Study of steady-state thermal model for white light LEDs thermal management application at encapsulant level

Trong-Nam Tran,[1,2] Van-Tuan Huynh,[1,2] Thi-Hanh-Thu Vu,[1,2] Nguyet-Thuan Phan,[1,2] Huynh-Tuan-Anh Nguyen,[1,2] Quang-Khoi Nguyen[*1,2]

[1]*Faculty of Physics and Engineering Physics, VNUHCM-University of Science, Hochiminh City, Vietnam,*
[2]*Vietnam National University Hochiminh City, Hochiminh City, Vietnam*

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Abstract—Thermal management for white LEDs at the encapsulant level is an important task to ensure that the device can operate at a high optical and color performance. In this study, a steady-state thermal model was built, and the finite element method was employed using Matlab software to identify the temperature distribution. The spatial temperature distribution of the encapsulant and blue LED die region was easily simulated and predicted. The obtained results help detect the temperature behavior inside the packaging volume and are meaningful for designing the package configuration.

Solid-state lighting (SSL) has been gradually replacing incandescent light bulbs owing to its advantages, including high energy efficiency, fast response, acceptable color rendering, long lifetime, and low cost [1–2]. The white light can be created by combining a blue LED die and a yellow phosphor [3]. There are many geometry configurations to package the phosphor-converted white light LEDs (pc-WLEDs), such as conformal, remote, and dome structures. Each package type of configuration will show different properties in packaging efficiency, spatial intensity distribution, and spatial color uniformity. Among them, the phosphor dome structure is one of the popular ways to package the pc-WLEDs. Figure 1 shows the white light generation method using a phosphor dome structure; the yellow phosphor powder is mixed with silicone gel and shaped in a hemisphere dome. This dome is covered on the top of the blue LED die. When the device is powered, a portion of blue light will excite the yellow phosphor and be converted into yellow light with a broad emission band from 500 nm to 750 nm. Mixing un-absorbed blue LEDs and generating yellow light will cause a “white perceiving” for human eyes.

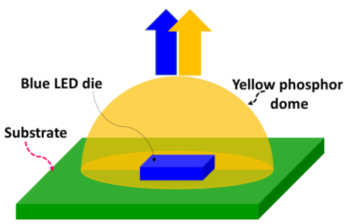

Fig. 1. White light generation method using phosphor dome structure.

* E-mail: nqkhoi@hcmus.edu.vn

During the operation of pcW-LEDs, heat is an inherent problem of the device. It thus caused thermal decay in output light, mechanical damage, and a shortened life span for LEDs. An apparent negative effect of temperature is the effect on the thermal decay of blue and yellow light [4–5]. Although there is much effort in improving the thermal stability of blue LEDs and yellow phosphor (YAG:Ce^{3+}), reaching the same thermal decay rate for both blue LEDs and yellow phosphor is still challenging. It thus leads to a color shift for output white light, which is related to an unbalanced power ratio between blue and yellow light. Figure 2 illustrates the negative effect of temperature on the optical property of white LED, where the blue light to yellow light power ratio is increased under the same heat conditions.

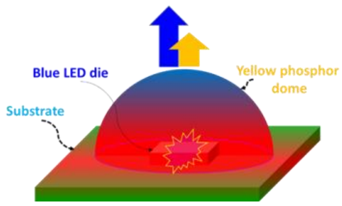

Fig. 2. Illustration of the negative effect of temperature on the optical property of white LED.

In general, the well-controlled effect of temperature leads to well-controlling quality for output white light in terms of CCT, CRI, luminous efficiency, lifespans, and mechanical properties [6–9]. So, the relation between thermal behavior to geometrical package and suitable driven electrical current should be well understood. An excellent thermal model is required to study the thermal behavior and package structure and operate the electrical current. Some thermal models have been reported, such as thermal modeling of the LED module using CFD software [10] and thermal model using COMSOL for doing the 3D simulation of thermal paths of the LED module that could effectively evaluate the final steady-state of the LED module [11], thermal model using the ANSYS to simulate the thermal performance and the temperature distributions of the flat surface high power GaN-based flip-chip light-emitting diodes [12], thermal model using the software of Ansys for simulation of the temperature distribution of the encapsulated LED structure where the phosphor is conformal coated onto the blue LED [13]. The thermal model for white LED thermal management application at the encapsulant level is still in demand. In this study, a steady-state thermal model was built, and the finite element method was employed using Matlab software to identify the temperature distribution. A general mathematical model for thermal models is defined and solved by Matlab software. The simulation is verified with thermal camera images from the corresponding experiment.

Firstly, the thermal effect on the color performance of output white light is simulated. For a more precise visualization of color shift, the simulation of chromatic shift corresponding to different B/Y ratios of 1, 1.25, 1.5, 2.0, 2.25, and 2.5 are conducted. Simulation results for the chromatic shift corresponding to different B/Y ratios are shown in Fig. 3. Changing the B/Y ratio not only causes the shift of color point toward the bluish region but also increases the CCT value of 5551 K up to a very high value of 10 648 K. This showed quality of output light is strongly modified under different B/Y ratio which is changed by heat problem.

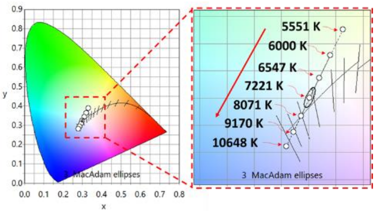

Fig.3. Chromatic shift corresponding to different B/Y power ratios.

For the best performance of pcW-LEDs, thermal management must be as good as possible. As a result, the operated electrical current or suitable package geometry can be recommended based on the thermal simulation results. Thus, it is essential to understand the temperature distribution in the package structure. Usually, it takes a short time to reach a steady state after pcW-LEDs are operated; it is essential to have an excellent thermal model at a steady state. In the general case of the 3-dimensional (3D) structure of pc-WLED, the spatial temperature distribution in the 3D packaging volume can be defined by solving the heat diffusion equation [14]:

$$k\nabla^2 T + \dot{q} = \rho C_p \frac{\partial T}{\partial t}, \tag{1}$$

where

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \tag{2}$$

is Laplace operator, k is the thermal conductivity, heat flux, ρ is the density, C_p is the specific heat, and T is the temperature, which is a space and time function. At steady state, for $\frac{\partial T}{\partial t} = 0,$ the heat diffusion can be reduced as:

$$k\nabla^2 T + \dot{q} = 0. \tag{3}$$

The heat transfer general equation in 3D space can be reduced to 2D space due to the asymmetry analysis of the pcW-LED structure [15]. Therefore, we only need to find the temperature distribution in the 2D space of any plane in the cross-section that is perpendicular to the substrate; in the next section, the temperature distribution in the 2D space of the plane (*x*-*z*) will be defined. Then, the temperature distribution in the 2D space of any other plane is identical to that of the plane (*x*-*z*). The heat transfer equation at the steady-state for (*x*-*z*) is:

$$k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}\right) + \dot{q} = 0. \tag{4}$$

At the steady state, the heat flux is constant over time $\dot{q} = 0$. Thus, the remaining work for solving the problem of 2D temperature distribution is defining the boundary condition. In this work, the boundary conditions are the same as in [15]. Using Matlab software to solve the heat equations is solved and visualized the temperature distribution. To understand the effect of injection current on the temperature behavior in the package volume, different cases of 100 mA, 350 mA, and 500 mA are simulated. The junction temperature corresponding to the injection current of 100 mA, 350 mA, and 500 mA is 50°C, 100°C, and 130°C.

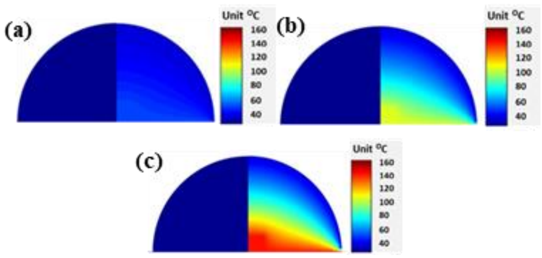

Fig. 4. Temperature distribution at different injection currents. (a) 100 mA, (b) 350 mA, (c) 500 mA.

Figure 4 shows the differences in temperature distribution at different injection currents: 100 mA, 350 mA, and 500 mA. For convenient comparison, each case will be put into two quartile parts: the left one is temperature distribution without operation, and the right one is the temperature distribution with operation. Temperature distribution is not different when using different injection currents but also in spatial locations. A higher value of injection current is used, and a higher temperature inside the package structure is observed. For cases using higher injection currents of 350 mA and 500 mA, it is easy to see that locations close to the LED die show the highest value. The temperature is gradually reduced from the LED die's location to the encapsulant lens's outer surface. In verification of the thermal model, an experiment will be conducted to confirm the similarity between the simulation results. The pcW-LEDs sample and the experimental setup were utilized to determine the temperature distribution by the thermal camera. The sample is operated at different injection currents of 100 mA, 350 mA, and 500 mA. The experimental setup is the same as our reported work [15]. The corresponding results are handled and shown in Fig 5. As shown in Figs. 5(a), 5(c), and 5(e), the range of minimum and maximum temperature for two case injection currents of 100 mA, 350 mA, and 500 mA is from 32.8ºC to 50ºC, from 34.2ºC to 101.7ºC, and from 32.8ºC to 134.5ºC respectively. The temperature of the hot spot of injection current cases 100 mA, 350 mA, and 500 mA are 49.6ºC, 101.7ºC, and 134.5ºC, respectively. These results showed that using a higher injection current increases the temperature of the hot spot. On the other hand, the difference in color in the detected temperature distribution indicated a clear difference in the LED die region surrounding and the encapsulant region. In detail, the temperature is decreased gradually from the LED die region to the outer surface, which is the interface between the encapsulant and air ambient. These temperature distribution results showed an inversely proportional relationship between the temperature value and the distance to the region containing the blue LED die. In comparison, it can be found that the temperature behavior at the cross-section closely matches the simulation (as shown in Fig. 4) and experimental results.

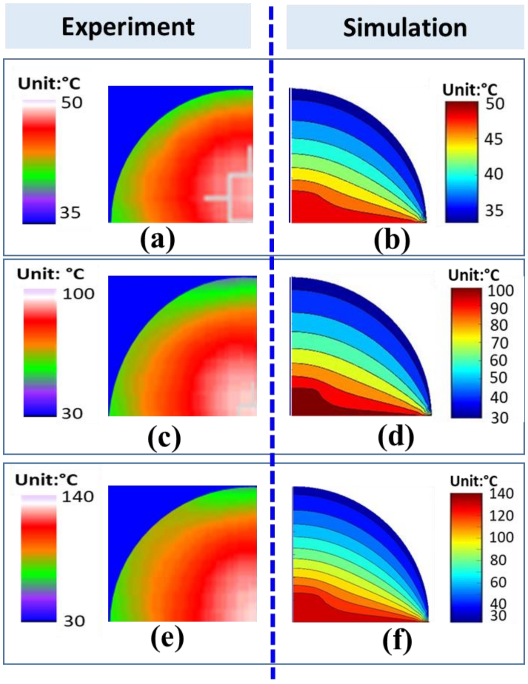

Fig. 5. The Measurement and interpolation result of steady-state temperature distribution corresponds to different injection electrical currents. (a) and (b) are cases of 100 mA in experiment and simulation.; (c) and (d) are cases of 350 mA in experiment and simulation.; (e) and (f) are cases of 500 mA in experiment and simulation, respectively.

The above simulation and thermal cameras only provide the temperature information at the observed surface. It is still necessary to determine the temperature value on each location of the considered plane or contour its temperature behavior. "How to visualize the internal spatial temperature?" is an essential task in terms of thermal management for electronic devices. Figures 5 (b), 5(d), and 5(f) show the interpolation temperature by FEM-based simulation for different cases of injection current of 100 mA, 350 mA, and 500 mA. The results showed a precise temperature contour that helped to easily determine the temperature value corresponding to each location inside the package volume of pcW-LEDs.

In conclusion, we have built and successfully demonstrated a steady-state thermal model wherein Matlab software employed the finite element method to identify the temperature distribution at the encapsulant level. Simulation results clearly show the influence of injection current and thermal conductivity difference on the temperature at different regions of the packaged part. The higher the injection electrical current is, the higher the temperature of pc-WLEDs is. The hot region is close to the LED die while the temperature gradually decreases from the LED die to the outer surface. These results indicate that the phosphor should be located far away from the LED die to avoid the heat effect on the phosphor efficiency. Besides, the spatial temperature distribution of the encapsulant region was easily simulated and predicted, and the model can interpolate the temperature behavior to visualize the temperature contour that helps to easily determine the value of temperature corresponding to each location inside the package volume of pcW-LEDs.

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