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Noninvasively probing the light-emitting diode temperature by magnetic nanoparticles

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The precise measurement of temperature information is of great importance in the thermal management of light-emitting diodes (LEDs). Hitherto, many methods have been proposed to measure the LED temperature, but none of them involve with magnetics. Herein, we developed a noninvasive and precise method to probe the LED temperatures based on magnetic nanoparticles (MNPs). Detailed measurement principle and experimental setup were introduced. Through this setup, the heating and cooling characteristics of LEDs were investigated with different voltage inputs. It is found that higher voltage input leads to higher LED temperature. When the input voltage is 5.2 V, the LED temperature is 326.8 K. The present noninvasive and precise method supplements the existing techniques of temperature measurement in terms of magnetics and opens up new avenues to measure the temperature information where conventional approaches may fail. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4930868]

I. INTRODUCTION

Light-emitting diode (LED) technology has created more turmoil in the lighting industry than anything occurring over the previous century.[1–3] The conventional incandescent and fluorescent light sources are increasingly being replaced by more compact, more energy-efficient, higher-reliability, longer-lived, and environment-friendlier high-power white LEDs.[4] However, with the increasing power integration and size shrinking, LEDs generate a considerable amount of heat and result in high temperature, which can reduce LEDs' internal quantum efficiency (IQE), deteriorate optical property, degrade the reliability, and shorten the lifetime, etc.[1,5,6] Thus, good thermal management is inevitably demanded for high-power LEDs.[4] In the thermal management, the precise measurement of LED temperature is primarily demanded. Conventional testing methods, like thermocouples, cannot measure the LED temperature accurately,[7] so we have to seek the alternative approaches. Hitherto, many methods have been proposed to measure the LEDs temperature, such as laser Raman spectroscopy,[8] photothermal reflectance modulation,[9] threshold voltage,[10] thermal resistance,[11] photoluminescence,[12] electroluminescence,[13] forward voltage,[14] infrared image,[5] etc. Each method has its pros and cons, and all are well applied in the LED temperature measurement. As far as we are concerned, none of these methods involve with magnetics. Here, we reported a noninvasive method to measure the LED temperatures by magnetic nanoparticles (MNPs). The measurement principle is based on Langevin equation which correlates the temperature and the excited magnetic intensity. A layer of MNPs was coated on the LED chip surface and then put in a homemade AC magnetic field (MF). The heating and cooling characteristics of LEDs were obtained and discussed.

II. EXPERIMENTAL

A. Sample fabrication

The MNPs used in this study are commercially available Fe_3O_4 powders. To observe the morphology and microstructure, we dissolved the MNPs in light mineral oil (EFH1, FerroTec, Inc.) with volume fraction of 5% and obtained the MNP-based colloidal suspension, and then dispersed the suspension onto a copper grid that is coated with a thin layer of carbon. We used a JEOL (JEM2000EX) transmission electron microscope (TEM) operating at an accelerating voltage of 75 kV and an AMT XR41-B 4 megapixel (2048 × 2048) bottom mount CCD camera. The TEM image of the MNP suspension was shown in Fig. 1. It is seen that most MNPs are dispersed separately in the light mineral oil though some single- and multi-particle aggregations are also observed. The average size of the MNPs is about 10 nm according to the TEM image and the product specification.

To fabricate the LED samples, we first fixed conventional blue LED chips (Epistar) on the bottom of reflector substrate by die attach materials. Golden wires were used to connect the electrodes and circuits on the substrate by a wire bonder (WT-2330, Wetel). The packaging of the blue LED chips was then completed and the bare LEDs could be lit up with blue emission. Then we coated a layer of MNPs (0.5 mg, minimum dose) on the blue chips directly, as shown in Fig. 2. Due to the MNPs coating layer, it is worried that

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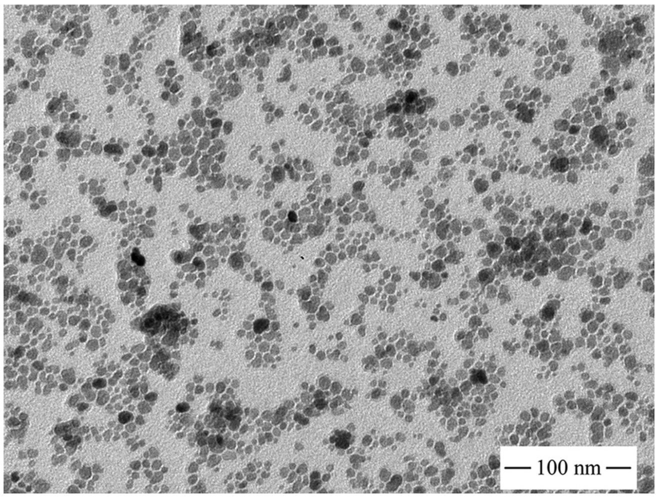

FIG. 1. TEM image of MNP suspension. The MNPs look darker due to higher electron density.

whether the MNPs influence on the light extraction. If so, more light would be trapped and converted into heat, resulting in higher temperature in the end. Thus, the influence of coated MNPs layer on the optical performance was first examined by an integrating sphere spectroradiometer system (LHS-1000, Everfine). Lacking of phosphors in LED samples, the luminous efficiency does not make sense, thus we measured the optical power of the LED samples. Before and after the MNPs coating, the optical powers were 857 mW and 850 mW at 350 mA input, respectively. From the result, the MNPs layer fails to make a difference on the light extraction, which implies that the temperature measured by MNPs is the same as that in the practical LED temperature.

B. Measurement principle

According to the Langevin equation, the magnetization of a superparamagnetic material has a one-to-one mapping relationship with temperature. If the applied magnetic field is in a sinusoidal format, $H = H_0 \sin(\omega t)$, the magnetization I of MNPs can be described as

$$I = NM\left(\frac{e^{\alpha}+e^{-\alpha}}{e^{\alpha}-e^{-\alpha}} - \frac{1}{\alpha}\right) = NM\left(\coth\alpha - \frac{1}{\alpha}\right), \qquad (1)$$

where N is the particle number in unit volume, M is the MNP's saturation magnetic moment. $\alpha = MH_0 \sin(\omega t)/(k_B T)$, where k_B is the Boltzmann's constant, H represents the magnetic field strength, and T is the absolute temperature. In our previous studies,[15–17] we have demonstrated that the sum of the first four items of the Fourier's expansion of Eq. (1) can represent the magnetization with enough accuracy. Therefore, we have

$$I = C_1 \sin(\omega t) + C_3 \sin(3\omega t) + C_5 \sin(5\omega t) + C_7 \sin(7\omega t) \qquad (2)$$

with four Fourier coefficients as

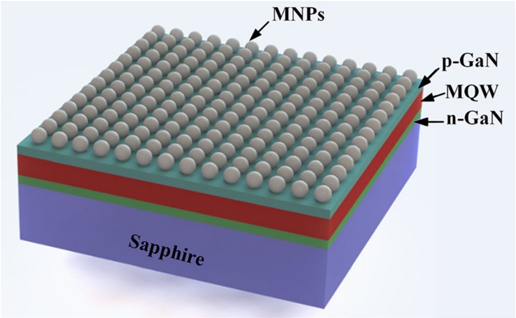

FIG. 2. LED sample with a thin MNPs coating layer.

$$\begin{bmatrix} C_1 \\ C_3 \\ C_5 \\ C_7 \end{bmatrix} = \begin{bmatrix} \frac{1}{3} & -\frac{1}{60} & \frac{1}{756} & -\frac{1}{8640} \\ 0 & \frac{1}{180} & -\frac{1}{1512} & \frac{1}{14400} \\ 0 & 0 & \frac{1}{7560} & -\frac{1}{43200} \\ 0 & 0 & 0 & \frac{1}{302400} \end{bmatrix} \begin{bmatrix} xy \\ x^3 y \\ x^5 y \\ x^7 y \end{bmatrix}, \qquad (3)$$

where $x = MH_0/(k_B T)$ and $y = NM$. In the measurement, we could obtain the amplitude of each harmonic response and from their ratios, we could eliminate the concentration and these ratios turn to be the function of the temperature. Detailed deduction process could be referred to our previous studies.[15–17] Therefore, we could apply this method to obtain the sample's temperature even without the MNPs' concentration information. From the measurement principle, the tested temperature is a lumped one, which characterizes the average temperature of the MNPs layer. Since the MNPs layer was coated directly on the LED chips, the tested temperature was assumed as the LED chip temperature in this study.

C. Experimental setup

The experimental setup was a homemade weak magnetic field measurement system based on the Helmholtz coil. As shown in Fig. 3, the system consisted of three parts: (a) exciting AC MF generator using two series of Helmholtz coils; (b) excited MF detector using a pair of magnetoresistive sensors (HMC1022, Honeywell) to collect signals from the LED samples; (c) data acquisition (DAQ) system based

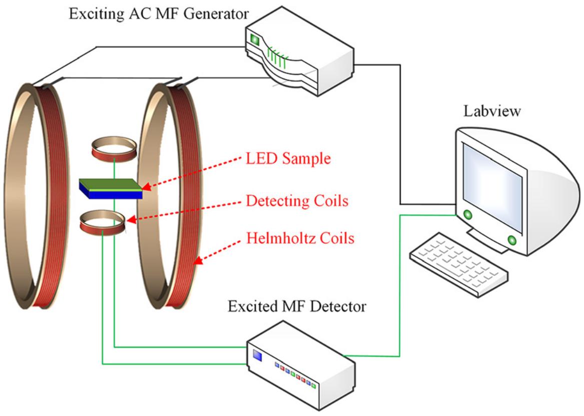

FIG. 3. Temperature measurement experimental setup.

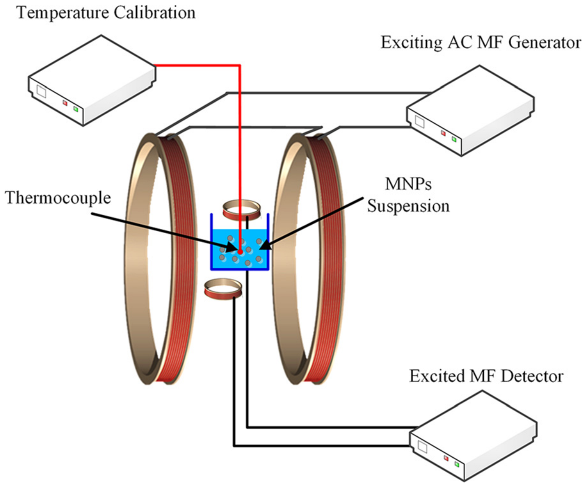

FIG. 4. Temperature calibration system.

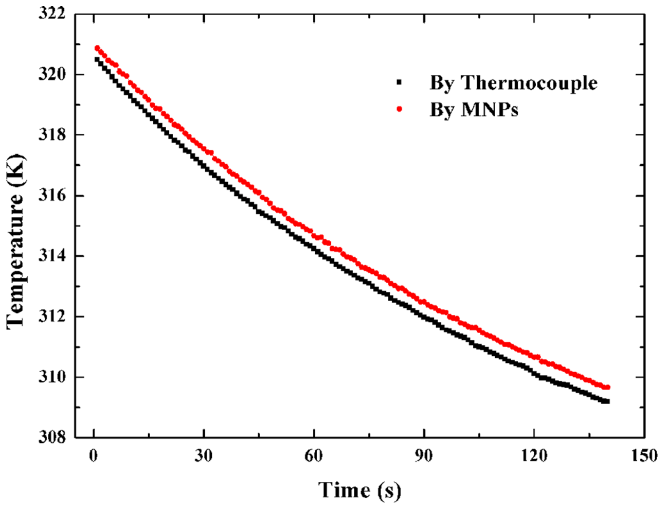

FIG. 5. Comparison of temperatures obtained by thermocouple and MNPs.

on a PCI multifunction card (USB-6356, NI). The amplitude of AC magnetization was calculated using a digital phase-sensitive detector (DPSD) algorithm in the Labview platform. The LED samples were placed at the center line of the Helmholtz coil between the two detecting coils. Based on the measurement principle, we recorded the amplitude of first- and third-order harmonic response in the experiment and the temperature information could be obtained by their ratio according to Eq. (3).

D. Calibration

Before measuring the LED temperature, we firstly calibrated the system with thermocouples. As shown in Fig. 4, we replaced the LED sample with a ferrofluid sample whose temperature can be easily obtained by thermocouples. We dissolved the MNPs in light mineral oil (EFH1, FerroTec, Inc.) with volume fraction of 5% and obtained the MNP-based colloidal suspension. Afterwards, the ferrofluid sample was oscillated by an ultrasonic oscillator. In the calibration, the ferrofluid sample was heated up to about 320 K using a water bath and maintained in hot water for 1 min until the sample's temperature became stable. Then both the temperature and magnetization were synchronously recorded as the ferrofluid sample naturally cooled down. The calibration results were shown in Fig. 5. It is seen that with time elapses, the temperatures obtained by the present setup and the thermocouples have the same trend and the average error is about 0.5 K. Therefore, the present setup could be used to measure the temperature with adequate accuracy.

III. RESULTS AND DISCUSSIONS

In the temperature measurement, we first used the DAQ (USB-6535, NI) to generate a steady sinusoid wave voltage signal with frequency of 375 Hz and amplitude of 7.5 V. The sinusoid wave signal was amplified by a linear power amplifier (AE 7224) and then to drive the Helmholtz coils to generate a steady AC magnetic field with frequency of 375 Hz and

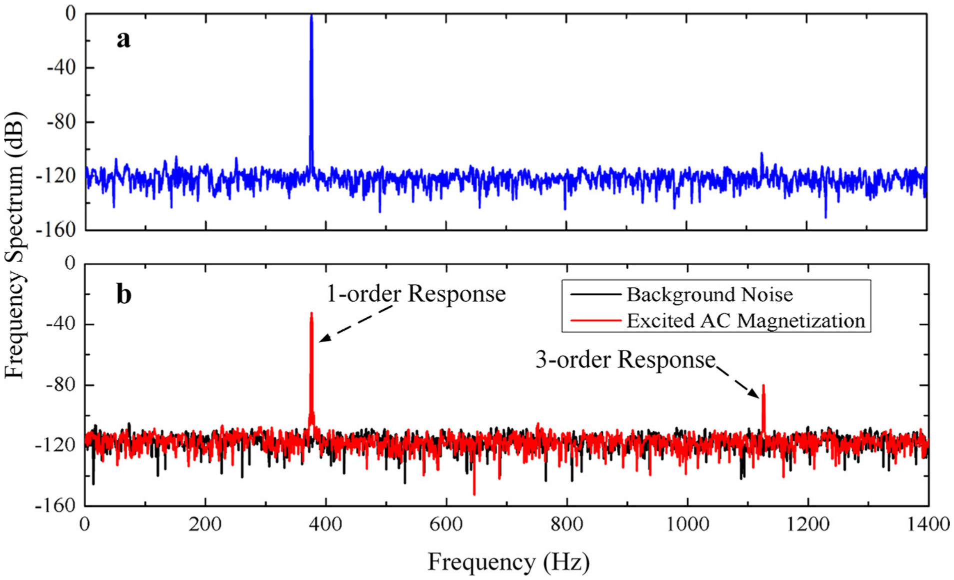

FIG. 6. (a) Frequency-domain sinusoid wave voltage signal in the Helmholtz coils and (b) frequency-domain plots of the background noise and signal intensity of the MNP's excited AC magnetization.

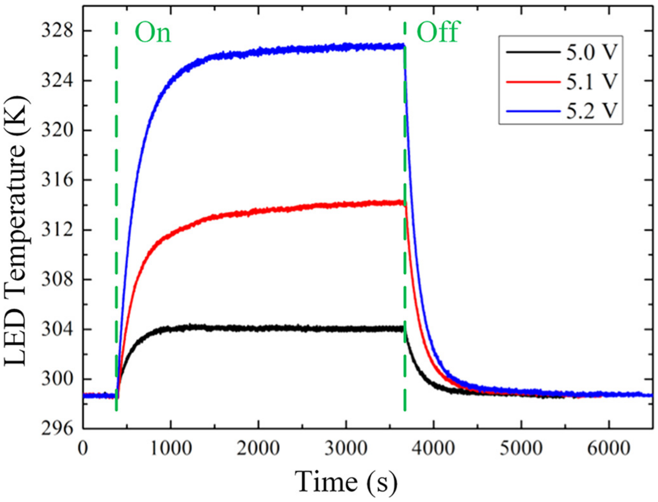

FIG. 7. Heating and cooling characteristics of LEDs under different voltages. LED samples were turned on to observe the heating characteristics until the temperatures become steady, and then were turned off to observe the cooling characteristics. The room temperature was kept at 298 K (25 °C).

amplitude of 12 G, as shown in Fig. 6(a). To make sure the stability of exciting magnetization, we connected a high-power electric resistor (2 Ω, 75 W) in series to monitor the exciting current in real-time, so as to realize the closed-loop control of exciting AC magnetic field generation module. Then, we put the LED sample in the exciting magnetic field, and the time- and frequency-domain plots of the background noise and signal intensity of the MNP's excited magnetization in the beginning were shown in Fig. 6(b). When putting the LED sample in the system, the first- and third-order harmonic responses were exactly at 375 Hz and 1125 Hz, and their intensities were −35 dB and −82 dB, respectively. With the ratio of the first- and the third-order harmonic response, we could obtain the temperature information according to Eq. (3).

In the temperature measurement, we recorded the variation of the magnetic signals in real time and deduced the corresponding temperature curves. Then, the transient turning-on and turning-off temperature responses of LED samples were shown in Fig. 7 at different voltage inputs. It is seen that when turned on, the input electricity converts to optical emission and heat simultaneously, thus the LED temperature increases gradually from room temperature (298 K) and becomes stable eventually when the heat generation and dissipation are balanced. The highest steady LED temperatures were 304.2 K, 314.3 K, and 326.8 K at 5.0 V, 5.1 V, and 5.2 V, respectively. This is because larger voltage input generates more heat and higher temperature. The larger slope of the temperature curves at larger voltage input implies faster temperature response of the system. Then we turned off the LEDs, and the temperature decreases sharply at first and then returns to room temperature eventually.

IV. CONCLUSION

In conclusion, we developed a noninvasive method to probe the LED temperature based on the MNPs in this study. The bridge between the temperature and the magnetization was built based on the Langevin equation. To probe the temperature, we established an experimental setup which includes an exciting AC MF generator based on Helmholtz coils, an excited MF detector, and DAQ system. The detailed experimental setup and measurement principle were introduced. Under the excitation of a steady AC magnetic field at 375 Hz, the first- and third-order harmonic responses were detected in the excited MF, and the corresponding temperatures were deduced with time. Based on such setup, we investigated the heating and cooling characteristics of LEDs at different input voltages. When the input voltage was 5.2 V, the LED temperatures were 326.8 K. The present MNPs-based method supplements the existing techniques to measure the LED temperature. But our current method could just deal with lumped temperature information rather the point-to-point temperature, thus we failed to obtain the lateral temperature profile along the LED chip surface. If improved, the MNPs-based method will be more promising in extensive applications. The MNPs-based method presented in this study is a noninvasive approach to probe the temperature with adequate accuracy, which opens up new avenues in temperature measurement applications. As long as we could coat or embed the MNPs on/inside the desired layer, we could measure the temperature by such experimental setup. It is not only can be used to measure the LED temperature but also can be further applied to measure the temperatures of phosphor layer, solder layer, thermal interfacial layer (TIM), etc., in IC/LED packaging.

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