Detailed Study of Optical and Thermal Performance for White Light-Emitting Diodes With Filament-Like Packaging Structures

Guanwei Liang, Yong Tang, Zhou Lu, Kejian Wu, Zongtao Li, *Member, IEEE*, and Jiasheng Li

***Abstract*— Retro filament white light-emitting diodes (WLEDs) have attracted great attention and are widely welcomed by consumers. The results of an investigation for the optical and thermal performance of filament-like WLEDs with various packaging structures are presented in detail. The optical simulation shows that the phosphor concentration on the chip-bonding side makes a great contribution to increasing backscattered blue light power. It means the backside should be packaged to improve blue light utilization. By controlling the phosphor coating structure, several filament-like LEDs were fabricated and subsequently investigated. The luminous efficacy (LE), correlated color temperature (CCT) and thermal reliability were measured, and then the structures were proposed and optimized. The optimal structure can maintain the equivalent LE compared with others under almost the same CCT. The CCT and light intensity spatial distribution were also analyzed based on the phosphor structure. The phosphor on the chip-bonding side contributes significantly to the CCT deviation. Consequently, the proposed structure filament-like WLEDs exhibited 2.23 and 5.42 ° lower working temperatures than the half packaging and full packaging structures under a driving current of 15 mA, respectively. Besides, the no-middle packaging structure was investigated in detail for optimal optical performance. After optimization, when the back surface dispensed 20 μL of phosphor resin, the LE increased from 182.9 to 188.3 lm/W at similar CCT with the CCT deviation changed from 1062 to 154.5 K significantly. Therefore, it was revealed that optimizing the packaging structure is an efficient method of enhancing the performance of filament-like WLEDs.**

***Index Terms*— Filament-like white light-emitting diodes (WLEDs), optical performance, phosphor structure, thermal reliability.**

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I. Introduction

White light-emitting diodes (WLEDs) are widely used on a daily basis, due to the factors including their high luminous efficacy (LE), energy saving, and long lifetime [1]–[3]. The most common method of producing WLEDs is by using blue LED chips to excite YAG yellow and red phosphor [4], which is the main method used in the industry. With the development of packaging technology, many products have been designed, such as surface mounted devices and chip-on-board products [5]–[7]. Due to restrictions associated with the frame and the board, these devices can only provide light in one direction with a lighting angle of less than 180° [8], [9]. However, greater lighting angles of up to 360° are required in many applications. It is well known that incandescent bulbs played an important role in the history of illuminance, although they consume a large amount of energy [10]. As a result, they will eventually be replaced in the commercial market by LEDs [11]. However, their convenience and nearly 360° lighting are always highly desirable in the pursuit of new product designs [8], [12].

Over the past few years, retro bulbs based on filament-like LEDs have been designed, which are popular in academic and industrial fields [13]–[15]. The blue LED chips are bonded on the strip board and packaged as filament-like LEDs. They are then encapsulated in a glass bulb to replace traditional filaments, ensuring the emitted light propagates in all directions. Evidently, the performance of these LED bulbs depends on the filament-like LED components. The morphology of the phosphor coating has a significant impact on the optical characteristic of WLEDs [16]–[18]. Herein, phosphor on filament-like LEDs is fabricated as a straight bar, such that the structure is not optimized. The phosphor packaging structure may cause different luminous flux, correlated color temperature (CCT) distribution, and other effects [19], [20]. It is necessary to consider the optical performance of different packaging structures. Moreover, the filament-like LEDs are also set in the sealed glass bulb with poor heat dissipation in industry products, leading to the difficult challenge of thermal management [11], [21]. There are several options for addressing this issue, but they introduce limitations with respect to the phosphor packaging structures. High thermal conductive materials are always chosen as the filament LED substrate [22], [23]. Xu *et al.* [8] used the ionic wind to enhance the heat dissipation ability of LED filament bulbs. Feng *et al.* [13] filled the glass bulb with high thermal conductive gases, such as helium, to decrease the working temperature of the filament LEDs. Moreover, Liu *et al.* [24] utilized numerical analysis approach to investigate the influence of the bulb sizes and the phosphor structure. However, a few works have been investigated critical performance issues of filament-like LEDs considering their packaging structure. In particular, the optimization of the phosphor packaging structure to improve the optical performance and thermal dissipation of filament LEDs has not been reported.

In this paper, we have investigated the effect of packaging structure of filament-like LEDs on the optical and thermal performances. Three kinds of phosphor packaging structures were designed and fabricated, including the half packaging structure, no-middle packaging structure, and full packaging structure. Optical simulations are carried out to study and optimize the packaging structure. According to the optimal packaging structure, different lighting systems were investigated by changing the phosphor manufacturing parameters.

II. Experiments and Preparations

A. Fabrications of Filament-Like LEDs With Various Packaging Structure

Retro style filament-like LEDs are popular in the commercial market, and a typical device is shown in Fig. 1(a). Their designed packaging structures can be seen in Fig. 1(b)–(d), including the half packaging, no-middle packaging, and full packaging. The half packaging structure was formed mainly by dispensing phosphor resin on the chip-bonding surface of the ceramic substrate, but also flowed to the two side surfaces due to the excess amount of phosphor and gravity. Both the surfaces but not the small side faces were equally encapsulated with phosphor resin in the fabrication of the no-middle packaging structure. In the full packaging structure, all the ceramic substrate surfaces were packaged. Besides, their correlated devices were simply named as HP-LED, NP-LED, and FP-LED, respectively. Due to the different packaging structures, the devices exhibit different optical and thermal performances.

As for the fabrication, 25 blue LED chips were died on a ceramic substrate and then serially bonded with Au wires prior to the introduction of the phosphor packaging first. An amount of yellow YAG phosphor (2BE558, Jiangsu Bree Optronics Co., Ltd., Nanjing, China) and red YAG phosphor (MPR series, Mitsubishi Chemical Co., Ltd., Tokyo, Japan) was uniformly dissolved in the silicon resin (WB-43-2, Shenzhen Earlysun Technology Co., Ltd., Shenzhen, China) with a phosphor concentration of 13.34 wt% and an average viscosity of 40 Pa·s. The filament-like WLEDs with various packaging structures were then fabricated using phosphor dispensing technology. By controlling the dispensing crafts, the phosphor distributed structure can be easily designed and fabricated on the ceramic substrate surfaces. For the HP-LED and NP-LED, a common cone shape dispensing needle was used. And a U-shaped dispensing needle was used for preparing FP-LED, and the phosphor resin would be squeezed and flowed to the small side faces to form the full packaging structure. Besides, as for NP-LED and FP-LED, when packaged with phosphor resin on one surface, they would be cured rapidly at 150 °C for 5 min. And then they would be packaged on the other surface. The amount of phosphor was kept constant during the dispensing process. Finally, the samples were cured at 170 °C for 4 h. Furthermore, a detailed study based on the optimal structure was performed to facilitate further improvement. As a result, different CCTs could be easily obtained by controlling the dispensing amount on the rear of the devices, for further optimizing the phosphor manufacturing parameters.

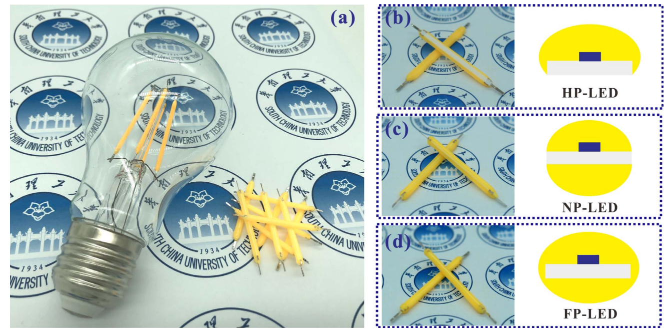

Fig. 1. (a) Photograph of filament-like WLEDs commercial products. (b)–(d) Various filament-like WLEDs with different packaging structures.

B. Modeling and Optical Simulation Methods

The retro-style filament-like LEDs always have a low CCT, and the number of phosphor particles could bring a great scatter phenomenon, which may influence the lighting performance in the backside. In a traditional package, the phosphor was dispensed on the chip side to obtain white light. It is necessary to consider the specific mechanism and influence of the phosphor parameters on the chip side to the lighting effect on the backside, which contributes to designing the packaging structure of filament-like LEDs. To study the effect of phosphor concentration on the chip-bonding side, the Monte Carlo ray-tracing method was used for optical simulation. Fig. 2 shows the cross-sectional view of the optical model of the HP-LED. The optical model consists of the ceramic substrate, LED chips, bonding resin and phosphor. The chips with a size of 0.73×0.27 mm^2 were set as the source with an exciting wavelength of 455 nm on the top surface. The refractive index of the bonding silicone and ceramic was set as 1.41 and 1.765, respectively. To obtain the effect of phosphor concentration on the backscattered light, different phosphor concentration from 0.25 to 2.5 g/cm^3 with various scattering coefficient was set as our previous study [25]. After ray tracing, the rays escaped from the backside were monitored by a hemispherical detector. And the yellow and blue light power was analyzed.

C. Optical and Thermal Performance Measurements

While finishing the packaging process, the specific performance of the optical and thermal parameters was studied in detail. LE and total CCT of the filament-like LEDs were tested

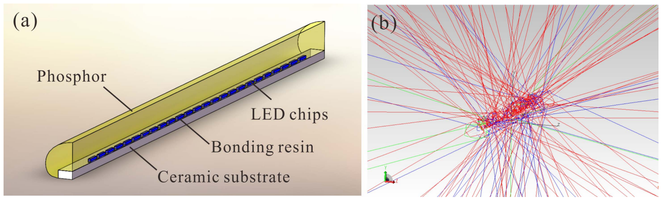

Fig. 2. (a) Packaging structure of HP-LED. (b) Optical model of HP-LED and light extraction direction trace.

by an integrating sphere from Instrument Systems Optische Messtechnik GmbH, Munich, Germany, which were powered by a KEITHLEY 2400 dc source with a driving current 15 mA. The devices were set in the center of the integrating sphere. And their optical performance stability with the increasing current was also measured. To study the spatial lighting performance of these LED devices, their angular distributions of luminance intensity and CCT were investigated based on the far-field testing method using our homemade measurement. The spectral probe revolved around the LED center from −90° to 90° for measurement and detail process could be found in our previous work [4]. Finally, the surface temperature distributions of filament-like LEDs devices were carried out by an FLIR A655SC.

III. Results and Discussions

After light simulation analyzed from the backside, Fig. 3 presents the calculated normalized blue light power and the percentage ratio between the yellow light intensity to the blue light (YBR). As the concentration increase from 0.25 to 2.5 g/cm^3, the blue light power increases gradually. This is because the light scattering phenomenon of YAG phosphor, more blue light would be backscattered to the backside [26]. The increasing blue light power in the backside will lower light efficacy without exciting the phosphor and make an influence on the lighting performance, such as CCT and light intensity. The YBR was calculated to analyze this issue, and the results show that the YBR decreases with the increasing phosphor concentration. Actually, more yellow light would also be excited to the backside due to the high phosphor concentration. But the increase of backscattered blue light is greater than the yellow light, leading to a decrease of YBR. Therefore, the backside should be packed with phosphor resin to improve their lighting performance of filament-like LEDs, which also needs further optimizing.

To discuss the luminance characteristic of the filament-like WLEDs, Fig. 4 gives their LE and spectrum, which exhibits almost similar LE characteristic and approximatively CCT for three kinds of filament-like LEDs. The LE is almost the same for the HP-LED and FP-LED, with an LE response of 185.8 lm/W. However, the CCT of HP-LED is 4107 K, which is 346 K lower than that of the FP-LED. NP-LED performed the best, with an LE of 190.1 lm/W at approximately 4468 K. It can be easily seen that the LE of the filament-like WLEDs is high [22], which is sufficiently high for the bulbs with several integrated components in daily life. Fig. 4(b) shows their spectrum, which demonstrates the small difference luminous output. Compared with the

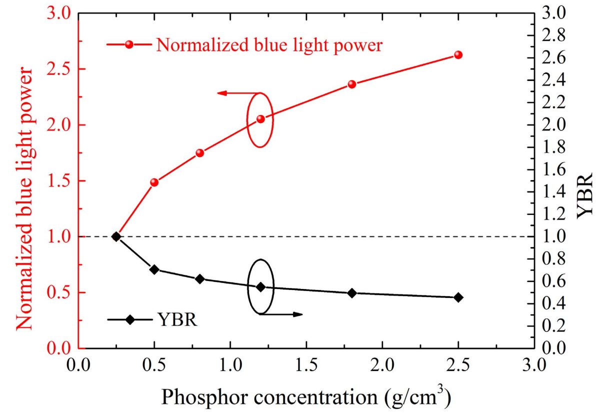

Fig. 3. Normalized blue light power and YBR for HP-LEDs with different phosphor concentration in the backside.

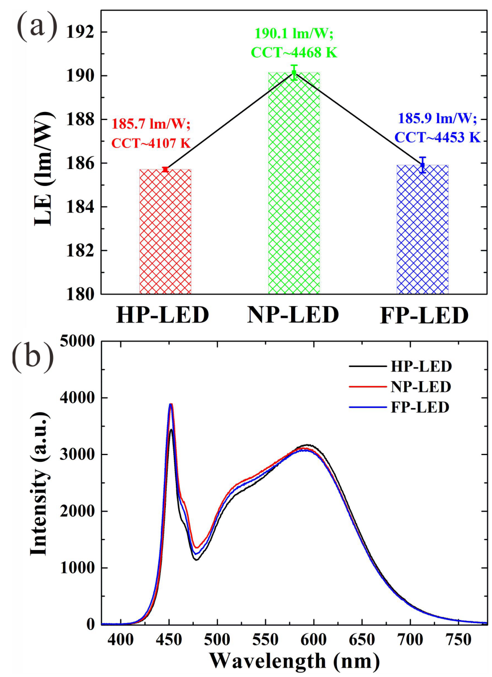

Fig. 4. Performance of filament-like WLEDs with different packaging structures at 15 mA: (a) LE at almost the same CCT and (b) spectrum.

HP-LED, the NP-LED and FP-LED exhibit higher blue and yellow light compositions but smaller red light. As a result of the total phosphor on one surface of the HP-LED, more blue light is converted to yellow and red light, and some yellow light will be absorbed by the red phosphor, leading to the lower blue-light spectrum and higher red-light spectrum. The spectra of NP-LED and FP-LED are almost the same, and the NP-LED is slightly larger than the FP-LED. Above, these filament-like LEDs perform a similar LE within a difference of 3% under almost the same CCT, which can be ignored in actual application. Therefore, this study would focus on their lighting effect in different spatial directions and thermal dissipation ability with different packaging structures.

The filament-like LEDs can achieve 360° of lighting effect, but seldom researches focus on their spatial lighting characteristics, which need to be studied in detail. To perform

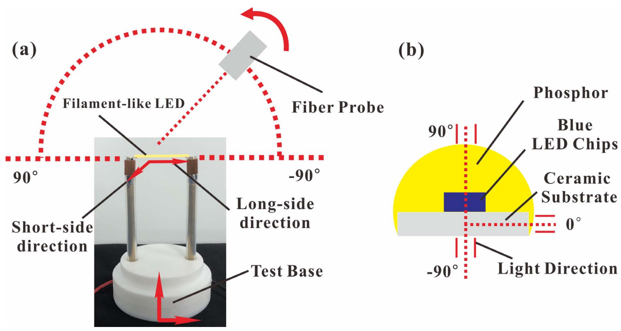

Fig. 5. Principle descriptions of (a) CCT and light intensity spatial distribution measurement for filament-like WLEDs and (b) typical testing angles.

this investigation, a testing base was designed for setting the components at different lighting direction, as shown in Fig. 5(a). To study their integral performance completely, three typical lighting directions were chosen according to the packaging structure. Fig. 5(b) shows the cross section of the tested angles of the LEDs, mainly including the −90°, 0°, and 90° directions.

The lighting effect in spatial directions of the components was investigated using the far-field test method, and the results are listed in Fig. 6. The spatial distribution is tested along with the long-side direction of the LED devices. As shown in Fig. 6(a)–(c), the CCT distribution in various directions behaves differently. For the HP-LED, the lowest CCT occurs at 0° because of the small blue light power and the higher phosphor amount. Most o the blue light was converted to the exciting light leading the lowest CCT. And the following CCT distribution appears at 90° as the result of the largest blue-light configuration and moderate phosphor amount. The CCT at −90° is the highest due to no phosphor package and the remaining unconverted blue light. The NP-LED and FP-LED have a similar CCT distribution in all direction. A small difference appears at 0° because the CCT of FP-LED is slightly lower than that of NP-LED. And the result at −90° is also the same as at 0°. This is mainly because the side surface of FP-LED was packaged with phosphor, affecting the CCT distribution. But, the CCT of FP-LED is slightly higher than that of NP-LED at 90° due to the movement of a little amount of phosphor to the ceramic substrate side surface. Obviously, the phosphor distribution makes a great effect on the lighting color distribution, which should be considered for the design of filament-like LEDs.

To support the CCT distribution, the YBR was also measured and calculated. During the YBR test, the blue and yellow light intensity can be obtained using the filter, respectively. Especially, the wavelength range of blue light is from 380 to 490 nm, and 490 to 780 nm for yellow light. The results are shown in Fig. 6(d)–(f). For most measured angles, the ratio increases gradually from 0° to 80° because of the Lambert intensity distribution for LED sources. The YBR is also different for the measuring angles, which corresponds to the CCT distribution. The small value of YBR supports the high CCT because of the small yellow light power ratio. Considering the results of HP-LED at −90° for example, the YBR is the smallest because the penetrating blue light is hardly converted to yellow light and small power yellow light is backscattered to penetrate the ceramic substrate, thereby fitting the results of the CCT distribution.

It can be easily determined that phosphor on the chip-bonding side contributes significantly to the CCT distribution. To analyze the influence, the CCT deviation is defined to characterize the CCT uniformity in one direction, which mainly depends on the difference between the biggest and the smallest CCT value from −80° to 80°. Fig. 7 shows the change of the CCT deviation in one direction. For these LEDs with different packaging structures, all the CCT deviation value at 90° is bigger than that at the other directions, caused by a large amount of blue light power. At −90°, the HP-LED owns the biggest deviation of 332 K, the next is NP-LED, and the smallest one is the FP-LED. At 90°, on the chip-bonding side, the HP-LED has the smallest deviation because of the large amount of phosphor. The phosphor amount on the chip-bonding side contributes to its thickness, which influences the CCT distribution at 90°. For HP-LED, the phosphor geometry benefits the blue-light converting to yellow light at 90° due to the thick phosphor thickness [27]. It contributes to weakening the blue light escaping, and more yellow light is emitted at 90°. The comprehensive effect leads to the smallest deviation for HP-LED. The deviation of NP-LED at 90° has a similar trend to that of the FP-LED. Naturally, the NP-LED has the biggest deviation of 781 K at 90°, only performs 186 K larger than FP-LED. As for the deviation at 0° and −90°, the NP-LED exits the bigger one than the FP-LED within a small difference of 116 and 34 K, respectively. This may be caused by the transparent blue light from the two small middle sides of the ceramic substrate. Considering the above-mentioned results for various lighting direction, the CCT deviation of the filament-like LEDs is attributed to the phosphor structure on the chip-bonding side. Therefore, it is important to take the packaging structure into consideration for high-quality lighting.

Above, the CCT distribution is quite different in various lighting angles, affecting their lighting uniformity. Herein, the total CCT deviation (the difference between the biggest and the smallest CCT in all direction) is defined to characterize the CCT uniformity of the filament-like LED components. The results are listed in Table I. The minimum CCT deviation value is associated with the HP-LED, and the largest value is associated with the FP-LED. The HP-LED has the smallest CCT deviation of 1025 K, followed by the NP-LED with a value of 1085 K, and the largest value of 1329 K is ascribed to the FP-LED. This is mainly because the CCT performs differently at 0° and 90° due to the phosphor distribution. It shows that these LEDs with different phosphor structures have a similar CCT deviation for spatial lighting, which needs further improving. In general, the HP-LED and NP-LED perform better than FP-LED.

Besides, the light intensity distribution is also distinct in all the directions for these LEDs. Fig. 8(a)–(c) represent the light intensity distribution. Similar to the CCT distribution, the light intensity exhibits a gradient change in the testing direction. For these packaging LEDs, they all have the highest intensity at 90°. The lowest intensity occurs at −90° except

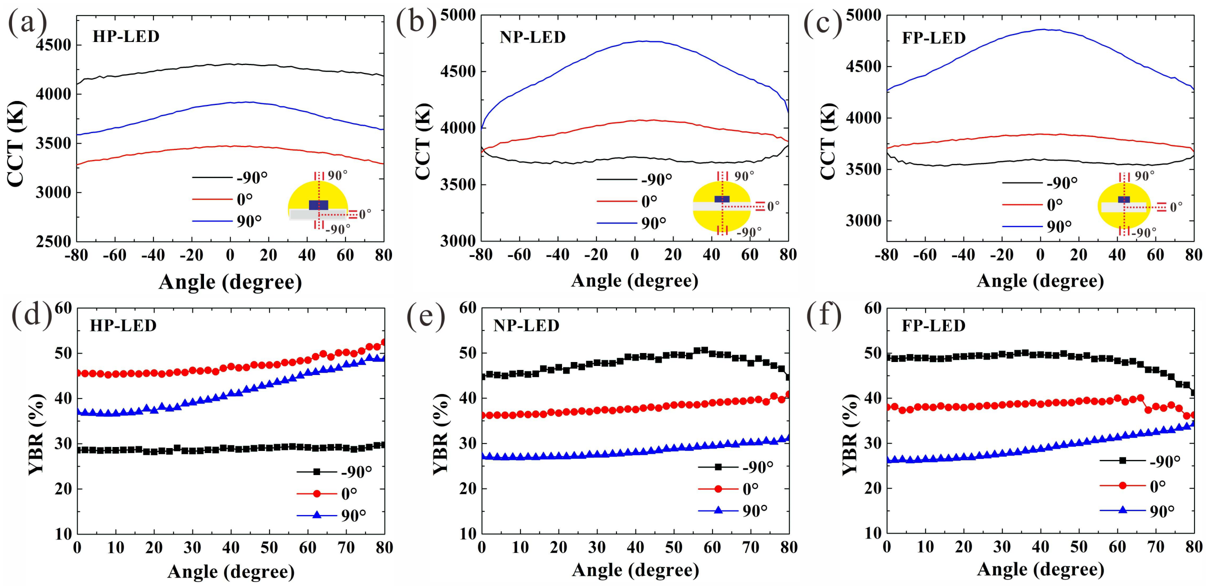

Fig. 6. Measurement for filament-like WLEDs (tested along the long-side direction) with different packaging structure under different testing angle: (a)–(c) CCT distribution and (d)–(f) YBR.

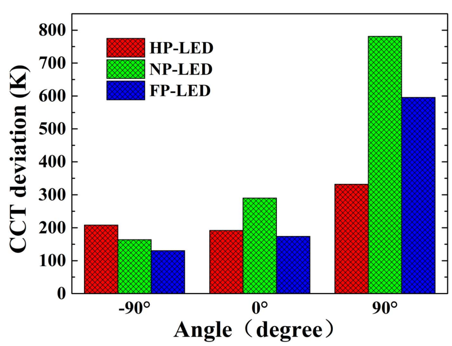

Fig. 7. CCT deviation of filament-like WLEDs in various measuring angle (tested along the long-side direction of WLEDs).

TABLE I
CCT Deviation of Filament-Like WLEDs With Various Packaging Structure

	HP-LED	NP-LED	FP-LED
Maximum CCT	4307.77	4769	4862.21
Minimum CCT	3282.52	3684	3533.21
CCT deviation	1025.25	1085	1329

for the HP-LED, which occurs at 0°. It is because the large amount phosphor flowed to the sidewall due to the gravity. The HP-LED has an approximative intensity at 0° and −90°, but the intensity is smaller than that at 90°. The NP-LED performs similarly in 0° and 90°, and the intensity is higher than −90°. Else, the light intensity gradient of FP-LED in three directions is clear, which is not suitable for lighting uniformity. The average intensity is extracted in Fig. 8(d). It is clear that the average intensity is similar at 0° and 90°. Except for the results at −90°, there is a big difference. The average intensity of the NP-LED at −90° is much smaller than that of the others. This may be caused by the small blue light power and a large amount of phosphor. More blue light would be consumed to obtain the exciting light, and a large amount of light would be absorbed by the increase light path [28]. Therefore, the phosphor on the backside of NP-LED should be optimized for light extraction and uniform lighting effect. It could be concluded that the filament-like LEDs exhibit great unevenness for 360° lighting applications, which should be addressed by optimizing the component setting structure in the bulb.

The principle of the light transfer trace is shown in Fig. 9. Exactly, the phosphor shape is formed by the dispensing process. Most of the light from the blue-chips excites the phosphor to generate yellow light at 90°, and the yellow light would be scattered into all directions. It is revealed that the phosphor layer parameters on the chip have a great influence on their optical performance. Thanks to the backscatter, some blue light is transmitted through the ceramic substrate to escape at both 0° and −90°. Therefore, whether 0° and −90° of the ceramic substrates are packaged with phosphor is a key parameter to the diversity of the lighting performance of filament-like LEDs. The phosphor manufacturing distribution may cause a different light path, leading to different lighting intensity.

In commercial application, the filament-like LEDs are always placed in the sealed glass bulb to ensure the light is emitted to all direction, and the LED devices' heat dissipation is poor. The working temperature of filament-like LED devices contributes a lot to their thermal stability and lifetime. The thermal management of them is a huge challenge to solve. To study the thermal effect on the packaging structure further, the surface temperature of the LED devices was tested with a driving current ranging from 10 to 23 mA. And the tested process can be seen in Fig. 10(a). The filament-like LEDs were driven by the KEITHLEY source, which temperature was collected by an infrared camera directly. In Fig. 10(b), as the driving current increased from 10 to 23 mA, all the working temperature of LEDs with different structures increased

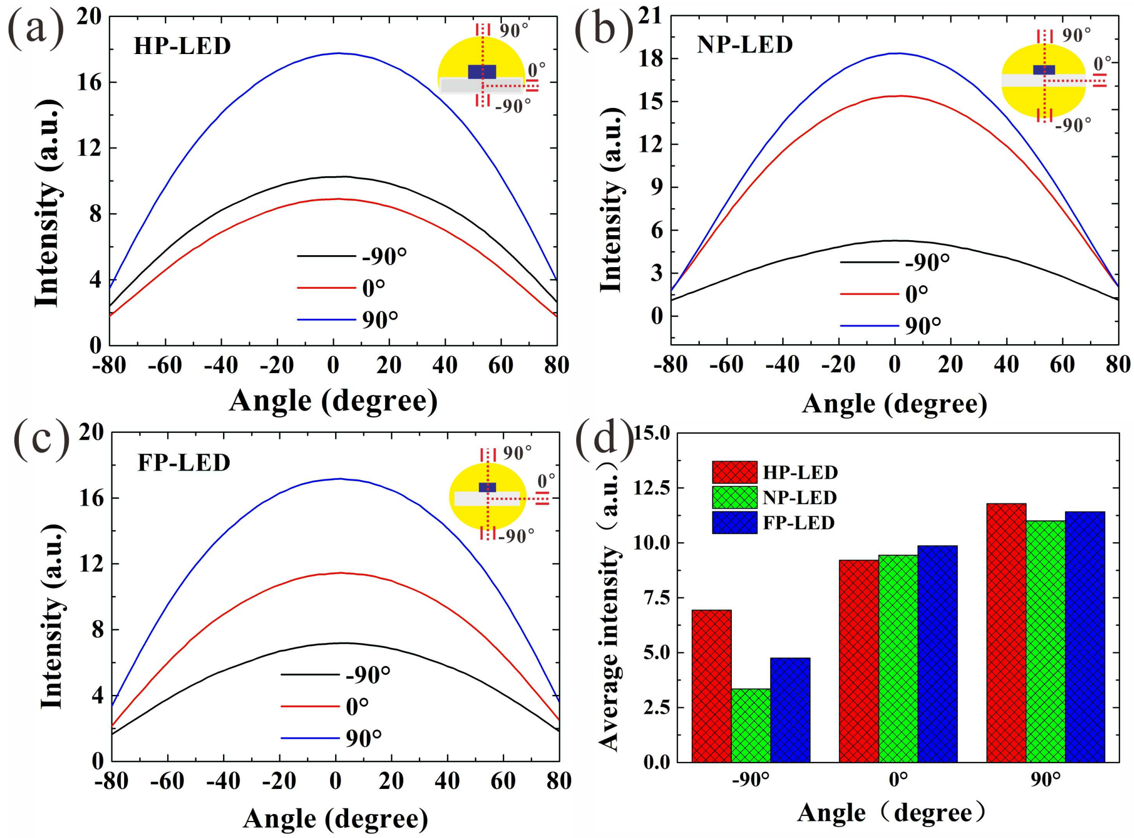

Fig. 8. Light intensity properties of filament-like WLEDs (tested along the long-side direction) with different packaging structure under different testing angle: (a)–(c) distribution and (d) average intensity.

immediately. In general, the biggest change occurred in the FP-LED because the ceramic substrate is all surrounded by phosphor resin. The largest increase of 61.1 °C from 65.9 °C to 127 °C was observed. In detail, the FP-LED has the highest temperature of 89.43 °C at 15 mA, followed by the HP-LED at 86.23 °C, and the lowest temperature occurs on the NP-LED with a value of 84.0 °C. The inset of Fig. 10(b) shows the infrared images of three structural filament-like LEDs. It can be clearly determined that the highest temperature appears in the middle of the devices because the LED chips distribute relatively concentrated on the ceramic substrate and the complex heat filed interacted by each chip [29]. The heat on both sides can be escaped more easily, leading to a lower temperature. It is well known that the heat mainly transfers from the LED component to air via convective heat transfer. The amount of phosphor remains the same, which means that the cooling area of the phosphor resin to the air is almost constant. Therefore, the cooling effect mainly depends on the ceramic substrate area exposed to the air. The ceramic substrate is fully packaged with phosphor in the FP-LED, and therefore, its cooling behavior is mainly via the resin to air, resulting in the largest temperature of these three configurations. Although the HP-LED has the largest cooling surface, the heat generated from the concentrating phosphor distribution overcomes the cooling effect. The highest working temperature of the HP-LED is 2.23 °C higher than that of the NP-LED with two small side surfaces. In addition, the heat reliability of the NP-LED performs the best with an increase of the current. In addition, the study focuses on the packaging structure of LED sources to solve their thermal problem without adding other cooling methods and the results are effective to the filament-like LEDs.

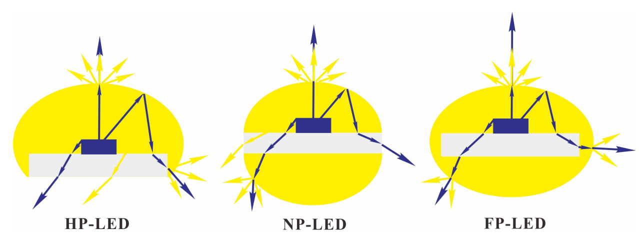

Fig. 9. Schematic of light exit direction of filament-like WLEDs with different packaging structure.

Based on the preceding observations, the driving current has a significant impact on the heat reliability of the LEDs, and it was revealed that the packaging structure plays a great role in heat dissipation. As a result, the NP-LED exhibits the perfect heat reliability and the lowest working temperature, which means that it exhibits a highly stable lighting effect. The optical performance stability with increasing current is measured, and the results are shown in Fig. 11. As the current increased from 5 to 120 mA, more blue light is generated, and more yellow light is excited. The CCT maintains a balance with the current injection and exhibits a small

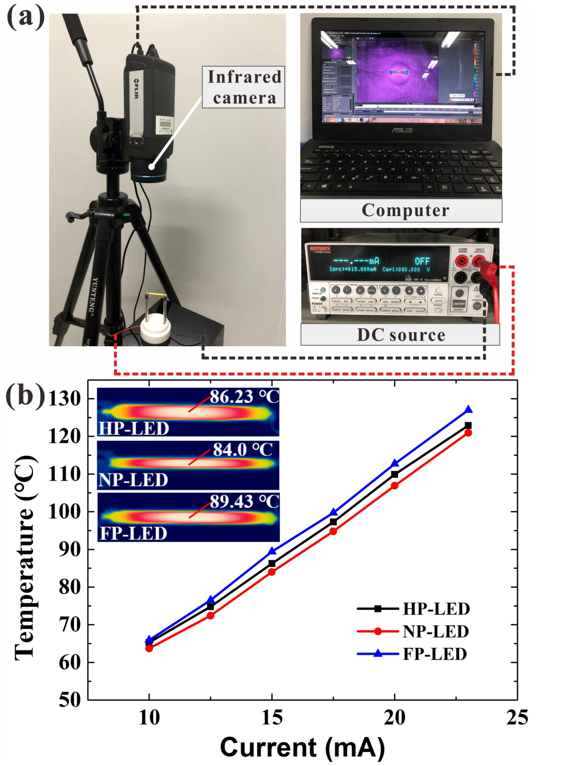

Fig. 10. Temperature fields of the three types WLEDs at 90° measured by infrared thermal imager: (a) measured process and (b) maximum temperature under different driving current and the inset is temperature images of three structural filament-like LEDs under 15 mA.

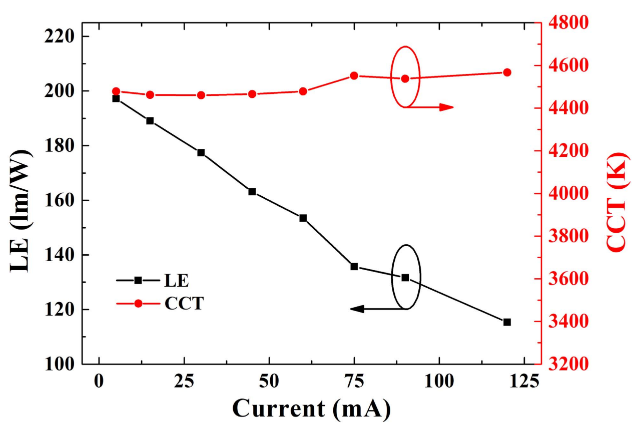

Fig. 11. LE and CCT of the NP-LEDs from 5 to 120 mA.

increase from 4478 to 4567 K with a deviation of 111 K. However, the LE was significantly reduced from 197.2 to 115.3 lm/W, due to the lower excitation efficiency of the large current. The results show that the NP-LED exhibits a good utilization efficiency of the phosphor, leading to a good CCT stability.

Above, the NP-LED packaging structure shows similar CCT deviation and better lighting distribution effect with other LEDs. And it also performs the better heat reliability performances, but the phosphor manufacturing parameters on the back surface still needs to be optimized for better lighting effect. After that, the amount of phosphor dispensed on the back surface increased from 0 to 55 μL, while the chip-bonding surface was maintained at 55 μL. The optical performance is presented in Fig. 12. As the phosphor amount increased, the LE increases gradually along with a decrease in the CCT. It was determined that the LE and CCT changed significantly when the back surface dispensed 20 μL of phosphor resin. The LE increased from 182.9 to 188.3 lm/W, and the CCT decreased from 5048 to 4588 K. Subsequently, the LE witnesses a slight increase within 1.8 lm/W and the CCT decreases within 120 K, which almost keep constant. Fig. 12(b) gives their spectrum. It is evident from the results that the peak of the blue light decreased and was converted to yellow and red light, leading to an increase of LE. The spectrum almost remained nearly constant as the amount of phosphor was increased. In particular, the CCT distribution at −90° was also tested, and the results are shown in Fig. 12(c). It is evident that the CCT changed significantly when 20 μL of phosphor resin was dispensed on the blank back surface. And the CCT deviation changed from 1062 to 154.5 K significantly. In addition, the CCT distribution was also slightly reduced as the amount of phosphor increased because more blue light at −90° was consumed, and more yellow and red light was generated. However, the average intensity decreased as the amount of phosphor increased, leading to irregular illumination in spatial lighting, as can be seen in Fig. 12(d). This is mainly caused by the decrease of transmittance and long light path due to the increasing phosphor amount. Based on these results, it can be revealed that the phosphor manufacturing parameter of NP-LEDs back surface can be optimized for 20 μL of phosphor resin dispensed on the blank back surface. It can not only maintain a similar lighting effect, including LE and CCT but also improve the average light intensity in the backside, contributing to lighting uniformity. Above, the related results can provide fabricating guidance in the design of lighting effects and cost savings.

With the change of the phosphor parameter on the backside of NP-LED, the heat dissipation ability may make a difference. Fig. 13 shows the working temperature of NP-LEDs with various encapsulation phosphor resin dispensing amount from 0 to 55 μL on their backside. It is obvious that the working temperature at 90° is higher than that at −90° as the result of larger blue light power and the greater phosphor excitations. As the dispensing amount increased, both the working temperature decrease, featuring a decrease of 4.8 °C at 90° and 6.4 °C at −90°. The increasing phosphor resin dispensing amount can significantly increase the filament-like LED surface area, resulting in an increase of convective heat transfer area, which enhances the convective heat transfer process effectively [24]. Therefore, the working temperature at 90° and −90° both reduced. It is evident that the amount of phosphor at −90° makes a great contribution to heat dissipation of LEDs at 90°. The cooling effect to the temperature at 90° become saturated when the dispensing amount is 40 μL, but keep helping lowing the temperature at −90°. It may be caused by the balance between the heat flux production of LED chips and a convective heat transfer process. In addition, the phosphor dispensed at −90° can be optimized and served for optical and thermal performance of filament-like LEDs.

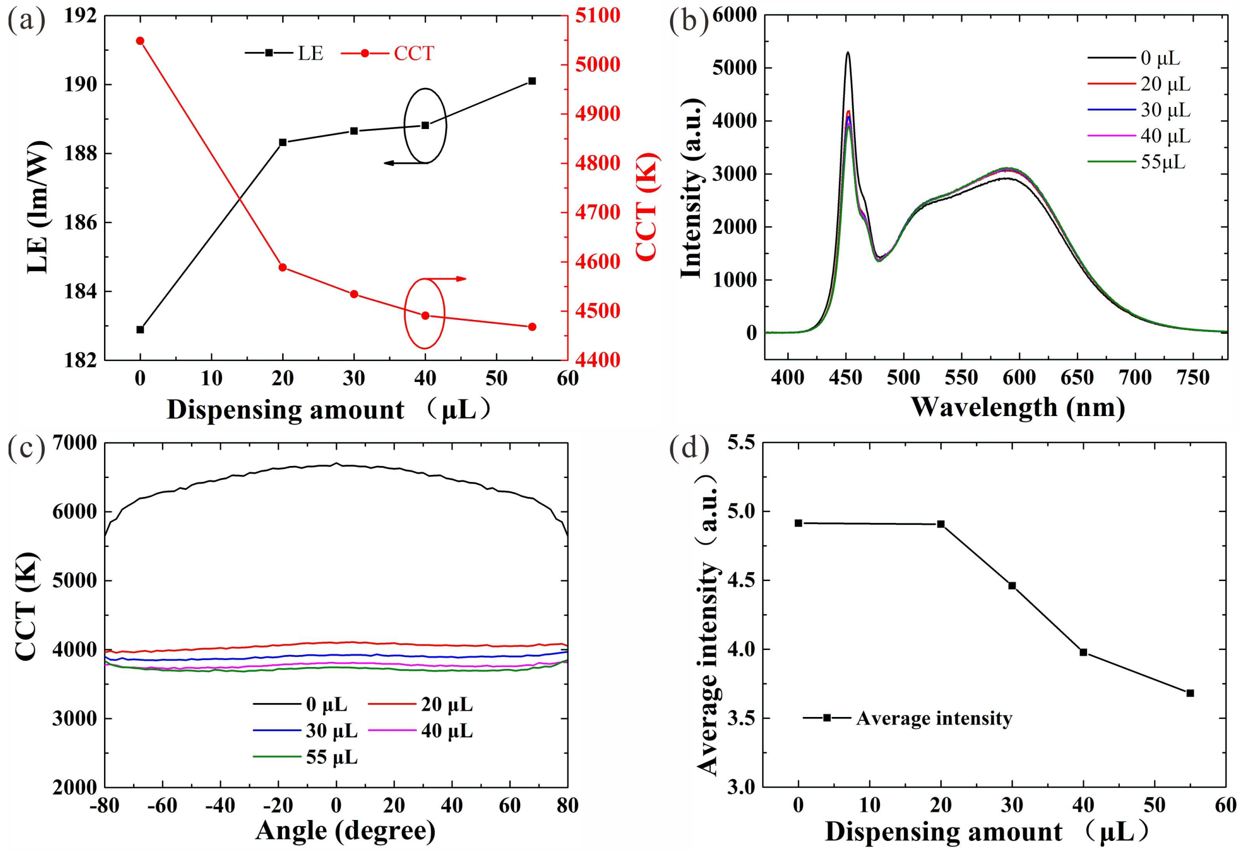

Fig. 12. Optical performance of the NP-LEDs (tested along the long-side direction) with various encapsulation phosphor resin dispensing amount under 15 mA: (a) LE and CCT, (b) spectrum, (c) CCT distribution under −90° measuring angle, and (d) average intensity under −90° measuring angle.

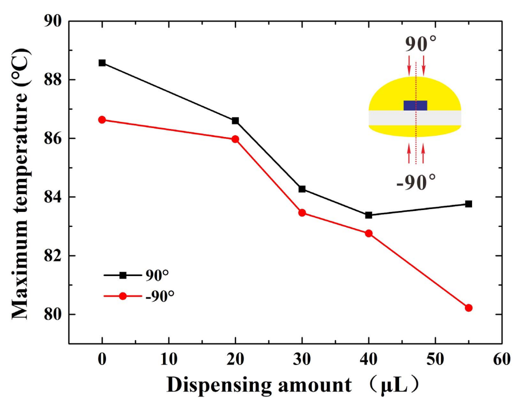

Fig. 13. Working temperature of NP-LEDs with various encapsulation phosphor resin dispensing amount on the backside under 15 mA.

IV. Conclusion

To enhance the performances of the filament-like LEDs, an effective method for optimizing the phosphor dispensing structure was proposed and investigated in detail for the first time. The optical and thermal performances of LEDs with various structures were measured and analyzed by physical measurement. The optical simulation shows that the back-side of the substrate should be packaged to improve blue light utilization. Based on optimizing the phosphor structure, the LED performances can be effectively improved. Overall, the optimal NP-LED could maintain an equivalent LE compared with the others, at almost 4300 K. The spatial CCT and light intensity distribution were different for different lighting directions and were different compared with each other. For the individual LEDs, the CCT deviation of the filament-like LEDs was attributed to the phosphor structure on the chip side. For the various packaging structure, the FP-LED had the largest total CCT deviation of 1329 K, following by the NP-LED at 1085 K, and the HP-LED was the best at 1025 K. The lighting intensity was quite uneven for 360° lighting conditions and the NP-LED performs better. This requires improvement in the future and maybe solve by the settlement structure in the bulbs. Nevertheless, the NP-LED had working temperatures that were 5.42 °C and 2.23 °C lower than the FP-LED and HP-LED for a driving current of 15 mA, respectively. It is reasonably believed that NP-LED with the lowing working temperature will have the longest lifetime. Furthermore, the phosphor manufacturing parameter on the back surface was also investigated, which can provide fabricating guidance in the design of lighting effects and cost savings. For NP-LED, the dispensing amount of phosphor at −90° can influence the CCT, light intensity and working temperature significantly. It was determined that the proposed amount of phosphor should be suitable for the required optical performance. When the back surface dispensed 20 μL of phosphor resin, the LE increased from 182.9 to 188.3 lm/W at a similar CCT and the CCT deviation changed from 1062 to 154.5 K significantly. In conclusion, a packaging structure that was proposed to enhance the performance of filament-like WLEDs was optimized. The presented results may serve as a guide in the product manufacturing process.

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