A Tunable Correlated-Color-Temperature Lighting with Two Blue LEDs and a Quantum-Dot Enhancement Film

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Abstract
We demonstrate a tunable correlated-color-temperature (CCT) scheme for quantum-dot (QD) lighting and backlight. The QDs are excited by two blue LEDs with different central wavelengths. Our experiment shows that the CCT of our device can be tuned from ~4900 K to >20,000 K. Warmer CCT suitable for general lighting can be obtained by enriching the red spectrum of the QDs. Optimizating the red and green QDs also helps to widen the color gamut in CIE1931 and to extend this approach for LCD backlight.

Author Keywords
Quantum dot devices, illumination design, color

1. Introduction
"Smart" illumination is an emerging technology to meet various application requirements [1, 2]. One of the "smart" features of this illumination is a real-time tunable spectrum showing variable correlated-color-temperature (CCT). For interior lighting, low CCT promotes relaxation while high CCT enhances working concentration. Therefore, mimicking the high CCT daylight and low CCT soft white color in indoor settings depending on different application conditions and time of day.

The most straightforward way to produce a CCT tunable white light is using tri-color LEDs (RGB) or quad-color LEDs (RGBY) as a color mixing cluster [3, 4]. By tuning the related RGB intensities independently, the mixed white light with any CCT can be achieved precisely. However, such device requires complicated and individual electronic setup, which boosts up the cost and limits its widespread applications in especially consumer electronics. Recently, LC film is proposed to realize real-time CCT tuning [5, 6]. By applying different voltages to the LC film, it shows good color rendering index (*CRI*), wide CCT tuning range (>2500 K) and small chromaticity offset [7]. The flaw of this approach is the limitation of white LED (WLED) configuration (blue LED + yellow phosphor).

Recently, colloidal quantum dots (QDs) exhibit several attractive features to generate vivid colors, such as high photoluminescence (PL) quantum efficiency, tunable emission wavelength through particle size control, and narrow emission bandwidth [8, 9].

As QDs are attractive to lighting, the photometric investigation of ultra-efficient LEDs employing QD luminophores [10] and several approaches about CCT tunable LED employing QDs have been proposed. For example, some researchers used electric field to perform real-time tuning of chromaticity of a LED by altering QD absorption or emission wavelengths [11]. The performance of this LED is good but the required electric field is quite high (>100 kV/cm) in order to get stable tuning range. QD suspension is also reported to enable a LED to achieve wide CCT tuning range effectively [12]. However, this LED requires mechanical setup to pump the RG QDs or RGY QDs.

In this paper, we demonstrate a real-time CCT tunable QD lighting scheme. The QDs are excited by two blue LEDs. One of the blue LEDs excites the RG QDs to generate a warmer white light spectrum, while the other generates a cooler one. By adjusting the relative brightness of each blue LED, the CCT of the mixed white point can be tuned from 4,500 K to over 20,000 K along the blackbody locus as well as maintaining a wide color gamut. This smart lighting device is promising for environmental lighting or LCD backlight to adapt the human reading and watching habit in an easy way.

2. Experiment
The ideal structure to realize the CCT-tunable QD lighting scheme is QD-based WLEDs, as shown in Fig. 1. Two blue LEDs B1 and B2 are respectively encapsulated in LED packages with red (R) and green (G) QDs as phosphor. The QDs emit saturated red and green light under the excitation of blue LEDs. As B2 provides a different central wavelength from B1, the excitation rate to R and G QDs of B2 is different from B1, leading to another white light spectrum with different CCT. Thus, it offers an additional parameter to tune the CCT of the mixed white light by adjusting the relative intensity of B1 and B2. To prove concept, in experiment we used a beam splitter (BS), two blue LEDs and two QDEFs, as shown in Fig. 2.

In our experiment, a QDEF taken from Amazon Kindle Fire was used as the color-conversion film. To measure the emission spectrum, we used a blue LED B1 to pump the QDEF and then recorded the emission profiles by a fiber spectrometer (USB 2000+, Ocean Optics). Figure 2(a) shows the central wavelengths and full-width-half-maximum (FWHM) of each peak. Results are R [610 nm, 34 nm], G [542 nm, 32 nm] and B1 [446 nm, 17 nm]. The transmission spectra of color filters (CFs) in commercial LCD TVs are also included in Fig. 2 (a) for comparison.

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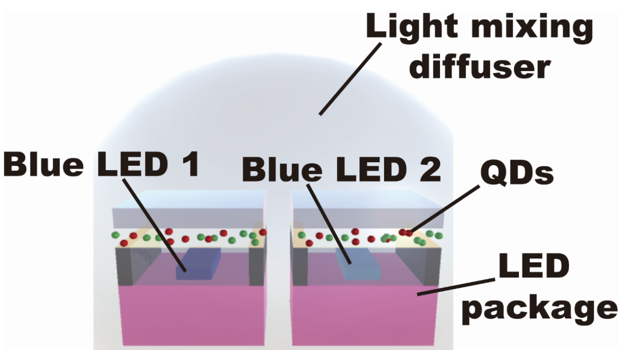

Fig. 1. The proposed CCT-tunable QD lighting scheme.

To tune the CCT, we used another blue LED B2 with a longer wavelength (466 nm) to excite another white light. Here this scheme the concentration of R and G QDs in QDEF for B2 should be different from that of B1 to widen the tuning range.

Figure 2 (b) and (c) depict the experimental setup. The concentration of R and G QDs in each QDEF is different (we can increase the concentration of QDs by stacking QDEFs) so that the CCT of one excited white light apparently differs from another. Two blue LEDs excite the two QD sheets to generate warm and cold white light. The white light is mixed in the BS and sent to the detector. The diffuser on the BS helps to enhance output uniformity.

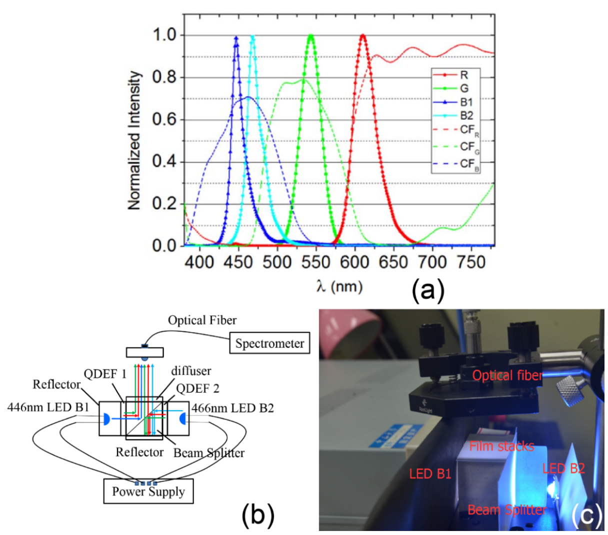

Fig. 2. (a) Emission spectrum of R, G QDs and exciting blue LEDs; (b) Schematic drawing of experimental setup and (c) experimental setup.

3. Results

To determine the tunable range of our experimental setup, we considered two extreme cases: only turning on the blue LED B1 and only turning on the blue LED B2. We first recorded the white light spectrum excited by LED B1 alone. The measured CCT in this case is 4909 K with a color coordinate of W_1 (X_{W1} = 0.195, Y_{W1} = 0.207, Z_{W1} = 0.156). Next, we repeated the same operation by only turning on LED B2. The measured CCT is over 20,000 K and the color coordinate is W_2 (X_{W2} = 0.199, Y_{W2} = 0.207, Z_{W2} = 0.442). The total white light spectrum of these two cases are illustrated in Fig. 3. We set W_1 as the warm extreme and W_2 as the cold extreme.

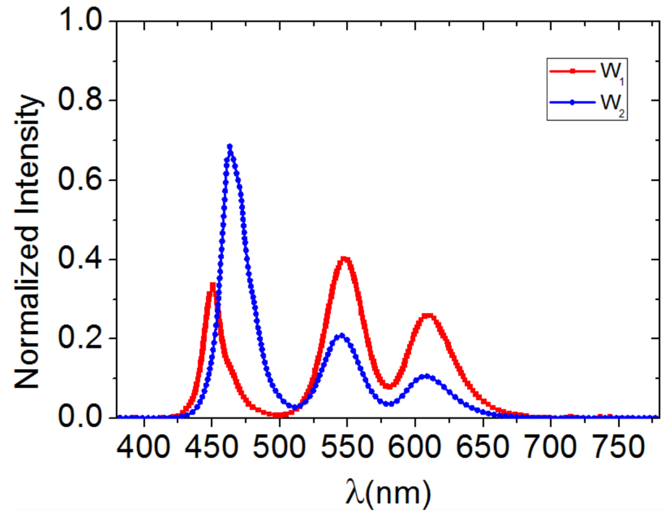

Fig. 3. Recorded white light spectra excited by LED B1 (W_1) and by LED B2 (W_2).

The CCT of the mixture of white point can be determined within the range from 4900 K to over 20,000 K by mixing W_1 and W_2. The tristimulus values of the mixed white point are matched by:

$$W_{mix}\left(aX_{W_1}+bX_{W_2}, aY_{W_1}+bY_{W_2}, aZ_{W_1}+bZ_{W_2}\right)=aW_1+bW_2, \quad (1)$$

where a and b denote the proportion of W_1 and W_2 in the mixed white light respectively; they satisfy the following relation a+b=1.

Table 1. CCT variation of the proposed CCT tunable backlight

(u,v)	CCT (K)	Applied voltage (V)/ Current (A) for W_1	Applied voltage (V)/ Current (A) for W_2
(0.2066, 0.3297)	4909	2.93/ 0.11	0/ 0
(0.2023, 0.3222)	5507	2.91/ 0.10	2.49/ 0.01
(0.1970, 0.3129)	6493	2.89/ 0.08	2.53/ 0.03
(0.1917, 0.3030)	8016	2.85/ 0.07	2.57/ 0.05
(0.1857, 0.2917)	11,014	2,80/ 0.05	2.60/ 0.07
(0.1789, 0.2789)	20,015	2.73/ 0.03	2.63/ 0.09
(0.1835, 0.2926)	>20,000	0/ 0	2.67/ 0.13

The relative intensity of LED B1 and LED B2 can be controlled by the applied voltage and current. The measured data are listed in Table 1 and the experimental results of the mixed white light are illustrated in Fig. 4. To visualize the relationship between CCT and chromaticity coordinates, the CIE1960 chromaticity diagram is introduced in our analysis because the blackbody locus in CIE1960 is normal to lines of equal CCT (shown in Fig. 5). The CCT variation track follows a straight segment from ~4900 K to >20,000 K along the blackbody locus, which accords to our analysis above. Moreover, the CCT can be tuned precisely: for example, D65 is an important standard illuminant for noon daylight and television backlight. The output white light in our experiment can be tuned to match D65 closely. Besides, the tunable range also covers D50 and D55, the deviations of the variation track from these two standard illuminants are fairly small.

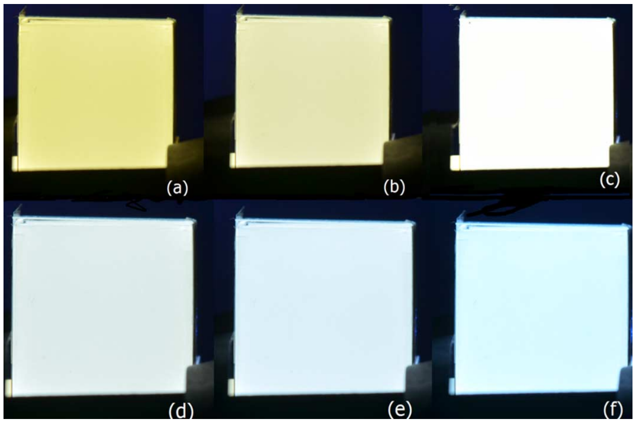

Fig. 4. Experimental results of the output white light with color temperature of: (a) 4909 K, (b) 5507 K, (c) 6493 K, (d) 8016 K, (e) 11,014 K, and (f) 29,715 K.

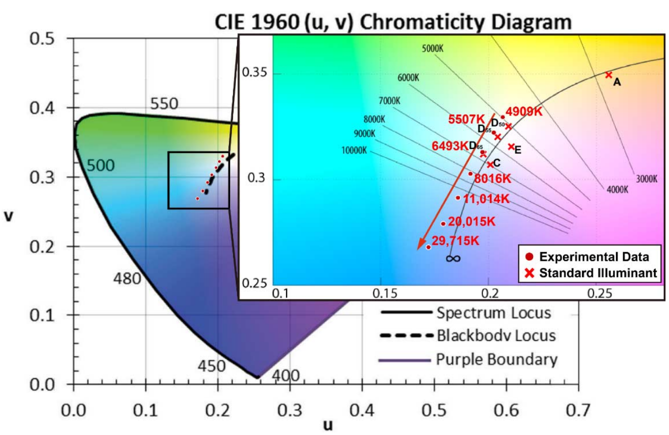

Fig. 5. CIE1960 chromaticity diagram of the tunable CCT by adjusting the proportion of W_1 and W_2 in the mixed white light.

4. Discussion

One of the applications of a CCT tunable device is general lighting. Considering this specific application, other parameters should also be included in addition to CCT, such as color rendering index (*CRI*), luminous efficacy of radiation (*LER*) and chromaticity coordinate deviation (*Duv*) in CIE1960. The *CRI* is defined by:

$$R_a = 100 - 4.6\Delta\overline{E}_{UVW} \tag{2}$$

where $\Delta\bar{E}_{UVW}$ is the mean color difference of the first eight color samples of 14 selected Munsell samples when illuminated by a reference illuminant versus by the tested source. Generally the reference illuminant is a blackbody when CCT < 5000 K while standard illuminant D is used in higher CCT cases. The *LER* is defined by:

$$LER = K_0 \frac{\int S_{out}(\lambda)V(\lambda)\,\mathrm{d}\lambda}{\int S_{out}(\lambda)\,\mathrm{d}\lambda} \tag{3}$$

where $S_{out}(\lambda)$ is the spectra power density of the output white light, $V(\lambda)$ is the standard luminosity function and K_0= 683 lm/W. The integral is operated within the visible light range. Finally, *Duv* is simply defined by:

$$Duv = \sqrt{\left(u-u_t\right)^2 + \left(v-v_t\right)^2} \tag{4}$$

where (u, v) is the chromaticity coordinate of the tested source and (u_t, v_t) is the chromaticity coordinate of the blackbody locus.

Table 2. Color performance of the proposed CCT tunable backlight

(u, v)	CCT (K)	*LER* (lm/W)	*CRI*	*Duv*
(0.2066, 0.3297)	4909	391.1	65.7	0.0072
(0.2023, 0.3222)	5507	356.1	71.4	0.0048
(0.1970, 0.3129)	6493	333.8	77.1	0.0037
(0.1917, 0.3030)	8016	311.9	80.2	0.0033
(0.1857, 0.2917)	11,014	288.6	81.1	0.0039
(0.1789, 0.2789)	20,015	263.2	78.1	0.0065
(0.1835, 0.2926)	>20,000	259.9	73.8	0.0104

Table 2 summarizes the calculated results. It shows both high CCT tuning precision and high *LER* in our experimental configuration. The *LER* in the range under 8000 K achieves higher than 300 lm/W; besides, the measured *CRI* is over 70 except the value at 4909 K (*CRI*=65.7). This result is comparable to the *CRI* of conventional GaN-based white LEDs (*CRI*=70~85). Finally, the chromaticity coordinates deviation (*Duv*) should be considered. As mentioned in Sec. 3, the *Duv* at the two extremes of the variation track is too large, making the light not "white". In the range from 5500 K to 11,000 K, |*Duv*| < 0.005 and is suitable for practical applications.

However, a meaningfully warmer tuning range is much important for general lighting applications. The main issue in our experiment is that the red QDs are orange-red since the commercial QDEFs we used are designed to reach sRGB standard for display; the concentration of red QDs is not high enough. By increasing the concentration of red QDs, all the parameters can be further optimized; the tunable range can also be extended to warmer region. For lighting purpose, setting the warm extreme W_1 near the standard illuminant A and the cold extreme W_2 near D_{75}, we can simulate the CCT variation track of the tunable device as shown in Fig. 6. The optimized parameters at particular coordinates are listed in Table 3.

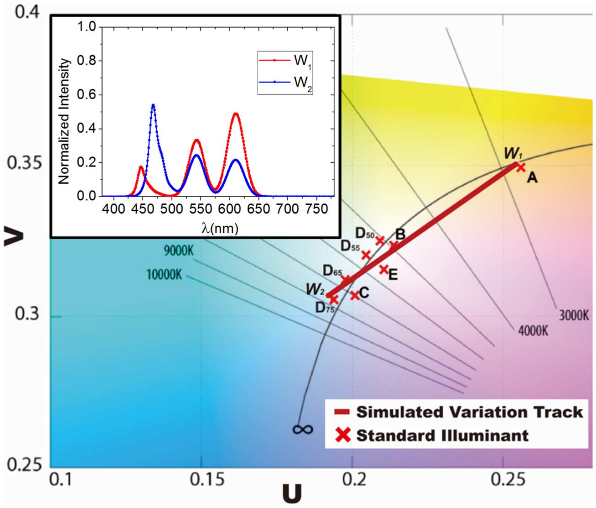

Fig. 6. Simulated CCT variation track in CIE 1960 by using red QDs with central wavelength of 626 nm. (Embedded: new W_1 and W_2)

Table 3. Selected color points on simulated variation track in Fig. 6

(u, v)	CCT (K)	*LER* (lm/W)	*CRI*	*Duv*
(0.2542, 0.3506)	2856	405.7	82.4	0.0015
(0.2279, 0.3321)	3953	365.1	88.1	0.0033
(0.2153, 0.3232)	4808	344.6	85.7	0.0031
(0.1992, 0.3119)	6502	320.4	82.4	0.0005
(0.1922, 0.3070)	7509	305.0	80.1	0.0049

After optimization, the CCT tunable range can be tuned to a warmer side along the blackbody locus. In this case, $|Duv| < 0.005$ is satisfied for all cases on the variation track. This result shows that higher concentration of red QDs helps to realize purer white light for real applications. Besides, the *CRI* can be increased to reach a value over 80, showing good color performance as conventional WLED for general lighting.

5. Summary

We have proposed a tunable correlated-color-temperature (CCT) scheme for quantum-dot technologies, which has the potential to be applied in general lighting. The red and green QDs are excited by two blue LEDs with different central wavelengths. Our experimental results show that the CCT can be tuned from ~4900 K to >20,000 K along the blackbody locus by simply adjusting the brightness of each LED. Our analysis verifies that optimizing the concentration of red QDs helps to mimic a better "white" light with warm CCT (~2800 K to ~7500 K) and smaller chromaticity coordinate deviation (*Duv*), which is preferred for general lighting. Our results show that this simple scheme for CCT tunable QD component diversifies the applications of smart lighting in different circumstances.

6. References

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