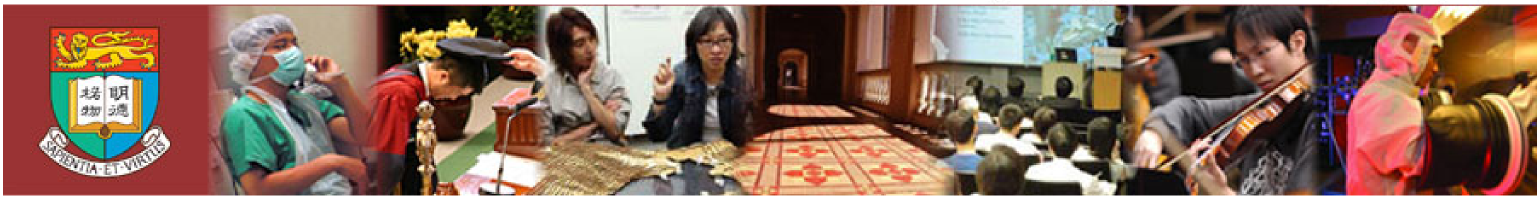

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Citation	IEEE Transactions on Power Electronics, 2012, v. 27 n. 4, p. 2176-2183
Issued Date	2012
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Estimation of Optical Power and Heat-Dissipation Coefficient for the Photo-Electro-Thermal Theory for LED Systems

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***Abstract*—With the use of wall-plug efficiency, estimation techniques for the optical power and heat-dissipation coefficient of LEDs are introduced in this paper to enrich the photo-electro-thermal theory, which has provided a framework for analyzing LED systems. The estimation methods consist of simple procedures for optical and electrical power measurements, which are easy for LED device manufacturers and system designers to follow. The extended theory has been tested with several types of LED devices, with reasonably good agreements between theoretical and practical results.**

***Index Terms*—Light-emitting diodes, optical characteristics, thermal design.**

I. Introduction

IN response to demands for high brightness, the driving power of LED packages has been continuously increasing. In high-power GaN-based LEDs, the current density can be as high as 200 A/cm^2. The light output of an LED package reaches a maximum level, at a certain current density, and then begins to decrease as current density increases. The effect of luminous flux reduction with increasing current has been largely studied and linked to several mechanisms, such as current leakage, by tunneling of electrons to the states of InGaN/GaN interfaces [1], the effects of auger recombination [2] and of built-in piezoelectric fields [3]. The interactions of photometric, electrical, and thermal aspects have been described mathematically in the photo-electro-thermal (PET) theory [4]–[6] for LED systems. The PET theory can be used to optimize the design of an LED system and determine the operating point of maximum luminous flux per watt. It can also be used to set criteria of the optimal thermal design of the appropriate heatsink for a given application. In addition, junction temperature is a critical parameter and affects luminous efficacy, maximum light output, and reliability [7]–[11]. However, it is impossible to directly measure the junction temperature due to encapsulation. Many research teams have reported measurements of the junction temperature of the LED by voltage–temperature dependence [12], micro-Raman spectroscopy [13], electroluminescence [14], thermography [15], and a noncontact method [16]. However, most measurement methods require complex equipment setups for precise junction temperature. In [5], the heat-dissipation coefficient of the LED is measured by submerging the LED into silicon oil. Such a measurement method provides accurate thermal measurements, but at the expense of a long experiment time period, because each steady-state measurement may take almost 3 h to obtain (i.e., thermal measurements can only be taken after the whole tank of silicon oil reaches its steady-state temperature).

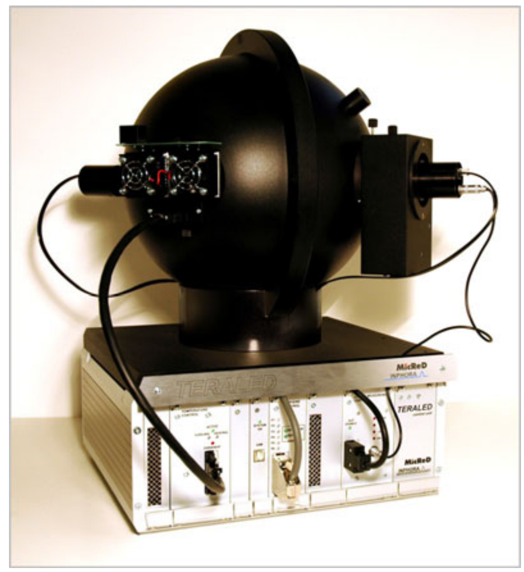

Fig. 1. Photograph of a TeraLED transient thermal tester.

In this paper, the PET theory is extended with the use of wall-plug efficiency as a function of current and temperature to determine the optical power and the heat-dissipation coefficient that are required in the theory. A fast measurement procedure consisting of a simple optical and electrical power measurement based on the use of the TeraLED transient thermal tester (T3ster system) (see Fig. 1) is illustrated. Based on this procedure, the optical power and the heat-dissipation coefficient of the LED can be estimated. The parameters obtained in this fast procedure are applied to the original PET theory to predict the optical power,

Manuscript received April 24, 2011; revised July 12, 2011; accepted August 11, 2011. Date of current version February 20, 2012. This work was supported by the Hong Kong Research Grant Council under Research Grant HKU-114411. Recommended for publication by Associate Editor J. M. Alonso.

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Digital Object Identifier 10.1109/TPEL.2011.2165736

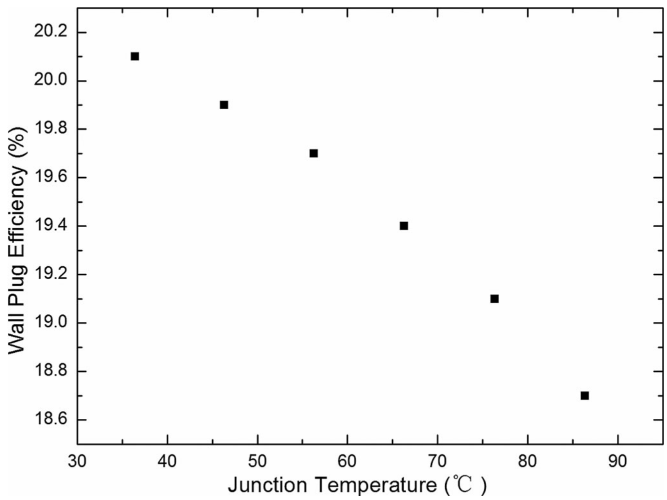

Fig. 2. Relation of wall-plug efficiency versus junction temperature under "constant electrical power" operation.

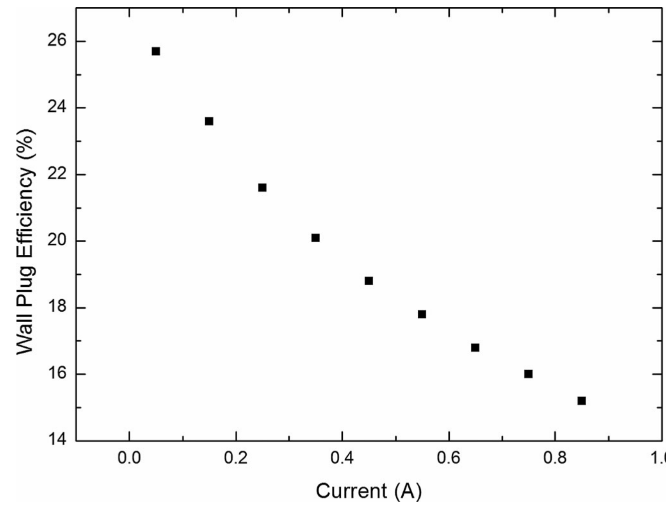

Fig. 3. Relation of wall-plug efficiency versus current under "constant junction temperature" operation.

heat-dissipation coefficients, and internal junction temperature that cannot be easily accessed in practice.

II. Wall-Plug Efficiency, Optical Power, and Heat-Dissipation Coefficient for the PET Theory

A. Procedure for Extracting the Parameters for Wall-Plug Efficiency and Optical Power

Let P_{opt} be the optical power of an LED device

$$P_{\mathrm{opt}} = \eta_W P_d \tag{1}$$

where η_W is the wall-plug efficiency and P_d is the electrical power of the LED.

Normally, the wall-plug efficiency depends on the junction temperature and the injection current [3]. The relationship is reflected in the junction temperature T_j and wall-plug efficiency η_W of the LED (model number CREE XREWHT-L1-0000-007F5) with the constant electrical power P_{d0} as shown in Fig. 2. These practical measurements in Fig. 2 are obtained with the use of a TeraLED T3ster system that provides practical measurements of the internal junction temperature of the LED device. The TeraLED T3ster system enables the temperature of the mounting plate (on which the LED device is placed) to be controlled. In the practical operating range, the relationship of the wall-plug efficiency η_W as a function of the junction temperature T_j for constant LED power P_{d0} operation is fairly linear and can, therefore, be approximated as a linear relationship

$$\eta_W(T_j, P_{d0}) = \alpha T_j + \beta \tag{2}$$

where α is a constant representing the slope and β is another constant. Both α and β can be obtained from the measurements in Fig. 2.

To establish the dependence of η_W on the LED current, the LED is operated in the pulse width of 300 μs and duty cycle of 0.03% in order to eliminate joule heating dependence on the efficiency. Using the T3ster system, the practical measurements of the η_W as a function of the LED current are obtained and shown in Fig. 3. It can be seen that η_W decreases as the injection current rises. Normally, the optical power–current curve can be divided into a nonlinear and a linear region [17]. In the nonlinear part, the optical power increases approximately quadratically with the current due to domination of nonradiative recombination. As the current increases, radiative recombination starts to dominate, and the optical power becomes linear with current. In practice, the electrical power P_d is approximately linearly proportional to the injection current at constant junction temperature T_{j0}, and therefore, η_W can be obtained as a quadratic polynomial function of P_d

$$\eta_W(T_{j0}, P_d) = \chi P_d^2 + \delta P_d + \gamma \tag{3}$$

where χ, δ, and γ are the constants that can be extracted from Fig. 3 with constant electrical power.

Based on the aforementioned analysis, η_W can be expressed in terms of P_d and T_j using a 2-D mathematical function. Similar modeling method based on the 2-D linear function for the forward voltage, which relates the junction temperature to the injection current, has been proposed in [18]. In this paper, the function of η_W is constructed as the following equation:

$$\eta_W(T_j, P_d) = \frac{(\alpha T_j + \beta)(\chi P_d^2 + \delta P_d + \gamma)}{\mu} \tag{4}$$

where μ is the intersection value of functions of (2) and (3), and is the value of η_W at point (T_{j0},P_{d0}) [19], [20].

Based on (1) and (4), the optical power can be expressed as

$$P_{\mathrm{opt}}(T_j, P_d) = \eta_W P_d = \frac{(\alpha T_j + \beta)(\chi P_d^3 + \delta P_d^2 + \gamma P_d)}{\mu}. \tag{5}$$

It should be noted that this extended theory can estimate the optical power of the LED at any junction temperature and electrical power. Equation (5) links the optical power to electrical power and the junction temperature together.

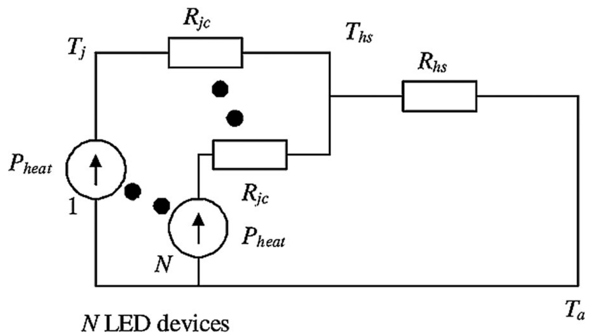

Fig. 4. Simplified dynamic thermal equivalent circuit of *N* LEDs mounted on the same heatsink.

B. Relationship of the Heat-Dissipation Coefficient and the Wall-Plug Efficiency

The heat-dissipation coefficient k_h in the original PET theory is an indication of the portion of the total input LED power that will be dissipated as heat. It can be expressed as

$$k_h = \frac{P_{\rm heat}}{P_d} = \frac{P_d - P_{\rm opt}}{P_d} = 1 - \eta_W. \tag{6}$$

Since η_W can be obtained from (4) based on the parameters extracted from the two-test procedures (i.e., constant-power and constant-junction-temperature tests) described previously, k_h can be calculated with the knowledge of η_W using (6). Therefore, this two-test procedure provides a fast way to determine k_h, provided that sophisticated equipment such as TeraLED T3ster system is available.

III. Extension to the Original PET Theory

A. Conventional Calculation Method

Under steady-state conditions, the thermal model of an LED system with *N* number of LED devices mounted on the same heatsink is shown in Fig. 4. Based on (6), the steady-state heatsink temperature $T_{\rm hs}$ and the internal junction temperature T_j can be expressed as

$$\begin{aligned} T_{\rm hs} &= T_a + R_{\rm hs}(NP_{\rm heat}) = T_a + NR_{\rm hs}P_d k_h \\ &= T_a + NR_{\rm hs}P_d(1-\eta_W) \end{aligned} \tag{7}$$

$$\begin{aligned} T_j &= T_{\rm hs} + R_{\rm jc}P_{\rm heat} = T_a + (R_{\rm jc}+NR_{\rm hs})P_d k_h \\ &= T_{\rm hs} + R_{\rm jc}(P_d - P_{\rm opt}) \\ &= T_a + (R_{\rm jc}+NR_{\rm hs})P_d(1-\eta_W) \end{aligned} \tag{8}$$

where $T_{\rm hs}$ is the heatsink temperature, T_a is the ambient temperature, $R_{\rm hs}$ is the thermal resistance of the heatsink, $R_{\rm jc}$ is the thermal resistance of the LED, and $P_{\rm heat}$ is the heat dissipation of the LED.

The total luminous flux ϕ_v of an LED system consisting of *N* LED devices can be expressed as

$$\phi_v = N \times E \times P_d. \tag{9}$$

The luminous efficacy E can be approximated as

$$\begin{aligned} E &= E_0[1 + k_e(T_j - T_0)] \\ &= E_0[1 + k_e(T_a - T_0) + k_e k_h(R_{\rm jc} + NR_{\rm hs})P_d)] \\ &= E_0[1 + k_e(T_a - T_0) + k_e(1-\eta_w)(R_{\rm jc} + NR_{\rm hs})P_d)] \\ &= E_0\Bigg\{1 + k_e(T_a - T_0) \\ &\quad + k_e\left[1 - \frac{(\alpha T_j + \beta)(\chi P_d^2 + \delta P_d + \gamma)}{\mu}\right](R_{\rm jc} + NR_{\rm hs})P_d)\Bigg\} \end{aligned} \tag{10}$$

where E_0 is the rated efficacy at the rated temperature T_0 (typically 25 °C in some LED data sheets) and k_e is the relative rate of reduction of luminous efficacy with increasing junction temperature and can be found in the data sheet.

For $\phi_v > 0$, the total luminous flux ϕ_v is

$$\begin{aligned} \phi_v &= NEP_d \\ &= NE_0\{[1 + k_e(T_a - T_0)]P_d + k_e k_h(R_{\rm jc} + NR_{\rm hs})P_d^2\} \\ &= NE_0\Bigg\{[1 + k_e(T_a - T_0)]P_d \\ &\quad + k_e\left[1 - \frac{(\alpha T_j + \beta)(\chi P_d^2 + \delta P_d + \gamma)}{\mu}\right](R_{\rm jc} + NR_{\rm hs})P_d^2\Bigg\}. \end{aligned} \tag{11}$$

Because k_e is negative and less than 1, (11) is in the form of $\phi_v = \alpha_1 P_d - \alpha_2 P_d^2$ where α_1 and α_2 are two positive coefficients. η_w decreases with an increasingP_d; k_h increases as P_d rises. As P_d is increased from zero, ϕ_v increases almost linearly because the second term is negligible when P_d is small. As P_d increases, the second negative term, which is proportional to the square ofP_d, will become increasingly dominant and will reduce ϕ_v significantly.

Combining (4) and (7), T_j can be determined as

$$T_j = \frac{(R_{\rm jc} + NR_{\rm hs})[P_d - \beta'(\chi P_d^3 + \delta P_d^2 + \gamma P_d)] + T_a}{1 + \alpha'(R_{\rm jc} + NR_{\rm hs})(\chi P_d^3 + \delta P_d^2 + \gamma P_d)} \tag{12}$$

where $\alpha' = \alpha/\mu$ and $\beta' = \beta/\mu$. The coefficients in (12) can be determined through the optical and electrical power measurement procedures explained previously, and $R_{\rm jc}$ and $R_{\rm hs}$ can been obtained from the data sheets. With the coefficients and device parameters obtained, LED system designers can predict the internal junction temperature of the LED at any electrical power using (12). However, it should be noted that the junction temperature has to be measured during the calibration for α and β.

B. Fast Calculation Method

In order to simplify the calculation method, one can take advantage of the special conditions adopted in the two-test procedure described in Section 2. Combining (8) with (2), the wall-plug efficiency η_W at constant electrical power can be expressed

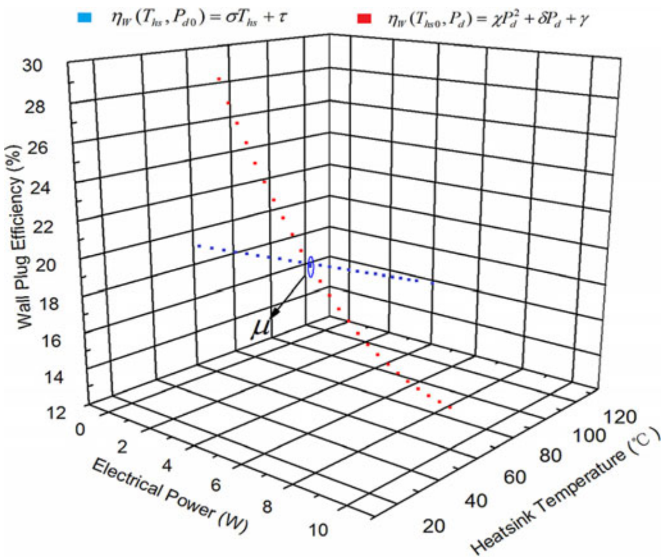

Fig. 5. Wall-plug efficiency of LED as a 2-D function of electrical power and heatsink temperature.

as

$$\eta_W(T_j, P_{d0}) = \alpha T_j + \beta = \alpha[T_{\rm hs} + R_{\rm jc}P_{d0}(1-\eta_W)] + \beta$$

$$\eta_W(T_j, P_{d0}) = \frac{\alpha(T_{\rm hs} + R_{\rm jc}P_{d0}) + \beta}{1 + \alpha P_{d0} R_{\rm jc}}. \tag{13}$$

With constant electrical power P_{d0}, the only variable parameter of (13) is $T_{\rm hs}$ and other items can be assumed constant coefficients. So the specific form of $\eta_w(T_j, P_{d0})$at constant power can be rearranged in the following form

$$\eta_W(T_{\rm hs}, P_{d0}) = \sigma T_{\rm hs} + \tau. \tag{14}$$

On the other hand, the heatsink temperature remains constant if the LED is placed on a mounting plate with a fixed heatsink temperature $T_{\rm hs0}$. So (3) can be expressed as

$$\eta_W(T_{\rm hs0}, P_d) = \chi P_d^2 + \delta P_d + \gamma. \tag{15}$$

Now, the general form of the wall-plug efficiency is

$$\eta_W(T_{\rm hs}, P_d) = \frac{(\sigma T_{\rm hs} + \tau)(\chi P_d^2 + \delta P_d + \gamma)}{\mu}. \tag{16}$$

It is important to note that while (16) has the same mathematical form as (4), (16) is expressed as a function of $T_{\rm hs}$ that is easy to measure and (4) as a function of T_j that is not easy to obtain. As shown in Fig. 5, μ is the intersection value of function for (14) and (15), meaning that μ corresponds to the value of η_W at point $(T_{\rm hs0}, P_{d0})$.

The optical power equation remains the same as (5)

$$P_{\rm opt}(T_{\rm hs}, P_d) = (\sigma' T_{\rm hs} + \tau')(\chi P_d^3 + \delta P_d^2 + \gamma P_d) \tag{17}$$

where $\sigma' = \sigma/\mu$ and $\tau' = \tau/\mu$.

The luminous flux is now expressed as

$$\begin{aligned}\phi_v &= NEP_d \\ &= NE_0\{[1 + k_e(T_a - T_0)]P_d + k_e k_h(R_{\rm jc} + NR_{\rm hs})P_d^2\} \\ &= NE_0\{[1 + k_e(T_a - T_0)]P_d \\ &\quad + k_e[1 - (\sigma' T_{\rm hs} + \tau')(\chi P_d^2 + \delta P_d + \gamma)](R_{\rm jc} + NR_{\rm hs})P_d^2\}.\end{aligned} \tag{18}$$

The junction temperature equation is now expressed as

$$T_j = R_{\rm jc}[P_d - (\sigma' T_{\rm hs} + \tau')(\chi P_d^3 + \delta P_d^2 + \gamma P_d)] + T_{\rm hs}. \tag{19}$$

Equations (16)–(19) provide the general equations for the wall-plug efficiency, optical power, luminous flux, and junction temperature, respectively, for an LED system. All the parameters and variables on the right-hand side of these equations are either known or measurable. These equations form the tool for designing and optimizing LED systems with measurable parameters and variables.

It should be noted that the aforementioned analysis assumes that all LEDs are identical in the LED system. In general, this is a common practice in public lighting (i.e., not decorative applications that require color changes) to use the same type of white LEDs in one system in order to avoid differences in color temperature and the binning systems among LED manufacturers. However, if the LED devices are not identical, the aforementioned theory can be extended to incorporate the use of nonidentical LEDs in an LED system by modifying (18) into

$$\sum_{m=1}^{N} \phi_{v\_m} = \sum_{m=1}^{N} E_m P_{d\_m} \tag{20}$$

where ϕ_{v_m} is the luminous flux, E_m is the luminous efficacy, and P_{d_m} is the power of the *m*th LED; *N* is the total number of LEDs in the system. A full analysis of an LED system based on nonidentical LEDs will be presented in the future.

IV. Experiment Verifications for the Extended PET Theory

The samples under test are mounted to a Peltier-cooled fixture that is attached to an integrating sphere in accordance with the recommendations of CIE. The Peltier-cooled fixture is used to stabilize the LED temperature for the optical measurements and it also serves as an actively temperature-controlled cold plate for thermal measurements [21]. Optical measurements of LED samples are made under thermal and electrical steady-state conditions with the TeraLED system. Once all optical measurements have been performed, the LED is switched OFF and the cooling transient of LED package is monitored with the use of the transient thermal tester (T3Ster). Besides the combined thermal and optical measurements, the temperature dependence of all parameters of the LED (such as the temperature dependence of the optical power, luminous flux, chromaticity coordinates, and wall-plug efficiency) can also be measured and recorded. The theoretical framework of evaluation by the T3Ster system is based on the distribution *RC* networks [22]. The T3ster system captures the thermal transient response in real time, records the cooling/heating curve and then evaluates the cooling/heating curve so as to derive the thermal characteristics [23]. For the calibration of temperature sensitive parameters, a small current of 5 mA is applied in the temperature range of 25–55 °C with

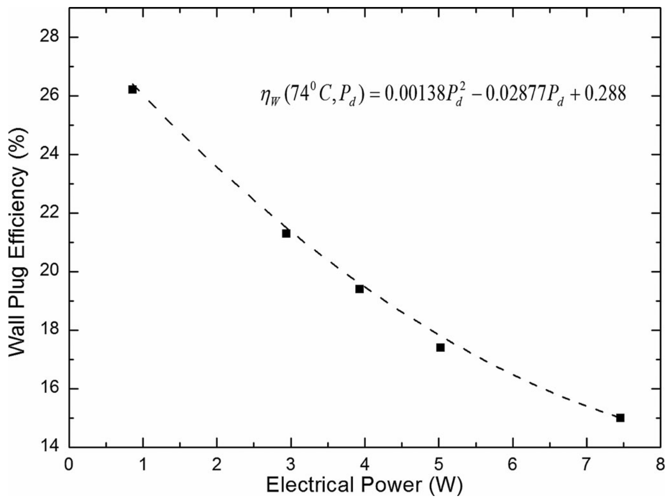

Fig. 6. Measured wall-plug efficiency versus electrical power of Sharp 4.4 W LED at constant heatsink temperature.

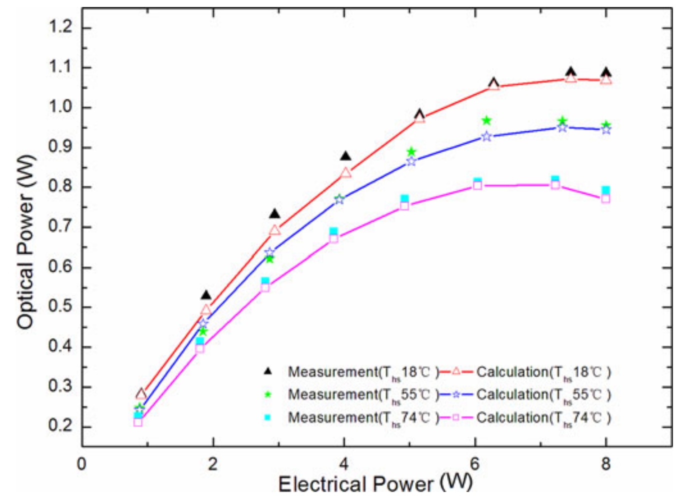

Fig. 8. Calculated and measured optical power versus electrical power for Sharp 4.4 W LED with different heatsink temperature.

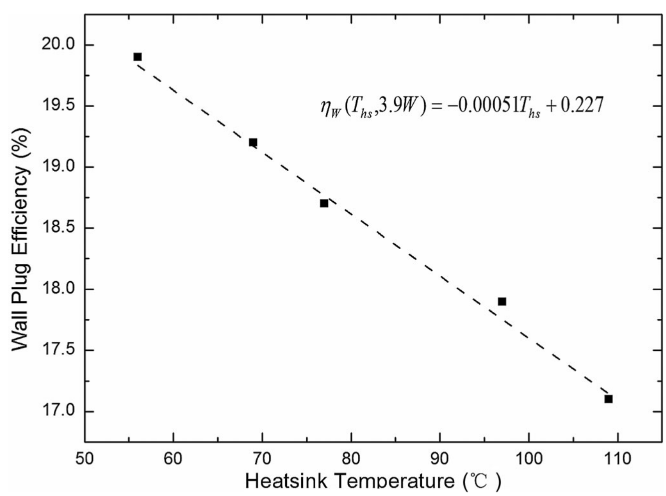

Fig. 7. Measured wall-plug efficiency versus heatsink temperature of Sharp 4.4 W LED at constant electrical power.

an increment of 10 °C. The light output and transient thermal curve are measured after driving the LED with the current for 20 min with the heatsink temperature kept constant.

A. Test on Sharp 4.4 W LED (Model Number: GW5BNC15L02)

One Sharp 4.4 W LED is mounted on the heatsink with a thermal resistance of 7.8 °C/W. The optical power and wall-plug efficiency are measured at different electrical power levels. The parameters required for (16) can be determined using curve-fitting technique in Figs. 6 and 7 as $\sigma = -0.00051$, $\tau = 0.227$, $\chi = 0.00138$, $\delta = -0.02877$, $\gamma = 0.288$, and $\mu = 0.187$. The wall-plug efficiency and optical power follow the forms of (16) and (17), respectively. It should be noted that δ is a negative coefficient, and χ and γ are the positive coefficients. γ is roughly a factor 200 larger than χ, meaning that the χP_d^3 term is relatively insignificant with low value of P_d. Based on these parameters, the theoretical and measured optical power curves are recorded and shown in Fig. 8. As P_d is increased from zero, $P_{\rm opt}$ increases almost linearly when P_d is small. As P_d continues to increase, the negative item δP_d^2 will reduce $P_{\rm opt}$ significantly. After reaching the maximum optical power, $P_{\rm opt}$ will drop with an increasing P_d. The optical power function is approximately a parabola and, therefore, has a maximum optical power P_d^*. This P_d^* will shift to lower value with an increasing heatsink temperature or heat dissipation, which indicates the dependence of the operating point P_d^* of the LED array systems on the junction temperature. The theoretical and measured optical power curves in Fig. 8 agree reasonably well for a set of heatsink temperature values.

The measured and calculated heat-dissipation coefficient k_h values are shown in Fig. 9. The theoretical curves of k_h are in good agreement with the measured ones. It is important to note that at a controlled heatsink temperature of 18 °C, k_h is about 0.76. When the heatsink temperature is 74 °C, k_h increases to 0.86. This practical result highlights the important fact that, even with the same LED power, k_h increases with increasing operating temperature. The thermal designs of LED systems are, therefore, critical to the photometric performance.

By substituting the calculated k_h and the parameters of $k_e = -0.0027$, $E_0 = 80$ lm/W, $R_{\rm jc} = 6.5$ °C/W, $T_0 = 25$ °C, $T_a = 18$ °C, and $N = 1$ into (18), the theoretical luminous flux can be determined, plotted, and compared with practical measurements as shown in Fig. 10 for a range of heatsink temperature. The theoretical curves of optical power (see Fig. 8) and luminous flux (see Fig. 10) are generally in good agreement with the measured ones particularly within the rated power range. The general shapes of these curves have been explained with the PET theory [4].

Measured junction temperatures are recorded and compared with theoretical values calculated with the use of (19) for an LED device with a thermal resistance $R_{\rm jc}$ between the junction and the case of 6.5 °C/W, which is considered as a constant value with electrical power and heatsink temperature. As shown in Fig. 11, the agreement between measured and calculated results is reasonably good. It is noted that junction temperature

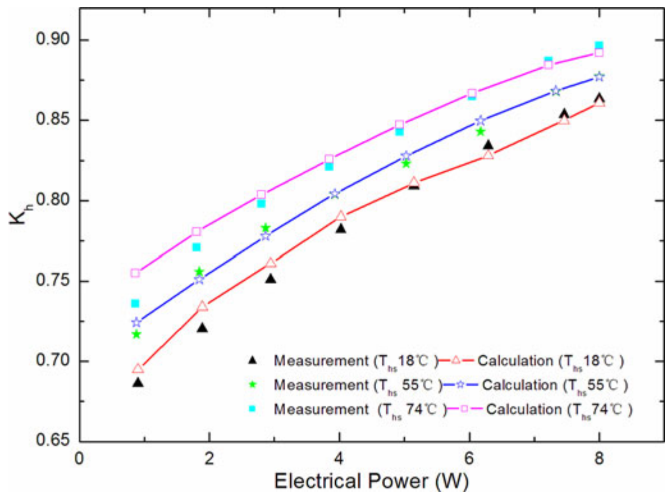

Fig. 9. Calculated and measured k_h versus electrical power for a Sharp 4.4 W LED with different heatsink temperature.

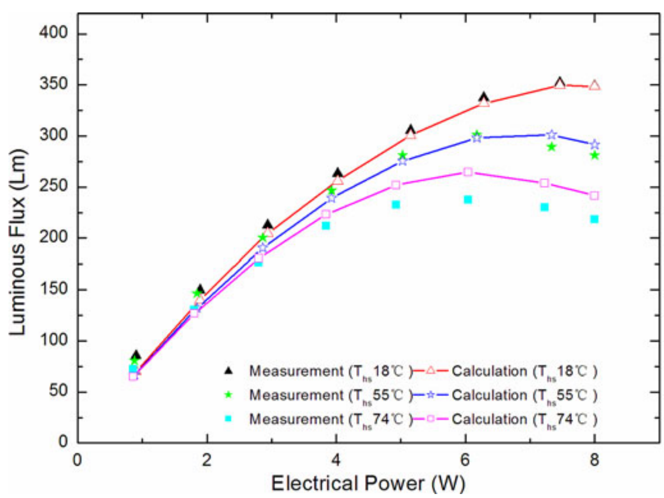

Fig. 10. Calculated and measured luminous flux versus electrical power for Sharp 4.4 W LED with different heatsink temperature.

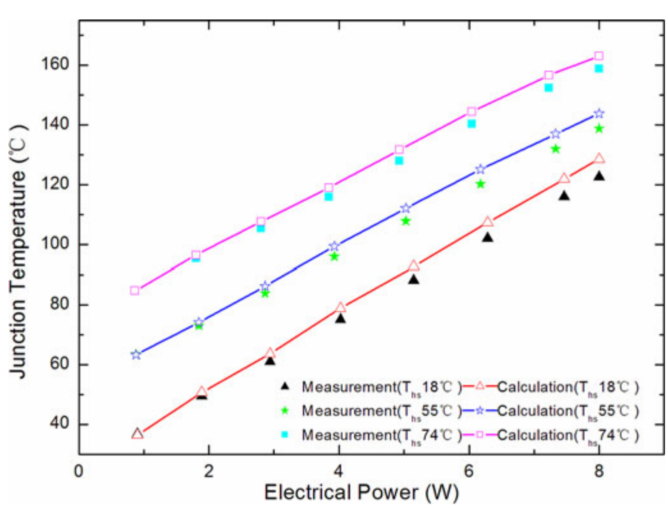

Fig. 11. Calculated and measured junction temperature versus electrical power for Sharp 4.4 W LED with different heatsink temperature.

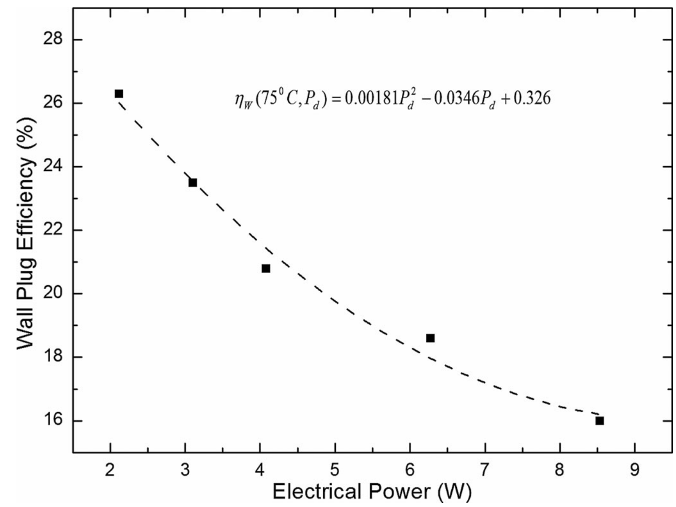

Fig. 12. Measured wall-plug efficiency versus electrical power of Sharp 8 W LED at constant heatsink temperature.

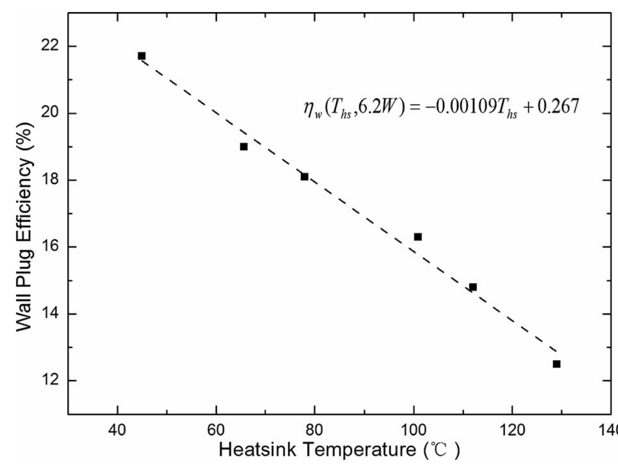

Fig. 13. Measured wall-plug efficiency versus heatsink temperature of Sharp 8 W LED at constant electrical power.

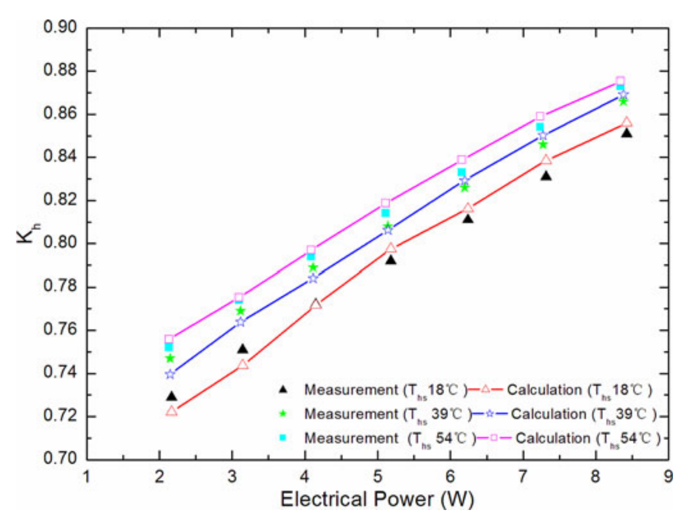

Fig. 14. Calculated and measured k_h versus electrical power for Sharp 8 W LED with different heatsink temperature.

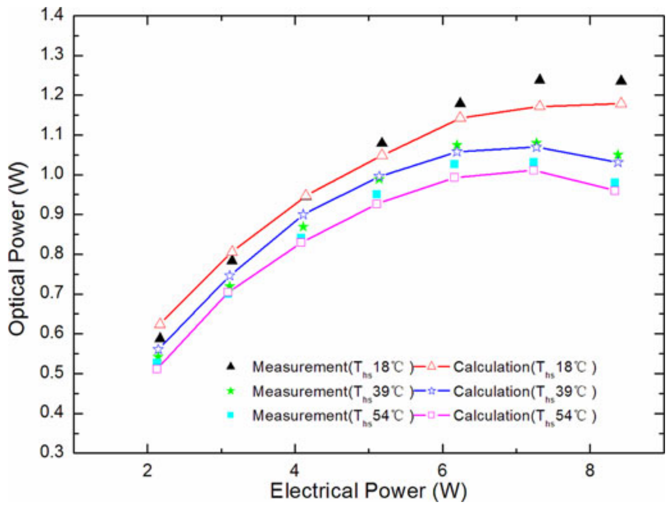

Fig. 15. Calculated and measured optical power versus electrical power for Sharp 8 W LED with different heatsink temperature.

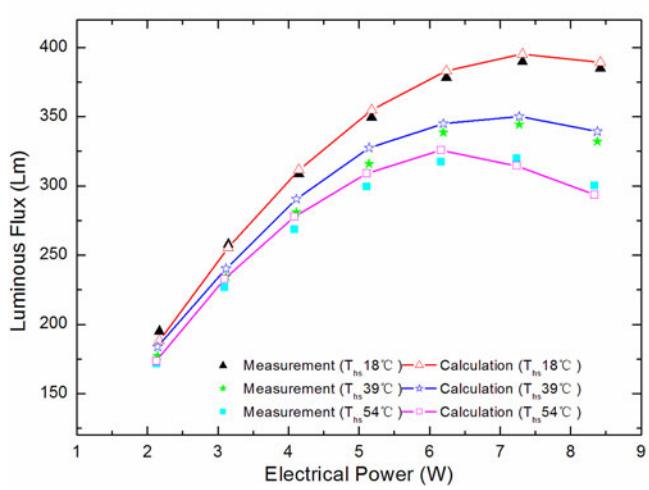

Fig. 16. Calculated and measured luminous flux versus electrical power for Sharp 8 W LED with different heatsink temperature.

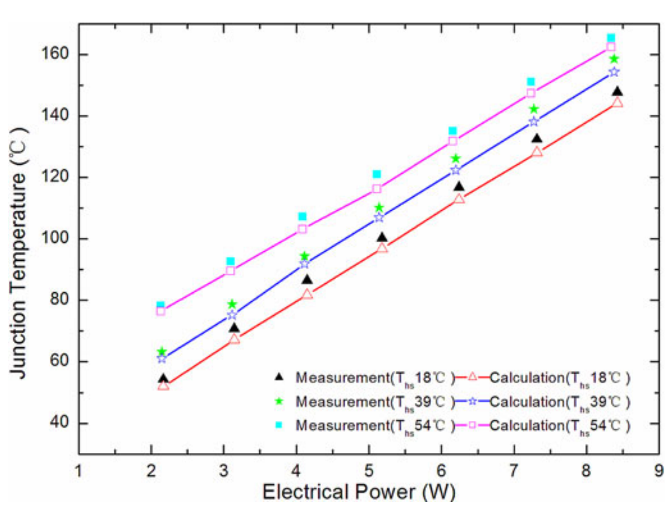

Fig. 17. Calculated and measured junction temperature versus electrical power for Sharp 8 W LED mounted on a heatsink.

prediction by application designer would be largely simplified if the device coefficients and thermal resistance were known in advance. Some device manufacturers provide typical experimental relationships of the wall-plug efficiency with electrical power and heatsink temperature. Inclusion of the coefficients for these functions (2) and (3) in the data sheets by LED device manufacturers could, therefore, be helpful device information for application designers.

B. *Test on Sharp 8 W LED (Model number: GW5BWF15L00)*

The extended PET theory is also tested with the use of Sharp LED devices. One Sharp 8 W LED device is mounted on the heatsink with a thermal resistance of 9.3 °C/W for practical evaluation. The optical power and wall-plug efficiency are measured at different electrical power. The parameters required for (16) can be determined using fitting measurement data with Figs. 12 and 13. Here, $\sigma = -0.00109$, $\tau = 0.267$, $\chi = 0.0018$, $\delta = -0.0346$, $\gamma = 0.326$, and $\mu = 0.180$. The equations for the wall-plug efficiency and optical power follow the form of (16) and (17). The measured and calculated k_h parameters are shown in Fig. 14. The theoretical curves of k_h are in good agreement with the measurements. Substituting the calculated k_h with the parameters of $k_e = -0.0039$, $E_0 = 96$ lm/W, $R_{\rm jc} = 6$ °C/W, $T_0 = 25$ °C, $T_a = 18$ °C, $N = 1$ into (18), the luminous flux can be determined.

The measured optical power and luminous flux for LED are shown with their respective calculated values in Figs. 15 and 16. The measured junction temperature and their theoretical values calculated with (19) for this LED with thermal resistance $R_{\rm jc}$ of 6 °C/W are shown in Fig. 17. The reasonably good agreements between these measured and calculated values confirm the validity of the proposed estimation method for the optical power and heat-dissipation coefficient.

V. Conclusion

An estimation method for the optical power and heat-dissipation coefficient of LED devices based on the wall-plug efficiency is proposed in this paper. The proposal consists of a practical procedure for the required optical and electrical power measurements. The parameters obtained in this fast procedure are applied to the original PET theory to predict the optical power, heat-dissipation coefficients, and internal junction temperature that cannot be easily accessed in practice. It is found that the heat-dissipation coefficient increases with junction temperature even when the LED power consumption remains constant. The estimation method presented in this paper extends the original PET theory to cover optical power, wall-plug efficiency, and the determination of the heat-dissipation coefficient. It is envisaged that the extended theory can be used as a design tool for LED system designs. LED manufacturers are encouraged to include more information such as heat-dissipation coefficient as a function of operating temperature in the data sheets as basic parameters for LED system designs.

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