LEDs on curved ceramic substrate with primary optics for modification of luminous intensity

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ABSTRACT

Unlike the conventional LED luminary with a planar substrate and only the forward emission, the proposed LED luminary with a curved ceramic substrate can perform both the forward and the backward emissions. Assembled with the proper primary optics, an illustrated LED bulb has been designed, fabricated and measured. The measured luminous intensity of the LED bulb has shown the backward emission and designed distribution with the beam-angle of 133°. To broaden the application areas, such a LED bulb on a curved substrate has been modularized as a streetlight. The measured results of the proposed streetlight have shown that the beam angle of the luminous intensity and the luminaire efficiency are 132° and 86%, respectively. Meanwhile, its luminous characteristics also fit the standard for lighting design of urban roads.

Keywords: LED lighting, curved substrate, ceramic substrate, LED's primary optics

1. INTRODUCTION

Because of the merits of mercury-free, high efficacy, good color rendering index (CRI), long lifetime and compact size, LED lighting draws more attention in recent years. Moreover, the LED is a durable, instantly ignited and smartly controllable light source [1]. However, due to the Lambertian radiation distribution, conventional LEDs cannot directly be used for some specific applications, such as road lighting or bulb-substituting [1-2]. To rearrange the illumination pattern, the method of a secondary freeform optical system has been proposed for road lighting with high illuminance ratio [2]. Moreover, along with the development of LED packaging technology, primary freeform optics for LED chip has been demonstrated to improve the optical efficiency in road lighting [3]. Although the LED luminary with freeform optics can achieve the desired luminous characteristics in road lighting, because of the geometry restriction, such a method cannot directly realize a LED bulb with both forward and backward radiation. To realize a LED bulb with the backward emission, a common method is to exploit diffuse surfaces. However, the out-coupling luminous flux is reduced around 10 %. Another method of curved ceramic substrate has been demonstrated to achieve the forward and the backward radiation efficiently [1].

In this study, we combine the approaches of the curved ceramic substrate and the freeform optics to realize a LED bulb with desired luminous intensity distribution. Meanwhile, by means of modularization, the proposed bulbs can perform as a streetlight. One example has been designed, fabricated and measured. The measured luminous intensity distribution has reached the desired beam angle and met the standard for urban road-lighting.

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2. DESIGN EXAMPLE

Using the curved substrate, one can design a LED bulb for the desired luminous intensity distribution. In this study, the LED bulb is not only for performing the bulb-like visual effect but also for applying to road-lighting which prefers the intensity distribution with a large beam angle. Meanwhile, for the purpose of energy saving, one of the requirements of the LED bulb is to have the efficacy of more than 80 lm/W. Along with other criteria, the requirements of the design are listed in Table 1.

Table 1. Referable operation conditions of the die and requirements of the target LED bulb

Requirements of the target LED bulb (before attached with the optics):				
	Number of dies	Substrate size	Luminous flux	Efficacy
Per bulb:	18	φ~=25 mm	> 360 lm	> 80 lm/W

Requirements of the target LED bulb (after attached with the optics):			
	Loss due to the optics	Beam angle of luminous intensity distribution	Backward radiation
Per bulb:	< 15%	> 120˚	> 5%

To fit the optical and mechanical requirements listed in Table 1, the primary calculation of a luminary model was performed in a simulation tool, LightTools. After the iterative calculations, the designed curved-substrate had 18 holes containing the dies in two concentric circles, as shown in Fig. 1. The vertical angles of the concentric circles were 17.5˚ and 32.5˚, respectively.

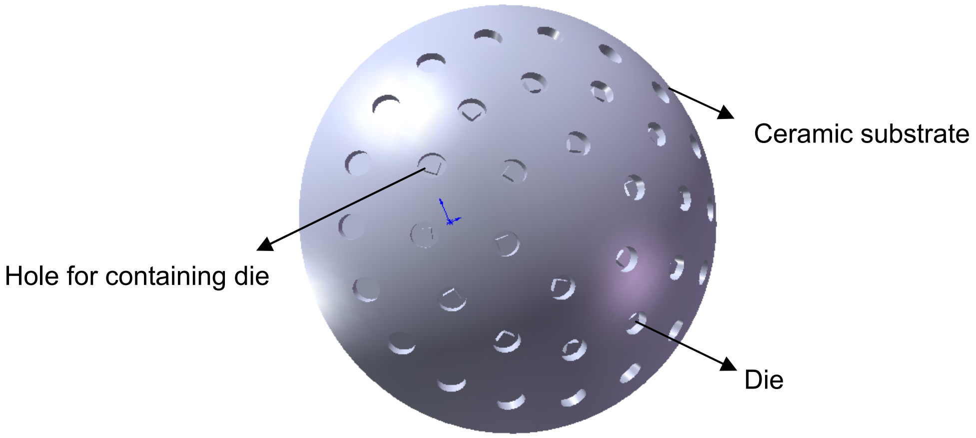
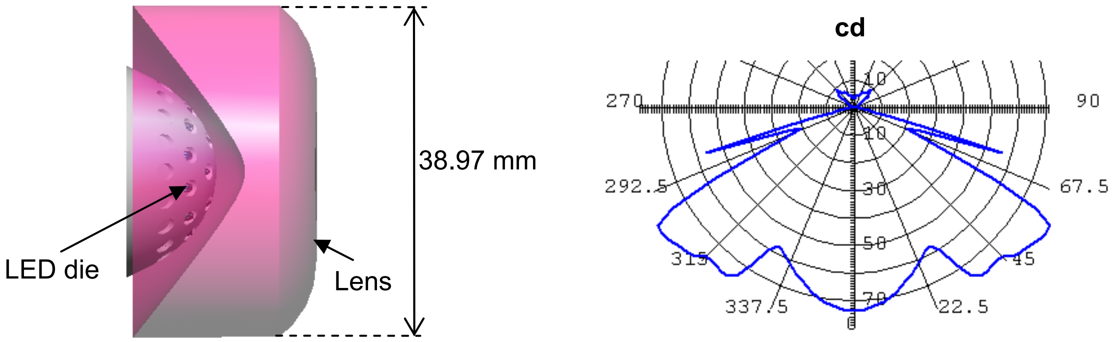


Figure 1. Schematic of the designed curved-substrate with LED dies

Since the curvature of the curved substrate was limited, the LED dies could not locate at an arbitrary large vertical angle. To attain the desired luminous intensity distribution, a primary freeform lens was designed based on geometrical ray-tracing. The material of the designed primary optics was PMMA, while the aperture diameter of the lens was 38.97 mm. Along with the designed curved-substrate, the simulated beam angle of luminous intensity distribution was 128˚, as illustrated in Fig. 2.

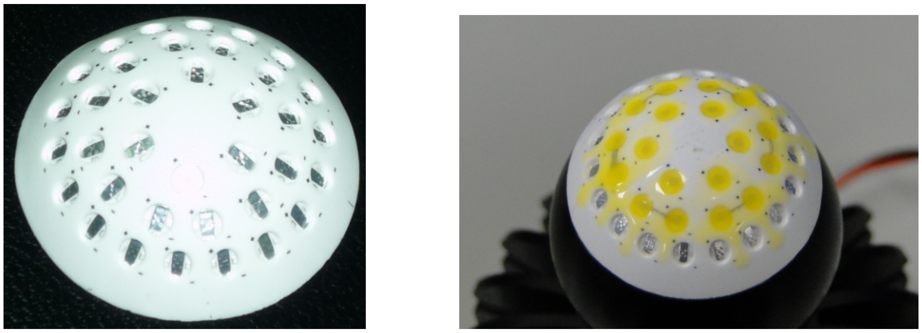


(a) (b)

Figure 2. (a) Curved LED substrate and primary lens and (b) simulated luminous intensity distribution

3. FABIRCATION

Based on the design in section 2, the curved substrate was fabricated by the technology of ceramic printed circuit board (PCB). For the designed substrate, it required 9 screen-printed layers and sintered by the low-temperature process. As a result, the electric circuits were embedded in the substrate and there was no bonded wire left as an obstacle along the lighting direction. Although only 18 LED dies were required, 36 holes were reserved in three concentric circles to test the curvature-limitation of the ceramic substrate. The fabricated ceramic substrate is shown in Fig. 3(a). From the visual examination, one could see that the dimensions of the holes in the 3rd circle encountered the distortion. Therefore, the blue LED dies were only bonded to the holes in the 1st and the 2nd circles. Then the yellow phosphor was coated to package the LED, as shown in Fig. 3(b).



(a) (b)

Figure 3. Fabricated (a) curved ceramic substrate and (b) phosphor-coated LED

By the ultra-precision machining technology, the designed primary lens was fabricated as the first sample. Since the material of the primary lens, PMMA, was a kind of optical plastic, the fabrication of the design was able to be done by the cheap machining process, instead of the expensive molding process.

4. MEASUREMENT

Using an infrared thermal camera, the thermal image of the phosphor-coated LED was taken, as shown in Fig. 4. The temperature on the phosphor was the highest, 58.57˚C, and remained in the tolerance of the lens material, PMMA (< 90˚C).

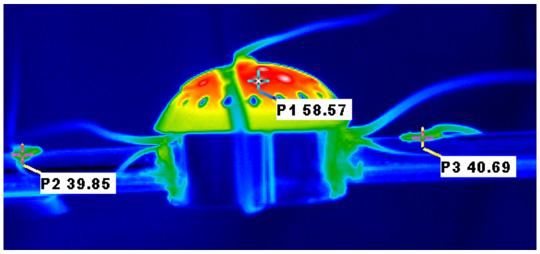
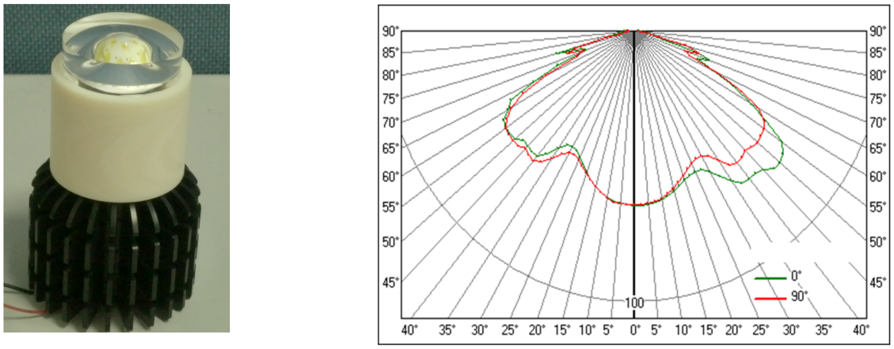


Figure 4. Thermal image of phosphor-coated LED

Before attached with the primary optics, the phosphor-coated LED was measured, as the characteristics recorded in Table 2. The results had agreed with the requirements listed in Table 1. Then the primary lens and the phosphor-coated LED were assembled to be a LED bulb, as shown in Fig. 5(a). The measured results, as shown in Table 3 and Fig. 5(b), also fitted the requirements listed in Table 1.

Table 2. Measured results of the phosphor-coated LED

Number of dies	shell size	Luminous flux	Efficacy
18	φ=25.05 mm	390.3 lm	84.1 lm/W



(a) (b)

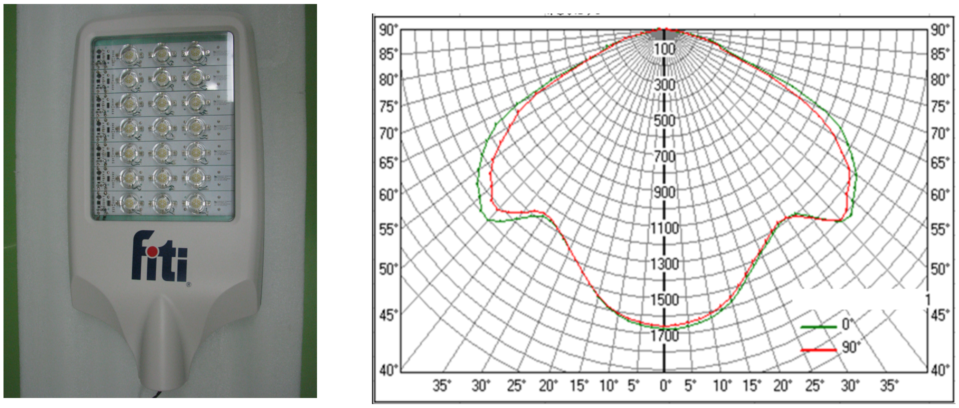
Figure 5. (a) Photo and (b) measured luminous intensity distribution of the LED bulb

Table 3. Measured results of the LED bulb

Loss due to the optics	Beam angle of luminous intensity distribution	Backward radiation
2%	133˚	6.5%

5. DEMONSTRATION AS A STREETLIGHT

With some modifications of the mechanical and the electrical layouts, the proposed LED bulb can be reproduced multiply and demonstrated as a streetlight. Regard one phosphor-coated LED with its primary optics as one unit. In this demonstration, 21 units were assembled to realize a streetlight. To improve the yield rate, since the LED dies were only bonded to the holes in the 1st and the 2nd circles, the holes in the 3rd circle were omitted and the electronic layout was made required changes. On the other hand, the fin-like heat-sink for the LED bulb was replaced mechanically by the heat-pipe embedded in the base of the streetlight. After the fabrication and assembly of every component, a streetlight with LEDs on curved substrates was completed, as shown in Fig. 6(a). The measured luminous flux of this luminaire and the luminaire efficiency were 5725 lm and 86%, respectively. Also, the luminous intensity distribution was measured with the beam angle of 132˚, as shown in Fig. 6(b). The results showed that due to the boundary effect of the housing and the white PCB serving as a back-reflector, the luminous intensity distribution in the large angle was cut out and the central intensity was enhanced.



(a) (b)

Figure 6. (a) Photo and (b) measured luminous intensity distribution of the demonstrated streetlight

The measured luminous intensity distribution of the demonstrated LED streetlight was then exploited to make the road-light planning. Using the light planning software, Dialux, we analyzed the characteristics of demonstrated LED streetlight under the conditions of pole-height: 8m, distance between two poles: 24 m and road width: 7 m. According to the Chinese standard for lighting design of urban roads, CJJ 45-2006, the demonstrated LED streetlight fitted the requirements of the local roads, as the analyzed data and the standard values listed in Table 4.

Table 4. Comparison of the requirements of local road in CJJ45-2006 standard with the characteristics of the demonstrated LED streetlight

	CJJ 45-2006	Demonstrated LED streetlight			
Tilt angle	-	0˚	5˚	10˚	15˚
Average luminance (cd/m^2)	0.5	0.54	0.54	0.54	0.54
Overall uniformity of luminance[1] (cd/m^2)	≥ 0.4	0.5	0.5	0.5	0.5
Longitudinal uniformity of luminance[1] (cd/m^2)	-	0.8	0.7	0.7	0.7
Average illuminance (lux)	8	9.87	9.93	9.97	9.95
Uniformity of illuminance[1] (lux)	≥ 0.3	0.508	0.522	0.529	0.537
Threshold increment[2] (%)	≤ 15	4	4	4	4
Surrounding ratio[1,3]	-	0.7	0.7	0.7	0.7

[1] the minimum value is considered, [2] that is the influence from glare to visibility, [3] that is the ratio of average illuminance on a strip beside the carriageway to that on an adjacent strip of carriageway itself [4-5].

Although the LED streetlight was demonstrated only for the local roads, the applications of such a streetlight shall be broader. For example, since the housing blocked the luminous intensity distribution of the streetlight, the modification of housing by integrating the primary lens arrays as one covering lens can lead to the higher intensity in the large angle and also the less luminous loss. As a result, the illuminated area can be extended, leading to a longer distance between poles and a reduced cost. Meanwhile, the enhanced luminous flux brings the higher luminance; then the characteristics of the modified streetlight can reach the requirements of the collected roads and even the major roads, as the standard values defined in CJJ 45-2006.

6. CONCLUSIONS

The proposed LED luminary with a curved ceramic substrate and a primary freeform-lens was demonstrated as a LED bulb to perform both the forward and the backward emissions. By means of the iterative calculations in the optical simulation software, the locations of LED dies on the curved substrate were designed to bring the backward emission. To attain the desired luminous intensity distribution, a primary freeform lens was designed based on geometrical ray-tracing. The designed LED bulb was then fabricated and measured. The measured luminous intensity of the LED bulb showed the designed distribution and the beam-angle of 133°, while other desired specifications, such as the forward and the backward emissions, were also achieved. To extend the LED bulb to a streetlight, the phosphor-coated LEDs on a curved substrate with one primary lens were regarded as a unit, and 21 units were assembled with related electronics and mechanics to form the streetlight. The measured beam angle of the luminous intensity and the luminary efficiency of the streetlight were 132° and 86%, respectively. Meanwhile, its luminous characteristics fit the requirements of local roads according to the standard of CJJ 45-2006.

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