Effect of manufacturing defects on optical performance of discontinuous freeform lenses

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Abstract: Discontinuous freeform lens based secondary optics are essential to LED illumination systems. Surface roughness and smooth transition between two discrete sub-surfaces are two of the most common manufacturing defects existing in discontinuous freeform lenses. The effects of these two manufacturing defects on the optical performance of two discontinuous freeform lenses were investigated by comparing the experimental results with the numerical simulation results based on Monte Carlo ray trace method. The results demonstrated that manufacturing defects induced surface roughness had small effect on the light output efficiency and the shape of light pattern of the PMMA lens but significantly affected the uniformity of light pattern, which declined from 0.644 to 0.313. The smooth transition surfaces with deviation angle more than 60 degrees existing in the BK7 glass lens, not only reduced the uniformity of light pattern, but also reduced the light output efficiency from 96.9% to 91.0% and heavily deformed the shape of the light pattern. Comparing with the surface roughness, the smooth transition surface had a much more adverse effect on the optical performance of discontinuous freeform lenses. Three methods were suggested to improve the illumination performance according to the analysis and discussion.

OCIS codes: (080.4298) Nonimaging optics; (220.3630) Lenses; (220.4610) Optical fabrication; (230.3670) Light-emitting diodes.

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1. Introduction

Light emitting diodes (LEDs) are regarded as one of the most important light sources in solid-state lighting for their advantages in low power consumption, high reliability, long life, variable color and environmental protection. Therefore LED has begun to play an important role in many applications, such as backlighting for liquid crystal display, street and tunnel lighting, automotive lighting and interior illumination [1,2]. However, in most illumination applications, secondary optics is essential to LED illumination systems since the light pattern of LED can not directly meet the requirements of different illumination applications. Freeform lens has becoming a trend of LED secondary optics design for its advantages in high design freedom, small size and precise light irradiation control [3]. To deal with freeform lens design, many different methods had been proposed, such as simultaneous multiple-surface lens design method [4], tailored freeform lens surface design method [5], discontinuous freeform lens design method [6,7], etc.. Although all of these methods had been proven feasible in theory and some of them had been validated by ray trace simulation method, most of them ignored manufacturing feasibility in practical use, especially for the effect of manufacturing defects on the optical performance of the designed freeform lens, which is one of the most important issues in illumination applications.

Among the design methods mentioned above, discontinuous freeform lens design method is an emerging method due to its advantages in easy surface construction in computer, accurate light irradiation control and good simulation illumination performance [6,7]. Since the surface of this kind of freeform lens is constructed by a series of discrete sub-surfaces, micro-sized level ultra precision multi-axes diamond machining systems are needed for the lens or the lens mold fabrication. However, during mass production (i.e., injection molding), many manufacturing factors, such as surface morphology of mold, injection molding temperature and pressure, viscosity of liquid, etc., will affect the surface morphology of the discontinuous freeform lens and thereby affect the optical performance of the lens. Surface roughness and smooth transition between discrete sub-surfaces are two of the most common manufacturing defects existing in discontinuous freeform lenses. This paper focuses on the effect of these two manufacturing defects on the light output efficiency, shape and uniformity of light pattern of the kind of discontinuous freeform lens. The objectives of this research are to find out the effect of manufacturing defects on the optical performance and to come up with possible improvements.

2. Design method and optical modeling

To improve the illumination performance of LED lighting systems, a modified discontinuous freeform lens design method is suggested. The method is briefly described as follows [8]: Firstly, according to energy conservation [9], as shown in Fig. 1(a), we divide space distribution of light energy of LED source and illumination target into several cells with equal luminous flux ($d\Omega$) and area (dS) respectively. Then we establish the energy mapping relationship between these cells. Secondly, we calculate the coordinate and normal vector of each point on the freeform surface according to the energy mapping relationship, Edge Ray principle and Snell law. Thirdly, we construct freeform optics using the points obtained in the second step [4,6]. Finally, we validate freeform lens design by Monte Carlo ray trace simulation. Based on this method, random shape uniform beam pattern, such as circularity, rectangle, etc., could be designed, especially for the small size light source design cases.

To meet the requirements of street illumination, according to the design method, two discontinuous freeform lenses were designed to form a 30 meters long and 10 meters wide uniform rectangle illumination area at the height of 8 meters, which is acceptable for LED street lighting. The materials of these two lenses are polymethyl methacrylate (PMMA) and

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BK7 (named K9 in China) optical glass, and with refract index of 1.49 and 1.59 respectively. The numerical models for LED module with these discontinuous freeform lenses are shown in Fig. 2.(a) and Fig. 3.(a).

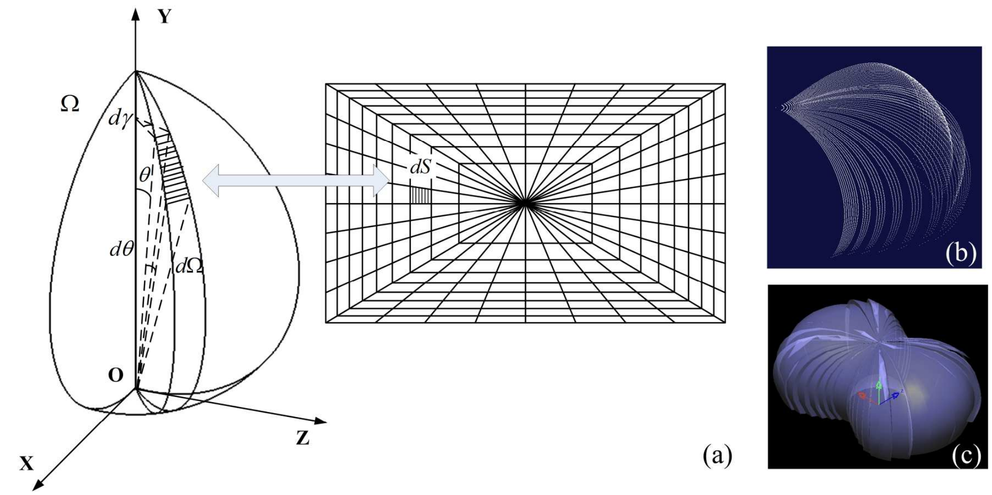

Fig. 1. Schematic of a modified discontinuous freeform lens design method: (a) establish energy mapping between light source and target; (b) calculate point cloud of the lens surface; and (c) construct the lens surface.

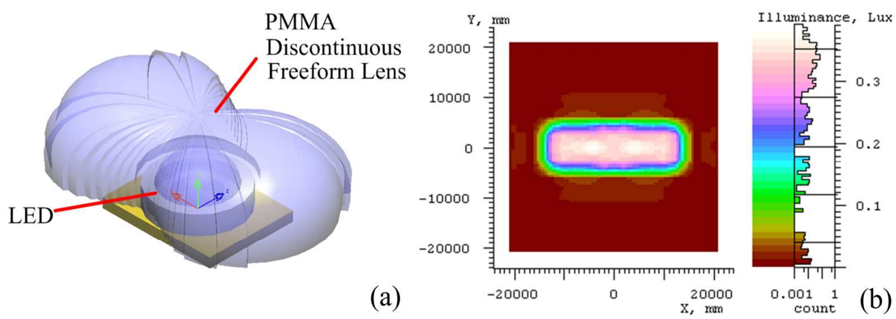

Fig. 2. (a) A numerical model for LED module with PMMA discontinuous freeform lens and (b) its illumination performance in simulation.

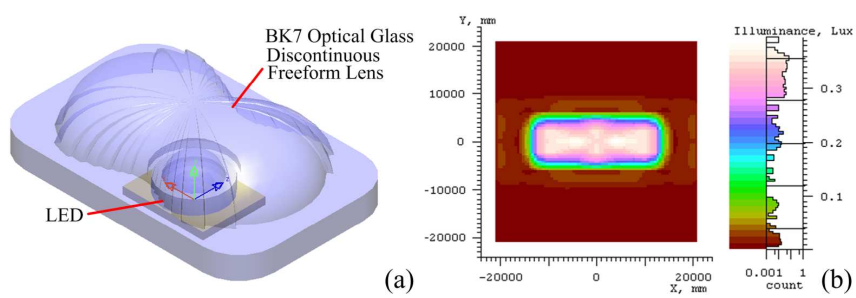

Fig. 3. (a) A numerical model for LED module with BK7 optical glass discontinuous freeform lens and (b) its illumination performance in simulation.

We simulated the freeform lens numerically by the widely used Monte Carlo ray tracing method. Firstly, a precise CREE XLamp LED optical model was built by comparing the similarity between the simulation light intensity distribution curve and the experimental measurement, which is quantified by the normalized cross correlation (NCC) [10]. As to the

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modeling algorithm for a LED model mentioned in reference [11], we adjusted the scattering characteristic and index of some packaging materials used in LED, such as phosphor, polymer, silicone, etc., until the NCC reached as high as 99.0%. Thus, the precise optical modeling for LED was finished. Then two whole LED modules with different freeform lenses were simulated by one million rays. Figure 2 (b) and Fig. 3 (b) show simulation illuminance distributions on two test areas with the same size of 42 meters long and 42 meters wide that are 8 meters away from LED modules. In both simulation results, we can find that more than 95% light energy is uniformly distributed in the central area of about 28 meters long and 10 meters wide, which is consistent with the design target. During the central area, the minimal and average illuminances in simulation are 0.172 lx and 0.267 lx respectively for the PMMA lens, and 0.180 lx and 0.274 lx respectively for the BK7 glass lens. Consequently, the uniformity of the light patterns with PMMA lens and BK7 glass lens are 0.644 and 0.657 respectively. The light output efficiency of the PMMA lens is 93.2%, and the efficiency of the BK7 glass lens reaches as high as 96.9%. Most of the lost lights have a total internal reflection at the interface of lens and air and are absorbed by LED. The other lost lights are mainly due to lens material absorption and Fresnel loss on the surface of lens.

3. Experiments

3.1 Surface morphology

As shown in Fig. 4, these two discontinuous freeform lenses were also manufactured by injection molding method. We observed the shape and surface morphology of these two discontinuous freeform lenses by microscopy. To control the irradiation directions of lights accurately, a sharp transition surface between two discrete sub-surfaces was designed. The transition surface is nearly perpendicular to the two adjacent sub-surfaces and the deviation angle is less than 5 degrees. By comparing Fig. 5 (a) with Fig. 5 (b), we can find that the shape of the manufactured PMMA lens is quite in agreement with the designed lens. The transition surface of the lens is sharp and the boundaries between two discrete sub-surfaces are clear. However, as shown in Fig. 6, when we increase the magnification of microscopy, we can clearly find that there are a lot of micron-sized particles distributed on the surface of lens, especially on the transition surfaces, where are supposed to be smooth. Further more, some parts of this discontinuous freeform lens are totally composed of numbers of discontinuous particles with the size of tens of micrometers and the surface morphology of these parts is quite different from the expected one, which will result in severe scattering. These particles were produced during manufacturing processes and were mainly caused by the unpolished surface of mould. Moreover, unsuitable injection molding temperature, pressure, and viscosity of liquid also could result in these particles.

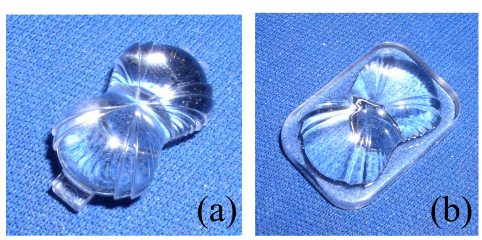

Fig. 4. (a) The PMMA discontinuous freeform lens and (b) the BK7 optical glass discontinuous freeform lens.

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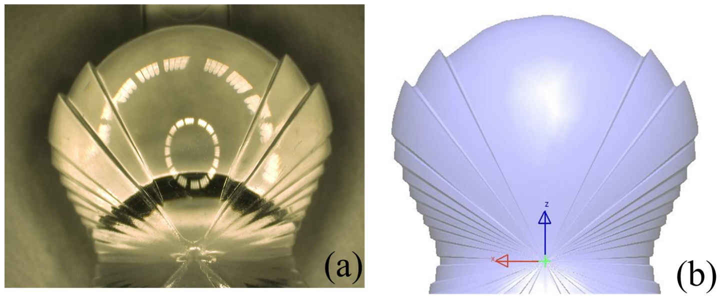

Fig. 5. (a) Microphotograph of the PMMA lens and (b) numerical optical model of the PMMA lens.

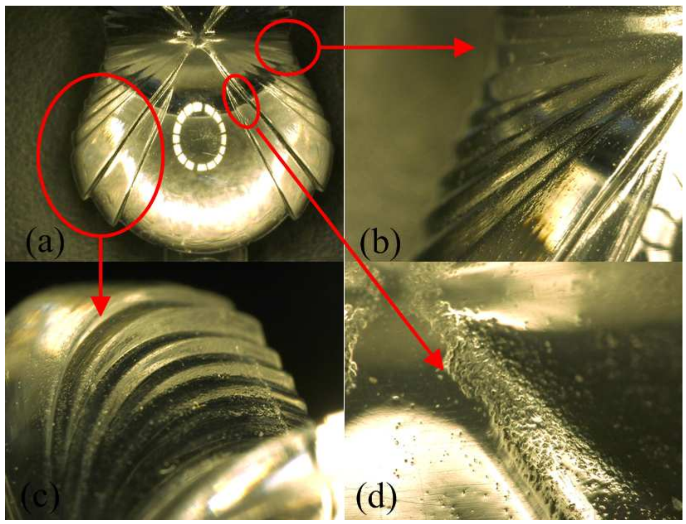

Fig. 6. Micrographs of different part of the PMMA discontinuous freeform lens.

Figure 7 shows the comparison of manufactured BK7 glass lens with its numerical optical model, from which we can find that although the shape of the manufactured BK7 glass lens is approximately similar with the designed one, significant differences existing at the positions of transition surfaces and upper side of some discrete sub-surfaces. The transition surfaces of the BK7 glass lens were also designed sharp, however, as shown in Fig. 7 (a), they become quite smooth in the manufactured lens and the boundaries between two discrete sub-surfaces also are blurry, especially at the middle part of the lens. Moreover, since some discrete sub-surfaces are narrow, the deformation of their edges caused by the smooth transition will significantly affect the whole shape of these sub-surfaces, which will result in the irradiation directions of lights have a large deviation from the expect directions. The smooth transition surfaces were mainly caused by the low processing precision of the mould. The same reasons as mentioned in PMMA manufacturing, such as unsuitable injection molding temperature, pressure, viscosity, etc., could also result in these manufacturing defects. From Fig. 7 (a) and Fig. 7 (c), we can find that there are only a little tiny particles distributed on the surface of the BK7 glass lens and the surface is much smoother than the PMMA lens.

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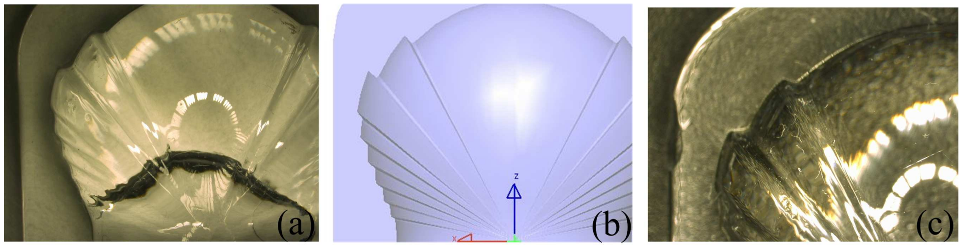

Fig. 7. (a) Microphotograph of the BK7 glass lens, (b) numerical optical model of the BK7 glass lens, and (c) partially enlarged view of the BK7 glass lens.

3.2 Optical performance testing

To test the optical performance of these two discontinuous lenses, LED freeform lens test modules were built. As shown in Fig. 8, these are two freeform lens test modules and each of them is mainly composed of four parts: a 1W high power CREE XLamp LED, a discontinuous freeform lens, a lamp frame with heat sink and fins, and a driving circuit for the power input of the LED.

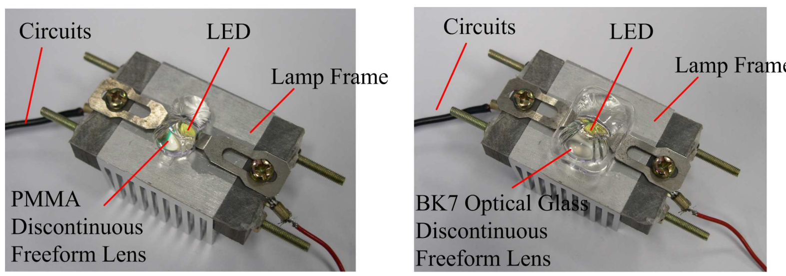

Fig. 8. The LED discontinuous freeform lenses test modules.

The total luminous flux of LED module with and without freeform lens were measured by UV-VIS-near IR spectrum photo colorimeter measurement and integrating sphere. The light output efficiency of the PMMA lens reaches as high as 90.5%, which is quite close to the simulation results. Figure 9 depicts the light pattern at 70 centimeters away from LED. We can find that most of the light energy is distributed in a nearly rectangle area with the length of 240 centimeters and width of 83 centimeters, and it will enlarge to 27.5 meters long and 9.5 meters wide at the height of 8 meters according to light rectilinear propagation principle, which is also quite in agreement with the expected shape. However, obvious dark stripes exist on the light pattern, especially in the middle-upper part of the pattern, which will decrease the uniformity of the pattern and the performance of illumination. We arranged 30 test points equally spaced on the light pattern and measured the illuminance of each point by illuminance meter. The minimal illuminance, appearing at the dark stripe, is 10.7 lx and the calculated average illuminance is 34.2 lx, so the uniformity is only about 0.313, which is much lower than the simulated uniformity. Moreover, we also can find that the relative positions of these dark stripes on the light pattern are the same as the relative positions of transition surfaces on the lens surface.

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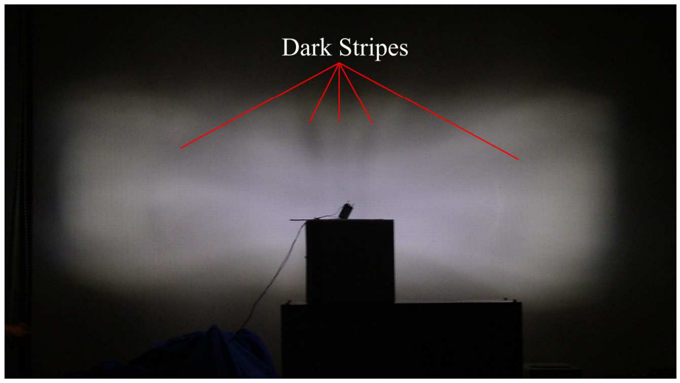

Fig. 9. Light pattern of the PMMA lens at 70 centimeters away from LED.

The optical performance of the BK7 glass lens was also tested. The light output efficiency of the lens is 91.0%. Although this efficiency is slightly higher than that of the PMMA lens as the BK7 optical glass has a higher transmittance than PMMA, it is much lower than the simulation results. Comparing with the experimental and simulation results, the efficiency decline of the BK7 glass lens is up to 5.9%, which is higher than that of the PMMA lens (2.7%). Light pattern at 70 centimeters away from LED is shown in Fig. 10. We can find that the illumination performance of the BK7 glass lens is quite poor, not only the light energy distribution on the target plane is non-uniform, but also the shape of the light pattern is not rectangle. Obvious dark and bright stripes exist on the light pattern, especially at the positions of central part and the directions of diagonal. The BK7 glass lens could not control the lights effectively and some lights irradiate out of the designed rectangle area, which results in fan shaped light energy distribution at left and right ends of the light pattern. Since the shape of the light pattern is quite different from rectangle, it is meaningless to calculate the average illuminance and uniformity.

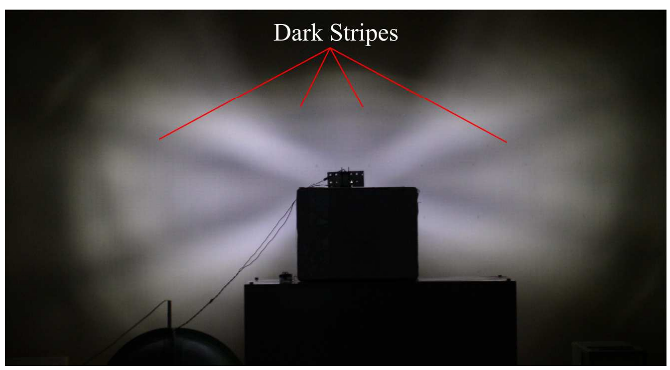

Fig. 10. Light pattern of the BK7 optical glass lens at 70 centimeters away from LED.

From comparisons between the simulation results and the experimental results as shown in Table 1, we can find that the experimental light output efficiency and shape of light pattern of the PMMA lens are quite close to the simulation ones, but dark stripes exist, which mainly result in low uniformity of the experimental light pattern. However, the BK7 glass lens has poor illumination performance and the experimental results are quite different from the designed goals.

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Table 1. Comparisons between simulation results and experimental results.

		Light Output Efficiency of the Freeform Lens	Shape of Light Pattern (8m High)	Dark Stripes	Uniformity
PMMA Lens	Simulation	93.2%	28m ×10m	No	0.644
	Experiment	90.5%	27.5m ×9.5m	Yes	0.313
BK7 Glass Lens	Simulation	96.9%	28m ×10m	No	0.657
	Experiment	91.0%	Non-rectangle	Yes	-

4. Analysis and discussion

Surface roughness and smooth transition surfaces are two major kinds of manufacturing defects exist in the PMMA lens and the BK7 glass lens respectively. Roughness surface of lens could increase the chance of light scattering at the interface of lens and air. By comparing Fig. 11 (a) with Fig. 11 (b), we can find that roughness optical surface scatters lights randomly and the directions of exit lights are quite different from the designed ones. The scattered lights generated at the roughness transition surface will deviate from the expected irradiation directions and probably will overlap with other lights, which will result in dark stripes appearing in the direction of transition surfaces on the light pattern. The dark stripes not only affect the visual effect, but also decrease the illuminance of this illumination area, which will result in low uniformity. Moreover, although lights are scattered by roughness surfaces, most of them just change the irradiation direction and still can exit from the lens surface, this is the reason why defects induced surface roughness has small effect on the light output efficiency of lens. Fortunately, the area of transition surfaces accounts for only less than 10% of the whole lens surface area, therefore the dark stripes also have small effect on the shape of light pattern.

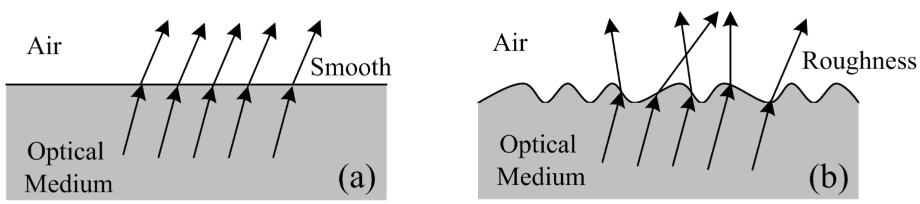

Fig. 11. (a) Schematic of lights propagation at smooth and (b) roughness optical surface.

Smooth transition surfaces will change the exit directions of lights when lights irradiate on these surfaces. As shown in Fig. 12, the deviation angle θ of the transition surface increases from about 5 degrees to more than 60 degrees when the transition surface becoming smooth. By comparing Fig. 12 (a) with Fig. 12 (b), we can find that most lights, which are supposed to exit from the lens at the sharp transition surface, will have a total internal reflection (TIR) at the smooth transition surface as the large deviation angle. As shown in Fig. 12 (b), the TIR will significantly change the propagation directions of lights in the lens and the exit directions of lights at the lens's surface. Since the area of the smooth transition surfaces account for a high ratio (more than 30%) of the whole BK7 glass lens surface area as shown in Fig. 7, more than 30% lights exit deviating seriously from the designed directions, which will induce the generation of dark and bright strips, change the shape of light pattern and significantly affect the illumination performance. Furthermore, the shape deformation of some narrow sub-surfaces caused by smooth transition surfaces will also change the directions of lights and results in poor illumination performance. Moreover, the TIR increases the propagation length of lights, which will increase the lights absorption by glass and decrease the light output efficiency. Even worse, as the reason of TIR, a small part of lights irradiate to

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the bottom of the lens, thus this part of light energy is totally lost. These are reasons why the efficiency decline of the BK7 glass lens is higher than that of the PMMA lens.

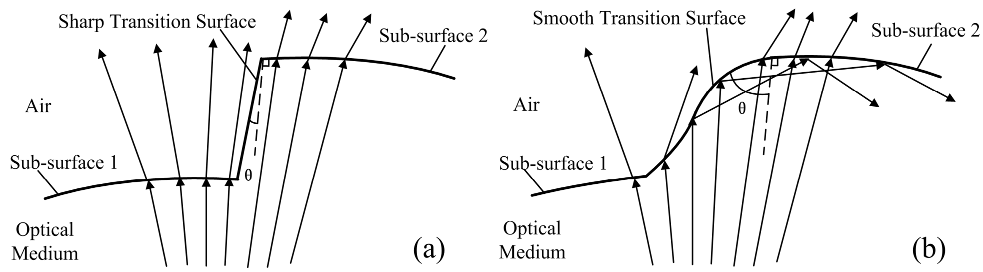

Fig. 12. (a) Schematic of lights propagation at the sharp transition surface and (b) the smooth transition surface.

To improve the optical performance of the freeform lens, several suggestions are provided as follows: (1) Improving surface construction algorithm in the discontinuous surface freeform lens design method and to ensure that the lens's surface is continuous and smooth, and this is the radical way to reduce the defects generated during manufacturing; (2) Improving and optimizing the manufacturing process control, such as pressure, temperature, viscosity of polymer, etc., and enhancing the precision of manufacturing; and (3) Utilizing discontinuous surface freeform lens array during designing LED illumination systems. As the illumination area is overlapped by multi-light patterns irradiating from different positions and directions of the illumination system, dark stripes existing on one light pattern might be overlapped by bright illumination areas of other light patterns and we cannot distinguish them anymore.

5. Conclusions

Surface roughness and smooth transition between two discrete sub-surfaces are two of the most common manufacturing defects existing in discontinuous freeform lenses. In this study, the effects of these two manufacturing defects on the optical performance of two discontinuous freeform lenses were investigated. These two lenses were manufactured by materials PMMA and BK7 optical glass respectively. Optical analyses of these two discontinuous freeform lenses by using modeling and experiment were conducted. The results demonstrated that manufacturing defects induced surface roughness had small effect on the light output efficiency and the shape of light pattern of the PMMA lens but significantly affected the uniformity of light pattern, which declined from 0.644 to 0.313. We also found that, the manufacturing defects induced smooth transition surfaces with deviation angle more than 60 degrees existing in the BK7 glass lens, not only reduced the uniformity of light pattern, but also reduced the light output efficiency from 96.9% to 91.0% and heavily deformed the shape of the light pattern. Comparing with the surface roughness, smooth transition surface has a much more adverse effect on the optical performance of discontinuous freeform lenses. Three methods were suggested to improve the illumination performance of discontinuous freeform lenses in the future work.

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