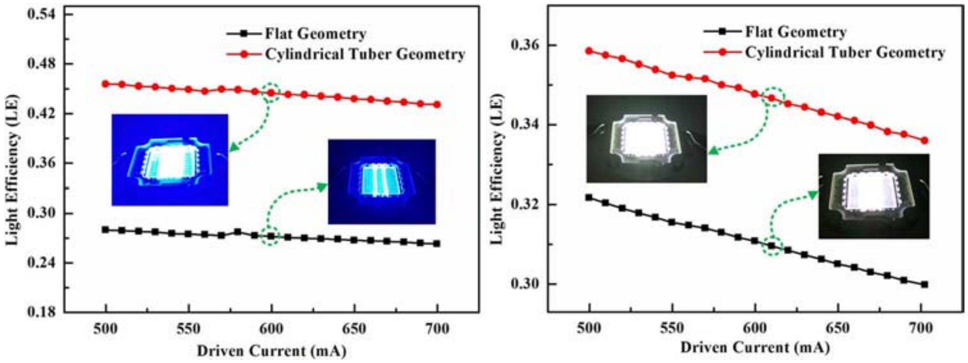
IEEE Photonics Journal
An IEEE Photonics Society Publication

A Cylindrical Tuber Encapsulant Geometry for Enhancing Optical Performance of Chip-on-Board Packaging Light-Emitting Diodes

Volume 8, Number 3, June 2016

Xingjian Yu
Bin Xie
Bofeng Shang
Qi Chen
Xiaobing Luo, Senior Member, IEEE



DOI: 10.1109/JPHOT.2016.2555619

A Cylindrical Tuber Encapsulant Geometry for Enhancing Optical Performance of Chip-on-Board Packaging Light-Emitting Diodes

Xingjian Yu, Bin Xie, Bofeng Shang, Qi Chen, and
Xiaobing Luo, ***Senior Member, IEEE***

School of Energy and Power Engineering, Huazhong University of Science and Technology,
Wuhan 430074, China

DOI: 10.1109/JPHOT.2016.2555619

Manuscript received March 22, 2016; revised April 13, 2016; accepted April 14, 2016. Date of publication April 21, 2016; date of current version April 29, 2016. This work was supported in part by the National Science Foundation of China under Grant 51376070 and Grant 51576078 and in part by the 973 Project of the Ministry of Science and Technology of China under Grant 2011CB013105. Corresponding author: X. Luo (e-mail: Luoxb@hust.edu.cn).

Abstract: Low light efficiency and poor angular color uniformity (ACU) are the key challenges of chip-on-board packaging light-emitting diodes (LEDs). In this paper, we demonstrate a phosphor geometry, and its controlling method for enhancing the optical performance of chip-on-board packaging LEDs, its fabrication flexibility, and availability are validated by experiments, and its effect on the optical performance is analyzed by optical simulations and experiments. The simulation results show that compared with the conventional flat geometry, the cylindrical tuber geometry can effectively improve the light efficiency and ACU, and the light efficiency enhancement increases with correlated color temperature. Experimental results show that for the case that the encapsulation layer only consists of silicone, the proposed geometry enhances the light efficiency up to 63.1%. In addition, for another case, in which the encapsulation layer consists of silicone and phosphor particles, when the average correlated color temperature (CCT) is about 5000 K, the proposed geometry increases the light efficiency by 11.7%, and the angular CCT deviations for the flat geometry and the proposed geometry are 1805 and 475 K, respectively.

Index Terms: Light-emitting diodes (LEDs), chip-on-board packaging, cylindrical tuber encapsulant geometry, optical performance enhancement.

1. Introduction

Phosphor-converted white light-emitting diodes (pcLEDs) have developed quickly in recent years and have been widely applied in many illumination areas from indoor lighting to street light. With the advantages of good reliability, high efficiency, low cost, and long lifetime, they have been regarded as the next generation of light source [1], [2].

For industrial application, pcLEDs are manufactured into single-chip packaging module or integrated into chip-on-board (COB) packaging module. The COB packaging modules have some advantages over the single-chip packaging module in solid state illumination application, such as high optical intensity, simple packaging process, low cost and compact size [3]. However, compared with the single-chip packaging modules, the COB packaging modules require better thermal management due to the compact size and high power [4], [5]. Moreover, the light efficiency (LE) of COB packaging modules are low because of the total internal reflection (TIR) that happens at the flat encapsulant-air interface [3], [6]–[8]. On the flat interface, the TIR phenomenon happens at a critical angle θ_c as small as $38^\circ \sim 45^\circ$ caused by the refractive index difference of the materials (encapsulant $\approx 1.4 \sim 1.6$, air $= 1$), as a consequence, amount of light propagates back and forth inside the device and fails to emit outwardly [6]–[8]. Meanwhile, due to the flat interface, the COB packaging modules also fail to have good angular color uniformity performance (ACU) [8], [9]. The low LE and poor ACU hinder the further applications of COB packaging modules.

Some methods were reported to diminish the TIR effect, such as patterned LED chip [10], [11], patterned leadframe substrate (PLS) [6] and roughened encapsulation layer [7], [9]. Although these can improve the LE and ACU of COB packaging modules, they are highly relied on the precise and expensive equipment or complex molds which add the cost as well. Our previous study shows that coating a thin TiO2 nanoparticle layer under the main encapsulation layer also can effectively enhance the LE and ACU of COB packaging [8].

Besides the methods mentioned above, it is reported that domed-shape encapsulation layer is beneficial for diminishing the TIR effect [1], [3]. However, due to the small contact angle of encapsulant on the substrate and the larger coating surface of COB module [12], [13], the encapsulation layer tends to be flat geometry [3].

In this paper, we proposed an economically feasible encapsulant coating method to realize domed-shape encapsulation layer for large area COB packaging module. By utilizing the thermosetting property of the silicone, a cylindrical tuber encapsulant geometry was achieved. The detailed theory and implementation were described, and its fabrication flexibility and availability were proved by experiments and optical simulations. Compared with the flat encapsulant geometry, the proposed domed-shape geometry can significantly improve the LE and ACU.

2. Methodology

The encapsulants used in our study are pure silicone (Dow Corning OE-6550) and phosphor gel, which consists of silicone and phosphor particles (Intermix phosphor YAG-04). Generally, the silicone would spontaneously spread over the LED substrate due to the small contact angle of silicone on the substrate [12], [13], which leads to the TIR phenomenon. However, the silicone is reported to be thermosetting, which means its viscosity increases with time when it is heated [14], and the increasing rate of the viscosity is highly related to the temperature [15].

We characterized the viscosity evolution of silicone as a function of time and substrate temperature with a rheometer (MCR302). Fig. 1 shows the time evolution of the silicone viscosity at substrate temperatures of 90 °C, 100 °C, and 120 °C, it indicates that the viscosity of silicone increases faster after it being dropped onto the substrate with higher temperature. Therefore, it comes into a condition that the wetting behaviors of phosphor gel could be controlled by heating the substrate and a domed-shape phosphor layer geometry could be achieved.

To verify the assumption mentioned above, the wetting behaviors of silicone on a heated aluminum substrate were investigated. Fig. 2 shows the experimental platform for capturing the geometry change of silicone droplets. It mainly consists of high speed camera, micro motion platform, inject pump, computer, and heater. During the experiments, silicone droplets with initial radius of $1.1 \pm 10^\circ$ mm were dropped onto the heated aluminum substrate by the injection pump, the substrate temperature was controlled by the heater with precision of ±1 °C, the geometry change were recorded by the high speed camera (SA3 120 K). Fig. 3 shows the time evolution of dynamic contact radius at substrate temperature of 30 °C and 150 °C, it indicates that at 30 °C, it takes a long time (far more than 35 s) for the silicone to reach the final state, however, it takes only a short time (less than 2 s) at 150 °C. Fig. 4 shows the side-view of the final geometries of silicone droplets at 30 °C, 80 °C, 130 °C, and 150 °C, respectively. It indicates that the final contact radius R decreases with the substrate temperature, the final geometry is

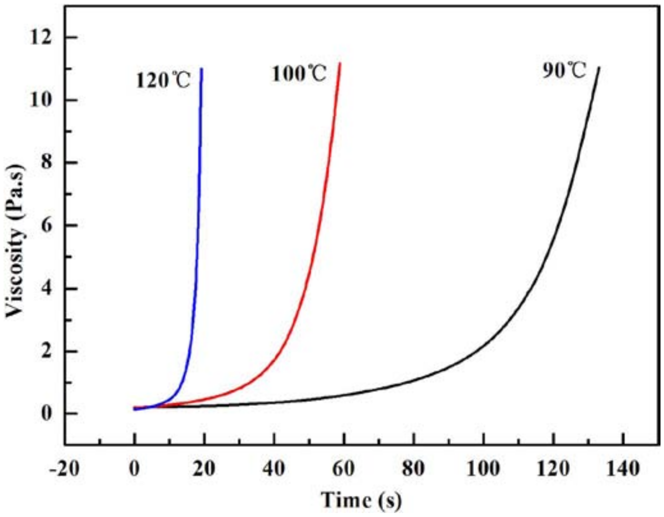


Fig. 1. Time evolution of the silicone viscosity at different substrate temperatures.

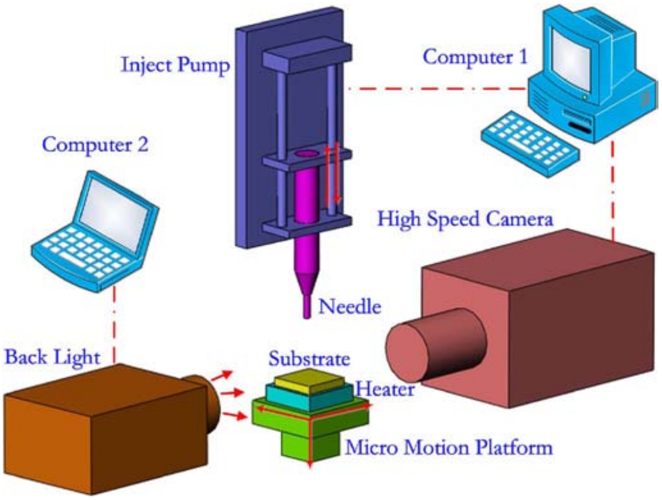


Fig. 2. Experimental platform for capturing the geometry change of silicone droplets.

thin film at 30 °C, while a domed-shape geometry is obtained at 150 °C. Measurement shows that the final contact radius *R* at 30 °C and 150 °C are 3.03 mm, and 2.07 mm, respectively. Therefore, for encapsulant coating, substrate temperature of 150 °C would be favorable.

3. Experiments

Experiments were conducted to package COB modules with flat encapsulant geometry and cylindrical encapsulant geometry. The encapsulants used in our experiments are pure silicone and phosphor gel, the phosphor concentration was set as 0.2 g/ml.

Fig. 5(a) shows the structure of the COB packaging module, it consists of substrate, square dam and conventional blue LED chip array. The coating areas surrounded by the dam is of the size of 20 mm × 20 mm, within the coating area, 20 pieces of LED chips are bonded in two parallel columns, the size of the LED chips is 1 mm × 1 mm × 0.1 mm, the distances between two chip columns, chip column and boundary are 6 mm and 7 mm, respectively.

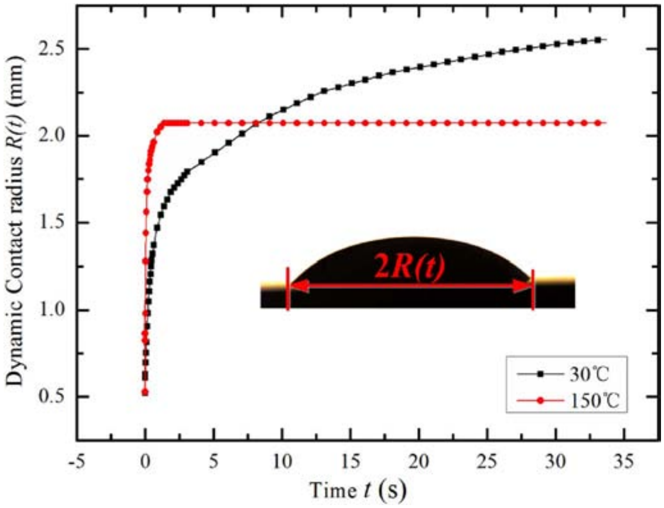


Fig. 3. Time evolution of dynamic contact radius at 30 °C and 150 °C.

Fig. 4. Side view of the final geometries at 30 °C, 80 °C, 130 °C, and 150 °C, respectively.

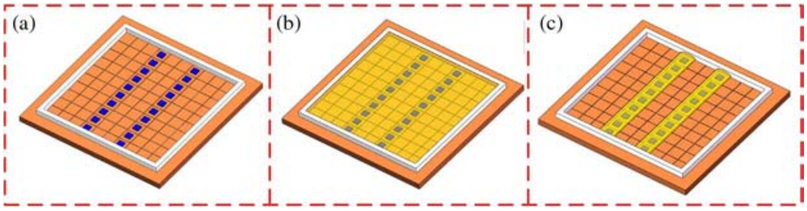


Fig. 5. Schematic of LED COB packaging modules and encapsulant geometries. (a) COB packaging module. (b) Flat geometry. (c) Cylindrical tuber geometry.

Fig. 5(b) and (c) show the flat encapsulant and cylindrical tuber encapsulant packages. For the flat geometry, the encapsulant was dropped onto the substrate at 30 °C and cured in an oven at 150 °C for 1 hour. For the proposed geometry, the substrate was pre-heated to 150 °C, then the encapsulant was dropped onto the substrate and LED chips, the wetting behaviors of encapsulant was restricted by the heated substrate and cylindrical tuber geometry was formed, kept the module heating for 1 hour to cure the encapsulant.

The color distribution of the LED packaging module was recorded every 5 degrees for the viewing angle from −90° to +90° with a colorimeter (XYC-I). The optical performance of LED packaging modules was measured with a spectroradiometer equipped with an integrating sphere of 1 meter in diameter (ATA-1000).

4. Optical Simulations

Since experiments just can get limited data, we also used optical simulation to compare. We studied the LE and ACU performance of COB packaging with flat phosphor geometry and cylindrical tuber phosphor geometry through Monte Carlo ray tracing simulation. The simulation

TABLE 1

Parameters of Each Layer in Simulated LED Chip

Symbol	Thickness (um)	Wavelength	454um	470um
Sapphire	100	Refractive Index	1.77	1.77
		Absorption Coefficient (mm^{-1})	0	0
N-GaN	4	Refractive Index	2.43	2.36
		Absorption Coefficient (mm^{-1})	2	1.5
MQW	0.1	Refractive Index	2.51	2.39
		Absorption Coefficient (mm^{-1})	120	8
P-GaN	0.3	Refractive Index	2.43	2.36
		Absorption Coefficient (mm^{-1})	2	1.5

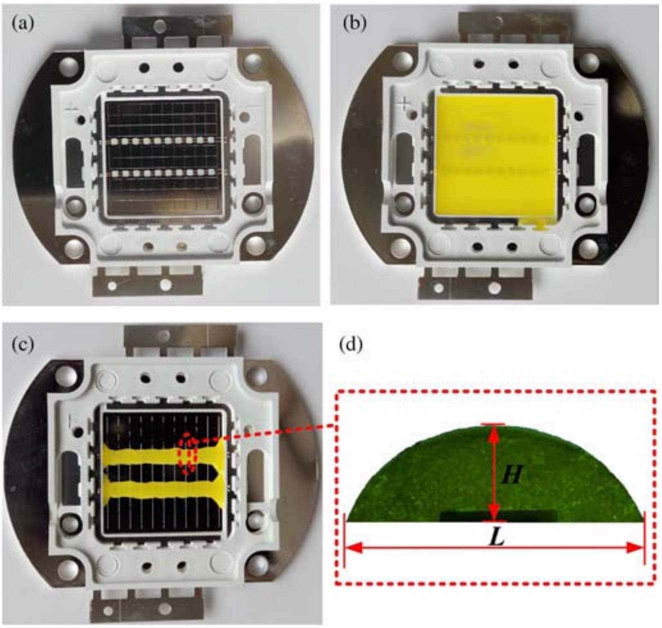


Fig. 6. COB modules and encapsulant geometries. (a) COB LED module. (b) Flat geometry. (c) Cylindrical tuber geometry. (d) Cutaway view.

models were set as the same with the experiments, it consists of conventional blue LED chip array, substrate and phosphor layer. The size of LED chips is 1 mm × 1 mm and the distance between the centers of each adjacent chips is 2 mm. The thickness, refractive indexes, and absorption coefficients of the each layer of the LED chips are described in Table 1 [16]. The refractive index of the packaging phosphor gel was set as 1.53. The substrate was assumed to be coated with a reflecting layer (Ag) and the optical parameters of the top surface of the substrate are 95% reflection and 5% absorption.

In the simulations, the phosphor particles size were assumed to be uniformly distributed in the phosphor layer with diameter of 13 μm. Blue and yellow lights were characterized by specific wavelengths of 454 nm and 570 nm, respectively. Different CCTs were obtained by adjusting the concentration of phosphor mixture.

5. Results and Discussion

Fig. 6 shows the COB modules and encapsulant geometries obtained from the experiments. Fig. 6(a) shows the COB packaging module used in the experiments, and the material of the

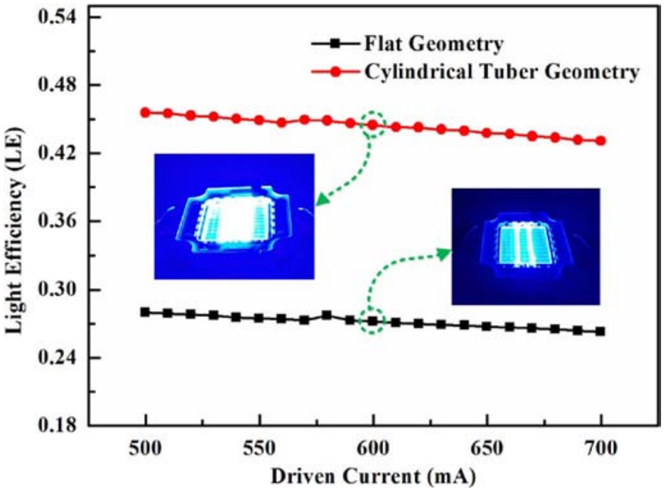


Fig. 7. LE of the two geometries when the encapsulant is pure silicone at driven current from 500 to 700 mA.

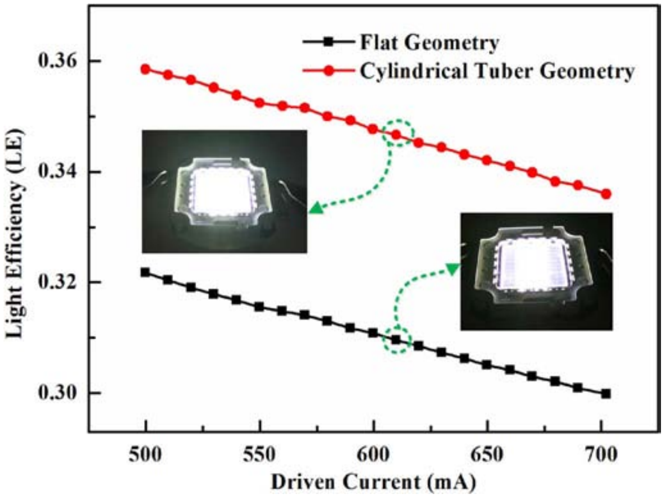


Fig. 8. LE of the two geometries when the encapsulant is phosphor gel at driven current from 500 to 700 mA.

substrate is aluminum. Fig. 6(b) shows flat encapsulant geometry, and its thickness is 0.8 mm. Fig. 6(c) and (d) shows cylindrical tuber encapsulant geometry and its cutaway view, and its contact line *L* and height *H* are 2.5 mm and 0.8 mm, respectively.

Fig. 7 shows the LE of the two geometries when the encapsulant is pure silicone at driven current from 500 mA to 700 mA, here we define the light efficiency (LE) by the ratio of the optical output power to the input electrical power. We calculated and found that a LE enhancement of 63.1% was achieved under each driven current. Fig. 8 shows the LE of the two geometries when the encapsulant is phosphor gel with phosphor concentration of 0.2 g/ml at driven current from 500 mA to 700 mA, and a LE enhancement of 11.7% was achieved under each driven current.

The different LE performances of the two geometries could be explained as follows. Fig. 9 schematic indicates the light emission of the two geometries when the encapsulants are pure silicone and phosphor gel, respectively. Fig. 9(a) and (b) shows the light emission of the pure

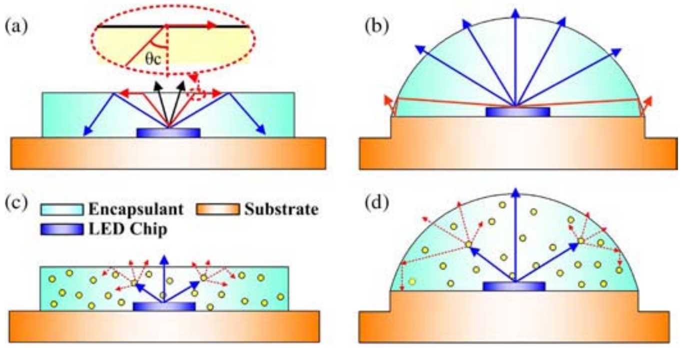


Fig. 9. Schematic representation of the light emission of the two geometries. (a) and (b) Pure silicone layer. (c) and (d) Phosphor gel layer.

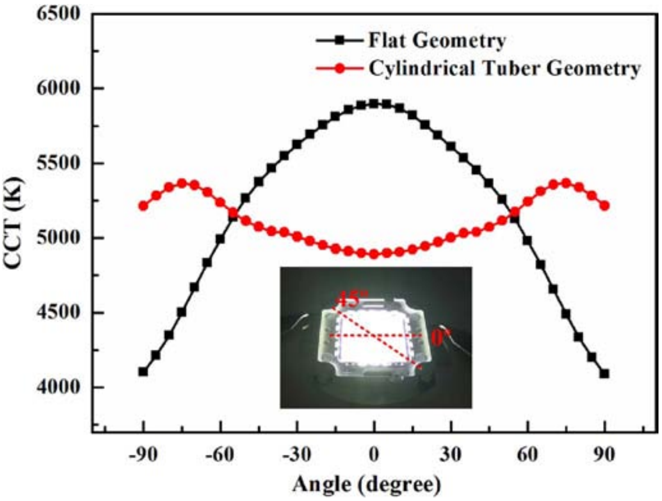


Fig. 10. Color distributions of the two geometries from −90° to +90° when the average CCT is about 5000 K.

silicone layer, for the flat geometry, due to the high refractive index difference of the materials (silicone = 1.53, air = 1), the total internal reflection (TIR) happens at a critical angle θ_c of 41°, which leads to the failure of light emission. However, for the cylindrical tuber geometry, due to the domed-shaped encapsulant-air interface, most of the light can emit out. Therefore, the LE presents a large enhancement. However, when the encapsulant consists of silicone and phosphor particles shown in Fig. 9(c) and (d). For the flat geometry, light beyond the critical angle θ_c would be scattered and redirected by the phosphor particles, and part of the redirected light can emit out. However, for the cylindrical tuber geometry, the phosphor particle scattering effect would cause part of the redirected light fails to emit out. Therefore, the LE enhancement of the cylindrical geometry is much less than that of the pure silicone layer.

Fig. 10 shows the color distributions of the two geometries from −90° to +90° when the average CCT is about 5000 K, we calculated the angular CCT by averaging the angular CCT from the viewing angle of 0° and 45°. From Fig. 9, we can see that the ACU performance of the cylindrical tuber geometry is better than the flat geometry, here we characterize the ACU performance by the angular CCT deviation defined as the maximum angular CCT minus minimum angular CCT, and the angular CCT deviations of the two geometry are 1805 K and 475 K.

For the above experimental cases, we just get two groups of data at the pure blue and 5000 K CCT cases. For further compare the effect of the two geometries, we used optical simulation to

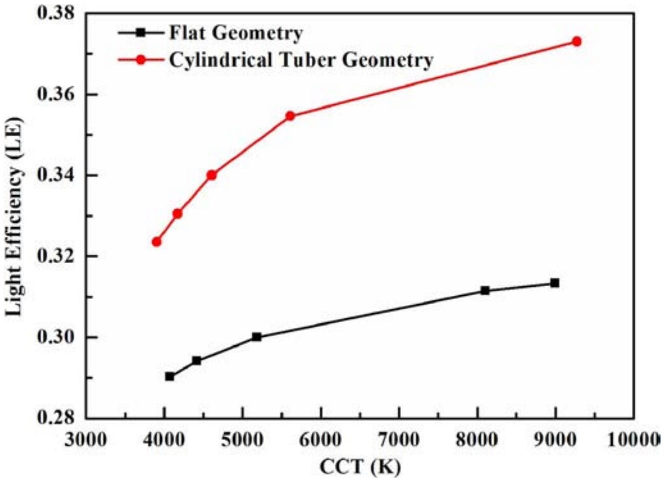


Fig. 11. Simulated results of the LE of the two geometries under different CCTs.

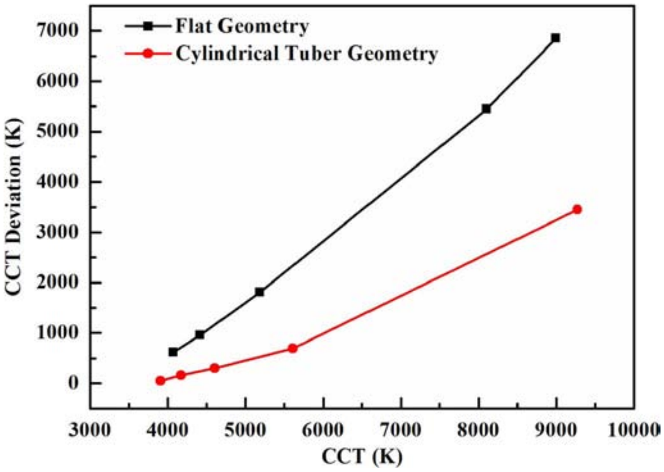


Fig. 12. Simulated results of CCT deviations of the two geometries under different CCTs.

extend the comparison at different CCT conditions. Fig. 11 shows the simulated results of the LE of the two geometries under different CCTs. It indicates that the cylindrical tuber geometry have higher LE, to be more specific, with the CCT increase from 4000 K to 9000 K, and the LE enhancement increase from 8.1% to 15.5%. The LE enhancement is 11.9% at 5000 K, which is corresponding to the experimental result (11.7%@5000 K). Fig. 12 shows the simulated results of CCT deviations of the two geometries under different CCTs, and it indicates that the cylindrical tuber geometry has better ACU performance under all the CCTs.

6. Conclusion

In this paper, we proposed a cylindrical tuber encapsulant geometry for enhancing the optical performance of COB packaging LEDs. Experiments and optical simulations based on ray-tracing method were conducted, COB packaging modules with flat encapsulant geometry were used to make comparison. The simulation results show that compared with the flat geometry, the cylindrical tuber geometry has higher LE and better ACU performance under the CCTs from 4000 K to 9000 K, and the LE enhancement increases with the CCT, and when the CCT increases from 4000 K to 9000 K, the LE enhancement increase from 8.1% to 15.5%. The experimental results show that for the main encapsulation layer only consists of silicone, the proposed geometry enhances the LE up to 63.1%. In addition, for another case in which the encapsulation layer consists of silicone and phosphor particles, when the average CCT is about 5000 K, the proposed geometry increases the light efficiency by 11.7%, and the angular CCT deviations of the flat geometry and the proposed geometry are 1805 K and 475 K.

References

[1] S. Liu and X. B. Luo, *LED Packaging for Lighting Applications: Design, Manufacturing and Testing*. New York, NY, USA: Wiley, 2011.

[2] A. Zukauskas, M. S. Shur, and R. Caska, *Introduction to Solid-state Lighting*. New York, NY, USA: Wiley, 2002.

[3] J. H. Lau, *Chip on Board: Technologies for Multichip Modules*. Norwell, MA, USA: Kluwer, 1994.

[4] C. Yuan *et al.*, “Locally reinforced polymer-based composites for efficient heat dissipation of local heat source,” *Int. J. Therm. Sci.*, vol. 102, pp. 202–209, Apr. 2016.

[5] C. Yuan, B. Xie, M. Y. Huang, R. K. Wu, and X. B. Luo, “Thermal conductivity enhancement of platelets aligned composites with volume fraction from 10% to 20%,” *Int. J. Heat Mass Transfer*, vol. 94, pp. 20–28, Mar. 2016.

[6] Z. T. Li *et al.*, “Light extraction improvement for LED COB devices by introducing a patterned leadframe substrate configuration,” *IEEE Trans. Electron Devices*, vol. 60, no. 4, pp. 1397–1430, Apr. 2013.

[7] D. Wu, K. Wang, and S. Liu, “Enhancement of light extraction efficiency of multi-chips light-emitting diode array packaging with various microstructure arrays,” in *Proc. IEEE 61st Electron. Compon. Technol. Conf.*, May/Jun. 2011, pp. 242–245.

[8] H. Zheng *et al.*, “Optical performance enhancement for chip-on-board packaging LEDs by adding TiO2/silicone encapsulation layer,” *IEEE Electron Device Lett.*, vol. 35, no. 10, pp. 1046–1048, Oct. 2014.

[9] C. Y. Liu *et al.*, “Improvement of emission uniformity by using micro-cone patterned PDMS film,” *Opt. Exp.*, vol. 22, no. 4, pp. 4516–4522, Feb. 2014.

[10] Y. J. Wang, J. G. Lu, and H. P. D. Shieh, “Efficiency enhancement of organic light-emitting diodes on flexible substrate with patterned inverted conical structure,” *IEEE Photon. J.*, vol. 8, no. 1, Feb. 2016, Art. no. 1600108.

[11] H. Xiao *et al.*, “Improvements on optical and chromatic uniformities of light-emitting diodes with microscale-roughness-controlled surfaces,” *IEEE Photon. J.*, vol. 7, no. 4, Aug. 2015, Art. no. 1600908.

[12] H. Zheng, J. L. Ma, and X. B. Luo, “Conformal phosphor distribution for white lighting emitting diode packaging by conventional dispensing coating method with structure control,” *IEEE Trans. Compon., Packag. Manuf. Technol.*, vol. 3, no. 3, pp. 417–421, Mar. 2013.

[13] X. J. Yu, B. F. Shang, B. Xie, M. Y. Huang, and X. B. Luo, “Spreading behaviors of silicone droplet impact on flat solid surface: Experiments and VOF simulations,” in *Proc. 16th Int. Conf. Electron. Packag. Technol.*, Aug. 2015, pp. 1058–1061.

[14] Y. M. Wang, H. Zheng, R. Hu, and X. B. Luo, “Modeling on phosphor sedimentation phenomenon during curing process of high power LED packaging,” *J. Solid State Lighting*, vol. 1, no. 2, pp. 1–9, Apr. 2014, doi: 10.1186/2196-1107-1-2.

[15] N. Kiuna *et al.*, “A model for resin viscosity during cure in the resintransfer moulding process,” *Composites A, Appl. Sci. Manuf.*, vol. 33, no. 11, pp. 1497–1503, Nov. 2002.

[16] H. Zheng, S. Liu, and X. B. Luo, “Enhancing angular color uniformity of phosphor-converted white light-emitting diodes by phosphor dip-transfer coating,” *J. Lightw. Technol.*, vol. 31, no. 12, pp. 1987–1993, Jun. 2013.