IEEE Photonics Journal
An IEEE Photonics Society Publication

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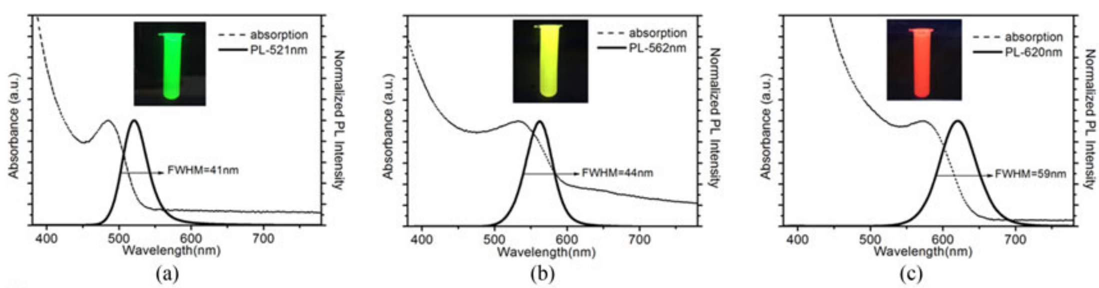
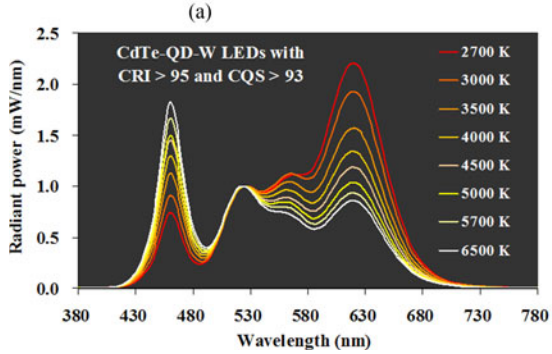
Volume 8, Number 5, October 2016

Wu Yang
Ping Zhong
Shiliang Mei
Qiuhang Chen
Wanlu Zhang
Jiatao Zhu
Ruiqian Guo
Guoxing He





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R(9-12)	82	81	82	84	86	85	87	88
R13	99	99	100	99	97	99	97	95
R15	92	93	95	97	96	96	95	92
CQS	94	93	93	93	93	93	93	93
LLE (lm/W)	267	271	272	270	267	268	263	256

DOI: 10.1109/JPHOT.2016.2615282
1943-0655

IEEE photonics SOCIETY
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Photometric Optimization of Color Temperature Tunable Quantum Dots Converted White LEDs for Excellent Color Rendition

Wu Yang,[1] Ping Zhong,[2] Shiliang Mei,[1] Qiuhang Chen,[1] Wanlu Zhang,[1] Jiatao Zhu,[1] Ruiqian Guo,[1] and Guoxing He[2]

[1]Engineering Research Center of Advanced Lighting Technology, Ministry of Education, Institute for Electric Light Sources, Fudan University, Shanghai 200433, China
[2]Department of Applied Physics, Dong Hua University, Shanghai 200051, China

DOI:10.1109/JPHOT.2016.2615282

Manuscript received September 6, 2016; revised September 30, 2016; accepted October 2, 2016. Date of publication October 7, 2016; date of current version October 20, 2016. The work was supported by the National Natural Science Foundation of China under Grant 61377046, Grant 61144010, Grant 61177021, and Grant 51575099. Corresponding authors: R. Guo and G. He (e-mail: rqguo@fudan.edu.cn; gxhe@dhu.edu.cn).

Abstract: The photometric optimization for maximizing limited luminous efficacy (LLE) of correlated color temperature (CCT) tunable quantum dots (QDs) converted white light-emitting diode (LED) (QD-WLED) with green, yellow, and red QDs excited by a blue chip was developed under the constraints of the designated color rendering index (CRI) and color quality scale (CQS). The results show that CCT tunable (2700–6500 K) QD-WLEDs with both excellent color rendition and high luminous efficacy should use three narrow emission QDs. The optimal CCT tunable QD-WLEDs with CRI $\geq$ 95 and CQS $\geq$ 93 consist of a blue chip (461.0, 25 nm) and green (519.7, 30 nm), yellow (569.2, 30 nm), and red (622.9, 30 nm) QDs, and their LLEs could reach 270–292 lm/W. Simulation demonstrates that QD-WLEDs using a blue chip (460.0, 25 nm) and the green (521, 41 nm), yellow (562 nm, 44 nm), and red (620, 59 nm) CdTe QDs could realize CCT tunable white lights with CRIs of 95–96, CQSs of 93–94, and LLEs of 256–272 lm/W, which increase by 12–21%, compared with that of optimal phosphor-coated white LEDs (pc-W LEDs). Finally, LEs of both QD-WLED and pc-W LED were estimated. The requirements of the overall efficiency of QDs film were present if the CCT tunable QD-WLEDs were competitive to the CCT tunable pc-W LEDs.

Index Terms: Light emitting diodes (LEDs), quantum dots (QDs), luminous efficacy, correlated color temperature (CCT), color rendering index (CRI).

1. Introduction

Today, the most commonly used white light-emitting diodes (LEDs) are based on the integration of traditional broadband phosphors on blue InGaN/GaN chips. Although traditional phosphor powders are able to generate a white spectrum with a high color rendering, simultaneously accomplishing a high luminous efficacy (LE) remains a challenge. As new-generation phosphor materials, semiconductor nanocrystals or colloidal quantum dots (QDs), which have tunable and relatively narrow emission across the visible spectral range and small overlap between their emission and absorption spectra in comparison with traditional phosphors, have attracted great interest due to their promising applications including white LEDs [1]–[3], display backlights [4], biomedical imaging [5], solar cells [6], and sensors [7]. Among these applications, QDs-converted white LED (QD-WLED) is the most attractive application. In order to obtain a well-designed QD-WLEDs suitable for lighting applications, criteria such as the color rendering index (CRI) [8] or the color quality scale (CQS) [9], as well as LE, have to be simultaneously considered when designing the spectrum, i.e., there are tradeoffs between CRI and LE. CRI and CQS are the most important figures of merit of white-light source for the evaluation of color rendition. Furthermore, the color quality of the white-light source is also evaluated in terms of the correlated color temperature (CCT), which illustrates the temperature of a closest Planckian black-body radiator or the daylight to the operating point on the chromaticity diagram. The elements in QDs are usually in group II-VI, such as CdTe [10]; group III-V, such as InP [11]; and group I-III-VI, such as $CuInS_2$ [12]. It is well-known that II-VI and III-V type QDs have a narrow emission spectrum, however, I-III-VI type QDs have a broad emission spectrum if the size distribution of QDs is narrowed [13]. It was reported that many QD-WLEDs using II-VI [14]–[19], III-V [11], [20]–[22], and I-III-VI [23]–[27] type QDs can attain high color quality white lights with CRI $\geq$ 90. However, they have exhibited LEs of less than 70 lm/W. Zhang *et al.* synthesized Cu-doped InP/ZnS/InP/ZnS core/shell/shell/shell QDs [28]. These QDs exhibited two-color emission: the Cu ions doped into the core of the QDs gave the red emission and the InP shell sandwiched between ZnS layers emitted green color. The QD-WLED constructed by hybridizing these QDs with a blue LED chip acquired a CRI of 91 and a CCT of 5130 K. Yuan *et al.* synthesized Mn and Cu co-doped ZnInS QDs to realize two color emissions from the dopant states [29]. The green emission in these QDs was associated with the Cu ions while Mn ions were responsible for the reddish emission. The QD-WLED prepared using these QDs reached a CRI of 95 and an LE of 73.2 lm/W at a CCT of 5092 K. Yang *et al.* reported that a triple-shell coated InP/ZnS QD-based blue/green/amber/red four-package white LED offers good color qualities (CRI = 87–91, CQS = 83–87, and R9 = 41–57), moderate luminous efficiency performance (LE = 27, 25, 26, and 22 lm/W for 6500, 5000, 3500, and 2700 K, total applied current = 80 mA) [30]. Recently, Yoon *et al.* reported that CCT tunable QD-WLEDs using an InGaN blue LED, green-emitting Zn-Ag-In-S, and red-emitting Zn-Cu-In-S QDs exhibit a moderate LE performance (LE = 26.7–39.6 lm/W) and excellent color qualities (CRI = 94–97, CQS = 93–97, and R9 = 87–98) at CCTs of 2700–6500 K [31] and CCT tunable QD-WLEDs

The optical parameters including the peak wavelength (WL), full-width-at-half-maximum (FWHM), and the relative radiant flux of each color QDs need to be carefully designed to achieve high-quality QD-WLED, which can compete with traditional phosphor-coated white LED (pc-W LED). In our previous work, optimization of QD-WLEDs was studied under the constraint of both a designated CCT and CRI for radiation luminous efficacy [32]. However, the down-conversion energy loss was not considered, and the optimal peak WLs were dependent on CCT. The challenge in the design of QD-WLEDs with a tunable CCT consists of achieving excellent colorimetric performances over a reasonable range of CCTs, while at the same time maximizing LE. The photometric optimization of CCT tunable QD-WLEDs with excellent color rendition has not been explored till date. In this work, the photometric optimization for maximizing limited luminous efficacy (LLE) of CCT tunable QD-WLED, including down-conversion energy loss, was developed under the constraint of designated color rendering properties. Unity quantum efficiency was adopted to consider the ideal case in the optimization. The down conversion energy loss (Stokes shift energy loss) was taken into account in calculating LLE in our scenario such that LLE is defined as the ratio of luminous flux to the total power consumed by the source, including the radiant flux and the Stokes shift energy loss. The CCT was tuned by changing power density ratios of light components while keeping chromaticity coordinates on the Planckian locus for CCT below 5000 K, or the daylight locus for CCT above 5000 K, that is, the chromaticity difference from the Planckian or daylight locus on the CIE 1960 uv chromaticity diagram (Duv) is equal to zero. The reason for a constraint of Duv = 0 is to avoid being out of the range of the chromaticity tolerance quadrangles of white-light sources [33], [34] due to the deviations of peak WLs and FWHMs of LEDs and QDs [32]. The optimal peak WLs and FWHMs of a blue chip, green, yellow, and red QDs, as well as photometric and colorimetric performances for maximizing LLE under CRI $\geq$ 95 and CQS $\geq$ 93 at CCTs of 2700–6500 K with Duv = 0 were presented. In our experiments, CdTe QDs, which roughly meet the requirement of the optimal peak WLs, have been prepared, and the simulation shows that CdTe-QD-WLED could achieve the expected colorimetric performances. Finally, the LEs of both QD-WLEDs and pc-WLEDs were estimated. The requirements of the overall efficiency of QDs film were present if the CCT tunable QD-WLEDs were competitive with the CCT tunable pc-W LEDs.

2. Optimization of CCT Tunable QD-WLEDs

For the QD-WLED, the chosen WLs for each color component are varied between 430 and 500 nm for blue, between 500 and 550 nm for green, between 550 and 590 nm for yellow, and between 590 and 660 nm for red in our optimization. In addition, the FWHMs are varied between 20 and 30 nm for blue [21]–[23], and between 30 and 50 nm for green, yellow and red. In optimization, a fast Pareto genetic algorithm [24] is chosen because it is able to scan a vast set of solutions, does not depend on a starting solution, is useful for complex problems, and most importantly can be easily modified to estimate the Pareto optimal set. A CCT tunable QD-WLED consists of a blue (430–500 nm) chip, green (500–550 nm), yellow (550–600 nm) and red (600–650 nm) QDs. The relative spectral power distribution (SPD) of QD-WLED, SQD-W(λ) is given by [35]

$$S_{QD-W}(\lambda) = q_B S_B(\lambda, \lambda_{0B}, \Delta\lambda_B) + \sum_{i=1}^{3} q_i S_i(\lambda, \lambda_{0i}, \Delta\lambda_i) \quad (1)$$

where S_B, q_B, λ_{0B}, and $\Delta\lambda_B$ refer to the relative SPD, proportion of the relative SPD, peak WL, FWHM, respectively, for a blue chip. The subscripts i = 1, 2, and 3 refer to green, yellow, and red QDs, respectively. S_i, q_i, λ_{0i}, and $\Delta\lambda_i$ refer to the relative SPD, proportion of the relative SPD, peak WL, and FWHM, respectively, for each QDs. For the QD-WLED, FWHM ranges are selected as 25–35 nm for the blue chip, and 30–50 nm for green, yellow and red QDs. We employ Ohon's model [36] of SPD for the blue chip. The SPD of QDs is modeled as a Gaussian function on the photon energy scale [37]. Because of three mixed constraints, 4 × 3-dimensional space will be reduced to 9-D space for a particular CCT [38].

Unity quantum efficiency is adopted to consider the ideal case in this model. Thus, the limited luminous efficacy (LLE), including down-conversion energy loss, can be calculated by [39]

$$LLE = \frac{683 \int_\lambda V(\lambda) S_{QD-W}(\lambda) d\lambda}{\int_\lambda (q_B + q_{ab}) S_B(\lambda, \lambda_{0B}, \Delta\lambda_B) d\lambda} \quad (2)$$

where $q_{ab} = \sum_{i=1}^{3} q_i \int_\lambda S_i(\lambda, \lambda_{0i}, \Delta\lambda_i)\lambda d\lambda / \int_\lambda S_B(\lambda, \lambda_{0B}, \Delta\lambda_B)\lambda d\lambda$, and V($\lambda$) is 1988 CIE photopic luminous efficiency function. In order to optimize peak WL and FWHM of the CCT tunable QD-WLED, we introduce an objective function

$$F = \sum_{j=1}^{8} LLE_j(q_B, \lambda_{0B}, \lambda_{0G}, \lambda_{0Y}, \lambda_{0R}, \Delta\lambda_B, \Delta\lambda_G, \Delta\lambda_Y, \Delta\lambda_R) \quad \text{(under conditions of CRI} \geq 95 \text{ and CQS} \geq 93) \quad (3)$$

where the subscripts j = 1, 2, 3, 4, 5, 6, 7, and 8 refer to 2700, 3000, 3500, 4000, 4500, 5000, 5700, and 6500 K of CCTs (Duv = 0). Hence, the optimization problem reduces to finding maximum of the objective functions (F). In optimization, a fast Pareto genetic algorithm [40] is chosen because it is able to scan a vast set of solutions, does not depend on a starting solution, is useful for complex problems, and, most importantly, can be easily modified to estimate the Pareto optimal set.

The optimal peak WLs and FWHMs, as well as their photometric and colorimetric performances of CCT tunable QD-WLEDs with CRI ≥ 95 and CQS ≥ 93 at CCTs of 2700 to 6500 K (Duv = 0) have been obtained by nonlinear program for maximizing F. The simulation results show that the optimal peak WLs for a blue chip, green, yellow and red QDs are 461.0, 519.7, 569.2, and 622.9 nm, respectively. The optimal FWHM of the blue chip is 25 nm, and the optimal FWHM for each QDs

TABLE 1
Simulated Photometric and Colorimetric Performances of the Optimal CCT Tunable QD-WLEDs With the Blue Chip (461.0, 25 nm) and the Green (519.7, 30 nm), Yellow (569.2, 30 nm), and Red (622.9, 30 nm) QDs for CRI ≥ 95 and CQS ≥ 93 at CCTs of 2700–6500 K (Duv = 0)

CCT (K)	2700	3000	3500	4000	4500	5000	5700	6500
CRI	96	97	96	96	96	96	96	95
R(9–12)	90	89	88	89	88	89	88	85
R13	100	97	94	96	97	96	97	99
R15	98	99	97	96	95	96	95	92
CQS	93	93	93	93	93	93	93	93
LLE (lm/W)	288	291	292	288	283	283	277	270

should be as narrow as possible (the smallest value in our simulations is 30 nm). It is pointed out that the green (519.7, 30 nm), yellow (569.2, 30 nm), and red (622.9, 30 nm) QDs excited by the blue chip (461.0, 25 nm) can achieve CCT tunable (2700–6500 K) QD-WLEDs with excellent color rendition. The photometric and colorimetric performances of the optimal CCT tunable QD-WLEDs are shown in Table 1. R(9–12) in the table is the average of the special color rendering indices R9 to R12 of the four saturated colors (red, yellow, green, and blue). The simulation results show that the optimal QD-WLEDs could realize CCT tunable white-lights with CRIs of 95–97, R(9–12)s of 85-90, CQSs of 93 and LLEs of 270–292 lm/W at CCTs of 2700 to 6500 K (Duv = 0). Furthermore, their special CRIs of R13 and R15 corresponding to the colors of the skin on the faces of European and Chinese women are also very high. Both R13 and R15 are especially important for interior lighting. At the same time, it also shows that it is not necessary to use four or more QDs [41], [42] to achieve QD-WLED with excellent photometric and colorimetric performances.

If CCT tunable QD-WLEDs consist of a blue chip, green (or yellow), and red QDs, the simulation results show that optimal FWHMs of green (or yellow) and red QDs must be increased to 70 and 81 nm, respectively. For such wide FWHM requirements of the green and red spectrum, it is not necessary for us to quantum dots instead of traditional phosphors. Moreover, their LLEs will be reduced to between 251 and 244 lm/W, that is, the LLEs of optimal CCT tunable QD-WLEDs with two QDs will be less than that of optimal CCT tunable QD-WLEDs with three QDs for CRI ≥ 95 and CQS ≥ 93. Therefore, CCT tunable QD-WLEDs with both excellent color rendition and high luminous efficacy should use a blue chip with three narrow emission QDs.

3. Experimental Details

The optimal QDs may not be commercially available, and the FWHM values of actual QDs are also difficult to match to those of the optimal QDs. In order to test whether the actual QDs can realize CCT tunable QD-WLED with CRI ≥ 95 and CQS ≥ 93, CdTe QDs with the typical FWHM of current QDs, which basically meet the requirements of WL, were prepared. Thioglycolic acid (TGA, 98%) and Rhodamine 6G (99%) were purchased from Aladdin. Sodium borohydride ($NaBH_4$, 99%), tellurium powder (200 mesh, 99.8%), cadmium chloride hemi(pentahydrate) ($CdCl_2 \cdot 2.5H_2O$, 99%), and all other solvents were purchased from Shanghai Chemical Reagents Company and used as received. All the chemicals were used without further purification. Distilled water was used throughout. NaHTe was used as the Te precursor for CdTe QDs synthesis. It was prepared on the basis of a procedure described elsewhere [43] with slight modifications. In brief, 0.1021 g (0.8 mmol) of Te powder was mixed with 0.0605 g (1.6 mmol) of $NaBH_4$ in a 25 mL three-necked flask with one connected to the vacuum line, and one neck connected to a separating funnel and another neck for sampling. The

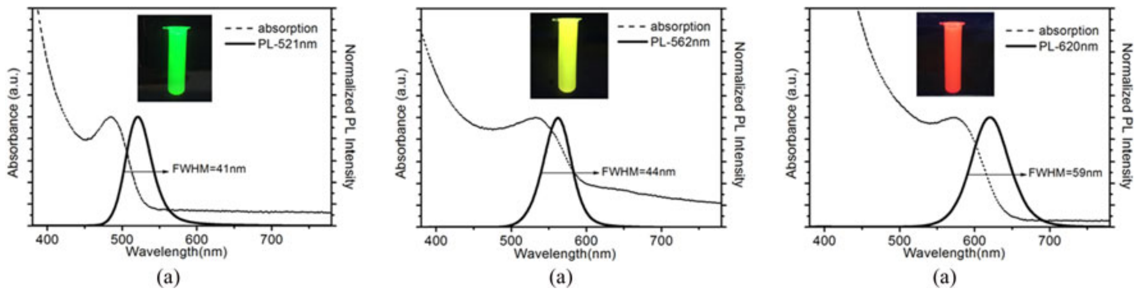

Fig. 1. Measured UV-Vis absorption and normalized PL spectra of (a) green, (b) yellow, and (c) red CdTe QDs under 460 nm excitation wavelength. (Inset) Fluorescence photographs of green, yellow, and red QDs, respectively.

molar ratio of $NaBH_4/Te$ was 2:1. The air in the system was pumped off and replaced with N_2. After the reactor was filled with N_2, 5 mL of N_2-saturated distilled water was added through a separating funnel. The reaction was operated under N_2 flow at room temperature with magnetic stirring for about 3–5 hours. The reaction was completed when the precursor solution was transformed to white sodium tetraborate precipitation and then got a clear NaHTe solution. The CdTe QDs were synthesized by using $CdCl_2 \cdot 2.5H_2O$ and NaHTe as precursors based on a method reported earlier [44], [45]. Typically, 0.4567 g (2 mmol) of $CdCl_2 \cdot 2.5H_2O$, and 0.18 mL (2.4 mmol) of TGA solution were dissolved in 150 mL of distilled water with magnetic stirring, and the pH of the solution was adjusted to 9.5 by dropwise addition of 2.0 M NaOH solution. The solution was placed in a three-necked flask and was deaerated by N_2 bubbling for 40 min. Then, freshly prepared NaHTe solution was quickly injected into the Cd precursor solution under vigorous stirring at room temperature. Then the reaction mixture was heated to 90 °C under N_2 conditions with a condenser attached. Timing started when the temperature reached 90 °C. The reaction mixture was refluxed for 6, 16, and 23 hours in order to synthesize green, yellow, and red QDs, respectively. The as-prepared CdTe QDs were precipitated with an excess of ethanol, purified repeatedly with a solvent combination of distilled water/ethanol by a centrifugation (9,000 r/min/10 min), and finally dispersed in distilled water for further UV-vis and photoluminescence (PL) spectra characterization. The strong size dependence of optical properties of CdTe QDs was monitored to reflect the mean particle size and size distribution through the temporal evolution of UV-visible and PL spectra. The absorption and PL spectra of QDs were collected at room temperature by ultraviolet spectrophotometer (Shimadzu, UV-3600) and fluorescence spectrophotometer (Shimadzu RF-5301PC), respectively. The PL quantum yield (QY) of CdTe QDs was estimated by comparing the integrated emission of a dilute QD dispersion in distilled water with that of Rhodamine 6G ethanol solution at room temperature, assuming its PLQY as 95% [46]. Fig. 1 presents typical UV-visible absorption and normalized PL spectra of green (521 nm), yellow (562 nm), and red (620 nm) CdTe QDs under 460 nm excitation wavelength, where narrow HWFMs of 41, 44, and 59 nm, as well as well distinct excitonic absorption peaks at 485, 533 and 572 nm, respectively, can be seen, indicating that three QDs possessed a good size monodispersity. Together with PL bandwidth, PLQY of water-soluble CdTe QDs reported previously is strongly dependent on emission wavelength, typically showing the high (e.g., 30–60%) and low values (e.g., 9–26%) in green, yellow, and red wavelengths specified above, respectively [47]–[50]. Meanwhile, PLQYs of our green, yellow and red CdTe QDs were measured to be 39%, 45% and 57%, respectively.

4. Results and Discussion

4.1. Simulation of CCT Tunable QD-WLED With CdTe QDs

The QD-WLEDs with a blue chip (460, 25 nm), the green (521, 41 nm), yellow (562, 44 nm), and red (620, 59 nm) CdTe QDs at CCTs of 2700–6500 K (Duv = 0) are simulated. The relative radiant flux

TABLE 2
Simulated Relative Radiant Flux (Φ_e%) of Each Color Component, Photometric, and Colorimetric Performances of CCT Tunable CdTe-QD-WLEDs With the Blue Chip (460, 25 nm), the Green (521, 41 nm), Yellow (562, 44 nm), and Red (620, 59 nm) CdTe QDs for CRI ≥ 95 and CQS ≥ 93 at CCTs of 2700–6500 K (Duv = 0)

CCT (K)	2700	3000	3500	4000	4500	5000	5700	6500
$\Phi_{e,b}$ (%)	9.25	11.84	15.96	19.62	22.88	24.71	28.19	31.44
$\Phi_{e,g}$ (%)	16.57	17.89	19.60	20.89	21.63	23.51	23.62	23.46
$\Phi_{e,y}$ (%)	15.02	15.93	16.48	16.25	15.98	15.27	15.03	14.80
$\Phi_{e,r}$ (%)	59.16	54.34%	47.97	43.24	39.52	36.52	33.16	30.30
CRI	95	95	96	96	96	96	96	95
R(9–12)	82	81	82	84	86	85	87	88
R13	99	99	100	99	97	99	97	95
R15	92	93	95	97	96	96	95	92
CQS	94	93	93	93	93	93	93	93
LLE (lm/W)	267	271	272	270	267	268	263	256

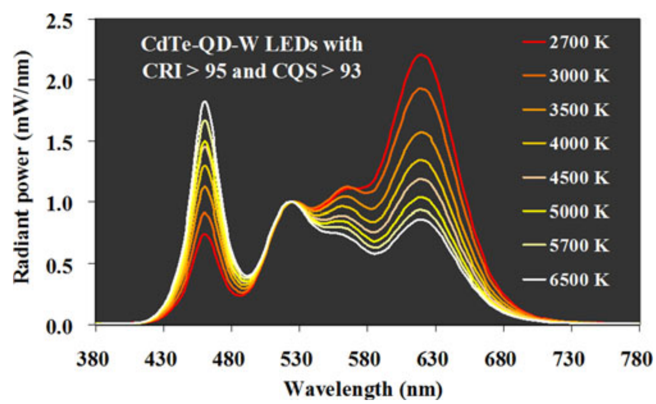

Fig. 2. Simulated optimal SPDs of the CdTe-QD-WLEDs with a blue chip (460, 25 nm), green (521, 41 nm), yellow (562, 44 nm), and red (620, 59 nm) CdTe QDs for CRI ≥ 95 and CQS ≥ 93 at CCTs of 2700–6500 K (Duv = 0).

(Φ_e%) of each color component and the photometric and colorimetric performances of QD-WLEDs with the CdTe QDs (CdTe-QD-WLED) at CCTs of 2700–6500 K (Duv = 0) are shown in Table 2. The optimal SPDs of CCT tunable CdTe -QD-WLEDs for CRI ≥ 95 and CQS ≥ 93 at CCTs of 2700–6500 K (Duv = 0) are shown in Fig. 2. The simulation results show that the CdTe-QD-WLEDs could realize CCT tunable white lights with CRIs of 95–96, R(9–12)s of 81–88 and CQSs of 93–94 at CCTs of 2700–6500 K (Duv = 0). Also, their special CRIs of R13 and R15 could reach 95–100 and 92–97, respectively. The results show QD-WLED using current II-VI and III-V type QDs with narrow FWHMs could attain excellent color quality CCT tunable white-lights with CRI ≥ 95 if the peak wavelength of each QD is selected properly.

As compared with the pc-W LED with traditional phosphors, the pc-W LEDs consisting of a blue chip, green, yellow, and red phosphors with CRI ≥ 95 and CQS ≥ 93 at CCTs of 2700–6500 K (Duv = 0) are simulated. Eleven silicate green (507–546 nm), nine silicate yellow (554–

TABLE 3
Simulated Relative Radiant Flux (Φ_e%) of Each Color Component, Photometric, and Colorimetric Performances of Optimal CCT Tunable pc-W LEDs With the Blue Chip (460, 25 nm), the EG2762 (525, 76 nm), EY4453 (565, 105 nm), and R6436 (630, 99 nm) Phosphors for CRI ≥ 95 and CQS ≥ 93 at CCTs of 2700–6500 K (Duv = 0)

CCT (K)	2700	3000	3500	4000	4500	5000	5700	6500
$\Phi_{e,b}$ (%)	7.83	10.17	13.90	17.23	20.13	22.09	25.23	28.18
$\Phi_{e,g}$ (%)	16.76	18.83	22.33	25.35	27.87	30.19	31.94	33.04
$\Phi_{e,y}$ (%)	20.16	20.90	19.49	16.75	13.55	12.53	9.57	7.24
$\Phi_{e,r}$ (%)	55.25	50.10	44.28	40.68	38.45	35.19	33.26	31.54
CRI	95	95	96	96	96	96	96	95
R(9–12)	84	84	85	87	89	88	88	86
R13	98	98	99	99	97	99	96	94
R15	93	94	96	96	94	96	93	90
CQS	94	93	93	93	93	93	93	93
LLE (lm/W)	220	227	232	233	232	235	232	229

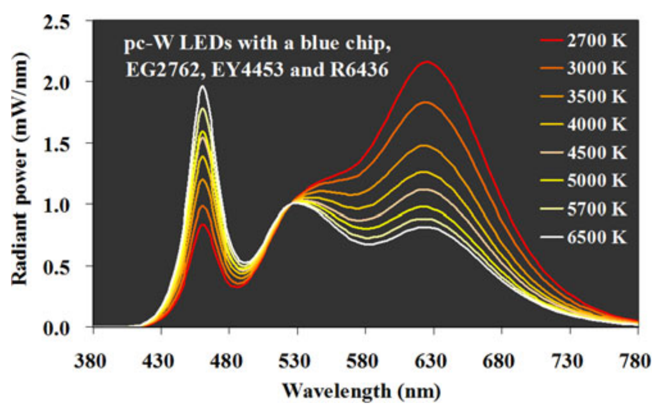

Fig. 3. Simulated optimal SPDs of the pc-W LEDs with a blue chip (460, 25 nm), EG2762 (525, 76 nm), EY4453 (565, 105 nm), and R6436 (630, 99 nm) phosphors for CRI ≥ 95 and CQS ≥ 93 at CCTs of 2700–6500 K (Duv = 0).

606 nm) phosphors, and six nitride red (630–667 nm) phosphors (Intematix Corporation) are used in optimization [51]. The optimized WLs of a blue chip, silicate green phosphors, silicate orange phosphors and nitride red phosphors are 460, 525 nm (EG2762), 565 nm (EY4453), and 630 nm (R6436), respectively. The FWHMs of the blue chip, EG2762, EY4453 and R6436 phosphors are 25, 76, 105, and 99 nm, respectively. The relative radiant flux (Φ_e%) of each color component, photometric, and colorimetric performances of the optimal CCT tunable pc-W LEDs with a blue chip, EG2762, EY4453, and R6436 phosphors for CRI ≥ 95 and CQS ≥ 93 at CCTs of 2700–6500 K (Duv = 0) are shown in Table 3. The optimal SPDs of CCT tunable pc-W LEDs for CRI ≥ 95 and CQS ≥ 93 at CCTs of 2700–6500 K (Duv = 0) are shown in Fig. 3. The results show that colorimetric performances of the optimal CCT tunable pc-W LEDs are very close to that of the CCT tunable CdTe-QD-WLEDs. However, LLEs of the optimal CCT tunable pc-W LEDs decrease

TABLE 4
Estimated LE_S (lm/W) of the Optimal pc-W LEDs, CdTe-QD-WLEDs With Typical QDs' FWHM of 40–60 nm and the Optimal QD-WLEDs With QDs' FWHM of 30 nm for CRI ≥ 95 and CQS ≥ 93 at CCTs of 2700–6500 K ($\eta_{eB} = 50\%$)

	η (%)	2700 K	3000 K	3500 K	4000 K	4500 K	5000 K	5700 K	6500 K
Optimal pc-W LED	90	100	103	106	106	106	108	107	105
	50	69	71	73	74	74	75	75	74
	60	83	85	86	87	87	88	87	86
CdTe-QD-WLED	70	96	98	99	99	99	100	99	98
	80	109	111	112	112	111	112	110	108
	90	121	123	124	124	122	123	121	119
	50	75	77	78	79	79	79	79	78
	60	89	91	93	93	92	93	92	91
Optimal QD-WLED	70	103	105	107	106	106	106	105	103
	80	117	119	120	119	118	118	117	114
	90	131	132	133	132	130	130	128	125

by 11% to 18% compared with that of CCT tunable CdTe-QD-WLEDs due to wider FWHMs of traditional phosphors adopted in pc-W LEDs.

As for tunability of CCT or the changing of power density ratios of light components, there are many approaches as follows: 1) The CCT could be tuned by adjusting concentration ratio of green, yellow, and red QD in QDs film [31], while the device itself is not tunable once its color temperature has been chosen; 2) the CCT could be tuned at real-time by altering quantum dot absorption or emission wavelengths and oscillator strengths using electric fields [52], by varying the liquid volume of each QD suspension with different photoluminescence colors [53], and by using a dynamic color filter consisting of a voltage-tunable liquid crystal (LC) cell sandwiched between two cholesteric LC films [54].

4.2. Estimate of Luminous Efficacy for QD-WLED and pc-W LED

For the real blue chip, traditional phosphors and current QDs, we chose that the radiant efficiency (η_{eB}) of a blue chip is 50%, the overall efficiency (η) of the phosphor layer consisting of multicolor phosphor blends is 90%, and η of the film consisting of multiple QDs is 50–90%. The luminous efficacy (LE) can be estimated by

$$\mathrm{LE} = \frac{683\eta_{eB}\int_\lambda V(\lambda)S_{WLED}(\lambda)d\lambda}{\int_\lambda (q_B + q_{ab})S(\lambda,\lambda_{0B},\Delta\lambda_B)d\lambda} \tag{4}$$

where $q_{ab} = q_i \sum_{i=1}^{3} \int_\lambda S(\lambda,\lambda_{0i},\Delta\lambda_i)\lambda d\lambda / \eta \int_\lambda S(\lambda,\lambda_{0B},\Delta\lambda_B)\lambda d\lambda$. The subscripts $i = 1, 2,$ and 3 refer to green, yellow, and red QDs, respectively. The LEs of the optimal pc-WLEDs, CdTe-QD-WLEDs with typical QDs' FWHM of 40–60 nm and the optimal QD-WLEDs with QDs' FWHM of 30 nm for CRI ≥ 95 and CQS ≥ 93 at CCTs of 2700–6500 K are shown in Table 4. The results show that LEs of the optimal pc-WLEDs with $\eta_{eB} = 50\%$ and $\eta_{pho\,layer} = 90\%$ for CRI ≥ 95 and CQS ≥ 93 are expected to reach 100–108 lm/W at CCTs of 2700–6500 K. If the LE of CCT tunable QD-WLEDs is higher than that of the optimal tunable pc-W LEDs for CRI ≥ 95 and CQS ≥ 93, the overall efficiencies of the QDs film for both CdTe-QD-WLED and the optimal QD-WLED have to be greater than 75%

and 70%, respectively. The results indicate the requirement of the overall efficiency of QDs film if the CCT tunable QD-WLEDs are competitive with the traditional CCT tunable pc-WLEDs. Due to the fact that the low PLQYs of our CdTe QDs and total efficiency (η) of CdTe QD film could be less than 50%, we have not been able to fabricate such QD film with η above 50%. It is exactly what we need to do as far as further research in the future.

The PLQY of the QDs and the light extraction efficiency of the QDs film are the limiting factors of the overall efficiency (η) of the film. As for the improvement of the PLQY of the QDs, there are many approaches as follows: 1) transition metal doping, which can increase the Stokes shift and reduce the self-absorbance; 2) forming core/shell structure, in which the shell provides a physical barrier between the optically active core and the surrounding medium, thus making the QDs less sensitive to surface chemistry and photo-oxidation. The shell further provides an efficient passivation for the surface trap states and increases the effective exciton recombination, giving rise to a strongly enhanced PLQY; 3) surface modification, which can prevent the QDs from aggregating and improve the monodispersity of QDs. As a result, the PLQY of the QDs can be obviously improved; 4) hybridization of inorganic QDs with organic compounds, which can make the Forster resonance energy transfer possible and thus improve the PLQY; 5) microwave-assisted method, with which the QDs with higher PLQY can be synthesized.

If the QDs with high PLQY are synthesized, the following procedure is forming a QDs film. Therefore, how to improve the light extraction efficiency of the QDs film is very critical to the final luminous efficiency. As for the improvement of the light extraction efficiency of the QDs film, there are also some approaches as follows: 1) preventing the QDs from aggregating together, which can reduce the fluorescence quenching resulted by the aggregation of QDs. The synthetic procedure of the QDs film can be optimized by controlling the concentration of the QDs, the uniformity of the QDs dispersed in the film and the thickness of the film; 2) selecting the suitable media materials for the QDs dispersion, the objective of which is to reduce the light reflectivity and improve the light extraction; 3) optimizing the surface morphology of the QDs film, the methods of which include surface roughening by wet etching, making micro/nano structures by nanoimprinting, dry etching, and self-assembly.

5. Conclusions

The CCT tunable QD-WLEDs with both excellent color rendition and high luminous efficacy should use three narrow emission QDs excited by a blue chip. The peak WLs of a blue chip, green, yellow and red QDs of optimal QD-WLEDs with CRI $\geq$ 95 and CQS $\geq$ 93 at CCTs of 2700–6500 K (Duv = 0) are 461.0, 519.7, 569.2, and 622.9 nm, respectively. The optimal FWHM of each color should be as narrow as possible. Furthermore, the green (521, 41 nm), yellow (562, 44 nm), and red (620, 59 nm) CdTe QDs, which basically meet the requirements of optimal peak WL, have been prepared, and the simulation results show that the CdTe-QD-WLEDs could realize CCT tunable white lights with CRIs of 95–96, R(9–12)s 81–88 CQSs of 93–94, and LLEs of 256–272 lm/W which increase by 12–21% compared with that of optimal CCT tunable pc-WLEDs using traditional phosphors at CCTs of 2700–6500 K (Duv = 0). Finally, LEs of optimal QD-WLEDs with $\eta_{eB} = 50\%$ and $\eta_{QDs\,film} = 50$–90%, as well as LEs of optimal pc-W LEDs with $\eta_{eB} = 50\%$ and $\eta_{pho\,layer} = 90\%$, were estimated. The results show that the overall efficiencies of the QDs film for QD-WLEDs with QDs' FWHM of 40–60 nm and the optimal QD-WLED with QDs' FWHM of 30 nm should be larger than 75% and 70%, respectively, if the LE of the CCT tunable QD-WLEDs are higher than that of the optimal CCT tunable pc-W LED for CRI $\geq$ 95 and CQS $\geq$ 93. These results provide an important basis for the design and manufacture of CCT tunable QD-WLEDs with high performances.

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