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An Estimation Method for the Efficiency of Light-Emitting Diode (LED) Devices

Xuehui Tao† and Bin Yang*

†*Department of Signal and Control Engineering, Soochow University, Suzhou, China

Abstract

The efficiency of light-emitting diode (LED) devices is a significant factor that reflects the capability of these devices to convert electrical power into optical power. In this study, a method for estimating the efficiency of LED devices is proposed. An efficiency model and a heat power model are established as convenient tools for LED performance evaluation. Such models can aid in the design of LED drivers and in the reliability evaluation of LED devices. The proposed estimation method for the efficiency and heat power of LED devices is verified by experimentally testing two types of commercial LED devices.

Key words: Efficiency, Heat power, Junction temperature, Light-emitting diode

I. INTRODUCTION

Light-emitting diode (LED) devices are now widely applied in general lighting systems, such as those used in commercial buildings, industrial buildings, and residences, because of their high efficiency, good reliability, long life span, and low power consumption. These devices are expected to become prevalent light sources in the near future. Unlike traditional gas discharge lamps, white LEDs nearly do not emit infrared light and ultraviolet light [1]. Apart from the electrical power used to generate optical power, all the residual electrical power of LEDs is converted into heat power.

Heat can degrade the internal and external quantum efficiency of LEDs. The performance and lifetime of LEDs are greatly affected by junction temperature [2]. The effects of junction temperature on the many aspects of LED performance have been extensively investigated. For example, models of luminous flux, which decreases with junction temperature, were proposed in [3], [4]. The variation of peak wavelength with junction temperature was studied, and the sensitive factor between peak wavelength and junction temperature was identified in [5], [6]. The relationship between chromaticity coordinates and junction temperature was determined in [7], [8]. The mathematical model of forward voltage as a function of junction temperature [9], [10], [11] is widely applied in the industry. The mechanism of efficiency, which decreases with temperature, was explored in [12], [13], but no efficiency model was established.

Injection current is another important factor of efficiency droop [14], [15]. The efficiencies of LEDs with microchips of varying sizes were experimentally compared in [14]. The experimental results presented the noteworthy effect of current density on efficiency droop [14]. Carrier loss mechanisms, including auger recombination [16], [17], carrier leakage [18], carrier delocalization [19], and electron overflow [20], [21], are known to be the cause of injection current that results in efficiency droop. Therefore, efficiency droop is a result of the simultaneous action of junction temperature and injection current. For this case, a model of efficiency as a function of both injection current and junction temperature is necessary and significant. An efficiency model can aid in the evaluation of the photometric and thermal performance of LEDs.

In the present work, a method for estimating the efficiency of LED devices is introduced. Unlike existing models, the proposed model of LED efficiency includes not only the effect of junction temperature but also the effect of injection current. The proposed model can specifically be used as a tool to estimate the efficiency of LEDs operated at practical conditions while considering the simultaneous action of junction temperature and current. The method for

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Recommended for publication by Associate Editor Jee-Hoon Jung.
†Corresponding Author: xhtao@suda.edu.cn
Tel: +86 18362638304, Soochow University
*Department of Signal and Control Engineering, Soochow University, China

determining the new parameters of the efficiency model is illustrated in detail. Furthermore, a calculation equation for the dissipated heat power of LED devices is proposed. The efficiency and heat power models are not only applicable to performance and reliability evaluation but also helpful in LED driver design. The validity of the estimation method for efficiency and heat power is verified with experimental measurements.

II. MODELING FOR EFFICIENCY AND HEAT POWER OF LED DEVICES

A. Modeling for Efficiency of LED Device

To build a general model, the efficiency of a LED device is measured under two independent operating conditions. The tests are performed in the TeraLED-T3ster system [22] (Fig. 1). The LED device is mounted on an active temperature-controlled plate installed in the TeraLED equipment. The junction temperature is monitored by measuring the forward voltage of the LED device. The temperature-sensitive parameter is calibrated in advance by driving the LED with a small current of 5 mA. The LED device is then driven with a practical operating current. After the LED junction temperature reaches a steady state, the TeraLED equipment begins to measure the optical parameters, such as efficiency, luminous flux, and optical power. Once the measurements are accomplished, the LED device is turned off, and the T3ster equipment begins to capture the thermal transient response in real time to record the cooling curve. The thermal characteristics, such as junction temperature, thermal time constant, and thermal capacitance, are derived from the evaluation of the cooling curve.

In the first set of tests, the injection current of the LED device is maintained at a constant value while the efficiency of the LEDs under different junction temperatures is recorded. In the second set of tests, the junction temperature of the LEDs is set to be constant, and the efficiency of the LED device under different injection currents is measured. A pre-calibration of the case temperature is needed to set the junction temperature to a target value. Fig. 2 provides the measured efficiency at different junction temperatures. Fig. 3 provides the measured efficiency at different injection currents. The efficiency of each point in the curve of Fig. 3 is measured with the same junction temperature to eliminate the effect of self-heating. In Figs. 2 and 3, each testing condition needs to be reset for each measurement point.

Fig. 2 shows that efficiency linearly decreases with junction temperature. From Fig. 3, efficiency is observed to exponentially decrease as injection current increases.

Fig. 2 also demonstrates that for various injection currents, efficiency exhibits different decrease curves. The efficiency lines exhibit various slopes and intercepts. Therefore, on the basis of this phenomenon, the efficiency equation is characterized as

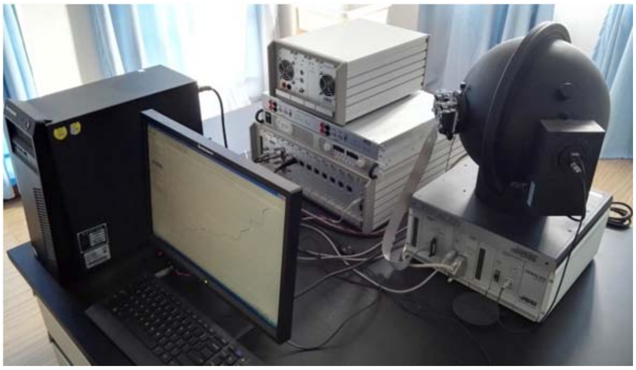

Fig. 1. Joint test system of TeraLED-T3ster equipment.

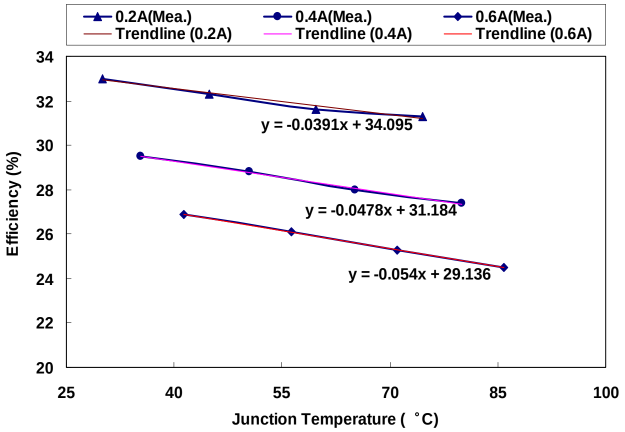

Fig. 2. Efficiency degradation with increasing junction temperature.

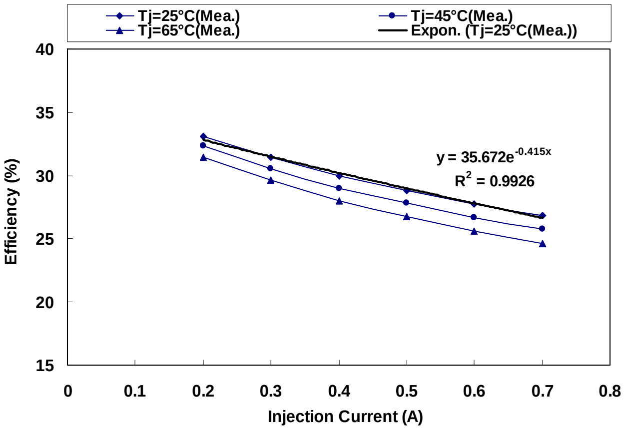

Fig. 3. Efficiency degradation with injection current.

$$\eta = -c_t(T_j - T_o) + \eta\big|_{25^oC} \tag{1}$$

where η is efficiency and c_t is designated as the temperature coefficient of efficiency, which represents the degradation rate of efficiency with increasing junction temperature. $\eta\big|_{25^oC}$ is efficiency at a junction temperature of 25 °C. T_o is the typical temperature equal to 25 °C.

Temperature coefficient c_t expresses the intensity of the

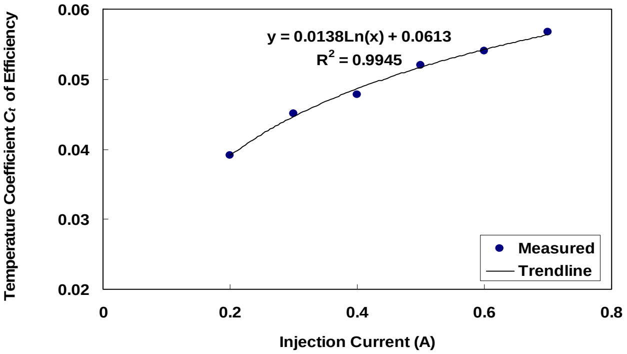

Fig. 4. Temperature coefficient of efficiency at different injection currents.

effect of temperature on efficiency. In Fig. 2, the slope of each curve is distinct, which means that the intensity of the effect of temperature on efficiency is various. With this phenomenon, the temperature coefficient c_t is investigated. Fig. 4 shows the temperature coefficient c_t at different injection currents. As c_t reflects the intensity of efficiency, which decreases with junction temperature, each value of c_t in Fig. 4 is directly read from the slope of the η-T_j curve in Fig. 2. Fig. 4 shows that c_t increases with the injection current in logarithm form. The temperature coefficient of efficiency as a function of current is expressed as

$$c_t = c_{ti} \ln I + c_{to} \tag{2}$$

where c_{ti} and c_{to} are constant coefficients.

In Fig. 2, the intercepts of the measured curves with the y-axis are the values of efficiency at a junction temperature of 25 °C, i.e., $\eta|_{25^{\circ}C}$. The curves at different injection currents feature various intercepts, hence, $\eta|_{25^{\circ}C}$ varies with the current.

In Fig. 3, the first line is $\eta|_{25^{\circ}C}$, which reflects the change in $\eta|_{25^{\circ}C}$ with the injection current. Through curve fitting, we find that the first line follows an exponential function. Therefore, $\eta|_{25^{\circ}C}$ is expressed in Equ. (3) as

$$\eta|_{25^{o}C} = c_o \exp\left(-c_i I\right) \tag{3}$$

where c_o represents the maximum efficiency at a junction temperature of 25 °C and c_i denotes the decay coefficient of efficiency with the current at a junction temperature of 25 °C.

With Equs. (1), (2), and (3), the overall efficiency equation of an LED device is finally expressed as

$$\eta = -\left(c_{ti} \ln I + c_{to}\right)\left(T_j - T_o\right) + c_o \exp\left(-c_i I\right) \tag{4}$$

B. Modeling for Dissipated Heat Power of LED Device

For LED devices, heat is primarily generated from three regions, namely, contacts, cladding layers, and active region. In the region of the contacts and cladding layers, heat is mainly generated by the current that passes through the parasitic resistances. In the active region, heat is created by a non-radiative recombination. At a low current, heat generated in the parasitic resistances of the contacts and cladding layers is small because of the small joule heating of I^2R, whereas the heat generated in the active region is dominant. At a high current, the heat from the contacts and cladding layers becomes important because of the increase in I^2R.

The dissipated heat power of an LED device can be calculated by subtracting the emitted power from the applied electrical power. The relationship of the power distribution of an LED device is given by

$$P_{heat} = P_d - P_{opt} \tag{5}$$

where P_{heat} is the dissipated heat power of an LED device, P_d is the applied electrical power, and P_{opt} is the emitted optical power.

The efficiency of LED devices characterizes their energy conversion capability. It is defined as the ratio of optical power to input electrical power, that is,

$$\eta = \frac{P_{opt}}{P_d} \tag{6}$$

Therefore, according to Equs. (5) and (6), the heat power equation is obtained as

$$P_{heat} = P_d - \eta P_d \tag{7}$$

By substituting the LED efficiency equation in Equ. (4) into the heat power equation in Equ. (7), the equation of dissipated heat power as a function of both injection current and junction temperature is obtained as

$$P_{heat} = \left[1 + \left(c_{ti} \ln I + c_{to}\right)\left(T_j - T_o\right) - c_o \exp\left(-c_i I\right)\right] P_d \tag{8}$$

C. Method for Determining Coefficients c_{ti}, c_{to}, c_i, and c_o

The coefficients of c_{ti}, c_{to}, c_i, and c_o, in the efficiency equation in Equ. (4) and heat power equation in Equ. (8) are related to device properties. For various types of LED devices, these coefficients differ. When adopting the efficiency model (4) and heat power model (8) to evaluate LED performance, the coefficients in the two equations should be determined in advance.

1) Determining Coefficients c_{ti} and c_{to}: In Equ. (2) and Fig. 4, coefficients c_{ti} and c_{to} are used to describe the temperature coefficient c_t. Therefore, coefficients c_{ti} and c_{to} can be determined through the temperature coefficient c_t, which is the degradation rate of efficiency versus junction temperature.

For a constant injection current, the degradation rate of efficiency versus junction temperature is the same as the degradation rate of efficiency versus case temperature because junction temperature and case temperature has the following relationship: $T_c = T_j - R_{jc}k_hP_d$. Therefore, the degradation rate can be realized by measuring the LED efficiencies under two different case temperatures.

The specific procedures are as follows.

Step 1: The LED device is driven with injection current I_1, and LED efficiency is measured at two different case temperatures, T_{c1} and T_{c2}. The measured efficiencies are recorded as η_1 and η_2, respectively. With the measured points (T_{c1}, η_1) and (T_{c2}, η_2), the degradation rate of efficiency can be determined and recorded as c_{t1}.

Step 2: The same LED device is driven with another current I_2, and the measurements in *Step 1* are repeated. The obtained degradation rate of efficiency at current I_2 is recorded as c_{t2}.

Step 3: By substituting c_{t1} and c_{t2} into Equ. (2), two calculation equations are obtained as

$$c_{t1} = c_{ti} \ln I_1 + c_{to} \tag{9}$$

$$c_{t2} = c_{ti} \ln I_2 + c_{to} \tag{10}$$

where I_1, I_2, c_{t1}, and c_{t2} are the parameters obtained in *Step 1* and *Step 2*.

With the above mentioned two equations, the coefficients c_{ti} and c_{to} of an LED device are determined.

2) Determining Coefficients c_i and c_o: Coefficients c_i and c_o in Equ. (3) are used to express $\eta|_{25^\circ C}$. Thus, c_i and c_o can be determined by measuring $\eta|_{25^\circ C}$ at two different driving currents, I_1 and I_2. To maintain the junction temperature of the LED device at 25°C, its case temperature should be pre-calibrated with the relation of $T_c = T_j - R_{jc} k_h P_d$.

By substituting the measured $\eta|_{25^\circ C\text{-}1}$ at current I_1 and measured $\eta|_{25^\circ C\text{-}2}$ at current I_2 into Equ. (3), two calculation equations are obtained as

$$\eta|_{25^\circ C\text{-}1} = c_o \exp\left(-c_i I_1\right) \tag{11}$$

$$\eta|_{25^\circ C\text{-}2} = c_o \exp\left(-c_i I_2\right) \tag{12}$$

where $\eta|_{25^\circ C\text{-}1}$ and $\eta|_{25^\circ C\text{-}2}$ are the measured $\eta|_{25^\circ C}$ at current I_1 and I_2, respectively.

The coefficients c_i and c_o are determined by solving Equs. (11) and (12), respectively.

III. EXPERIMENTAL VERIFICATION

Two types of commercial LED devices from different manufacturers are used to verify the validity of the proposed estimation method for efficiency and heat power. The tested type-one LED is a CREE XLamp XR-E LED (Cree XREWHT-L1-0000-00C01) [23], whereas the tested type-two LED is SEOUL N42180 LED (N42180-EC01) [24] (Fig. 5). The measurements, including the thermal parameter and optical parameter measurements, are conducted with a TeraLED-T3ster equipment [25], [26]. The LED samples are mounted to a Peltier-cooled fixture that is installed in the integrating sphere of the TeraLED-T3ster equipment. The Peltier-cooled fixture includes an active temperature-controlled plate, which is used to stabilize LED temperature for optical and thermal measurements. The optical measurements of the LED devices are accomplished in the TeraLED equipment after the junction temperature reaches a thermal steady state. The thermal measurements of the LED devices are conducted in the T3ster equipment connected to the TeraLED equipment. After the optical measurements, the TeraLED equipment switches off the LED devices and instructs the T3ster equipment to begin monitoring the cooling transient of the LED devices. With this combined equipment, the temperature-dependent parameters, such as efficiency, luminous flux, optical power, and heat power, are measured.

(a) Type-one LED device. (b) Type-two LED device.

Fig. 5. Tested components of type-one and type-two LED devices.

A. Determining Coefficients c_{ti}, c_{to}, c_i, and c_o for the Two Types of LED Devices

1) Coefficient Determination for Type-one LED Device: The type-one LED device is first driven with a current of $I_1 = 0.3$ A. LED efficiency is measured at two different case temperatures. Fig. 6 shows the practically measured two points of efficiency. The degradation rate of efficiency is 0.0451. Therefore, $c_{t1} = 0.0451$ at a current of 0.3 A. The type-one LED device is then driven with another current, $I_2 = 0.7$ A. At two different case temperatures, $T_{c1} = 25$ °C and $T_{c2} = 70$ °C, LED efficiency is calculated, as shown in Fig. 6 with a blue color. The measured temperature coefficient of efficiency is $c_{t2} = 0.0567$ at a current of 0.7 A.

By substituting the data of $I_1 = 0.3$ A and $c_{t1} = 0.0451$ and the data of $I_2 = 0.7$ A and $c_{t2} = 0.0567$ into Equ. (2), two calculation equations for c_{ti} and c_{to} are obtained as

$$0.0451 = c_{ti} \ln(0.3) + c_{to} \tag{13}$$

$$0.0567 = c_{ti} \ln(0.7) + c_{to} \tag{14}$$

By solving the two equations, the coefficients c_{ti} and c_{to} of the type-one LED device are respectively determined as

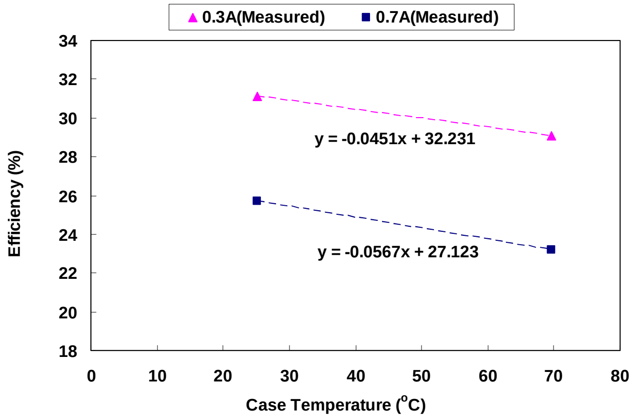

Fig. 6. Measured efficiency of type-one LED device at $I_1 = 0.3$ A and $I_2 = 0.7$ A.

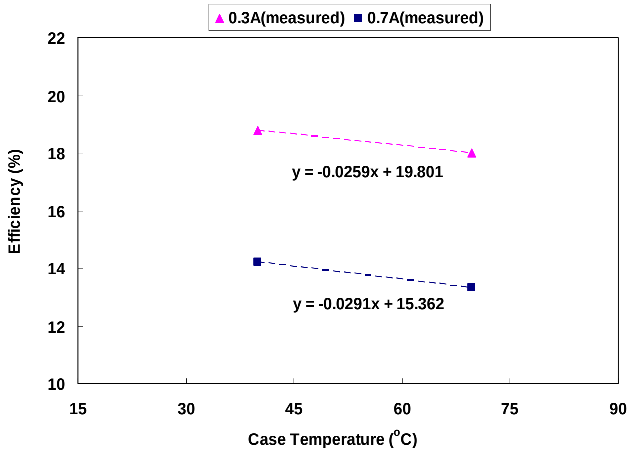

Fig. 7. Measured efficiency of type-two LED device at case temperatures $I_1 = 0.3$ A and $I_2 = 0.7$ A.

$$c_{ti} = 0.0137,\quad c_{to} = 0.0616$$

To determine the coefficients c_o and c_i, the efficiency at the junction temperature of 25 °C, i.e., $\eta|_{25^{\circ}C}$, is measured. The measurements are carried out at two different currents, 0.3 and 0.6 A. The measured $\eta|_{25^{\circ}C}$ at current $I_1 = 0.3$ A is 31.426. At injection current $I_2 = 0.6$ A, the measured $\eta|_{25^{\circ}C}$ is 27.786.

By substituting the data of $I_1 = 0.3$ A and $\eta|_{25^{\circ}C\text{-}1} = 31.426$ and the data of $I_2 = 0.6$ A and $\eta|_{25^{\circ}C\text{-}2} = 27.786$ into Equ. (3), the calculation equations for c_o and c_i are obtained as

$$31.426 = c_o \exp\left(-0.3c_i\right) \tag{15}$$

$$27.786 = c_o \exp\left(-0.6c_i\right) \tag{16}$$

By solving Equs. (15) and (16), the coefficient of c_i and c_o are determined as $c_i = 0.41$ and $c_o = 35.54$, respectively.

2) Coefficient Determination for Type-two LED Device: At driving current $I_1 = 0.3$ A, the efficiency of the type-two LED device is measured at two different case temperatures. At $T_{c1} = 40$ °C, the measured efficiency is $\eta = 18.76$. At $T_{c2} = 69.6$ °C, the measured efficiency is $\eta = 18.00$ (Fig. 7). The degradation rate of efficiency with junction temperature is $c_{t1} = 0.0259$. At driving current $I_2 = 0.7$ A, the same procedure is repeated, and the measured degradation rate is $c_{t2} = 0.0291$.

TABLE I

TYPE-ONE LED DEVICE PARAMETERS

c_{ti}	c_{to}	c_o	c_i
0.0137	0.0616	35.54	0.41

By substituting the data of $I_1 = 0.3$ A and $c_{t1} = 0.0259$ and the data of $I_2 = 0.7$ A and $c_{t2} = 0.0291$ into Equ. (2), coefficients c_{ti} and c_{to} of the type-two LED device are calculated as $c_{ti} = 0.0037$ and $c_{to} = 0.0304$, respectively.

To obtain coefficients c_o and c_i, $\eta|_{25^{\circ}C}$ at two different injection currents is measured. With the same procedure, the determined parameters are $c_i = 0.58$ and $c_o = 22.9$.

B. Verification of Proposed Estimation Model for Efficiency and Heat Power of LED Devices

1) Type-one LED Device: The efficiency of the type-one LED device is estimated with the proposed estimation model. The obtained coefficients c_i, c_o, c_{ti}, and c_{to} for the type-one LED device are shown in Table I.

By substituting the parameters in Table I into Equ. (4), the efficiency equation of the type-one LED device is obtained as

$$\begin{aligned}\eta = &-\left(0.0137\ln I + 0.0616\right)\left(T_j - T_o\right) \\ &+ 35.54\exp\left(-0.41I\right)\end{aligned} \tag{17}$$

With Equ. (17), the variation of efficiency with junction temperature is calculated and plotted in Fig. 8. Efficiency linearly decreases with junction temperature. For different injection currents, efficiency exhibits different decrease curves. To compare the calculated data with the measured data, the measured efficiencies under the same operating condition are plotted in Fig. 8 in blue color. The measurements are performed with the TeraLED-T3ster equipment. Junction temperature is calibrated with the Peltier-cooled fixture and T3ster equipment. The maximum error between the calculations and the measurements is observed at a low current (0.2 A). As the current increases, the model becomes increasingly accurate. Therefore, this model is highly suitable for high-powered LED lighting sources. In Fig. 8, the maximum error between the calculated results and the measured results is 0.37, whereas the average error is 0.16. In general, the calculated and measured results achieve good agreement.

The variation of efficiency with injection current is also evaluated. The calculated variation of efficiency with current according to Equ. (17) is plotted in Fig. 9 in pink color. The measured variation of efficiency with current under the same

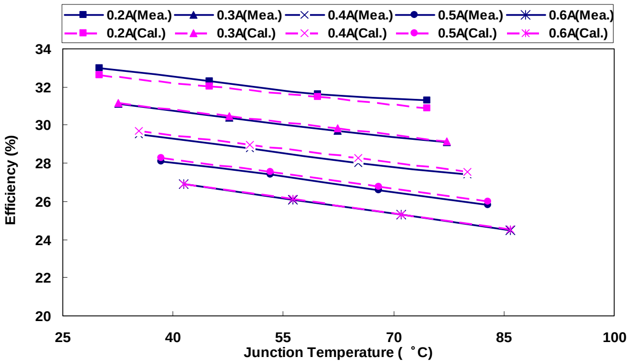

Fig. 8. Calculated and measured efficiency versus junction temperature of type-one LED device.

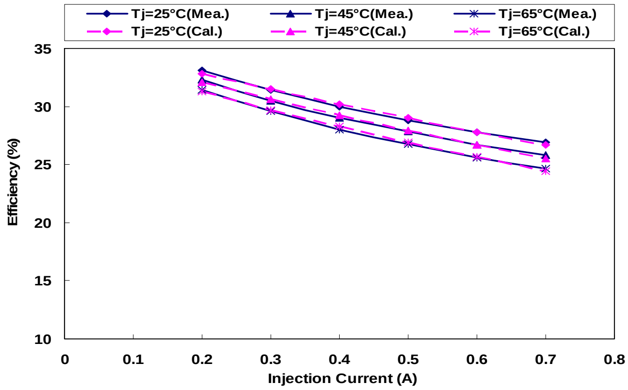

Fig. 9. Calculated and measured efficiency versus injection current of type-one LED device.

operating condition is plotted in Fig. 9 in blue color. Efficiency exponentially decreases with injection current. The maximum error is observed at a low current and low junction temperature, namely, 0.2 A and 25 °C, respectively. The maximum error between the estimation and the measurement is 0.29, and the average error of all the measured data is 0.15. In general, the calculated and measured values show good agreement.

The heat power of the type-one LED device is estimated with the proposed heat power model. By substituting the parameters in Table I into Equ. (8), the specific heat power equation of the type-one LED device is

$$P_{heat} = [1+\left(0.0137\ln I + 0.0616\right)(T_j - T_o) - 35.54\exp\left(-0.41I\right)]P_d \tag{18}$$

According to Equ. (18), the heat power of the LED device is calculated. Fig. 10 shows the calculated and measured heat power. The maximum error for the heat power estimation of the type-one LED device is 0.019. The average error of the type-one LED device is 0.004. Thus, the calculated heat power is highly consistent with the measured heat power.

2) Type-Two LED Device: To verify the proposed efficiency equation, which can be applied to other types of LED devices, another commercial LED device is tested. The coefficients of the type-two LED device are listed in Table II.

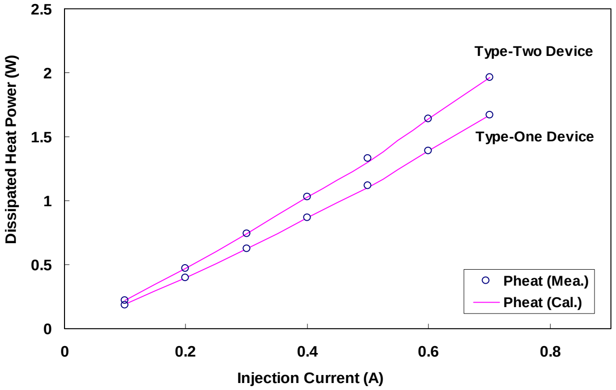

Fig. 10. Calculated and measured dissipated heat power of LEDs.

TABLE II

TYPE-TWO LED DEVICE PARAMETERS

c_{ti}	c_{to}	c_o	c_i
0.0037	0.0304	22.9	0.58

By substituting the parameters in Table II into Equ. (4), the efficiency equation of the type-two LED device is obtained as

$$\eta = -\left(0.0037\ln I + 0.0304\right)(T_j - T_o) + 22.9\exp\left(-0.58I\right) \tag{19}$$

On the basis of Equ. (19), the variation of efficiency with junction temperature when the injection current is kept constant is calculated and plotted in Fig. 11. The efficiency of the type-two LED device under the same operation condition is measured and plotted in Fig. 11 in blue color. Similar to that of the type-one LED device, the maximum error of the type-two LED device is observed at a low current. Meanwhile, the accuracy of the model increases as the current increases. The average error between the calculations and measurements is 0.15, whereas the maximum error is 0.35. The calculated results agree well with the measured results. This good agreement verifies the validity of the proposed equation.

The effect of the injection current on the efficiency of the type-two LED device is also investigated. Fig. 12 shows the variation of efficiency with the injection current. Efficiency exponentially decreases with the injection current. The maximum error of 0.33 is observed at a low current. The average error is 0.15. Therefore, the calculated results based on Equ. (19) are highly consistent with the measured results, thus confirming the validity of the proposed efficiency equation.

The heat power of the type-two LED device is calculated by substituting coefficients $c_{ti} = 0.0037$, $c_{to} = 0.0304$, $c_o = 22.9$, and $c_i = 0.58$ into Equ. (8). The heat power calculation equation of the type-two LED device is given by

$$P_{heat} = [1+\left(0.0037\ln I + 0.0304\right)(T_j - T_o) - 22.9\exp\left(-0.58I\right)]P_d \tag{20}$$

where $T_o = 25$ °C.

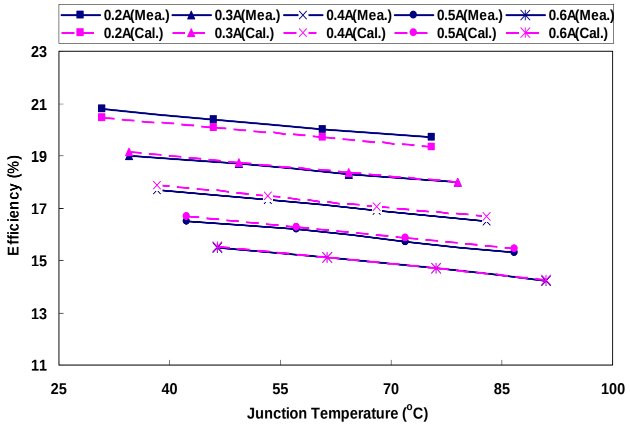

Fig. 11. Calculated and measured efficiency versus junction temperature of type-two LED device.

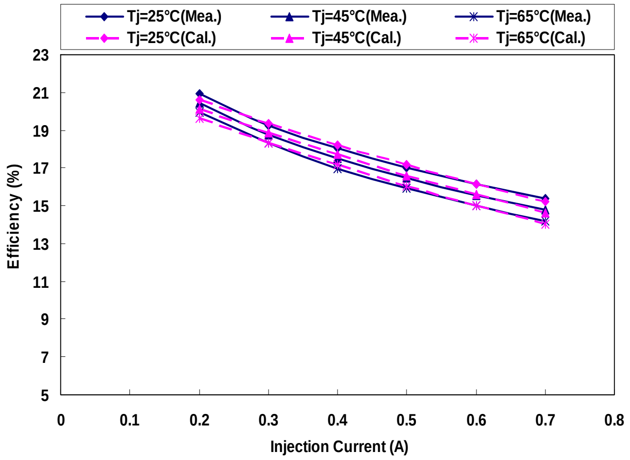

Fig. 12. Calculated and measured efficiency versus injection current of type-two LED device.

The calculated and measured heat power at different injection currents of the type-two LED device is shown in Fig.10. The maximum error for the heat power estimation of the type-two LED device is 0.028, whereas the average error of the type-two LED device is 0.006. The good consistency of the data verifies the validity of the heat power equation in Equ. (20) and the effectiveness of the estimation method.

On the basis of the tested and estimated results from Figs. 8–12, the following observations and insights are derived.

1) Junction temperature and injection current perform important functions in the reduction of efficiency. Efficiency exponentially decreases with injection current and linearly decreases with junction temperature.
2) With regard to the effect of junction temperature, Figs. 8–11 show that efficiency uniformly decreases with junction temperature. Hence, the effect of junction temperature is constant for a constant current. The effect of junction temperature on efficiency is represented by factor c_t in this paper. However, c_t differs for various currents. The temperature coefficient c_t increases with the current in the logarithm. Such finding can aid in the design of LED drivers. For a DC current driving technology, designers could use the linear relationship between efficiency and junction temperature to achieve a constant efficiency output by controlling the junction temperature of LED devices. The proposed equation of c_t is applicable to the determination of the specific relation of efficiency and junction temperature for practical driving currents.
3) As shown in Figs. 9 and 12, in a low current region, efficiency decreases by 2% for each 0.1 A of current. By contrast, in high current regions, the decrease of efficiency becomes slow. This phenomenon indicates that when junction temperature is kept constant and the effect of self-heating is consequently eliminated, the decrease of efficiency with the current is faster in low current regions than in high current regions. The efficiency model can be adopted to estimate the emitted efficiency before choosing a suitable driving current.
4) The increase in the heat power of LED devices is the result of the combined action of junction temperature and injection current. As shown in Fig. 10, the growth rate of heat power increases with the increasing current. This phenomenon indicates that the effect of injection current on dissipated heat power gradually accelerates. One reason is that at high current levels, the heat power generated from the parasitic resistance I^2R becomes increasingly important. Thus, high current driving accelerates the aging of LED devices.

IV. CONCLUSION

Efficiency reflects the energy conversion capability of LED devices. In this study, an estimation method for the efficiency and heat power of LED devices is proposed. An efficiency model and a heat power model are established. The method for determining each coefficient in the model is introduced. The behaviors of efficiency and heat power under each operating condition are then analyzed and explained in detail. The temperature coefficient c_t of efficiency is found to increase in logarithm with the current. The efficiency and heat power models provide a convenient tool for LED manufacturers to estimate the photometric and thermal performance of LED devices. The results of this work will contribute to the reliability evaluation of LED devices.

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Xuehui Tao was born in China. She received her B.S. degree in Electronic Science and Technology and M.S. degree in Electronics Engineering from Southwest Jiaotong University, China. She obtained her Ph.D. degree from Electronics Engineering from the City University of Hong Kong, Hong Kong, in 2012. She is currently an Associate Professor in the Department of Signal and Control Engineering, Soochow University, China. Her current research interests include the design and reliability study of power electronic devices and power electronic systems.

Bin Yang was born in Jiangsu, China, in 1993. He received his B.S. degree in Electrical Engineering from Soochow University, Suzhou, China, in 2014. He is currently working toward an M.S. degree in Power Electronics in the Department of Signal and Control Engineering, Soochow University, China. His current research interest is the design of switching model power supply, which involves LED driver design and power factor correction technology.