

# New reversing design method for LED uniform illumination

Kai Wang,<sup>1</sup> Dan Wu,<sup>1</sup> Zong Qin,<sup>1,2</sup> Fei Chen,<sup>1</sup> Xiaobing Luo,<sup>1,3</sup> and Sheng Liu<sup>1,2,\*</sup>

<sup>1</sup>Division of MOEMS, Wuhan National Laboratory for Optoelectronics, College of Optoelectronics Science and Engineering, Huazhong University of Science & Technology, Wuhan 430074, China

<sup>2</sup>Institute for Microsystems, School of Mechanical Science and Engineering, Huazhong University of Science & Technology, Wuhan 430074, China

<sup>3</sup>School of Energy and Power Engineering, Huazhong University of Science & Technology, Wuhan 430074, China  
\*victor\_liu63@126.com

**Abstract:** In light-emitting diode (LED) applications, it is becoming a big issue that how to optimize light intensity distribution curve (LIDC) and design corresponding optical component to achieve uniform illumination when distance-height ratio (DHR) is given. A new reversing design method is proposed to solve this problem, including design and optimization of LIDC to achieve high uniform illumination and a new algorithm of freeform lens to generate the required LIDC by LED light source. According to this method, two new LED modules integrated with freeform lenses are successfully designed for slim direct-lit LED backlighting with thickness of 10mm, and uniformities of illuminance increase from 0.446 to 0.915 and from 0.155 to 0.887 when DHRs are 2 and 3 respectively. Moreover, the number of new LED modules dramatically decreases to 1/9 of the traditional LED modules while achieving similar uniform illumination in backlighting. Therefore, this new method provides a practical and simple way for optical design of LED uniform illumination when DHR is much larger than 1.

©2011 Optical Society of America

**OCIS codes:** (220.2945) Illumination design; (220.3630) Lenses; (230.3670) Light-emitting diodes; (220.4298) Nonimaging optics.

---

## References and links

1. M. G. Craford, "LEDs for solid state lighting and other emerging applications: status, trends, and challenges," Proc. SPIE **5941**, 1–10 (2005).
2. E. F. Schubert, *Light-Emitting Diodes* (Cambridge University Press, 2006).
3. S. Liu and X. B. Luo, *LED Packaging for Lighting Applications: Design, Manufacturing and Testing* (John Wiley and Sons, 2011), (to be published).
4. I. Moreno, "Configurations of LED arrays for uniform illumination," Proc. SPIE **5622**, 713–718 (2004).
5. I. Moreno, M. Avendaño-Alejo, and R. I. Tzonchev, "Designing light-emitting diode arrays for uniform near-field irradiance," Appl. Opt. **45**(10), 2265–2272 (2006).
6. Z. Qin, K. Wang, F. Chen, X. B. Luo, and S. Liu, "Analysis of condition for uniform lighting generated by array of light emitting diodes with large view angle," Opt. Express **18**(16), 17460–17476 (2010), <http://www.opticsinfobase.org/oe/abstract.cfm?uri=oe-18-16-17460>.
7. A. J. W. Whang, Y. Y. Chen, and Y. T. Teng, "Designing uniform illumination systems by surface-tailored lens and configurations of LED arrays," J. Disp. Technol. **5**(3), 94–103 (2009).
8. Y. Ding, X. Liu, Z. R. Zheng, and P. F. Gu, "Freeform LED lens for uniform illumination," Opt. Express **16**(17), 12958–12966 (2008), <http://www.opticsinfobase.org/abstract.cfm?uri=oe-16-17-12958>.
9. K. Wang, S. Liu, F. Chen, Z. Qin, Z. Y. Liu, and X. B. Luo, "Freeform LED lens for rectangularly prescribed illumination," J. Opt. A, Pure Appl. Opt. **11**(10), 105501 (2009).
10. F. Chen, S. Liu, K. Wang, Z. Y. Liu, and X. B. Luo, "Free-form lenses for high illuminance quality light-emitting diode MR16 lamps," Opt. Eng. **48**(12), 123002 (2009).
11. K. Wang, F. Chen, Z. Y. Liu, X. B. Luo, and S. Liu, "Design of compact freeform lens for application specific Light-Emitting Diode packaging," Opt. Express **18**(2), 413–425 (2010), <http://www.opticsinfobase.org/abstract.cfm?uri=oe-18-2-413>.
12. K. Wang, D. Wu, F. Chen, Z. Y. Liu, X. B. Luo, and S. Liu, "Angular color uniformity enhancement of white light-emitting diodes integrated with freeform lenses," Opt. Lett. **35**(11), 1860–1862 (2010).

13. H. Yang, J. W. M. Bergmans, T. C. W. Schenk, J.-P. M. G. Linnartz, and R. Rietman, "Uniform illuminance rendering using an array of LEDs: a signal processing perspective," *IEEE Trans. Signal Process.* **57**(3), 1044–1057 (2009).
14. H. Ries and A. Rabl, "Edge-ray principle of nonimaging optics," *J. Opt. Soc. Am. A* **11**(10), 2627–2632 (1994).
15. S. Kobayashi, S. Mikoshiba, S. Lim, and L. C. D. Backlights, (John Wiley and Sons, 2009).
16. I. Moreno and C. C. Sun, "LEDs array: where does far-field begin," *Proc. SPIE* **7058**, 70580R, 70580R-9 (2008).
17. 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).

## 1. Introduction

Light-emitting diodes (LEDs), with increasing luminous efficiency and cost performance in recent years, have greater applications in daily life, such as backlighting for LCD TV, headlamp of vehicle, road lighting, commercial lighting, etc. [1–3]. Within these applications, uniform illumination of LED array is crucial and at the same time is required by most applications. A lot of research work has been done in this area. I. Moreno *et al* proposed a method to achieve uniform illumination by optimizing the distance-height ratio (DHR) of LED array when the irradiance distribution  $E(r, \theta)$  of LED has an expression of  $E(r, \theta) = E_0(r)\cos^m\theta$  [4,5]. Q. Zong *et al* improved I. Moreno's method making it also suitable when the light source has large view angle [6]. Although these methods are effective to obtain uniform illumination, the light intensity distribution curve (LIDC) of light source should be given as the input parameter during design, which makes their applications limited. In practical applications, sometimes the DHR is given and the LIDC is what required to design and to optimize. Obviously methods mentioned above cannot handle this problem. To solve this problem, A. J. W. Whang *et al* proposed a reversing design method for uniform illumination system by integrating surface-tailored lens with configurations of LED arrays [7]. However, they only considered the situation when  $E(r, \theta) = E_0(r)\cos^m\theta$ , which makes the maximum DHR  $[4/(m+2)]^{1/2}$  less than 1.41 resulting in application limited.

Moreover, algorithm of lens by which realizing required LIDC is another important issue need to concern during design. Although the emitting angle can be adjusted at will by surface-tailored lens in Ref. 7, emitting angle is unable to describe the light intensity distribution of LED or LED integrated with lens accurately. In recent years, freeform lens has becoming a trend for optical design of LED lighting with advantages of high efficiency, precise light irradiation control, high design freedom and small size [8–12]. Therefore freeform lens is more likely to provide a new way to obtain required LIDC by which achieving uniform illumination.

In this study, a new reversing design method for LED uniform illumination is proposed, including design and optimization of LIDC to achieve high uniform illumination and a new algorithm of freeform lens to generate the required LIDC by LED light source. This method is practical and simple. High uniform illumination is achieved successfully when DHR has a larger range compared to the maximum value reported in previous work. Moreover, complicated LIDCs are also able to be realized at will by the new algorithm of freeform lens, which makes it possible to design new LED optical components for uniform illumination.

In various LED applications, LED backlighting, especially application in large scale LED TV, has become the main driver of LED marketing growth in 2010. According to the proposed new design method, new LED modules integrated with freeform lenses for slim direct-lit backlighting will be designed as examples in this study. Actually, this new design method is not only suitable for LED backlighting application, but also available for other LED illumination applications, such as LED interior lighting, commercial lighting, office lighting, warehouse lighting, etc.. Since the design processes of these applications are quite similar, we only take the optical design of new slim direct-lit LED backlighting as an example in the following discussion.

## 2. Problem statement

In LED lighting, illumination in terms of square LED array is the most widely applied, for example LED backlighting, interior lighting, etc.. In this study the design method will be

discussed based on the square LED array. Analyses of other arrangements of LED array, like linear or circular ring, are quite similar and not included in this discussion. As shown in Fig. 1, a  $M \times N$  (even number) square LED array is set at the  $xy$  plane. The distance between two adjacent LED light sources is  $d$ . One LED light source consists of an LED module and a freeform lens to generate the required LIDC, wherein the freeform lens could be secondary optics or primary optics. The distance between the LED array and the target plane is  $z_0$ . In this design, values of  $d$ ,  $z_0$  and  $DHR = d/z_0$  are given by customer design requirements, and our work is to optimize the LIDC of LED light source to achieve uniform illumination on the target plane. There are two key issues which are needed to concern. One is how to optimize the LIDC and the other is how to design freeform lens to realize the required LIDC. Detail design method will be discussed in the following section.

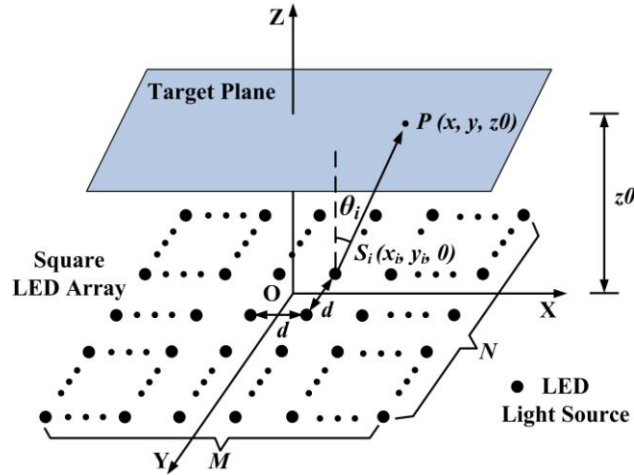


Fig. 1. Schematic of square LED light source array and the target plane.

### 3. Design method

The flowchart of this reversing design method is shown in Fig. 2. First of all, an original LIDC is calculated according to two uniform illumination criterions. Secondly simulation of lighting performance of LED array on the target plane is conducted by Monte Carlo ray tracing. If the simulation result cannot meet requirements, we introduce more verification points to optimize the LIDC until it can achieve good performance. Then we use the algorithm to design special freeform lens to generate the optimized LIDC. Finally we validate the whole design and realize the LED optical component for uniform illumination.

#### 3.1 Reversing design method of LIDC for uniform illumination

Considering circular symmetry of the light intensity distribution of LED light source as well as convenience for calculation, the light intensity distribution  $I(\theta)$ , expressed in the form of LIDC, can be described by a polynomial of  $\theta$  as follows:

$$I(\theta) = a_0 + a_1\theta^2 + a_2\theta^4 + a_3\theta^6 + a_4\theta^8 \quad (1)$$

where  $\theta$  is the emitting angle between the ray and the  $Z$ -axis. By using this expression of  $I(\theta)$ , different kinds of LIDCs including complicated ones are able to be expressed and calculated. Next we will calculate the illuminance of an arbitrary point  $P(x, y, z_0)$  on the target plane as shown in Fig. 1. Firstly, the illuminance  $E_i(x, y, z_0)$  generated by LED light source  $S_i(x_i, y_i, 0)$  at point  $P(x, y, z_0)$  can be calculated as follows:

$$E_i(x, y, z_0) = \frac{I(\theta_i) \cos \theta_i}{r_i^2} = \frac{I(\theta_i) z_0}{r_i^3} = \frac{I(\theta_i) z_0}{[(x-x_i)^2 + (y-y_i)^2 + z_0^2]^{3/2}} \quad (2)$$

where  $\theta_i = \arctan\{[(x-x_i)^2 + (y-y_i)^2]^{1/2}/z_0\}$ . Therefore the total illuminance  $E(x, y, z_0)$  generated by all  $M \times N$  LED light sources at point  $P(x, y, z_0)$  can be expressed as follows:

$$E(x, y, z_0) = \sum_{i=1}^{M \times N} E_i(x, y, z_0) \quad (3)$$

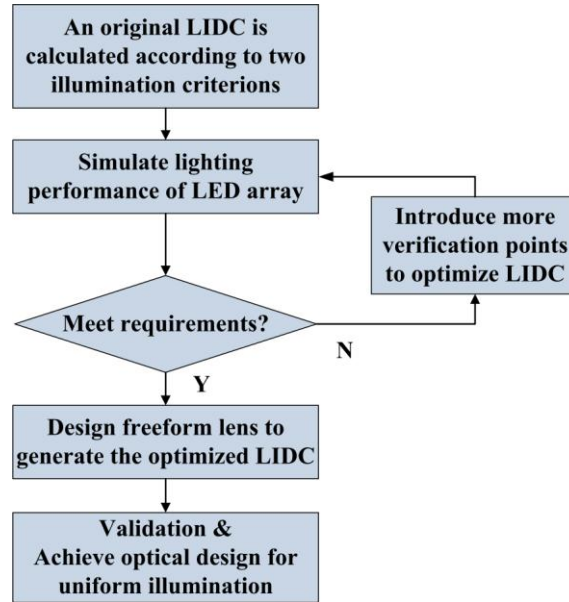


Fig. 2. Flowchart of this new reversing design method for LED uniform illumination.

To obtain LIDC satisfying uniformity requirement, we introduce two uniform illumination criteria in this study. One criterion is the Sparrow's criterion to achieve maximally flat at the central region and the other is small illuminance variation between the side point and the central point on the target plane.

For the first criterion, by differentiating  $E(x, y, z_0)$  twice and setting  $x = 0$  and  $y = 0$ , a function  $f(a_0, a_1, a_2, a_3, a_4) = \partial^2 E / \partial x^2 \Big|_{x=0, y=0}$  is acquired with variables of  $a_0, a_1, a_2, a_3$  and  $a_4$ . According to the Sparrow's criterion,  $f(a_0, a_1, a_2, a_3, a_4) = 0$  will lead to uniform illuminance at the region across the central point [4,5]. By solving the equation of  $f(a_0, a_1, a_2, a_3, a_4) = 0$ , four independent variables and one dependent variable are obtained, for example,  $a_0 = a_0, a_1 = a_1, a_2 = a_2, a_3 = a_3$ , and  $a_4 = g(a_0, a_1, a_2, a_3)$ . Obviously other criterion is needed to confine the values of these variables further more.

Although using Sparrow's criterion is able to achieve uniform illuminance at the central region, it cannot guarantee uniform distribution of illuminance across the whole target plane. Therefore another criterion of small illuminance variation is needed. CV(RMSE), abbreviation of coefficient of variation of root mean square error, is a useful concept to evaluate the uniformity of illuminance [6,13]. A group of points on the target plane are sampled and the value of CV(RMSE) is the ratio of RMSE to the mean value of the samples:

$$CV(RMSE) = RMSE / \bar{x} \quad (4)$$

where  $\bar{x}$  is the mean value. Unfortunately few standard adopts CV(RMSE) as an evaluation index for uniformity of illuminance. Thus CV(RMSE) is able to evaluate lighting performance but cannot be regarded one criterion. In this design, we introduce a ratio of  $R(x_j, y_j, z_0)$  as another criterion:

$$R(x_j, y_j, z0) = \frac{E(x_j, y_j, z0)}{E(0, 0, z0)} \quad (5)$$

where  $E(x_j, y_j, z0)$  is the illuminance of point  $Q_j(x_j, y_j, z0)$  except the central point on the target plane. Ratio  $R(x_j, y_j, z0)$  reflects the illuminance variance between side point and the central point. To obtain high uniformity, the range of  $R(x_j, y_j, z0)$  is set as  $0.85 \leq R(x_j, y_j, z0) \leq 1.15$ , which further confine the ranges of variations of the four independent variables. During design, point  $Q_j$  is regarded as verification point and proper selection of these points is a key issue. For example, if all  $Q_j$  points are around the central point, illuminance uniformity of side points becomes unpredictable. Therefore, suitable verification points which can reflect the whole illuminance distribution across the target plane should be selected as references, like  $(M/2, N/2, z0)$ ,  $(M/2-d, N/2-d, z0)$ , etc. More verification points could be introduced to optimize LIDC to meet requirements.

According to the analysis above, it is clear that values of  $a_0, a_1, a_2, a_3$  and  $a_4$  are adjusted to meet criterions of  $f(a_0, a_1, a_2, a_3, a_4) = 0$  and  $0.85 \leq R(x_j, y_j, z0) \leq 1.15$  and at the same time to have a reasonable  $I(\theta)$  during optimization. The designed LIDC will be validated by ray tracing simulation and optimized further more if necessary. Based on this reversing method, the optimized LIDC is able to be acquired easily to achieve uniform illumination. We should note that the calculated  $I(\theta)$  just reflects the characteristic of light intensity distribution of light source and its values are meaningless. The calculated  $I(\theta)$  will be normalized if necessary during following design.

### 3.2 Algorithm of freeform lens for required LIDC

In this section, algorithm of freeform lens will be introduced by which special freeform lens could be designed to generate the optimized LIDC. This algorithm includes three main steps: establishing light energy mapping relationship between the light source and the required light intensity distribution, constructing lens and validating lens design by ray tracing simulation. The first step is the key issue in this design.

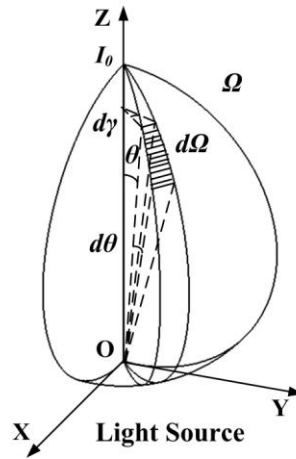


Fig. 3. Schematic of light energy distribution of a light source.

In this design, light emitted from the light source (LED module) is regarded as the input light, and light exited from the lens (secondary optics or primary optics) is regarded as the output light. During Step 1, firstly the light energy distributions both of light source and the optimized LIDC are divided into  $B$  parts equally. As shown in Fig. 3, the light energy distribution  $\Omega$  of light source could be regarded as composed by a number of unit conical object  $\Omega_0$ , which represents the luminous flux within the angular range with field angle  $d\gamma$  in

the latitudinal direction and  $d\theta$  in the longitudinal direction. The luminous flux  $\Phi_{input\_0}$  of  $\Omega_0$  can be expressed as follows:

$$\phi_{input\_0} = \int I_{input}(\theta) d\omega = \int_{\gamma_1}^{\gamma_2} d\gamma \int_{\theta_1}^{\theta_2} I_{input}(\theta) \sin \theta d\theta \quad (6)$$

where  $d\omega$  is the solid angle of one unit conical object. Since the light intensity distribution is circular symmetry,  $\gamma_1 = 0$  and  $\gamma_2 = 2\pi$  are set and the 3D design problem is changed into a much simpler 2D problem as shown in Fig. 4. Then  $\Phi_{input\_0}$  and the total luminous flux of the light source can be expressed as follows:

$$\phi_{input\_0} = 2\pi \int_{\theta_1}^{\theta_2} I_{input}(\theta) \sin \theta d\theta \quad (7)$$

$$\phi_{input\_total} = 2\pi \int_0^{\pi/2} I_{input}(\theta) \sin \theta d\theta \quad (8)$$

Since total luminous flux of light source is divided into  $B$  parts, then the field angle  $\Delta\theta_{input\_k}$  of each sub-source along longitudinal direction can be obtained by iterative calculation as follows:

$$2\pi \int_{\theta_{input\_k}}^{\theta_{input\_k+1}} I_{input}(\theta) \sin \theta d\theta = \frac{\phi_{input\_total}}{B} \quad (k = 1, 2, \dots, B, \theta_{input\_1} = 0) \quad (9)$$

$$\Delta\theta_{input\_k+1} = \theta_{input\_k+1} - \theta_{input\_k} \quad (k = 1, 2, \dots, B) \quad (10)$$

Thus the light source has been divided into  $B$  sub-sources with equal luminous flux. The directions of rays, which define the boundary of one sub-source  $\Omega_{input\_k}$ , have been also calculated out as  $\theta_{input\_k}$ . Therefore, using the same calculation method and setting the optimized LIDC as  $I_{output}(\theta)$ ,  $\theta_{output\_k}$  can be also obtained which divides the light energy of output light into  $B$  parts equally.

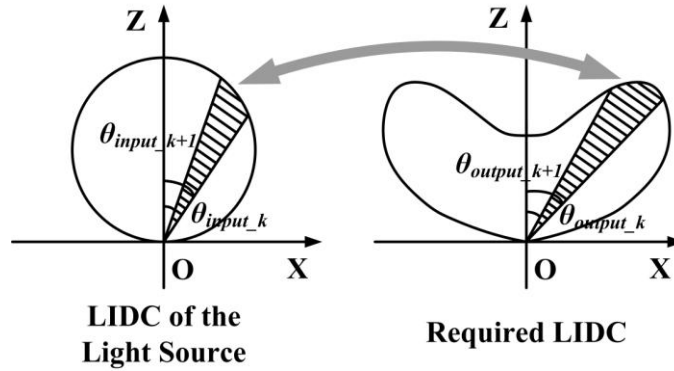


Fig. 4. Schematic of light energy mapping relationship between the light source and the required LIDC.

Then we establish light energy mapping relationship between  $\Omega_{input\_k}$  and the same order of  $\Omega_{output\_k}$ . As shown in Fig. 4, since light energy of light source and optimized LIDC both are divided into  $B$  parts equally, if light energy within the range of  $\theta_{input\_k}$  to  $\theta_{input\_k+1}$  is able to be mapped to and redistributed within the range of  $\theta_{output\_k}$  to  $\theta_{output\_k+1}$ , then the light intensity distribution of light source could be converted to the required light intensity distribution of output light, by which obtaining the optimized LIDC. According to the edge ray principle [14], rays from the edge of the source should strike the edge of the target. In this design, the target means the region constructed by output rays. Therefore if we desire to map the light energy in  $\Omega_{input\_k}$  into the output region of  $\Omega_{output\_k}$ , we should ensure that two rays, which

construct the  $\Omega_{input_k}$  as boundary, exit as the boundary of  $\Omega_{output_k}$  after being refracted by the freeform lens. In other words, input ray with emitting angle of  $\theta_{input_k}$  establish mapping relationship with the output ray with exiting angle of  $\theta_{output_k}$ . Thus the light energy mapping relationship between the light source and the required LIDC has been established.

Since we have obtained the emitting directions of input rays and the corresponding exiting directions of output rays, it is easy to design a freeform lens to meet this mapping relationship according to Snell's law and surface lofting method. Moreover, due to detailed construction process of freeform lens and validation are the same as the methods proposed in Ref. 9 and Ref. 10, Step 2 and Step 3 will not be discussed in detail in this study. In addition, sometimes the LIDC generated by freeform lens is possible to be deteriorated by extended source. This problem is also able to be solved by the feedback optimal freeform optics design method presented in Ref. 11. Therefore, by using the algorithm mentioned above, it is able to design freeform lens to realize the required LIDC by which achieving uniform illumination.

#### 4. Design examples

We will take LED backlighting as an example to verify the new design method. There are two types of LED backlighting, side-lit and direct-lit [15]. With limitation by the light transport distance in light guide plate (LGP), side-lit is not suitable for large or ultra large LED backlighting. Direct-lit has advantages not only size scalable, but also able to local dimming which could enhance contrast ratio and decrease power consumption for LED TV. Therefore direct-lit probably will become the develop trend for ultra large LED backlighting.

However, since the light intensity distribution of LED module used in backlighting usually is Lambertian type, the maximum DHR is around 1 when achieving uniform illumination. In other words, the distance between adjacent two LED modules are quite small when the thickness of LED backlighting unit is small, which results in huge number of LED modules used in large LED TV causing high cost and assembly inconvenience. For example, about 4500 LED modules will be needed for a 40" LED TV when the thickness is 10mm. On the other hand, if we want to reduce the number of LED modules, the thickness should be increased (e.g. ~20mm) to provide enough light mixing space to achieve uniform illumination. Therefore, high cost and large thickness are two major barriers for the direct-lit LED TV to extend marketing further more. In this design example, we try to design special LED optical component to obtain uniform illumination using less LED modules when the thickness is small of 10mm.

Figure 5(a) shows an optical model of a traditional LED backlighting module. Power consumption of this LED module is 0.068W when driven by 20mA and its total luminous flux is 6.5lm. The size of the LED chip is  $280\mu\text{m} \times 280\mu\text{m}$ . As shown in Fig. 5(b), LIDC of this LED module is Lambertian type of  $I(\theta) = I_0 \cos\theta$ , where  $I_0$  is the light intensity when the emitting angle  $\theta = 0$ . The distance  $z_0$  between square LED modules array and the receiving plane is 10mm. Considering periodical distribution of LED modules array, an area with the size of  $6 \times 6$  LED modules array on the receiving plane is set as the testing area, which is able to reflect the whole lighting performance on the receiving plane. In addition, since a part of lights emitted by the outside LED modules will be reflected by the reflection box in direct-lit backlighting, only the uniformity of illuminance  $U (E_{min}/E_{max})$  of central area of  $4 \times 4$  LED modules array is considered in this design.

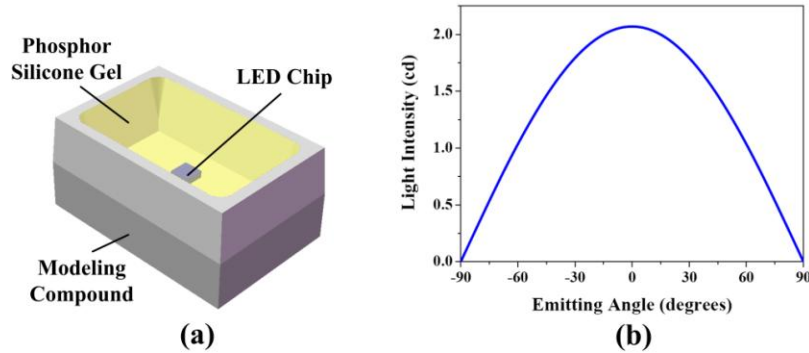


Fig. 5. (a) Optical model of a traditional 0.068W LED module for direct-lit backlighting and (b) its LIDC.

Ray tracing simulation results of the traditional LED modules array by 7 million rays are shown in Fig. 6. The value of CV(RMSE) is calculated through  $23 \times 23 = 529$  sampled points. We can find that the uniformity  $U$  is at a high level of 0.902 and CV(RMSE) is as low as 0.0167 when DHR is 1 and  $d = 10\text{mm}$ . Its lighting performance is very good. However, the uniformity  $U$  decreases to 0.446 and CV(RMSE) increase to 0.2201 when DHR increase to 2 as shown in Fig. 6(b), which cannot meet requirements. Even worse lighting performance is obtained when DHR increase to 3. As shown in Fig. 6(c), the uniformity  $U$  is only 0.155 and CV(RMSE) is as high as 0.5688. Therefore, it is hard for traditional LED module to achieve good performance in direct-lit backlighting when DHR is larger than 1.

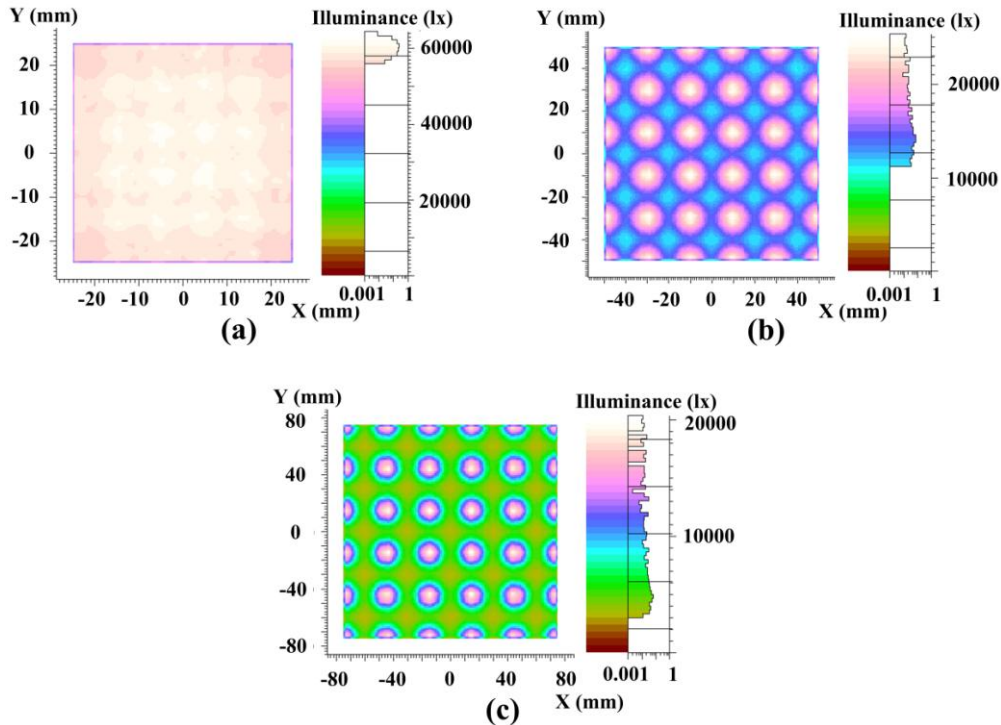


Fig. 6. Lighting performance of traditional LED modules array on the receiving plane 10mm away when DHR increases from 1 to 3: (a) DHR = 1,  $U = 0.902$ , CV(RMSE) = 0.0167; (b) DHR = 2,  $U = 0.446$ , CV(RMSE) = 0.2201; and (c) DHR = 3,  $U = 0.155$ , CV(RMSE) = 0.5688.

According to the design method mentioned above, LIDC was optimized to achieve good lighting performance when DHR is 2. Based on the Sparrow's criterion,  $a_0 = a_0$ ,  $a_1 = 6.994809a_0 - 4.261381a_2 - 4.099808a_3 - 1.781556a_4$ ,  $a_2 = a_2$ ,  $a_3 = a_3$ , and  $a_4 = a_4$  were obtained first. Then according to the second criterion, four verification points of  $R(d/2, d/2, z_0)$ ,  $R(7/6d, 7/6d, z_0)$ ,  $R(3/2d, 3/2d, z_0)$  and  $R(3/2d, d, z_0)$  were introduced to evaluate the uniformity of the whole testing area. Finally,  $a_0 = 1.0$ ,  $a_1 = 0.878827$ ,  $a_2 = 1.0$ ,  $a_3 = 0.8$  and  $a_4 = -0.8$  were obtained when  $R(d/2, d/2, z_0) = 1.01$ ,  $R(7/6d, 7/6d, z_0) = 0.967$ ,  $R(3/2d, 3/2d, z_0) = 0.946$  and  $R(3/2d, d, z_0) = 0.956$ . The optimized normalized LIDC, whose view angle is much larger than that of Lambertian type, is shown in Fig. 7(a). In addition, Fig. 7(b) depicts its lighting performance on the receiving plane. We can find that the uniformity  $U$  reaches as high as 0.936 and CV(RMSE) is lower than 0.01, which can meet requirements and are much better than the performance of Lambertian LIDC when DHR is 2, and even better than the performance when DHR = 1.

Figure 8(a) depicts a new LED module for direct-lit backlighting integrated with a special silicone gel freeform lens, which was designed with refractive index of 1.54 according to the algorithm of freeform lens for required LIDC. The optical efficiency, defined as the ratio of light energy of incident light to that of emergent light of one optical component, of this lens is 94.5% when considering material absorption and Fresnel's loss. The silicone gel freeform lens is easy to manufacture by molding process. The height of the freeform lens is set as 1.8mm. Since the distance from the LED chip to the outside surface of the lens is more than 5 times of the chip size, the LED chip could be regarded as a point source during design of freeform lens according to the far-field conditions of LEDs [16]. The normalized simulated LIDC of the freeform lens irradiated by Lambertian type LED chip is shown in Fig. 8(b). Normalized cross-correlation (NCC) [17] is used to quantify the similarity between the simulated LIDC and the optimized LIDC. We can find from the Fig. 8(b) that simulated LIDC is quite similar with the optimized LIDC and the NCC reaches as high as 99.88%, which demonstrates that the new algorithm for freeform lens is effective. It is need to note that the point source assumption could not be acceptable when the NCC is lower than 97% during the freeform lens design. Feedback method [11] will need to be included in the algorithm to overcome the extended source problem and to enhance the NCC. Lighting performance of these new LED modules array on the receiving plane is also shown in Fig. 8(c) with results of  $U = 0.915$  and  $CV(RMSE) = 0.0128$ . This lighting performance is similar with that of the optimized LIDC and is also quite good for backlighting.

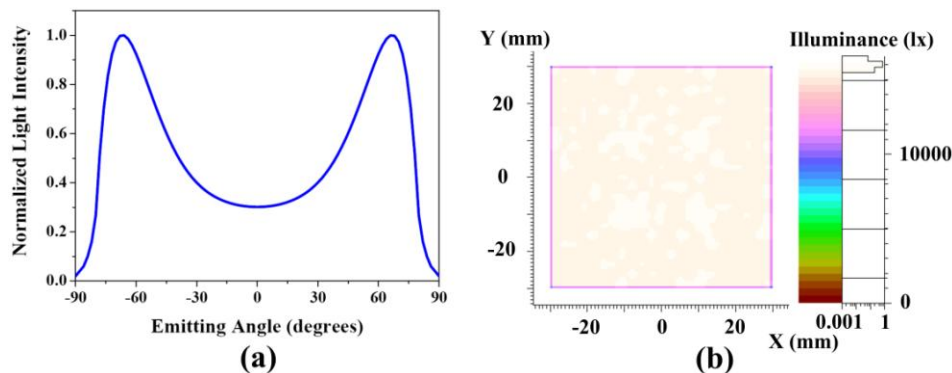


Fig. 7. (a) Optimized LIDC and (b) its lighting performance on the receiving plane when DHR = 2:  $U = 0.936$ ,  $CV(RMSE) = 0.0097$ .

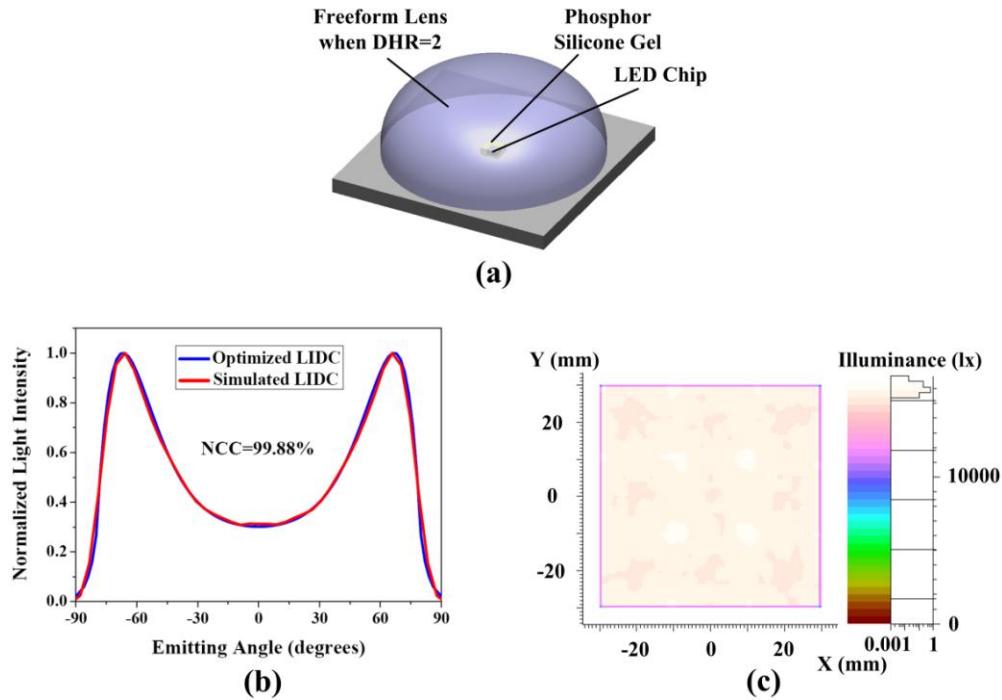


Fig. 8. (a) A new LED module integrated with a special silicone gel freeform lens for direct-lit backlighting when DHR = 2, (b) comparison of LIDCs between the simulated and the optimized results, and (c) lighting performance of these new LED modules array,  $U = 0.915$ ,  $CV(RMSE) = 0.0128$ .

By using this reserving design method, LIDC was optimized and a special freeform lens was also designed to achieve good lighting performance in terms of high illuminance uniformity when DHR is 3. The new LED backlighting module integrated with the freeform lens and its lighting performance are shown in Fig. 9. We can find that the uniformity of illuminance on the receiving plane is much better than that of Lambertian LIDC when DHR is 3, achieving  $U = 0.887$  and  $CV(RMSE) = 0.0224$ . Although these results are a little worse than that of optimized LIDC when DHR is 2, they can meet requirements very well. Therefore, uniform illumination is able to be achieved easily by this new method when DHR is much larger than 1. Therefore, in this design, the number of new LED modules is only 1/9 of the traditional LED modules when achieve similar uniform illumination in backlighting. Consequently, this reserving design method provides an effective way to dramatically decrease the number of LED modules when also able to achieve good lighting performance in slim LED backlighting with thickness of 10mm.

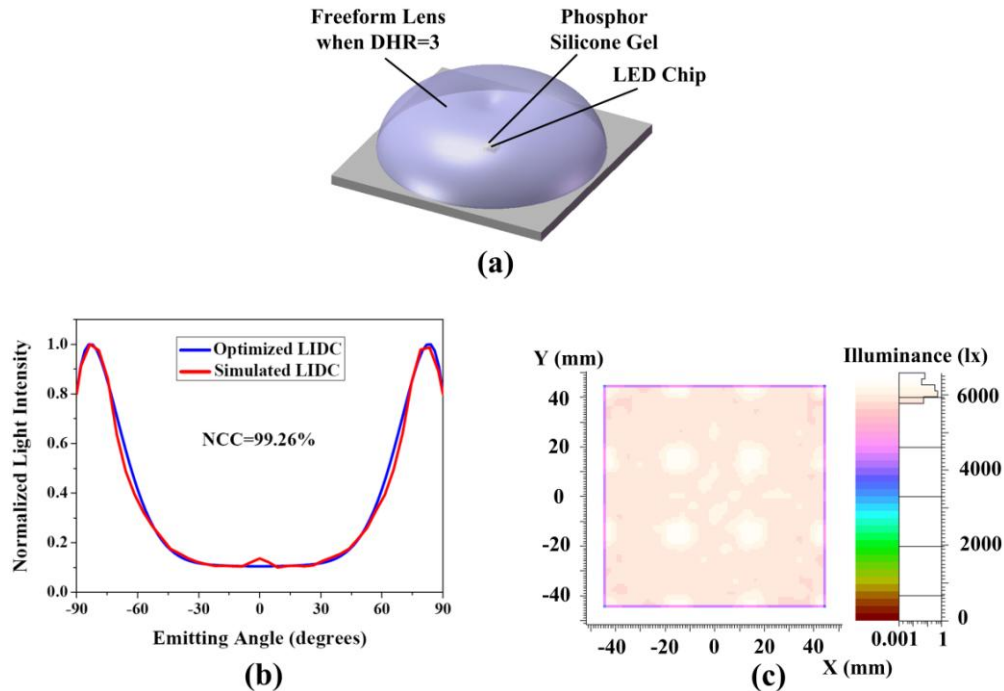


Fig. 9. (a) A new LED module integrated with a special silicone gel freeform lens for direct-lit backlighting when DHR = 3, (b) comparison of LIDCs between the simulated and the optimized results, and (c) lighting performance of these new LED modules array,  $U = 0.887$ ,  $CV(RMSE) = 0.0224$ .

## 5. Conclusions

In this study, a new reversing design method is proposed to solve the problem of optimizing LIDC and designing corresponding optical component to achieve LED uniform illumination when the DHR is given. This method includes design and optimization of LIDC to achieve high uniform illumination and a new algorithm of freeform lens to generate the required LIDC by LED light source. Slim direct-lit LED backlighting with thickness of 10mm is designed as an example. According to this new design method, two new LED backlighting modules integrated with freeform lenses are successfully designed generating optimized LIDCs to achieve uniform illumination. Uniformities of illuminance increase from 0.446 to 0.915 and from 0.155 to 0.887 when DHRs are 2 and 3 respectively. The range of DHR to achieve uniform illumination is much larger than the maximum range reported in previous reversing design. This reserving design method provides an effective way to dramatically decrease the number of LED modules when also able to achieve good lighting performance in slim direct-lit LED backlighting. Besides backlighting, this design method is also able to apply to other lighting applications, like LED interior lighting, commercial lighting, etc. Therefore, this new method provides a practical and simple way for the optical design of LED uniform illumination when DHR is much larger than 1.

## Acknowledgments

This work was supported by Nature Science Foundation of China (NSFC) Key Project under grant number 50835005, NSFC Project under grant number 50876038, High Tech Project of Ministry of Science and Technology under grant number 2008AA03A184 and GuangDong Real Faith Optoelectronics Inc.