Optical Engineering 48(12), 123002 (December 2009)

Free-form lenses for high illumination quality light-emitting diode MR16 lamps

Fei Chen
National Laboratory for Optoelectronics
Division of MOEMS
and
Huazhong University of Science and Technology
School of Optoelectronics Science and Engineering
Wuhan, 430074 China

Sheng Liu
National Laboratory for Optoelectronics
Division of MOEMS
and
Huazhong University of Science and Technology
Institute for Microsystems
School of Mechanical Engineering
and
School of Optoelectronics Science and Engineering
Wuhan, 430074 China
E-mail: victor_liu63@126.com

Kai Wang, MEMBER SPIE
National Laboratory for Optoelectronics
Division of MOEMS
and
Huazhong University of Science and Technology
School of Optoelectronics Science and Engineering
Wuhan, 430074 China

Zongyuan Liu
National Laboratory for Optoelectronics
Division of MOEMS
and
Huazhong University of Science and Technology
Institute for Microsystems
School of Mechanical Engineering
Wuhan, 430074 China

Xiaobing Luo
National Laboratory for Optoelectronics
Division of MOEMS
and
Huazhong University of Science and Technology
School of Energy and Power Engineering
Wuhan, 430074 China

Abstract. Light-emitting diode (LED) MR16 lamps, regarded as one typical general lighting product of LEDs, are being widely used in many applications. Light efficiency into a main beam and uniformity are two key issues for high quality illumination of LED MR16 lamps. In this study, a practical and precise nonimaging optical design method is presented, and two novel 90- and 120-deg free-form lenses for high illumination quality LED MR16 lamps are designed according to this method. Based on the Monte-Carlo ray-tracing method, numerical simulation results demonstrate that the light output efficiencies of these novel lenses reach as high as 98% and are 17% higher than that of traditional total internal reflection (TIR) MR16 lens. Moreover, more than 89% of light exiting from the surfaces of these novel lenses irradiate within the desired receive target, while only 60% irradiate for traditional TIR lens. The uniformities of illuminance distribution across the target of these novel MR16 lamps also are much higher. In addition, these novel lenses are both quite compact and no more than 1/5 of that of the TIR lens. Therefore, these LED MR16 lamps integrated by novel lenses provide an effective solution to high quality illumination. *© 2009 Society of Photo-Optical Instrumentation Engineers.* [DOI: 10.1117/1.3274677]

Subject terms: free-form lens; light-emitting diode; MR16.

Paper 090261RR received Apr. 13, 2009; revised manuscript received Sep. 22, 2009; accepted for publication Oct. 20, 2009; published online Dec. 21, 2009.

1 Introduction

Theoretically, light-emitting diodes (LEDs) have many advantages, such as good reliability, long life, variable color, and low power consumption.[1] Since the LED's lumen efficiency has increased rapidly in recent years, the LED has begun to play an important role in many applications, such as backlighting for cell phones and other LCD displays, street lighting, and interior and exterior automotive lighting.[2,3] One typical general lighting product of LEDs is the LED MR16 lamp. MR16 lamps are typically used as outdoor spotlights or accent lighting for part of a room, in restaurants, museums, or retail displays. The light distribution of LEDs is always similar to Lambert, which is not suitable for MR16 lamp illumination, therefore secondary optics design is essential. Two issues of LED MR16 lamps, the color-rendering index (CRI) and color temperature

---

0091-3286/2009/$25.00 © 2009 SPIE

(CT), have been investigated to improve illumination quality.[4] Moreover, light efficiency into main beams and uniformity are another two issues for high quality illumination of LED MR16 lamps. A uniform and circular light pattern can enhance the light efficiency into main beams and uniformity. At present, due to the poor design of the lens, which cannot control irradiation directions of lights effectively, the light efficiencies into the main beams and uniformities of many products existing in the market are quite low,[5] which results in poor illumination performance and difficulties in meeting the requirements of high quality illumination. Most lights irradiating from the LED, especially lights generating at the center of LED die, should be accurately designed to irradiate at the desired points on the target plane to obtain a uniform and circular light pattern. Until now, there are multimethods to gain a uniform and circular light pattern, such as a total internal reflection (TIR) lens, free-form lens, and LED array. However, with the method of the TIR lens, it is difficult to generate a uniform light pattern and the divergence angle is always small. And with the method of the LED array, several LEDs should be arranged in a special form, which is not suitable to the MR16 lamp. Concerning the free-form lens method, lots of work has been done, and there are multieffective algorithms to design free-form lenses, such as the simultaneous multiple surface (SMS) method,[6] tailored method,[7] and discontinuous free-form lens method.[8] All these methods can be used to design a free-form lens that will generate a prescribed illuminance distribution on the target plane. However, these methods are too complicated to obtain a uniform and circular light pattern. Therefore, an improved lens design method is needed to control lights much more accurately. In this study, we present a novel lens design method, and with this method a novel type of free-form lenses for LED MR16 lamps are designed. These lenses had small volume and compact size, and only less than 1/5 that of a traditional total internal reflection (TIR) lens. A precise optical model of Cree®XLamp® XR-E LED (Cree, Durham, North Carolina) was also established as the light source of novel LED MR16 lamps. The numerical simulation, based on the Monte-Carlo ray-tracing method, shows that more than 89% of lights exiting from the lens surface irradiate within the desired receive target, and the lamps with this type of lens have a higher uniformity illuminance distribution across the target and smaller volumes of lens. But in the case of designing a small divergence angle lens, the efficiency of lights irradiating within the desired receive target drops, which is elaborated later.

2 Problem Statement

The MR16 lamp is designed to form a uniform and circular light pattern on a target for accent lighting. The light distribution of a LED is always similar to Lambert, which is not suitable for MR16 lamp illumination; therefore, secondary optics design is essential to form a uniform and circular light pattern on the target plane. In this work, we focus on the method of free-form secondary lens to generate a uniform and circular light pattern. This secondary optical design belongs to the category of the problem of circularly prescribed illumination. As shown in Fig. 1, the lens refracts the incident ray **I** into output ray **Q**, and irradiates **O** at corresponding point Q on the circularly target plane. According to the energy mapping relationship, the edge ray principle, and Snell's law, the coordinates and normal vector of point P on the surface of the free-form lens is able to be calculated. In this work, we present a novel lens design method based on nonimaging optics,[9] and design two novel lenses with free-form surfaces for LED MR16 lamps that can control almost all the lights of arbitrary angles from the light source to the target plane.

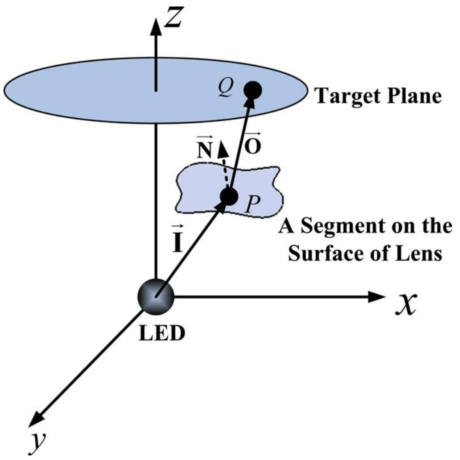

Fig. 1 Schematic of the circularly prescribed illumination problem.

3 Novel Nonimaging Optical Design Method

To improve the illumination performance, a novel nonimaging optical design method is suggested to enhance the uniformity of light pattern and the optical efficiency into a main beam and to reduce the optical system volume. The method is briefly described in Fig. 2 and consists of three main steps as follows.

3.1 *Establishment of Light Energy Mapping Relationship*

Since the circular target and light intensity distribution of the light source both have central symmetry, the lens is also designed as central symmetry. Then only the contour line C_0 of the lens' cross section needs to be calculated, and then the lens can be formed by rotating this contour line around the symmetry axis.

In this design, the light source and illumination target plane are divided into M grids with equal luminous flux Φ_0 and area S_0, respectively. Then a mapping relationship is built between a couple of light source grids and target plane grids. Therefore, the average illuminance $E_0=\Phi_0/S_0$ of each target plane grid is the same, and a uniform light pattern can be obtained when the grid is quite small compared with the whole target plane.[10]

First, since the light source has central symmetry, we divide the light source's intensity space distribution into M grids with equal luminous flux ϕ_0 only in the longitude direction. The light source's intensity space distribution $I(\theta)$ can be obtained from an experiment where θ is the angle between the ray and the symmetry axis of the light source, as shown in Fig. 3. Suppose the total flux of light

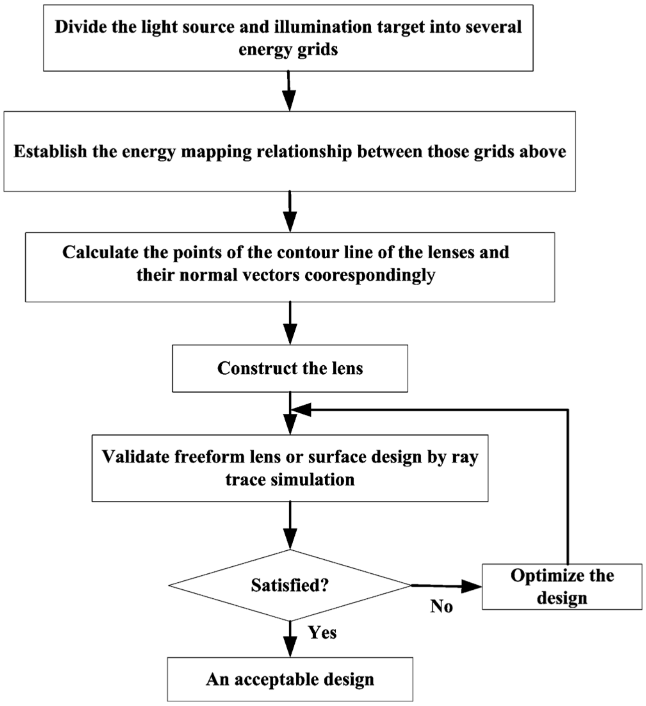

Fig. 2 Design flowchart of the circular free-form lens design method.

source is ϕ_{total}; according to the principle of photometry, the relationship between luminous flux ϕ and light intensity I is expressed as:

$$I = \frac{d\phi}{d\omega}. \tag{1}$$

The solid angle $d\omega$ can be expressed as:

$$d\omega = \sin(\theta) d\theta d\varphi. \tag{2}$$

So we can obtain the following equations:

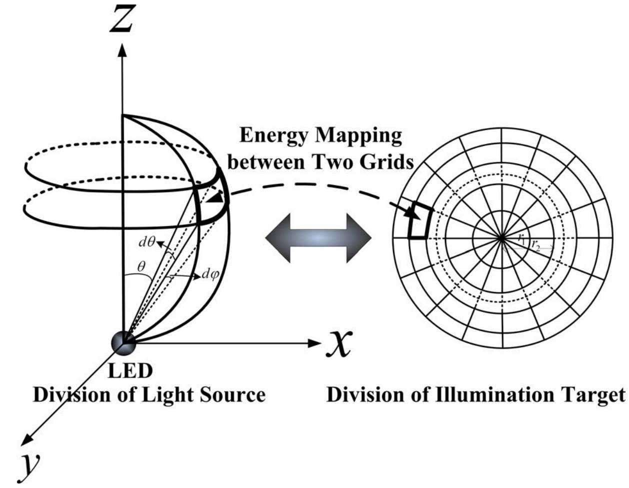

Fig. 3 Schematic of light energy mapping between the light source and target.

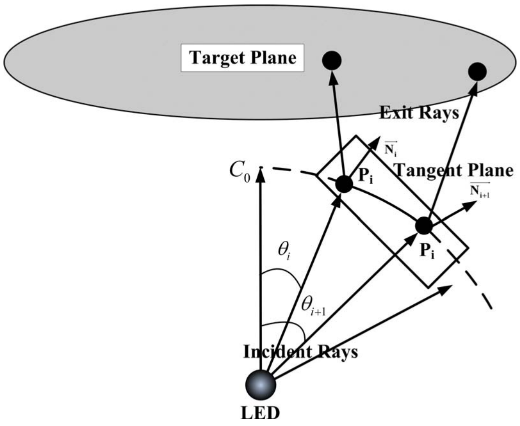

Fig. 4 Calculations of the points on the contour line C_0 of a lens.

$$d\phi = I(\theta)\sin(\theta) d\theta d\varphi,$$

$$\phi = \int_0^{2\pi} \int_0^{\pi/2} I(\theta)\sin(\theta) d\theta d\varphi. \tag{3}$$

The edge angle $\theta_1, \theta_2 \ldots, \theta_i$ $(i=1,2,\ldots M)$ of each part, which defines the direction of edge light of each source grid, can be calculated from Eq. (4).

$$\phi_0 = \frac{\phi_{\text{total}}}{M}$$

$$\int_0^{\theta_i} 2\pi I(\theta)\sin(\theta) d\theta = i\phi_0. \tag{4}$$

Secondly, we divide the illumination target plane into M concentric rings with the same area S_0. Suppose the radius of the illumination target is R. Then the area of the illumination target equals πR^2, and the area of each concentric ring S_0 equals $\pi R^2/M$. As the area of a circle with a radius of r_i is the summation of i concentric rings, we get the following equation:

$$\pi r_i^2 = i\frac{\pi R^2}{M}. \tag{5}$$

Then the radius r_i $(i=1,2,\ldots M)$ of each ring on the illumination target can be calculated from Eq. (6).

$$r_i = R\sqrt{\frac{i}{M}}. \tag{6}$$

3.2 *Construction of Lens*

There are four steps to calculating the contour of lens. First of all, as shown in Fig. 4, we fix a point as the vertex of a lens which is the first point (P_1) on the curve C_0, and the normal vector of this point is also determined to be vertical up. The second point on the curve C_0 can be determined by the intersection of incident ray and the tangent plane of the previous point. Secondly, the direction of the exit ray can be calculated by the point obtained in the first step and the

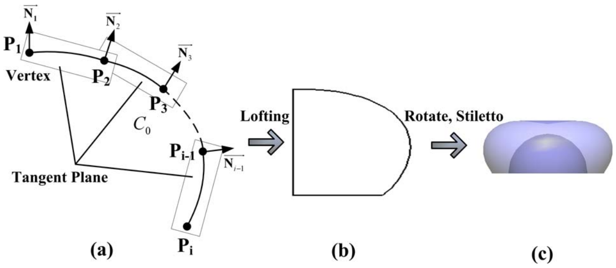

Fig. 5 The progress of construction of the novel free-form lens.

corresponding point on the target plane. Thirdly, as shown in Fig. 4, we calculate the present point's normal vector by incident ray and exit ray using the inverse procedure of Snell's law, which is expressed as follows,

$$[1+n^2-2n(\vec{\mathbf{O}}\cdot\vec{\mathbf{I}})]^{1/2}\vec{\mathbf{N}}=\vec{\mathbf{O}}-n\vec{\mathbf{I}}, \tag{7}$$

where $\vec{\mathbf{I}}$ and $\vec{\mathbf{O}}$ are the unit vectors of incident and refracted rays, $\vec{\mathbf{N}}$ is the unit normal vector on the refracted point, and n is the index of refraction in the lens. Finally, we can get all the points and their normal vectors on the curve C_0 in this chain of calculation [Fig. 5(a)]. Then we fit these points to form the lens' contour [Fig. 5(b)] and rotate this contour to get the entity of the lens [Fig. 5(c)]. To fix the LED, a hemisphere inner cavity is needed at the bottom surface of the lens that will not change the direction of the lights irradiating from the light source.

3.3 *Validation of Lens Design*

Since it is costly to manufacture a real circular free-form lens, numerical simulation based on the Monte-Carlo ray trace method is an efficient way to validate the lens design. According to the simulation results, a slight modification is needed to make the illumination performance better, such as radius of the hemisphere inner cavity, installation position of the free-form lens, etc.

4 Design Examples

4.1 *Precise Optical Modeling for the Light-Emitting Diode*

A precise optical model of the light source should be established before simulation. A Cree®XLamp® XR-E LED (Cree, Durham, North Carolina) is adopted as the light source in this study, and Fig. 6 shows the material object and numerical model of this LED. The flow chart for building the light source is shown in Fig. 7. A precise LED optical model can be 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).[11] The NCC is written as Eq. (8):

$$\mathrm{NCC}=\frac{\sum_x (A_x-\bar{A})(B_x-\bar{B})}{\left[\sum_x (A_x-\bar{A})^2\sum_x (B_x-\bar{B})^2\right]^{1/2}}, \tag{8}$$

where $A_x(B_x)$ is the simulation intensity or irradiance (experimental) value, and $\bar{A}(\bar{B})$ is the mean value of $A(B)$, which are different from each other with the changing angle value along the x axis. Due to the modeling algorithm for a LED model mentioned in Ref. 11, we adjusted the scattering characteristic and index of some packaging material used in the LED until the NCC reached as high as 97.6% (as shown in Fig. 8), which is quite acceptable for the simulation of the lighting performance. Thus, the precise optical modeling for a Cree®XLamp® XR-E LED is finished.

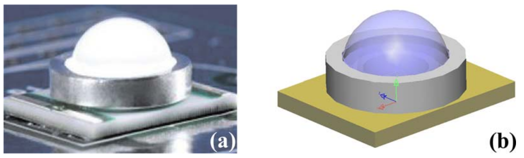

Fig. 6 (a) Material object and (b) numerical model of Cree®XLamp® XR-E LED.

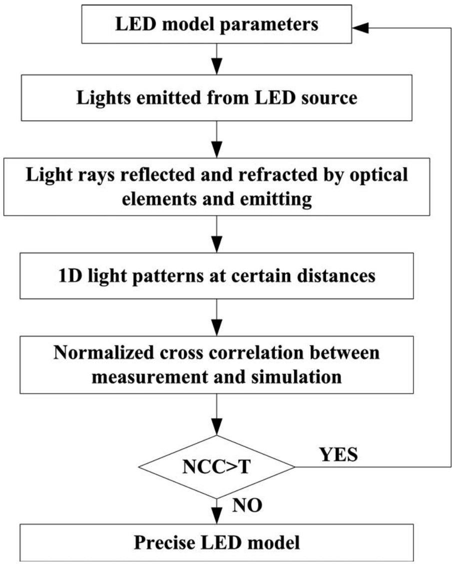

Fig. 7 Modeling algorithm for a LED model.

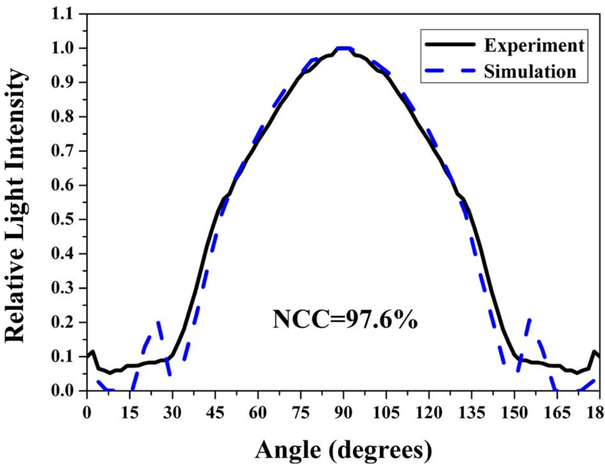

Fig. 8 Simulation light distribution curve versus experimental measurement for the LED light source.

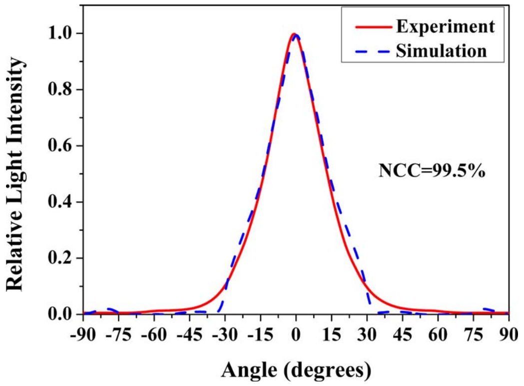

Fig. 9 Simulation light distribution curve versus experimental measurement for the LED MR16 lamp existing on the market.

4.2 *Design of Free-Form Lenses*

To compare the optical performance of a traditional TIR lens and novel LED MR16 lenses, we should model the TIR lens accurately. The modeling algorithm used in Sec. 4.1 was adopted. First, we measured the TIR lens and then modeled the lens with the parameters measured before. Second, we measured the light distribution curve of the LED MR16 lamp existing on the market. Third, we simulated the TIR lens model with the Monte-Carlo ray-tracing method. Finally, we contrasted the simulation result of the TIR lens model and the experimental results of the LED MR16 lamp and adjusted the parameters of the TIR lens to make NCC reach as high as 99.5%, which is shown in Fig. 9. The TIR lens model is shown in Fig. 10(a).

In this work, two novel LED MR16 lamp lenses with divergence angles of 90 and 120 deg, respectively, have been designed as examples. As the comparisons show in Fig. 10, the height, diameter, and volume of the 90-deg lens are 5.6 mm, 5.2 mm, and 105 mm^3, respectively, and are 5.6 mm, 15 mm, and 508 mm^3 for the 120-deg lens. However, the size of the traditional MR16 lens existing on the market, always with this type of TIR lens, is much larger than those novel lenses with a height of 10 mm, diameter of 28 mm, and volume more than 3000 mm^3. The volume of these novel lenses is no more than 1/5 of that of the TIR lens. Thus these novel MR16 LED lenses provide a better and more effective way for some compact size illumination applications.

4.3 *Simulation Results and Analysis*

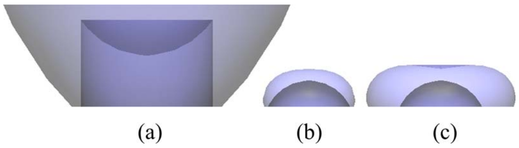

Fig. 10 (a) A TIR lens for LED MR16 lamp existing on the market. (b) The novel 90-deg LED MR16 lamp lens. (c) The novel 120-deg LED MR16 lamp lens.

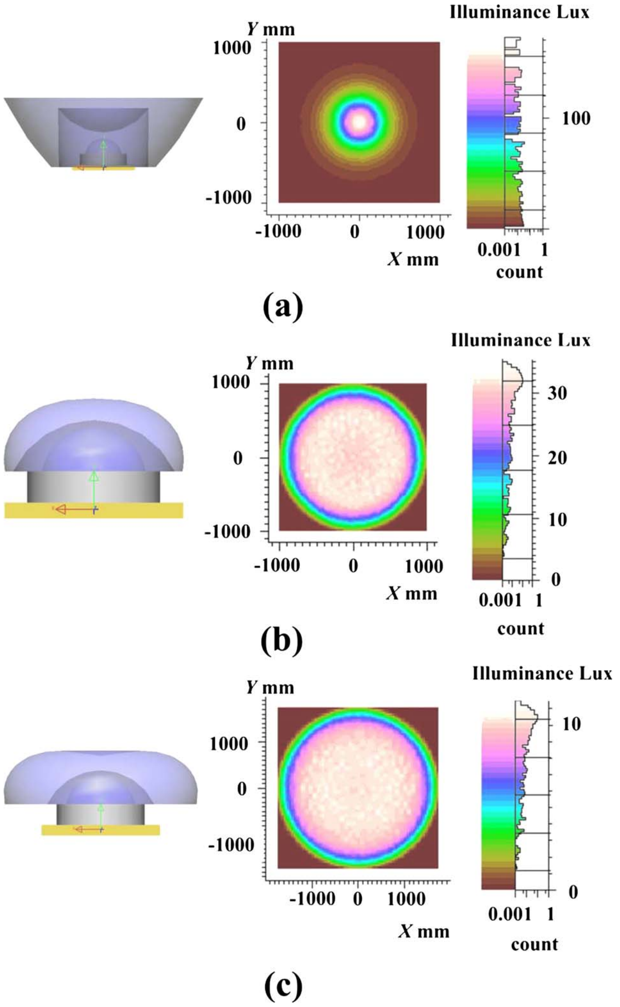

Fig. 11 Simulation illumination performance of different LED MR16 lenses on a test plane: (a) a TIR LED MR16 lamp lens; (b) the novel 90-deg MR16 lens; and (c) the novel 120-deg MR16 lens.

We simulated the TIR LED MR16 lens and the designed novel free-form lenses numerically by the widely used Monte-Carlo ray-tracing method. Figure 11 shows the simulation illuminance distribution on a test area 1 m away from the LED module. The light output efficiencies (LOEs) of these two novel free-form lenses reach as high as 98%, and less than 82% for the TIR lens. This probably is due to the fact that some lights irradiate downward after being reflected several times at the internal surface of the TIR

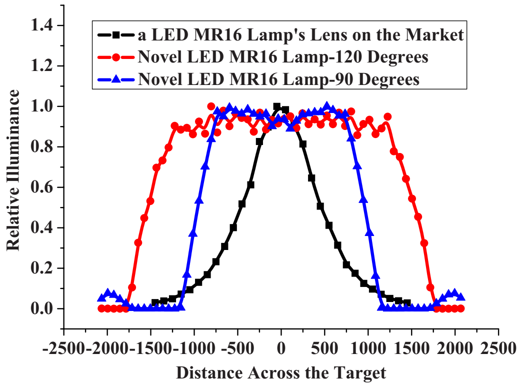

Fig. 12 Relative illuminance distributions of different kinds of LED MR16 lenses.

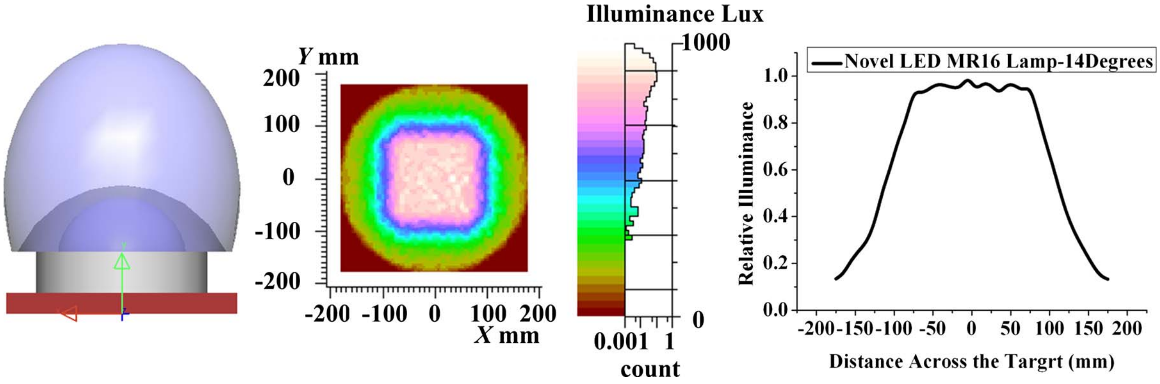

Fig. 13 Novel 14-deg MR16 lens and its simulation results.

lens, and these lights are totally lost. For the 90-deg MR16 lens, 89% of lights exit from the lens surface into the main beam, and 90% for the 120-deg MR16 lens, which is much higher than that of the TIR lens with only about 60% of lights exiting from the lens into the main beam.

For MR16 lamps, the uniformity u of a light pattern is always defined by the following equation:

$$u = \frac{E_{\min}}{E_{\max}}, \tag{9}$$

where $E_{\min}$ is the minimal illuminance on the target plane, and $E_{\max}$ is the maximal illuminance on the target plane. In the numerical simulation, as the illuminance of each point on the target plane is related to the number of grids and the number of lights traced, which is set in the software, the simulation uniformity u is different in different settings of software. So we just choose a simulated illuminance distribution chart and relative illuminance distribution curve of cross section through the simulated illuminance distribution chart to represent the uniformity of light pattern.

As shown in Figs. 11 and 12, the novel LED MR16 lamps have a much higher uniformity illuminance distribution across the target compared with a traditional LED MR16 lamp with a TIR lens, especially for the central illumination area. Thus the novel LED MR16 could provide a higher quality and more comfortable illumination performance in applications.

Moreover, we use this method to design a free-form lens while limiting the divergence angle to as little as 14 deg. The novel 14-deg MR16 lens and corresponding simulation result are shown in Fig. 13. For the 14-deg MR16 lens, the cut-off line of the light pattern becomes blurred and the efficiency of lights irradiating within the desired receive target falls to 60%. And the LED die is projected onto the target obviously. The cause of this phenomenon is that the curvature of the lens becomes larger when the divergence angle is small, which will cause point-to-point design, and the optical system is more powerful for imaging.[12] So there is an obvious rectangle-shaped illumination area on the target plane. However, the novel 14-deg MR16 lens also has a higher uniformity illuminance distribution across the target compared with the traditional LED MR16 lamp with a TIR lens.

From the simulation results, obvious light rings exist at the edge of the light pattern, especially with lenses of small divergence angles. This is mainly caused by two reasons. 1. Some lights, especially for those with large mergence angles, could not irradiate to the desired points on the target only by one refracted optical surface. To control large mergence angle lights more effectively, two or more optical surfaces need be designed simultaneously in future work. 2. The LED light source is simplified to a point light source during the free-form optics calculation. However, in truth the LED is an extended source with a length of 1 mm and a width of 1 mm, and lights generated at the edge of the LED could not irradiate at the desired points on the target, which also resulted in light rings. Considering more than one point light source distributed at different positions of the LED simultaneously during calculation is one possible solution to the extended light source problem.

5 Conclusions

In this study, to improve illumination performance, a novel nonimaging optical design method is suggested. Based on this method, two novel free-form lenses are designed as examples for LED MR16 lamps. Simulation results show that the novel LED MR16 lamp lenses of small volume and compact size have high optical efficiencies into main beams and high uniformity illuminance distribution across targets, which are much better than that of the products existing on the market, especially for the large divergence angle MR16 lens. However, obvious light rings still exist at the edge of the beam pattern when the lens divergence angle is small, which probably could be reduced by designing two or more optical surfaces and point light sources simultaneously in future work.

Acknowledgments

This work was supported by the Nature Science Foundation of China (NSFC) Key Project under grant number 50835005, and GuangDong Real Faith Optoelectronics Incorporated.

References

1. M. Alan, “Solid state lighting-a world of expanding opportunities at LED 2002,” *III-Vs Rev.* **16**(1), 30–33 (2003).
2. V. Derlofske and M. W. McColgan, “White LED sources for vehicle forward lighting,” *Proc. SPIE* **4776**, 195–205 (2002).
3. K. Wang, X. B. Luo, Z. Y. Liu, B. Zhou, Z. Y. Gan, and S. Liu, “Optical analysis of an 80-W light-emitting-diode street lamp,” *Opt. Eng.* **47**(1), 013002 (2008).
4. D. Brown, D. Nicol, and I. Ferguson, “Investigation of the spectral properties of LED-based MR16 bulbs for general illumination,” *Opt. Eng.* **44**(11), 111310 (2005).
5. K. Wang, S. Liu, X. B. Luo, Z. Y. Liu, and F. Chen, “Optical analysis of a 3 W light-emitting diode (LED) MR16 lamp,” presented at the 9th Intl. Conf. Electron. Packag. Technol. High Density Packag., Shanghai, China, July (2008).
6. P. Benítez, J. C. Miñano, J. Blen, J. Chaves, O. Dross, M. Hernández, and W. Falicoff, “Simultaneous multiple surface optical design method in three dimensions,” *Opt. Eng.* **43**(7), 1489–1502 (2004).
7. H. Ries and J. Muschaweck, “Tailoring freeform lenses for illumination,” *Proc. SPIE* **4442**, 43–50 (2001).
8. L. Wang, K. Y. Qian, and Y. Luo, “Discontinuous free-form lens design for prescribed irradiance,” *Appl. Opt.* **46**(18), 3716–3723 (2007).
9. R. Winston, J. C. Miňano, and P. Benítez, *Nonimaging Optics*, Elsevier Academic Press, New York (2005).
10. W. A. Parkyn, “Illumination lenses designed by extrinsic differential geometry,” *Proc. SPIE* **3428**, 389–396 (1998).
11. C. C. Sun, T. X. Lee, S. H. Ma, Y. L. Lee, and S. M. Huang, “Precise optical modeling for LED lighting verified by cross correlation in the midfield region,” *Opt. Lett.* **31**(14), 2193–2195 (2006).
12. Y. Y. Chen, I. J. Chen, A. J. Wang, and L. T. Chen, “Analysis of die-imaging and yellow hue phenomena in LED TIR lens,” *Proc. SPIE*, **7059**, 70590O (2008).

Fei Chen is a PhD candidate at Wuhan National Laboratory for Optoelectronics. He received his BS degree in optical information science and technology from Huazhong University of Science and Technology, Wuhan, China, in 2008. His research interests include LED optical design and LED chip structure design.

Sheng Liu is a special professor, the director of the Institute of Microsystems, and the director of the MOEMS Division at Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan, China. He obtained his PhD from Stanford University in 1992. His main research interests are LED, MEMS, IC packaging, mechanics, and sensors. He has published more than 200 technical articles and filed more than 50 patents.

Kai Wang is a PhD candidate student at Wuhan National Laboratory for Optoelectronics. He received his BS degree in optical information science and technology from Huazhong University of Science and Technology, Wuhan, China, in 2006. His research interests include LED optical design and LED chip structure design.

Zongyuan Liu is a PhD candidate student at Wuhan National Laboratory for Optoelectronics. He received his BS degree in mechanical design and manufacture and automation from Huazhong University of Science and Technology, Wuhan, China, in 2006. His research interests include LED packaging and LED module structure design.

Xiaobing Luo is a professor at Huazhong University of Science and Technology (HUST), Wuhan, China. He works in the School of Energy and Power Engineering and Wuhan National Laboratory for Optoelectronics at HUST. He received his PhD in 2002 from Tsinghua University, China. His main research interests are heat and mass transfer, LEDs, microfluidics, MEMS, sensors, and actuators. He has published 55 papers, and applied for or been granted 37 patents in the United States, Korea, Japan, Europe, and China.