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Abstract. Unlike the conventional light-emitting diode (LED) luminaire with a planar substrate and only the forward emission, the proposed LED luminaire with a curved ceramic substrate can perform both the forward and the backward emissions and inherits the merits of good heat-dissipation and low cost from the ceramic substrate. 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 deg. 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 deg and 86%, respectively. Meanwhile, its luminous characteristics also fit the Chinese standard for lighting design of urban roads. [DOI: 10.1117/1.JPE.2.026501]

Keywords: light-emitting diode lighting; curved substrate; ceramic substrate; light-emitting diodes; primary optics.

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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 luminaire 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. The backward radiation for a bulb illuminating the ground means the radiation toward the ceilings, equivalent to the radiation with the vertical angle between 90 and 270 deg (equal to 90 to 180 deg and -90 to -180 deg in another expression). 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]

Since the ceramic substrate has the merits of good heat-dissipation and low cost, this study combines the curved ceramic substrate with the freeform optics to realize a LED bulb with desired luminous intensity distribution. Meanwhile, by means of modularization, the proposed

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bulbs can perform as a streetlight with high flexibility. 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.

2 Theory

Unlike a conventional planar substrate, the proposed LED in this article adopts a curved substrate. To investigate the optical properties of the LED with a curved substrate, a simple model is illustrated in Fig. 1. Consider that a luminous source is located on a hemispherical surface. The radius of the surface and the angle between the source center and the vertical line were r and θ_0, respectively. Assume that a receiver is x away from the center of the curved substrate. The areas of the source and the receiver are denoted as dA and dA', respectively. The line connecting source and receiver centers and the normal of source surface form an angle of θ, while that and the receiver surface form θ'. Then the distance between the source and the receiver can be derived as:

$$R = (x - r \sin \theta_0)/ \sin \theta' . \tag{1}$$

According to the photometry, if the luminance of the source is L, then the illuminance on the receiver is

$$dE' = L \cdot dA \cdot \cos \theta \cdot \cos \theta' / R^2. \tag{2}$$

When there are n sources on the same hemispherical substrate, from Eqs. (1) and (2), the illuminance can be expressed as:

$$E'(x) = \sum_n L_n \cdot dA_n \cdot \cos \theta_n \cdot \cos \theta'_n \cdot \sin^2 \theta'_n / (x - r \cdot \sin \theta_{0n})^2. \tag{3}$$

If uniform illuminance is necessary, $E'(x)$ shall be a constant. Therefore, one can adjust the parameters of L, dA, and θ_0 to force Eq. (3) as a constant and realize the uniform illuminance.

To count the far-field luminous intensity distribution, a practical approximation is that the distance between source and receiver centers, R, is long enough. Then θ' is regarded as a viewing angle. Assume the source as a perfect Lambertian source. The luminous intensity distribution of this source can be approximated as:

$$dI(\theta') = dI_0(\theta_0) \cdot \cos \theta. \tag{4}$$

When n sources on the hemispherical substrate are considered, the overall luminous intensity distribution is derived:

$$I(\theta') = \sum_n dI_{0n}(\theta_{0n}) \cdot \cos \theta_n. \tag{5}$$

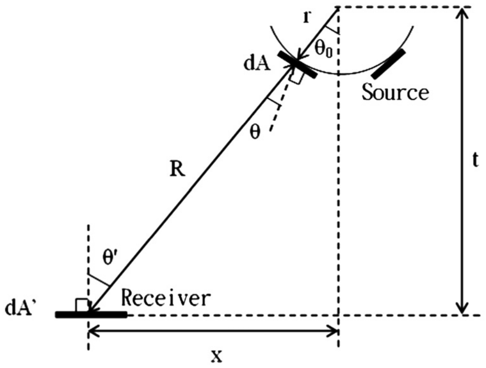

Fig. 1 Schematic of luminous sources located on a curved substrate.

From Eq. (5), the luminous intensity distribution of the luminaire can be designed by properly modulating the dI and θ_0.

3 Design Example

According to the derived equations, one can design a LED bulb by using the curved substrate 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 the wing shape. Hence, the beam angle, defined as the full width at the half maximum, shall be larger than 120 deg. 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 operating conditions of the blue dies which we referred to and the requirements of the design are listed in Table 1.

According to the requirements listed in Table 1, the location of every die and the lens form of the primary lens need to be designed. The design flow is illustrated as Fig. 2.

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

Referable operation conditions of the die:						
	Emitting area	Luminous flux	Driving current	Power consumption	Efficacy	
Per die:	0.6×0.6 mm^2	20 lm	150 mA	0.25 W	80 lm/W	
Requirements of the target LED bulb (before attached with the optics):						
	Number of dies	Substrate size	Luminous flux	Color rending index	Color temperature	Efficacy
Per bulb:	18	$\varphi \sim = 25$ mm	>360 lm	>85	5500 ~ 6500 K	>80 lm/W
Requirements of the target LED bulb (after attached with the optics):						
	Loss due to the optics[a]	Beam angle of luminous intensity distribution			Ratio of backward radiation[b]	
Per bulb:	<15%	>120 deg			>5%	

[a] Loss due to the optics: the ratio of the flux emitted from the LED bulb with the optics to that without the optics.
[b] Ratio of backward radiation: the ratio of the flux of backward radiation to the total flux emitted from the LED bulb.

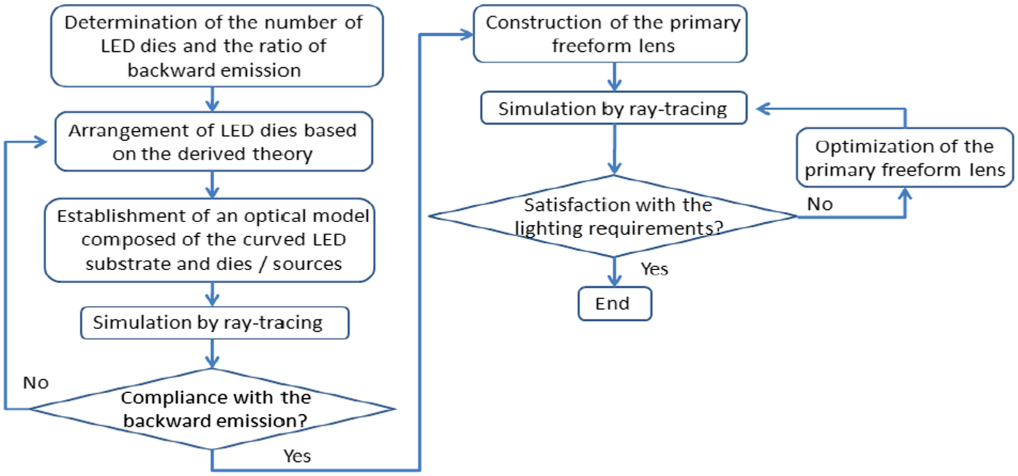

Fig. 2 Flow diagram of designing LED on curved substrate with primary optics.

For simplifying the model, the dies of every LED bulb were arranged in concentric circles. Due to the requirement of backward emission, the vertical of the outer dies should be larger than 30 deg when LED radiation was assumed as the Lambertian pattern which could be characterized by the beam angle. Along with the required number of dies, the substrate size and the wire spacing (limited by the fabrication ability), one design with 12 dies in the outer circle and six dies in the inner one was proposed. To fit other optical and mechanical requirements listed in Table 1, the primary calculation of a luminaire model was performed in a simulation tool, LightTools. The size of every die was given as $0.6 \times 0.6 \times 0.3\ \mathrm{mm}^3$. The shell-like substrate had an aperture diameter of 25 mm and 18 holes in two concentric circles, as shown in Fig. 3. According to the fabrication limits in wire-spacing and substrate curvature as well as the verifications in simulation, a curvature radius of 14 mm was designed and the vertical angles of the two concentric circles were 17.5 and 32.5 deg, respectively, as shown in Fig. 4. Noticeably, the above design was not unique, because the dies in a circle with its vertical angle larger than 32.5 deg could theoretically achieve the backward emission. However, the fabrication of holes in such a circle might encounter difficulties due to the fragile ceramic substrate. To examine the fabrication ability, some testing holes were designed along the most outer circle, as the third concentric circle shown in Fig. 3.

According to the theory mentioned in Sec. 2, the designed curved-substrate can realize the backward radiation. The simulated luminous intensity distribution, as illustrated in Fig. 5, also shows that there were some rays aiming along the vertical angles between 90 and 270 deg, matching the requirement of backward radiation.

Although the designed LED bulb without optics could achieve the backward radiation, the luminous intensity was not as a wing shape and the ratio of backward radiation was not as much as demand. The main reason was that the curvature of the curved-substrate had limitation, causing the LED dies not to locate at a large-enough vertical angle. Thus, a primary freeform lens was designed based on the mentioned design flow, as illustrated in Fig. 2, while the

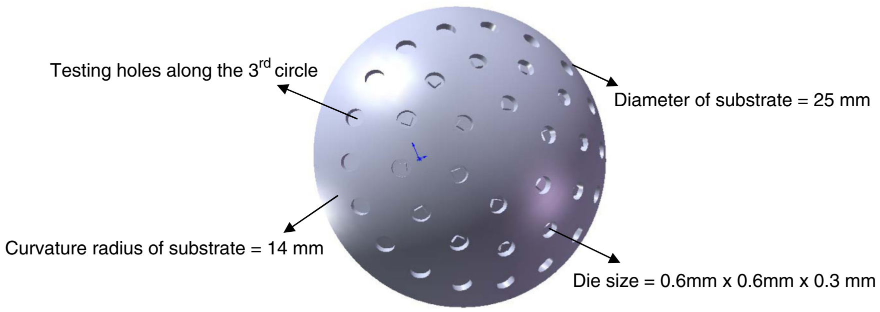

Fig. 3 Top view of the designed curved-substrate with LED dies.

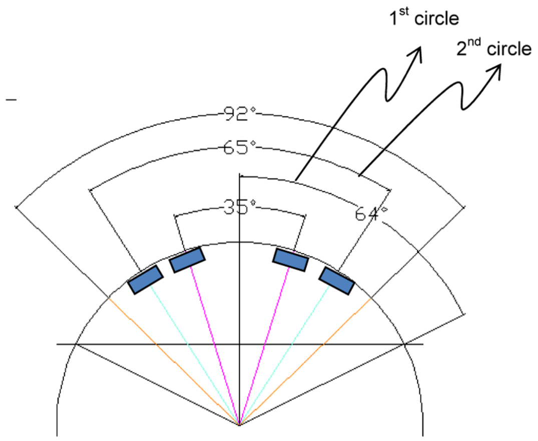

Fig. 4 Schematic of the locations of the concentric holes.

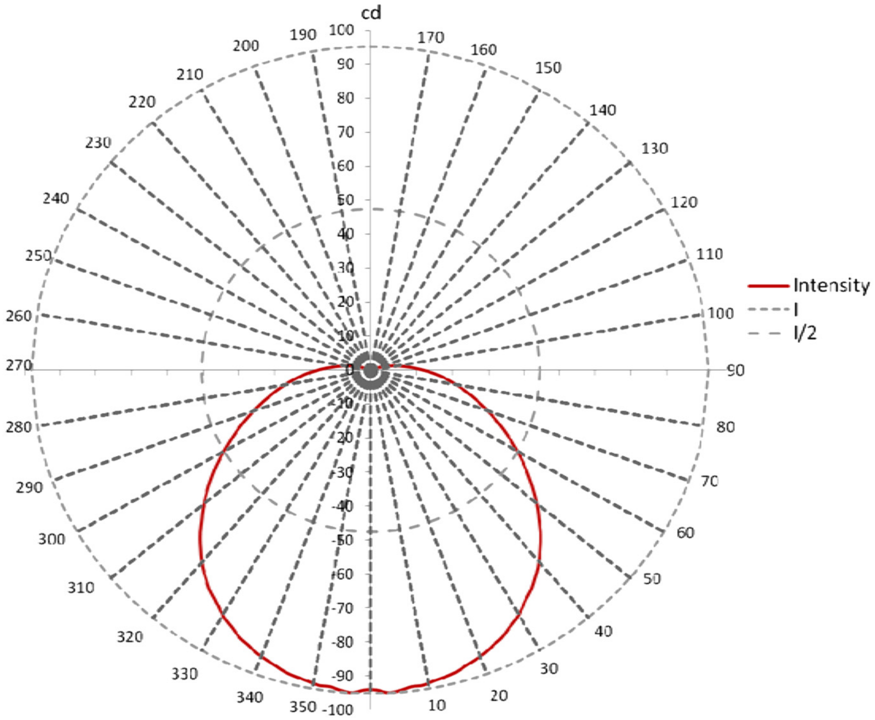

Fig. 5 Simulated luminous intensity distribution of LED bulb without lens.

optimization was done on the simulation platform. 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 deg, as illustrated in Figs. 6 and 7.

After iteratively checking the fabrication practicability, the primary lens was modified, as shown in Fig. 8, to fit the molding process and to keep the optical performances.

4 Fabrication

Based on the design in Sec. 3, the curved substrate was fabricated by the technology of ceramic printed circuit board (PCB). For the designed substrate, it required nine 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. The 18 holes in the most outer circle, the third circle, were used to test the curvature-limitation of the ceramic substrate. Meanwhile, six dies were connected in series as one group and six groups were connected in parallel, as illustrated in Fig. 9. It is noted that the central positive and negative electrodes collected the electrodes of the six groups and were located at the bottom side of

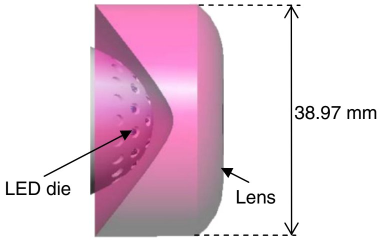

Fig. 6 Curved LED substrate and primary lens.

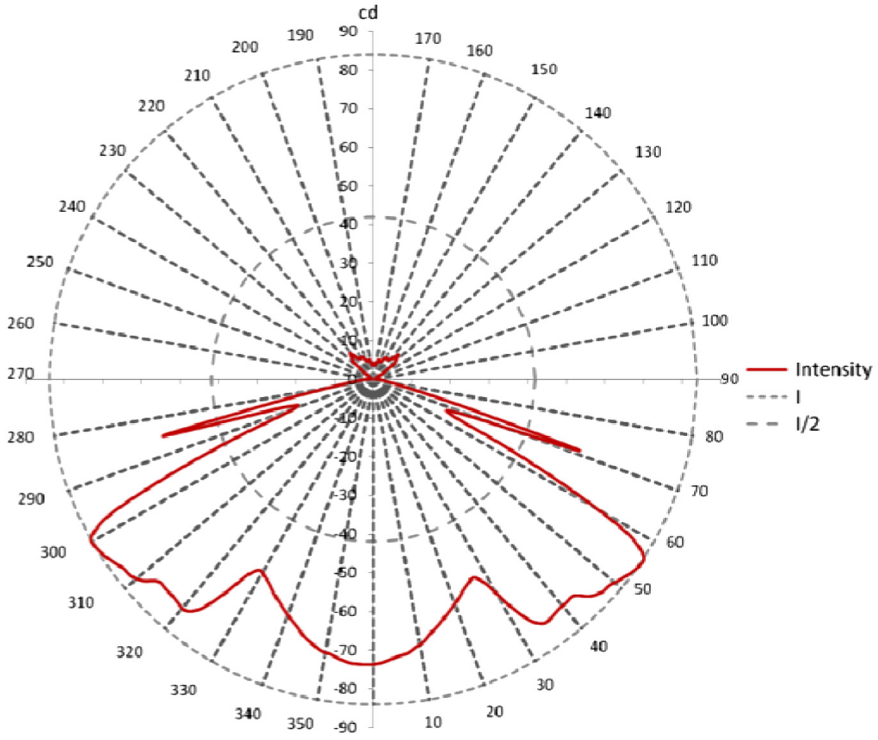

Fig. 7 Simulated luminous intensity distribution.

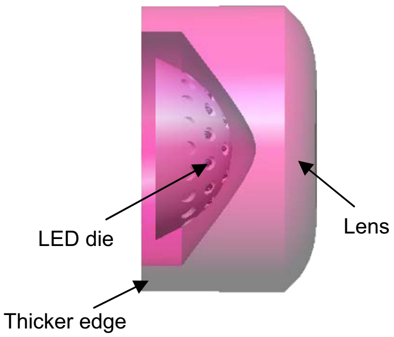

Fig. 8 Curved LED substrate and modified primary lens.

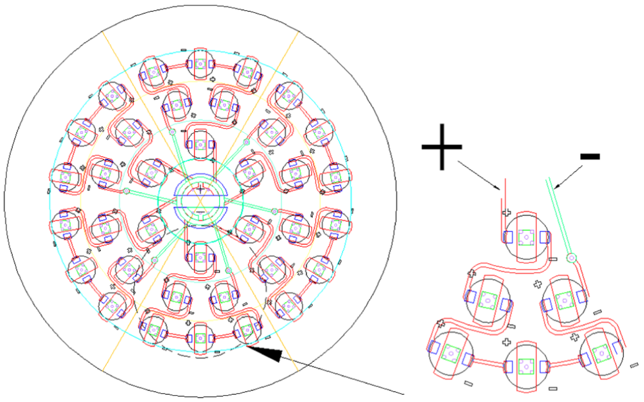

Fig. 9 Electric circuit design of the ceramic PCB.

the substrate. Therefore, the out-coupling wires did not affect the illumination. The fabricated ceramic substrate is shown in Fig. 10(a). From the visual examination, one could see that the dimensions of the holes in the third circle encountered the distortion, from a disk shape to an ellipse. It implied that the vertical angles of the LED dies in the third circle could not be well-controlled. Therefore, the blue LED dies were only bonded to the holes in the first and second circles, which also matched with the design. Then the yellow phosphor was coated to package the LED. After that, out-coupling wire-connection and heat-sink mounting were treated to the sample, as shown in Fig. 10(b).

By the ultra-precision machining technology, the first sample of the designed primary lens was fabricated. 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 either machining technology or injection molding process. For the prototype, the process of computer-numerical-control (CNC) machining or even ultra-precision machining is rather cheaper than the injection molding process due to the high mold-cost. However, when mass production is considered, the injection molding process will be more cost-effective. Since the published literature has provided references for the evaluation of the cost in injection molding,[4] the details are not discussed here. Although injection molding has the merits of high production output rates and low cost for every sample, it has disadvantages. For example, the associated parts for injection molding often take a long time to develop.[5] Therefore, designers and researchers can decide the process methods according to their demands and budgets.

5 Measurement and Discussion

From the simulated results about the color consistency of white LEDs, the packaging method, the concentration, and the thickness of the phosphor dominated the color variation.[6] Ideally, the thickness of phosphor should be uniform. In this paper, a factor of thickness variation was defined as $[(\text{maximum thickness} - \text{minimum thickness})/2]/\text{average thickness}$ to judge the quality of phosphor-coating process. The thickness variation was 66% in the primary measurement. To reduce the thickness variation and consequently improve color consistency, we designed and applied fixtures to control the amount of phosphor. Then the thickness variation of 4.1% was obtained while the thickness of every hole was ranged from 404.6 to 438.8 μm in the experiment. On the other hand, the measured variation in correlated color temperature (CCT), as depicted in Fig. 11, was from 5600 to 6400 K, satisfying the requirement of 5500 to 6500 K listed in Table 1.

Using an infrared thermal camera, the thermal image of the phosphor-coated LED was taken, as shown in Fig. 12. The temperature on the phosphor was the highest, 58.57℃, and remained in the tolerance of the lens material, PMMA (<90 ℃).

Before attached with the primary optics, the phosphor-coated LED was measured. The results, as recorded in Table 2, had agreed with the requirements listed in Table 1. Then the primary lens and the phosphor-coated LED were assembled as a LED bulb, as shown in Fig. 13(a). The measured characteristics and luminous intensity distribution of the LED bulb, as shown in Table 3 and Fig. 13(b), respectively, also fit the targets in Table 1.

Fig. 10 Fabricated (a) curved ceramic substrate and (b) phosphor-coated LED.

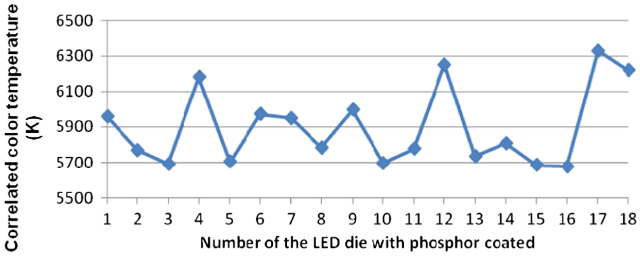

Fig. 11 Correlated color temperature of every LED die with the phosphor coated.

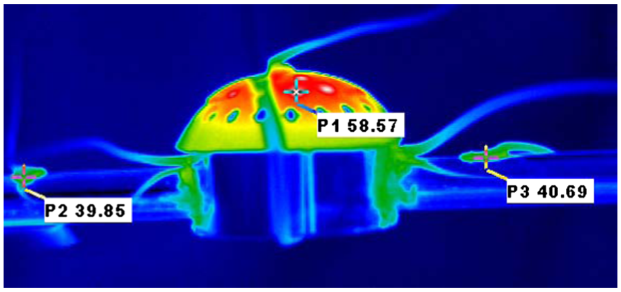

Fig. 12 Thermal image of phosphor-coated LED.

Table 2 Measured results of the phosphor-coated LED.

Number of dies	Shell size	Luminous flux	Color rending index	Color temperature	Efficacy
18	$\varphi = 25.05$ mm	390.3 lm	85	5798 K	84.1 lm/W

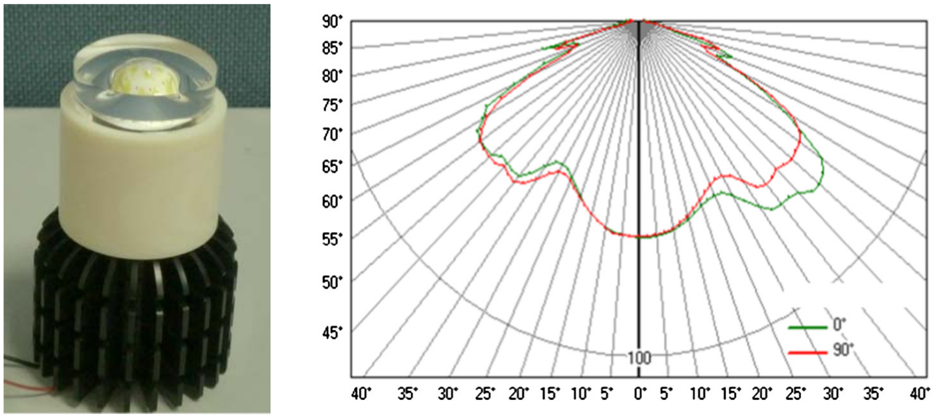

Fig. 13 (a) Photo and (b) measured luminous intensity distribution of the LED bulb.

Due to the mechanical limitation of goniophotometer, the measured luminous intensity distributed among the vertical angles of −90 to 90 deg (equivalent to 0 to 90 deg and 270 to 360 deg in the expression of Sec. 3), which belonged to the forward radiation. To count the backward radiation, an integrating sphere was used to measure the total luminous flux. Along with the measured forward luminous flux, the ratio of backward radiation was counted as 6.5%, fulfilling the requirement of more than 5%.

The loss due to the optics was calculated from the measured luminous fluxes of the optics-attached LED bulb and the LED bulb without optics. Since the ceramic substrate processed the diffuse white surface, it performed as a good reflector that recycled the lights reflected

Table 3 Measured results of the LED bulb.

Loss due to the optics	Beam angle of luminous intensity distribution	Ratio of backward radiation
2%	133 deg	6.5%

from the air-optics interfaces and benefited the luminous flux from LED chips to couple out to the ambiance. Also, because the surrounding mechanical components were designed with the least light-obstruction, the loss due to the optics mainly resulted from the material absorptions of the optics and the ceramic substrate. As a result, the measured loss, as low as 2%, fit the requirement of less than 15%.

Although the ceramics substrate had the merits of good heat-dissipation and low cost, there were limitations, such as the fragile property.[7] Then the proposed ceramics encountered the challenge of flexibility, implying that the bending angle of the substrate could not be arbitrarily large. Another challenge was the embedded wire-bonding. The fabrication processes had limited the minimum spacing of embedded wires. According to the experimental results, the shell-like substrate herein was extended to the maximum vertical angle of 64.9 deg, while the maximum vertical angle for the circle without deforming holes was 32.5 deg. As for the embedded wires, they were designed with spacing of 1 mm, based on the fabrication experience of the collaborative company, while the average wire spacing was 0.99 mm in measurement.

6 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 first and second circles, the holes in the third circle were omitted and the electronic layout was changed to three dies in series as one group and six groups in parallel. Mechanically, the fin-like heat-sink for LED bulb was replaced by the heat-pipe embedded in the base of the LED streetlight. After the fabrication and assembly of every component, a streetlight with LEDs on curved substrates was completed, as shown in Fig. 14. The measured luminous flux of this luminaire, luminaire efficiency, color temperature, and CRI were 5725 lm, 86%, 6217 K, and 85.1, respectively. Also, the luminous intensity distribution was measured with a beam angle of 132 deg, as shown in Fig. 15. 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.

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

Fig. 14 Demonstrated LED streetlight.

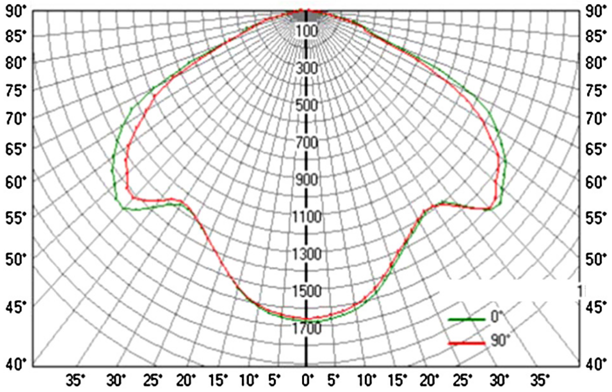

Fig. 15 Measured luminous intensity distribution of the demonstrated streetlight.

analyzed the characteristics of demonstrated LED streetlight under the conditions of pole-height: 8 m, distance between two poles: 24 m, and road width: 7 m. According to the Chinese standard for lighting design of urban roads, CJJ45-2006, the demonstrated LED streetlight fit the requirements of the local roads, as the analyzed data and the standard values listed in Table 4.

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 CJJ45-2006.

Additionally, since the practitioners can adjust the number of the units to manipulate the amplitudes of luminance and illuminance, the requirements of these two quantities for a specific road can be fulfilled by simply increasing or decreasing the number of the units. Hence, such a proposed streetlight constructed by modularization has high flexibility for road-lighting design.

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

	CJJ45-2006	Demonstrated LED streetlight			
Tilt angle	-	0 deg	5 deg	10 deg	15 deg
Average luminance (cd/m^2)	0.5	0.54	0.54	0.54	0.54
Overall uniformity of luminance (cd/m^2)[a]	≥0.4	0.5	0.5	0.5	0.5
Longitudinal uniformity of luminance (cd/m^2)[a]	-	0.8	0.7	0.7	0.7
Average illuminance (lux)	8	9.87	9.93	9.97	9.95
Uniformity of illuminance (lux)[a]	≥0.3	0.508	0.522	0.529	0.537
Threshold increment (%)[b]	≤15	4	4	4	4
Surrounding ratio[a,c]	-	0.7	0.7	0.7	0.7

[a] The minimum value is considered.

[b] That is the influence from glare to visibility.

[c] That is the ratio of average illuminance on a strip beside the carriageway to that on an adjacent strip of carriageway itself.[8,9]

7 Conclusions

The proposed LED luminaire 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. First, the luminous intensity and the illuminance for the curved substrate were derived theoretically. According to the derived theory, a primary model of LED dies on a curved substrate was designed to bring the backward emission. To obtain the luminous intensity distribution with the wing shape, a primary lens was designed by means of the optimization in an optical simulation tool. 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 deg, 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 luminaire efficiency of the streetlight were 132 deg and 86%, respectively. Meanwhile, its luminous characteristics fit the requirements of local roads based on the standard of CJJ45-2006. Furthermore, such a modularized streetlight possesses the merit of high flexibility for road-lighting design.

Acknowledgments

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Biographies and photographs of the authors are not available.