Design of smart light source based on bi-color LED with single duty cycle for correlated color temperature adjustment

Lingyuan Qiao1 · Huanyue Zhang2 · Jingjie Yu1 · Fan Cao1 · Yingming Gao1,2

Received: 9 June 2021 / Accepted: 18 August 2021 / Published online: 13 October 2021
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2021

Abstract
Color-adjustable light sources facilitate both mood lighting and daylight harvesting. A single duty cycle can be used by a bi-color LED to adjust the correlated color temperature (CCT) by associating it with the duty cycle of the pulse width modulation dimming signal of the cool and warm white LEDs. The one-to-one mapping relationship between the single duty cycle and the CCT is based on the color mixing theory of bi-color LEDs. A method to correlate the dimming signals for bi-color LEDs is presented. The influence of the time characteristics of the two basic signals on dimming and CCT adjustment is analyzed. The dimming system of bi-color LEDs is designed, and the method used to adjust the CCT with a single duty cycle is verified. The experiment showed that the CCT can be accurately adjusted by the proposed method.

Keywords LED · CCT · Pulse width modulation · Duty cycle

1 Introduction

Previous studies have shown that lighting correlated color temperature (CCT) and illumination can change people’s visual perception and emotion; they also play an important role in the control of human endocrine system activity, physiological rhythm, and psychological cognition. It has been identified that the light irradiation of high CCT light-emitting diodes (LEDs) has an impact on sleep, mood, and physical strength. Moreover, people exposed to cold white light experience better sleep quality and quantity than those exposed to warm white light (Curcio et al. 2016). A previous study (Kang et al. 2019) indicated that the interaction between illumination and CCT affects cognition and self-control. In addition to mood lighting, which affects the emotional feeling of humans, color-tunable light sources may be used for daylight harvesting. The CCT of daylight can vary from...
2000 K at sunrise to 5000 K for direct daylight at noon, even exceeding 10,000 K under overcast conditions. Along with the CCT, the illuminance of daylight also varies dynamically. Therefore, to create a near-exact visual sensation and energy-efficient lighting, an artificial light source (visually matched LED lamp) with independently tunable CCT and illuminance should preferably be introduced in daylight harvesting schemes (Malik et al. 2018; Boscarino and Moallem 2016). Jou presented a man-made lighting device of organic light-emitting diode (OLED) capable of yielding a sunlight-style illumination with various daylight chromaticity (Jou et al. 2009).

As is widely known, white light with different CCTs can be produced by a blue LED or near-ultraviolet LED stimulating proper yellow phosphors. However, it is difficult to tune CCT dynamically for one single LED the former mentioned over a wide range. Scientists have made great efforts to improve CCT tunable OLED. Shih presented a novel structure of OLED, through which CCT could be adjusted over a wide range with a relatively low and variable voltage (Shih et al. 2019). For R/G/B three-color (Muthu et al. 2002; Wang et al. 2010; Tang et al. 2014; Zhao and Lee 2012) or R/G/B/A four-color LEDs (Gilman et al. 2013), the Grassmann color law is applied to adjust the ratio of the luminosity of different color LEDs to produce white light. Ingo Speier proposed and discussed two LED modules with combinations of WW/G/B three-color and R/G/B/CW four-color LEDs (Speier and Salsbury 2006). These types of LED systems require three or more pulse-width-modulated (PWM) output channels, which make them difficult to practically realize. Among the many CCT regulation methods, the double white LED method is more convenient and practical than others. The PWM dimming method is used to adjust the luminous flux of high and low CCT LEDs and then mix them together to adjust the CCT. Lee proposed a closed-loop nonlinear scheme for precisely controlling the luminosity and CCT of a bi-color adjustable LEDs (Lee et al. 2016). Chen proposed a nonlinear method of CCT and luminous intensity control for bi-color white LEDs (Chen et al. 2015).

Color temperature and intensity tunable light source presents a significant opportunity to improve on existing lighting systems. They can be applied to smart and specialized lighting, which can be highly beneficial for healthcare settings in the residential, commercial, and industrial sectors. Xiu Ziren presented an indoor smart lighting system by bi-color LEDs combination method, both brightness and color temperature could be regulated wirelessly based on JenNet-IP protocol (). In order to stabilize the output of spectrum, Ivan Chew presented a novel closed-loop control algorithm with feedback from a spectral sensor, which allowed the light output spectrum to converge toward a target spectrum (Chew 2015). Measurement is essential to closed-loop control and its precision directly determines the control effect. Botero-Valencia developed a low-cost spectrometer using an Artificial Neural Network, with a resolution of 5 nm in the visible spectrum (Botero-Valencia et al. 2019).

At present, the related personnel apply PWM method to adjust the light and color, and achieve a certain precision control, but basically are the application of multi-channel, independent control of the light source involved in the mixing, which becomes complicated in the experimental and theoretical calculation. We use the bi-color LED color matching method to simplify the implementation of CCT regulation. Through association of the dimming duty cycle of cool and warm white LEDs, we transform the mapping relationship between the duty cycle and the CCT from two duty cycles to a single duty cycle. We call duty of PWM signal used to dim LED the dimming duty cycle in this paper. CCT calculation model of bi-color LED

The CCT represents the color attribute of light that has the temperature of blackbody radiation. According to the principle of color matching, the essence of color matching
Design of smart light source based on bi-color LED with single…

with bi-color LEDs is to change the ratio of cool light luminosity to warm light luminosity using dimming technology to adjust the CCT (Kim et al. 2009). We used the CCT calculation model proposed by Ref. (McCamy 1992), which is shown in Eq. (1):

\[
\begin{align*}
CCT &= -449n^2 + 3525n^2 - 6823.3n + 5520.33 \\
\end{align*}
\]

where \( n \) is the inverse slope, and \( x_m \) and \( y_m \) are the color coordinates of the mixed light, which can be obtained by

\[
\begin{align*}
x_m &= \frac{R_c D_c x_c + R_w D_w x_w}{R_c D_c + R_w D_w} \\
y_m &= \frac{R_c D_c y_c + R_w D_w y_w}{R_c D_c + R_w D_w}
\end{align*}
\]

where \( R_c = \frac{\Phi_c}{y_c} \), and \( R_w = \frac{\Phi_w}{y_w} \), \( \Phi_c \) represents luminous flux of cool white LED, \( \Phi_w \) represents luminous flux of warm white LED, \( D_c \) and \( D_w \) are the duty cycles of PWM signals respectively used to dim cool and warm white LED, \((x_c, y_c)\) and \((x_w, y_w)\) are the chromaticity coordinates respectively correspond to cool and warm white LED.

According to Eqs. (1) and (2), two duty cycles are required to obtain the CCT: the dimming duty cycles \( D_c \) and \( D_w \) of the high and low CCT light sources, respectively. They are independent and have no relation to each other, which makes it more difficult to determine the CCT (Daisheng et al. 2014). In a previous study (Liu Chengbi and Bo 2014), two complementary PWM signals with equal periods were used to adjust the high and low CCT light source respectively. Shown as in Fig. 1, in addition to the same period \( T \) and phase position, signal \( \text{PWM}_w \) is ON when \( \text{PWM}_c \) is OFF in each period, the two PWM signals are complementary, and it is obvious the dimming duty cycles of the two PWM signals meet the condition \( D_c + D_w = 1 \), according to the definition of duty cycle. However, the study did not conduct a theoretical analysis and did not establish the mapping relationship between the duty cycle and values of the photometry; thus, the CCT could not be accurately controlled.

Substituting \( 1 - D_w \) for \( D_c \) into Eq. (2), we obtain the mapping relationship between the CCT and warm light dimming duty cycle \( D_w \), as shown in Eq. (3). Clearly, it is more convenient to confirm the CCT using a single duty cycle compared with two independent dimming duty cycles.

**Fig. 1** PWM signals characterized as complementary
Using Eq. (3), we present the curve between the CCT and the dimming duty cycle $D_w$ of a warm white LED in Fig. 2. The relationship between the CCT and $D_w$ is nonlinear. The CCT decreases with an increase in the warm duty cycle $D_w$; it is lower than that of a cool white LED but higher than that of a warm white LED. The parameters of the cool and warm white LEDs used to obtain Fig. 2 are listed in Table 1.

**Table 1** Parameters of cool and warm white LEDs

| LED                     | (x, y)      | CCT(K)  | Luminous flux(lm) |
|-------------------------|-------------|---------|-------------------|
| Cool white light        | (0.2901,0.2917) | 8800    | 179.16            |
| Warm white light        | (0.4583,0.4257) | 2840    | 179.69            |

\[
\begin{align*}
\text{CCT} &= -449n^3 + 3525n^2 - 6823.3n + 5520.33 \\
n &= \frac{R_c(1-D_w)y_c + R_wD_wy_w}{R_c(1-D_w)x_c + R_wD_wx_w} - 0.3320 \\
&= \frac{R_c(1-D_w)y_c + R_wD_wy_w}{R_c(1-D_w)x_c + R_wD_wx_w} - 0.1858
\end{align*}
\]

Using Eq. (3), we present the curve between the CCT and the dimming duty cycle $D_w$ of a warm white LED in Fig. 2. The relationship between the CCT and $D_w$ is nonlinear. The CCT decreases with an increase in the warm duty cycle $D_w$; it is lower than that of a cool white LED but higher than that of a warm white LED. The parameters of the cool and warm white LEDs used to obtain Fig. 2 are listed in Table 1.

## 2 Dimming signals

### 2.1 Definition of dimming signals

A smart light source is characterized by its ability to adjust both the CCT and illumination, which is convenient for application in different environments, and achieves the goal of implementing one multi-use lamp. To simultaneously adjust the luminous flux and CCT of the light source, two basic PWM signals, PWM$_1$ and PWM$_2$, are defined; their periods are $T_1$ and $T_2$, respectively. The duty cycles $D$ and $d$, corresponding to PWM$_1$ and PWM$_2$, respectively, are shown in Fig. 3.

Using the two basic PWM signals, the generation of the dimming signals introduced in this study is shown in Fig. 4. The dimming signal of the warm white LED is PWM$_w$ = PWM$_1$ $\cap$ PWM$_2$, and that of the cool white LED is PWM$_c$ = PWM$_1$ $\cap$ PWM$_2$. When PWM$_1$ = 1, PWM$_w$ = PWM$_2$ and PWM$_c$ = PWM$_2$. Clearly, if the duty cycle $D_w$ of
Design of smart light source based on bi-color LED with single...

1.3

Fig. 3 Definition of the two basic PWM signals

PWM_1

\[ T_1 \cdot D \]

PWM_2

\[ T_2 \cdot d \]

PWM_1

\[ T_2 \]

PWM_2

Fig. 4 Generation of dimming signals for cool and warm white LEDs

PWM_w is \( d \), then the duty cycle \( D_c \) of PWM_c is \( 1 - d \), and the two duty cycles are associated. In particular, when \( \text{PWM}_1 = 0 \), then \( \text{PWM}_w = \text{PWM}_c = 0 \).

2.2 Analysis of dimming signals

The two basic signals \( \text{PWM}_1 \) and \( \text{PWM}_2 \) should satisfy the time-related constraint, or the precision of the color adjustment may deteriorate. According to the definition presented in Sect. 3.1, when \( \text{PWM}_1 \) is high voltage, the signals \( \text{PWM}_w \) and \( \text{PWM}_c \), which are used to dim the warm and cool light, respectively, are output. The relationship between the high voltage duration of signal \( \text{PWM}_1 \) and cycle \( T_2 \) of \( \text{PWM}_2 \) can be expressed by Eq. (4):

\[
T_1 \cdot D = k \cdot T_2 \pm t \quad (k = 1, 2, \cdots; 0 \leq t < T_2)
\]

where \( t \) represents a time period less than \( T_2 \) and \( k \) is the number of cycles of \( T_2 \) that are composed of the high voltage period of the \( \text{PWM}_1 \) signal.

According to Eq. (4), if \( t = 0 \), \( T_1 \cdot D \) is equal to \( T_2 \) multiplied by integer \( k \). Then, the duration of the warm light emission \( t_w \) is \( k \cdot T_2 \cdot d \), and that of the cool light emission \( t_c \) is \( k \cdot T_2 \cdot (1 - d) \) in one cycle of \( \text{PWM}_1 \). We set \( \Phi_c \) and \( \Phi_w \), which are the luminous
flux outputs corresponding to the constant working current of the cool and warm white LEDS, respectively.

$\Phi_{w,f}$ is the dimming luminous flux of the warm light:

$$\Phi_{w,f} = \frac{\Phi_w \cdot t_w}{T_1} = \frac{\Phi_w \cdot k \cdot T_2 \cdot d}{T_1} \quad (5)$$

$\Phi_{c,f}$ is the dimming luminous flux of the cool light:

$$\Phi_{c,f} = \frac{\Phi_c \cdot t_c}{T_1} = \frac{\Phi_c \cdot k \cdot T_2 \cdot (1 - d)}{T_1} \quad (6)$$

The ratio of $\Phi_{w,f}$ to $\Phi_{c,f}$ determines the mixed color:

$$\frac{\Phi_{w,f}}{\Phi_{c,f}} = \frac{\Phi_w \cdot d}{\Phi_c \cdot (1 - d)} \quad (7)$$

The mixed luminous flux is

$$\Phi_m = \Phi_w \cdot D \cdot d + \Phi_c \cdot D \cdot (1 - d) \quad (8)$$

It can be concluded from Eqs. (7) and (8) that the ratio of the luminous flux of cool light to that of warm light, i.e., the total luminous flux $\Phi_m$, is independent of the periods $T_1$ and $T_2$. However, it is affected by the luminous properties of the light source and the duty cycle of the dimming signal when the high voltage duration of PWM1 is equal to an integer multiple of $T_2$, which is the period of signal PWM2. In particular, when the luminous flux values $\Phi_C$ and $\Phi_W$, which correspond to the cool and warm light sources, respectively, are the same, the mixed luminous flux is independent of the duty cycle of the PWM2 signal and is equal to $\Phi_w \cdot D$ or $\Phi_c \cdot D$, which is affected only by the duty cycle of PWM1. This makes it possible to adjust the CCT while maintaining a constant illumination, which may be convenient for daylight-responsive lighting.

If $t$ is nonzero, a possible state described by Eq. (4) is illustrated in Fig. 5. Considering $PWM_w = PWM_2$ and $PWM_c = PWM_2$, when $PWM_1 = 1$, the duration $t_w$ of the warm light emission is $k \cdot T_2 \cdot d + t$, and the duration $t_c$ of the cool light emission is $k \cdot T_2 \cdot (1 - d)$.

$\Phi_{w,f}$ is the dimming luminous flux of the warm light:

---

**Fig. 5** One illustration of period correlation to PWM$_1$ and PWM$_2$
\[ \Phi_{w,T} = \frac{\Phi_w \cdot t_w}{T_1} = \frac{\Phi_w \cdot (k \cdot T_2 \cdot d + t)}{T_1}. \] (9)

\[ \Phi_{c,T} \] is the dimming luminous flux of the cool light:

\[ \Phi_{c,T} = \frac{\Phi_c \cdot t_c}{T_1} = \frac{\Phi_c \cdot k \cdot T_2 \cdot (1 - d)}{T_1} \] (10)

The ratio of \( \Phi_{w,T} \) to \( \Phi_{c,T} \), which determines the precision of the mixed color, is

\[ \frac{\Phi_{w,T}}{\Phi_{c,T}} = \frac{\Phi_w \cdot (k \cdot T_2 \cdot d + t)}{\Phi_c \cdot k \cdot T_2 \cdot (1 - d)} = \frac{\Phi_w \cdot \left( \frac{d + \frac{1}{kT_2}}{1} \right)}{\Phi_c \cdot (1 - d)} \] (11)

It is clear that Eq. (11) is influenced by \( k \) and \( t \). Considering \( \frac{t}{T_2} < 1, \frac{1}{kT_2} \) would be close to zero with an increase in \( k \). Given \( T_1 \) and Eq. (4) and considering that \( k \) is the number of cycles of \( T_2 \) that are composed of the high voltage duration of \( \text{PWM}_1 \), the frequency of \( \text{PWM}_2 \) should increase with an increase in \( k \). It can be concluded that Eq. (11) is independent of \( t \), and it converges to \( \frac{\Phi_w}{\Phi_{(1-d)}} \) as the frequency of \( \text{PWM}_2 \) increases.

The mixed luminous flux \( \Phi_m = \Phi_{w,T} + \Phi_{c,T} \) can be expressed as

\[ \Phi_m = \frac{\Phi_w \cdot (k \cdot T_2 \cdot d + t)}{T_1} + \frac{\Phi_c \cdot k \cdot T_2 \cdot (1 - d)}{T_1}. \] (12)

If the luminous flux \( \Phi_c \) is the same as \( \Phi_w \), \( \Phi_m \) can be expressed as \( \Phi_w \cdot \left( \frac{(kT_2 + t)}{T_1} \right) \) or \( \Phi_c \cdot \left( \frac{(kT_2 + t)}{T_1} \right) \). According to Eq. (4), \( kT_2 + t \) is equal to \( T_1 \cdot D \), and the mixed luminous flux \( \Phi_m \) is \( \Phi_w \cdot D \) or \( \Phi_c \cdot D \), which is independent of both \( t \) and \( d \).

Another state described by Eq. (4) is presented in Fig. 6. during the high voltage period of \( \text{PWM}_1 \), the duration of the warm light emission \( t_w \) is \( k \cdot T_2 \cdot d + T_2 \cdot d \), and the duration of the cool light emission \( t_c \) is \( k \cdot T_2 \cdot (1 - d) + t - T_2 \cdot d \).

\( \Phi_{w,T} \) is the dimming luminous flux of the warm light:

\[ \Phi_{w,T} = \frac{\Phi_W \cdot t_w}{T_1} = \frac{\Phi_W \cdot (k + 1) \cdot T_2 \cdot d}{T_1} \] (13)
Φ_{c,t} is the dimming luminous flux of the cool light:

\[ \Phi_{c,t} = \Phi_C \cdot \frac{t_c}{T_1} = \Phi_C \cdot \frac{(k - (k + 1) \cdot d \cdot T_2 + t)}{T_1} \]  

(14)

The ratio of Φ_{w,T} to Φ_{c,T} is

\[ \frac{\Phi_{w,T}}{\Phi_{c,T}} = \frac{\Phi_w \cdot (k + 1) \cdot T_2 \cdot d}{\Phi_c \cdot (k - (k + 1) \cdot d) \cdot T_2 + t} = \frac{\Phi_w \cdot d}{\Phi_c \cdot \left( \frac{k}{k+1} - d \right) + \frac{t}{(k+1)T_2}} \]  

(15)

The analysis of Eq. (15) is similar to that of Eq. (11). With an increase in the frequency of PWM2, Eq. (15) converges to \( \Phi_w \cdot d \), owing to the convergence of the denominator to \( \Phi_c \cdot (1 - d) \).

The mixed luminous flux \( \Phi_m = \Phi_{w,t} + \Phi_{c,t} \) can be expressed as

\[ \Phi_m = \frac{\Phi_w \cdot (k + 1) \cdot T_2 \cdot d}{T_1} + \frac{\Phi_c \cdot ( (k - (k + 1) \cdot d) \cdot T_2 + t )}{T_1} \]  

(16)

Similar to the analysis of Eq. (12), it can be concluded that \( \Phi_m \) is \( \Phi_c \cdot D \) or \( \Phi_w \cdot D \) when \( \Phi_c = \Phi_w \). That is, the mixed luminous flux \( \Phi_m \) is independent of both \( t \) and \( d \), and it is only affected by \( D \), which is the duty cycle of PWM1, given the same \( \Phi_c \) and \( \Phi_w \).

### 2.3 Generation of dimming signals

The dimming system of a bi-color LED smart light source consists of a power supply unit, control unit, and drive unit, as shown in Fig. 7. The input voltage of the system is 12 V, which was also implemented as the input voltage of the driving unit. The 12 V voltage is converted to 5 V by a power supply unit to power the control unit. The control unit is composed of a microcontroller (STC15F2K60S2, STCmicro Technology Ltd., Shenzhen, China) and gate circuit. It receives control instructions and generates dimming signals for the cool and warm lights. The drive unit adopts two constant current buck drivers (PT4115, H&M Semiconductor Ltd., Shenzhen, China) and is used to drive the cool and warm white LEDs. The cool and warm dimming signals generated from the control unit are respectively sent to the PWM dimming input terminals of the two buck drivers. The experimental dimming system of a bi-color LED is presented in Fig. 8.

![Fig. 7 Basic block diagram of bi-color LED system](image-url)
We set the period of the basic dimming signal $PWM_1$ to 1 ms at 10 levels; thus, the minimal duration of high voltage is 100 $\mu$s. The $PWM_2$ signal is also at 10 levels; its period is set to 100 $\mu$s to satisfy the requirement that the high voltage duration of $PWM_1$ is an integer multiple of the period of $PWM_2$, according to the discussion in Sect. 3.2. Using the timer of the microcontroller, the basic dimming signals $PWM_1$ and $PWM_2$ are output from P1.0 and P1.1, respectively, with the initial state of the high voltage.

Figure 9 presents a flow chart that describes how the output signals $PWM_1$ and $PWM_2$ are obtained through P1.0 and P1.1, respectively, by using a timer interrupt function. Two integer variables, counter1 and counter2, are used to determine the period and duty cycle of the signals corresponding to $PWM_2$ and $PWM_1$, respectively. The initial and final values of the two variables are set to zero and ten, respectively. Counter1 is incremented by one every time the
timer interrupt function is executed, and counter2 is incremented by one when counter1 accumulates from zero to ten.

Given a timing interval of 10 μs, two PWM signals can be obtained with the same duty cycle of 50% but with different periods (200 μs and 2 ms). When the two variables increase from zero to ten, they should be reset, and the output voltages of P1.0 and P1.1 should be reversed. If the output voltage of the pins is reversed when counter1 or counter2 is less than ten, two PWM signals may be output with an adjustable duty cycle and periods of 100 μs and 1 ms. For example, the output voltage of the pins was reversed when counter1 = 3 and counter2 = 6, two PWM signals with duty cycles of 30% and 60% could be obtained.

Given a timing interval of 10 μs, two basic signals PWM1 and PWM2 with the same duty cycle of 50% but different periods (1 ms and 100 μs) are presented in Fig. 10. The signals are used to dim the cool and warm white LEDs, respectively, and are obtained by the gate-circuit transformation of basic signals PWM1 and PWM2, as shown in Fig. 11.
3 Experiment and analysis

3.1 Test of linearity of PWM dimming

The test system includes a spectral radiometer (HAAS-2000), integrating sphere, computer, and current source. Two 3 W LEDs, cool and warm, were placed in the integrating sphere, and their chromaticity parameters were measured with a constant current 750 mA, as shown in Table 1. Considering that a high PN junction temperature would cause a color drift or light decay (Buso 2011; Louying et al. 2010), we welded the two LEDs on the aluminum substrate to dissipate heat to reduce the influence of temperature on the light source.

Using the system shown in Fig. 8, we obtained the corresponding relationship between the luminous flux of the LED and the dimming duty cycle, as shown in Fig. 12. There is good linearity between the luminous flux and the dimming duty cycle of the LED, owing to an $R^2$ (coefficient of determination) value close to 1.

The working current determines the CCT of the white light LED, which produces white light using a blue light stimulating yellow phosphor. PWM dimming is realized by a periodic on–off constant working current; therefore, the luminous flux can be adjusted while maintaining the CCT. In addition, PWM dimming is easier to realize with high precision (Svilainis 2008). However, PWM dimming causes LED flickering with low frequency, which would cause discomfort or even damage to human eyes (Liu Chengbi and Bo 2014). To make dimming comfortable, a high frequency, at least 1 kHz, should be adopted. The dimming frequency used in this test was 1.6 kHz.

3.2 Test of mixed luminous flux of bi-color LED

According to discussion in Sect. 4.1, the mixed luminous flux of a bi-color LED light source is linear and has a duty cycle $D$ of signal PWM$_1$, which is independent of duty cycle $d$ of signal PWM$_2$, when the luminous flux of cool light and warm light is equal. Therefore, the method used in this study can adjust the CCT as well as maintain a constant illumination. With the duty cycle $D$ of the PWM$_1$ signal set to one, the test results and theoretical values of the mixed luminous flux are given by Table 2. With variation of the duty cycle $d$
of the PWM2 signal, the maximum error of the mixed luminous flux between the theoretical value and the test result is 4%, the minimum error is 0.22%, and the average error is 1.82%. Clearly, the error between the test and calculation is minimal.

The test results of the mixed luminous flux with the duty cycle $D$ of PWM1 set to 0.2, 0.4, 0.6, and 0.8 are shown in Fig. 13. Given a duty cycle $D$, the difference of the luminous flux is small as the duty cycle $d$ varies. From the test, it can be concluded that duty cycle $d$ has no effect on the mixed luminous flux when the luminous flux of the cool light and warm light is equal.

### 3.3 Test of CCT

Three group test results, the theoretical values of the CCT, and the corresponding error are given in Table 3. With the variation of the duty cycle of the cool light dimming

| Duty cycle/d | Theory (lm) | Test (lm) | Error | Error % |
|--------------|-------------|-----------|-------|---------|
| 0            | 179.69      | 179.23    | 0.46  | 0.26    |
| 0.1          | 179.64      | 180.04    | 0.4   | 0.22    |
| 0.2          | 179.58      | 183.62    | 4.04  | 2.25    |
| 0.3          | 179.53      | 184.23    | 4.70  | 2.62    |
| 0.4          | 179.48      | 186.65    | 7.17  | 4.00    |
| 0.5          | 179.43      | 185.76    | 6.33  | 3.53    |
| 0.6          | 179.37      | 184.63    | 5.31  | 2.96    |
| 0.7          | 179.32      | 182.92    | 3.60  | 2.01    |
| 0.8          | 179.26      | 180.51    | 1.25  | 0.70    |
| 0.9          | 179.21      | 181.13    | 1.92  | 1.07    |
| 1            | 179.16      | 179.87    | 0.71  | 0.40    |

![Fig. 13 Mixed luminous flux vs. duty cycles $D$ and $d$](image-url)
signal, which is equal to $1 - d$ according to the Fig. 4, the maximum difference between the theoretical values and the test results of the CCT is 72 K, the minimum difference is 1 K, and the average error is 28 K. The results show that the method used in this study exhibits high accuracy.

Figure 14 shows the lighting effects obtained with the variation of CCTs and a constant illuminance of 570 lx. The power of a single light source is 3 W, and the distance between the light source and the target is 0.6 m. With the increase in $D_c$, the CCT changed from low to high, and the picture gradually appeared cooler.

Figure 15 shows the lighting effect with two CCTs and three illuminances; the duty cycle of PWM1 is $D$. The power of a single LED and the distance were the same as in the former experiment. The CCT of Fig. 15(a)–(c) is 3375 K, and that of Fig. 15(d)–(f) is 6528 K. Compared with the high CCT and high illumination Fig. 15f, the high CCT and low illumination Fig. 15d looks darker and cooler.

| $D_c$ | Theory (K) | Test1 (K) | Error1 (K) | Test2 (K) | Error2 (K) | Test3 (K) | Error3 (K) |
|-------|------------|-----------|------------|-----------|------------|-----------|------------|
| 0     | 2840       | 2838      | 2          | 2841      | 1          | 2842      | 2          |
| 0.1   | 3064       | 3088      | 24         | 3086      | 22         | 3090      | 26         |
| 0.2   | 3331       | 3375      | 44         | 3366      | 35         | 3362      | 31         |
| 0.3   | 3648       | 3671      | 23         | 3672      | 24         | 3684      | 36         |
| 0.4   | 4028       | 4039      | 11         | 4039      | 11         | 4027      | 1          |
| 0.5   | 4484       | 4434      | 50         | 4437      | 47         | 4455      | 29         |
| 0.6   | 5035       | 5051      | 16         | 5050      | 15         | 5040      | 5          |
| 0.7   | 5704       | 5722      | 18         | 5726      | 22         | 5744      | 40         |
| 0.8   | 6525       | 6528      | 3          | 6482      | 43         | 6574      | 49         |
| 0.9   | 7538       | 7532      | 4          | 7500      | 38         | 7492      | 46         |
| 1     | 8800       | 8854      | 54         | 8864      | 64         | 8872      | 72         |

**Fig. 14** Lighting effect with constant illumination and different CCTs
A low CCT matches low illumination, and high CCT matches high illumination; moreover, a reasonable combination of the CCT and illumination makes people comfortable. Figure 15d, which has low illumination and a high CCT, looks significantly uncomfortable compared with Fig. 15f, which has high illumination and a high CCT. The method that we used can easily adjust the illuminance and CCT.

4 Conclusion

To simplify CCT adjustment of bi-color LEDs, the duty cycle of two PWM dimming signals were correlated, and the mapping relationship between the CCT and a single duty cycle was given. A bi-color LED light source system was designed with a dimming signal and color matching signal that could adjust the CCT while maintaining a constant value for the luminous flux, which makes the method convenient for application in daylight harvesting, in addition to mood lighting. Experiments showed that the method used to adjust the CCT was simple to realize within a small error. Although CCT could be accurately adjusted within a wide range, the color rendering index (CRI) of the bi-color LED light source was as poor as warm or cool white LEDs'. Improvement of the CRI is an important subject to investigate. Moreover, it would be interesting to see the color rendering scores, using ANSI/IES TM-30-20, instead of CRI.

Acknowledgements The author would like to thank the Research Institute of Photonics, Dalian Polytechnic University, China for the experimental support; Thanks to Liaoning Provincial Department of Education for funding support of scientific research project (J2020019), the anonymous reviewers and the editor for their invaluable comments and suggestions; and Editage (www.editage.cn) for English language editing.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by YG and LQ. The first draft of the manuscript was written by LQ and all authors commented on the manuscript.

Funding This work was supported by Scientific research project of education department of Liaoning province (J2020019).
Declarations

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Consent to participate All the authors participated in the study and approved the final manuscript.

Consent to publish Our work is original and has not been published elsewhere in any form. All authors have agreed to publish in Optical and Quantum Electronics.

References

Andersen, M., Gochenour, S.J., Lockley, S.W.: Modelling ‘non-visual’ effects of daylighting in a residential environment. J Build Environ 70, 138–149 (2013)
Boscarino, G., Moullem, M.: Daylighting control and simulation for LED-based energy-efficient lighting systems. J. IEEE Trans Ind Informat 12(1), 301–309 (2016)
Botero-Valencia, J.S., Valencia-Aguirre, J., Durnus, D., Davis, W.: Multi-channel low-cost light spectrum measurement using a multilayer perceptron. Energy Build 199, 579–587 (2019)
Buso S (2011) White light solid state lamp with luminance and color temperature control. In: C. Brazilian power electronics conference: [proceedings]. Piscataway, N. J. IEEE, pp. 837–843
Chen, H.T., Tan, S.C., Hui, S.Y.: Nonlinear dimming and correlated color temperature control of bicolor white LED systems. J IEEE Trans Power Electr 30(12), 6934–6947 (2015)
Chew, I., Kalavally, V., Tan, C.P., Parkkinen, J.: A spectrally tunable smart LED lighting system with closed-loop control. IEEE Sens J 16(11), 4452–4459 (2016)
Curcio, G., Burattini, C., Piccardi, L. et al.: The effects of LED lighting on sleep and sleepiness. In: Congress of the European sleep research society. (2016)
Daisheng, Xu., et al.: Dimmable light source based on cold and warm white LED. J Opt 34(01), 226–232 (2014)
Gilman, J.M., Miller, M.E., Grimaila, M.R.: A simplified control system for a daylight-matched LED lamp. J Light Res Technol 45(5), 614–629 (2013)
Hawes, B.K., Brunyé, T.T., Mahoney, C.R., Sullivan, J.M., Aall, C.D.: Effects of four workplace lighting technologies on perception, cognition and affective state. Int J Ind Ergon 42(1), 122–128 (2011)
Jou, J.H., Wu, M.H., Shen, S.M., Wang, H.C., Chen, S.Z., Chen, S.H., Lin, C.R., Hsieh, Y.L.: Sunlight-style color-temperature tunable organic light-emitting diode. Appl. Phys. Lett. 95(1), 184 (2009)
Kang, S.Y., Youn, N., Yoon, H.C.: The self-regulatory power of environmental lighting: the effect of illuminance and correlated color temperature. J Environ Psychol 62, 30–41 (2019)
Kim, H., Liu, J., Jin, H.S. et al.: An LED color control system with independently changeable illuminance. In: International telecommunications energy conference. IEEE (2009)
Lee, A.T., Chen, H., Tan, S.C., Hui, S.Y.: Precise dimming and color control of LED systems based on color mixing. J. IEEE Trans Power Electron 31(1), 65–80 (2016)
Liu Chengbi, Lu., Bo, H.X.: A novel dimming and color matching scheme to drive LED luminaire. Lamps Light 01, 5–9 (2014)
Louying, Z., Yiping, C., Zongnan, L., et al.: Color drift in the whole life of high power LED. Liquid Cryst Disp 25(002), 210–214 (2010)
Malik, R., Ray, K.K., Mazumdar, S.: Wide-range, open-loop, CCT and illuminance control of an LED lamp using two-component color blending. IEEE Trans Power Electron 33(11), 9803–9818 (2018)
McCamy, C.S.: Correlated CCT as an explicit function of chromaticity coordinates. Color Res Appl 17(2), 142–144 (1992)
Mirjam, M., Friedrich, L., Aipparn, B., et al.: Effects of prior light exposure on early evening performance, subjective sleepiness, and hormonal secretion. Behav Neurosci 126(1), 196–203 (2012)
Muthu, S., Schuurmans, F.J., Pashley, M.D.: Red, green, and blue LEDs for white light illumination. IEEE Trans J Sel Top Quantum Electron 8(2), 333–338 (2002)
Shih, S.H., Jou, J.H., Chavhan, S.D., Su, T.H., Yuan, C.H., Wen, J.W., Chen, P.R., Tung, F.C., Tasi, Y.C.: High efficiency color-temperature tunable organic light-emitting diode. J Mater Chem C 7(48), 15322–15334 (2019)
Speier, I., Salsbury: Color temperature tunable white light LED system. In: Sixth international conference on solid state lighting, vol. 6337, p. 63371F. International Society for Optics and Photonics (2006)
Svilainis, L.: LED PWM dimming linearity investigation. Displays 29(3), 243–249 (2008)
Tang, C.-W., Huang, B.-J., Ying, S.-P.: Illumination and color control in red-green-blue light-emitting diode. IEEE Trans Power Electron 29(9), 4921–4937 (2014)
Wang, F.-C., Tang, C.-W., Huang, B.-J.: Multivariable robust control for a red-green-blue LED lighting system. IEEE Trans Power Electron 25(2), 417–428 (2010)
Ziren, X., Hao, L.: Application of color temperature tunable LEDs in smart lighting system. In: 2014 15th International Conference on Electronic Packaging Technology, pp. 1423–1426. IEEE (2014)
Zhao H., Lee S.W.R., Determination of driving current of RGB LEDs for white light illumination. In: 2012 13th International Conference on Electronic Packaging Technology & High Density Packaging. (2012)
Zhu, Y., Yang, M., Yao, Y., Xiong, X., Li, X., Zhou, G., Ma, N.: Effects of illuminance and CCT on daytime cognitive performance, subjective mood, and alertness in healthy adults. Environ Behav 51(2), 199–230 (2019)

Publisher’s Note  Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.