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High Spatial Color Uniformity of Phosphor Converted White Light-Emitting Diodes Using the Remote Packaging Structure

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ABSTRACT

The property of spatial color uniformity of white light-emitting diodes is an important requirement for high-quality lighting products. We experimentally conduct the improvement of spatial color uniformity of white LEDs by designing remote placed the yellow phosphor wavelength conversion layer from the blue LED. The angular correlated color temperature deviation can be decreased from 1100 K for the geenerated cool white light (CCT of approximately 6000 K). Effect of injection current on the output light is measured. The proposed structure is feasible, efficient, and meaningful to fabricate the white light with high quality in the field of solid-state lighting. The color rendering quality of output white light is further studied with the IES TM 30-18 assessment.

1. INTRODUCTION

Solid-state lighting (SSL) has been gradually replacing incandescent light bulbs owing to its advantages, including high energy efficiency, fast response, acceptable color rendering, long lifetime, and low cost [1-6]. Light emitting diodes (LED) lighting products with poor spatial color uniformity will cause a clear difference between blueish light and yellow light in the illuminated area. It thus decreases the quality of lighting in general, worse case it will cause an uncomfortable feeling for human eyes. It thus is a demand to enhance the spatial color uniformity for phosphor converted white light emitting diodes (pcW-LEDs) products. Figure 1 shows a photo of the yellow ring phenomenon which is popular for pcW-LEDs products. This problem has attracted much attention from researchers and many solutions have been proposed for the problem of non-uniformity spatial color distribution. Liu et al. proposed a method in which phosphor is conformal coated in a lens, and simulation results showed that an angular correlated color temperature deviation (ACCTD) value of about 900 K was obtained that corresponded to the CCT of white LEDs at about 6000 K [7]. Simmer et al. suggest using a planar color conversion element to achieve an ACCTD value as small as 300 K in simulation for the correlated color temperature (CCT) of pcW-LEDs around 5600 K [8]. Wang et al. proposed a single-lens design of silicone material to produce a uniform spatial CCT distribution, and simulation results show that an achievable ACCTD value as small as 40 K for the CCT of pcW-LEDs is 5000 K [9]. Shuai et al. proposed a phosphor structure with a convex shape on a metal reflector, and simulation results show that the ACCTD value is 200 K when the CCT of pcW-LEDs is 5000 K [10]. Huang et al. have proposed a method of conformal phosphor coating using pulsed spray to reduce the color deviation of white LEDs [11]. In addition, the method of manufacturing a white LED which adds scattering particles of TiO_2, ZnO, ZrO_2, etc. is also a solution to have a small ACCTD value [12-14].

Nguyen et al. simulate the effects of ZnO particles on the color homogeneity of phosphor-converted high-power white led light sources [12]. Chen et al. reported te improvement of angular-dependent CCT uniformity by ZrO_2 nano-particles in remote phosphor white LEDs [13] Wu et al. used TiO_2 nanoparticles in the white LED devices and obtained a nearly uniform space-color distribution [14]. Wu et al. have demonstrated that during the manufacturing process of LED products, the gold wire shape should be well-designed and optimized in order to improve the optical performance of products [15]. Sun et al. reported that a packaging structure with a silicone lens covering a phosphor dome performed an extremely small angular CCT deviation of 105 K in the simulation and 182 K in a corresponding real sample for a white LED with a CCT near 6500 K [16].

The remote structure is simple and feasible for white light generation. To our best knowledge, the study of remote structure for the white light generation with using phosphor plate is still not much reported yet. The utilizing of phosphor plate can cause an effect of likely Lambertian emission characteristic of output blue light and yellow. It is thus interesting to discover the property of spatial color uniformity of the structure by using the remote placing phosphor plate. In this study, we proposed a design for reducing the angular correlated color temperature deviation. Based on the emission characteristic of phosphor plate that can reduce optical path length (OPL) of blue and yellow light in the space, the output white light shows a low-value ACCTD of 1100 K. The obtained result indicates that the proposed structure is efficient in improving the spatial color uniformity for the pcW-LEDs products. This design can apply to enhance the color uniformity of different CCT values (e.g. 6500 K, 7500 K). The IES TM 30-18 assessment is also applied to studied color rendering quality of output white light.

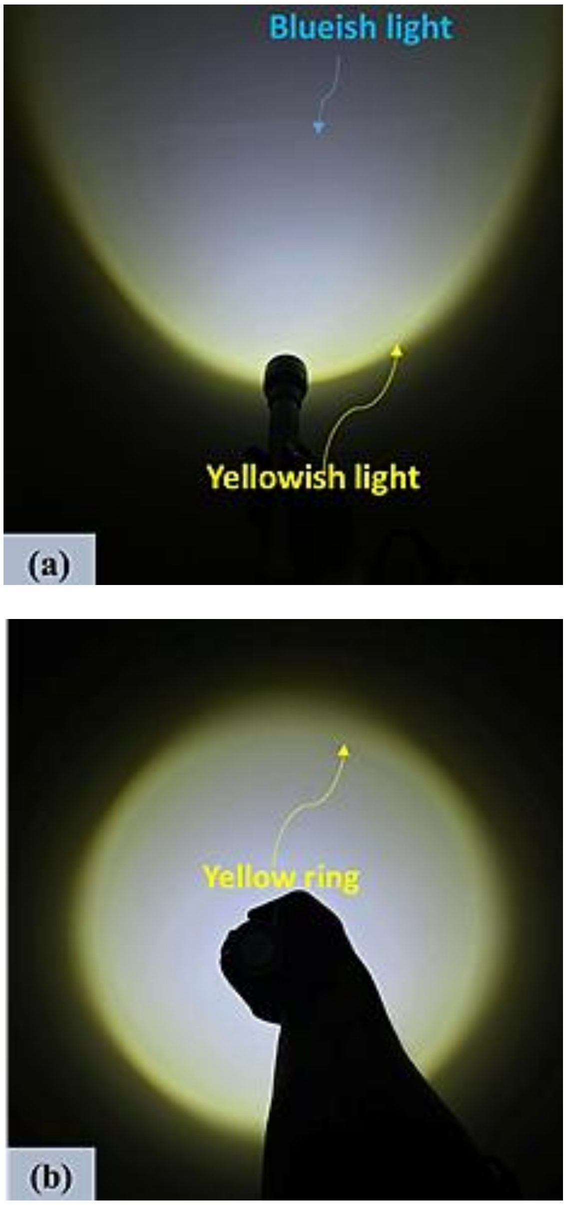

Fig. 1. Photo of (a) low spatial color uniformity of white LED products and (b) yellow ring phenomena.

2. DESIGNED REMOTE PHOPHOR PACKAGING STRUCTURE FOR HIGH SPATIAL COLOR UNIFORMITY AND ITS WORKING PRINCIPLE

Figure 2 shows cross section of the structure of white light generation using phosphor plate separate a distances from blue LED. The blue light LED die emits the blue light to excite the luminescent material Yttrium Aluminum Garnet doped with Cerium (YAG:Ce) in the YAG:Ce mixed Silicone plate. The absorbed blue light is then converted to yellow light. Although the emission distribution of yellow light by the YAG:Ce mixed Silicone plate is nearly Lambertian due to the strong scattering effect of YAG:Ce phosphor [17-19]. However, the spatial distribution of output blue light is not like Lambertian distribution, it thus causes the deviation of the ratio power of Blue and yellow light ratio power at different spatial emission angles. To have a high spatial color uniformity, it is necessary to have a highly consistent ratio power of blue and yellow light ratio power at different spatial emission angles. Based on these characteristics, a designed structure is proposed as shown in Fig. 2.

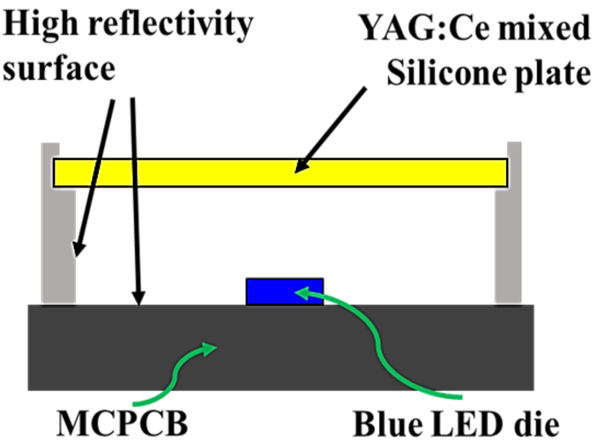

Fig. 2. Cross section of the structure of white light generation using phosphor plate separate a distances from blue LED.

The working of the proposed structure can be explained as follow. The like Lambertian emission characteristics of output light to make the B/Y more uniform in different angles. The distribution of Blue and yellow light is nearly Lambertian distribution leading to the power ratio B/Y is almost similar for different viewing angles. As a result, the ACCTD will be minimized. The output white light becomes more uniform.

3. PROPERTY OF THE OUTPUT WHITE LIGHT OF THE STRUCTURE OF WHITE LIGHT GENERATION USING PHOSPHOR PLATE SEPARATE A DISTANCES FROM BLUE LED

Before testing the spatial color uniformity, the property of the white light generation will be investigated first. Figure 3 shows the CCT and emission spectra versus the injection currents of the white light generation using the structure of phosphor plate separate a distances from blue LED.

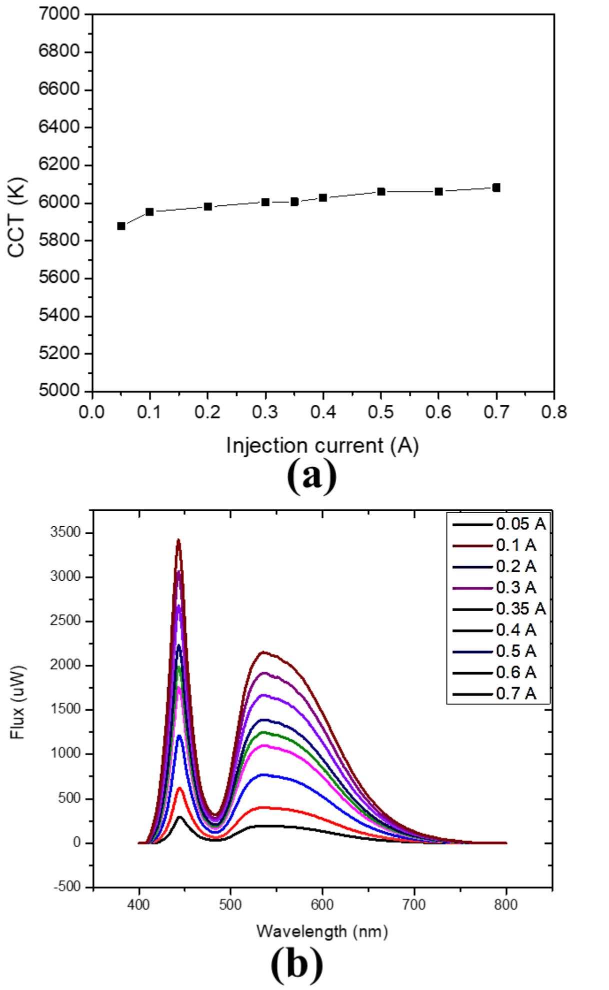

Fig. 3. Dependence of (a) CCT and (b) emission spectra versus the injection currents.

Figure 3 (a) shows the CCT value around 6000K which corresponds to the cool white light category. With the increase of injection current, the CCT variation is small. Figure 3 (b) shows the emission spectra of output white light at different injection currents of 0.05A, 0.1A, 0.2A, 0.3A, 0.35A, 0.4A, 0.5A, 0.6A, and 0.7A. The emission band includes two bands of blue and yellow bands. The higher value of injection currents is, the stronger intensity of the output emission bands is. The increase of blue bands caused by the increase of electrons and holes in the LED junctions layer leads to an increase in radiative recombination for blue photon generation. This led to an increase in an excited blue photon to the yellow phosphor-mixed silicone plate, there was more blue light being absorbed and then converted to yellow light. As a result, the intensity of output blue and yellow light is enhanced as the increase of injection current.

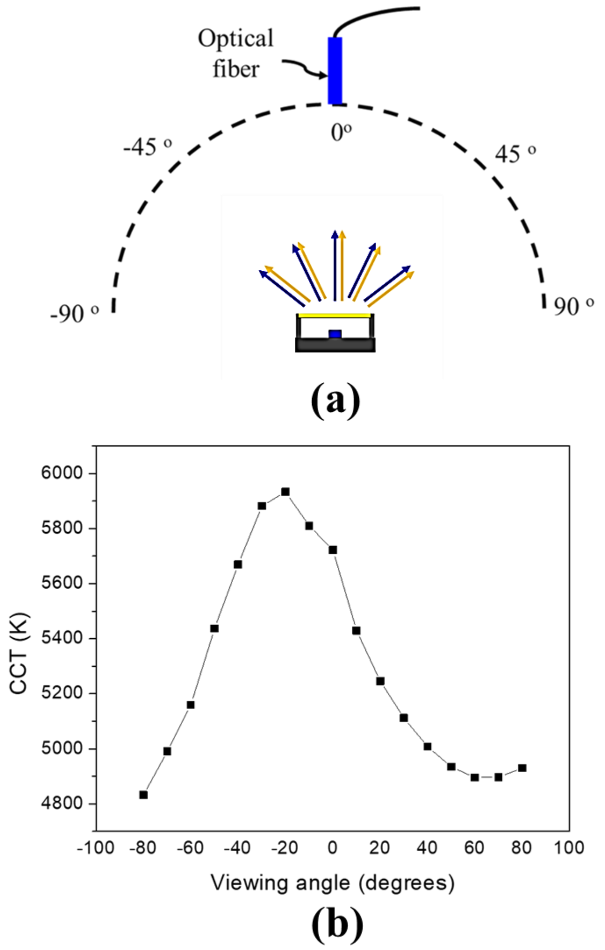

Fig. 4. (a) Illustration of the experimental setup for measurement of spatial CCT distribution, (b) The spatial color uniformity of white light generationtion using remote phosphor structure.

After understand the CCT and emission behavior versus the injection currents. The spatial color uniformity of white light is investigated and evaluated. The experimental setup is illustrated in Fig. 4(a). At each viewing angle, the white light signal optical fiber is collected and sent to the spectrometer to give out the value of CCT. The result of CCT at each value of the angle is shown in Fig. 4(b). The characteristics of spatial color uniformity can be evaluated by the value of angular CCT deviation which is calculated by the difference between maximum CCT and minimum CCT. The measurement result of ACCTD shows a small ACCTD of 1100 K for the output white light.

4. MORE ON THE IES TM 30-18 ASSESSMENT ON COLOR RENDERING QUALITY OF OUTPUT WHITE LIGHT

The traditional color rendering index (CRI) metric can be misleading, as it is based on only 8 test colors and does not consider the overall color spectrum. This can lead to inaccurately characterized light sources, particularly those with non-linear spectral distributions. TM-30-18 aims to overcome these limitations by utilizing a more extensive palette of colors. Thus, it is necessary to reduce the misinterpretations associated with CRI. In this study, the IES TM-30-18 standard is further applied. It is a method for evaluating the color fidelity and color rendering capabilities of light sources, particularly for white light sources such as LEDs. It was developed by the Illuminating Engineering Society (IES) in response to the limitations of traditional color rendering metrics like CRI. Applying IES TM-30-18 in the assessment of white light quality is crucial for providing a more accurate and comprehensive evaluation of how light sources render color. By addressing the limitations of traditional metrics such as CRI, TM-30-18 enhances the understanding of lighting's impact on color perception, ensuring that lighting solutions meet the diverse needs of various applications while supporting improved visual experiences.

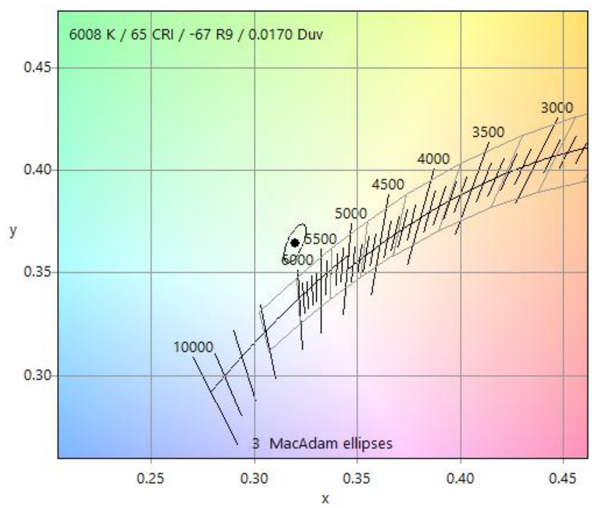

Fig. 5. Chromaticity coordinates of output white light at injection current of 350 mA.

The white LEDs are often driven at a current of 350 mA. Therefore, the case of white light at injection current of 350 mA is evaluated with applying the IES TM-30-18 standard. Figure 5 shows the chromaticity coordinates of output white light at injection current of 350 mA. The distance of its color point is 0.017 from the blackbody loscus curve. The value of general CRI is 65 and CCT is 6008 K.

Local color fidelity is the quantification of the magnitude of the typical shift for specific hues. It is calculated as the average color shift for the color evaluation samples within a hue-angle bin, transformed to have a range of 0 to 100. The values are abbreviated $R_{f,hj}$, where h stands for hue and j is the number of the hue angle bin, from 1 to 16. The $R_{f,hj}$ values provide more granular information than R_f that may be more relevant to a specific application where the object colors are known. Figure 6 shows the value of higher than 60, which is considered appropriate for the light source quality.

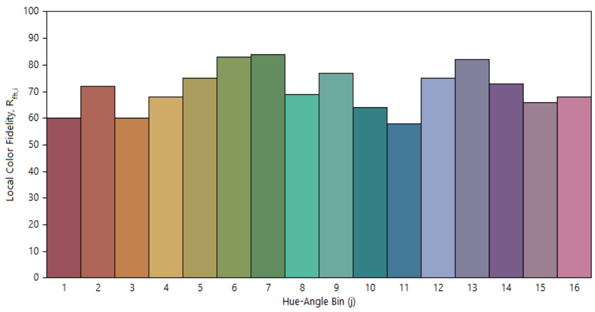

Fig. 6. Chroma shifts, hue shifts and R_f histograms for 16 hues of output white light at injection current of 350 mA.

Figure 7 shows the result of expanded color fidelity assessment. TM-30-18 provides a more comprehensive approach to assessing color quality by evaluating not just a light source's ability to render colors accurately, but also how it affects the appearance of a wide range of colors. It uses a series of test colors including 99 colors and compares how they appear under the tested light source versus under a reference illuminant. Some color are still poor, some are good. This disadvantage poses the need for a solution to improve the color rendering performance for output white light from this remote packaging structure.

TM-30-18 introduces two main metrics: the fidelity index (Rf) and the gamut index (Rg). Rf quantifies the color fidelity of the light source compared to a reference illuminant, while Rg assesses the saturation or vividness of the colors rendered. This dual focus allows for a more nuanced understanding of how a light source will affect color perception.

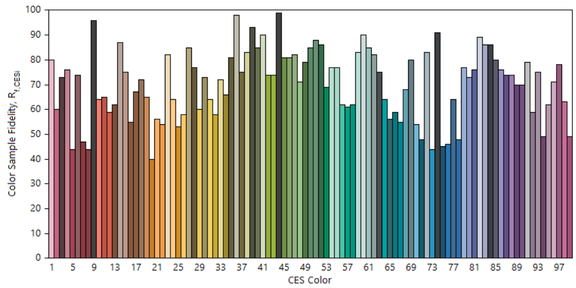

Fig. 7. Color Rf histogram for reference colors of output white light at injection current of 350 mA.

The relation between R_f and R_g is intrinsically tied. If R_f equals 100, there is no color shift; in that case, R_g must also be equal to 100. On the other hand, if R_f decreases there are some color shifts, and R_g can assume a value above or below 100. In principle, the increased saturation must come at a cost on color fidelity. It can trade one point of R_f for a point of Rg. (e.g., if it expects a “color-enhancing” light source with R_g higher than 120, the R_f value will be below 80). Figure 8 shows the ploting of R_g versus R_f of output white light at injection current of 350 mA. The value of R_f and R_g are 70 and 91, respectively. The location is located in the low-fidelity/low gamut zone. Although it is not preferred, this location is still advantageous in making light sources more efficient in terms of luminous efficiency.

To understand the intuitive way of the quality of light in this study, the color vector graphics (CVG) of the output white light at injection of 350 mA is further studied. The arrows in the CVG graph show how colors are distorted from their natural colors (which lie on the black circle) by the case of light sources in this study. This graph tells us how, on average, various colors are distorted. Its visual interpretation is intuitive, such as the outward arrows mean more saturated colors; the inward arrows mean duller (or unexciting) colors; the sideways arrows mean a hue shift; and no arrow means that the color isn’t distorted. Figure 9 shows the color vector graphic result. Results show the desaturate various colors, especially red, warm and cyan blue tones, making them look dull. They are characterized by a low R_f and a low R_g values of 70 and 91, respectively.

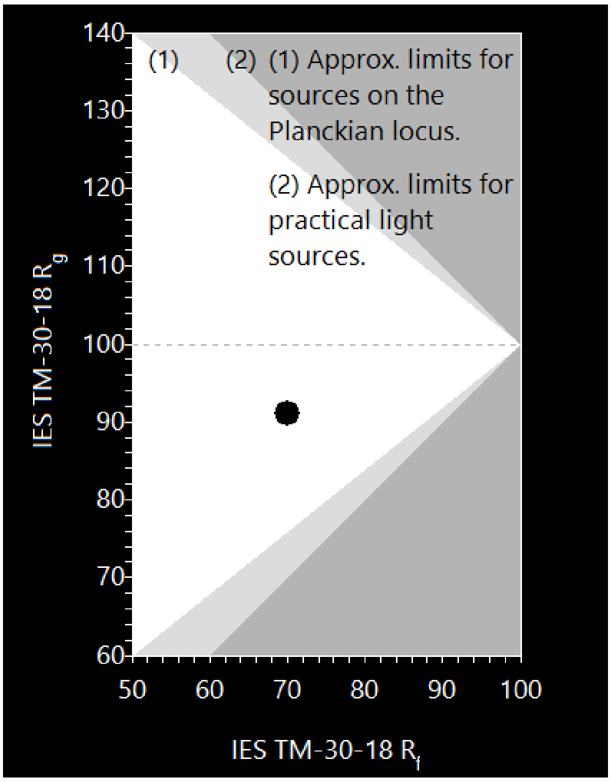

Fig. 8. Rg versus R_f plot of output white light at injection current of 350 mA.

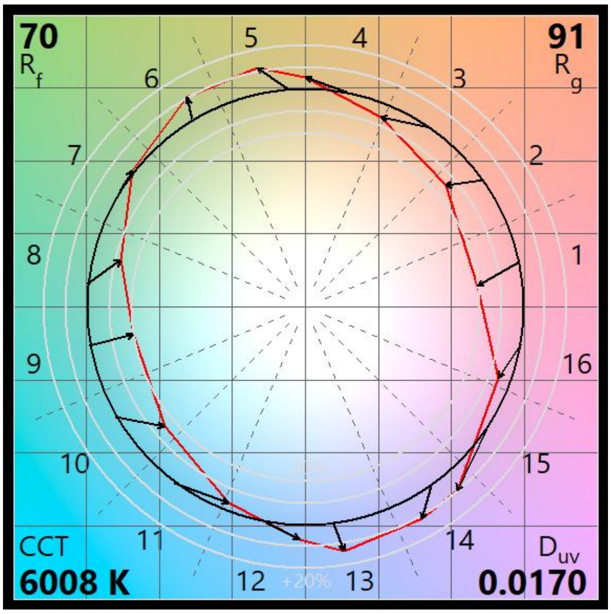

Fig. 9. Color vector graphics of output white light at injection current of 350 mA.

The gamut area plot visually represents the range of colors that a light source can reproduce compared to a reference source (typically an idealized blackbody radiator). The approach focuses on the saturation and fidelity of colors, allowing for a deeper understanding of how light affects color perception. The gamut area is the 2D representation of the color points, and the larger the area, the greater the diversity of colors that can be represented under that light source. The Gamut Area Index (GAI) is a quantitative measure that signifies how much wider the gamut area is compared to the reference light source. A higher GAI means better color reproduction capability. Figure 10 shows the light source has better color reproduction capability for color in the regions (no. 5, 6, 12, and 13) while poorer for color in the region of (no. 1, 2, 3, 8, 9, 10, and 11).

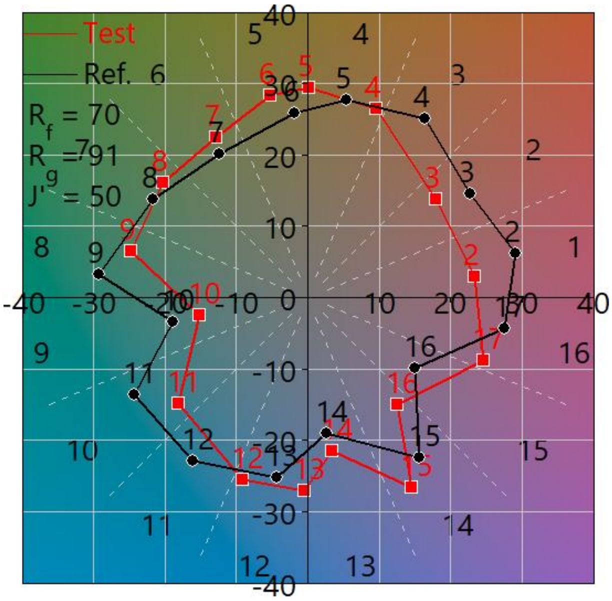

Fig. 10. Gammut area plot of output white light at injection current of 350 mA.

5. DISCUSSION

Remote phosphor technology is often used in solid-state lighting, particularly in LED systems, to produce a desired color temperature with high efficiency and quality. The configuration of a remote phosphor package can lead to a high spatial CCT due to several factors. The first factor is the uniformity of light source. In a remote phosphor configuration, the phosphor layer is situated separately a distance from the LED light source. This separation can help achieve a more uniform spatial distribution of light because the blue light emitted from the LED interacts uniformly with the phosphor layer, generating a more consistent color profile. The second factor is the mixing of colors performance. The physical distance allows for better mixing of the emitted light from different blue LED die or yellow phosphors before it reaches the viewer, improving the overall color quality and reducing hotspots.

Thirdly, the color quality is improved thanks to reduced color striations and increase waveguide effect . Because the phosphor interacts with the light source over a larger area, it minimizes color striations and enhances the perception of a more homogenous light output. This leads to a higher spatial CCT as the emitted light appears more consistent across different viewing angles and locations. Waveguide Effect in the remote phosphor structure because the phosphor layer can act as a waveguide, promoting even distribution of light and thereby enhancing the spatial CCT of the output.

Four, the thermal management efficiency is a potential characteristics. The remote phosphor packages can facilitate better thermal management since the LEDs can operate at lower temperatures. Lower operating temperatures reduce color shift, which is often caused by thermal effects in the light source. This stability helps maintain a consistent spatial CCT across the light field.

Fifth, phosphor composition and characteristics are customizable. The ability to use different types and combinations of phosphors allows designers to tailor the emitted light spectrum specifically to match desired CCT levels. The phosphors can be engineered to shift the spectra in such a way that they produce a higher spatial CCT. This study is subjected for future work.

Sixth, lighting application of this specific configuration is potential. The design and placement of the remote phosphor relative to the light source can be optimized based on specific lighting requirements (e.g., indoor vs. outdoor applications, task lighting vs. ambient lighting) which can also influence the effective CCT across a spatial area.

In gennneral, the high spatial correlated color temperature resulting from remote phosphor package configurations can be attributed to improved light mixing, better thermal management, uniform phosphor distribution, and engineered color characteristics. This technology enhances the quality and consistency of light emitted in various lighting applications, making it advantageous for settings that require precise color rendering or uniform illumination.

6. CONCLUSION

In this work, we reported a structure of white light generation with high spatial color uniformity by the structure of white light generation using phosphor plate separate a distances from blue LED. Based on the like Lambertian emission characteristics of output light from phosphor plate, the B/Y power ratios is more uniform in different viewing angles. As a result, the ACCTD will be minimized. The output white light becomes more uniform.

The investiagted result show that, the emission intensity of output blue and yellow light is enhanced as the increase of injection current. The CCT value around 6000 K which corresponds to the cool white light category. With the increase of injection current, the CCT variation is small. The measurement result of ACCTD shows a small ACCTD of 1100K for the output white light.

The obtained result indicates that the proposed structure is efficient in improving the spatial color uniformity for the pcW-LEDs products. In addition, this design can be a options to enhance the color uniformity of white light at higher CCT values (e. g. 6500 K, 7500 K).

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