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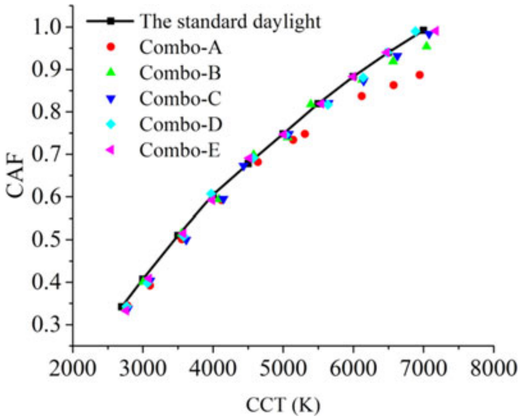

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Spectral Optimization of Three-Primary LEDs by Considering the Circadian Action Factor

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Abstract: For humans, nonvisual biological effects, which can be parameterized by the circadian action factor (CAF), are important for their health and work performance. In this paper, an approach by adjusting electrical currents of three-primary light-emitting diodes (RGB-LEDs) to tune the CAF and color coordinates to be close to those of the standard light with various correlated color temperature (CCT) (2700 K–6500 K) has been reported. This approach is based on deriving an empirical formula between the optical power and the electrical current. In order to meet the requirement of both high color rendering index (CRI) and better CAF, we theoretically perform further spectral optimization on RGB-LEDs and have found that peak wavelengths of 466, 547, and 615 nm for the blue, green, and red color component, respectively, turn out to be the best peak wavelength combination for obtaining both high CRI and high luminous efficacy of radiation of RGB-LEDs, while the CAF, CCT, and color coordinates of RGB-LEDs approach those of the standard light.

Index Terms: Light-emitting diode (LED), circadian action factor (CAF), color-rendering index (CRI), standard light.

1. Introduction

The light-emitting diode (LED), as a semiconductor device, is generally called the fourth-generation light source or “green light source” [1]. It is better than traditional light sources in many aspects, such as luminous efficacy (LE), lifespan, color-tunable property, and robustness, among others [2]. The rapid progress in LED development has been attributed to the significant improvement in device efficiency [3]–[4]. In addition to LED, the improvement of internal quantum efficiency (IQE) has played a key role in LED development. Specifically, the IQE of the InGaN LED has been improved by using large overlap quantum well concepts or new active material concepts [5]–[7]. However, a certain gap remains between the artificial LED light and the standard light in terms of their photometric and chromatic properties [8]–[9], especially the color rendering index (CRI) due to narrow spectral bandwidths of LEDs.

The optical information is essential for physiological systems of humans, because it not only provides the visual information but also affects their physical, physiological, and psychological behaviors [10], in which researchers call the latter "non-visual biological effects of light" [11]. Berson has previously discovered the third type of photoreceptors (denoted as intrinsic photosensitive retinal ganglion cells (ipRGCs)) in the retina of mammals in 2002 [12]. Researchers have also discovered that ipRGCs are sensitive to the blue-rich white light and are insensitive to the red-rich white light [13]–[14]. While the light enters human eyes, ipRGCs receive it, and non-visual biological effects are produced at the same time. This effect plays an important role in the formation and the release of the melatonin, cortisol, and other hormones, and finally affects the health and work performance of humans and other mammals. Such an effect may be desired during the day, but may need to be avoided during the night, to prevent the undesirable influence on the humans' circadian rhythm. To well characterize non-visual biological effects of the white light source in convenience, Berman has combined melatonin suppression spectra with the spectral luminous sensitivity function, and has proposed an impact factor, namely the circadian action factor (CAF) [15]. Generally, higher CAF values indicate that more light energy concentrates on the blue spectral region, which is associated with the melatonin suppression. In workplaces, the white light with high CAF values can enhance workers' level of vigilance and excitation, while in bedrooms the white light with low CAF values are required to help people relax [16]. Bellia *et al.* have combined different spectral power distributions (SPDs) within the visible light range (380 nm-780 nm) to obtain CAF values [17]. There exist studies on non-visual biological effects for different white light sources [18]–[19], including trichromatic white LEDs which consist of red, green, and blue LEDs and are generally called as RGB-LEDs. By adjusting each chip in RGB-LEDs independently, these LEDs are capable of producing high LE and CRI, with various correlated color temperatures (CCTs) and color coordinates (color-tunable properties), as well as with various CAFs.

In the evolution of lives on earth, the sun and its spectrum, and the alternation of day and night play an important role in the adaptation of human to the natural environment. As receptors of light, human eyes are deeply influenced by standard light, to which the structure and function of human eyes are developed more accustomed during the long-term daily work. Therefore, artificial light sources as LEDs are desired to exhibit comparable properties of the standard light, such as CCT and CAF. Previous relevant studies have been performed only by considering several well-known photometric and chromatic parameters, such as CCT, color coordinates, CRI, luminous efficacy of radiation (LER), and LE but have lacked considering the CAF [20]–[23]. In this work, we propose an approach by adjusting electrical currents of RGB-LEDs to provide an artificial LED light similar to the standard light. Thereafter, optimization studies have been carried out for achieving the combination of RGB-LEDs with both the good CRI and high LER.

2. Theory

In this study, we adopt the spectral circadian efficiency function (C(λ)) proposed by Gall [24] and the spectral luminous efficiency function (V(λ)), as shown in Fig. 1.

The luminous flux (Φ_v) can be defined as

$$\Phi_v = K_m \int_{380}^{780} P(\lambda)V(\lambda)d\lambda \tag{1}$$

where K_m= 683 lm/W denotes maximum spectral luminous efficiency at 555 nm, and $P(\lambda)$ denotes the SPD of light source. Similar to the definition of the luminous flux, the flux that demonstrates circadian effects (denoted as circadian flux) can be written as [24]

$$\Phi_c = K_c \int_{380}^{780} P(\lambda)C(\lambda)d\lambda. \tag{2}$$

Therefore, the circadian action factor that denotes the ratio of the circadian flux to the luminous flux can be expressed as [24]

$$\text{CAF} = \frac{K_c \int_{380}^{780} P(\lambda)C(\lambda)d\lambda}{K_m \int_{380}^{780} P(\lambda)V(\lambda)d\lambda} \tag{3}$$

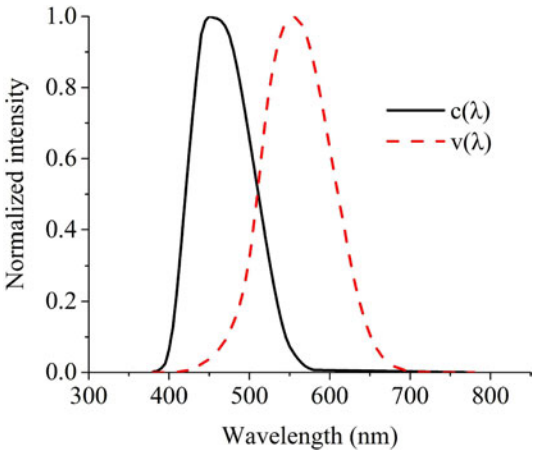

Fig. 1. Spectral luminous efficiency function (V(λ)) and the spectral circadian efficiency function (C(λ)).

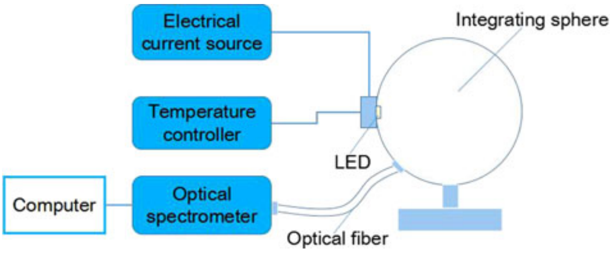

Fig. 2. Schematic measurement system for RGB-LEDs.

For simplicity, we suggest that $K_c = K_m$ in this study.

3. Experiments and Discussions

3.1. Experimental Setup

The schematic measurement system for RGB-LEDs is shown in Fig. 2. The RGB-LEDs is controlled by a temperature-controller (Keithley-2510, Keithley Inc.) and driven by three electrical current sources (Keithley-2400, Keithley-2611, Keithley Inc; GS-610, Yokogawa Inc.). Each LED chip is driven by one electrical current source. The emitting light is collected by a 500 mm integrating sphere, and transferred to an optical spectrometer (Spectro-320e, Instrument Systems Inc.) via optical fiber.

3.2. Experimental Samples

During the experiment, we adopt a family of commercial RGB-LEDs. Each primary LED has 1×1 mm^2 size and can be electrically adjusted independently with maximum current up to 350 mA. Average values of parts of electrical and optical parameters are listed in Table 1.

3.3. Procedure

In this part, we obtain required electrical currents of three primary chips of blue, green, and red (I_R, I_G, and I_B) to experimentally achieve the goal of matching the CAF, CCT, and color coordinates of the artificial light closely to those of the standard light (referring to the CRI 1995 test method, for low color temperature (CCT $<$ 5000 K), we adopt the Planckian radiator as the standard light, and for

TABLE 1
Spectral Parameters of Three-Primary LED Chips

Chip	Peak Wavelength (nm)	FWHM (nm)	Luminous Flux (lm)	Optical Power (W)	I(mA)	V(V)
Red	628.0	15.7	32.7	0.146	350	2.625
Green	515.0	33.2	41.6	0.095	350	3.444
Blue	455.0	23.8	11.1	0.251	350	3.945

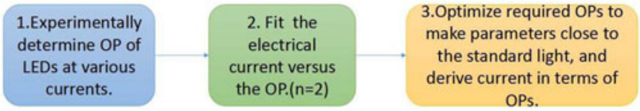

Fig. 3. Procedure of the experiment.

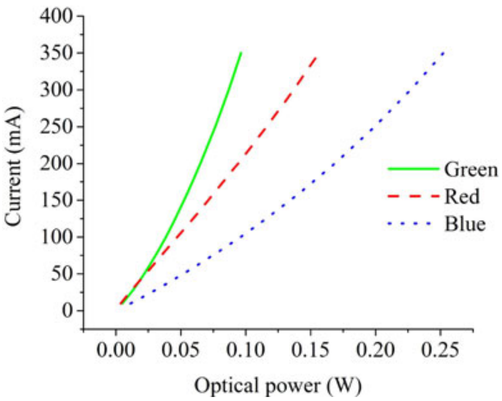

Fig. 4. Electrical current versus optical power of three-primary LED chips.

high color temperature (CCT ≥ 5000 K), we use the standard D65 as the standard light). However, the first task is regarded as finding the required optical power (OP) ratios of blue, green, and red LEDs (to achieve this goal) via simulations and optimizations. Second, we derive the empirical formula of optical powers versus currents. Finally, we calculated the electrical currents via these formula. The detail procedure is presented below and shown in Fig. 3.

Step I: Measure optical powers of blue, green, and red LED chips driven at different electrical currents (10 mA-350 mA) at the 300 K heat-sink temperature. Plot the optical power versus the electrical current (as shown in Fig. 4), from which nonlinear trends for blue, green, and red LEDs can be observed.

Step II: Polynomially fit (n = 2) the electrical current versus the optical power of three-primary LEDs.

$$I_R = 2342.31 \times P_R^2 + 2007.47 \times P_R + 4.21 \ (\mathrm{R}^2 = 0.9999)$$

$$I_G = 17922.52 \times P_G^2 + 2006.04 \times P_G - 0.83 \ (\mathrm{R}^2 = 0.9999)$$

and

$$I_B = 2319.36 \times P_B^2 + 796.41 \times P_B + 1.88 \ (\mathrm{R}^2 = 0.9999). \tag{4}$$

TABLE 2

CAF, CCT, I_R, I_G, I_B, δ of the Standard Light and RGB-LEDs With CCT of 3000 K to 7000 K. $\mathrm{CCT_a}$ is the CCT of the Standard Light; $\mathrm{CCT_b}$ is the CCT of RGB-LEDs

$\mathrm{CCT_a}$ (K)	$\mathrm{CAF_0}$	$\mathrm{CCT_b}$ (K)	$\mathrm{CAF_1}$	δ	CRI	$\mathrm{I_R}$ (mA)	$\mathrm{I_G}$ (mA)	$\mathrm{I_B}$ (mA)
3000	0.417	3169	0.519	25%	35	307	350	16
4000	0.605	4161	0.714	18%	40	240	350	29
4500	0.691	4640	0.786	14%	44	222	350	35
5000	0.748	5120	0.854	14%	45	209	350	40
5500	0.819	5601	0.913	11%	47	198	350	45
6000	0.883	6080	0.972	10%	48	191	350	51
6500	0.940	6561	1.022	9%	50	185	350	55
7000	0.992	7049	1.068	8%	51	179	350	59

Step III: For an expected CCT, parameters of P_R, P_G, and P_B of RGB-LEDs can be determined by carrying out spectral optimizations [25]. Then, through aforementioned equations, required currents of I_R, I_G, and I_B can be derived. Finally, we measure spectra of RGB-LEDs under different combinations of I_R, I_G, and I_B, and calculate their CAFs. The comparison between the CAF of RGB-LEDs (CAF_1) and the CAF of the standard light (CAF_0) with series of CCTs is listed in Table 2, with the deviation (δ) between these two CAFs defined by

$$\delta = \frac{|CAF_1 - CAF_0|}{CAF_0} \times 100\%. \tag{5}$$

As shown in Fig. 5(a), color coordinates of RGB-LEDs with the CCT from 3000 K to 7000 K are closely located on the Planckian locus and lie within the white region. However, CAFs deviate approximately 14% averagely (Max. 25% at 3000 K) from those of the standard light (see Table 2). Besides, CRIs of RGB-LEDs (CRI < 60) are insufficiently high for the high-quality lighting. The reason lies in the spectral deficiency in the visible range of 550 nm-600 nm, as shown in Fig. 5(b). Therefore, considering better CAF and CRI for high-quality and healthy lighting, we need to further seek more appropriate combinations of RGB-LEDs.

4. Further Optimization

The spectral optimization is performed by adjusting peak wavelengths and optical power ratios of RGB-LEDs, with Gaussian spectral shapes, constant FWHMs, and CCT from 2700 K to 7000 K. Then, we choose five sets of optimal combinations with both high CRIs and LERs, and the CAF which resemble the standard lights with various CCTs. The peak wavelengths and FWHMs of LED are illustrated in Table 3 (Combo-A, Combo-B, Combo-C, Combo-D, and Combo-E).

In Fig. 6(a), the CAF versus CCT has been plotted. As the CCT increases, the CAF increases, too. Among five LEDs, the CAF of Combo-A deviates from the CAF of the standard light, while CAFs of other Combos are not. Fig. 6(b) shows the CIE color coordinates of these five sets of LEDs. It can be observed that only the color coordinates of Combo-A stands off the Planckian locus. Then, we discuss the CRI and LER of five LEDs. As shown in Fig. 6(c) and (d), Combo-C (peak wavelengths with 466 nm, 547 nm, and 615 nm for the blue, green, and red color component) shows both highest CRI and LER within 2700 K-6500 K among five LEDs. Therefore, we only focus on the analysis of the best RGB-LEDs (Combo-C) below. The comparison between the Combo-C and the standard light is shown in Table 4, where the Duv is the color distance in the CIE 1960 UCS color space.

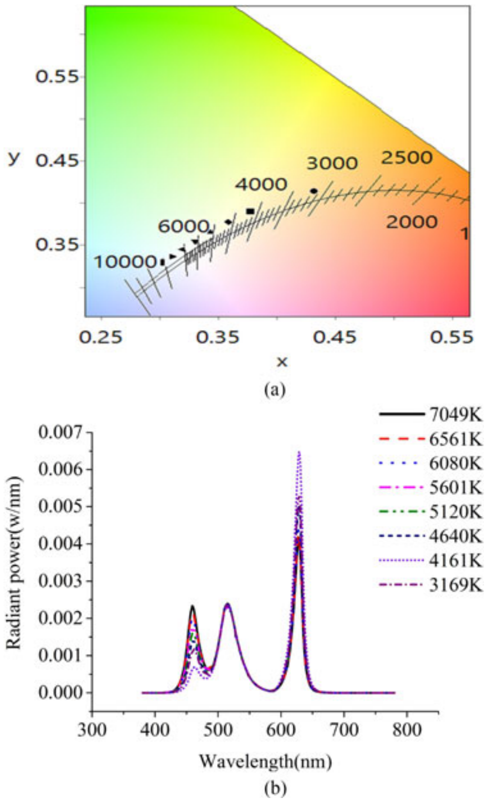

Fig. 5. (a) Color coordinates and (b) spectra of RGB-LEDs within the CCT range of 3000 K-7000 K.

TABLE 3

Peak Wavelength and FWHM of Five RGB-LEDs

Combo	Wavelength (nm)			FWHM (nm)		
	B	G	R	B	G	R
Combo-A	450.0	547.0	620.0	28.0	33.0	20.0
Combo-B	466.0	547.0	620.0	28.0	33.0	20.0
Combo-C	466.0	547.0	615.0	28.0	33.0	20.0
Combo-D	470.0	547.0	615.0	28.0	33.0	20.0
Combo-E	470.0	547.0	620.0	28.0	33.0	20.0

CAFs of Combo-C are all close to those of the standard light at all CCTs with Duv small than 0.01. Besides, all CRIs of Combo-C exceed 80.

As shown in Fig. 7, spectra of Combo-C (also of other Combos) cover 550 nm-600 nm, a range which is lack in Fig. 5(b) and is important for the achievement of high CAF and CRI. In practice, if we desire to achieve optimal results through experiments, we need to carefully adjust electrical currents of blue, green, and red LEDs with these presented theoretical optimal wavelengths and FWHMs. Due to the low efficiency of blue and green InGaN-based LEDs, however, especially for the

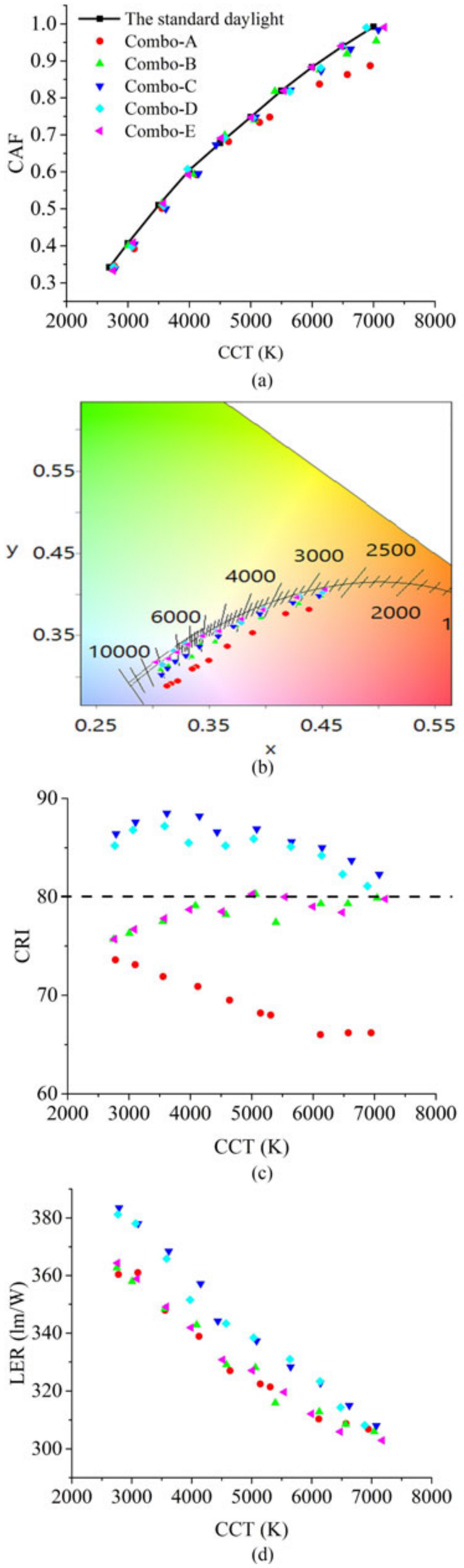

Fig. 6. (a) CAF, (b) color coordinates, (c) CRI, and (d) LER of five LEDs with the CCT of 2700 K-7000 K.

TABLE 4
LER, CAF, CRI and Duv of LED-C and the Standard Light

CCT (K)	White light	LER (lm/W)	CAF	CRI	Duv
2700	The standard light	147.3	0.342	100	–
	Combo-C	383.5	0.338	86.4	0.003
3500	The standard light	180.5	0.510	100	–
	Combo-C	368.5	0.500	88.5	0.004
4500	The standard light	196.0	0.691	100	–
	Combo-C	347.4	0.693	87.3	0.005
5500	The standard light	207.6	0.819	100	–
	Combo-C	328.3	0.821	85.6	0.006
6500	The standard light	204.8	0.940	100	–
	Combo-C	315.0	0.932	83.7	0.007

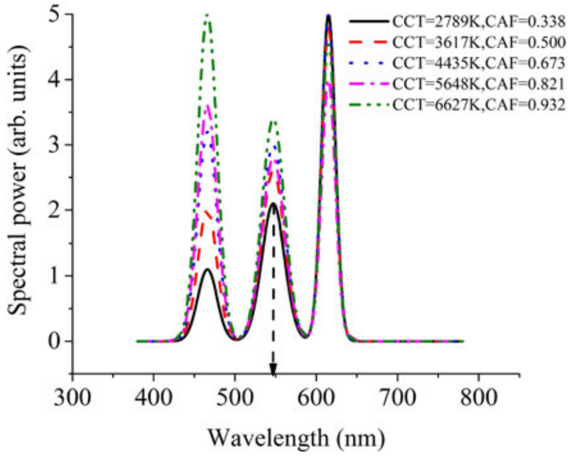

Fig. 7. Spectra of the Combo-C with various CCTs.

green LED at ~550 nm wavelength, it is significant to search for other materials having emissions in blue and green regions to fabricate high-efficiency three-primary LEDs.

5. Conclusion

We propose a method by adjusting electrical currents of RGB-LEDs to tune the CAF, CCT, and color coordinates to become close to the standard light with various CCTs. We have performed spectral optimizations to obtain optimal P_R, P_G, and P_B of RGB-LEDs, and derive required working currents of RGB-LEDs through the relationship between P and I. To meet requirements of both high CRI and better CAF, we have further performed the optimization by adjusting peak wavelengths and optical powers. Peak wavelengths with 466 nm, 547 nm, and 615 nm for the blue, green, and red color component turn out to be the best combination for obtaining both high CRI and high LER, with CAF, CCT, and color coordinates close to those of the standard light.

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