

Design of compact freeform lens for application specific light-emitting diode packaging

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Abstract: Application specific LED packaging (ASLP) is an emerging technology for high performance LED lighting. We introduced a practical design method of compact freeform lens for extended sources used in ASLP. A new ASLP for road lighting was successfully obtained by integrating a polycarbonate compact freeform lens of small form factor with traditional LED packaging. Optical performance of the ASLP was investigated by both numerical simulation based on Monte Carlo ray tracing method and experiments. Results demonstrated that, comparing with traditional LED module integrated with secondary optics, the ASLP had advantages of much smaller size in volume ($\sim 1/8$), higher system lumen efficiency ($\sim 8.1\%$), lower cost and more convenience for customers to design and assembly, enabling possible much wider applications of LED for general road lighting. Tolerance analyses were also conducted. Installation errors of horizontal and vertical deviations had more effects on the shape and uniformity of radiation pattern compared with rotational deviation. The tolerances of horizontal, vertical and rotational deviations of this lens were 0.11 mm, 0.14 mm and 2.4° respectively, which were acceptable in engineering.

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1. Introduction

Light-emitting diode (LED), with increasing luminous flux and lumen efficiency in recent years, has more and more applications in our daily life, such as road lighting, backlighting for

LCD display, headlamps of automobiles, interior and exterior lighting, etc [1–3]. Brighter, smaller, smarter and cheaper are development trends of both LED packaging modules and luminaires [3]. For example, smaller LED packaging using less material will decline the cost of LED modules. In LED applications, secondary optics are essential for most LED luminaires because radiation patterns of most LEDs are circular symmetry with non-uniform illuminance distribution, which cannot directly meet the requirements of specific applications (e. g. subrectangular radiation pattern required in road lighting). Freeform lens is an emerging optical technology with advantages of being high design freedom and being precise light irradiation control, which are useful for LED lighting design [4–8]. Traditional freeform lens, however, due to the category of secondary optics in nature, has disadvantages of large size in some space confined applications, possibly resulting in large volume and weight of both thermal management part and luminaires, relatively low system optical efficiency and inconvenience for customers to assembly.

In addition, the optical performances of many LED luminaires existing in the market are quite poor, mainly due to a lack of technology of secondary optics for many new LED companies. On the other hand, thousands of traditional lighting companies, which have been main bodies of employment and marketing and sales, are suffering from even poor understanding of LEDs, facing significant technical and societal challenges of transferring from traditional lighting to new LED business, proposing a strong need for easy to use LED technology. Therefore, if we integrate secondary optics with traditional LED packaging achieving new application specific LED packaging (ASLP), as shown in Fig. 1, it will not only decrease the size of LED modules and systems, and increase the efficiencies of LED luminaires, but also provide a convincing solution to LED lighting for old and new LED application companies.

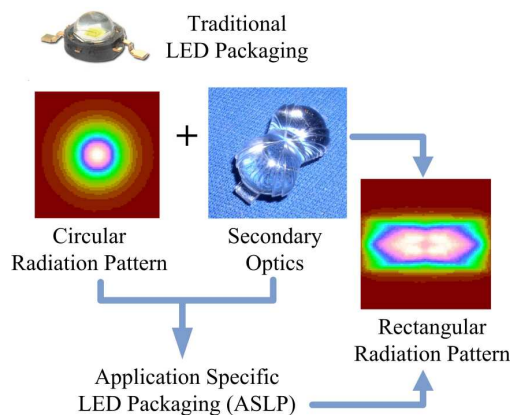


Fig. 1. Schematic of the concept of application specific LED packaging.

In this study, we demonstrated a practical design method of compact freeform lenses, mainly focusing on eliminating deteriorations caused by extended sources. A polycarbonate (PC) compact freeform lens for a new ASLP used in road lighting was designed based on this method. Optical performance of the ASLP was also studied both numerically and experimentally. Results demonstrated that the ASLP had high system optical efficiency and good lighting performance with subrectangular radiation pattern, which meet requirements of road lighting.

2. Problem statement

Extended source is a key issue challenging compact LED packaging freeform lens design. The size of high power LED chip is usually at a level of $1\text{ mm} \times 1\text{ mm}$ while the distance between the chip and outside surface of the packaging lens is about 2.5 mm or even smaller. Since the distance between source and lens is less than 5 times the source diameter, the LED chip could

not be regarded as a point source during packaging lens design according to the far field conditions of LED [9]. Thus the compact freeform lens should be designed based on an extended source. However, if we design a freeform lens according to the assumption of a point source while using the lens for an extended source, lighting performance will deteriorate significantly. Figure 2 (a) shows a freeform lens for LED tunnel lighting and its uniform rectangular radiation pattern when using a point source [8]. However, as shown in Fig. 2 (b), shape and uniformity of the radiation pattern deteriorate extremely when the source extending to an extended source with emitting area of $4\text{ mm} \times 4\text{ mm}$. Therefore, design method of freeform lens should be modified to improve lighting performance when using extended sources.

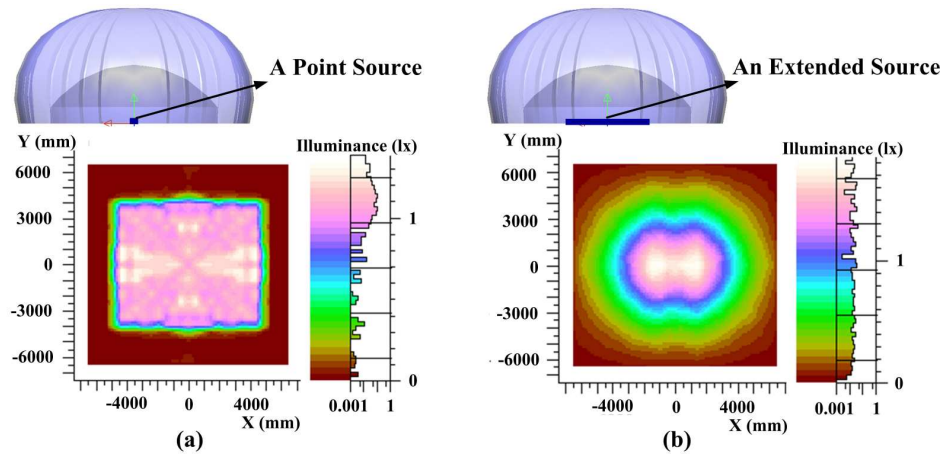


Fig. 2. Effect of extended sources on lighting performance of freeform lens.

Simultaneous multiple surfaces (SMS) method [4] is an effective way to deal with extended sources. The SMS method provides an optical system with two freeform surfaces that refract or reflect the rays of the input bundles into the rays of the corresponding output bundles and vice versa. The SMS method is mainly used in design of secondary optics so far. In this study we will present a practical design method of compact freeform lens for extended sources, which is quite suitable for designing freeform packaging lenses of new ASLPs.

3. Design method of compact freeform lens for extended sources

The design method includes three parts: establishing light energy mapping relationship between source and target, constructing lens and validating lens design by numerical simulation. Rectangular target plane is adopted as an example in the following design. Normally, refractive indexes of encapsulants and lens of LED packaging are usually different with each other. For example, refractive index is 1.586 for PC and is a range from 1.4 to 1.6 for silicone. It is hard to find an interface that will not deflect rays emitted from an extended source when rays transmit through the interface of two materials with different refractive indexes. In this method, optimization of overall lighting performance is to be achieved by adjusting optimization coefficients of target grids and reconstructing the outside surface of lens. Thus there is no strict restriction of the shape of lens' inner surface and it is to be designed as inner concave spherical surface in this method. We will focus on the construction of the outside surface of lens in this study.

3.1 Establishment of light energy mapping relationship

Since the LED source and target plane both are of axial symmetry, only one quarter of them are to be considered in this discussion. First of all, the one quarter light energy distribution of source is divided into $M \times N$ grids with equal luminous flux. As shown in Fig. 3, the source's intensity distribution Ω is specified by coordinates (u, v) , where u is the angle between ray

and X axis, and v is the angle between Z axis and the plane containing ray and X axis. The volume of Ω represents the total luminous flux Φ_{total} of this one quarter source. Luminous flux of unit object $d\Omega$ could be expressed as Eq. (1):

$$\phi(u, v) = \int_{v_j}^{v_{j+1}} \int_{u_i}^{u_{i+1}} I(u, v) \sin u \, du \, dv \quad (1)$$

where $I(u, v)$ is the light intensity distribution of source. We divide Ω into M parts along u direction and N parts along v direction equally, and then each division point $S(u_i, v_j)$ on the surface of Ω could be obtained through solving Eq. (2) and Eq. (3) as follows:

$$\int_0^{\pi/2} \int_0^{u_i} I(u, v) \sin u \, du \, dv = \frac{i\phi_{total}}{M} \quad (i = 0, 1, \dots, M) \quad (2)$$

$$\int_0^{v_j} \int_0^{\pi/2} I(u, v) \sin u \, du \, dv = \frac{j\phi_{total}}{N} \quad (j = 0, 1, \dots, N) \quad (3)$$

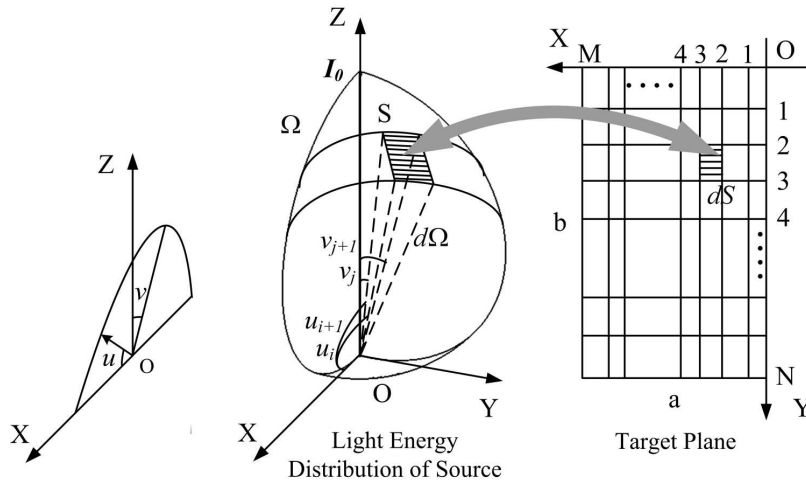


Fig. 3. Schematic of light energy mapping between source and target plane.

Secondly, as shown in Fig. 3, the one quarter rectangular target plane is also divided into $M \times N$ grids by rectangular grids dS . The (x, y, z) Cartesian coordinates specify the points on the target plane. To overcome the problem of lighting performance deterioration caused by extended sources, rectangular grids with unequal area are adopted in this method. The width (W_{grid}) and length (L_{grid}) of each grid on the target plane can be expressed as Eq. (4) and Eq. (5):

$$W_{grid,i} = \frac{C_{wi}a}{M} \quad (i = 0, 1, \dots, M) \quad (4)$$

$$L_{grid,j} = \frac{C_{Lj}b}{N} \quad (j = 0, 1, \dots, N) \quad (5)$$

where C_{wi} and C_{Lj} are optimization coefficients of grids which can optimize the light energy distribution on the target. C_{wi} and C_{Lj} both are equal to 1 when dealing with point source problem. During design for an extended source, we adjust these two coefficients to make the trend of illuminance distribution on the target plane to be inverse of the trend of lighting performance deterioration caused by the extended source. Then the optimized illuminance distribution will compensate for the deterioration caused by the lights irradiating from the edge area of LED chip and much better lighting performance would be obtained.

According to edge ray principle [10], rays from the edge of the source should strike the edge of the target. This principle is true in 2D, and in 3D the skew invariant will lead to loss, but which could be partly recovered by increasing the number of grids. Therefore if we desire to map the light energy in $d\Omega$ into the target grid dS , we should ensure that four rays, which construct the $d\Omega$ as boundary, irradiating at the four corresponding end points of the target grid dS after refracted by the lens. Thus the light energy mapping relationship between the source and the target plane has been established.

3.2 Construction of freeform lens

In this section we will find out the lens which can realize the mapping between the source and the target plane. There are three main steps:

Step 1. Construction of the seed curve. The seed curve is the first curve to generate other lens curves. As shown in Fig. 4, we fix a point P_0 as the vertex of the seed curve. The second point $P_{1,1}$ on the seed curve is calculated by the intersection of incident ray $\mathbf{I}_{1,1}$ and the tangent plane of the previous point. Then we can obtain the normal vector $\mathbf{N}_{1,1}$ of the second point according to the Snell's law expressed as Eq. (6):

$$[1 + n^2 - 2n(\mathbf{O} \cdot \mathbf{I})]^{1/2} \mathbf{N} = \mathbf{O} - n\mathbf{I} \quad (6)$$

where \mathbf{I} and \mathbf{O} are the unit vectors of incident and refracted rays, \mathbf{N} is the unit normal vector on the refracted point and n is the refraction index of the lens. Based on this algorithm we can obtain all other points and their normal vectors on the seed curve.

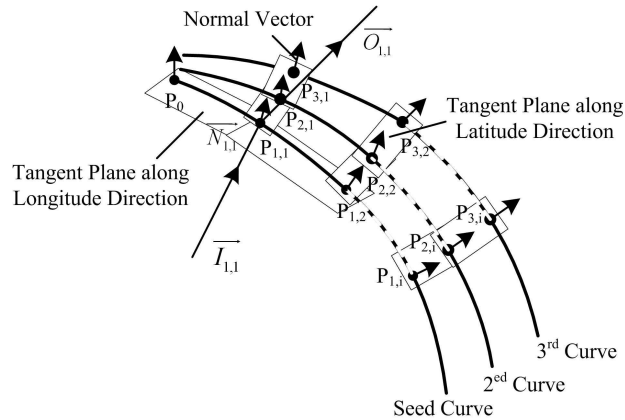


Fig. 4. Schematic of generation of points on the outside surface of freeform lens.

Step 2. Generation of other curves. First of all we calculate the second curve. As shown in Fig. 4, different from the seed curve algorithm, point i on the second longitude curve is calculated by the intersection of incident ray and the tangent plane of point i on the previous curve. Then the following curves, such as 3rd curve, 4th curve, etc., are easy to obtain based on this algorithm.

Step 3. Construction of surface. The lofting method [11] is utilized to construct smooth surface of lens between these curves.

3.3 Validation of lens design

Since it is costly to manufacture a real freeform lens, numerical simulation based on the most widely used Monte Carlo ray tracing method is an efficient way to validate the lens design. Monte Carlo ray tracing method traces the desired number of rays from randomly selected points on the surface of, or within the volume of, the sources and into randomly selected angles in space. The selection of starting points and ray direction is based on probabilistic functions that describe emissive characteristics of light sources. Each ray starts with a specific

amount of power, determined by each source's characteristics; this power is then modified by the various surfaces hit by the ray in its path through the system. These rays are then collected on specified receiver surfaces for statistical analysis and graphical display. An extended source (e. g. 1 mm × 1 mm LED chip) is adopted during simulation. According to simulation results, we optimize the coefficients of C_{wi} and C_{Lj} until lighting performance of lens meets requirements of some specific applications. Then we obtain the final design of the compact freeform lens. The coefficients of C_{wi} and C_{Lj} are usually within range from 0.2 to 2.

4. Design of ASLP for road lighting

Since significance of road lights in LED community, demonstrated by a recent Chinese government program and other programs around the world, an ASLP for road lighting is to be designed as an example in this study. A PC compact freeform lens with refract index of 1.586 will be designed to form a 32 m long and 12 m wide rectangular radiation pattern at height of 8 m (as shown in Fig. 5), which can meet the requirements of road lighting.

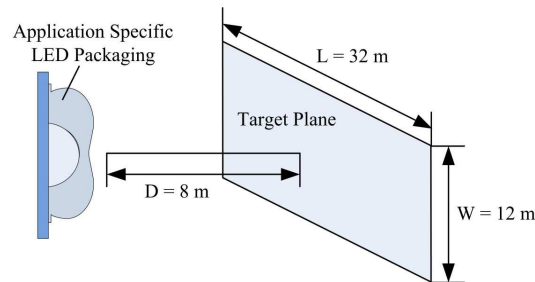


Fig. 5. Schematic of design target of ASLP for road lighting.

4.1 Optical modeling

Light intensity distribution curves (LIDCs) of LED chip and LED chip covered by phosphor layer are two key issues for accurate LED packaging optical modeling. This is because most white LEDs are obtained either by integrating blue LED chips with yellow phosphor or by integrating RGB LED chips in one packaging module. Vertical electrode LED chip with size of 1 mm × 1 mm × 0.1 mm was adopted for the lens design and phosphor layer with thickness of about 70 μm was conformally coated on the chip. Figure 6 depicts that the measured LIDCs of the chip and the chip coated by phosphor are quite similar with the standard Lambert distribution. Therefore Lambert source with emitting area of 1 mm × 1 mm would be used as equivalent source during optical design and simulation.

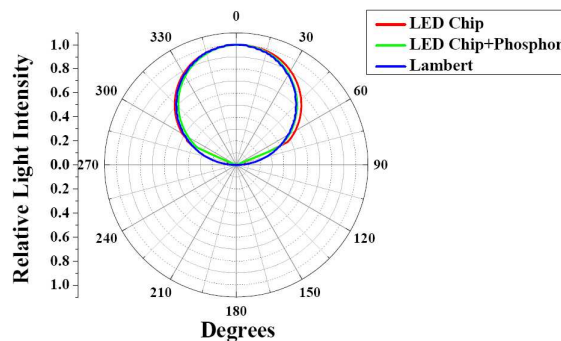


Fig. 6. Light intensity distribution curves of LED chip and LED chip coated by phosphor layer.

4.2 Design of compact freeform lens

As shown in Fig. 7, a PC compact freeform lens was designed according to the method as mentioned above. Firstly, we divided the one quarter source and target plane both into $200 (M) \times 100 (N) = 20000$ grids with equal luminous flux and unequal area respectively and established light energy mapping relationship between these grids. Secondly, we calculated coordinates and normal vector of each point on the freeform surface and constructed the lens utilizing these points. Finally, we validated lighting performance of the lens through simulation and obtained final design after optimizing coefficients of target.

The distance between LED chip and the central point at the outside surface of lens decides the size of the compact freeform lens. To provide enough space for LED packaging process (e. g. wire bonding), the radius of inner concave spherical surface is set as 1.8 mm. Considering the requirements of PC lens manufacturing process, for example the thinnest thickness of PC lens should be larger than 0.3 mm, the limit of the distance is 2.5 mm of the PC compact freeform lens for ASLP based on leadframe and heat sink. We set the distance as 2.5 mm in our design. The volume and largest value of length, width and height of the PC freeform lens (including the base) are 45.5 mm^3 , 6.4 mm, 5.8 mm and 3.8 mm respectively, and the volume is close to that of the most widely used PC domed lens for LED packaging.

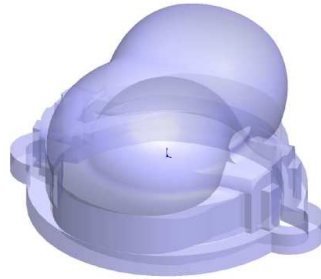


Fig. 7. A PC compact freeform lens for ASLP for road lighting.

4.3 ASLP module

As shown in Fig. 8 (a), a new ASLP design for road lighting was achieved by integrating this PC lens with traditional LED packaging based on leadframe and heat sink. Detail optical structure of the ASLP includes an LED chip, phosphor layer, silicone and the PC freeform lens. As the detail optical structure of traditional LED packaging shown in Fig. 8(b), we can find that during the ASLP packaging process, all changes we need to do is only fixing a PC freeform lens but a PC domed lens on the frame, and that is quite compatible with current LED packaging processes, which makes it easier for LED manufacturers to adopt this new technology with little change of existing process.

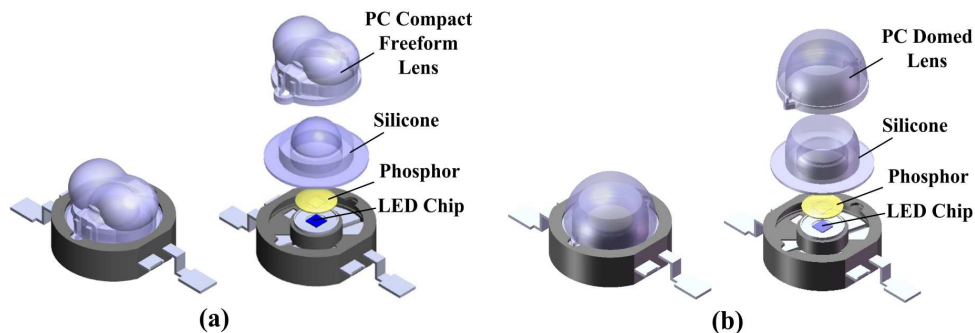


Fig. 8. Comparison of detail optical structures between (a) an ASLP and (b) a traditional LED packaging.

Figure 9 depicts an LED module for road lighting consisting of a traditional LED and a secondary optical element with kind of freeform lens. From comparison shown in Fig. 9, we can find that the height and volume of the ASLP are only about 1/2 and 1/8 of that of the traditional LED module, which provides an effective way for designing size compact LED lighting systems and also provides more design freedom for new concept LED luminaires.

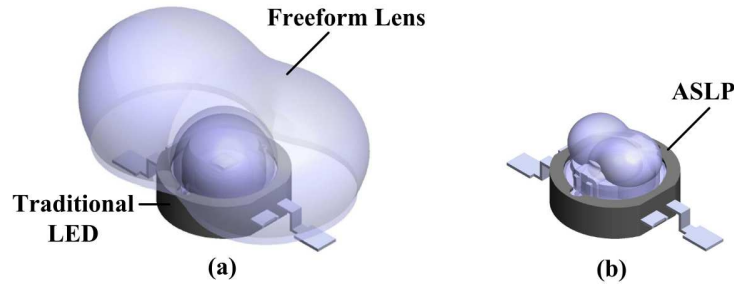


Fig. 9. Comparison of size between (a) a traditional LED module and (b) the ASLP for road lighting.

4.4 Simulation of lighting performance

We simulated the optical performance of the ASLP numerically by the Monte Carlo ray tracing method and then the whole ASLP was simulated by one million rays. As shown in Fig. 10, the ASLP forms a subrectangular radiation pattern with the length of 33.4 m and width of 13.6 m at the height of 8 m, which is in agreement with the expected shape. The utilization ratio of the ASLP reaches as high as 95.1%, which means more than 95% light energy exiting from the ASLP is delivered into the desired lighting area. This utilization ratio is quite close to that of good designed freeform lens and even higher than that of some secondary optics with poor design (~80%).

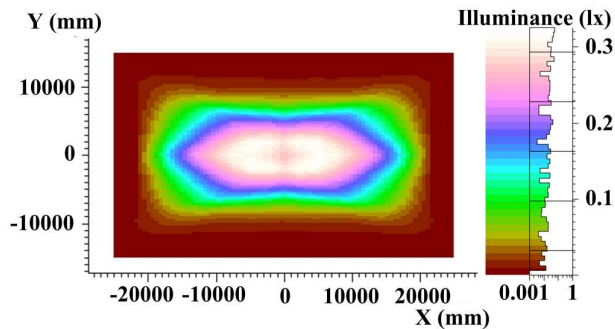


Fig. 10. Simulation lighting performance of the ASLP at height of 8 m.

Since ASLP has good lighting performance and can replace the traditional LED lighting module with secondary optics directly, system optical efficiency which decides the final performance of LED luminaires becomes the most important issue. Light output efficiency (LOE) is defined as the ratio of light energy exiting from lens to light energy incidenting into lens. LOE of the PC compact freeform lens is 94.2%, which is slightly lower than that of traditional PC domed lens of 96.0%. This phenomenon is caused by the reason that incident angles of most incident rays at the outside surface of freeform lens are larger than that of domed lens, and that results in more Fresnel reflection loss occurred in the compact freeform lens. Considering the utilization ratio of 95.1%, the system optical efficiency of the ASLP reaches as high as 89.6%. The LOE of traditional freeform lens is always at a low level of about 90% because of Fresnel reflection loss from two surfaces of lens and absorption of material. As shown in Table 1, considering the light loss (~10%) of secondary optics as well

as the utilization ratio (assuming the same with ASLP), the system optical efficiency of LED module for road lighting is only about 82.2%, which is 7.4% lower than that of ASLP. Therefore the ASLP has good lighting performance and higher system optical efficiency and could be directly used for road lighting and no secondary optics are needed, which makes it convenient for old and new LED luminaires designers and manufacturers to use and also will further reduce the cost of LED luminaires.

Table 1. Simulation comparison of system optical efficiencies between traditional LED module and ASLP for road lighting

	LED Module Integrated with Secondary Optics	ASLP
Light Output Efficiency of LED Packaging Lens (η_{LOE})	96.0% (Domed Lens)	94.2% (Freeform Lens)
Light Output Efficiency of Secondary Optics (η_{SO})	90.0%	—
Utilization Ratio (η_{UR})	95.1%	95.1%
System Optical Efficiency ($\eta_{SOE} = \eta_{LOE} \times \eta_{SO} \times \eta_{UR}$)	82.2%	89.6%
Enhancement	—	7.4%

4.5 Tolerance analyses

The tolerance is an important issue for freeform lenses. Since the same scale installation or manufacturing error (for example 0.1 mm) has more effect on lighting performance of small size freeform lens, tolerance is especially important for the compact freeform lens for ASLP. In this study the tolerance analyses will be focused on installation errors, including deviations in horizontal (d_H) and vertical up (d_V) directions and rotational deviation (θ_R) of the lens (as shown in Fig. 11). To evaluate deterioration of lighting performance, coefficient of effective lighting area (η_{ELA}) is adopted in this study. Effective lighting area (A_{EL}) is defined as the area on the target plane containing more than 95% light energy exiting from lens. We use A_{ELE} and A_{ELO} to express effective lighting area of ASLP with and without errors respectively. Then η_{ELA} can be obtained as Eq. (7):

$$\eta_{ELA} = \frac{A_{ELE}}{A_{ELO}} \quad (7)$$

We define the value of η_{ELA} as 1 when there are no errors. The worse the lighting performance is the smaller the η_{ELA} will be. Thus η_{ELA} is able to reflect effects of various errors on lighting performance of the ASLP.

The effects of installation errors on lighting performance of the ASLP are shown in Fig. 11. Horizontal deviation d_H and vertical deviation d_V of the lens have significant effects on the shape as well as the uniformity of radiation pattern. When d_H increasing from 0.1 mm to 0.5 mm, the radiation pattern becomes asymmetric and the right pattern is much brighter than the left one, which results in decline of η_{ELA} from 0.87 to 0.46. Moreover, when d_V increases, size of radiation pattern becomes small and light energy concentrates on left and right ends of the pattern, causing low uniformity. η_{ELA} also sharply declines from 0.91 to 0.50 when d_V increases from 0.1 mm to 0.5 mm. However, we can find that rotational deviation θ_R has less effect on the shape and uniformity of radiation pattern comparing with d_H and d_V . η_{ELA} only declines from 0.97 to 0.78 when θ_R increases from 1° to 5° . Therefore, it seems that lighting performance is more sensitive to the installation errors in the horizontal and vertical directions.

The deteriorated radiation pattern, whose η_{ELA} is larger than 0.85, is still acceptable in engineering. Therefore, the limits on the tolerance of horizontal, vertical and rotational deviation of the freeform lens are 0.11 mm, 0.14 mm and 2.4° respectively, which are acceptable for mass production. Since the two glue-injection holes at the base of the PC

compact freeform lens confine deviation of lens in horizontal direction, we should pay more attention to minimizing or even avoiding vertical and rotational deviations during LED packaging process.

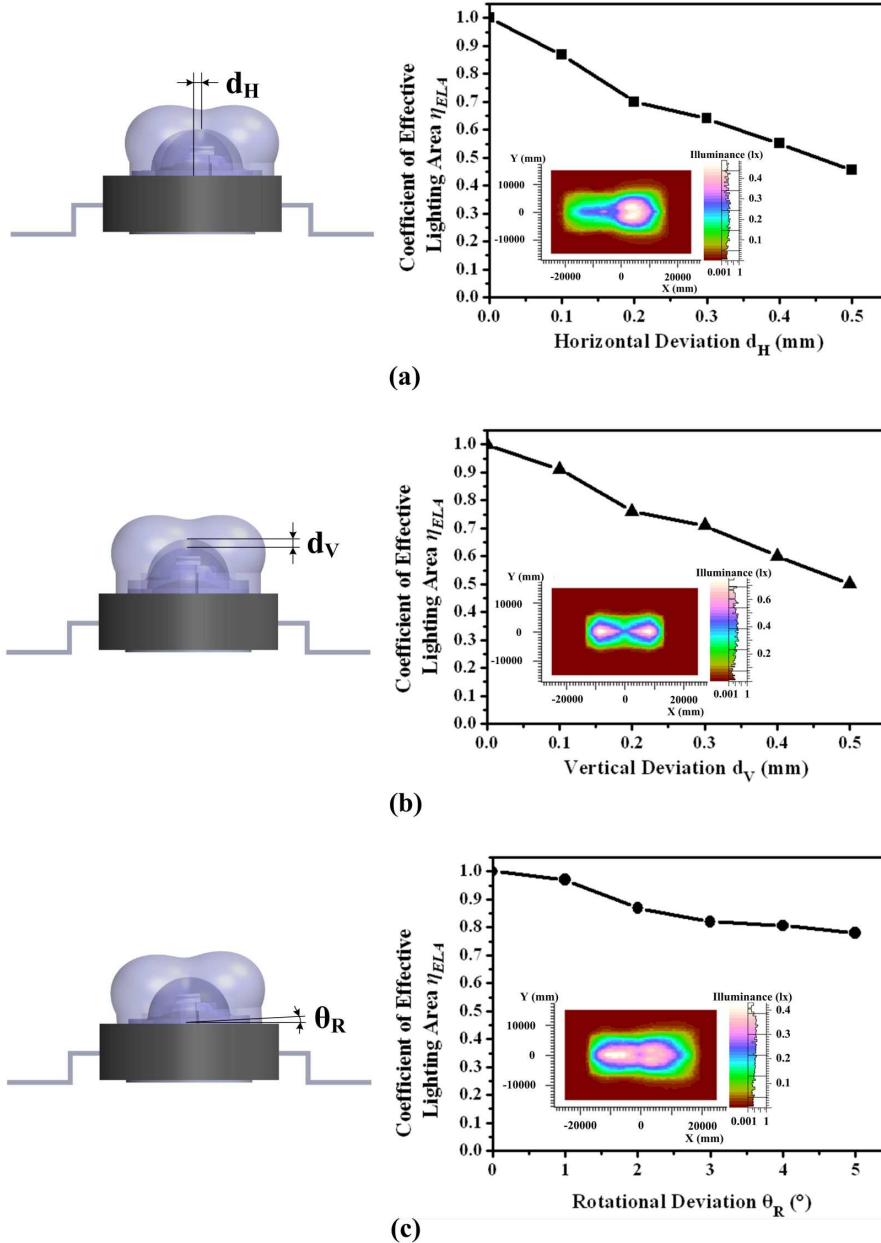


Fig. 11. Effects of installation errors on lighting performance of the ASLP: (a) horizontal deviation d_H ; (b) vertical deviation d_V and (c) rotational deviation θ_R .

5. Experimental results

As shown in Fig. 12 to Fig. 13, the PC compact freeform lens was manufactured by injection molding method and a white light ASLP for road lighting was also manufactured by integrating the lens with traditional LED packaging. From comparison shown in Fig. 14, we

can find that the size of ASLP is quite close to that of traditional LED but is much smaller than that of LED module for road lighting. Thus the ASLP will reduce the size of LED luminaires and make it easier for customers to assembly.

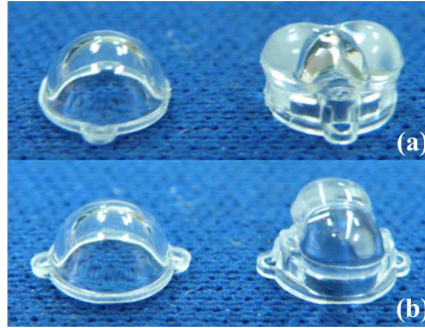


Fig. 12. (a) Front view of and (b) left view of a PC domed lens (left) and a PC compact freeform lens (right).

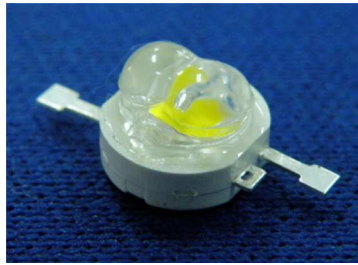


Fig. 13. White light ASLP for road lighting.

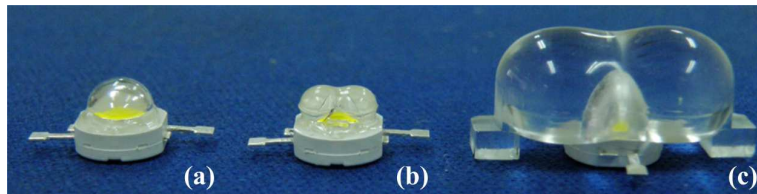


Fig. 14. (a) Traditional LED packaging, (b) ASLP and (c) LED module for road lighting.

Figure 15(a) and Fig. 15(b) show the lighting performance of a traditional LED and the ASLP respectively. The radiation pattern of the traditional LED is circular with non-uniform illuminance distribution, while the ASLP redistributes LED's light energy distribution and forms a subrectangular radiation pattern on the target plane, which is more uniform than the circular radiation pattern. The target plane is 58.5 cm away from LED. Experimental results demonstrate that 92.8% light energy of ASLP is distributed in a subrectangular area with length of 240 cm and width of 90 cm, and it will be enlarged to 32.8 m long and 12.3 m wide at the height of 8 m, which is very close to the simulation results and is also in agreement with the expected performance.

Illuminance distribution of radiation pattern of the ASLP is shown in Fig. 16. We can find that illuminance distribution in the central area is more uniform than the edge area of radiation pattern. Most light energy is uniformly distributed within the central area about 160 cm long and 60 cm wide and illuminance declines sharply out of this area. Although illuminance distribution is not uniform enough within the whole subrectangular radiation pattern, it is already acceptable for road lighting in engineering.

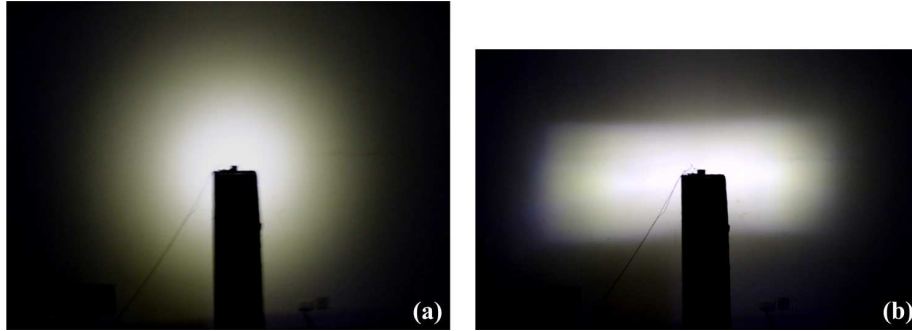


Fig. 15. Lighting performance of (a) a traditional LED packaging and (b) the ASLP.

Unit: lx

Y \ X	120 cm	100 cm	80 cm	60 cm	40 cm	20 cm	0	20 cm	40 cm	60 cm	80 cm	100 cm	120 cm
50 cm	5.4	7.0	8.3	9.7	11.1	11.6	11.9	11.7	11.2	9.8	8.2	6.8	5.2
40 cm	6.2	12.7	16.6	16.8	17.9	18.3	17.8	18.4	17.8	16.4	16.1	12.5	6.0
30 cm	6.9	15.4	21.3	30.4	34.5	33.6	31.4	33.2	34.0	30.7	21.1	15.6	7.0
20 cm	7.3	16.5	27.8	40.9	47.5	48.9	44.2	48.6	47.3	41.2	27.5	16.9	7.4
10 cm	7.8	18.8	35.1	53.0	60.7	61.6	59.5	61.1	60.2	52.8	34.8	18.6	7.7
0	8.5	20.9	41.8	64.1	68.7	67.3	62.1	67.5	69.1	63.9	41.2	20.1	8.1
10 cm	7.8	18.3	34.9	53.3	61.5	62.0	58.7	62.3	61.3	53.1	35.2	17.9	7.8
20 cm	7.6	17.2	28.3	41.3	47.8	49.4	44.7	49.1	46.9	41.8	28.1	16.7	7.5
30 cm	7.3	15.9	21.4	31.1	34.2	33.8	30.8	34.0	34.3	30.1	20.8	15.1	7.1
40 cm	6.5	13.0	16.3	17.0	17.6	18.4	17.2	18.9	18.0	17.1	16.5	13.1	6.8
50 cm	5.7	7.3	8.4	10.1	10.9	11.4	11.5	11.3	11.1	10.0	8.6	7.1	5.8

Fig. 16. Illuminance distribution of radiation pattern of the ASLP.

System lumen efficiencies of the traditional LED module and ASLP were also investigated as a key issue. The experimental utilization ratio of ASLP is slightly lower than the simulation result. As shown in Table 2, although the lumen efficiency and utilization ratio of traditional LED are slightly higher than that of ASLP, without light loss caused by secondary optics, system lumen efficiency of the ASLP reaches as high as 94.7 lm/W, which is 8.1% higher than that of the LED module integrated with secondary optics. Therefore, ASLP provides a solution to LED lighting system with higher system lumen efficiency.

Table 2. Experimental comparison of system lumen efficiencies between the traditional LED module and the ASLP for road lighting

	LED Module Integrated with Secondary Optics	ASLP
Average Lumen efficiency of LED (η_{LE})	103 lm/W	102 lm/W
Light Output Efficiency of Secondary Optics (η_{SO})	90.0%	—
Utilization Ratio (η_{UR})	94.5%	92.8%
System Lumen efficiency of LED Module ($\eta_{SLE} = \eta_{LE} \times \eta_{SO} \times \eta_{UR}$)	87.6 lm/W	94.7 lm/W
Enhancement	—	8.1%

6. Conclusions

In this study, a practical design method of compact freeform lens for extended sources was introduced in detail and a PC compact freeform lens for road lighting was designed according to this method. Integrated with the lens, a new application specific LED packaging (ASLP) module for road lighting was presented. Packaging process of the ASLP was quite compatible

with current LED's. Simulation and experimental results demonstrated that, compared with traditional LED integrated with secondary optics, ASLP had advantages of much smaller size in volume ($\sim 1/8$), higher system lumen efficiency ($\sim 8.1\%$), lower cost and more convenience for customers to design and assembly. Tolerance analyses were also conducted. Horizontal deviation and vertical deviation had more effects on the shape and uniformity of radiation pattern comparing with rotational deviation. The tolerance of horizontal, vertical and rotational deviations of the compact freeform lens were 0.11 mm, 0.14 mm and 2.4° respectively, which were acceptable for mass production in engineering. Therefore ASLP will provide an effective way to high performance LED lighting and probably become the trend of LED packaging. However, the uniformity of illuminance of radiation pattern should be improved further more by optimizing the inner surface of the compact lens simultaneously in the future work to promote the ASLP technology to serve for more LED specific applications, such as backlighting, projector, etc..

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