, their contributions to the \(PB(\theta)\) are different.

![Image](image_url)

**Fig. 2.** 2D COB WLED models used for calculations: (a) shows the blue rays reaching at the same point of the detector; (b) shows the blue rays reaching at the same point of the RPF.

On one hand, the amount of blue rays emitted with different \(\alpha\) is not the same owing to the illumination characteristic of LED chips, which is commonly treated as the Lambert distribution. On the other hand, the power of blue rays that propagate into the TFS-RPF inside surface with different \(\beta\) is not the same because of the Fresnel loss. In other words, the change in the thickness of the TFS-RPF unit, which the blue rays propagate into with larger \(\alpha\) or \(\beta\), has less influence on the \(PB(\theta)\), as the power of these blue rays is relatively lower. Consequently, the thickness weighting coefficient \(\delta(x,z,u,w)\) is defined to characterize the sensitivity of the \(PB(\theta)\) to the thickness of the TFS-RPF unit at point \((u,w)\) with incident blue rays emitting from point \((x,z)\), which can be written as

\[
\delta(x,z,u,w) = \left(1 - R(\beta_{l_{xz-uw}})\right)I(\alpha_{l_{xz-uw}}), \tag{11}
\]

where \(I(\alpha_{l_{xz-uw}}) = \cos(\alpha_{l_{xz-uw}})\) is the emission strength coefficient to describe the amount of blue rays emitting from the LED source with emission direction \(l_{xz-uw}\); and \(R(\beta_{l_{xz-uw}})\) is the Fresnel reflection when blue rays with emission direction \(l_{xz-uw}\) propagating into the TFS-RPF unit at point \((u,w)\), as per the following.

\[
R(\beta_{l_{xz-uw}}) = \frac{1}{2} \left[ \frac{\sin^2(\beta_{l_{xz-uw}} - \gamma_{l_{xz-uw}})}{\sin^2(\beta_{l_{xz-uw}} + \gamma_{l_{xz-uw}})} + \frac{\tan^2(\beta_{l_{xz-uw}} - \gamma_{l_{xz-uw}})}{\tan^2(\beta_{l_{xz-uw}} + \gamma_{l_{xz-uw}})} \right], \tag{12}
\]

where \(\gamma_{l_{xz-uw}} = \arcsin(d_1 \sin(\beta_{l_{xz-uw}})/d_2)\); \(d_1\) and \(d_2\) are the refractive indexes of the TFS-RPF and the isolated layer (which in this paper is air), respectively. It can be seen that \(\delta(x,z,u,w)\) ranges from 0 to 1, and thus larger \(\delta(x,z,u,w)\) means that more blue rays with emission direction \(l_{xz-uw}\) are able to propagate into the TFS-RPF unit at \((u,w)\); thus,
changing the thickness of this TFS-RPF unit has greater impact on the \( PB(\theta) \). Therefore, the \( CDC(\theta) \) is weighted by the \( \delta(x,z,u,w) \) when being used to adjust the thickness of the TFS-RPF unit at point \((u,w)\) with incident blue rays emitted from point \((x,z)\); for convenience, the thickness of the TFS-RPF unit at point \((u,w)\) is defined as \( t(u,w) \) (or \( t(\theta) \)) subsequently. Moreover, Fig. 2(b) shows that the blue rays emitting from different locations of the COB source can potentially propagate into the same TFS-RPF unit at point \((u,w)\), and most of these blue rays can contribute to the \( PB \) at different \( \theta \). Thus, the change in \( t(u,w) \) has a different degree of influence on the \( PB \) at different \( \theta \). In other words, adjustment of \( t(u,w) \) by the \( CDS \) at different \( \theta \) according to the \( \delta(x,z,u,w) \) is required. Consequently, the \( t(u,w) \) at the \( n \)th feedback iteration process \( t_n(u,w) \) can be written as

\[
t_n(u,w) = t_{n-1}(u,w) \left[ 1 + \frac{1}{L} \int \frac{\delta_n(x,z,u,w)}{\delta_n(x,z,u_{sz-ik},w_{sz-ik})} (CDC_n(\theta_{ik}) - 1) \, dx \right],
\]

where \( \theta_{ik} \) is the viewing angle at point \((i,k)\) of the detector; \((i,k)\) is the point where blue rays with emission direction \( \vec{l}_{sz-um} \) intersect the detector; \( u_{sz-ik} \) and \( w_{sz-ik} \) are the coordinates where blue rays emitting from point \((x,z)\) to \((i,k)\) intersect the TFS-RPF inside surface; \( L \) is the lighting surface diameter of the COB source; and \( z \) is a constant related to the height of the COB lighting surface. The method proposed above can be used to determine the optical properties and geometry of TFS-RPFs.

### 2.3 Simulation setup

The commercial software packages FDTD Solutions and Tracepro have been utilized in this study. Figure 3(a) shows the particle size distributions of YAG: Ce phosphor (density 4.5 g/cm\(^3\), refractive index 1.78). The average particle size and standard deviation are 13.7 \( \mu m \) and 5.0 \( \mu m \), respectively. The particles are assumed to be spherical in the simulation. Figure 3(b) shows the FDTD model of the YAG:Ce phosphor particle. A 3D FDTD simulation region was used with a boundary condition of a perfectly matched layer (PML). A total-field scattered-field source (TSS) with a center wavelength of 455 nm was set to surround the phosphor particle. The background is silicone with refractive index of 1.54. The transmission detector box (TDB) was used to preserve the electromagnetic field information in order to calculate the \( P_{as}(\lambda) \), \( P_{as}(\lambda) \), and \( P_{as}^{\text{abs}}(\lambda,\theta,\phi) \) [25]. The grid size was 10 nm and the shutoff level was set to \( 10^{-5} \) to ensure accurate results. In the Monte Carlo ray-tracing model, two typical wavelengths of 455 nm and 565 nm were used for the blue LED chips and TFS-RPFs, respectively [3]. The TFS-RPL was mixed with the silicone and the YAG:Ce phosphor. The COB was packaged by the silicone and had a circular light-emitting surface which was produced by horizontal blue LED chips (size 0.76 \( \times \) 0.56 mm) distributed in a 6 \( \times \) 7 array. The spherical detector was 500 mm from the center of the COB WLEDs.
3. Results and discussion

The method proposed above was performed to improve the CU of COB WLEDs with TFS-RPFs. The \( r \) was set to be 7.75 mm and the initial \( t_0(\theta) \) was set to be a constant of 0.5 mm; the RPFs at this stage of \( N = 0 \) have two spherical surfaces and are defined as TSS-RPFs. Figure 4 shows the \( PY(\theta) \) and the \( PB(\theta) \) of COB WLEDs with RPFs obtained at different CTFB iteration times \( N \). It should be noted that both the \( PY(\theta) \) and \( PB(\theta) \) are normalized to their total light output power, in order to show the difference in their distributions more clearly. This reveals that the \( PY(\theta) \) distributions barely change at different \( N \), meaning that the change of \( t(\theta) \) has almost no influence because of the isotropy of the excitation emission direction. However, there are large changes of \( PB(\theta) \) distributions for different \( N \). It can be seen that \( PB(\theta) \) becomes smaller at central angles, but becomes larger at edge angles as the \( N \) increases, and its distribution is more and more similar to that of the \( PY(\theta) \), meaning that the balance between the \( PB(\theta) \) and the \( PY(\theta) \) has greatly improved. Therefore, the CU can be increased by TFS-RPFs, especially when the CTFB iteration process is performed according to Eq. (13).
This improvement occurs because the $t(\theta)$ has been adjusted by the color deviation (unbalance between $PY(\theta)$ and $PB(\theta)$ distributions), as shown in Fig. 5(a). With increasing $N$, the $t(\theta)$ at central angles become larger, indicating that the increase of $t(\theta)$ helps to decrease $PB(\theta)$. Contrarily, the decrease of $t(\theta)$ helps to increase $PB(\theta)$. One reasonable explanation is that the increasing (decreasing) $t(\theta)$ contributes to the decrease (increase) in the power of blue light that propagates through the TFS-RPF units located at $\theta$ owing to the higher probability of down-conversion events. It is evident that these results are satisfied with the principle of the proposed CTFB method. In addition, it should be noted that the RPFs for $N > 0$ are all TFS-RPFs as the $t(\theta)$ is no longer constant.

Figure 5(b) shows the $CDC(\theta)$ at different $N$. It can be seen that the $CDC$ at $0^\circ \sim 45^\circ$ is larger than 1, especially when $N < 5$. This means that the output color is mixed with a higher proportion of blue light at central angles, which is also the reason that the $t(\theta)$ at central angles increases with increasing $N$. On the contrary, the $CDC$ at $60^\circ \sim 90^\circ$ is smaller than 1, indicating that the output color is mixed with less proportion of blue light at edge angles, which causes the $t(\theta)$ to decrease at edge angles with increasing $N$.

Furthermore, the $CDC$ at different $\theta$ tends towards 1 as $N$ increases, meaning that the $YBR(\theta)$ is more and more closer to the $TC$, leading to a uniform color distribution. An interesting result is that further increase or decrease of the $CDC$ towards 1 becomes more difficult; after $N > 7$, the increase of the $CDC(75^\circ \sim 90^\circ)$ and the decrease of the $CDC(0^\circ \sim 45^\circ)$ become obviously slower. This means that control of the $YBR(\theta)$ by $t(\theta)$ is more and more difficult, and thus it is very difficult for the $YBR(\theta)$ to be the $TC$ when $N$ is too large. One explanation is that TFS-RPFs have an inside and outside freeform surface instead of the regular spherical surface; when the same blue ray propagates into and escapes from the TFS-RPFs, there is a small difference between the incident angle and the emergent angle owing to the optical refraction at the two interfaces. The inconsistency of the incident and emergent direction may disturb the relationship between the $t(\theta)$ and the $PB(\theta)$; this inconsistency becomes especially significant when the freeform shapes greatly deviate from the spherical shape, causing $t$ to have no influence on the $PB$ in the same $\theta$ and the $CDC(\theta)$ only showing a slight change. Moreover, a $CDC$ with small $\theta$ is more likely to be 1 while a $CDC$ with large $\theta$ is likely to be far from 1. Thus, the $YBR$ with smaller $\theta$ is more easily controlled by $t(\theta)$. We think that the scattering effect of the TFS-RPF and the illumination characteristic of the COB source are responsible for this issue. We calculated the geometry of TFS-RPFs by only using the blue rays emitted directly from the COB source, i.e., not scattered, to adjust the $PB(\theta)$ through several feedback iteration processes; however, in reality there was a contribution to the $PB(\theta)$ by the blue rays scattered by phosphor. As for the $PB$ at large $\theta$, its value mainly depends on the scattered blue rays owing to the Lambert illumination distribution of the COB source with lower power at larger $\theta$. On the contrary, the $PB$ at small $\theta$ depends mainly on the blue rays that have not been scattered. Those nonscattered blue rays are adjusted by the $t(\theta)$ to obtain a certain $PB(\theta)$; thus, it is more effective to control the $PB$ at smaller $\theta$. 
To explain the CU of COB WLEDs with TFS-RPFs more conveniently, we defined the CU as the maximum deviation of the YBRθ. It should be noticed that the unbalance of the power distribution is the primary reason for color variation; therefore, we would rather use the power distribution instead of the CIE coordinates to explain the CU. Figure 6 shows the CU and LE of COB WLEDs at different N. It is obvious that the CU increases with increasing N, resulting from the balance between PBθ and PYθ distributions as shown in Fig. 4; this further indicates that adjusting tθ can be used to control the PBθ and improve the CU. However, the increase becomes less obvious with increasing N, owing to the inconsistency of the propagation direction of the blue rays, phosphor scattering effect, and illumination characteristics of the COB source as discussed above. After 19 feedback iteration processes, optimized TFS-RPFs were achieved with thickness from 0.12 mm to 0.98 mm, as shown in Fig. 5 (a). The optimized COB WLED (when N = 19, with TFS-RPFs) can achieve a CU of 90.1%, which is an increase of 37.6% compared with the referenced COB WLED (when N = 0, with TSS-RPFs). Contrarily, the tθ of COB WLEDs has a slight reduction as N increases, which is mainly owing to the difference in the amount of down-conversion events occurring in RPFs. However, the reduction in the LE of the optimized COB WLED is just less than 1% compared with the referenced COB WLED, and can be neglected in practice.
According to the theoretical results, the optimized TFS-RPFs and reference TSS-RPF, consisting of silicone and YAG:Ce phosphor (phosphor concentration: 20 wt%), were fabricated by the compression molding method as shown in Fig. 7(a). Then, they were assembled to the COB source with a circular lighting surface generated by 42 square-shaped horizontal blue chips. The COB WLEDs were mounted to a heat sink and spectrally measured with an integrating sphere from Instrument Systems. The drive current was provided by an adjustable DC source from Keithley. The angular CCT distributions were measured by our lab-developed angular CCT tester (T950) at a typical drive current of 350 mA, as shown in Fig. 7(b). The optimized COB WLED with a TFS-RPF has a very uniform CCT distribution almost entirely concentrated on ~4100 K, while the referenced COB WLED with a TSS-RPF has a dispersed CCT distribution ranging from 4000 to 4600 K. The maximum CCT deviation $\Delta CCT_{\text{max}}$ of the optimized WLED is 141.7 K, which is just 26.2% of that of the reference WLED ($\Delta CCT_{\text{max}} = 540.8$ K). This demonstrates that the TFS-RPFs can effectively improve the CU of COB WLEDs through reasonable optimization by our proposed method.

4. Conclusion

In this study, we have improved the CU for COB WLEDs by using TFS-RPFs obtained by the proposed method. The FDTD, Monte Carlo ray-tracing, and CTFB methods were combined to determine the optical properties and geometry of the TFS-RPFs. In order to optimize the CU, we utilized the angular color deviation to modify $t_{\theta}$ of TFS-RPFs by several CTFB iteration processes, which is realized by the inverse relationship between the amount of blue photons escaping from RPFs and the PRFs thickness. The extended source was also used for calculations, considering the integration effect of blue photons reach the same location of the detector and the RPFs. The results show that $PY_{\theta}$ almost remained constant during different CTFB iteration processes, while $PB_{\theta}$ changes obviously, leading the $CDC_{\theta}$ to tend towards 1 with increasing $N$. Moreover, the trend of $PB_{\theta}$ with increasing $N$ is totally opposite to that of $t_{\theta}$ owing to the CTFB effect. This means that the color balance can be achieved simply by controlling the $PB_{\theta}$ through proper design of the $t_{\theta}$ of the TFS-RPFs. Interestingly, the results also indicate that the inconsistency of the propagation direction of the blue rays, scattering effect of TFS-RPFs, and illumination characteristics of the COB source can potentially affect the impact of the TFS-RPF on the CU of COB WLEDs, which may diminish its ability to control the $PB_{\theta}$. After 19 feedback iteration processes, the optimized COB WLED with a TFS-RPF can achieve a $CU$ of 90.1%.
which is 37.6% more than the reference COB WLED with a TSS-RPF, and the reduction in LE is less than 1% and can be generally neglected. The optimized TFS-RPFs (thickness from 0.12 mm to 0.98 mm) and TSS-RPFs (thickness is 0.5 mm) were fabricated according to the theoretical results and assembled into COB WLEDs. Experimental results show that the $\Delta \text{CCT}_{\text{max}}$ of the optimized COB WLED with a TFS-RPF is 141.7 K, which is just 26.2% of that of the reference COB WLED with a TSS-RPFs ($\Delta \text{CCT}_{\text{max}} = 540.8$ K) at an average CCT of about 4200 K. This demonstrates that the TFS-RPFs can effectively improve the CU of COB WLEDs through reasonable optimization by our proposed method.

In future, much work is still required to study this phosphor architecture, such as with phosphor materials with different scattering abilities and sources with different sizes and illumination characteristics.

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