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Abstract: The optical, color, electrical, and thermal properties of an LED devices are highly dependent on one another. The luminous flux variation and correlated color temperature (CCT) shifting of white LED sources is attributed to luminous efficacy and emission spectrum shifting with the electrical power and heat-dissipation power. An analysis model that includes the luminous flux, CCT, electrical power, and junction temperature of the white LED sources with bilevel driver is proposed in this paper. The proposed model can describe that the stabilized luminous flux and CCT of the white LED system with bilevel driver is a result of the complex interactions among the given electrical power of bilevel, duty cycle, thermal resistances, junction temperature, and the physical parameters of the LED sources. Reduction variation of CCT and luminous flux of the white LED device with bilevel driver over a dimming range has been practically achieved. The proposed method can be easily adopted for improving the CCT and luminous flux stabilization of the white LED device with a bilevel driver.

Index Terms: Lighting system, bi-level driving, optical and color control, light-emitting diode (LED), correlated color temperature (CCT), luminous flux.

1. Introduction

High luminous efficacy, long lifetime, high reliability make high-power light-emitting diode (LED) a good candidate for applications on general indoor lighting. Although a high input power produces high luminous flux, it also simultaneously generates heat. The junction temperature are essential reliability parameters for LEDs because they can affect the lifetime, efficiency, forward voltage drop, and spectral power distribution of the device [1], [2]. Therefore, the thermal management of LED is crucial to their reliability and efficiency [3], [4].

There are many two common dimming techniques (DC and PWM) introduced for the different types of lighting devices. Due to the variation in luminous flux as a function of input power of LEDs, reduction light output of the LED with PWM driver is clearly pointed out, compared to DC driver under the same average power. However, PWM driver is difficult to keep a high precision DC using a simply power method. Therefore, high precision DC dimming is a challenging work due to small
dynamic resistance of LED device. PWM driver could provide high precision dimming by using duty
cycle of the power pulse.

Most of the injection electrical power is converted into thermal dissipation power. With increasing
electrical power, reduction quantum efficiency affects the luminous efficacy and color shifting of
the LED. The luminous flux for a LED system attains a maximum value at a given electrical power,
and then droops with electrical power. The relationship of the photometric, electrical and thermal
aspects of the LED have been described by a photo-electro-thermal (PET) theory for LED systems
and applications [5]. It has been demonstrated that operating the LED at its rated power does not
necessarily guarantee an optimal luminous performance unless proper thermal design is considered
[6]. It was reported in some literature that since the luminous flux of LEDs tends to saturate at high
electrical power with PWM driving. The issue has been addressed by the bi-level driving method [7].
The method is to reduce the duration of time during which the LEDs are operated at high
peak electrical power. The bi-level driving method has been extended to the general n-level driving
method for further improving the luminous efficacy of LEDs [8].

The color variation of white LED device is attributed to emission spectrum shifting with the
electrical power and heat dissipation power. A high color quality for white LED source is demanded
in the general lighting. It is to achieve high color reliability in white LEDs, highly reliable materials
for the packaging, such as phosphors, transparent silicon, blue chips and reflectors, are developed.
Furthermore, well-structured packages preventing heat accumulation in the phosphor materials of
the LED device, which help in reducing color deviation should be employed [9].

The color and optical characteristics of white LEDs with DC, PWM, and bi-level driver are discussed
in [10]. The previous work mainly focuses on the complex interactions and the impact of bi-level
driving method on the color-shift properties of white LED. Two color-shift reduction methods is
presented based on a mathematical color-shift model [11]. A traditional AC-DC power conversion
for LED application converts the AC mains voltage into a stable DC voltage with the help of a
large electrolytic capacitor as an energy storage and buffer. It should provides a constant current
source, which means that the capacitor in the intermediate stage has to be large enough to absorb
the energy difference. However, it can not be entirely eliminated. Therefore, a current ripple with a
DC level is the waveform commonly found the output of LED application. The current ripple cause
flicker, which is the cyclical variation of light in time [12]. The human being is unable to directly
perceive flicker perturbations with a frequency higher than 90 Hz. However, indirect perception of
flicker is possible due to stroboscopic effects at frequency of 100 Hz or fast eye motions [13].

White LED source should fit the flicker needs of dimming driver and conformed to color-shift
requirement. The color tolerance specifications for white LED sources with different CCT are listed
in [14]. The luminous flux and color variation of white LED source are different under different driving
technology.

This paper provides a work describing the practical trend of the color shifting and luminous
flux variation for white LED sources with bi-level driver. It presents a model including the complex
multi-physical parameters of injection power, junction temperature, luminous flux, and CCT with
dimming control. It proposes a method to reduce CCT shifting and luminous flux variation for white
LED system with bi-level driver. Experimental results are provided to validate the model and the
proposed design.

2. Thermal and Photometric Modeling of Led Lighting System With
Bi-Level Driver

2.1 Optical and Color Properties of LEDs as a Function of Junction Temperature and
Forward Current

The luminous flux of white LED source is highly related to junction temperature. The luminous flux
of the white LED source reaches a maximum value at a given electrical power and then droop with
electrical power. At high electrical power, the luminous flux perform nonlinear property and increase
slowly. Finally, it shows a saturate tendency due to several mechanisms, such as current leakage by
tunneling of electrons to the states of InGaN/GaN interfaces, effect of auger recombination, effect
of built-in piezoelectric fields [15]. In order to present complex interactions among electrical power, junction temperature, CCT and luminous flux of the white LED system with bi-level driver, it is necessary to independently extract their effects on color and optical property by using experimental design.

The relationship is reflected in the junction temperature and luminous flux of the white LED device with the constant current of 0.3 A as shown in Fig. 1. It shows the experimental results based on LED device mounted on a temperature-controllable heatsink. The variated trend of the luminous flux with junction temperature of LED with constant current is fairly linear.

Using the Everfine HAAS-2000 spectroradiometer system, the experimental results for the luminous flux versus current of the white LED device with constant junction temperature of 48.5 °C are given in Fig. 2. It can be seen that luminous flux increases with electrical effects. At the constant junction temperature, the measured luminous flux perform linearly behavior with injection current. The luminous flux with current variation can be divided into nonlinear and linear range. The light output nonlinerly increases with the current within nonlinear range due to non-radiative recombination. If injection power continue to increases, radiative recombination become to dominate.

If the LED is mounted on the heatsink with different thermal resistance, the junction temperature should increase to steady state. With increasing current, the rapid self-heating of junction lead to the light output to reach maximum value at much lower electrical power.
Fig. 3. Measured CCT versus current of the white LED device with constant junction temperature of 48.5 °C.

Fig. 4. Measured CCT versus junction temperature of the white LED device with constant current of 0.3 A.

Fig. 3 shows the measured CCT with current from 0.1 A to 0.9 A under constant junction temperature of 48.5 °C, where CCT decreases with increasing current. The reason for the experimental trend is that the blue light with the enhanced electrical effect becomes less absorbed by the yellow phosphor. On the other hand, Fig. 4 shows that measured CCT with junction temperature under constant current of 0.3 A. It is attributed to the emission spectrum shifting with thermal effect.

2.2 Luminous Flux of White LED Device With DC Driver

According to the PET theory, the total luminous flux \( \phi_v \) can be expressed as in the following:

\[
\phi_v = \alpha_1 P_d - \alpha_2 P_d^2 \quad [5].
\]

Where \( P_d \) is the electrical power, \( \alpha_1 \) and \( \alpha_2 \) are positive parameters. The luminous flux of LED devices mounted on a heatsink with DC driver can be given as:

\[
\phi_v = N E_0 \left\{ \left[ 1 + k_e(T_a - T_0) \right] P_d + k_e k_h (R_{jc} + N R_{hs}) P_d^2 \right\}
\]

(1)

Where \( N \) is LED number, \( R_{jc} \) is thermal resistance of LED, \( R_{hs} \) is thermal resistance of heatsink, \( E_0 \) is luminous efficacy with the junction temperature of 25 °C, \( k_e \) is temperature sensitivity coefficient of luminous efficacy, \( k_h \) is heat dissipation coefficient, \( T_a \) is ambient temperature, \( T_0 \) is reference temperature.
The equation (1) can provide quantitative expression of luminous flux with electrical power and DC driver. It is clearly shown that luminous flux should reach a maximum level with electrical power. The maximum level of light output is dependent on the size and thermal resistance of heatsink. If the electrical power exceeds the certain point, the luminous flux starts to drop rapidly.

### 2.3 Luminous Flux of White LED Device With Bi-Level Driver

Bi-level driver is similar with PWM model. It pulsates between a higher current $I_{\text{high}}$ and a lower nonzero current $I_{\text{low}}$, and duty cycle $D$ is the duration of higher current normalized to the pulse repetition time. It switched between the higher current $I_{\text{high}}$ and lower current $I_{\text{low}}$, as shown in Fig. 5. It shows that line 1 and line 2 joining $I_{\text{high}}$ and $I_{\text{low}}$ is the linear variation of the average luminous flux $\phi_{\text{ave}}$ at the average current $I_{\text{ave}}$. In particular, dimmable LED lamps with bi-level driver is a novel configuration. In this driver, the average luminous flux $\phi_{\text{ave}}$ must comprise two distinct luminous flux values corresponding to the higher current $I_{\text{high}}$ and lower current $I_{\text{low}}$. In the case of LED lamps with bi-level driver, LEDs with the higher luminous flux $\phi_{\text{high}}$ and LEDs with the lower luminous flux $\phi_{\text{low}}$ is shown in the product. The higher luminous flux $\phi_{\text{high}}$ and the lower luminous flux $\phi_{\text{low}}$ can be determined by the PET theory of equation (1). Therefore, average luminous flux $\phi_{\text{ave}}$ is as a function of the higher luminous flux $\phi_{\text{high}}$ and the lower luminous flux $\phi_{\text{low}}$. It can be shown in the following

$$\phi_{\text{ave}} = f(\phi_{\text{high}}, \phi_{\text{low}})$$

Where the higher luminous flux $\phi_{\text{high}}$ and the lower luminous flux $\phi_{\text{low}}$ is as a function of the higher current $I_{\text{high}}$ and lower current $I_{\text{low}}$ respectively according to (1).

Mathematically, the average current $I_{\text{ave}}$ and average luminous flux $\phi_{\text{ave}}$ with duty cycle $D$ can be expressed as [16]

$$I_{\text{ave}} = DI_{\text{high}} + (1 - D)I_{\text{low}}$$

$$\phi_{\text{ave}} = D\phi_{\text{high}} + (1 - D)\phi_{\text{low}}$$

It can be indicated that for any working point for given luminous flux exists between the higher current and lower current range. If $I_{\text{low}} = 0$ and $\phi_{\text{low}} = 0$, the equations (3) and (4) is the current and luminous flux expression of PWM mode. If $I_{\text{high}} = I_{\text{low}} = I_{\text{ave}}$, $\phi_{\text{high}} = \phi_{\text{low}} = \phi_{\text{ave}}$ and $D = 0$, the equations (3) and (4) become the DC driver (line 0). Under bi-level driver, the luminous flux can be changed based on the boundary of line 1 and line 2 using by $D$, $I_{\text{high}}$ and $I_{\text{low}}$. Compared with the DC and PWM driver, the light output control for bi-level driver perform better flexibility and luminous efficacy. It can be clearly seen that the controlled range between $I_{\text{high}}$ and $I_{\text{low}}$ is dependent on average current and luminous flux.
As shown in Fig. 5, variation of luminous flux and junction temperature \( (\Delta \Phi_{12} \text{ and } \Delta T_{j,12} ) \) is attributed to bi-level current \( (I_{low-1} \text{ to } I_{low-2} \text{ and } I_{high-1} \text{ to } I_{high-2} ) \) with given duty cycle and average current. With the constant average current, the \( \Delta \Phi_{12} \text{ and } \Delta T_{j,12} \) between different bi-level current increases with the thermal resistance of heatsink. The LED device with higher level current \( I_{high} \) has low operated efficiency due to higher heat dissipation coefficient and thermal effect.

### 2.4 A Simplified Model of Luminous Flux for the White LED Device With Bi-Level Driver

In this section, a simplified mathematical luminous flux model under bi-level driver will be derived for the case of LEDs driven by a bi-level current. The average forward current \( I_{ave} \) and the luminous flux of the LED at steady state can be respectively expressed as in the (3) and (4). Putting (3) and (4) into (1), with the change in both higher current level \( I_{high} \) and lower current level \( I_{low} \), the average luminous flux for the white LED device with bi-level driver can be expressed as

\[
\phi_{ave} = D \phi_{high} + (1 - D) \phi_{low} = D E_{high} P_{d,high} + (1 - D) E_{low} P_{d,low} \\
= D E_{high} l_{high} V_{ave} + (1 - D) E_{low} l_{low} V_{ave} \\
= D [NE_{high} \{[1 + k_{high,e}(T_a - T_o)] l_{high} V_{ave} + k_{high,h} R_{jc} (R_{jc} + N R_{hs}) \} I_{high}^2 V_{ave}^2] \\
+ (1 - D) [NE_{low} \{[1 + k_{low,e}(T_a - T_o)] l_{low} V_{ave} + k_{low,h} R_{jc} (R_{jc} + N R_{hs}) \} I_{low}^2 V_{ave}^2] \quad (5)
\]

According to (5), the luminous flux of the white LED device with bi-level driver is highly dependent on \( I_{high}, I_{low} \) and duty cycles. Several important observations can be drawn from the equation.

(i) Equation (5) not only relates the average luminous flux \( \phi_{ave} \) to sensitivity coefficient of luminous efficacy/heat dissipation at higher and lower current level \( E_{high}, D \text{ and } E_{low}, D \) \( k_{low,e}, k_{high,e}, k_{high,h}, k_{low,h} \), the thermal resistance of the heatsink \( R_{hs} \) and the device \( R_{jc}, \) but it also includes the higher/lower current level \( l_{high}, l_{low} \) and the duty cycle. It is a model that integrates the photometric, electrical, and thermal aspects of the LED system with bi-level driver altogether.

(ii) As \( k_{high,e}, k_{low,e} \) for higher and lower current level is both negative and less than 1, when the average current is increased for low value, the luminous flux perform nonlinear behavior. It should reach the maximum value at certain average current. If the average current continues to increase, the average luminous flux starts to droop rapidly. The higher current level \( l_{high} \) should increase the heat dissipation coefficient and thermal effect on LED junction. In this case, the maximum average luminous flux of given average current will shift to a lower value.

(iii) For a given thermal resistance of heatsink and LED device, the reduction higher current level with improve thermal effect can increase maximum operated point.

(iv) For a given current level \( I_{high} \text{ and } I_{low} \), the variation of the luminous flux is dependent on both the thermal resistance of heatsink \( R_{hs} \) and duty cycle \( D \). If a higher thermal resistance of the heatsink is chosen, the duty cycle \( D \) should be decreased along with a lower average current \( I_{ave} \).

(v) For bi-level driving, with the same average current the luminous flux with duty cycle sensitivity is higher with a lower heatsink thermal resistance. If a larger heatsink \( (i.e., \text{lower } R_{hs}) \) is used, the shift scope for luminous flux is large under the identical variation of duty cycle \( D \).

### 2.5 A Simplified Model of CCT for the White LED Device With Bi-Level Driver

In this section, a simplified mathematical CCT-shift model will be derived for the case of LEDs driven by a bi-level current. As shown in Figs. 3 and 4, the CCT of the white LED device is related to the operated current and junction temperature. It means that the CCT of the white LED device with the higher current and lower current level is different value due to quantum confined Stark effects and junction heat. As shown in (2), the average luminous flux \( \phi_{ave} \) comprises the higher luminous flux \( \phi_{high} \) and the lower luminous flux \( \phi_{low} \). The nonlinear variation of CCT is dependent on luminous flux. If light of \( \phi_{low} \) is required, LEDs with the lower color temperature \( CCT_{low} \) are turned on. If light of \( \phi_{high} \) is required, LEDs with CCT of the lower color temperature \( CCT_{high} \) are turned on. Subsequently,
for light of luminous flux between $\phi_{high}$ and $\phi_{low}$, LEDs with bi-level driver are turned on and driven using by higher and lower current level such that the overall combined light emitted from the lamp includes the $CCT_{high}$ and $CCT_{low}$. Therefore, average CCT is as a function of the higher luminous flux $\phi_{high}$ and the lower luminous flux $\phi_{low}$. It can be shown in the following

$$CCT_{ave} = f(\phi_{high}, \phi_{low}) \quad \quad (6)$$

The average CCT of the white LED device with bi-level driver can be expressed as the color-mixing model of the white LED device with non-identical color performance from high/low current level [16]. The average CCT of the white LED device with bi-level driver at steady state can be respectively expressed as

$$CCT_{ave} = \frac{\phi_{high} + \phi_{low}}{CCT_{high} + CCT_{low}} \quad \quad (7)$$

Putting (5) into (7), the average CCT of the white LED device with bi-level driver can be rewritten as

$$CCT_{ave} = \frac{\phi_{ave}(D, E_{high,0}, E_{low,0}, k_{high,h}, k_{low,h}, k_{high,b}, k_{low,b}, I_{high}, I_{low}, R_{jc}, R_{hs})}{\phi_{high}(E_{high,0}, k_{high,h}, k_{high,b}, I_{high}, R_{jc}, R_{hs}) + \phi_{low}(E_{low,0}, k_{low,h}, k_{low,b}, I_{low}, R_{jc}, R_{hs})} \quad \quad (8)$$

Equation (8) shows a basic average CCT model of the white LED device with bi-level driver. It is the key equation linking the average CCT under bi-level driver, sensitivity coefficient of luminous efficacy/ heat dissipation at higher and lower current level $E_{high,0}/k_{high,h}$ and $E_{low,0}/k_{low,h}$, the higher/lower current level $I_{high}/I_{low}$ and the duty cycle, the thermal resistance of the heatsink $R_{hs}$ and the device $R_{jc}$. Generally, the junction temperature of the white LED device is related to the current level, duty cycle, heatsink size, and ambient temperature. It can be shown from (7) and (8) that the CCT approach the values corresponding to higher current and lower current under large and small duty cycles. With the other range, the mixing CCT shows nonlinear behavior with duty cycles. To investigation nonlinear properties of CCT, it should describe the color-shift properties under bi-level driver using by numerical calculations, while the proposed model can provide direct insights on the physical parameters that link to the CCT variation. It is noted that (7) and (8) can extend to a further development of the color modeling.

3. Practical Results and Discussions

In this section, the results of color and optical properties of the white LED device with bi-level driver are discussed. The luminous efficacy and stabilized CCT can be achieved based on a suitable dimming range. The boundary between higher current level and lower current level of the white LED device with a suitable heatsink can improve the optimal working range. The stabilized color variation can be accomplished based on active junction temperature with a temperature-controlled heatsink.

Fig. 6 shows that the measured luminous flux versus duty cycle of the white LED device with different higher and lower current level under bi-level driving method. The lower current level $I_{low}$ is maintained at 0.3 A, while the higher current level $I_{high}$ is chosen to be 0.7 A and 1 A respectively. As the higher current level $I_{high}$ is increased from 0.5 A to 0.7 A accompanied by keep constant $I_{low}$ of 0.1 A, the luminous flux is firstly increased from 181 lm to 198 lm. However, the luminous flux will drop faster as $I_{high}$ increase [luminous flux reduced to 167 lm at $I_{high} = 0.1$ A] due to poor luminous efficacy of higher current level. It is clearly shown that the maximum luminous flux of the white LED device with bi-level driver is highly dependent on higher current level, lower current level and duty cycle. With the constant of higher current level, the luminous flux increase with $I_{low}$ increasing under the large range of duty cycle. Fig. 7 shows that the measured luminous flux versus current curve of the white LED device under bi-level driver is nonlinear behavior. With the same dimming range, the luminous flux variation is different. The maximum luminous flux variation is about 133 lm with the current switching between 0.2 A and 0.68 A. If the selected dimming current range cuts across
Fig. 6. Measured luminous flux versus duty cycle of the white LED device with different higher and lower current level under bi-level driving method.

Fig. 7. Measured luminous flux versus current of the white LED device under bi-level driving method.

the inflection point of parabolic curve in Fig. 7, with the same dimming range, luminous flux variation could be reduced to 46 lm if $I_{\text{high}} = 0.91$ A and $I_{\text{low}} = 0.43$ A.

Fig. 8 shows the measured CCT and calculated as a function of duty cycle for the white LED device under different the higher/lower current level with bi-level driver. The lower current level $I_{\text{low}}$ is maintained at 0.3 A, while the higher current level $I_{\text{high}}$ is chosen to be 0.7 A and 1 A respectively. As the higher current level $I_{\text{high}}$ is increased from 0.7 A to 1 A accompanied by keep constant $I_{\text{low}}$ of 0.3 A, the CCT is firstly increased from 4830 K to 4977 K. The maximum deviation between calculated and measured results is 3.2%. The average deviation between theoretical and experimental values is about 2.1%. The calculated and measured results of the CCT have good agreement with different higher/lower current level and duty cycle.

Fig. 9 shows the measured CCT as a function of current for the white LED device with bi-level driver. The junction temperature of the white LED device dynamically varies based on the switching actions between the higher current level and the lower current level. For a given current level ($I_{\text{low}}$ and $I_{\text{high}}$), the average current is dependent on the duty cycle. With the thermal and electrical effect on the LED, the variation CCT is a similar parabolic behavior. The maximum CCT variation is about 310 K with the current switching between 0.32 A and 1 A. It can exceed the allowable CCT tolerance given in [12], where the non-perceivable CCT variation at target setpoint of 4500 K is about 243 K.
According to the parabolic trend of CCT variation with dimming range, a proper choice of the range from $I_{\text{low}}$ to $I_{\text{high}}$ could be kept stabilized color variation. CCT variation could be reduced to 180 K if $I_{\text{high}} = 0.74$ A and $I_{\text{low}} = 0.11$ A.

From the results, the following observations are noted.

(i) CCT of the white LED device with bi-level driver is not constant between the higher and lower current levels. The overall CCT variation can be significantly reduced with a proper choice of current level (from $I_{\text{low}}$ to $I_{\text{high}}$) and it could be kept stabilized color variation over the full dimming range.

(ii) The variation trend for CCT of the white LED device with bi-level driver versus average current is related not only to the average current and junction temperature, but also the full dimming range.

(iii) A smaller dimming range does not necessarily lead to a smaller luminous flux/CCT variation. As shown in Figs. 7 and 9, if the dimming current range cuts across the inflection point of parabolic curve, the CCT and luminous flux variation could be minimized.

(iv) If the heatsink size is limited to certain space, the heat concentrations appear in LED junction, the inflection point of parabolic curve in Figs. 7 and 9 should move to a lower current. Therefore, the dimming range should limit to the inflection point, which means the white LED device with a small operated range.
4. Conclusions

The color-shift and luminous flux variation of the white LED device with bi-level drive are discussed using a simplified model proposed in this paper. It is emphasized that the CCT and luminous flux of the white LED device with bi-level driver is a complex relationship among the higher current level, lower current level, duty cycle, thermal resistance, heat dissipation coefficient, and the physical parameters of the LED device. It is found that a smaller dimming range does not necessarily lead to a smaller luminous flux/CCT variation. If the dimming current range cuts across the inflection point of luminous flux/CCT variation curve with parabolic trend, the CCT and luminous flux variation could be reduced to a minimum level. Reduction variation of CCT and luminous flux of the white LED device with bi-level driver over a dimming range has been practically achieved. The proposed method can be easily adopted for improving the CCT and luminous flux stabilization of the white LED device with a bi-level driver.

References