Parametric optimization method for the design of high-efficiency free-form illumination system with a LED source

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A parametric optimization method is proposed in the design of a high-efficiency free-form illumination system. The proposed method is intended to provide rectangular uniform illumination with a light emitting diode (LED) source. An initial illumination system is first constructed and parameterized. The parameters of the initial system are optimized according to actual simulation results, and one design sample is presented. A liquid crystal on silicon (LCoS) micro-projector test module is fabricated and tested based on the design sample. Compared with the conventional micro-projectors using rotational symmetry devices, the micro-projector system designed with the parametric optimization method can send 1.65 times the source power to the LCoS active area with a 4:3 target ratio, and the uniformity reaches 98%.

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Rotational devices (e.g., total internal reflecting lens) are usually used in the design of lighting systems with a rectangular target region, such as the projection system. However, rotational symmetry has its theoretical limitation in achieving high light efficiency. Rectangular illumination systems provide an efficient way to overcome this limitation. In designs for rectangular illumination systems for light emitting diodes (LEDs), the optical surfaces are usually constructed with the point light source approximation; several methods are available to deal with this problem[1−5]. The main idea of the methods involves establishing a solid angle-to-area mapping between the point light source radiation and the target region. Among the mapping methods, the variable separation mapping method[5] provides an efficient way of constructing illumination systems with a point light source; discontinuities are introduced onto the free-form surfaces to reduce the accumulated surface normal deviations. However, in the design of micro illumination systems where the size of the LED sources cannot be neglected, mapping methods with point light source approximation are no longer effective[6].

In the design of illumination systems with surface-emitting light sources, two types of approximate methods may be used. One is the simultaneous multiple surface method (SMS)[7], and the other is the feed-back modification method[6]. The SMS method is specialized for designing free-form surfaces with surface-emitting sources. In the SMS method, two free-form surfaces are designed simultaneously, but these increase the processing difficulties. Moreover, solving Monge-Amphere type differential equations increases the difficulties in designing. The feed-back modification method offers an efficient way to deal with the deviations of illumination caused by the size of the LED and the surface normal deviations[6], but this method is still an approximate method because free-form surfaces are still constructed with point light source approximation. Thus, the possible solution for free-form surfaces is finite, and the illumination system designed with this method cannot be expected to be the optimal solution.

In this letter, a parametric optimization method for the design of rectangular illumination systems is proposed. First, an initial illumination system is constructed with point light source approximation using the mapping method. The initial illumination system is then parameterized, and the parameters are denoted by C_1. Second, the illumination distribution of the target region is simulated using an actual LED, denoted by $H_1(x, y)$. The average of $H_1(x, y)$ is defined as the initial desired illumination distribution on the target region, and is denoted by T_1. Afterward, the parameters C_1 are optimized to be C_2, based on the genetic algorithm. After $n-1$ (where the size of n is viable) times of genetic operation, C_1 transforms into C_n. If the deviations between H_n and T_n is small enough, and the light efficiency is high enough, C_n are considered as the coefficients of the optimal illumination system. In this method, free-form surfaces are no longer constructed with point light source approximation and would thus have an infinite possible solution. Hence, for the first time, obtaining the optimal rectangular illumination system for an actual LED source is possible. Moreover, due to the parameterization of the illumination system, other lenses of the illumination system, apart from the free-form lens, can be optimized together. To illustrate the effectiveness of the proposed method, a design example is provided, and a micro-projector test module is fabricated to test the optical performance. In comparison with the conventional projectors that use rotational devices, the micro-projector, which is designed with the parametric optimization method, can send 1.65 times of the source power to the liquid crystal on silicon (LCoS) active area with a 4:3 target ratio, and the uniformity reaches 98%.

The fundamental idea of the free-form illumination system design is to establish a solid angle-to-area mapping between the source radiation and the target region.

As shown in Fig. 1, the solid angle-to-area mapping is established according to the energy conservation law[5]:

$$\iint\limits_{\Omega} I(u,\nu)\mathrm{d}\Omega = \iint\limits_{S} E(x,y)\mathrm{d}s, \quad (1)$$

where $I(u,\nu)$ is the radiant intensity of the point light source at the direction (u,ν), and $E(x,y)$ is the irradiance at point (x,y) on the target region. Ω is the effective solid angle of the source, which can be used in actual application, and S is the area of the target region.

As shown in Fig. 2(a), lens2 is the free-form lens, and its first surface is a plane. A spherical collimation lens (lens1) is initially designed to reduce the deflection angle of the rays on the free-form surface. In most cases, due to the cover lens of LED sources (Fig. 2(a)), the LED and the collimation lens may have an inevitable gap. The circular illumination on the first surface of the free-form lens is formed by the rays from the point light source with inclination angles smaller than $\theta_\mathrm{m} = \arctan(D/2d)$. Hence, the solid angles between 0 and θ_m shown in Fig. 2(b) are defined as effective solid angles, and the source radiation within the effective solid angle forms the effective source radiation, which has a solid angle boundary of a conical surface (Fig. 2(b)).

To achieve the solid angle-to-area mapping, tessellations are applied to the effective source radiation and the target region simultaneously.

According to Eq. (1) and the tessellations shown in Fig. 3, the relation between ν and y can be obtained from the following equation:

$$\Big[\int I(u,\nu)\cos u\mathrm{d}u\Big]\mathrm{d}v = \Big[\int E(x,y)\mathrm{d}x\Big]\mathrm{d}y, \quad (2)$$

where for each ν, the relation between u and x can be obtained from the following equation:

$$\Big[\int I(u,\nu)\mathrm{d}v\Big]\cos u\mathrm{d}u = \Big[\int E(x,y)\mathrm{d}y\Big]\mathrm{d}x. \quad (3)$$

The mapping acquired from Eqs. (2) and (3) are denoted by $u = U(x,y)$ and $v = V(y)$.

A solid angle-to-area mapping is established between the point light source radiation and the target region. Each of the (u,v) coordinates stands for the propagation direction of a source ray. With regard to the physical meaning of the mapping, a source ray with the propagation direction (u,v) should be deflected onto the corresponding point (x,y) on the target region via the illumination system. Single free-form surface illumination systems can be constructed by directly coupling the source rays and their corresponding points on the screen[6]. However, in the design of a lens system, several optical surfaces may exist between the source and the free-form surface. For this reason, the free-form surface cannot be directly constructed by coupling the source rays and their corresponding points on the screen.

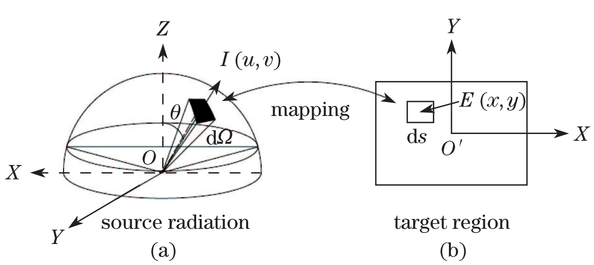

Fig. 1. Mapping between the source differential solid angle dΩ and the target region differential area ds.

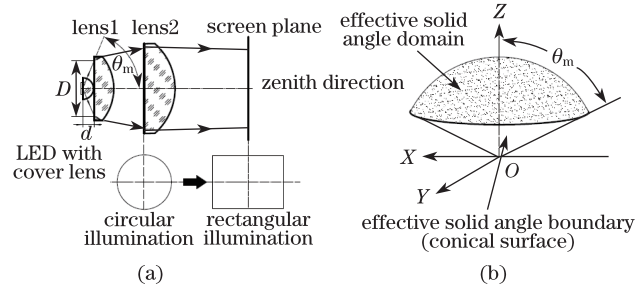

Fig. 2. (a) Definition of the effective solid angle θ_m; (b) definition of the effective solid angle boundary.

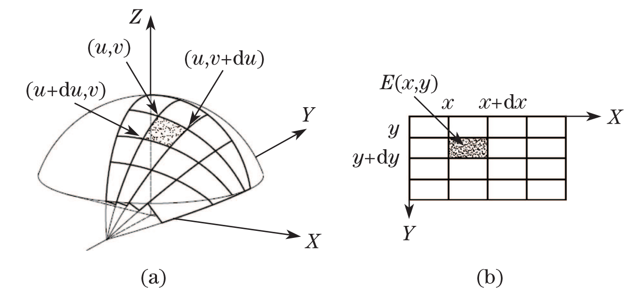

Fig. 3. (a) Tessellations of the effective source radiation; (b) tessellations of the target region.

As shown in Fig. 4, immediate rays $\boldsymbol{I}_{i,j}$ and $\boldsymbol{I}_{i+1,j}$ are the ray-tracing results of the source rays ($\boldsymbol{R}_{i,j}$ and $\boldsymbol{R}_{i+1,j}$) on the first surface of the free-form lens. Solving the free-form surface points is equivalent to solving the refraction points of the immediate rays. If the refraction point of ray $\boldsymbol{I}_{i,j}$ is known and is defined as $S_{i,j}$, the exiting ray vector $\boldsymbol{O}_{i,j}$ can be derived according to the following equation:

$$\boldsymbol{O}_{i,j} = \overrightarrow{S_{i,j}T_{i,j}}\Big/\Big|\overrightarrow{S_{i,j}T_{i,j}}\Big|. \quad (4)$$

As shown in Fig. 5(a), according to the Snell's Law and Eq. (4), the normal surface of point $S_{i,j}$ can be derived from the following equation:

$$[\boldsymbol{I}_{i,j} - (\boldsymbol{N}_{i,j}\cdot\boldsymbol{I}_{i,j})\boldsymbol{N}_{i,j}]n_\mathrm{lens} = [\boldsymbol{O}_{i,j} - (\boldsymbol{N}_{i,j}\cdot\boldsymbol{O}_{i,j})\boldsymbol{N}_{i,j}]n_\mathrm{air}, \quad (5)$$

where n_lens and n_air are the refractive indices of the free-form lens and air, respectively. $\boldsymbol{N}_{i,j}$ (normalized vector) is the ideal normal surface of point $S_{i,j}$. The aim is to construct the free-form surface with the normal surface of $\boldsymbol{N}_{i,j}$ at the corresponding refraction point $S_{i,j}$.

In assuming that S is an arbitrary point on the tangent plane of $S_{i,j}$, the tangent plane of the refraction point $S_{i,j}$ with the ideal normal surface $\boldsymbol{N}_{i,j}$ can be expressed as

$$\overrightarrow{SS_{i,j}}\cdot\boldsymbol{N}_{i,j} = 0. \quad (6)$$

As shown in Fig. 5(b), the adjacent refraction point $S_{i+1,j}$ can be derived by solving the intersection of ray

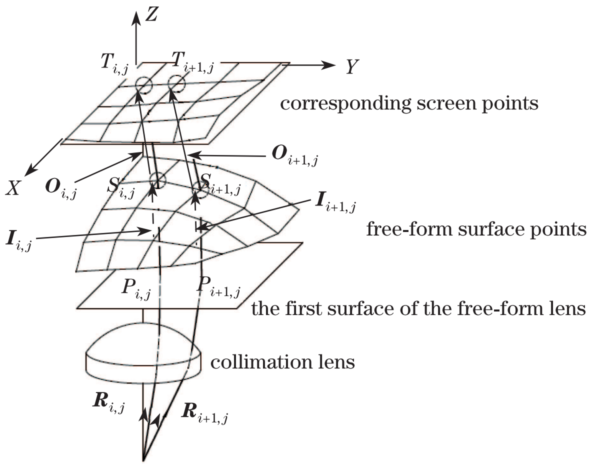

Fig. 4. Generation of intermediate rays.

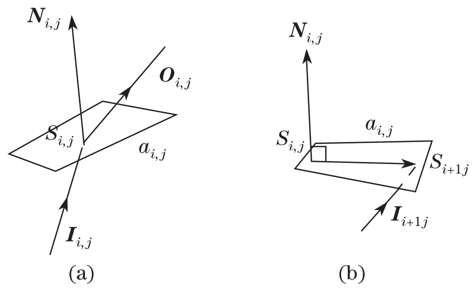

Fig. 5. (a) Scheme for the calculation of the normal surface of point $S_{i,j}$; (b) refraction points iteration ($\alpha_{i,j}$ is the tangent plane of $S_{i,j}$).

$\boldsymbol{I}_{i+1,j}$ and the tangent plane of the refraction point $S_{i,j}$[5]. If the initial refraction point S_{11} is known, all the other refraction points can be derived according to recurrence relation of a certain order, and a smooth surface can be constructed from these points with the non-uniform rational B-spline theory[8].

An illumination system is obtained with point light source approximation. To design the optimal illumination system for the actual LED source, a parametric optimization method is proposed. In this method, the illumination system obtained with point light approximation is considered as an initial illumination system, and the initial illumination system is first parameterized. Then, based on the genetic algorithm, the system coefficients are optimized according to the simulation results using an actual LED source. In comparison with that in the feed-back modification method, the free-form surfaces no longer belong to a certain category, including the surfaces constructed with point light approximation or the surfaces constructed with refraction points recurrence mentioned above. Hence, the possible solution to this parametric optimization method is infinite, and a much better solution can be obtained.

The free-form surface is represented by a refraction point cloud. The spherical collimation lens can be represented by a group of coefficients, such as the thickness and the radius. The free-form surface can also be represented by a group of coefficients according to the following polynomial:

$$z = \sum_{i=1}^{P} \sum_{j=0}^{i} C(i,j) x^{2(i-j)} y^{2j}, \tag{7}$$

where i and $j(i = 1, 2, \cdots, P; j = 0, 1, 2, \cdots, i)$ are integers, and P is half the highest power of the polynomial. $C(i, j)$ represents the coefficients of the free-form surface shown in Eq. (7). $C_k(k = 0, 1, 2, 3 \cdots)$ denotes the coefficients of the illumination system, including the coefficients of the collimation lens and the free-form lens. The initial illumination system's coefficients C_0 can be acquired based on the surface fitting of the free-form surface according to Eq. (7).

The illumination distribution of the initial illumination system is simulated with an actual LED source, and the simulation result is denoted by $H_1(x, y)$. S represents the area of the target region, with consideration for the viewing angle characteristics of the nematic liquid crystal cells[9]; not all effective source radiation can be used, and the desired illumination distribution on the target region is defined as $T_1 = \frac{1}{S} \iint\limits_S H_1(x, y)\mathrm{d}x\mathrm{d}y$. Generally, to increase the uniformity, the desired illumination distribution is defined as the average of $H_k(x, y)$:

$$T_k = \frac{1}{S} \iint\limits_S H_k(x, y)\mathrm{d}x\mathrm{d}y. \tag{8}$$

To evaluate the deviations between the simulated illumination distribution and the desired illumination distribution, a weighted merit function is defined as

$$\beta(\eta_k, H_k, T_k) = w_e(\eta_k - 0.7)^2 + \sum_{i=1;j=1}^{i=M;j=N} w_{i,j}[H_k(x_i, y_j) - T_k]^2, \tag{9}$$

where η_k is the light efficiency of the illumination system, and its optimization target is 0.7. The target region is equally divided into $M \times N$ cells, as shown in Fig. 6.

The merit function evaluates the weighted deviations between the simulated illumination distribution and the desired illumination distribution of the target region. The merit function of the initial illumination system is calculated as $\beta(\eta_1, H_1, T_1)$. Based on the genetic algorithm, the coefficients C_0 are modified according to genetic operation (selection, crossover, and mutation). Generally, in the kth genetic operation ($k = 1, 2, 3 \cdots$), the optimized system coefficients C_{k+1} can be obtained after the merit function $\beta(\eta_k, H_k, T_k)$ is calculated. After $n - 1$ times of genetic operation, C_n are considered as the optimal solution when $\beta(\eta_{n-1}, H_{n-1}, T_{n-1})$ is small enough. The optimal illumination system can be constructed with the coefficients C_n. The flow chart of the parametric optimization method is shown in Fig. 7.

A design sample of the proposed method is discussed in this section. An illumination system is designed and manufactured. The design task is to illuminate the LCoS chip[10] of a micro-projector uniformly; the uniformity should be higher than 95%, and the light efficiency of the LCoS active area should be higher than 60% (neglecting the effect of polarization). The size of the active area

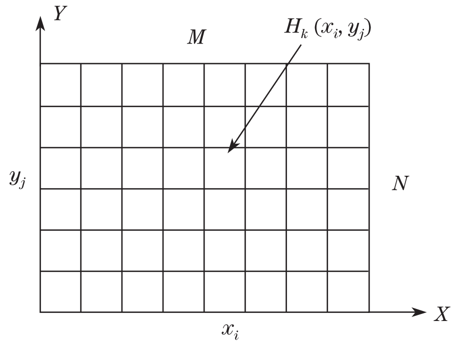

Fig. 6. Target region equally divided into $M \times N$ cells for the merit function calculation.

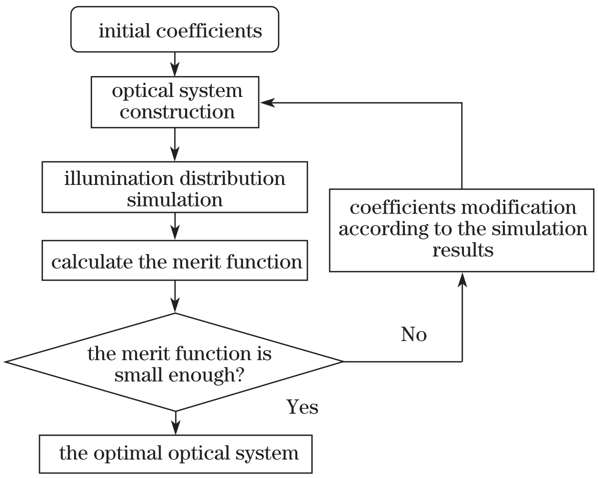

Fig. 7. Flow chart of the parametric optimization method.

(the target region) of the LCoS chip is 4.4×5.8 (mm), and the light source is a CREE Xlamp[11] source.

As shown in Fig. 8, rays from the LED should be refracted through the polarization splitting prism (PBS) onto the LCoS active area by lens1 and lens2. Lens1 is the collimation lens, and lens2 is the free-form lens. The refractive indices of the collimation lens, the free-form lens, and the PBS are 1.81264, 1.59102, and 1.76176, respectively.

A collimation lens is first designed, and a free-form lens is obtained with point light approximation. The simulated illumination distribution $H_1(x, y)$ is obtained based on the Monte Carlo method, as shown in Fig. 9.

According to the simulation result, the uniformity of the LCoS active area for the initial illumination system is 70.5%, and the light efficiency is 69%. To improve the uniformity, the parametric optimization method is applied on the initial illumination system. In assuming that the highest power of the polynomial in Eq. (7) is 10, the initial illumination system is parameterized based on surface fitting, according to the following polynomial:

$$z = \sum_{i=1}^{5} \sum_{j=0}^{i} C(i, j) x^{2(i-j)} y^{2j}. \qquad (10)$$

The coefficients of the free-form lens are shown in the second column of Table 1.

According to Eq. (8), the desired illumination distribution of the LCoS active area can be expressed as

$$T_k = \frac{1}{4.4 \times 5.8} \iint\limits_{|x| \leqslant 2.2; |y| \leqslant 2.9} H_k(x, y) \mathrm{d}x \mathrm{d}y. \qquad (11)$$

According to Eqs. (9) and (11), based on the genetic algorithm, the coefficients are modified 100 times to obtain the optimal solution. The optimal coefficients are shown in the third column of Table 1. The simulated illumination distribution of the optimal illumination system is shown in Fig. 10(b).

In comparison, with the initial illumination system shown in Fig. 10(a), the optimal illumination system has a uniformity that rises from 70.5% to 98% and light efficiency of 65%.

A micro-projector test nodule is fabricated to verify the proposed design method, shown in Figs. 11(a) and (b).

The collimation and free-form lenses are manufactured by the diamond machining systems. By means of film coating, energy loss of the refraction surfaces is reduced. As shown in Fig. 11(c), the lighting module consists of five parts, namely, the collimation lens, the free-form lens, the optical tube, the CREE Xlamp LED, and the

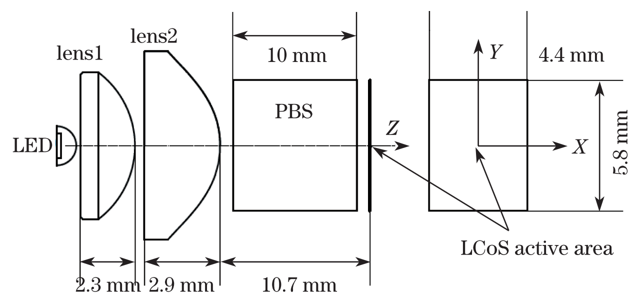

Fig. 8. Design example specification.

Table 1. Free-form Lens' Coefficients before and after Parametric Optimization

Serial Number	Initial Coefficient	Optimal Coefficient
C(1,0)	−0.122355	−0.109121
C(1,1)	−0.156283	−0.149604
C(2,0)	−0.0157491	−0.0100586
C(2,1)	−0.0317918	−0.0253945
C(2,2)	−0.0141598	−0.00280262
C(3,0)	0.00236191	0.00132906
C(3,1)	0.0125694	0.010432
C(3,2)	0.0086132	0.00645104
C(3,3)	0.00222929	0.0000382886
C(4,0)	−0.00017041	−0.000084121
C(4,1)	−0.00152617	−0.001132
C(4,2)	−0.00223533	−0.00172042
C(4,3)	−0.000764979	−0.000485793
C(4,4)	−0.000177821	0.0000134668
C(5,0)	0.00000501362	0.000002.09965
C(5,1)	0.0000670184	0.000040361
C(5,2)	0.000147699	0.0000965855
C(5,3)	0.000115969	0.0000734184
C(5,4)	0.0000250176	0.0000116611
C(5,5)	0.00000629863	−0.000000411624

metal radiator. The lighting and the imaging modules are assembled together, as shown in Fig. 11(d). The LED source has a driving current of 350 mA. The total luminous flux of the micro-projector test module is measured by illuminometer and integrating sphere, and the actual light efficiency of the LCoS active area is calculated as 61.2%, which is close to the simulation result. In comparison with conventional projectors that use rotational devices, such as the TIR lens, which has a light efficiency of about 40%, the new system can send 1.65 times the source power to the LCoS active area.

The optical performance of the micro-projector test module is shown in Fig. 12.

The projection distance is 1 m, and the diagonal length of the target region on the screen is 21 inches. The illumination distribution of the screen is tested by an illuminometer, and the ANSI uniformity reaches 90%. Considering the machining error of the free-form lens and the installation error of the micro-projector test module, the deviation between the simulation and testing results is reasonable.

A parametric optimization method in the design of high light efficiency free-form illumination system for an actual LED source is demonstrated. The illumination system is parameterized and optimized with the genetic method. A rectangular illumination system is acquired after 100 modification times of coefficients, based on which an LCoS micro-projector test module is fabricated and tested. The tested uniformity reaches 98%, and light efficiency reaches 1.65 times that of conventional micro-projector systems. The proposed method can be widely used in general lighting design, and especially in designing illumination systems with special requirements.

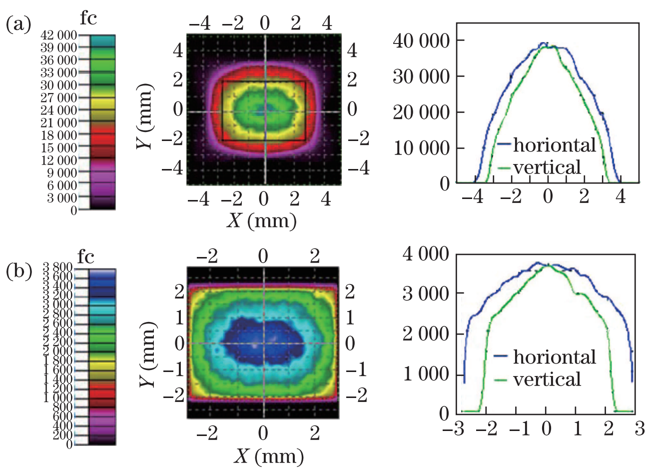

Fig. 9. Monte Carlo simulation results of the initial illumination system. (a) Illumination distribution of the entire LCoS plane; (b) illumination distribution of the LCoS active area.

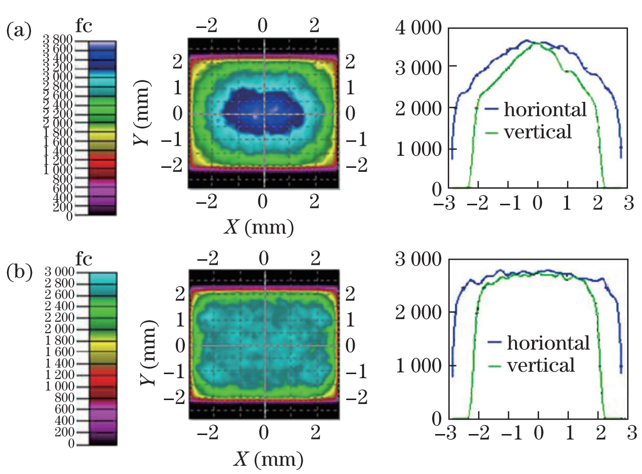

Fig. 10. Monte Carlo simulation results before and after parametric optimization. (a) Initial illumination system; (b) optimal illumination system.

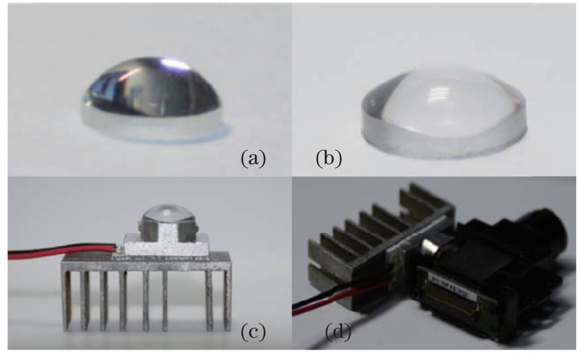

Fig. 11. Micro-projector freeform illumination system test modules.

Fig. 12. Optical performance of the micro-projector test module.

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