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Studying CdS:In green phosphor's impacts on white-light emitting diode with higher luminous flux

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A lumen efficiency (LE) simulation model with the Monte Carlo method is introduced to the white-light-emitting diode devices that utilize the red LED (light-emitting diode) dyes instead of red-emitting phosphors (R-WLEDs). By simulating this model, the desirable spectrum-related indices and photometric efficiencies, which are adequate for superior chromatic consistency (or $R_f > 97$), can be accomplished for R-WLEDs under the correlated color temperature (CCT) range of 5000–8000 K. The structure of the R-LED has LEDs in red and blue colors (650 nm and 448 nm) combined with phosphors possessing yellow and green emissions (586 nm and 507 nm). In comparison with pc-WLEDs (WLEDs operating with conversion phosphors) and QD-WLEDs (WLED devices with quantum dots), pc/R-WLED devices could present its outperformance to the others and become a promising way to achieve remarkable chromatic generation, particularly under the condition of small color temperature limit, and act as a substitute for the pc-WLED devices.

Keywords: *WLEDs, double-layer phosphor, Monte Carlo theory, color homogeneity, luminous flux*

1. Introduction

There are three forms of mixed-type WLED (white-light emitting diode) devices with considerable performances, such as pc/WLED, QD-WLED, and pc/R-WLED. In reality, researchers have been extensively working on achieving the remarkable chromatic generation and great performance of the natural lights for the artificial illumination sources. Thus, when it comes to the advancing development of white LEDs, especially the mixed-type models, the color rendering index (CRI) or R_a [1] and the lumen efficiency (LE) [2] are highly concentrated. The earlier studies [3–5] examined WLED devices' enhancement by achieving the highest radiation lumen efficiency (LER) or limited lumen efficiency (LLE) under several limited conditions, including pre-determined correlated color temperature (CCT) and R_a. Besides, when utilizing the LLE, it is necessary to take into account the Stokes shift's wasted energy [6]. By utilizing the adjustable-CCT pc/R-WLED devices, consisting of blue InGaN and red AlGaInP chips with green- and yellow-emission phosphors under the CCT range of 2700–6500 K, when R_9 and R_a exceeded 98, the LER values exceeding 296 lm/W and ranging from 327 lm/W to 371 lm/W were obtained [7]. The QD-WLED devices, possessing QDs (quantum dots) that generate red, yellow, and green lights under the blue LED's excitation, yielded LER values of 327–371 lm/W when R_a and R_9 are equal to 95, in the CCT range of 2700–6500 K [8]. Several QDs excited by blue chips were integrated into WLED structures to obtain improvements in white-light chromatic properties, such as $CsPb(Cl_{0.1}Br_{0.9})_3$ with cyan emission, $CsPb(Br_{0.5}I_{0.5})_3$ and $CsPb(Br_{0.9}I_{0.1})_3$ with green emissions, and $CsPb(Br_{0.2}I_{0.8})_3$ with red emission. With the presence of these QDs, it is possible to generate white illuminations with adjustable CCTs when the R_a values are from 96 to 97, and LLE values are from 243 lm/W to 254 lm/W, under the CCT range of 2700–6500 K [9]. A study suggested a R/Y/C WLED package, in which the combination of the red AlGaInP LED, the pc-Y LED,

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and pc-C LED devices were demonstrated, for the white-illuminating generation with adjustable CCTs through several R_a, R_9, and LLE values under two CCT ranges of 2700–6500 K and 2731–6533 K [10]. In that work, pc-Y LED and pc-C LED parts utilized blue InGaN LED dyes, but the phosphors were different. The former used the orange and green phosphors while the latter applied only green phosphor (580 nm) to combine with the LED dye.

Since R_a, a common parameter used to determine the chromatic generation could yield positive evaluations for illuminations that display low-quality chromas in saturated entities [11, 12], the indices of R_f (abbreviated for chroma fidelity) and R_g (abbreviated for relative chroma gamut) were proposed [13]. The International Commission on Illumination (CIE) acknowledged these indexes [14]. The R_f values in pc/R-WLED devices, the QD-WLED devices, and the R/Y/C WLED packages appeared to be <95, which means the chromatic generation features in these devices did not reach an equal value to the R_a of CIE. According to Zhang et al. [14], the LED device with four channels of yellow, blue, red, and green could provide a significant chromatic generation with R_f in the range of 93–94, R_a in the range of 95–97, and LER in the range of 299–339 lm/W under CCTs of 2800–6500 K. Meanwhile, under the same CCT limit, the LED layout with 17 channels, including 13 forms of LEDs with thin bands and 4 forms of WLEDs based on conversion phosphor, had R_f, R_g, and LER values of 93–97 lm/W, 100–102 lm/W, and 282–312 lm/W, respectively [15]. As of now, there has not been any document regarding the LE in the said LED layout but the LLE would be backed up by the theory that claims the equivalence between the input photons and the output photons. For the task of determining the photometric efficiency in the three forms of mixed-type WLED devices, the LE model for the pc/R-WLED is required. So far, the spectral enhancement for pc/R-WLED devices through achieving the highest LE value with a pre-determined R_f has been barely reported. Hence, our research focuses on this spectral improvement approach and establishes the LE model for the pc/R-LWED device.

Our LE model consists of R_e values for the red and blue LEDs and Q_e values for the bi-color phosphor sheet. With the support from the Monte Carlo and the LightTools program, the desired LE model and packaging design of the pc/R-WLED are effectively simulated. The Monte Carlo method could enable the effective simulation for the interaction and transportation of radiation and particles, which has been applied to applications related to radiation shielding, medical and biomedical radiation physics, and semiconductor devices [16]. The bi-color phosphor film used in our research consists of the green CdS:In and the yellow YAG:Ce^{3+} phosphors. The CdS-based materials have been favored in solar photocatalysis owing to their narrow bandgap of 2.4 eV, which is also responsive to visible light. Besides, CdS presents enhanced optical absorption and strong chemical stability that are suitable for LED applications [17]. Besides, the CdS-quantum dots (CdS-QDs) were reported to present a simple composition and significant luminescence with a considerably improved photocatalysis feature in the visible region of light [18]. Thus, the CdS-based materials could be promising candidates for further developments of WLED devices. The application of CdS:In is to achieve the enhancement of green spectra to combine with the blue and red spectra from the blue chip and red chip of the studied pc/R-WLED. The idea of enabling this combination, based on the RBG (red-blue-green) principle, is to stimulate the color balance for greater color uniformity and fidelity of white light. The optical-performance simulation and investigation indicate the close connection between the concentration of green CdS:In and the illumination quality (both in chroma and luminous features) of a pc/R-WLED. The YAG:Ce^{3+} concentration is also influenced by the change in CdS:In weight percentages (wt%), which could be significantly beneficial to the enhancement of LE and chromatic production of the examined mixed-type WLED.

Additionally, this research displayed the desirable indexes of spectrum for a chromatic element, along with photometric and colorimetric efficiencies, for pc/R-WLED to exhibit greater strength of LE under CCT values ranging from 5000 K to 8000 K with $R_f \geq 97$. In addition to LE, this

research examined the photometric efficiencies in three forms of mixed-type WLED devices possessing a value of R_f = 97. The research also presents and discusses four potential pc/R-WLED devices that have LE values ranging from 120 to 124 under various CCT values: 5000 K, 5700 K, 6500 K, and 8000 K.

2. Materials and Simulations

2.1. Green-Emitting CdS:In Phosphor Materials

First, CdS:In phosphor was prepared by putting the dry CdS and In_2O_3 powders with suitable amounts (see Table 1) into a quartz ampoule and then thoroughly mixed with a Vortex mixer. Then the quartz ampoule was sealed under vacuum at roughly 1 × 10 torr. The ampoule was tempered for 10 hours at the temperature of 900°C. The ampoule was opened and then the substance was pulverized into mortar. After the process, the obtained material had a uniform light green appearance. In the case that the color was not consistent, the substance underwent the same tempering step again in an ampoule under vacuum conditions. The resulting phosphor was greenish-yellow in color with a green emission peak at approximately 519 nm, and can be excited by either any ultraviolet (UV) or observable blue lighting, with an exponential decay time <1 s [19].

Table 1. The composition of CdS:In

Ingredient	Mole %	By weight
CdS	99%	1 g
In_2O_3	1%	7.95 mg

2.2. pc/R-WLED Simulation

We recreated the layer of phosphor in the WLEDs having flat layers of silicone using the LightTools 9.0 and the Monte Carlo technique. The recreation procedure is a two-stage process in which the initial step is to define the desired WLED structure and simulate it accordingly. The next step is to adjust and monitor the change of CdS:In concentration to analyze its impacts on optical-efficiency parameters of the WLED. To assess how the YAG:Ce^{3+} and CdS:In phosphor compounding can initiate the changes to WLED's optical parameters, comparisons among the WLEDs' outputs need to be demonstrated and it is necessary to create certain contrasts. Particularly, the investigation on the phosphor compounds at the four different average CCT levels of 5000 K, 5700 K, 6500 K, and 8000 K, and the two-layer remote phosphor is carried out. In Figure 1, we can see a depiction of WLED lamps having conformal phosphor compounding at a high CCT of 8500 K. It is also indicated that the facets of WLEDs' recreation do not involve CdS:In. The reflector's bottom length, height, and top surface length are measured at 8 mm, 2.07 mm, and 9.85 mm, respectively. The batch of nine similar LED chips is covered in conformity with a yellow-phosphor sheet and is attached to the reflector's cavity. The chip has a default 0.08 mm thickness, dimension of 1.14 mm long and 0.15 mm tall, a radiated flux of 1.16W, and a peak wavelength of 453 nm.

2.3. Models for Enhancing Photometry

The formula below determines the relative spectral power distribution (RSPD) in the pc/R-WLED device that contains LEDs treated with phosphor, along with phosphors in yellow and green colors, under blue and red LEDs' excitation [20]:

$$S_{pc/R}(\lambda) = k_{pc} S_{pc}(\lambda) + k_r S(\lambda, \lambda_r, \Delta\lambda_r) \quad (1)$$

In Eq. (1), $S_{pc}(\lambda)$ and $S(\lambda, \lambda_r, \Delta\lambda_r)$ represent the RSPD in the examined pc/LED and the red LED. λ_r represents the red-LED peak wavelength, and $\Delta\lambda_r$ represents the red-LED full width at half maximum (FWHM). k_{pc} and k_r represent the relative spectrum's fractions in the pc/LED and the red LED, which notably offer merely a free parameter for the RSPD in the pc/R-WLED. The formula below determines the RSPD for the pc-LED [21]:

$$S_{pc}(\lambda) = q_b S(\lambda, \lambda_b, \Delta\lambda_b) + q_g S(\lambda, \lambda_g, \Delta\lambda_g) + q_y S(\lambda, \lambda_y, \Delta\lambda_y) \quad (2)$$

In Eq. (2), $S(\lambda, \lambda_b, \Delta\lambda_b)$, $S(\lambda, \lambda_g, \Delta\lambda_g)$ and $S(\lambda, \lambda_y, \Delta\lambda_y)$ indicate the RSPDs for the blue spectra bypassing the phosphor sheet, the phosphors in

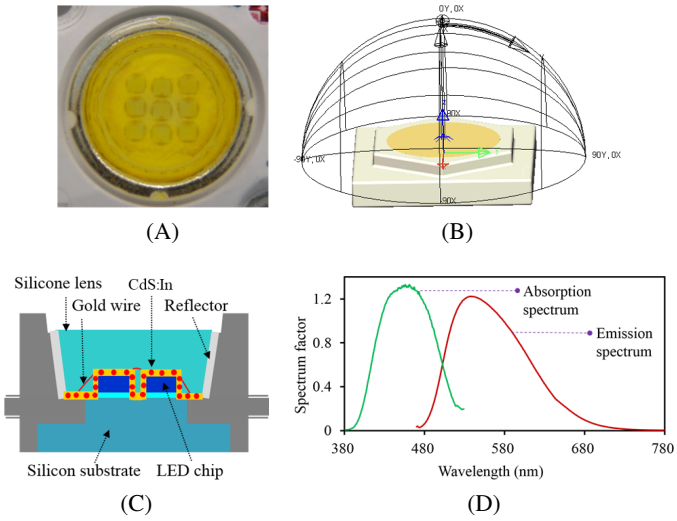


Fig. 1. **(A)** Photograph of the WLEDs, **(B)** illustration of WLEDs, **(C)** simulation of WLEDs, **(D)** the measured spectra of YAG:Ce^{3+} phosphor

green and orange colors. λ_b, λ_g, and λ_y indicate the peak wavelengths for the blue LED, the phosphors in green and orange. $\Delta\lambda_b$, $\Delta\lambda_g$, and $\Delta\lambda_y$ are the FWHM values of the mentioned components. q_b, q_g, and q_y indicate the relative spectrum's fractions for the blue spectra bypassing the phosphor sheet, the phosphors in green and orange. Additionally, q_b, q_g, and q_y offer merely two free parameters for the RSPD in pc-LED. The Ohno model [22] for the SPD values in the blue-red LEDs is utilized. The phosphor's SPDs would be considered a Gaussian function on the photon power rate [23]. The formula below determines the quantity of small-power photons generated by the phosphor sheet that contains yellow or green phosphor mixtures for each second:

$$N_p = \frac{k_{pc} q_g}{hc} \tag{3}$$

The formula below determines the quantity of photons with significant power absorbed into the green or yellow phosphor layer for each second:

$$N_{ab} = \frac{q_{ab}}{hc} \int_\lambda S(\lambda, \lambda_b, \Delta\lambda_b)\lambda d\lambda \tag{4}$$

In Eq. (4), q_{ab}, h, and c represent the blue illumination's absorbed fraction, Planckian constant, and the speed of light, correspondingly. Q_e for the green or yellow phosphor sheet would be considered N_p or N_{ab}. The formula below determines q_{ab}:

$$q_{ab} = \frac{k_{pc} q_g \int_\lambda S(\lambda, \lambda_g, \Delta\lambda_g)\lambda d\lambda}{Q_e \int_\lambda S(\lambda, \lambda_b, \Delta\lambda_b)\lambda d\lambda} + \frac{k_{pc} q_y \int_\lambda S(\lambda, \lambda_y, \Delta\lambda_y)\lambda d\lambda}{Q_e \int_\lambda S(\lambda, \lambda_b, \Delta\lambda_b)\lambda d\lambda} \tag{5}$$

The following formula determines the radiant efficacy in the blue LED:

$$R_{e,b} = \frac{1}{P_{in,b}} \int_\lambda (k_{pc} q_b + q_{ab}) S(\lambda, \lambda_b, \Delta\lambda_b) d\lambda \tag{6}$$

While the radiant efficiency in the red LED could be expressed as:

$$R_{e,r} = \frac{1}{P_{in,r}} \int_\lambda k_r S(\lambda, \lambda_r, \Delta\lambda_r) d\lambda \tag{7}$$

In Eq. (7), $P_{in,b}$ and $P_{in,r}$ present the input energy in the blue and red LED devices. The formula below can be used to calculate the LE in the pc/R-WLED, which consists of the radiant efficacy in red and blue LEDs, along with the green or yellow phosphor sheets' quantum efficacy [24]:

$$LE = \frac{683}{(P_{inb} + P_{inR})} = \frac{683 \int_\lambda V(\lambda) S_{pc/R}(\lambda) d\lambda}{D} \tag{8}$$

where: $D = \frac{1}{R_{e,b}} \int_\lambda (k_{pc} q_b + q_{ab}) S(\lambda, \lambda_b, \Delta\lambda_b) d\lambda + \frac{1}{R_{e,r}} \int_\lambda k_r S(\lambda, \lambda_r, \Delta\lambda_r) d\lambda$.

In Eq. (8), $V(\lambda)$ represents the 1988 CIE photopic lumen efficacy function. To accomplish the enhancement of pc-/R-WLED's spectrum with adjustable CCT, it is necessary to get the fundamental formation of the standard LE for the pc/R-WLED device with adjustable CCT containing red and blue LED devices, with both $R_{e,b}$ and $R_{e,r}$ measured at 60%; along with the green or yellow phosphor sheet with Q_e equal to 90% when R_f is equal or greater 97 [25]:

$$F = \sum_{j=1}^{8} LE_j(k_{r,j}, \lambda_b, \lambda_g, \lambda_y, \lambda_r, \Delta\lambda_b, \Delta\lambda_g, \Delta\lambda_y, \Delta\lambda_r) \quad (9)$$

where R_f is ≥ 97 and D_{uv} is equal to 0.

In Eq. (9), j is equal to the values of 1, 2, 3, 4, 5, 6, 7, and 8 that represent the CCT values of 5000 K, 5700 K 6500 K, and 8000 K. The mixed-type LED devices' color appeared to remain across the Planckian locus (CCT $<$ 5000 K) or daylight CCT point (CCT $>$ 5000 K). The color distinction between the Planckian and daylight point on the 1960 uv color graph, D_{uv}, would be 0 in value. Such a result is meant for preventing the deviation from the limit of the color tolerance quadrangles for the white illuminations [19], which is caused by the peak wavelength's aberrations as well as the FWHM values for the LED devices and the phosphors. In the case of pc/R-WLED, the wavelengths selected range from 450 nm to 470 nm (blue LED), from 490 nm to 550 nm (green-emission phosphor), from 550 nm to 600 nm (yellow-emission phosphor), and from 600 nm to 650 nm (red LED). The FWHM values range from 25 nm to 35 nm in the blue LED, from 70 nm to 120 nm in the phosphors in green and yellow, and from 20 nm to 30 nm in the red LED. Putting the 12-dimension parameter space through the three chroma-blending limitations will yield the position of the possible vectors over the hyperspace possessing nine dimensions for the objective function F to exclude k_{pc}, q_b, q_g, q_y. As such, the issue of enhancement becomes the task of determining the greatest objective function F. For the enhancement, we utilize a quick Pareto original algorithm as the algorithm can offer a huge number of solutions, regardless of the initiating solution. It can help with complicated issues and allows effortless alterations to serve the purpose of gauging the Pareto desirable solutions.

3. Results and Analysis

The YAG:Ce^{3+} has been recognized for the high luminescent feature but the high doping concentration resulted in low homogenous white light. Since it is essential to have both blue and red spectral energies to generate good white light, the YAG:Ce^{3+} phosphor is deficient in pumping red ones. Not only does the color property decrease but also the total light extraction efficiency when high doping YAG:Ce^{3+} amount is utilized. This could be ascribed to a large amount of light trapped in the gap between the phosphor sheet and the chip, leading to a higher probability of light reabsorption that finally promotes the energy loss of the WLED. In other words, the luminous output of the WLED probably decreases. Such disadvantages could be improved by lowering the doping concentration of YAG:Ce^{3+}. However, this concentration reduction could not completely solve the chromatic issue related to red-spectral deficiency. Therefore, the use of red LED is to improve the red color elements for the white light. Regarding the use of green phosphor CdS:In, it aims at enhancing the color uniformity via balancing the blue, red, and green colors, while reducing the effects of high YAG:Ce^{3+} concentration. The green spectral is enhanced, and the yellow phosphor concentration is reduced when the doping concentration of CdS:In increases, as can be seen in Figures 2 and 3.

Particularly, Figure 2 shows that the YAG:Ce^{3+} yellow-phosphor concentration displays a decline linked to the heightened CdS:In green-phosphor concentration. Such opposite introduces key functions of CCT-stability maintenance and influences internal absorption and scattering abilities of phosphor sheets. As the absorption and scattering features are impacted, the color attributes of white light will change consequently. Hence, the choice of CdS:In concentration is one of the decisive factors to determine the LE and chromatic performance of the pc/R-WLED devices. As the said con-

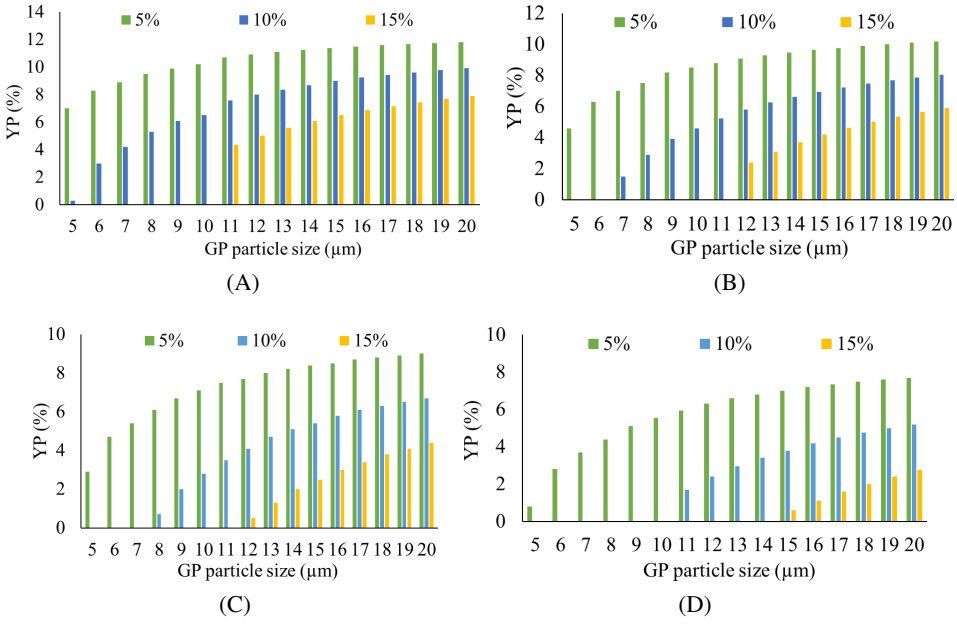


Fig. 2. Simulated results of yellow-phosphor concentration when varying green-phosphor CdS:In concentration with increasing particle size: **(A)** 5000 K; **(B)** 5700 K; **(C)** 6500 K; **(D)** 8000 K

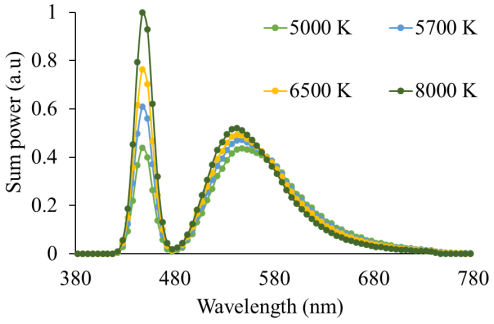


Fig. 3. The simulated WLEDs' emission power when adding CdS:In phosphor

centration raises from 5 wt% to 15 wt%, the concentration of YAG:Ce^{3+} goes down to maintain the average CCT levels, in all four CCT cases.

Figure 3 demonstrates the influence of green-phosphor CdS:In concentration on the emission strength of the pc/WLED. Based on the given data, as well as the objectives of manufacturers, the suitable concentration for CdS:In to be integrated would be determined. If the chroma properties are the priority, the luminescent flux can display a minor decline in its intensity, and vice versa. From Figure 3, it can be inferred that white-light generation is possible to obtain from the combination of three spectral zones, including blue, yellow, and green-orange. Here, the emission strengths are recorded at 5000 K, 5700 K, 6500 K, and 8000 K CCTs. The 420–480 nm and 500–640 nm emission regions show enhancements as the corresponding CCT is higher, which denotes the improvement in luminescent flux. Moreover, these data demonstrate the promoted scattering intensity of blue light within the WLED. Greater scattering chances would lead to greater uniformity of the chroma scale. Regulating good color uniformity at a high CCT point is a significantly challenging task for remote phosphor packages in WLEDs. So, the observed enhancements in emission spectra and scattering probability when using CdS:In are noticeable and important to the advancement of WLEDs.

Color uniformity is one of the critical chromatic features of a white-light source. It is noted that human eyes are more sensitive to chromatic gradients or deviations than the illuminance differences [26]. Therefore, minimizing the color deviations is crucial to enhance the color quality of the LED emitting white light, implying the probability of increasing WLED's prices in the lighting market

due to its heightened color uniform adequacy and fidelity. The CdS:In phosphor, on the other hand, is one of the most popular phosphor materials for pc-WLED devices, and it could offer the economical factor; as such it may have widespread application. Notably, when adding the green phosphor CdS:In, the color deviation is significantly reduced, as can be seen in Figure 4. The variation among the essential chroma elements displays a notable reduction connected to the green-phosphor CdS:In addition, at four specific CCTs. This reduction in color differences could be a function of the absorption characteristic in green-phosphor CdS:In film. Generally, the chromaticity follows the RGB color basis, thus adding CdS:In is beneficial to the green light enhancement. The granules of green phosphor convert the blue light into green light as the said phosphor absorbs the blue light generated by the chip of LED. Besides the blue light mentioned, the granules of CdS:In also introduce the yellow-light absorption but have weaker strength. In other words, the absorption of blue light perform by this green phosphor is more significant. Furthermore, with CdS:In in the phosphor configuration, the scattering features could be improved considerably, which is also crucial to the heightening of chromatic homogeneity. As mentioned above, the reduction of yellow phosphor amount with increasing concentration of CdS:In promotes the scattering of lights, this mechanism acts as an integrator to redistribute the color elements and stimulate the combination efficiency to produce white light. Moreover, with the enhanced scattering ability, the lights from the chip and phosphor layer are transmitted in multiple directions to sufficiently reach the right and left edges of the WLED structure, offering a greater chance of light mixing in these regions to reduce the yellow-ring effects. In short, the improved scattering efficiency and green light components with CdS:In contribute to optimizing the chromatic uniformity of the WLED.

Determining the WLEDs' chromatic performance is related to other factors, not solely the chromatic uniformity; they are the rendering properties of the light source. It is undeniable that great chromatic uniformity helps to ensure visual comfort for users but the overall adequacy of

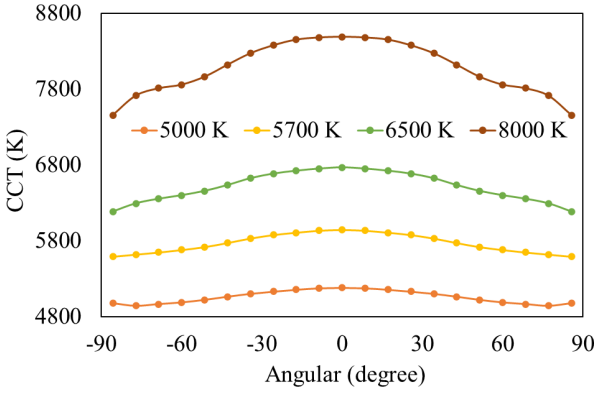


Fig. 4. The simulated angular-dependent CCTs when adding CdS:In green phosphor. CCT, correlated color temperature

white-light chromaticity cannot be fulfilled. Consequently, other chromatic indices are proposed to access the unreached aspects of lighting color performance, color rendition. The CRI is one of the popular parameters to evaluate the chromatic rendering ability of white-light source on tested objects. It can assess the effectiveness in the ability to reproduce an object's color of the white light when it lightens that object. However, the CRI is somehow ineffective to present an accurate color fidelity evaluation as this parameter just allows a small color gamut, about eight color samples, for color reproduction. The color quality scale (CQS), on the other hand, allows color generation to perform on 15 color samples, thus more color shades are examined, resulting in higher accuracy. Besides, when applying CQS for color tests, it means all the features of CRI, human visuality, and chromatic coordinates are specifically analyzed. Therefore, the CQS can be regarded as a powerful and efficient metric to provide a more accurate assessment for the color-recreation ability of a light source [23].

The CRI and CQS values of the WLED with increasing weight percentages of CdS:In can be observed in Figures 5 and 6, respectively. As can be seen in Figures 5 and 6, the concentration of 15% CdS:In presents the lowest CRI and CQS, regardless of the CCT values. This means the concentration increase of CdS:In can cause the CRI and CQS to reduce. This might be the result of the supplemented green spectral energy being too excessive

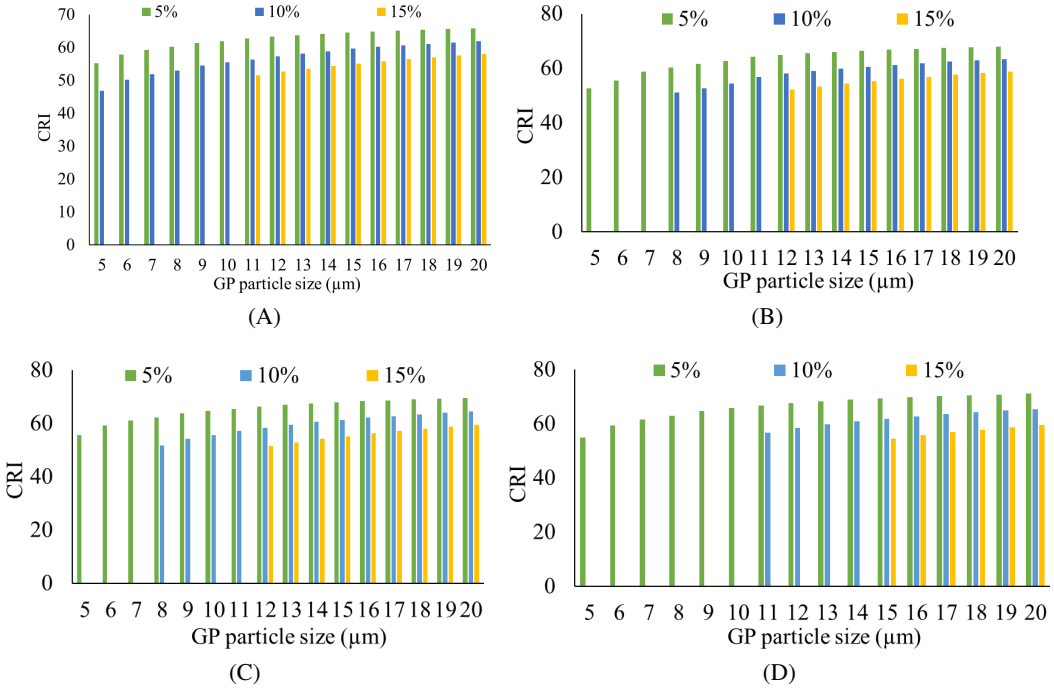


Fig. 5. Simulated CRI values when varying green-phosphor CdS:In concentration with increasing particle size: **(A)** 5000 K; **(B)** 5700 K; **(C)** 6500 K; **(D)** 8000 K. CRI, color rendering index

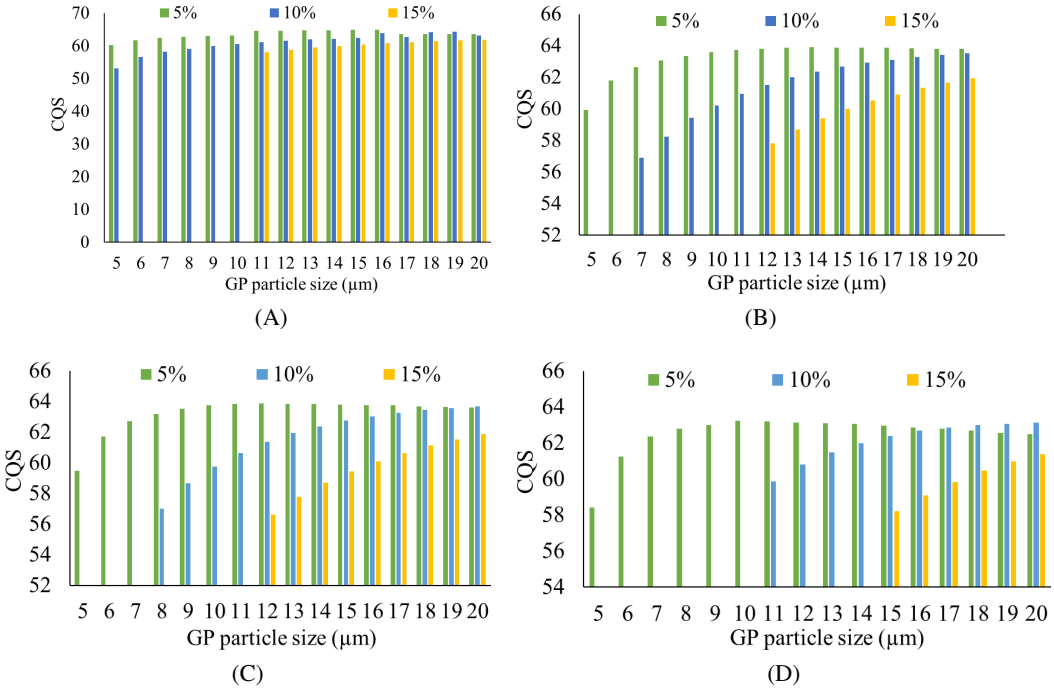


Fig. 6. Simulated CQS values when varying green-phosphor CdS:In concentration with increasing particle size: **(A)** 5000 K; **(B)** 5700 K; **(C)** 6500 K; and **(D)** 8000 K. CQS, color quality scale

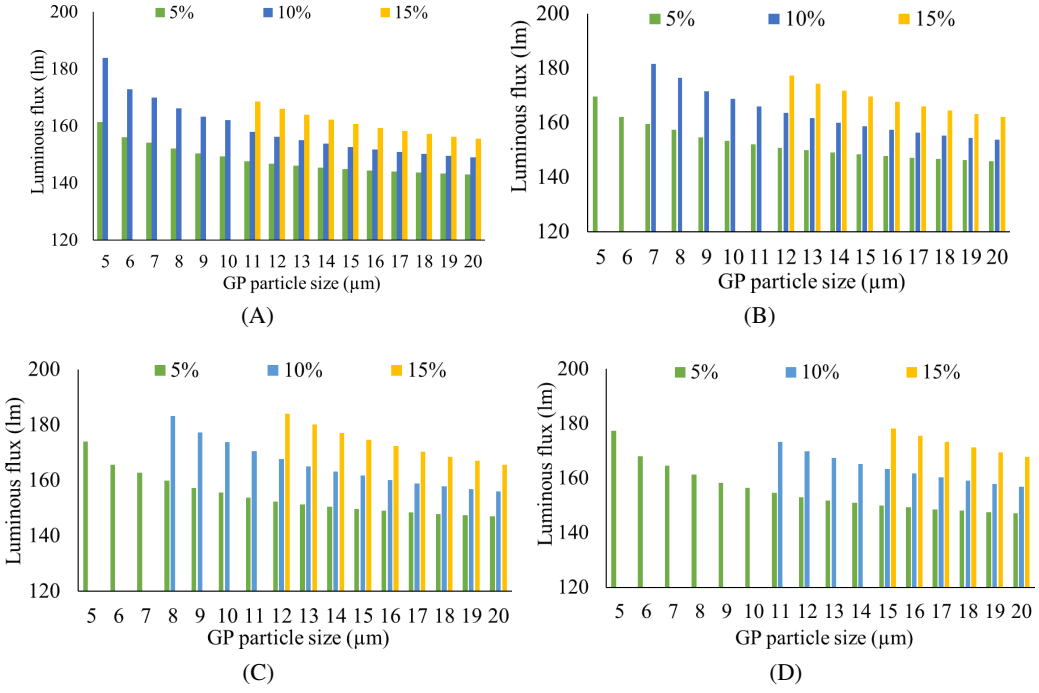


Fig. 7. Simulated luminous flux when varying green-phosphor CdS:In concentration with increasing particle size: **(A)** 5000 K; **(B)** 5700 K; **(C)** 6500 K; **(D)** 8000 K

to keep the stability and consistency among the essential colors, which are blue, yellow, and green-orange, owing to the over-added concentration of CdS:In. This imbalance will initiate the degradation in color rendition and reproduction of WLED light. However, when the increasing CdS:In concentration is introduced and kept $<$10 wt%, there is no notable reduction in CQS. More than 10 wt% CdS:In apparently causes degradation in performances of either CRI or CQS, according to the mentioned explanation of color imbalance by redundant green-light energy. This also reinforces the importance of selecting an adequate weight percentage of green-phosphor CdS:In.

Generally, in a WLED, the enhanced color properties may get the LE decreased. Thus, the luminescent flux intensity in the remote phosphor configuration using a dual-layer packet with the presence of CdS:In should be investigated and demonstrated. Figure 7 shows that the produced lumen is offered a substantial boost as the CdS:In concentration goes from 5 wt% to 15 wt% at all determined CCTs (5000–8000 K). This improvement is attributed to the lower yellow phosphor concentration, as mentioned above. The back-scattering and light trapped events are common to the WLED package with a high concentration or thicker layer of yellow YAG:Ce^{3+}, thus the reabsorption and energy loss are likely to be significant.

Therefore, when the smaller yellow phosphor doping concentration is presented, the higher drawback connected to the backscattering-causing low extraction efficiency can be addressed. Thus, CdS:In has fulfilled its responsibility in offering the LE enhancement. Last but not least, it is essential to take both lumen and color performances into consideration before determining the concentration of CdS:In for WLED applications.

4. Conclusions

Our research demonstrates how the green phosphor CdS:In can affect the light attributes in the two-layer phosphor package. Through the Monte Carlo recreation on the computer, our research confirms that CdS:In can be chosen to boost the chro-

matic homogeneity, which applies to the WLED devices at a small color temperature of 5000 K as well as color temperature >8000 K. The attained results of the study are significant, one of which shows the reduction in color deviation, the key factor to bettering the color homogeneity. Additionally, the CRI and CQS exhibit greater values when the CdS:In concentration is $\leq$ 10 wt%. More than 10 wt% CdS:In can cause the reduction in both rendering parameters due to the degraded color balance initiated by redundant green-light proportion. Meanwhile, the luminous flux is heightened with the rise in CdS:In concentration, thanks to the effective minimization of back-scattered and trapped lights. Therefore, the discovery of the research has met its goal of boosting the chromatic performance and lumen, a complex task for the remote phosphor package. Finally, the decision of suitable green-emitting CdS:In concentration must not be ignored and should depend on the manufacturer's goals. This article can provide vital data to be used for reference when it comes to getting better chromatic homogeneity and lumen in WLED devices.

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