Near-infrared image-based method for vision enhancement in monitoring structure and temperature behavior of phosphor conformal coating white LEDs type

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Abstract—We proposed and demonstrated a method for observing the structure of phosphor-converted white light-emitting diodes (pcW-LEDs) while operating. By incorporating infrared (IR) filters placed in front of the camera, the unclear phenomena of the pcW-LEDs structure in the image have been improved significantly compared to those without IR filters. The NIR image is a good selection for observation of the light-emitting device during its working process without a glaring effect. In addition, a thermal camera was utilized to capture the temperature behavior of the white LEDs' phosphor conformal coating under different injection currents to supplement comprehensive information.

Solid-state lighting (SSL) is an essential field in improving the quality of life for humans. There are many publications related to light-emitting diodes, which report solutions to enhance the quality of LEDs and solve problems for LED products. Phosphor-converted white light emitting diodes (pcW-LEDs) have gradually replaced traditional lamps due to features characteristics such as energy saving, fast response, color performance, and long life [1–4]. The pcW-LEDs are usually fabricated by combining blue LED die and yellow phosphor. Figure 1(a) shows a conformal coating packaging for white light generation, and commercial pcW-LEDs are demonstrated in Fig. 1(b).

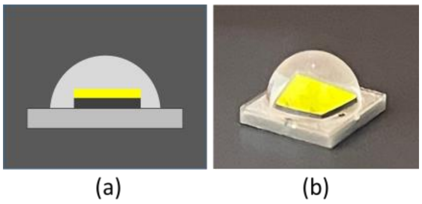

Fig. 1. (a) Illustration of conformal coating packaging for white light generation, (b) photo of a commercial pcW-LEDs.

Blue light is emitted from InGaN to hit the yellow phosphor layer; then, blue light is absorbed and converted to a longer wavelength, which is called yellow light. The remaining unabsorbed blue light goes out, and the encapsulant lens will mix with the converted yellow light to generate the white light. As a result, the emission spectrum of generated white light will include a blue band, a yellow band, and a near-infrared emission spectrum. Due to the limitation of quantum efficiency (related to both LED die and yellow phosphor material) and Stokes shift, the heat is generated during the operating process of pcW-LEDs. Negative thermal effects cause damage to the structure, modification of mechanical properties, damage to bond contact, and geometrical shape [5–8]. The thermal effect also affects the emission efficiency of the pcW-LEDs [9]. When a pcW-LEDs is operated, many phenomena/changes in temperature, emission character, or mechanical modification will occur. Usually, the optical image-based method is a useful tool to detect these phenomena. However, there are still some challenges/obstacles, such as over-bright spots and unclear resolution in the character of light-emitting structures, that lead to many difficulties for researchers in finding information related to the phenomena that interest them. Figure 2(a) shows the blurring phenomena in optical images of powering pcW-LEDs strings. Even when the mode of adjusting exposure was applied, the structure of pcW-LEDs still was not clearly displayed. There is a demand to solve this problem.

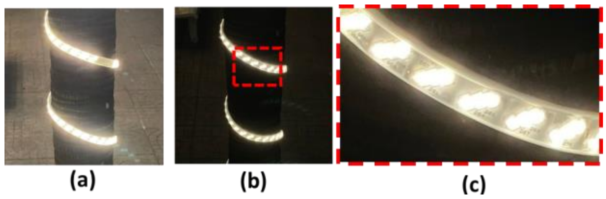

Fig. 2. Unclear phenomena in the photo when taken for powering pcW-LEDs under (a) normal conditions, (b) adjusting exposure mode of camera, and (c) Enlarged part of the red dash line rectangle in photo (b).

In this paper, we proposed and demonstrated a method to improve the over-bright spot in the images of pcW-LEDs when observing it while it is working. This method is applied to test the effect of the injection electrical

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current on the observable display of the NIR image and the effective emission area in the packaged volume structure. The obtained NIR images not only show a clear vision of the structure of the device but also provide the emission character of the different parts of pcW-LEDs (e.g., LED die, phosphor layers, and encapsulant lens).

Figure 3 shows the emission spectrum of pcW-LEDs, which were detected from a wavelength range of 350 nm to 950 nm. For convenience, the emission spectrum is divided into three sub-regions: blue emission band (400 nm to 490 nm), yellow band (490 nm to 700nm), and NIR emission band (700 nm to 1000 nm). The emission spectrum indicated that although the range of the spectrum is broad, the emission power of the blue band, yellow band, and NIR band are different. The most intensive emission bands are the blue band and yellow band, while the emission of the NIR band is weaker compared to that of the blue and yellow emission bands.

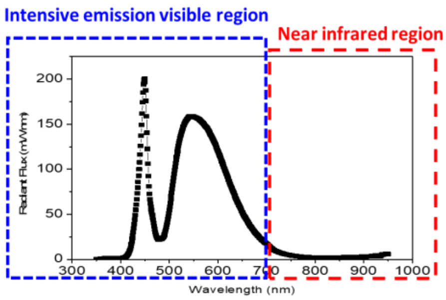

Fig. 3. Emission spectrum characteristics of pcW-LEDs.

The working principle of the proposed method for reducing the over-bright spots in the image is described as follows. Two characteristics are considered for improving the over-bright spots. The first one is based on the difference in emission power of the blue band, yellow band, and NIR band, wherein the NIR band has the lowest radiant flux compared to that of the remaining bands. The second one is the high sensitivity of the imager camera to visible light, which is an inherent characteristic of the material constructed for imager sensors. Based on this principle, an IR filter is placed in front of the camera to block the intensive spectrums in the visible region while passing through the NIR band. As a result, the over-bright spots caused by the high sensitivity of the imager camera to visible light are removed. The illustration for the experimental setup is shown in Fig. 4.

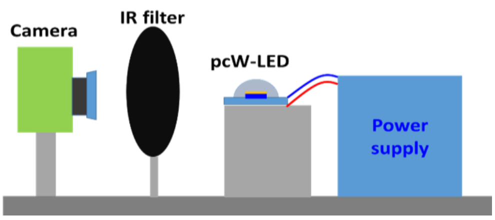

Fig. 4. Illustration for experimental setup wherein an IR filter is placed in front of the camera.

Firstly, it is necessary to understand the performance of different IR filters. Thus, three types of filters were used, and the corresponding images were taken and analyzed. Figure 5 shows the transmission of three types of IR filters, including IR 720 nm, IR 760 nm, and IR 850 nm, respectively. These filters allow the spectral range longer than wavelengths of 720 nm, 760 nm, and 850 nm to pass through while blocking almost another wavelength in the visible light. These filters' transmission is as high as in the 85% to 90 % range.

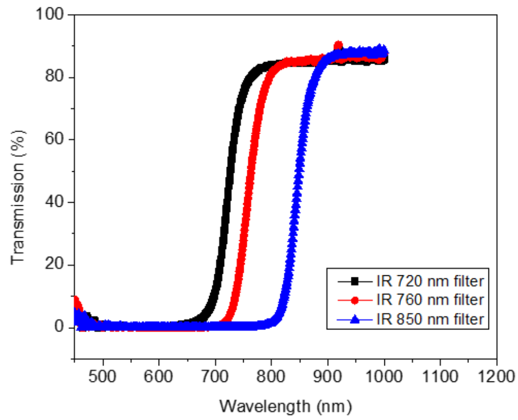

Fig. 5. Transmission of three types of IR filters.

It is expected to have clear images of internal structure. The correspondent images obtained from the experiments are shown in Fig. 6. Figure 6(a) shows the images when using the filter of IR 720 nm; the images are clear in the substrate, encapsulant lens, LED die, and phosphor regions. Figure 6(b) shows the images when using the filter of IR 760 nm; the clear level in the images for the substrate, encapsulant lens, LED die, and phosphor regions is lower than that of the case in Fig. 6(a);. The shape of the encapsulant lens is clear enough. Although the image of the LED die, which is covered by the yellow phosphor, was not clear, the emission properties of these regions are still valuable. In a different response in image quality. Figure 6(c) shows the images when using a filter of IR 850 nm. The images of the substrate, encapsulant lens, LED die, and phosphor regions are unclear. In general, the behavior in image quality of a working pcW-LEDs showed a close dependence on the transmission of each wavelength band of the used IR filter. Based on the response of image quality, the IR filter of 720 nm is most suitable for our research purpose, and it is thus used in the following experiment of the study.

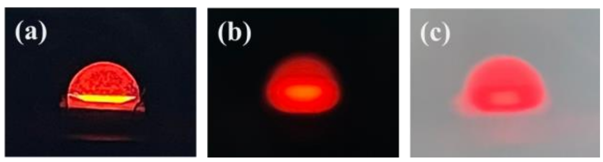

Fig. 6. Dependence of obtained images on different IR filters.

After selecting a suitable IR filter for the study, the IR filter 720 nm is applied to take images of sample pcW-LEDs under different injection electrical currents. The experimental setup is similar to that shown in Fig. 4, and the experimental results are shown in Fig.7. Figures 7(a)–(d) are photos of sample pcW-LEDs taken by the optical camera through IR filter for the different cases of injection electrical current of 0.05A, 0.15A, 0.25A and 0.35A, respectively. Qualitatively, it is easy to see the effect of injection on the image's brightness. The higher the injected current is, the brighter the image is. The image's brightness increases for both the encapsulant lens and blue die-covered phosphor parts. This increase disclosed that stronger NIR radiation is generated when using higher injection currents. The stronger NIR radiation is related to the wavelength conversion process when yellow phosphor is excited by blue light, which is generated from blue LED die. In general, the clear obtained images indicated that the filter IR 720 nm method is applicable well for taking images of bright devices when it operated at injection electrical currents of 0.05A, 0.15A, 0.25A, and 0.35A, respectively.

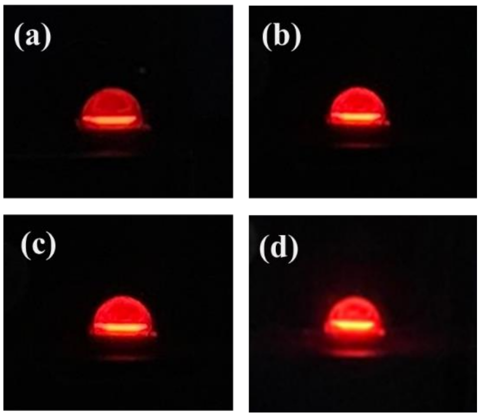

Fig. 7. NIR images of sample pcW-LEDs under different injection electrical currents.

To supplement more comprehensive information and better understand the temperature behavior, we measured the temperature behavior of a white LED cut in half of the encapsulated dome [10–11]. Figure 8 shows that the higher temperature at the central region corresponds to LED chip-coated phosphor and is related to more substantial heat generated when white LEDs are operated at higher injection currents.

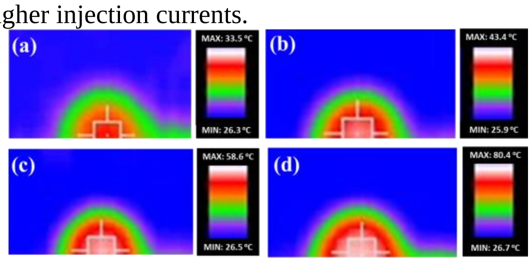

Fig. 8. NIR images of sample pcW-LEDs under different injection electrical currents. (a) 50 mA, (b) 150 mA, (c) 250 mA and (d) 350 mA.

In conclusion, we proposed and demonstrated a method to overcome the challenges of over-bright spots in the images when monitoring a powering pcW-LEDs device. The principle of the method focuses on detecting NIR radiation while blocking the visible light from the camera. The suitable IR filter for the clear NIR image is IR 720 nm. When using filters IR 760 nm and 850 nm, the NIR images are blurred. The filter IR 720 was applied to test the effect of injection current of 0.05A, 0.15A, 0.25A, and 0.35A, respectively, on the emission behavior of the pcW-LEDs sample. The higher the injected current is, the brighter the image is. The image's brightness increases for both the encapsulant lens and blue die-covered phosphor parts. The sample structure, including the encapsulant lens and the LED die-covered yellow phosphor, is easily detected while it is working. The obtained results indicated that the proposed method is helpful for research related to pcW-LEDs to identify the structure of the sample during the operating process, defining the effective emitting area of the device (e.g., LED die, a phosphor layer, die side, outer surface, encapsulant lens). It is possible to promote future NIR image-based research related to the SSL field. In addition, the temperature behavior under different injection currents was measured by a thermal imaging camera for the white LED sample cut in half of the encapsulated dome. The central region where LED chip-coated phosphor shows a higher temperature is related to stronger heat generation when white LEDs are operated at higher injection currents. The near-infrared image-based method and thermal camera image complement each other and provide comprehensive information for monitoring the structure and temperature behavior of phosphor conformal coating white LED type.

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