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Spectral Optimization of Two-Phosphor-Coated White Light-Emitting Diodes

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ABSTRACT
The optimal spectra of two-phosphor-coated white light-emitting diodes with correlated color temperatures (CCTs) of 2700 K to 6500 K have been obtained by nonlinear program for maximizing luminous efficacy of radiation (LER) under different conditions of color rendering indices (CRIs), color quality scale (CQS), and special CRIs of R9 for strong red, The simulation results show that the two-phosphor-coated LEDs consisting of the InGaN blue chip, traditional yellow/green phosphors and red-emitting QDs could realize white lights with LER ≥ 337 lm/W for CRI ≥ 90 and CQS ≥ 80, LER ≥ 315 lm/W for CRI ≥ 97, CQS ≥ 94 and R9 ≥ 94 at CCTs of 2700 K to 6500 K. The changes of LER, CRI, CCT, and chromaticity difference (Δuv) have been observed to be associated with the shifts of peak wavelength (λ_p) and full width at half-maximum (FWHM) affected by LED operating temperatures. Furthermore, a solution of warm-white LED, which is consists of the InGaN blue chip (λ_B = 459 nm and $FWHM_B$ = 30 nm), traditional yellow/green phosphors ($\lambda_{Y/G}$ = 552 nm and $FWHM_{Y/G}$ = 50 nm) and red-emitting QDs (λ_R = 621 nm and $FWHM_R$ = 19 nm) with LER = 379 lm/W, CRI = 90, CQS = 86 and R9 = 88 at CCT = 2700 K, is recommended in order to achieve warm-white light with high photometric and colorimetric performance.

Keywords
Solid state lighting, light emitting diodes, correlated color temperature, color rendering index, luminous efficacy of radiation.

1. INTRODUCTION
White light-emitting diodes (LEDs) have promising features such as small size, safety, long lifetime, and are mercury-free, so they are expected to replace conventional incandescent and fluorescent lamps for general lighting applications in the near future [1]. The features of long lifetime and mercury-free would contribute to solving environmental problems. The widespread use of solid state lighting (SSL) is of great importance to significantly reduce the global electricity consumption and the use of fossil fuels. Today, the most commonly used SSL sources are based on the integration of traditional broadband phosphors on blue InGaN LEDs [2]. In recent years, a great amount of effort has been devoted to improve the performance of phosphor-coated white (pc-W) LEDs by choosing proper phosphor materials and structures [3]–[5]. The luminous efficacy of radiation (LER) and luminous efficacy (LE) are related to each other via power conversion efficiency (PCE), i.e., LE = LER×PCE [6]. For a given PCE, a high LE requires a high LER. However, color rendering index (CRI) [7] is also a critical criterion for evaluating the performance of pc-W LEDs. In general, increases of CRI lead to decreases of LER [8]. An improved indicator, Color quality scale (CQS), which attempts to rectify the shortcomings of the CRI, was proposed by the National Institute of Standards and Technology (NIST) [9]. Consequently, optimization procedures involving parametric values of LER, CRI and/or CQS will prove essential. For pc-W LED, in 2008, Zukauskasa et al. investigated four-hump solutions that allow for attaining a number of rendered colors (Nr) =100% [10] at correlated color temperature (CCT) of 3000 K and 6500 K [11]. In their studies, LER values are 286 lm/W for CCT = 3000 K, and 278 lm/W for CCT = 6500 K, respectively. In 2011, He et al. obtained the optimal spectra of pc-W LEDs with one blue (450 nm) InGaN chip, one red (634 nm) AlGaInP chip, green (507 nm) and yellow (580 nm) silicate phosphors at CCTs of 2700 K to 6500 K by nonlinear program for maximizing LER under conditions of both CRI and R9 above 98 [12]. The highest LER value is 334 lm/W at CCT = 2700 K among all CCT values. A solution for producing white LED cluster using the red LED and the pc-W LED with green and yellow phosphors excited by a blue LED die was proposed in order to overcome the low conversion efficiency of red phosphor [13-14]. It was reported that the optimal spectra of white LED cluster consisting of AlGaInP red LED (628 nm) and the pc-W LED packaged by combining silicate green (530 nm) and orange (586 nm) phosphors with a InGaN blue chip (452 nm). It could realize white-light with CRI = 90, CQS = 90, R9 = 92, as well as LER = 357 lm/W at CCT = 2700 K. The real white LED cluster with CRI = 90, CQS = 89, R9 = 90, LER = 358 lm/W, and LE = 117 lm/W at CCT = 2653 K has been realized [15]. In 2012, Zhong et al. explored four-hump white LEDs with nanocrystal quantum dots (QDs) at CCTs of 2700 K to 6500 K [16]. The highest LER values are 403 lm/W for CRI = R9 at CCT = 2700 K, and 381 lm/W for CRI = R9 = 90 as well as 371 lm/W for CRI = R9 = 95 at CCT = 3000 K among all CCT, respectively. Recently, Guo et al numerically investigated three-hump InGaN-based white LEDs precoated with traditional yellow/green phosphors and red-emitting quantum dots (QDs) at CCTs of 2700 K to 6500 K for CRI ≥ 90 and CQS ≥ 80, as well as CRI ≥ 97, CQS ≥ 94, and R9 ≥ 94. [17]. However, Guo's approaches could yield local results by reason of choosing a larger step size of peak height for each hump. In this paper, we investigated three-hump SPDs emitted by InGaN-based white LEDs, using traditional yellow/green phosphors (such as YAG: Ce^{3+}) and red-emitting QDs, and corrected the optimal results reported by Guo. Furthermore, phosphor-coated white (pc-W) LEDs with CRI ≥ 90,

CQS ≥ 85, and R9 ≥ 85 for CCTs of 2700 K to 6500 K were simulated, and optimal results were presented.

2. OPTIMIZATION OF PC-W LED

2.1 Model of pc-W LED

The pc-W LED is consists of a InGaN blue chip, traditional yellow/green phosphors and red-emitting QDs, where the InGaN blue chip and red-emitting QDs are considered as the single narrowband (NB) hump, and traditional yellow/green phosphors is considered as the middle wideband (WB) hump. The spectral power distribution (SPD) of a single narrowband (NB) hump, was given by [18]

$$S_{NB}(\lambda,\lambda_p,w_b) = \Phi(\lambda,\lambda_p,w_b) = [G(\lambda,\lambda_p,w_b) + 2G(\lambda,\lambda_p,w_b)^5]/3 \tag{1}$$

where $G(\lambda,\lambda_p,w_b) = \exp[-(\lambda-\lambda_p)^2/w_b{}^2]$. λ, λ_p and w_b denote wavelength, peak wavelength, and full width at half-maximum (FWHM), respectively.

The hump for the middle wideband (WB) can be adequately modeled by superimposing two humps, as described by

$$S_{WB}(\lambda,\lambda_p,w_b) = \Phi(\lambda,\lambda_{p1},w_{b1}) + \Phi(\lambda,\lambda_{p2},w_{b2}) \tag{2}$$

where $\lambda_{p1} = \lambda_p - a\, w_b$, $\lambda_{p2} = \lambda_p - b\, w_b$, $w_{b1} = c\, w_b$, and $w_{b2} = d\, w_b$. Symbols a, b, c, and d are fitting parameters. Consequently, the model of three-hump SPD can be given as

$$S(\lambda) = H_B S_{NB}(\lambda,\lambda_B,w_B) + H_{Y/G} S_{WB}(\lambda,\lambda_{Y/G},w_{Y/G}) + H_R S_{NB}(\lambda,\lambda_R,w_R) \tag{3}$$

where (λ_B, $\lambda_{Y/G}$, λ_R), (w_B, $w_{Y/G}$, w_R), and (H_B, $H_{Y/G}$, H_R) represent the peak wavelengths, FWHMs, and peak heights of blue, yellow/green, and red, respectively.

In our laboratory, SPDs of white LEDs, which are emitted by an InGaN-based blue die and YAG:Ce^{3+}-based yellow/green phosphor, were measured by the HAAS-2000 spectrometer with an integration sphere manufactured by EVERFINE Corporation. During measurements, white LEDs were placed in a temperature-controlled oven maintained at the room temperature (300 K) under a DC of 350 mA. The temperature-controlled oven is used to warrant the constancy of ambient temperature. Fig. 1 shows experimental SPDs versus models, which are nearly identical (with R-square = 0.9969). This model may also remain applicable to other phosphors, since their SPDs exhibit similar shapes of YAG-humps [12].

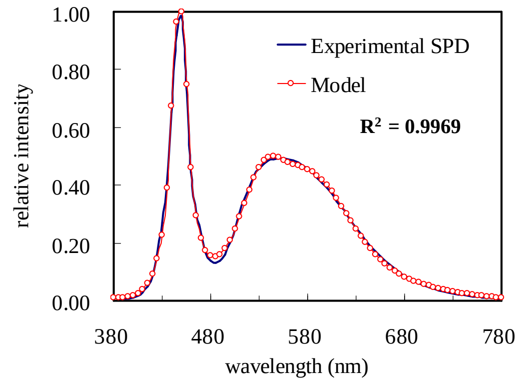


Fig. 1. Experimental SPDs vs. models

2.2 Objective function of optimization

In our paper, we have selected spectra that exhibit three peaks at λ_B = 450 – 490 nm, $\lambda_{Y/G}$ = 500 – 590 nm, and λ_R = 600 – 660 nm indicating blue, yellow/green, and red colors. Typically, FWHM for blue chips is approximately 30 nm, while those of traditional phosphors and emerging QDs are located within 50 – 130 nm and 19 – 49 nm or wider [6], [19], [20], respectively. Clearly, there are two NB humps and one WB hump. Each NB hump is associated with three attributes (λ_p, w_b, H), and the WB hump is associated with five attributes (λ_{p1}, w_{b1}, λ_{p2}, w_{b2}, H). Therefore, totally and theoretically, there are 2×3 + 5 = 11 attributes that can be varied. Subjecting the 11-dimensional parameter space to three color-mixing constrains results in the location of the feasible vectors on the hypersurface with 8 dimensionality [21]. In our numerical simulations, however, realizing that FWHM (w_B) of blue LED can remain unaltered, we actually are able to reduce eight to seven. In order to optimize spectra of two-phosphor-coated white LEDs with different requirements of color rendering at CCTs of 2700 K to 6500 K, we introduce two objective functions:

$$F_1(\lambda_B,\lambda_{Y/G1},\lambda_{Y/G2},\lambda_R,w_{Y/G1},w_{Y/G2},w_R) = \text{LER} \quad (\text{CRI} \geq 90 \text{ and CQS} \geq 80 \text{ at CCT} = i) \tag{4}$$

$$F_2(\lambda_B,\lambda_{Y/G1},\lambda_{Y/G2},\lambda_R,w_{Y/G1},w_{Y/G2},w_R) = \text{LER} \quad (\text{CRI} \geq 97, \text{ both CQS and R9} \geq 94 \text{ at CCT} = i) \tag{5}$$

where i = (2700 K, 3000 K, 3500 K, 4000 K, 4500 K, 5000 K, 5700 K, 6500 K). Notice that the chromaticity difference from the Planckian or daylight locus on the CIE 1960 uv chromaticity diagram (D_{uv}) is smaller than 0.0054 [7]. Hence the optimization problem reduces to finding maxima of the objective function. The parameters in the objective function are dependent on λ_B, $\lambda_{Y/G1}$, $\lambda_{Y/G2}$, λ_R, $w_{Y/G1}$, $w_{Y/G2}$, and w_R. The peak heights of yellow/green and red humps are dependent on the peak height of blue hump, CCT and D_{uv}. So the spectral optimization is carried out by optimizing the wavelength and FWHM of each hump.

A common approach to such multi-objective problems, where the different objectives might be in trade-off, is to investigate the set of Pareto optimal solutions [22]. A Pareto optimal solution is optimal in the sense that improving one objective would degrade the performance for at least one other objective. This means that without any further information, one of these Pareto optimal solutions cannot be regarded as better than any other one. Although there are several global optimization algorithms available in the literature, in this work, genetic algorithms (GA)

[23] were chosen because they are able to scan a vast set of solutions, they do not depend on a starting solution, they are very useful for complex problems, and most importantly, they can be easily modified to estimate the Pareto optimal set. For multi-objective problems, where there might not be one optimal solution, the single-objective GA is modified to evolve towards the Pareto optimal front. Several multi-objective evolutionary algorithms (MOEA) are described in literature [22]. The MOEA selected in this research is the non-dominated elitist NSGA-II genetic algorithm, a widely accepted benchmark in the MOEA research community [24]. A complete description of the NSGA-II algorithm is beyond the scope of this article, and the interested reader is kindly referred to the paper by Deb, et al [25].

3. RESULTS AND DISCUSSIONS

3.1 Optimal Results

The optimal peak wavelength, FWHM and peak height of each hump as well as their photometric and colorimetric performance with CRI ≥ 90 and CQS ≥ 80 at CCTs of 2700 K to 6500 K (D_{uv} ≤ 0.0054) have been obtained by nonlinear program for maximizing F1. The simulation results are shown in Table 1. The results show that the optimal LER value should be 402 lm/W for CRI ≥ 90 and CQS ≥ 80 under CCT = 2700 K at λ_B = 464 nm, $\lambda_{Y/G}$ = 550 nm, λ_R = 615 nm, w_B = 30 nm, $w_{Y/G}$ = 56 nm, and w_R = 19 nm rather than 381 lm/W at λ_B = 464 nm, $\lambda_{Y/G}$ = 554 nm, λ_R = 617 nm, w_B = 30 nm, $w_{Y/G}$ = 69 nm, and w_R = 19 nm reported by Guo [17]. The optimal SPDs for CRI ≥ 90 and CQS ≥ 80 at CCTs of 2700 K to 6500 K are shown in Fig. 2 in order to clearly present our optimization results.

Table 1. Optimal peak wavelengths, FWHMs, peak heights, photometric and colorimetric performances with CRI ≥ 90, CQS ≥ 80, and D_{uv} ≤ 0.0054 at CCTs of 2700 K to 6500 K.

Target CCT (K)	2700	3000	3500	4000	4500	5000	5700	6500
CCT (K)	2700	3000	3500	4000	4500	5000	5700	6500
$D_{uv}\times10^{-3}$	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
λ_B (nm)	464	463	462	461	460	460	460	459
$\lambda_{Y/G}$ (nm)	550	548	545	543	541	540	539	537
λ_R (nm)	615	614	613	612	611	611	610	609
w_B (nm)	30	30	30	30	30	30	30	30
$w_{Y/G}$ (nm)	56	56	51	50	50	50	50	50
w_R (nm)	19	19	19	19	19	19	19	19
a	0	0	0	0	0	0	0	0
b	0	0	0	0	0	0	0	0
c	1	1	1	1	1	1	1	1
d	1	1	1	1	1	1	1	1
H_B	0.2730	0.2730	0.2730	0.2730	0.2730	0.2730	0.2730	0.2730
$H_{Y/G}$	0.4058	0.3071	0.2265	0.1833	0.1562	0.1462	0.1244	0.1111
H_R	2.4307	1.6449	1.0210	0.7348	0.5775	0.4838	0.3800	0.3199
CRI	90	90	90	90	90	90	90	90
CQS	84	84	86	85	85	85	85	85
R9	10	8	14	14	11	12	9	7
LER (lm/W)	402	399	390	379	368	363	350	337

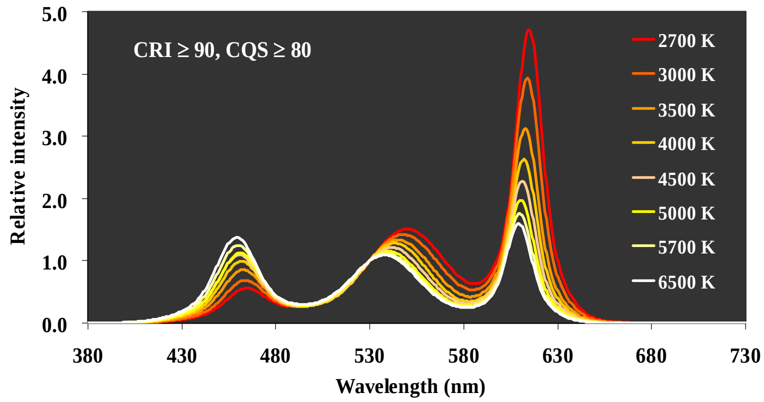


Fig. 2. Optimal SPDs with CRI ≥ 90 and CQS ≥ 80 at CCTs of 2700 K to 6500 K (D_{uv} ≤ 0.0054).

Comparing with the optimal results reported by Guo [17], the increases of optimal LERs for CRI ≥ 90 and CQS ≥ 80 at CCTs of 2700 K to 6500 K are shown in Table 2. The results show that optimal LERs at CCTs of 2700 K to 6500 K are higher than that reported by Guo due to shorter wavelengths of red QDs and narrower FWHMs of yellow/green phosphors adopted in our optimal spectra, and that the maximum increase of LER is up to 5.5 % at CCT = 2700 K. Furthermore, the curves of optimal LER versus CCT for CRI = 90 obtained by authors and Guo are shown in Fig. 3. The results show that the highest LER value should be 402 lm/W at CCT = 2700 K among all CCT values rather than 390 lm/W at CCT ≈ 3000 K reported by Guo.

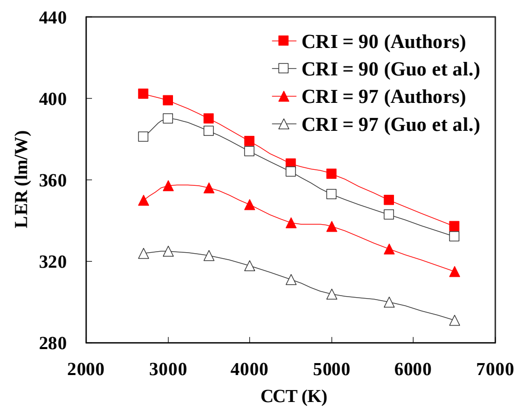


Fig. 3. Optimal LERs versus CCT for CRI = 90 and CRI = 97 obtained by authors and Guo et al.

Table 2. Increases of optimal LER for CRI≥ 90, CQS ≥ 80 at CCTs of 2700 K to 6500 K comparing with the optimal results reported by Guo et al [17]

CCT (K)	2700	3000	3500	4000	4500	5000	5700	6500
Increase of LER (%)	5.5	2.3	1.6	1.3	1.1	2.8	2.0	1.5

The optimal peak wavelength, FWHM and peak height of each hump as well as their photometric and colorimetric performance with CRI ≥ 97, CQS ≥ 94, and R9 ≥ 94 at CCTs of 2700 K to 6500 K (D_{uv} ≤ 0.0054) have been obtained by nonlinear program for maximizing F2. The simulation results are shown in Table 3. The results show that the optimal LER value should be 357 lm/W for CRI ≥ 97, CQS ≥ 94 and R9 ≥ 94 under CCT = 3000 K at λ_B = 455 nm, $\lambda_{Y/G}$ = 571 nm, λ_R = 625 nm, w_B = 30 nm, $w_{Y/G}$ = 95 nm, and w_R = 19 nm rather than 323 lm/W at λ_B = 459 nm, $\lambda_{Y/G}$ = 561 nm, λR = 631 nm, w_B = 30 nm, $w_{Y/G}$ = 130 nm, and w_R = 30 nm reported by Guo [17]. The optimal SPDs for CRI ≥ 90, CQS ≥ 94 and R9 ≥ 94 at CCTs of 2700 K to 6500 K are shown in Fig. 4 in order to clearly present the optimization results.

Table 3. Optimal peak wavelengths, FWHMs, peak heights, photometric and colorimetric performances with CRI ≥ 97, CQS ≥ 94, R_9 ≥ 94, and D_{uv} ≤ 0.0054 at CCTs of 2700 K to 6500 K.

Target CCT (K)	2700	3000	3500	4000	4500	5000	5700	6500
CCT (K)	2700	3000	3500	4000	4500	5000	5700	6500
$D_{uv}\times10^{-3}$	0.0009	0.0024	0.0032	0.0043	0.0054	0.0054	0.0054	0.0054
λ_B (nm)	456	455	459	456	454	457	456	455
$\lambda_{Y/G}$ (nm)	578	571	568	563	557	549	534	524

λ_R (nm)	627	625	624	623	623	622	621	621
w_B (nm)	30	30	30	30	30	30	30	30
$w_{Y/G}$ (nm)	98	95	94	100	109	103	103	101
w_R (nm)	19	19	19	19	19	19	19	19
a	0.4097	0.4032	0.4090	0.4027	0.3555	0.3123	0.1952	0.1086
b	-0.0546	-0.0621	-0.0600	-0.0675	-0.1003	-0.1391	-0.2554	-0.3475
c	0.9898	0.9579	0.8723	0.8600	0.7523	0.6990	0.6699	0.6238
d	0.5102	0.5263	0.5319	0.5477	0.6176	0.6561	0.6776	0.7446
H_B	0.2730	0.2730	0.2730	0.2730	0.2730	0.2730	0.2730	0.2730
$H_{Y/G}$	0.6999	0.5220	0.3214	0.2793	0.2316	0.1968	0.1668	0.1419
H_R	3.2859	2.2763	1.1805	0.9207	0.6726	0.5353	0.4124	0.3091
CRI	97	97	97	97	97	97	97	97
CQS	94	94	94	95	95	95	94	94
R_9	94	94	94	94	94	94	94	94
LER (lm/W)	350	357	356	348	339	337	326	315

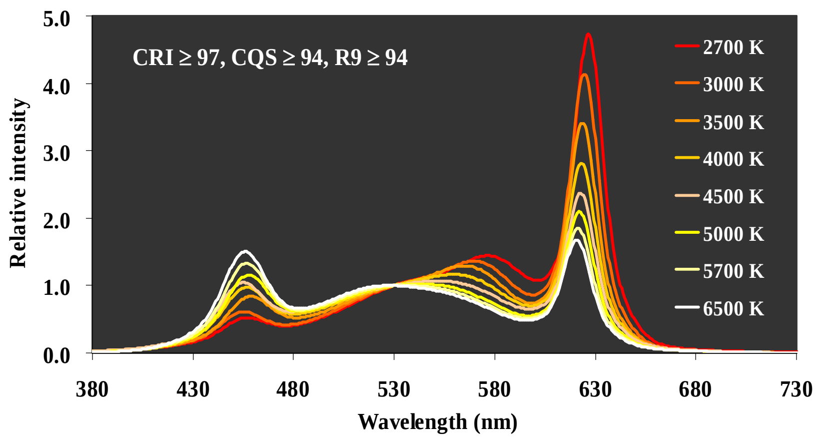


Fig. 4. Optimal SPDs wirh CRI ≥ 97, CQS ≥ 94 and R9 ≥ 94 at CCTs of 2700 K to 6500 K (Duv ≤ 0.0054).

Comparing with the optimal results reported by Guo [17], the increases of optimal LERs for CRI ≥ 97, CQS ≥ 94 and R9 ≥ 94 at CCTs of 2700 K to 6500 K are shown in Table 4. The results show that optimal LERs at CCTs of 2700 K to 6500 K are higher than that reported by Guo due to narrower FWHMs of yellow/green phosphors as well as red QDs adopted in our optimal spectra, and that the maximum increase of LER is up to 10.9 % at CCT = 5000 K. The curves of optimal LER versus CCT under CRI = 97 for authors and Guo are shown in Fig. 3. The results show that the highest LER value should be 357 lm/W at CCT = 3000 K among all CCT values rather than 325 lm/W reported by Guo.

Table 4. Increases of optimal LER for CRI ≥ 97, CQS ≥ 94 and R9 ≥ 94 at CCTs of 2700 K to 6500 K comparing with the optimal results reported by Guo et al [18]

CCT (K)	2700	3000	3500	4000	4500	5000	5700	6500
Increase of LER (%)	8.0	9.8	10.2	9.4	9.0	10.9	8.7	8.2

3.2 Photometric and Colorimetric Sensitivity Studies

In reality, operating junction temperatures of LED will shift during operating lifetimes. This shift will affect SPDs of three-hump LEDs, which subsequently will affect LER and CRI values among others [19], [26], [27]. Therefore, some more analyses that investigate the sensitivity of LER, CRI, CCT, and D_{uv} against spectral parameters such as peak wavelength and FWHM are warranted. Under temperature ranges of 288 to 338 K, the peak wavelengths and FWHMs of InGaN-based blue chip, YAG:Ce^{3+} based yellow/green phosphor and QDs vary for approximately 5 nm [17], [19], [28], guiding us to adopt the same variations in our numerical simulations.

In this paper, the changes of LER, CRI, CCT, peak wavelengths, and FWHMs can be defined as

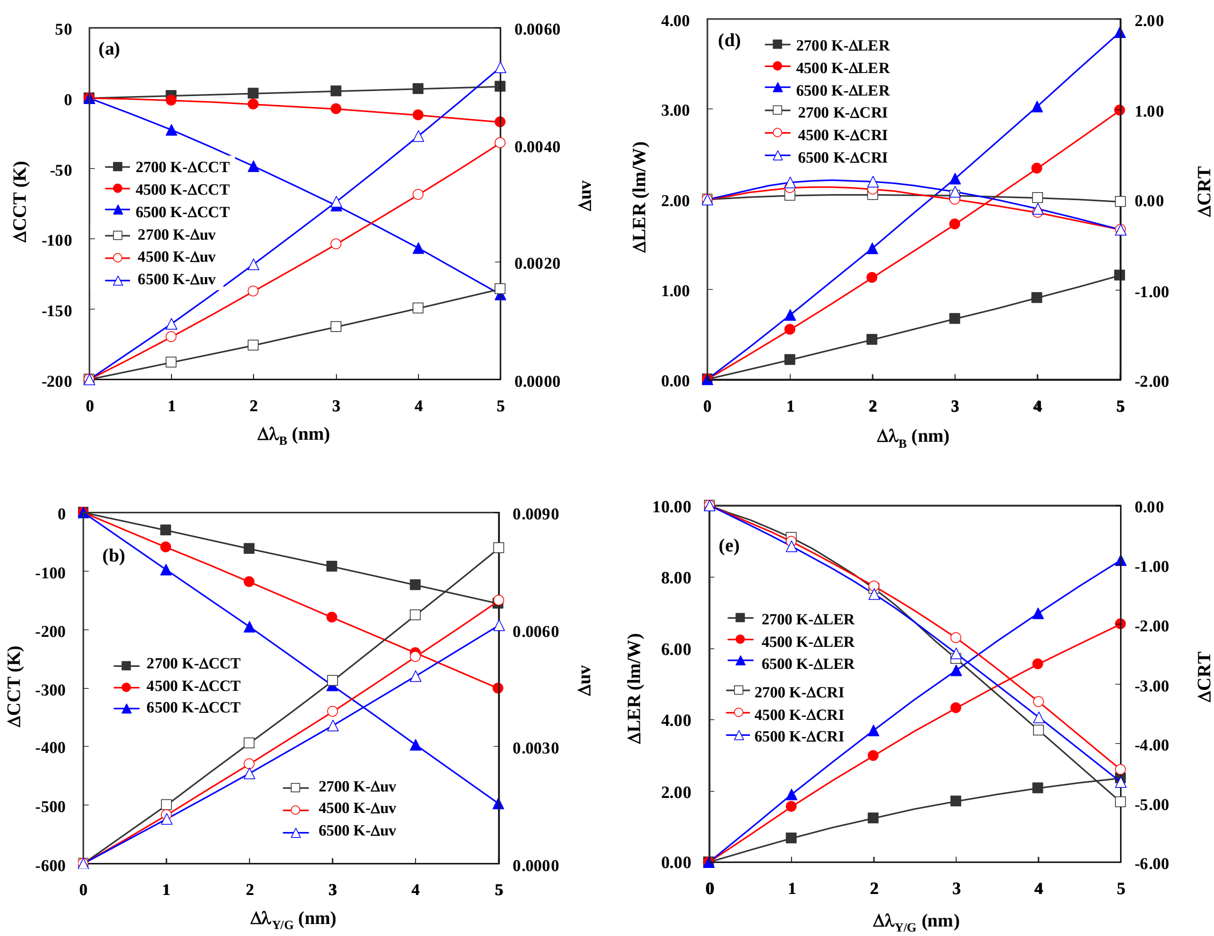
$$\Delta x = x - x_0$$

$$(x = \mathrm{CCT, LER, CRI}, \lambda_B, \lambda_{Y/G}, \lambda_R, w_B, w_{Y/G}, \text{ and } w_R) \tag{6}$$

where x_0 represents the reference (i.e., optimal) value of x. Also, the color distance between the arbitrary point (u, v) and reference point (u_0, v_0) on the 1960 UV chromaticity diagram can be given as

$$\Delta uv = \sqrt{(u - u_0)^2 + (v - v_0)^2} \tag{7}$$

In the sensitivity studies, we take the optimal SPDs of CRI = 90 under CCT = 2700 K, 4500 K, and 6500 K as our nominal cases (shown in Table 1, second, sixth, and ninth columns). In Fig. 5 (a)–(c), we plot ΔCCT and Δuv versus the peak wavelength shifts. For all wavelengths, maximum changes of CCT values take place at CCT = 6500 K, suggesting that highest instabilities may be induced due to changes of peak wavelengths for cool white LEDs. From Fig. 5 (a)–(c), both ΔCCT and Δuv induced by $\Delta\lambda_{Y/G}$ are larger than that by $\Delta\lambda_B$ or $\Delta\lambda_R$. The changes of CCT induced by $\Delta\lambda_B$ are less than 140 K for CCT = 6500 K, especially for CCT< 4500 K, the changes of CCT are less than 30 K. Under three different CCT conditions, the Δuv values induced by $\Delta\lambda_R$ are less than 0.0023, but Δuv values induced by $\Delta\lambda_{Y/G}$ is larger than 0.006. In Fig.5 (d)–(f) shows ΔLER and ΔCRI versus the peak wavelength shifts. In Fig. 5(d), as the blue wavelength shifts increases, LER value is observed to increase, however little changes of CRI are observed under three different CCT conditions. Although LER increases appear more desirable than the optimized condition identified in Table 1 (first, sixth, and ninth columns), D_{uv} values may lie beyond 0.0054. For example, under CCT = 2700 K, D_{uv} values have been found to be 0.0069. In Fig. 5(e), as $\Delta\lambda_{Y/G}$ increases, LER value is observed to increase, as we expected, CRI value is observed to decrease. In Fig. 5(f), as $\Delta\lambda_R$ increases, LER value decreases, however CRI value start to increases, reaches a maximum and then to drops down.



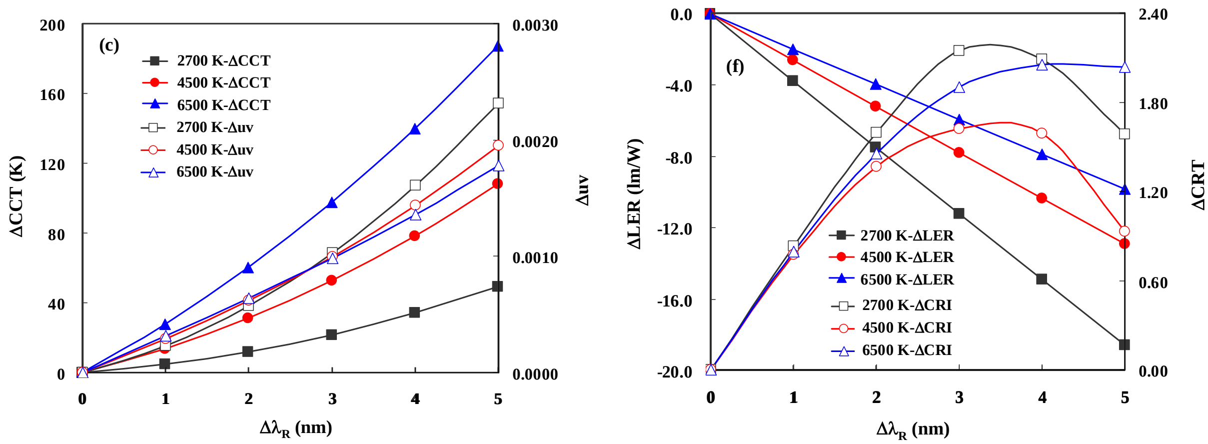
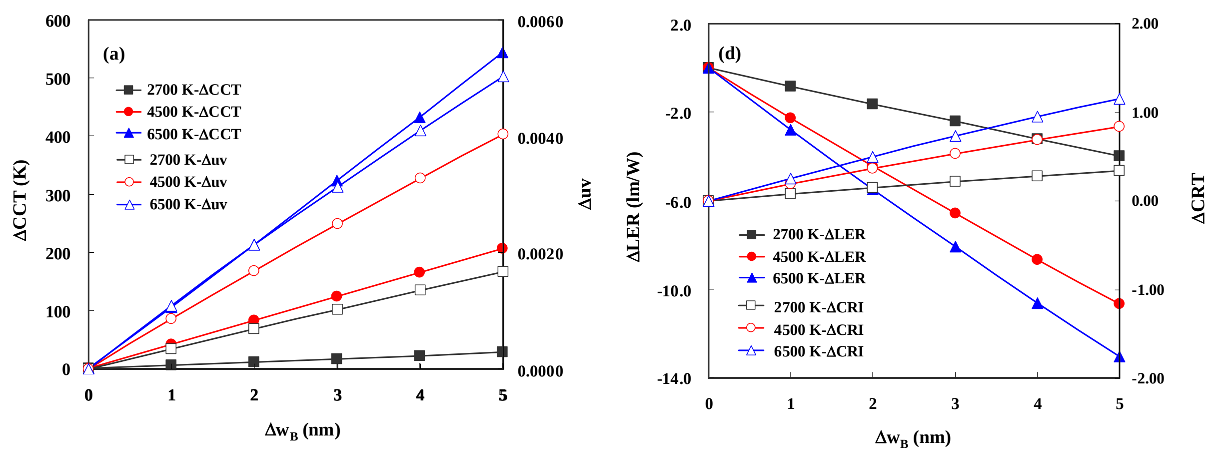


Fig. 5. ΔCCT and Δuv versus peak wavelength shift: (a) blue, (b) yellow/green, and (c) red, as well as ΔLER and ΔCRI versus peak wavelength shift: (d) blue, (e) yellow/green, and (f) red.

In Fig. 6(a)–(c), we show ΔCCT and Δuv versus the deviation of FWHMs. Similarly, largest changes of CCT values occur at CCT= 6500 K for all FWHMs. The changes of CCT induced by deviations of $w_{Y/G}$ are far less than that induced by Δw_B or Δw_R. The changes of CCT induced by $\Delta w_{Y/G}$ are less than 66 K under three different CCT conditions, indicating that we may ignore the influence of $\Delta w_{Y/G}$ on CCT. The Δuv values induced by Δw_R are far larger than that induced by Δw_B or $\Delta w_{Y/G}$. Finally, Fig. 6(d)–(f) exhibits LER and CRI behaviors versus the deviation of FWHMs. For all wavelengths, maximum changes of CRI are less than 1.2 under three different CCT conditions, indicating that we may ignore the influence of the deviation of FWHMs on CRI.



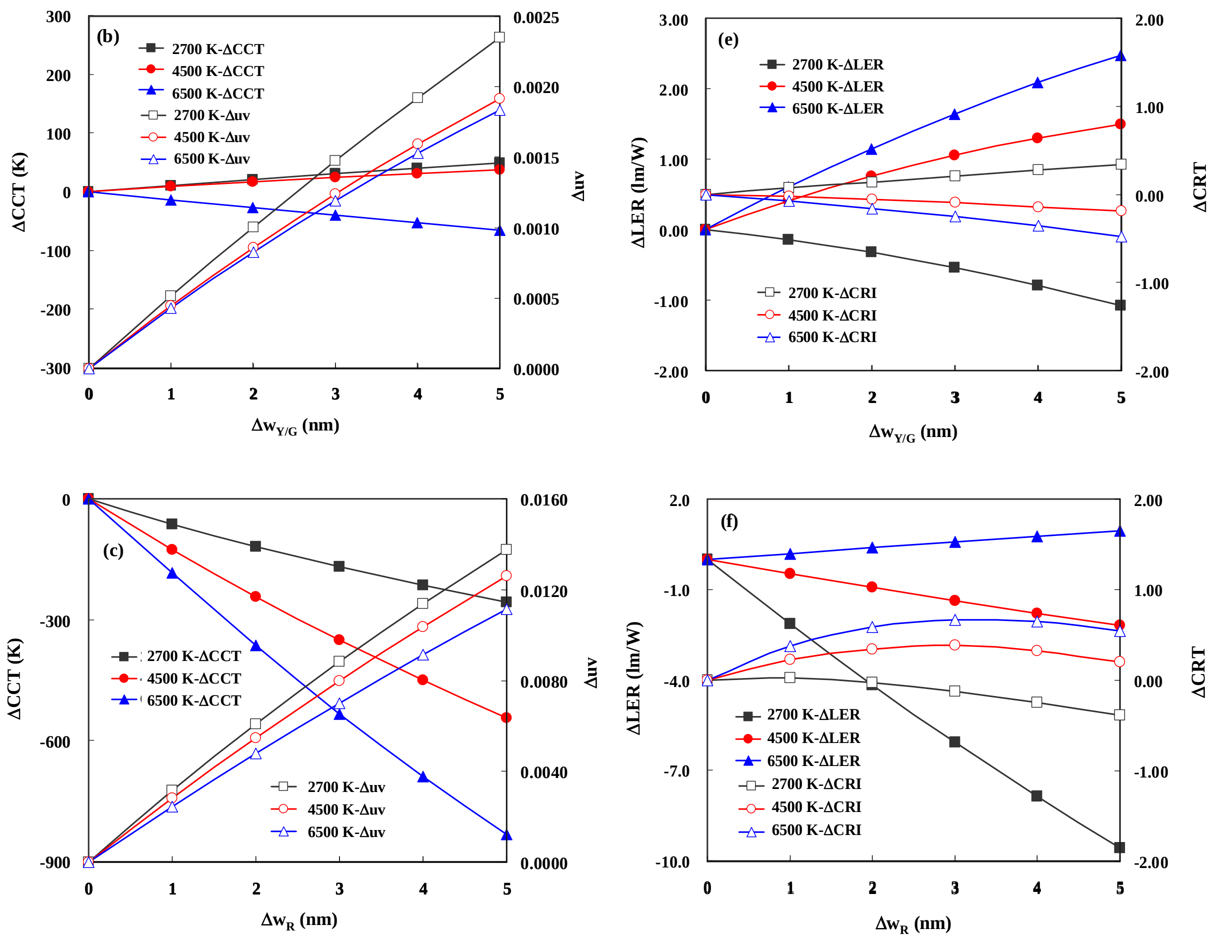


Fig. 6. ΔCCT and Δuv versus the deviation of FWHMs: (a) blue, (b) yellow/green, and (c) red, as well as ΔLER and ΔCRI versus the deviation of FWHMs: (d) blue, (e) yellow/green, and (f) red.

3.3 Further Optimization of pc-W LED with CRI ≥ 90, CQS ≥ 85, R9 ≥ 85

Unfortunately, all R9 values for CRI = 90 and CQS ≥ 80 with the optimal LER are below 14 from Table 1. The special CRI R9 is considered because the red-green contrast is very important for color rendering [29, 30], and red tends to be problematic. Lack of red component shrinks the reproducible color gamut and makes the illuminated scene look dull. In addition, the CQS values of optimal spectra for CRI = 90 with the optimal LER are about 85, and the D_{uv} values are 0.0054. Form Fig. 5(a)-(c) and Fig. 6(a)-(c), the D_{uv} values could be lager than 0.0054 due to the peak wavelength shifts and the deviations of FWHMs, which could be out of the range of the chromaticity tolerance quadrangles of white-light sources [31, 32]. So the colorimetric properties of CQS ≥ 85, R9 ≥ 85, and D_{uv} ≤ 0.0027 are considered in optimization of two-phosphor-coated white LED with CRI ≥ 90.

Table 5 shows optimal the peak wavelengths, FWHMs, peak heights, as well as photometric and colorimetric performances with CRI ≥ 90, CQS ≥ 85 and R9 ≥ 85, and D_{uv} ≤ 0.0027 at CCTs of 2700K to 6500 K. The highest LER value is 379 lm/W at CCT = 2700 K among all CCT values. The optimal SPDs are shown in Fig. 7.

Table 5. Optimal peak wavelengths, FWHMs, peak heights, photometric and colorimetric performances with CRI ≥ 90, CQS ≥ 85, R9 ≥ 85, and D_{uv} ≤ 0.0027 at CCTs of 2700 K to 6500 K

Target CCT (K)	2700	3000	3500	4000	4500	5000	5700	6500
CCT (K)	2700	3000	3500	4000	4500	5000	5700	6500
$D_{uv}\times10^{-3}$	2.7	2.5	2.7	2.0	2.7	2.7	2.7	2.7
λ_B (nm)	459	460	460	459	459	459	459	458
$\lambda_{Y/G}$ (nm)	552	552	550	548	546	545	543	542

λ_R (nm)	621	621	620	619	618	618	617	617
w_B (nm)	30	30	30	30	30	30	30	30
$w_{Y/G}$ (nm)	50	50	50	50	50	50	50	50
w_R (nm)	19	19	19	19	19	19	19	19
a	0	0	0	0	0	0	0	0
b	0	0	0	0	0	0	0	0
c	1	1	1	1	1	1	1	1
d	1	1	1	1	1	1	1	1
H_B	0.2730	0.2730	0.2730	0.2730	0.2730	0.2730	0.2730	0.2730
$H_{Y/G}$	0.3866	0.2978	0.2225	0.1784	0.1536	0.1438	0.1236	0.1106
H_R	2.2025	1.4750	0.9450	0.6828	0.5421	0.4553	0.3684	0.3062
CRI	90	90	90	90	90	90	90	90
CQS	86	85	86	85	85	85	85	85
R9	88	90	89	89	87	85	87	91
LER (lm/W)	379	378	373	365	357	353	341	329

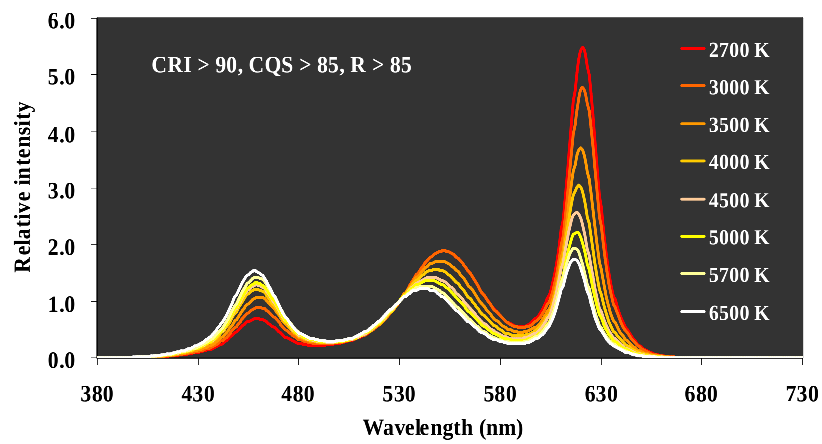


Fig. 7. Optimal SPDs with CRI ≥ 90, CQS ≥ 85 and R9 ≥ 85 at CCTs of 2700 K to 6500 K (D_{uv} ≤ 0.0027).

4. CONCLUSIONS

The optimal peak wavelength, FWHM and peak height of each hump as well as their photometric and colorimetric performance of three-hump InGaN-based white LEDs precoated with traditional yellow/green phosphors and red-emitting quantum dots (QDs) with CRI ≥ 90 and CQS ≥ 80, as well as with CRI ≥ 97, CQS ≥ 94, and R9 ≥ 94 at CCTs of 2700 K to 6500 K (D_{uv} ≤ 0.0054) are obtained with a nonlinear program for maximizing LER. The highest LER value is 402 lm/W for CRI ≥ 90 and CQS ≥ 80 at CCT = 2700 K among all CCT values, as well as 357 lm/W for CRI ≥ 97, CQS ≥ 94, and R9 ≥ 94 at CCT = 3000 K. The changes of LER, CRI, CCT, and D_{uv} have been observed to be associated with the shifts of peak wavelengths and FWHMs affected by LED operating temperatures, and higher instabilities may be induced for cool white LEDs (CCT = 6500 K) than for warm white LEDs (CCT = 2700 K) within the analysis of CCT versus spectral parameters. Furthermore, a solution of pc-W LEDs, which is consists of the InGaN blue chip (λ_B = 459 nm and w_B = 30 nm), traditional yellow/green phosphors ($\lambda_{Y/G}$ = 552 nm and $w_{Y/G}$ = 50 nm) and red-emitting QDs (λ_R = 621 nm and w_R = 19) with LER = 379 lm/W, CRI = 90, CQS = 86 and R9 = 88 at CCT = 2700 K, is recommended in order to achieve warm-white light with high optical performance.

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