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An optical-thermal model for laser-excited remote phosphor with thermal quenching

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ABSTRACT

Laser-excited remote phosphor (LERP) has been reported to be an effective approach to produce high-luminance white light based on laser diodes (LDs). However, the local phosphor temperature may easily reach thermal quenching point due to the local high light power density, resulting in a significant drop/deterioration of efficiency, reliability and lifetime. In this paper, we focused on the phosphor thermal quenching and developed an optical-thermal coupling model to predict the high phosphor temperature of LERP. From this model, both accurate phosphor heating and temperature can be obtained by iteration. For validation, experiments were performed to verify the model and good agreement was observed between the measurements and the theoretical predictions. Based on the validated model, the critical incident power against thermal quenching under various factors was systematically studied. It was found in the experiments that when a 680 mW laser spot with a diameter of 1.0 mm was projected onto a phosphor layer, the phosphor temperature was as high as 549.0 °C, which would result in severe thermal quenching and even silicone carbonization. It was also found that increasing pump spot from 0.5 mm to 3.0 mm can dramatically enhance critical power by 19 times. The effect of decreasing phosphor layer thickness on critical power enhancement was explained by the model. Some suggestions were also provided to prevent thermal quenching and improve the optical/thermal performance of LERP.

1. Introduction

High-power phosphor-converted light-emitting diodes (pc-LEDs) have gained wide applications in general lighting [1]. However, the state-of-the-art LEDs are still suffering from the "efficiency droop", i.e. a decrease of quantum efficiency at high operating current density [2]. In contrast, laser diodes (LDs) can achieve higher efficiency at high current density, because the Auger recombination no longer grows after the threshold current [3,4]. Moreover, LDs also exhibit other excellent characteristics, including directional beam pattern and small light-emitting area, enabling the capability of high-luminance and collimated lighting [4,5]. Similar to white LEDs, pc-LDs gain more attention with their advantages of high efficiency, low cost, and compact size [6–8]. Laser-excited remote phosphor (LERP) has been commonly used in pc-LD packaging [9,10].

In LERP, light emitted from the LD chip is usually focused onto a phosphor layer, and the luminance is usually much higher than that of conventional white LEDs [11]. Consequently, the phosphor temperature will be much higher than LEDs due to the extremely higher radiant power density from LDs. High phosphor temperature will result in the severe thermal quenching problem, which will decrease the efficiency, deteriorate the reliability, and shorten the lifetime of LERP [12]. Although thermal quenching has been regarded as a significant obstacle to the development of high-luminance pc-LDs, there are quite few efficient/accurate tools/methods for evaluation. Either the phosphor temperature or the heat flux generated by the phosphors are quite hard to measure in the experiments.

Monte-Carlo ray-tracing simulations together with finite element method (FEM) have been widely used to evaluate the optical and thermal performances of pc-LEDs [13–15]. In the most methods used for phosphor modeling in pc-LEDs, the optical and thermal effects were independent of each other and this may not lead to misunderstanding because phosphor temperature is relatively low and the thermal quenching effect is not severe. But for pc-LDs, the thermal quenching is too significant to be ignored. In general, the temperature dependence of phosphor quantum efficiency was usually not considered, making it impossible to evaluate thermal quenching [16]. Actually, light scattering, absorption, conversion, and thermal quenching are interacted with each other, making it difficult and complicated for the numerical simulation. Moreover, the quantum efficiency has complex dependencies on

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Nomenclature

A	cross-sectional area, mm^2
A_{conv}	total convective area, mm^2
A_n, B_n	Fourier coefficients
Bi	Biot number, $hD/(2\lambda)$
c	phosphor concentration, g/cm^3
d	thickness, mm
D	diameter, mm
E_0	fitted activation energy, 6500 1/cm
$E(z)$	forward-scattering light function, W
$F(z)$	back-scattering light function, W
h	convective coefficient, W/(m^2 K)
i	ith iteration
$J_1(\cdot)$	Bessel function of first kind
k_B	Boltzmann constant
L	length, mm
P_{in}	incident laser power, W
P_{limit}	critical incident power, W
P_{out}	total output light power, W
Q_{ph}	phosphor heating power, W
R	thermal resistance, K/W
R_s	thermal spreading resistance, K/W
T_a	ambient temperature, °C
T_c	critical phosphor temperature, °C
T_{ph}	phosphor temperature, °C
W	width, mm
W_0	fitted frequency factor, 4×10^{13} 1/s
z	invasion depth, mm

Greek symbols

γ	reflection coefficient
δ_n	eigenvalues, $J_1(\delta_n) = 0$
ε	relative source size, $D_{\text{spot}}/D_{\text{ph}}$
ζ	relative thickness, $d_{\text{ph}}/(D_{\text{ph}}/2)$
η	phosphor quantum efficiency
λ	thermal conductivity, W/(m·K)
τ_r	radiative lifetime, s
τ_{nr}	non-radiative lifetime, s

Subscript

a	ambient
bond	bonding layer
B	blue light
conv	convection
eq	equivalent
hs	heat sink
mir	mirror layer
ph	phosphor layer
spot	laser spot
tot	total
Y	yellow light

temperature and it is hard to establish the exact relationship between them. Recently, to tackle this problem, Correia et al. proposed a method to mesh the phosphor layer using tetrahedral element discretization and stored the optical and thermal flux. Despite its complexity in meshing, this method proved to be an effective way to characterize the overall performance of pc-LED/LDs [16]. Alternatively, Lenef et al. used a diffusion-approximation radiation transport model to calculate optical effects and then coupled with FEM to study the thermal effects of pc-LDs [12,17]. In our previous papers, we have established a phosphor scattering model based on the Kubelka–Munk theory to analyze the phosphor heating effects in pc-LEDs [18,19]. We also build the thermal resistance model to predict the junction temperature of LEDs with high accuracy [20,21]. Can we apply these models to evaluate the thermal quenching directly? The answer may be NO because (1) the phosphor scattering model only considers the light-to-heat conversion part with a constant phosphor quantum efficiency (QE) and (2) the thermal resistance model only consider the heat dissipation part. Actually, the essence of thermal quenching is the temperature dependence of phosphor QE. An intuitive but feasible way is to combine our previous two models together with considering the temperature-dependent phosphor QE simultaneously.

In this paper, we attempted to develop an optical-thermal coupling model to study phosphor quenching effects on optical/thermal performance of LERP. The interacted optical and thermal effects were coupled by introducing the temperature dependence of phosphor QE. In this way, the existing phosphor model could be extended to evaluate phosphor thermal quenching effects under extremely high radiant power density of LDs. In addition, the complicated light-to-light and light-to-heat processes were simplified into a series of analytical equations and could be solved in a fast and accurate way. Optical and thermal experiments were conducted to verify the model. Based on this model, we systematically studied the effects of various factors on critical radiant power against thermal quenching. Finally, practical guidelines were provided to enhance radiant limit for high-reliability LERPs.

2. Model establishment

Fig. 1 illustrates the schematic of the optical-thermal model for LERP. A typical reflective LERP package consists of LD chip, phosphor layer, mirror layer, bonding layer, and heat sink [12,17]. The blue light and converted yellow light will be reflected on the mirror surface, and the output white light is in the opposite direction of incident light. Along with light conversion and mixing process, there is also light-to-heat conversion known as phosphor heating [22]. Due to the relatively low thermal conductivity of phosphor-silicone mixture ($\sim$0.2 W m^{-1} K^{-1}), the heat generated within the phosphor layer may not be dissipated efficiently, resulting in local high phosphor temperature and thermal quenching problem. As shown in Fig. 1, the present model consists of two sub-models, i.e. (a) phosphor scattering model and (b) steady-state thermal resistance model, and they are connected through the interaction between phosphor heating power Q_{ph} and phosphor temperature T_{ph}.

The first sub-model, i.e. phosphor scattering model, has been proposed and developed to evaluate phosphor heating for pc-LEDs [18,19,23,24]. As shown in Fig. 1(a), when the collimated laser beam is projected onto the phosphor layer, light absorption, scattering and conversion processes happen simultaneously. In this case, four light components can be derived as forward-scattering and back-scattering energy for blue and yellow light $E_B(z)$, $E_Y(z)$, $F_B(z)$ and $F_Y(z)$, respectively. Based on the energy conservation law and the modified Kubelka–Munk theory, four differential equations can be established with respect to the four light components. It should be pointed out that the boundary conditions are different from that of pc-LEDs and need to be re-expressed as follows.