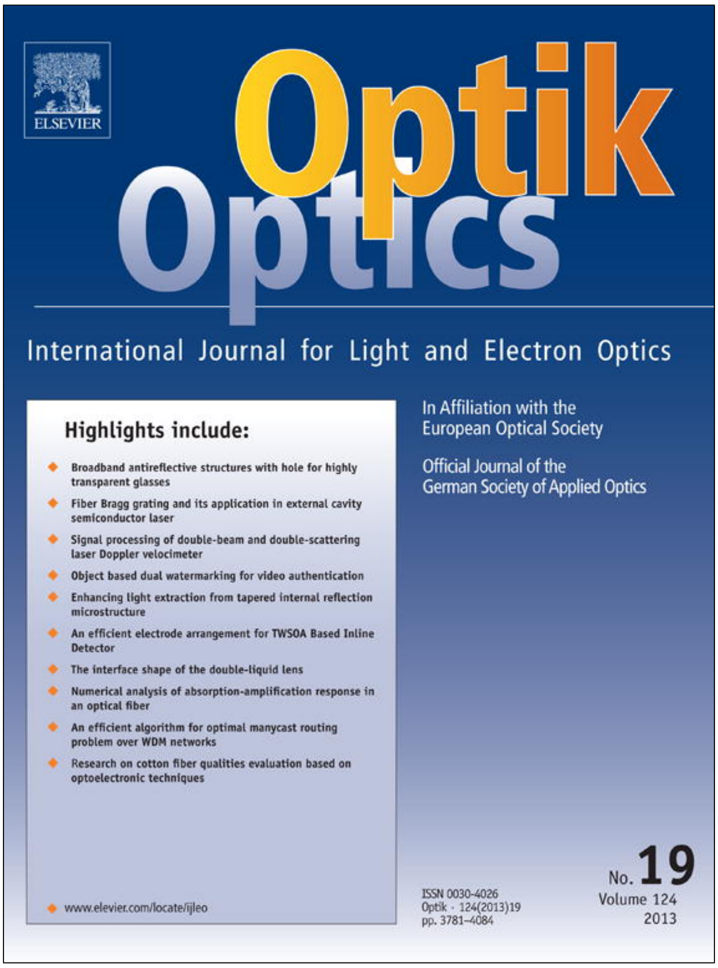
ELSEVIER
Optik
Optics
International Journal for Light and Electron Optics
Highlights include:
Broadband antireflective structures with hole for highly transparent glasses
Fiber Bragg grating and its application in external cavity semiconductor laser
Signal processing of double-beam and double-scattering laser Doppler velocimeter
Object based dual watermarking for video authentication
Enhancing light extraction from tapered internal reflection microstructure
An efficient electrode arrangement for TWSOA Based Inline Detector
The interface shape of the double-liquid lens
Numerical analysis of absorption-amplification response in an optical fiber
An efficient algorithm for optimal manycast routing problem over WDM networks
Research on cotton fiber qualities evaluation based on optoelectronic techniques
www.elevier.com/locate/ijleo
In Affiliation with the European Optical Society
Official Journal of the German Society of Applied Optics
ISSN 0030-4026
Optik · 124(2013)19
pp. 3781–4084
No. 19
Volume 124
2013

Optik 124 (2013) 3895–3897

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Design of double freeform-surface lens for LED uniform illumination with minimum Fresnel losses

Run Hu [a,b], Zhiqiang Gan [c], Xiaobing Luo [a,b,*], Huai Zheng [a], Sheng Liu [b,c]

[a] School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[b] Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China
[c] School of Optoelectronic Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

ARTICLE INFO

Article history:
Received 30 June 2012
Accepted 25 November 2012

Keywords:
Light-emitting diode (LED)
Non-imaging optics
Freeform lens
Fresnel loss
Illumination

ABSTRACT

In this study, we demonstrated a double freeform-surface lens to realize uniform illumination and minimum Fresnel losses for light-emitting diode (LED). In the present design, the inner surface and outer surface of the freeform lens were designed simultaneously, thus the light path can be controlled more flexibly. The detailed calculation and design process were presented. Monte Carlo ray-tracing simulation and Fresnel losses calculation were conducted to validate the present freeform lens. The simulation and calculation results indicated that the present freeform lens could enhance the illumination uniformity greatly and realize minimum Fresnel losses as low as 7.67%.

1. Introduction

As the dominant candidate for the next generation light source, light-emitting diode (LED) has been widely used on our daily life such as backlighting for LCD display, road lighting, headlamp for vehicle, landscape lighting, or even indoor luminaries [1–5]. The direct output of LED, however, is usually a circle spot with non-uniform illumination, which is hard to meet the illumination requirement. To solve this problem, appropriate optics including primary lenses or secondary lenses, are essential for high quality LED illumination. Our group has conducted a lot of research on the freeform lens design method [6–13]. However, in our previous freeform lens designs, we just consider the outer surface of the freeform lens, while keeping the inner surface as hemispherical for simplicity. In fact, the light emanated from the LED light source will be refracted twice before reaching the target plane. Fresnel losses are therefore inevitable and will cause a waste of light energy. Therefore in this letter, based on the previous work of our group, we designed a double freeform-surface lens for LED uniform illumination with minimum Fresnel losses. Fresnel losses calculation and Monte Carlo ray-tracing simulations were conducted to demonstrate the effectiveness of this design method.

* Corresponding author at: School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China.
Tel.: +86 13971460283; fax: +86 27 87557074.
E-mail address: luoxb@mail.hust.edu.cn (X. Luo).

0030-4026/$ – see front matter © 2012 Elsevier GmbH. All rights reserved.
http://dx.doi.org/10.1016/j.ijleo.2012.12.019

2. Design method

As shown in Fig. 1, rays emanated from the light source located at the original point O are refracted twice when transmitting from the inner and outer surfaces of the freeform lens. The inner surface refracts the incident ray $\overrightarrow{OA}$ into the first output ray $\overrightarrow{AB}$, which is the incident ray for the outer surface. The outer surface refracted the second incident ray $\overrightarrow{AB}$ into second output ray $\overrightarrow{BR}$, and irradiates at corresponding point R on the target plane. According to the Snell's law [14], we have

$$\left.\begin{aligned} n_1 \sin\varphi_i &= n_2 \sin\varphi_j \\ n_2 \sin\psi_i &= n_1 \sin\psi_j \end{aligned}\right\} \tag{1}$$

where φ_i and φ_j are the incident angle and refractive angle on the inner surface, respectively, ψ_i and ψ_j are the incident angle and refractive angle on the outer surface, respectively, n_1 is the refractive index of air and equals 1.00, and n_2 is the refractive index of the lens material. The Fresnel losses generated during the refraction on the inner surface and the outer surface can be calculated as follows, respectively [14]

$$\left.\begin{aligned} FL_{1i} &= \frac{1}{2}\left[\frac{\sin^2(\varphi_i-\varphi_j)}{\sin^2(\varphi_i+\varphi_j)} + \frac{\tan^2(\varphi_i-\varphi_j)}{\tan^2(\varphi_i+\varphi_j)}\right] \\ FL_{2i} &= \frac{1}{2}\left[\frac{\sin^2(\psi_i-\psi_j)}{\sin^2(\psi_i+\psi_j)} + \frac{\tan^2(\psi_i-\psi_j)}{\tan^2(\psi_i+\psi_j)}\right] \end{aligned}\right\} \tag{2}$$

Note that Δd_{1i} and Δd_{2i} are the deviation angle of the incident ray and the refractive ray on the inner surface and the outer surface,

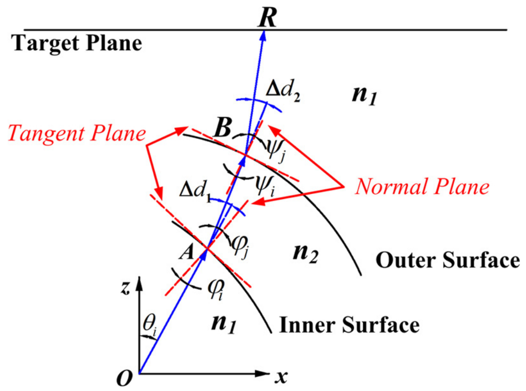

Fig. 1. Schematic of twice refractions through the lens.

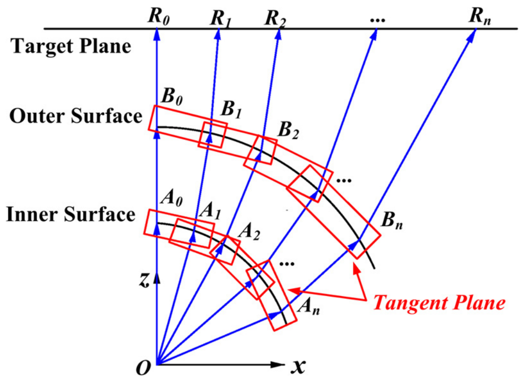

Fig. 3. Schematic of points generation on the inner surface and the outer surface of the double freeform-surface lens.

respectively. Therefore as shown in Fig. 1, the first deviation angle can be expressed as $\Delta d_{1i} = \left|\varphi_i - \varphi_j\right|$ and the second deviation angle can be expressed as $\Delta d_{2i} = \left|\psi_i - \psi_j\right|$. With Eqs. (1) and (2), we can transform the Fresnel losses as the functions of the two deviation angles

$$FL_{1i} = f(\Delta d_{1i}), \quad FL_{2i} = f(\Delta d_{2i}) \tag{3}$$

For each ray transmitting through the lens with the light intensity as $I(\theta_i) = I_0 \cos\theta_i$, the total Fresnel losses can be calculated as

$$\begin{aligned} FL(\theta_i) &= I(\theta_i)\,[FL_{1i} + (1 - FL_{1i})FL_{2i}] \\ &= I_0 \cos\theta_i (FL_{1i} + FL_{2i} - FL_{1i}FL_{2i}) \end{aligned} \tag{4}$$

In this study, we adopted the non-imaging optical design method to design the double freeform-surface lens [6–8,11]. For simplicity, we designed a symmetry freeform lens as an example. At first, we built the light energy mapping relationship between the light source and the target plane. The light source and the target plane were meshed as M grids equally. As a result, we obtained the edge angle θ_i ($i = 1, 2, \ldots, M$) of each ray emanated from the light source and the coordinates of the corresponding point R on the target plane. Compared to the distance between the light source and the target plane, the lens was very small. Thus the coordinates of the R point could be used to calculate the angle ζ_i in Fig. 2 between the output ray $\overrightarrow{BR}$ and the z axis. Therefore, the total deviation angle of each ray, i.e. the sum of Δd_{1i} and Δd_{2i}, could be calculated as

$$\Delta d_i = \Delta d_{1i} + \Delta d_{2i} = \left|\theta_i - \zeta_i\right| \tag{5}$$

With the limiting condition in Eq. (5), we can optimize the Δd_{1i} and Δd_{2i} of each ray for minimum Fresnel losses by applying

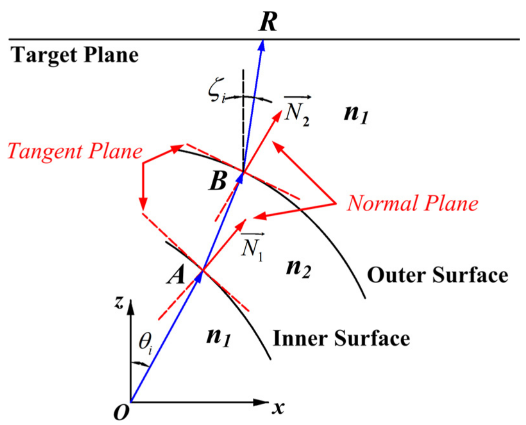

Fig. 2. Schematic of the relationship between the rays and the normal vectors.

Eqs. (3) and (4). As a result, we could obtain a series of optimized deviation angles Δd_{1i} and Δd_{2i} ($i = 1, 2, \ldots, M$). The total Fresnel losses of all the rays and the percentage of the whole luminous flux of the light source could be calculated as Eqs. (6) and (7), respectively.

$$FL_{total} = 2\pi \sum_{i=1}^{i=M-1} \int_{\theta_i}^{\theta_{i+1}} FL(\xi)\sin\xi d\xi \tag{6}$$

$$\eta = \frac{FL_{total}}{\Phi} = \frac{FL_{total}}{2\pi I_0} \tag{7}$$

Next, we designed the double freeform-surface lens to realize minimum Fresnel losses. As shown in Fig. 2, according to Snell's law [14], we could re-write Eq. (1) as

$$n_1 \frac{\overrightarrow{OA}}{\left|\overrightarrow{OA}\right|} \times \overrightarrow{N_1} = n_2 \frac{\overrightarrow{AB}}{\left|\overrightarrow{AB}\right|} \times \overrightarrow{N_1} \tag{8}$$

$$n_2 \frac{\overrightarrow{AB}}{\left|\overrightarrow{AB}\right|} \times \overrightarrow{N_2} = n_1 \frac{\overrightarrow{BR}}{\left|\overrightarrow{BR}\right|} \times \overrightarrow{N_2} \tag{9}$$

where $\overrightarrow{N_1}$ and $\overrightarrow{N_2}$ are the unit normal vectors of the inner surface and outer surface, respectively.

To calculate the contour line of the freeform lens, as shown in Fig. 3, we firstly fixed point A_0 and point B_0 as the vertex of the inner and outer surface of the lens, respectively. The normal vectors at these two points were vertical up. The second point A_1 on the inner surface could be calculated by the intersection of the incident ray $\overrightarrow{OA_1}$ and the tangent plane of the point A_0. With the optimized deviation angle Δd_{11} and Δd_{21} obtained above, we could obtain the ray $\overrightarrow{A_1B_1}$ and ray $\overrightarrow{B_1R_1}$. The second point B_1 on the outer surface could be calculated by the intersection of the ray $\overrightarrow{A_1B_1}$ and the tangent plane of the point B_0. Then applying Eqs. (8) and (9), we could calculate the unit normal vectors and the tangent planes at point A_1 and point B_1. And then we could obtain the third point A_2 on the inner surface by the intersection of the incident ray $\overrightarrow{OA_2}$ and the tangent plane of the point A_1. By repeating this process until the edge angle θ_i equalled 90°, we could get all the points and their unit normal vectors on the inner and outer surface. After obtaining all the coordinates on the inner and outer surfaces, we fit these points to form the contour line of the lens's cross section and then got the freeform lens by rotating the contour line around the symmetry axis.

3. Validation and results

In order to validate the present method, we designed a double freeform-surface lens with 4 mm and 6 mm initial heights of the inner and outer surfaces, respectively. Since the LED die was only 0.5 mm × 0.5 mm, the die could be considered as point light source.

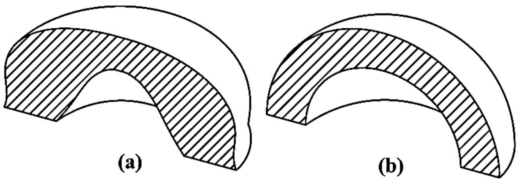

Fig. 4. Half 3D models of (a) double freeform-surface lens and (b) conventional hemispherical lens.

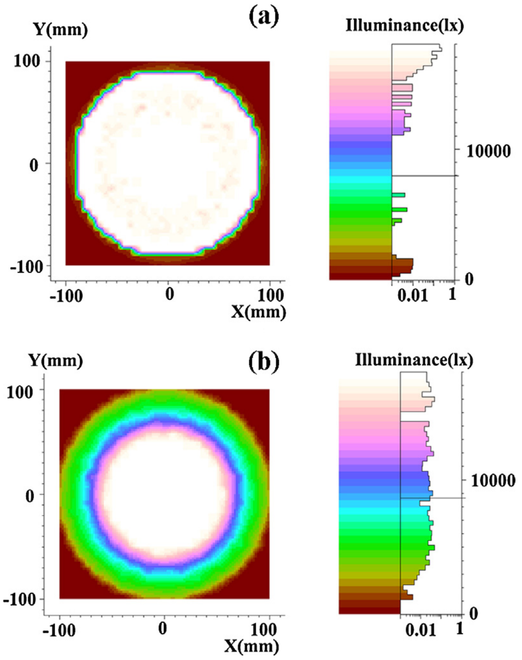

Fig. 5. Illumination performance of (a) double freeform-surface lens and (b) hemispherical lens on the target plane.

The half 3D models of the freeform lens and the conventional hemispherical lens were shown in Fig. 4. The materials of the lenses were selected as polymethyl-methacrylate whose refractive index is 1.4935. Monte Carlo ray-tracing method was adopted and one million rays were used to simulate the illumination performance of the two lenses. In the simulations, the distance between the light source and the target plane was 50 mm and the radius of the target plane was 100 mm. To evaluate the uniformity of the illumination performance, the variation coefficient of root mean square error, or *CV*(*RMSE*) in short, was calculated, which is defined as [15]

$$CV(RMSE) = \frac{RMSE}{\bar{x}} \tag{10}$$

where *RMSE* is the standard error and $\bar{x}$ is the mean value of the sample points of the target plane. The smaller the *CV*(*RMSE*) is, the higher the illumination uniformity is.

The Monte Carlo simulation results of the two lenses were illustrated in Fig. 5. Compared with illumination performance of the conventional hemispherical lens in Fig. 5(b), we can see that the illumination uniformity of the double freeform-surface lens was enhanced visually in Fig. 5(a). The *CV*(*RMSE*) of present freeform lens was 0.1330, while the *CV*(*RMSE*) of the hemispherical lens was as high as 0.7616. We also calculated the Fresnel losses of the two lenses. In fact, the smaller the incident angle φ_i is, the smaller the Fresnel losses will be [14]. As for the hemispherical lens, the rays were emanated from the light source radially and reached the inner and outer surface of the lens at normal incidence. Therefore, the hemispherical lens had the minimum Fresnel losses. By calculation, we obtained that the percentage of Fresnel losses of the hemispherical lens was 7.64%, while that of present double freeform lens was 7.67%. These results were almost the same, which means that the present double freeform-surface lens also had the minimum Fresnel losses. The results agreed with our initial motivation behind this study. Therefore, compared with the conventional hemispherical lens, the present double freeform-surface lens could enhance the illumination performance while keeping the Fresnel losses minimum.

4. Conclusions

In summary, a double freeform-surface lens with minimum Fresnel losses was designed for LED uniform illumination. Fresnel losses produced when rays transmitted across the lens were calculated and minimum Fresnel losses were realized by controlling the first and the second deviation angles. Monte Carlo ray-tracing simulations of both the present freeform lens and conventional hemispherical lens were conducted. The Fresnel losses calculation and Monte Carlo simulations validated that the present double freeform-surface lens could enhance illumination uniformity and realize minimum Fresnel losses. Meanwhile, the present design method is an effective way to design double freeform-surface lens for specific application.

Acknowledgements

This work was supported in part by 973 Project of The Ministry of Science and Technology of China (2011CB013105), and in part by National 863 Project of The Ministry of Science and Technology of China (2011AA03A109).

References

[1] J.B. Jiang, S. To, W.B. Lee, B. Cheung, Optical design of a freeform TIR lens for LED streetlight, Optik 121 (2010) 1761–1765.
[2] C.F. Chen, C.C. Wu, J.H. Wu, Modified wide radiating lenses of the power-chip light emitting diodes for a direct-lit backlight, Optik 121 (2010) 847–852.
[3] R. Hu, X.B. Luo, S. Liu, Study on the optical properties of conformal coating light-emitting diode by Monte Carlo simulation, IEEE Photonics Technol. Lett. 23 (20) (2011) 1673–1675.
[4] R. Hu, X.B. Luo, H. Feng, S. Liu, Effect of phosphor settling on the optical performance of phosphor-converted white light-emitting diodes, J. Lumin. 132 (2012) 1252–1256.
[5] L. Zhu, S.Y. Huang, P.T. Lai, H.W. Choi, Fiber-coupled light-emitting diode with a capillary-bonded hemispherical lens, IEEE Photonics Technol. Lett. 23 (24) (2011) 1857–1859.
[6] F. Chen, S. Liu, K. Wang, Z. Qin, Z.Y. Liu, X.B. Luo, Free-form lenses for high illuminance quality light-emitting diode MR16 lamps, Opt. Eng. 48 (12) (2009) 123002.
[7] K. Wang, F. Chen, Z.Y. Liu, X.B. Luo, S. Liu, Design of compact freeform lens for application specific light-emitting diode packaging, Opt. Express 18 (2) (2010) 413–425.
[8] K. Wang, S. Liu, F. Chen, Z. Qin, Z.Y. Liu, X.B. Luo, Freeform LED lens for rectangularly prescribed illumination, J. Opt. A: Pure Appl. Opt. 11 (2009) 105501.
[9] S. Zhao, K. Wang, F. Chen, D. Wu, S. Liu, Lens design of LED searchlight of high brightness and distant spot, J. Opt. Soc. Am. A 28 (5) (2011) 815–820.
[10] S. Wang, K. Wang, F. Chen, S. Liu, Design of primary optics for LED chip array in road lighting application, Opt. Express 19 (S4) (2011) A716–A724.
[11] R. Hu, X.B. Luo, H. Zheng, Q. Zong, Z.Q. Gan, B.L. Wu, S. Liu, Design of a novel freeform lens for LED uniform illumination and conformal phosphor coating, Opt. Express 20 (13) (2012) 13727–13737.
[12] K. Wang, D. Wu, Z. Qin, F. Chen, X.B. Luo, S. Liu, New reversing design method for LED uniform illumination, Opt. Express 19 (S4) (2011) A830–A840.
[13] F. Chen, K. Wang, Z. Qin, D. Wu, X.B. Luo, S. Liu, Design method of high-efficient LED headlamp lens, Opt. Express 18 (20) (2010) 20926–20938.
[14] M. Bass, V.N. Mahajan, Handbook of Optics, 3rd Edition, Volume I: Geometrical and Physical Optics, Polarized Light, Components and Instruments, McGraw Hill, New York, 2010 (Chapter 12).
[15] W.A. Hendricks, K.W. Robey, The sampling distribution of the coefficient of variation, Ann. Math. Stat. 7 (3) (1936) 129–132.