

RESEARCH

Open Access



# Analysis and modeling for illuminance and signal-to-noise of smart traffic information system

Yaoting Chen<sup>1,2\*</sup> and Huanting Chen<sup>3</sup>

\*Correspondence:

[chenyaoting23@163.com](mailto:chenyaoting23@163.com)

<sup>2</sup> Analysis and Application  
for Business Big Data of Fujian  
Provincial Key Laboratory,  
Zhangzhou 363000, China  
Full list of author information  
is available at the end of the  
article

## Abstract

The traffic lights using by light emitting diode (LED) are able to indicate and provide the information about the ambient. The signal transmission performance of traffic system is related to a variety of factors such as the signal-to-noise ratio (SNR), illuminance. Several factors are influence on illuminance and SNR, such as eatsink temperature and driver parameters. It has not been any substantial investigate on the operated effects of traffic light with sinusoidal waveform driver on illuminance and SNR. With the use of heatsink temperature and driver parameters of the LED source with sinusoidal waveform driver, prediction modeling for the illuminance and SNR of the mixed white LED sources with heatsink temperature, frequency, amplitude voltage, bias voltage and amplification factors are proposed in this paper to enhance the illuminance and SNR model of LED source inside smart traffic information system. The proposed model should carry out a series of calibration step for illuminance, heatsink temperature and driver parameters, which are easy for traffic designer and source system designers to follow in the traffic information system. The proposed model has been measured for the mixed white LED sources, with reasonably good agreements between theoretical and practical results.

**Keywords:** Mixed white LED source, Optical characteristics, Electrical parameters, Sinusoidal waveform driver, Signal-to-noise ratio, Illuminance

## Introduction

The main advantages of traffic lights with LED application are better luminous efficiency and reliability, compared to incandescent-based traffic lights. Traffic flow can be controlled using by traffic lights [1]. For a given location, the traffic lights are able to indicate and provide the information about the ambient. In existing traffic information systems, the signals of traffic light are used to transmit traffic message using by display traffic jam on a map.

Flicker is dependent on operated parameters of LED source, such as spectrum, frequency, bias voltage, amplitude factor, voltage amplitude, and distance [2, 3]. The signal-to-noise ratio (SNR) is a key factor of the signal transmission of smart traffic information

system. The signal transmission performance of traffic system is related to a variety of factors such as the SNR, illuminance and frequency [4].

The value of SNR is 15 dBs for minimum acceptable range of traffic information application [5]. However, it is incorrect to assume that the SNR is constant in smart traffic system applications. It should point out that both of the light output of traffic application are sensitive to the operated conditions of LED sources. The light output of LED source with forward voltages and frequency were compared to evaluate the effects of the electrical properties on the SNR [6].

Several factors are influence on signal transmission of traffic information system. These factors include heatsink temperature and driver parameters, which is not considered into the system modeling. SNR is a key parameter of smart traffic information applications; however, it has not been any substantial investigate on the operated effects of traffic light with sinusoidal waveform driver on illuminance and SNR. Flicker for traffic lights is highly dependent on the driver operation.

A periodic waveform is dependent on several parameters, such as voltage amplitude, duty cycle, frequency etc. Therefore, the properties of a sinusoidal waveform can be determined as bias voltage, amplitude voltage, frequency and amplification factors. The properties of a sinusoidal waveform influences on human eye response. If frequencies is higher than 70 Hz, obvious detection of light flicker can cause uncomfortable symptoms of human beings [7]. Flicker also can be observed in signal transmission when the traffic light interacts with moving objects.

It is important mentioned that many light sources inside smart traffic information system display obvious flicker. Reduction flicker of light sources inside traffic information system is using by electronic solutions, which is major cause of lower power efficiency [8]. Reduction flicker of light source can also acquire using by slow-decay phosphors [9]. The optical variation performance of LED source with sinusoidal waveform driver in smart traffic information system is not well understood. In practice, the electronic engineer or the signal designers are not familiar with optical control for LED application with luminous efficiency, color characteristics, and reliability design.

The practical performance of the mixed light output of the mixed white LED source with a warm white LED and a cool white LED under sinusoidal waveform driver is investigated. The proposed model includes the variations on the heatsink temperature, bias voltage, amplitude voltage, frequency and amplification factors. The proposed model can estimate the illuminance and SNR with different heatsink temperature and driver parameters that cannot be easily evaluated in practice. The proposed model cover extends the illuminance and SNR of LED source inside smart traffic information system to include the key parameters of sinusoidal waveform. It is pointed out that the proposed model can be used as a design tool for traffic designs. The work is important to signal transmission of smart traffic information system designers because the operating temperature and driver parameters of LED sources may change.

## Methods

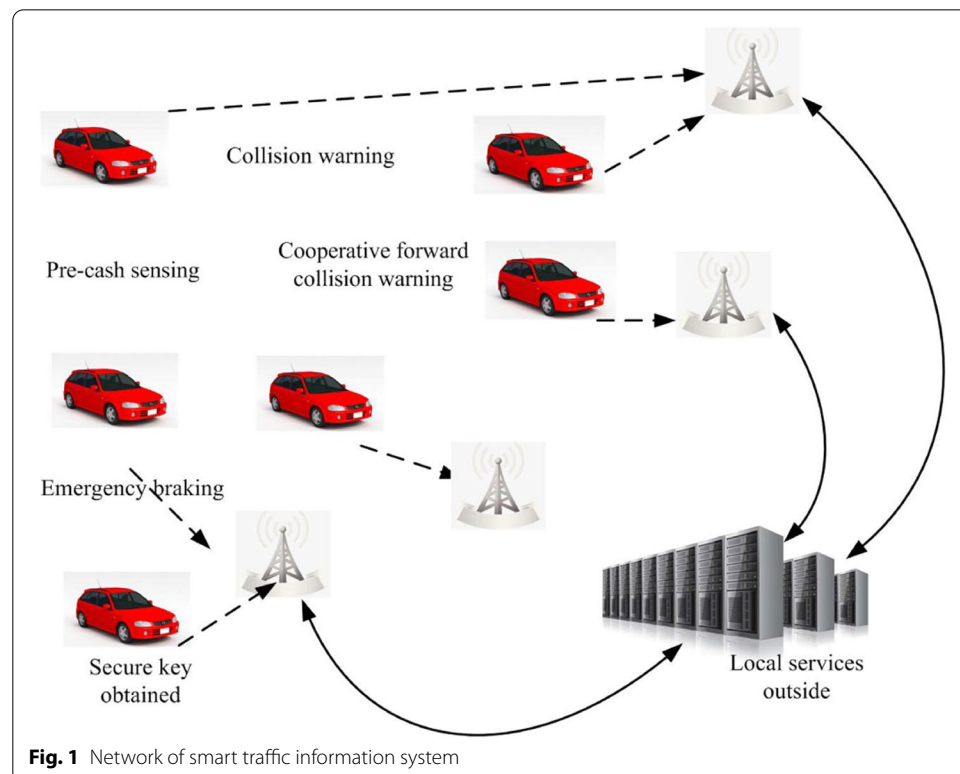
Smart traffic information system transmits information from light source to detector. The most important ability of smart traffic information system is to detect signals including given information with background noise [10, 11]. Traffic light can be used

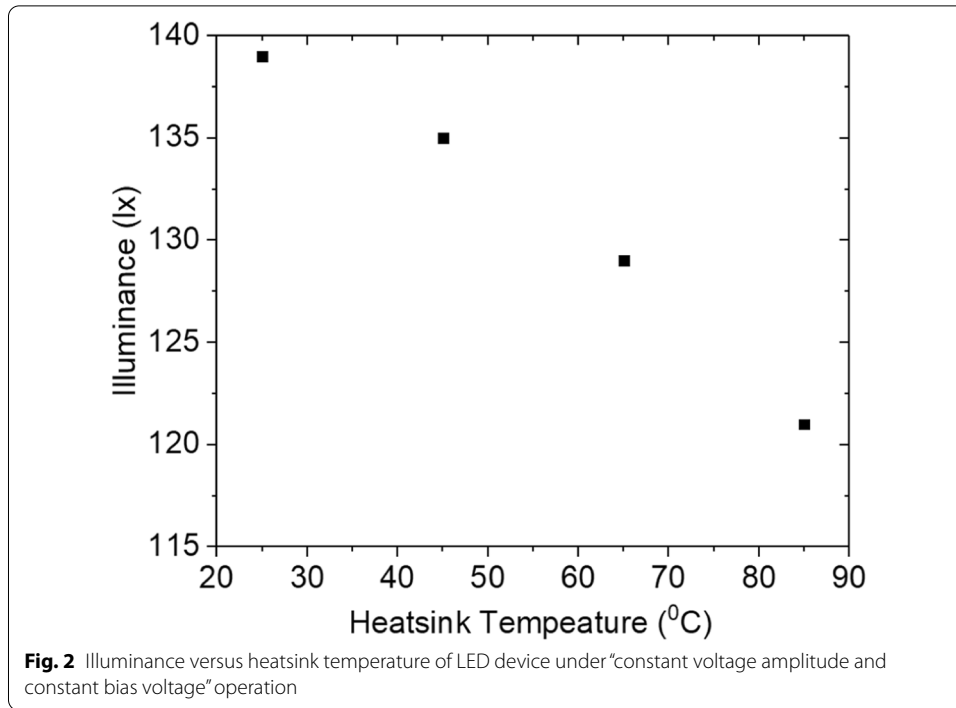
for signal transmission based on vehicle infrastructure system. The network of smart traffic information includes left turn assistant, lane change warning, and pre-cash sensing [3, 12, 13], as shown in Fig. 1.

The SNR is related to the acquired light power, which means that smart traffic information system perform high signal transmission mass with low signal loss. The noise sources of smart traffic information system are critical factors of signal distortion performance.

The LED should be used as signal transmission and lighting application. The illuminance, heatsink temperature and driver parameters of LED systems are highly related to each other. Modelling of the photometric, electric, thermal and colorimetric aspects of white LED devices is proposed [14]. The photo-electro-thermal (PET) theory has provided a series studying for the white LED system. There are given technical specifications for LED systems based on Energy Star Program and IEC standards [15, 16]. The proposed new PC-LED model considered several factors, such as energy-storage and dynamic properties of the phosphor coating. This new model can accurately predict dynamic optical and energy loss in PC LED device [17, 18].

Normally, the illuminance is dependent on the heatsink temperature, voltage amplitude, and bias voltage. The relationship is reflected on the heatsink temperature and illuminance of LED with the constant voltage amplitude and bias voltage as shown in Fig. 2. LED sample is mounted on a temperature-controllable heatsink. The illuminance as a function of the heatsink temperature for constant LED voltage amplitude and bias voltage operation is fairly linear. Therefore, the illuminance of LED as a





function of the heatsink temperature  $T_{hs}$  for constant LED voltage amplitude  $V_{a,0}$  and bias voltage  $V_{b,0}$  operation can be approximated as a linear relationship.

$$E(T_{hs}, V_{a,0}, V_{b,0}) = \alpha_1 T_{hs} + \alpha_2 \quad (1)$$

Where  $\alpha_1$  is a constant representing the slop and  $\alpha_2$  is another constant. Both  $\alpha_1$  and  $\alpha_2$  can be obtained from the measurement in Fig. 2.

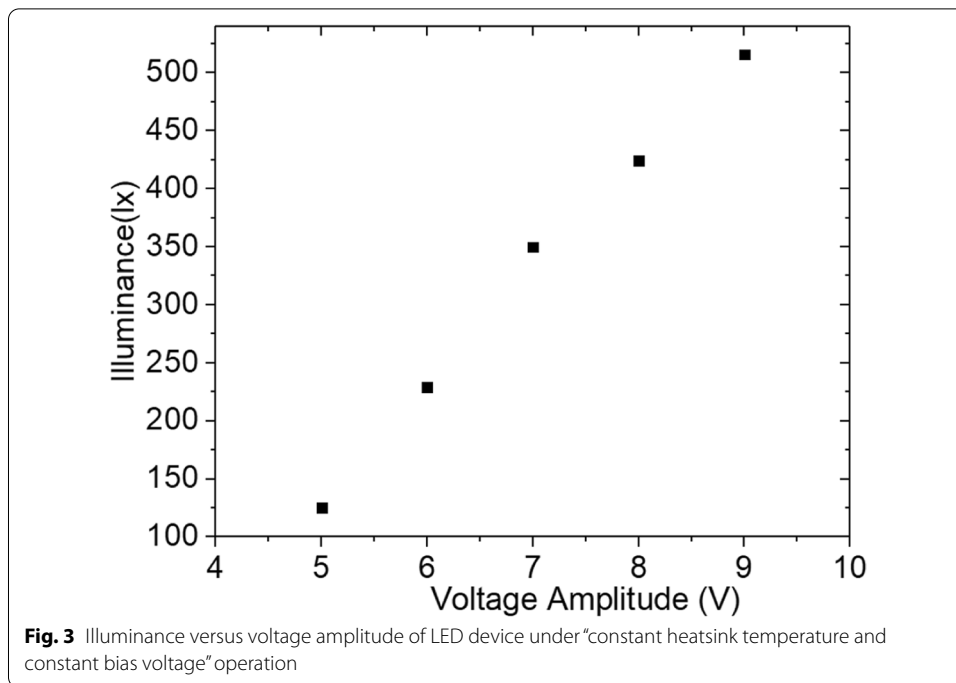
Using the Everfine LFA-3000 light flicker analyzer system, the practical measurements of the illuminance as a function of the LED voltage amplitude under “constant heatsink temperature and constant bias voltage” operation are obtained and shown in Fig. 3. Therefore, it can be given as

$$E(V_a, T_{hs,0}, V_{b,0}) = \beta_1 V_a^2 + \beta_2 V_a + \beta_3 \quad (2)$$

Where  $\beta_1$ ,  $\beta_2$ , and  $\beta_3$  are coefficients that can be extracted from Fig 3 with constant heatsink temperature and bias voltage.

Based on the above analysis,  $E$  can be obtained as heatsink temperature  $T_{hs}$  and voltage amplitude  $V_a$  with constant bias voltage using a two-dimensional mathematical function. Similar modeling method based on the 2D linear behavior has been proposed to [14]. Therefore, the illuminance  $E$  can be constructed as in the following

$$E(V_a, T_{hs}, V_{b,0}) = \frac{E(T_{hs}, V_{a,0}, V_{b,0})E(V_a, T_{hs,0}, V_{b,0})}{c_1} \quad (3)$$



Where  $c_1$  is intersection values of (1) and (2). It should be pointed out that the model can predict the illuminance of the LED at any heatsink temperature and voltage amplitude with constant bias voltage. Equation (3) links the illuminance to heatsink temperature and voltage amplitude together under constant bias voltage operation.

The illuminance of the LED device is highly related to the bias voltage. To establish the dependence on illuminance  $E$  on the bias voltage, the LED device is operated in the bias voltage 1 to 5 V under constant heatsink temperature  $T_{hs,0}$  and constant voltage amplitude  $V_{a,0}$  operation. Generally, illuminance  $E$  obviously increases with bias voltage, as shown in Fig. 4. The theoretical model of the illuminance behavior as quadratic function of the bias voltage is indicated in Fig. 4, as shown in the following.

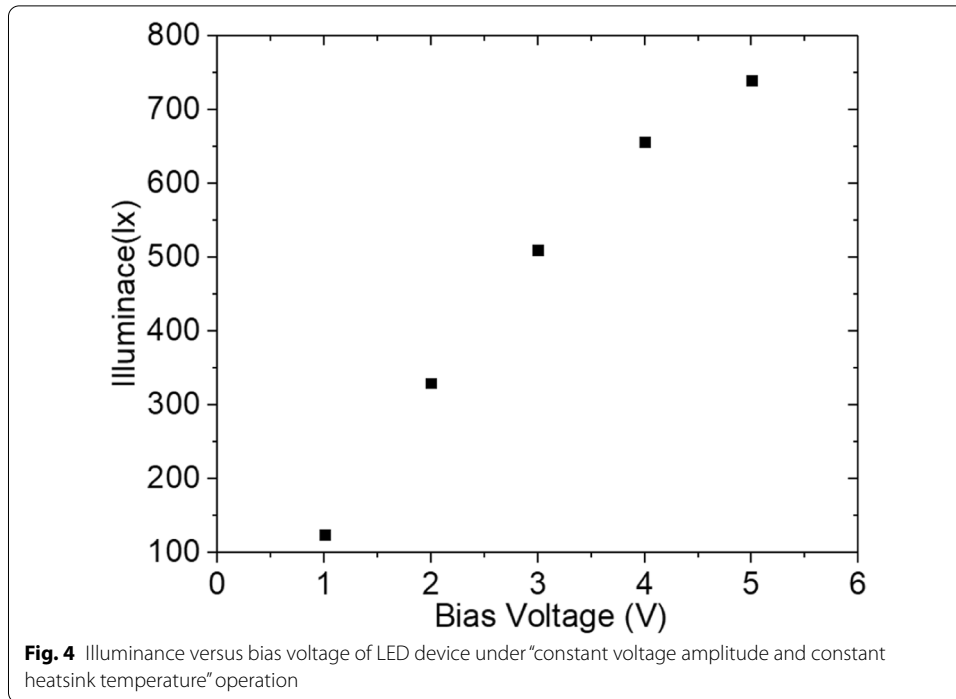
$$E(V_b, A_{a,0}, T_{hs,0}) = \chi_1 V_b^2 + \chi_2 V_b + \chi_3 \quad (4)$$

Where  $\chi_1$ ,  $\chi_2$  and  $\chi_3$  are coefficients that can be extracted from the experimental results in Fig. 4.

Combined with (3) and (4), the behavior of the illuminance of the LED is given by 3-D nonlinear function, as shown in (5), where  $c_2$  is the intersection value of function of (3) and (4). It is a model that combines the heatsink temperature  $T_{hs}$ , amplitude voltage  $V_a$  and bias voltage  $V_b$  aspects of an LED source.

$$E(V_a, T_{hs}, V_b) = \frac{E(T_{hs}, V_{a,0}, V_{b,0})E(V_a, T_{hs,0}, V_{b,0})E(V_b, A_{a,0}, T_{hs,0})}{c_2} \quad (5)$$

The experimental results of the illuminance behavior of the LED are related to bias voltage with constant amplification factors and frequency. It can be seen that illuminance curve is similar with Fig. 4. In practice, the illuminance  $E$  is approximately



nonlinearly proportional to the bias voltage  $V_b$  at constant amplification factors  $A_{f0}$  and constant frequency  $f_0$ , so it can be given as

$$E(V_b, A_{f0}, f_0) = \delta_1 V_b^2 + \delta_2 V_b + \delta_3 \quad (6)$$

Where  $\delta_1$ ,  $\delta_2$  and  $\delta_3$  are coefficients that can be extracted from experimental results of the illuminance as a function of the LED bias voltage with constant amplification factors and frequency.

Figure 5 shows the practical measurements of the illuminance  $E$  as a function of the LED amplification factors  $A_f$  with constant bias voltage  $V_{b0}$  and constant frequency  $f_0$ . Therefore, the illuminance can be expressed as

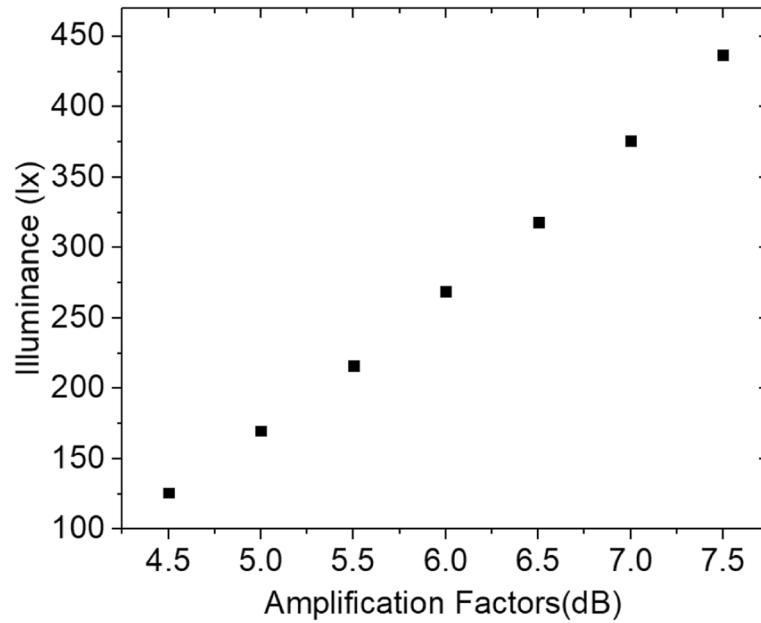
$$E(A_f, V_{b0}, f_0) = \varepsilon_1 A_f + \varepsilon_2 \quad (7)$$

Where  $\varepsilon_1$  and  $\varepsilon_2$  are coefficients that can be extracted from Fig. 5.

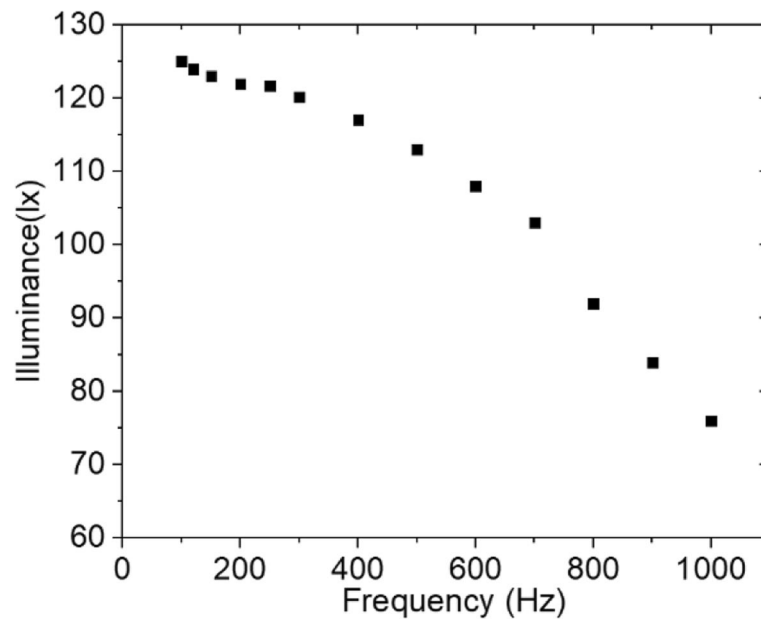
Based on the above analysis,  $E$  can be related to amplification  $A_f$  and bias voltage  $V_b$  using a two-dimensional function. Combined (6) and (7), illuminance of the LED device with bias voltage and amplification factors with constant frequency can be given as

$$E(A_f, V_b, f_0) = \frac{E(A_f, V_{b0}, f_0)E(A_{f0}, V_b, f_0)}{c_3} \quad (8)$$

Where  $c_3$  is intersection values of (6) and (7). It should be pointed out that this model can estimate the illuminance variation of the LED at any bias voltage and amplification factors with constant frequency. Equation (8) links the illuminance to bias voltage and amplification factors together.



**Fig. 5** Illuminance versus amplification factors of LED device under “constant bias voltage and constant frequency” operation



**Fig. 6** Illuminance versus frequency of LED device under “constant bias voltage and constant amplification factors” operation

Figure 6 shows the practical measurements of the illuminance  $E$  as a function of the LED frequency  $f$  with constant bias voltage  $V_{b,0}$  and constant amplification factors  $A_{f,0}$ . Therefore, the illuminance can be expressed as

$$E(A_{f,0}, V_{b,0}, f) = \mu_1 f^2 + \mu_2 f + \mu_3 \quad (9)$$

Where  $\mu_1$ ,  $\mu_2$  and  $\mu_3$  are coefficients that can be extracted from the practical measurements of the illuminance as a function of the frequency with constant amplification factors and bias voltage, as shown in Fig. 6.

Combined with (8) and (9), illuminance of the LED device with bias voltage, amplification factors and frequency can be given as

$$E(A_f, V_b, f) = \frac{E(A_{f,0}, V_{b,0}, f) E(A_f, V_{b,0}, f_0) E(A_{f,0}, V_b, f_0)}{c_4} \quad (10)$$

Where  $c_4$  is intersection values of function of (8) and (9). It should be pointed out that this equation can estimate the illuminance of the LED at any bias voltage, amplification factors and frequency. Equation (10) links the illuminance to bias voltage, amplification factors and frequency together.

Combined with (5) and (10), the illuminance as function of the LED device with five-dimensional parameters can be determined as

$$E(V_a, T_{hs}, V_b, A_f, f) = \frac{\left[ \frac{E(T_{hs}, V_{a,0}, V_{b,0}) E(V_a, T_{hs,0}, V_{b,0}) E(V_b, A_{a,0}, T_{hs,0})}{c_2} \frac{E(A_{f,0}, V_{b,0}, f) E(A_f, V_{b,0}, f_0) E(A_{f,0}, V_b, f_0)}{c_4} \right]}{c_5} \\ = \frac{\left[ \frac{E(T_{hs}, V_{a,0}, V_{b,0})}{c_2} \frac{E(A_f, V_{b,0}, f)}{c_4} \right]}{c_5} \quad (11)$$

Therefore, the overall illuminance of a mixed white LED device  $E_t(V_a, T_{hs}, V_b, A_f, f)$  with a cool white LED and a warm white LED is shown as Eq. (12)

$$E_t(V_a, T_{hs}, V_b, A_f, f) = E_c(V_a, T_{hs}, V_b, A_f, f) + E_w(V_a, T_{hs}, V_b, A_f, f) \\ = \frac{\left[ \frac{E_c(T_{hs}, V_{a,c}, V_{b,c})}{c_{2,c}} \frac{E(A_f, V_{b,c}, f)}{c_{4,c}} \right]}{c_{5,c}} + \frac{\left[ \frac{E_w(T_{hs}, V_{a,w}, V_{b,w})}{c_{2,w}} \frac{E(A_f, V_{b,w}, f)}{c_{4,w}} \right]}{c_{5,w}} \quad (12)$$

Where  $\Phi_c(V_a, T_{hs}, V_b, A_f, f)$  is individual illuminance of the cool white LED and  $\Phi_w(V_a, T_{hs}, V_b, A_f, f)$  is individual illuminance of the warm white LED.

Several important observations should be pointed out from Eq. (12):

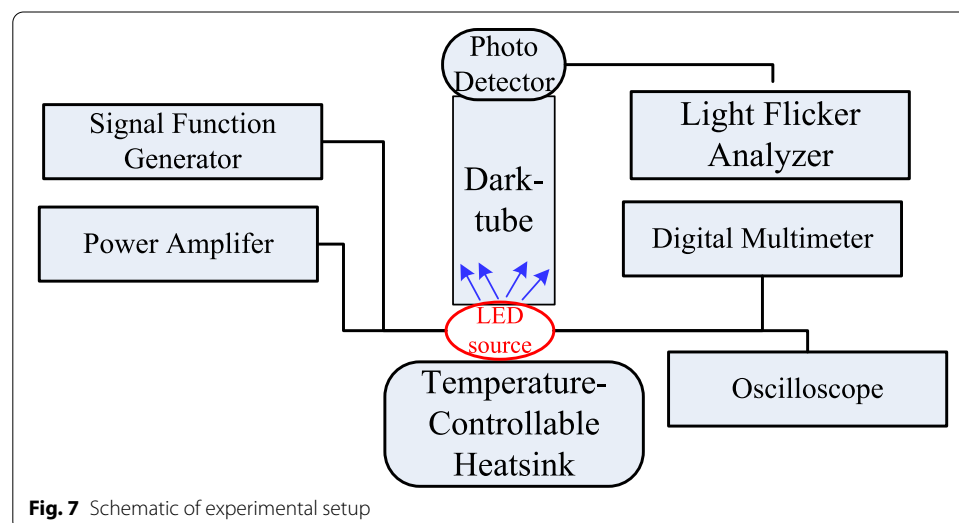
- (1) Equation (12) relates the illuminance to the heatsink temperature  $T_{hs}$ , frequency  $f$ , amplitude voltage  $V_a$ , bias voltage  $V_b$  and amplification factors  $V_f$  altogether. It is an equation that integrates the heatsink temperature and driver parameters of the LED device altogether.
- (2) LED device manufactures can use heatsink temperature  $T_{hs}$ , frequency  $f$ , amplitude voltage  $V_a$ , bias voltage  $V_b$  and amplification factors  $V_f$  in Eq. (12) to quantify the overall illuminance of a mixed white LED device. This new equation quantitatively sums up the relationship of illuminance, heatsink temperature  $T_{hs}$ , frequency  $f$ , amplitude voltage  $V_a$ , bias voltage  $V_b$  and amplification factors  $V_f$ .
- (3) The required parameters of the proposed model are calibrated from a series of measurement as shown in Figs. 2, 3, 4, 5, and 6.

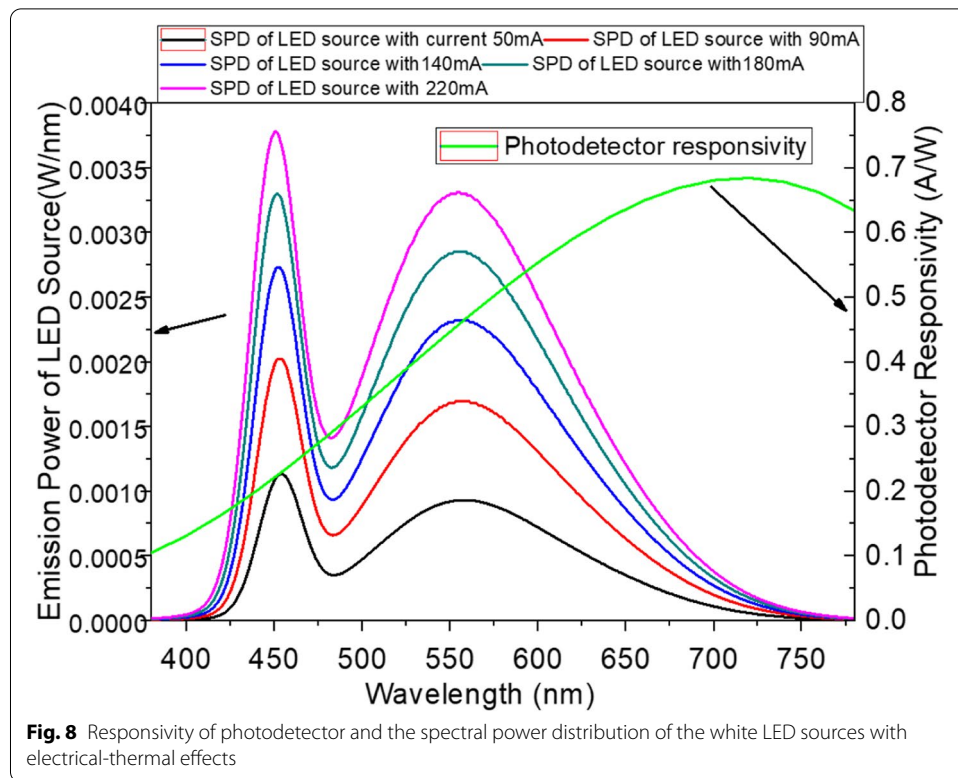


## Results and discussion

In the experiments, a cool white LED (CREE-XPE 1W) and a warm white LED (CREE-XPE 1W) making up the mixed white LED sources is mounted on a temperature-controllable heatsink. The rated CCT of the cool white and warm white LED are 5000 K and 2900 K respectively. The descriptions have been added above Fig. 7. Figure 7 shows the schematic of experimental setup. The light flicker analyzer (FA-3000) shows the waveform of the light output of the LED system with a sinusoidal wave of a given parameters (frequency: 100 Hz, heatsink temperature: 25 °C, amplitude voltage: 6 V, bias voltage: 2 V, amplification factors: 5 dB). A high power mixed white LED was electrically driven with different heatsink temperature. A wide band amplifier (Texas Instruments ATA-122D) adds the signal function (Gigol DG5071) to the DC component coming from DC power supply. The signal amplifying function with high speed is injected into the LED. The light output of the LED was captured from detector (FA-3000). The heatsink temperature is from 25 °C to 85 °C. The voltage amplitude is from 5 V to 9 V. The bias voltage is from 1 V to 5 V. The amplification factors are from 4.5 to 7.5. The frequency is from 100 Hz to 2000 Hz.

The illuminances of LED source are measured through the dark-tube, as shown in Fig. 7. The LED source is connected to photodetector by the dark-tube. The distance between the source and photo detector is 20 cm. Therefore, the environments have not influence on measured results of photodetector. The measured optical performance of the mixed white LED source is dependent on the responsivity for the photodetector and the spectral power distribution of the LED source. Fig 8 shows responsivity of the photodetector and spectral power distribution of LED source with different current. It is clearly shows that the responsivity for the photodetector is different from wavelength distribution. The spectral power distribution of LED source exhibit variation due to thermal and electrical factors. As shown in Eqs. (1) and (12), the signal-to-noise ratio and illuminance of the LED source is highly related to spectral power distribution of LED source.



**Table 1** Required coefficients for proposed model of cool white LED

Coefficient	Value	Coefficient	Value	Coefficient	Value
$a_{1,c}$	-0.3	$\chi_{2,c}$	5.3	$c_{3,c}$	130.5
$a_{2,c}$	147.5	$c_{2,c}$	125.3	$\mu_{1,c}$	-0.00005
$\beta_{1,c}$	97.7	$\delta_{1,c}$	-5.31	$\mu_{2,c}$	0.0041
$\beta_{2,c}$	-355.1	$\delta_{2,c}$	178.2	$\mu_{3,c}$	124.2
$c_{1,c}$	128.5	$\epsilon_{1,c}$	103.4	$c_{4,c}$	129.7
$\chi_{1,c}$	155.7	$\epsilon_{2,c}$	-347.2	$c_{5,c}$	128.4

The illuminance of cool white LED and warm white LED is measured at different heat-sink temperature  $T_{hs}$ , frequency  $f$ , amplitude voltage  $V_a$ , bias voltage  $V_b$  and amplification factors  $V_f$ . The required coefficients of cool white LED and warm white LED in Eq. (12) can be extracted in Tables 1 and 2.

Putting coefficients of Tables 1 and 2 into Eq. (12), the theoretical illuminance  $E_t(V_a, V_b, T_{hs}, f, V_f)$  with different heatsink temperature  $T_{hs}$ , frequency  $f$ , amplitude voltage  $V_a$ , bias voltage  $V_b$  and amplification factors  $V_f$  can be determined. The illuminance is measured at different operation conditions. The theoretical and measured illuminance curves are measured and shown in Figs. 9, 10, and 11. The theoretical results have good agreement with experiment result in Fig. 9 for a set of heatsink temperature, voltage amplitude, and bias voltage. The average deviation between the calculations and the measurements are about 7.9%. The maximum deviation between the calculations and the measurements are 13.6%. For experiments, a temperature-controlled heatsink

**Table 2** Required coefficients for proposed model of warm white LED

Coefficient	Value	Coefficient	Value	Coefficient	Value
$a_{1,w}$	− 0.42	$\chi_{2,w}$	4.5	$c_{3,w}$	112.3
$a_{2,w}$	121.6	$c_{2,w}$	102.2	$\mu_{1,w}$	− 0.00004
$\beta_{1,w}$	76.5	$\delta_{1,w}$	− 4.2	$\mu_{2,w}$	0.0034
$\beta_{2,w}$	− 295.2	$\delta_{2,w}$	154.3	$\mu_{3,w}$	103.2
$c_{1,w}$	96.6	$\varepsilon_{1,w}$	91.4	$c_{4,w}$	102.5
$\chi_{1,w}$	132.5	$\varepsilon_{2,w}$	− 267.5	$c_{5,w}$	105.5

is adjusted to control heatsink temperature of LED sample. The LED sources consist of multiplicity conductor materials. The temperature-controlled heatsink could not provide high-precision control on the junction temperature. It means that the practical junction temperature may be lower than target value due to imperfect heat flow path. That is major cause of errors between the calculations and measurements of Fig 9.

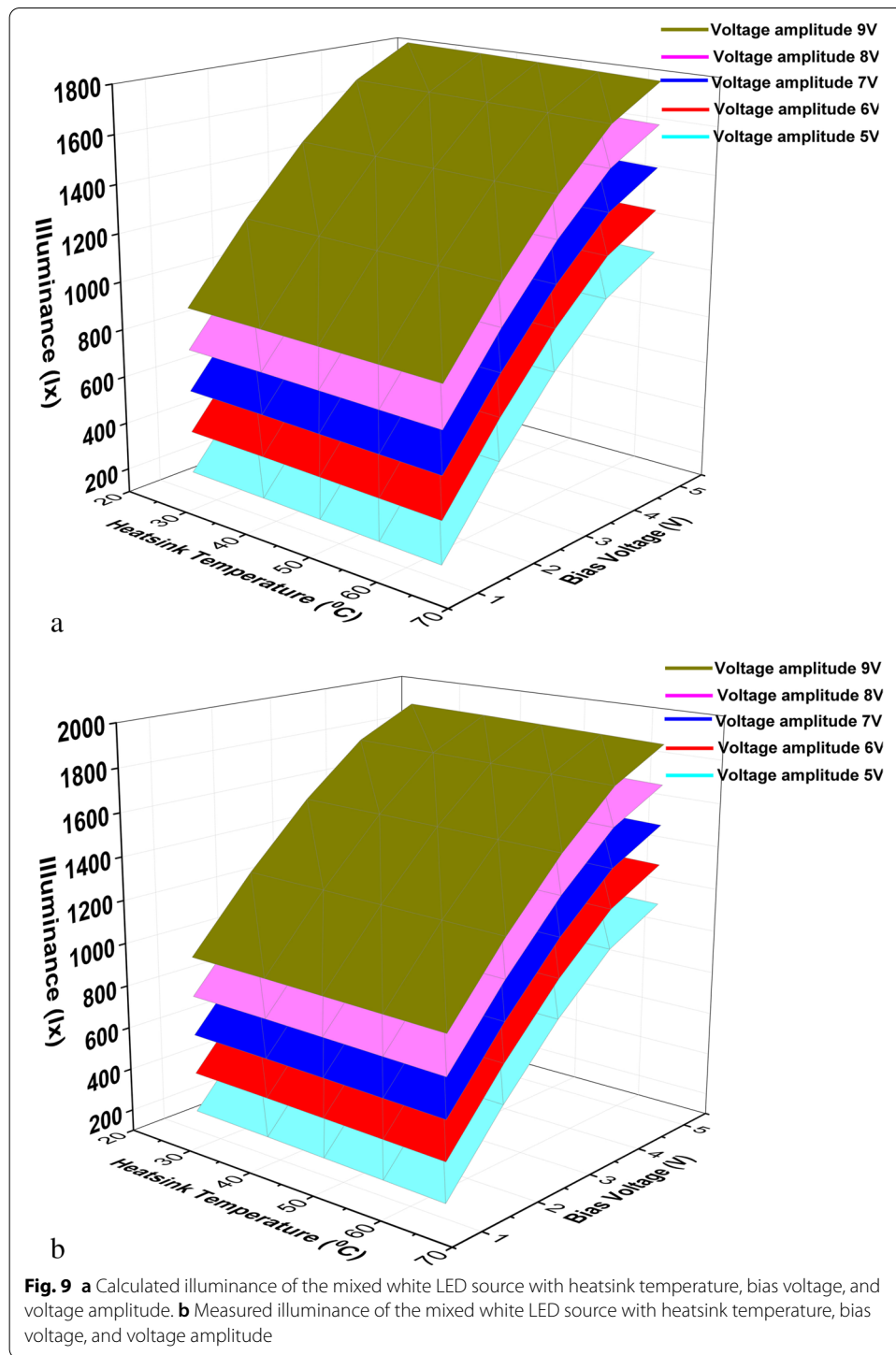
Based on coefficients in the Tables 1 and 2, the illuminance of the mixed white LED as a function of amplification factor, bias voltage and voltage amplitude is calculated using (12) and plotted in Fig. 10. In general, the calculated results are consistent with the practical measurements. The average deviation between the theoretical and experimental results is about 8.9%.

The measured and calculated illuminance of the mixed white LED source with frequency, bias voltage and voltage amplitude are shown in Fig. 11. The theoretical curves of illuminance are in good agreement with the measured ones. Given a constant bias voltage 4 V and voltage amplitude 5 V, it is important to note that at a controlled frequency of 100 Hz, illuminance is about 985.5 lx. When the frequency is 1000 Hz, illuminance decreases to 860.5 lx. It is noted that illuminance decreases with increasing operating frequency under constant power.

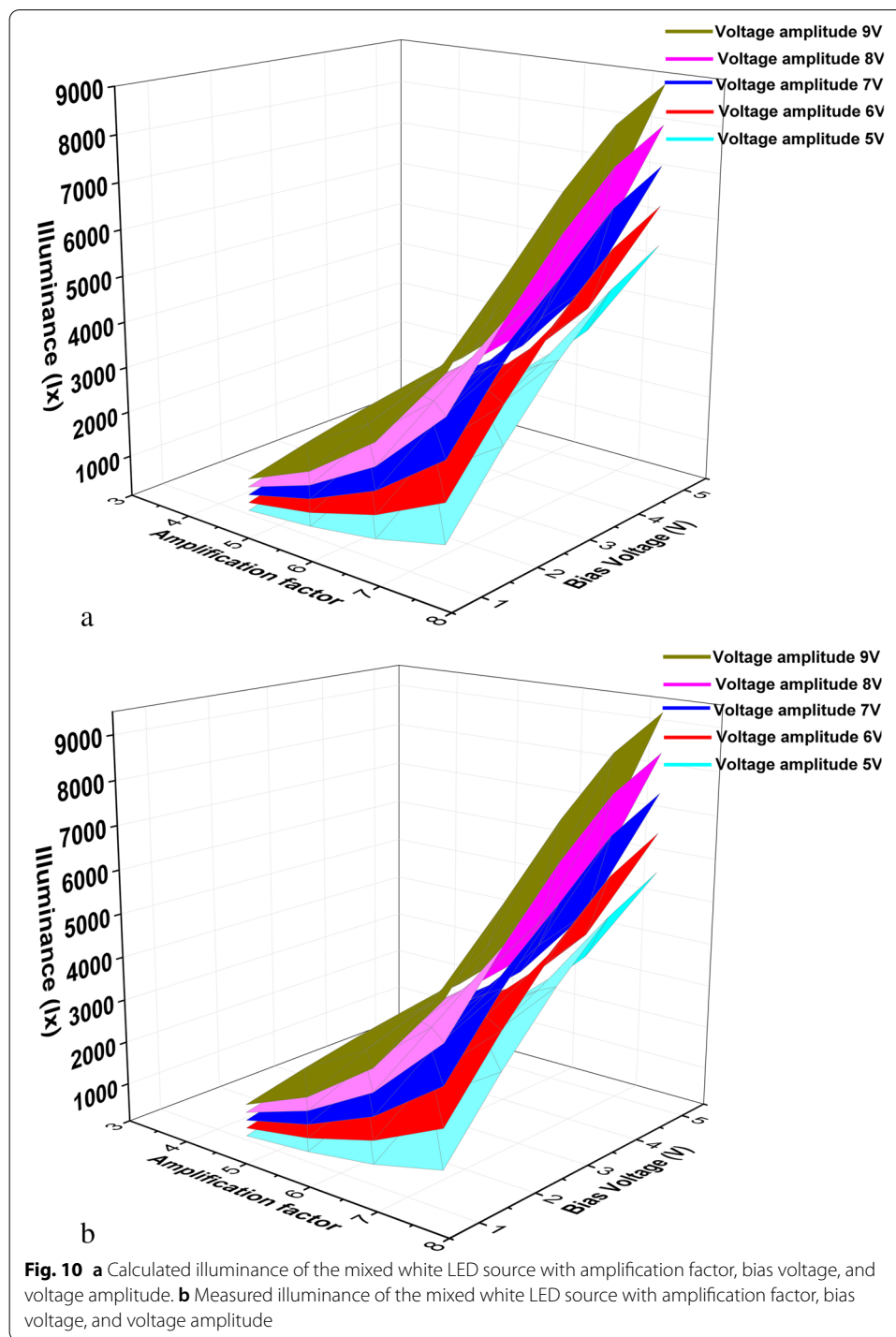
Figure 12 shows the calculated and measured SNR of the mixed white LED sources with frequency, bias voltage and voltage amplitude. The calculated values using the proposed model are generally consistent with the measurements. The average deviation between the theoretical and experimental results is about 13.5%. The variation SNR of the mixed white source with the bias voltage of 1V and voltage amplitude of 5 V is about 10.1% from frequency of 100 Hz to 2000 Hz. It is noted that the variation of SNR with frequency and voltage amplitude are kept within obvious ranges.

## Conclusions

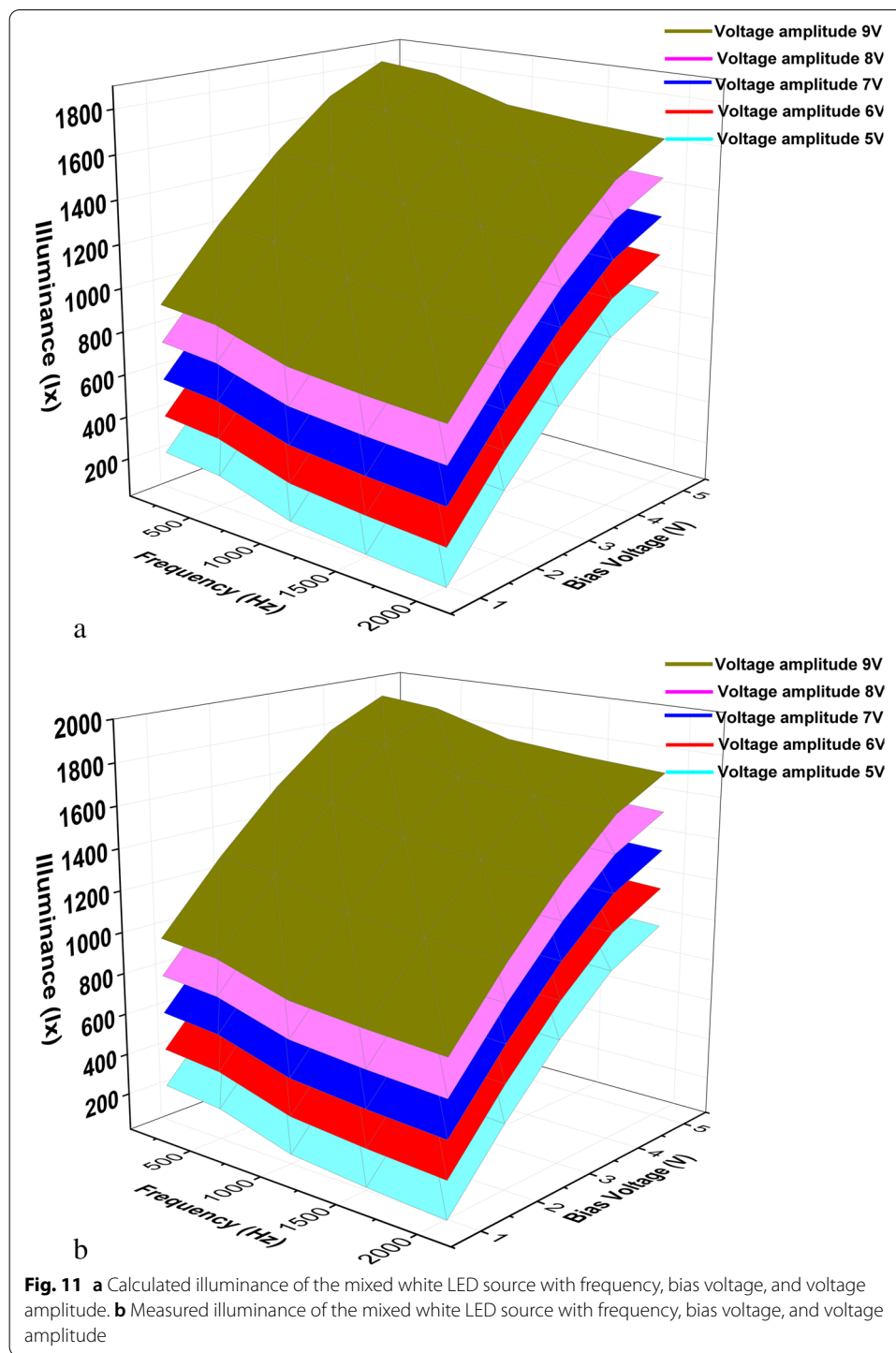
Currently, the LED optical model is investigated with DC, PWM, bi-level, and n-level driver. Actually, the optical performance for traffic light is related to sinusoidal waveform driver. In other words, the optical performance and SNR of traffic source using by LED device can be affected by sinusoidal waveform driver. There is still a lack of understanding on such aspects, which are important for the optimization of the traffic light design. In this paper, we attempted to develop a five-dimensional model to study sinusoidal waveform driver and heatsink temperature effects on illuminance and SNR performance of traffic light with LED source. A prediction method for the illuminance and SNR of the mixed white LED source with a warm white LED source and



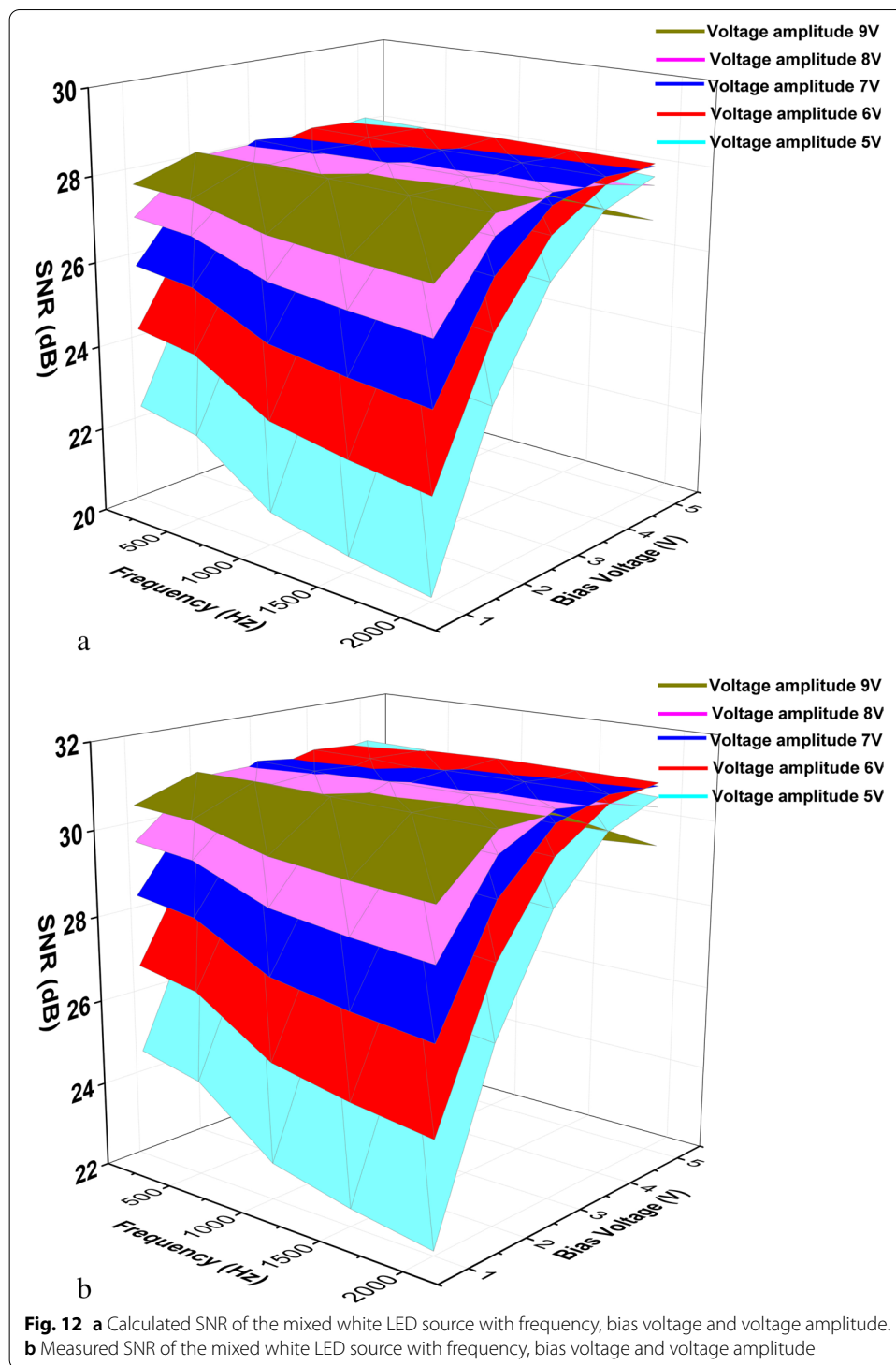
a cool white LED source as function of heatsink temperature, frequency, amplitude voltage, bias voltage and amplification factors is proposed in this paper. The proposed model can estimate the illuminance and SNR with different heatsink temperature and driver parameters. The proposed model cover extends the illuminance and SNR of LED source inside smart traffic information system to include the key parameters of



sinusoidal waveform. In general, the calculated results using by the proposed model are consistent with the practical measurements. The average deviation between the theoretical and experimental illuminance and SNR with different conditions is about 8.9% and 13.5% respectively. It is pointed out that the proposed model can be used as a design tool for traffic designs. LED manufacturers are encouraged to provide more



results such as illuminance and SNR as a function of frequency, bias voltage, amplification factors and amplitude voltage in the datasheets as basic coefficients for LED system designs for traffic information system. It should be pointed out that required parameters of the proposed modeling are specific parameters for traffic light using by



LED source. The re-calibration measurements should be carried out if the traffic light is used by the different type of LED.



### Abbreviations

$\alpha_1$ : Constant representing the slop and  $\alpha_2$  is another constant;  $\beta_1$ ,  $\beta_2$ , and  $\beta_3$ : Coefficients that can be extracted from Fig. 3 with constant heatsink temperature and bias voltage;  $c_1$ : is intersection values of (4) and (5);  $\chi_1$ ,  $\chi_2$  and  $\chi_3$ : Coefficients that can be extracted from the experimental results in Fig. 4;  $\delta_1$ ,  $\delta_2$  and  $\delta_3$ : Coefficients that can be extracted from experimental results of the illuminance as a function of the LED bias voltage with constant amplification factors and frequency;  $\varepsilon_1$  and  $\varepsilon_2$ : Coefficients that can be extracted from Fig. 5;  $c_3$ : Intersection values of (9) and (10);  $\mu_1$ ,  $\mu_2$  and  $\mu_3$ : Coefficients that can be extracted from the practical measurements of the illuminance as a function of the frequency with constant amplification factors and bias voltage;  $c_4$ : Intersection values of function of (11) and (12);  $\Phi_c (V_{a,c}, T_{hs,c}, V_{b,c}, A_{fc}, f_c)$ : Individual illuminance of the cool white LED;  $\Phi_w (V_{a,w}, T_{hs,w}, V_{b,w}, A_{fw}, f_w)$ : Individual illuminance of the warm white LED.

### Acknowledgements

Not Application.

### Authors' contributions

All authors contributed to the development and completion of this paper. YC did the conceptualization, preparation of manuscript, validation, formal analysis, data curation, and writing. HC performed the experiment and writing. All authors have read and agreed to the published version of the manuscript.

### Funding

This research was funded by National Natural Science Foundation of China (Grant Number: 61975072, 62001200), Natural Science Foundation of Fujian Province (Grant Number: 2020J01820), Industry-University-Research Collaboration Foundation of the Fujian Province (Grant Number: 2020H6017), Social Science Foundation of the Fujian Province (Grant Number: FJ2019B143) and Natural Science Foundation of the Zhangzhou (Grant Number: ZZ2019J15). Program for Innovative Research Team in Science and Technology in Fujian Province University (Optoelectronic Materials and Device Application), Natural Science Foundation of the Fujian Higher Education Institutions (Grant Number: JAT200316), National College Students' innovation and entrepreneurship training program (202110402001, 202110402013, 202110402028X).

### Availability of data and materials

The data presented in this study are available on request from the corresponding author. The data are not publicly available due to copyright considerations.

### Declaration

### Competing interests

The authors declare that they have no competing interests.

### Author details

<sup>1</sup>School of Business, Minnan Normal University, Zhangzhou 363000, China. <sup>2</sup>Analysis and Application for Business Big Data of Fujian Provincial Key Laboratory, Zhangzhou 363000, China. <sup>3</sup>College of Physics and Information Engineering, Minnan Normal University, Zhangzhou 363000, China.

Received: 23 December 2021 Accepted: 3 February 2022

Published online: 09 March 2022

### References

- Nian LX, Pei XM, Zhao ZL, Wang XZ (2019) Review of optical designs for light-emitting diode packaging. *IEEE Trans Compon Packag Manuf Technol* 9:642–648
- Akanegawa M, Tanaka Y, Nakagawa M (2001) Basic study on traffic information system using LED traffic lights. *IEEE Trans Intell Transp* 2:197–203
- Khan LU (2017) Visible light communication Applications, architecture, standardization and research challenges. *Digit Commun Netw* 3:78–88
- Lehman B, Wilkins AJ, Berman SM, Poplawski ME, Miller NJ (2011) Proposing metrics of flicker in the low frequencies for lighting application. *Leukos* 7:189–195
- Hussein HS, Hagag M, Farrag M (2020) Extended spatial-index LED modulation for optical MIMO-OFDM wireless communication. *Electronics* 9:168
- Uddin MS, Cha JS, Kim JY, Jang YM (2011) Mitigation technique for receiver performance variation of multi-color channels in visible light communication. *Sensors* 11:6131–6144
- Bialic E, Nguyen DC, Vaufrey D (2014) LED dynamic electro-optical responses and light-fidelity-application optimization. *Appl Opt* 53:7195–7201
- Wilkins AJ (1986) Intermittent illumination from visual display units and fluorescent lighting affects movements of the eyes across text. *Hum Factors* 28:75–81
- Karunatilaka D, Zafar F, Kalavally V, Parthiban R (2015) LED based indoor visible light communications: state of the art. *IEEE Commun Surv Tut* 17:1649–1678
- Spagnolo GS, Lecese F (2021) LED rail signals: full hardware realization of apparatus with independent intensity by temperature changes. *Electronics* 10:1291
- Visser D, Desieres Y, Swillo M, Luca ED, Anand S (2020) GaInP nanowire arrays for color conversion application. *Sci Rep* 10:22368
- Kahn JM, Barry JR (1997) Wireless infrared communications. *Proc IEEE* 85:263–298
- Lain JK, Chen YH (2021) An ANN-based adaptive for LED nonlinearity in indoor visible light communications. *Electronics* 10:948



14. Chen HT, Lee ATL, Tan SC, Hui SYR (2019) Electrical and thermal effects of light-emitting diodes on signal-to-noise ratio in visible light communication. *IEEE Trans Industrial Electron* 66:2785–2794
15. Chen HT, Hui SYR (2014) Dynamic prediction of correlated color temperature and color rendering index of phosphor-coated white light-emitting diodes. *IEEE Trans Ind Electron* 61:784–797
16. Hui SYR, Chen HT, Tao XH (2012) An extended photoelectrothermal theory for LED systems: a tutorial from device characteristic to system design for general lighting. *IEEE Trans Power Electron* 27:4571–4583
17. Lee ATL, Chen HT, Tan SC, Hui SYR (2016) Precise dimming and color control of LED systems based on color mixing. *IEEE Trans Power Electron* 31:65–80
18. Hui SYR, Lee ATL, Tan SC (2020) New dynamic photo-electro-thermal modeling of light-emitting diodes with phosphor coating as light converter part I: theory, analysis and modeling. *IEEE J Em Sel Top P* 20:777–779

### **Publisher's Note**

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

**Submit your manuscript to a SpringerOpen<sup>®</sup> journal and benefit from:**

- Convenient online submission
- Rigorous peer review
- Open access: articles freely available online
- High visibility within the field
- Retaining the copyright to your article

---

Submit your next manuscript at ► [springeropen.com](https://www.springeropen.com)

---