An efficient decay model for studying the luminous flux behavior of phosphor-converted white light-emitting diodes

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Abstract—We proposed a new idea for testing the thermal decay of light sources under the effect of heat where the lux meter is used rather than the integrating sphere, and the thermal camera is used rather than the thermocouple. The thermal decay behavior of the light is detected by using the lux meter. The thermal camera can provide the temperature value and the temperature distribution of the measured surface, which is more convenient than using the thermocouple. This fitting model is useful for determining the output light's decay rate under thermal effect.

Phosphor-converted white light-emitting diodes (pcW-LEDs) based solid-state lighting (SSL) have been intensively applied due to many advantages such as environment friendly, high energy efficiency, high color rendering performance, compact size, and brightness [1–4]. The pcW-LEDs-based applications in vehicle lamps, indoor lighting, agriculture, signal display, and medical devices are extensively developed [5–8]. Besides many advantages of pcW-LEDs, there is still an inherent issue of pcW-LEDs relating to generating heat, which originates from blue light emitting diodes (LED) chips and yellow phosphor during the operating process of pcW-LEDs. The thermal problem will cause many adverse effects on pcW-LEDs performance, such as optical performance (e.g., correlated color temperature (CCT) drift, output decrease of luminous), color performance (e.g., bluish light, blue light leakage), and mechanical damage. The traditional method of investigating thermal decay behavior uses the thermocouple and integrating sphere. Such a measurement setup is presented in Fig. 1. Advantage of this method is that it can detect real-time optical parameters such as CCT, color rendering index (CRI), luminous efficiency (lm/W), and forward voltage variant.

The problem of the thermal effect on the thermal decay of pcW-LEDs has been a hot topic that has attracted much attention from researchers [9–29]. Narendran *et al.* reported a novel method based on the analytical multi-physics simulation to predict the lifetime of LED systems by detecting the temperature of the T-point of LED by thermocouple and the changing of output light by the photodiodes [9]. Xiao *et al.* reported the experimental system for measuring the dynamic temperature distribution of bare blue LED (468 nm) with a 1 mm ×1 mm chip size [10]. Han *et al.* reported a method wherein a thermal camera was used to prove the improvement of heat dissipation in gallium nitride light-emitting diodes with embedded graphene oxide patterns [11]. Miao *et al.* studied the lifetimes of high-power LED lamps, which are investigated by step-stress accelerated testing. Step-stress accelerated tests are conducted on the LED light source using the thermal chamber and connected to other subsystems outside the aging furnace. Thus, the highest possible stress level can be reached for the LED light source. [12] Chang *et al.* reported a method of measuring the precise temperature distribution of GaN-based light-emitting diodes (LEDs) by quantitative infrared micro-thermography [13]. Gao *et al.* proposed a non-contact measurement method for determining LEDs' two-dimensional (2D) temperature distribution [14]. Liang *et al.* proposed a design for an appropriate reliability test plan applying to ultraviolet LEDs [15]. Hegedüs *et al.* reported an approach for LED lifetime modeling, which is based on the LM-80-08 testing method and supplemented by additional specific thermal measurements [16]. Alexeev *et al.* presented several novel methods to measure the junction temperature and to estimate the health of gallium nitride LEDs. The methods are based on measurements of the dynamic impedance and optical output [17]. Paisnik *et al.* studied the LEDs performance using the TERALED system in the 300 mm diameter integrating sphere equipped with a reference LED, a Si photovoltaic cell, a computer-controlled filter bank, and a temperature-controlled device under test (DUT) fixture [18]. Vaskuri *et al.* have studied the relationships between junction temperature, electroluminescence spectrum, and aging of light-emitting diodes, wherein all spectral data measured for the aging test were corrected for the spectral responsibility of the integrating sphere photometer [19]. In general, the reported studies used modern equipment that led to an expensive research cost (e.g., a disadvantage is a high investment in the facility, such as integrating sphere systems). The raised question: "How do you test the

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thermal decay cay using a simple experiment setup and facility method for handling the data related to the decay?" is an interesting topic. To our best knowledge, there is still not much report on this topic.

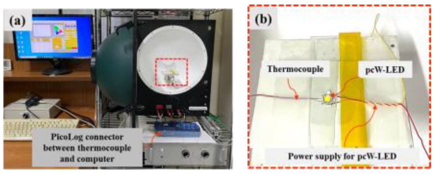

Fig. 1. A traditional setup for testing the thermal decay of pcW-LEDs.

The theoretical principle of the proposed method is based on the relation between output light and illuminance. Consider a target illuminated by a light source. Let $d\Phi$ be the output luminous flux of the light source, and dA is the target area shined by the incident light. The illuminance E of incident light is described by the equation:

$$E = \frac{d\phi}{dA} \tag{1}$$

According to the expression in Eq. (1), the illuminance is proportional to the output luminous flux. On the other hand, the output luminous flux is proportional to the working temperature. Thus, it can be deduced that illuminance is proportional to temperature. Therefore, it can be based on the behavior of illuminance to the temperature to understand the dynamic process of the output light to the temperature. The lux meter detects the illuminance, while the thermocouple or thermal camera detects the temperature. Based on this argument in the above section, a new method for investigating the thermal decay properties of white LED sources is proposed and described as follows. The illustration for the experimental setup is shown in Fig. 2. In this setup, pcW-LEDs are driven by the power supply at the constant injection current mode. The temperature of the back side of the pcW-LEDs is detected by the thermal camera. The incident illuminance is detected by the lux meter light detector part. The numerical illuminance and detected temperature data are shown in the Luxmeter display and thermal camera screens, respectively. This numerical data is recorded by the optical camera placed before the thermal camera and lux meter display screen.

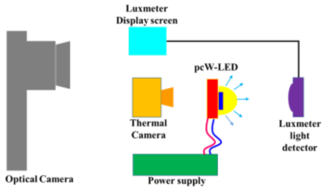

Fig. 2. Illustration of experimental setup for the proposed method.

In the application, the principal instruments are the lux meter, thermal camera, and power supply, as shown in Fig. 3.

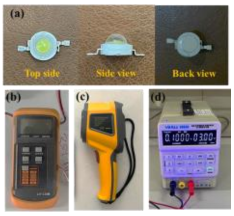

Fig. 3. Photo of tested sample and main instruments in the experiment: (a) cool white pcW-LEDs, (b) lux meter, (c) thermal camera, and (d) power supply.

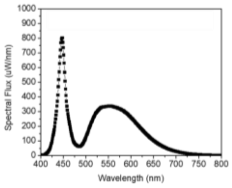

Fig. 4. The light source emission spectrum.

For investigating the thermal decay properties of these tested white LEDs sources, the cool white pcW-LEDs, lux meter, thermal camera, and power supply are set up as the illustration, as shown in Fig. 2. The corresponding experiment set up is shown in the Fig. 5.

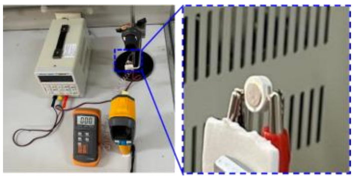

Fig. 5. Experimental setup for investigating the thermal decay properties of tested white LED sources.

Figure 6 shows thermal decay properties of tested white LEDs sources versus the temperature. The result showed the effect of temperature on the luminous flux which contributed by thermal degradation for the blue band and yellow emission band, when temperature of the back side of pcW-LEDs increased from 32^{o}C to 65^{o}C. The decreasing flux was caused by the increase of nonradiative recombination during both the blue and yellow light generation process. With the increasing temperature, non-radiative recombination is more dominant than radiative recombination, thus it makes the generated light lesser and the obtained luminous flux was lower. As a result, the behavior of obtained illuminance is decreased correspondingly.

Temperature distribution at the back side of pcW-LEDs at some times are picked out and shown in Fig. 7. The result indicated that over time, the temperature increased quickly after a short time. The area of the hotspot is extended rapidly. The hotspot is always located at the central position while the temperature of the outer side gradually lowers.

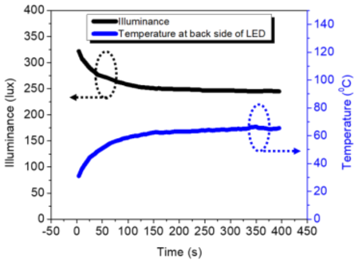

Fig. 6. The thermal decay properties of tested white LEDs sources versus the temperature.

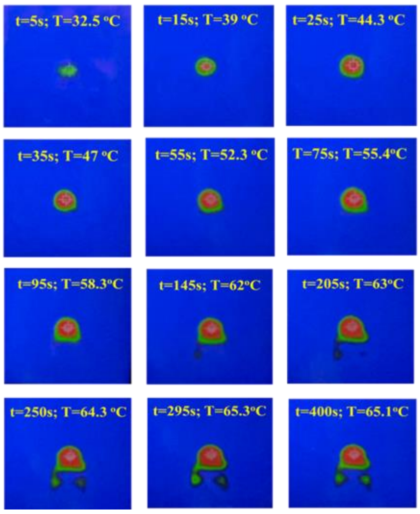

Fig. 7. Temperature distribution at the back side of pcW-LEDs.

For understanding of the effect of thermal effect on the decay of luminous flux. The result that shown in Figure 8a was analyzed through the fitting process using an exponential decay function to define the decay rate. A fitting mathematical model for thermal-induced decay of luminous flux was applied to find out the decay rate constant (or lifetime constant). In this study, the exponential decay function is chosen as follow:

$$E_t = E_0 \exp\left(-\frac{t-t_0}{\tau}\right)+E_c, \qquad (2)$$

where E_0 and E_t are luminous flux at an initial time and at the time t, respectively. The E_c is constant. The τ is the lifetime constant. The the decay rate $\wedge$ is related to the lifetime constant τ as $\wedge = 1/\tau$.

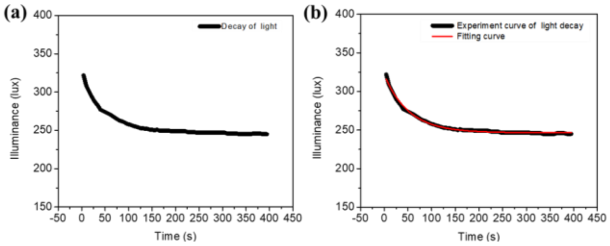

Fig. 8. (a) The thermal decay of flux over the time and (b) Fitting results using exponential decay function.

Based on the above fitting modeling, the software Origin is used to fit the decay curve. The fitting result was shown in Fig. 8(b), and the value of lifetime constants (or decay rates) was listed in Table 1. The fitting curves using an exponential decay function were well matching with experimental curves. The decay rate is calculated by the inverse proportion of the lifetime constant.

Table 1. Value of lifetime constant and decay rate that obtained from the fitting

Injection current (A)	Lifetime constant τ (s)	Decay rate τ^{-1} (1/s)
0.35	52.18	0.019

In summary, an efficient method for testing the thermal decay of light sources under the effect of heat is proposed and demonstrated. The dynamic process of thermal decay is investigated by applying the fitting model. This fitting model is useful for finding out the decay rate of output light under different effects of thermal influence. Along with the advantage of low cost and ease of set up, the proposed method is helpful for research which is related to thermal management, thermal decay testing, LEDs based optical design.

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