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Freeform illumination lens design combining energy and intensity mapping

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Abstract. A composite method combining energy and intensity mapping is proposed to address the issue of surface error caused by the irregular sampling phenomenon in freeform illumination lens design. In the combined method, the central region of the freeform lens is designed by the intensity mapping method, whereas the peripheral region is designed by the energy-mapping method. Furthermore, an iterative feedback optimization is added to scale out the application in extended light sources. As an evaluating example, a freeform lens with a 120-deg viewing angle, fitted with an appropriate number of points is designed by the proposed combined method. Compared with that designed by the energy method, the lens forms a more uniform illumination on the target surface without the appearance of a hot spot in the central region. The proposed method also exhibits superiority in extended-source design, where only a one-time optimization is needed to achieve the preset uniformity with the proper choice of coefficients. © 2017 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.56.4.045101]

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1 Introduction
With the excellent characteristics of high efficiency, long lifetime, compact size, and environment friendliness, light emitting diodes (LEDs) have been on their way to supersed conventional light sources, such as incandescent bulbs and fluorescent lamps.1,2 Due to the Lambertian light distribution, an LED cannot be directly applied to general lighting, for the irradiance decreases drastically along the radius on the target surface and thus becomes nonuniform.3 Hence, primary or secondary optics are needed to achieve uniform illumination on the target surface, among which a freeform surface is quite favorable owing to its accurate light control, flexible spatial layout, and high-design freedom characteristics.4 Many methods have been proposed to design the freeform surface, such as trial and error method, nonimaging tailoring method,5,6 the simultaneous multiple surface (SMS),7,8 differential equation method,3 and variable separation method.9,10 The trial and error method is time-consuming and quite dependent on the designer’s experience.3 In the nonimaging tailoring method, a set of nonlinear partial differential equations are obtained based on a given specific light source and the illumination distribution. By solving them, the freeform surface is constructed.5,6 However, the tailoring method cannot be applied to general lighting design, for it is only suitable for point light sources. The differential equation method proposed by Ding also suffers from this problem. SMS is an ideal candidate to solve the extended-source problem, where multiple surfaces are taken into account at the same time to achieve uniform illumination.7,8 The problem is that multiple freeform surfaces make the optical system more complex and this is not suitable for practical applications. Among all the design methods, the variable separation method has been demonstrated as an effective, practical one to achieve uniform illumination for point and extended sources, with wide applications in road lighting,10–12 automobile lighting,11 projector lighting,13 backlighting,14 and some novel lighting applications such as UV, plant, as well as fishing lighting.15–17

In the variable separation method, the light source and target surface are separated into many subintervals, allowing an incident ray and corresponding exiting ray to be mapped based on Snell’s law as well as the energy conservation law. There are two main coordinate-corresponding types, energy and intensity mapping. The definition is dependent on the energy or intensity used to describe the incident and exiting rays. Actually, the energy method is more widely applied in lighting design due to its flexible and practical characteristics.10–12,15,18–20 However, there are some potential issues with energy mapping, such as relatively a large surface error and hot spots in the illumination pattern.21,24 Shown in Fig. 1(a). The large surface error is due to the irregular sampling, caused by the equal-energy principle. Ma et al. proposed a composite ray mapping method to solve this problem, where the central region of the source light distribution is sampled in the $(u, v)$ coordinate and the peripheral region is sampled in the $(\theta, \phi)$ coordinate so as to eliminate the irregular sampling phenomenon. The simulation results show that illumination uniformity is better, for the lens surface error is greatly eliminated.21 Similar to the method above, we also propose a composite method combining energy and intensity mapping, denoted as the combined mapping method. As shown in Fig. 1(b), the central region of a freeform lens is designed by the intensity method for arbitrary subintervals that can be applied to eliminate the irregular sampling phenomenon. The peripheral region is designed by the energy-mapping method and feedback optimization is added to expand its extended-source applications.
According to energy conservation law, the existing light power should be equal to incident light power, where the energy absorbed by the encapsulating material and Fresnel’s loss at the interface are neglected. For a rotationally symmetric light source, the relationship should satisfy

\[ \int_{0}^{2\pi} \int_{0}^{\theta_m} I_s(\theta) \sin \theta \, d\theta \, d\varphi = \int_{0}^{\theta_m} I_T(\theta') \sin \theta' \, d\theta', \quad 0 \leq \theta_i \leq \theta_m, \tag{1} \]

where the domain \([0, \theta_m]\) is the designing angle range by source-target luminous intensity mapping. The minimum exiting angle \(\theta_m\) is defined by the average illumination value, which is obtained by calculating the average value of illumination distribution subtracting the peak values. The central positions, where the illumination values exceed the average value, belong to the designing scope. As shown in Fig. 2(a), \(\theta_i\) and \(\theta_o\) are the incident angle and the refracted angle, respectively. \(I_s(\theta_i) I_T(\theta_o)\) are the luminous intensity of the light source at the incident angle \(\theta_i\) to the normal axis and the luminous intensity at the exiting angle \(\theta_o\) to the normal axis on the target surface. \(I_s(\theta_i)\) is expressed as \(I_0 \cos \theta_i\) for a point light source, which is a Lambertian source and can be expressed as a fitted polynomial for an extended light source as\(^{22}\)

\[ I_s(\theta_i) = I_0 \sum_{i=0}^{n} \beta_i \theta_i^i, \tag{2} \]

where \(I_0\) is unit light intensity, \(\beta\) is the polynomial coefficient, and \(n\) is the order of this polynomial. The larger \(n\) is, the more accurate the curve fitting will be and the more complex the expression will be. Normally, \(n\) should not be < 9.\(^2\) Here, the value of \(n\) is set as 10.

In our design, a circular light spot is taken into account. According to photometry laws, the illumination value can be expressed as

\[ E_{\theta_o} = \frac{I_T(\theta_o) \cos^3 \theta_o}{h^2}, \tag{3} \]

where \(E_{\theta_o}\) is the irradiance on the target surface. \(h\) represents the distance between the target surface and the light source.

To guarantee the same irradiance on the target surface, we must have

\[ \frac{E_{\theta_o}}{E_0} = \frac{I_T(\theta_o) \cos^3 \theta_o}{I_T(0)} = 1. \tag{4} \]

The relation between the central incident light intensity \(I_s(0)\) and refractive light intensity \(I_T(0)\) is shown

\[ I_T(0) = \lambda I_s(0), \tag{5} \]

where \(\lambda\) is the ratio coefficient related to the maximum refractive angle \(\theta_{o, max}\).

Based on Eqs. (4) and (5), we have

\[ I_T(\theta_o) = \lambda I_s(0) \cos^3 \theta_o. \tag{6} \]

For the calculation of \(\lambda\), we have\(^{24}\)

\[ \lambda = \frac{1}{\tan^2 \theta_{o, max}}. \tag{7} \]

Combining Eqs. (1), (2), (6), and (7), we can obtain the corresponding emergence angles \(\theta_o\) based on the divided incident angles \(\theta_i\).

### 2.2 Source-Target Luminous Energy Mapping

#### 2.2.1 Division of solid angle for the light source

As regards the light source in our design shown in Fig. 2(b), the total luminous flux in the designed angle domain \(\Phi_{\text{energy}}\) should be the total flux \(\Phi_{\text{total}}\) subtracting the flux in the central region \(\Phi_{\text{intensity}}\) and it can be shown as

\[ \Phi_{\text{energy}} = \Phi_{\text{total}} - \Phi_{\text{intensity}} = \int_{0}^{2\pi} \int_{0}^{\pi/2} I_s(\theta) \sin \theta \, d\theta \, d\varphi, \tag{8} \]

where the domain \([\theta_{min}, \pi/2]\) is the designed angle range by source-target luminous energy mapping.

To simply the design process in the energy-mapping method, the total energy of the light source is divided into \(N\) subsources with equal luminous flux. The energy of each subsouce is \(1/N\) times the total luminous flux \(\Phi_{\text{energy}}\). According to Eq. (8), we obtain
Calculating Coordinate Points of Freeform Lens

From Eq. (12), we can obtain

\[ r_i = r_{i+1} = \sqrt{r_i^2 + \frac{2S}{\Phi} \int_{\theta_{i-1}}^{\theta_i} I_5(\theta) \sin \theta d\theta}, \]

where \( \theta_i \) and \( \theta_{i+1} \) correspond to the inner and outer existing angle of \( (i + 1) \text{th} \) angle range, respectively. Based on Eq. (9), all the subangles corresponding to the equally divided energy can be calculated.

2.2.2 Division of target surface zone for the illumination area

Similarly, the energy absorbed by the encapsulating material and Fresnel’s loss at the interface are neglected. In our design, the received energy on the target surface equals the total energy emitted by the LED light source according to the energy conservation law. To match the number of subzones and subsolid angles, the illumination area is also divided into \( N \) subzones. Therefore, the irradiance value of the \( i + 1 \text{th} \) subzone is

\[ E_T(i) = \int_{\theta_{i-1}}^{\theta_i} I_5(\theta) \sin \theta d\theta = \frac{\Phi_{\text{energy}}}{\pi R_{\text{min}}^2 - \pi R_{\text{min}}^2}, \]

where \( r_i \) and \( r_{i+1} \) are denoted as the inner and outer radii of \( i + 1 \text{th} \) circular ring, respectively. \( S \) is the designing zone area defined by the energy-mapping method. \( R_{\text{min}} \) and \( R_{\text{max}} \) are denoted as the minimum and maximum radii of the designing zone, respectively. From Eq. (10), we can obtain

\[ r_{i+1} = \sqrt{r_i^2 + \frac{2S}{\Phi} \int_{\theta_{i-1}}^{\theta_i} I_5(\theta) \sin \theta d\theta}. \]

2.3 Calculating Coordinate Points of Freeform Lens Surface

2.3.1 Calculating the coordinates of central-zone points

For the intensity-mapping method, Snell’s law can be written as

\[ n \sin \theta_i = \sin \theta_{i+1}, \]

where \( \theta_i \) and \( \theta_{i+1} \) are regarded as the incident and refractive angles, respectively.

Through the geometric relation on the refractive freeform surface as shown in Fig. 2(a), we can obtain

\[ \theta_i = \theta_T - \theta_0, \]

\[ \theta_{i+1} = \theta_T - \theta_1, \]

where \( \theta_T \) is the slope angle of the tangential vector \( T \), \( \theta_0 \) is the incident angle. Substituting Eqs. (13) and (14) into Eq. (12), we can obtain

\[ \theta_T = \tan^{-1} \left( \frac{n \sin \theta_i - \sin \theta_{i+1}}{n \cos \theta_i - \cos \theta_{i+1}} \right). \]

Therefore, the tangential vector at point \( P \) can be expressed as

\[ T = \left[ 1, \frac{n \sin \theta_i - \sin \theta_0}{n \cos \theta_i - \cos \theta_0} \right]. \]

Through Eq. (16) and a serial of emergence angles \( \theta_{i+1} \) as well as incident angles \( \theta_i \) (obtained in Sec. 2.1), the freeform lens coordinates in the central zone can be calculated.

2.3.2 Calculating the coordinates of peripheral-zone points

When calculating the coordinates of peripheral-zone points, we need to know the concrete coordinate of the starting point and the normal vector \( N_1 \) at this point. The position coordinate of the starting point can be obtained by the ending point designed by the intensity-mapping method. In addition, we define \( N_2 \) as the normal vector at the end point calculated by the intensity-mapping method. There exists an angle deviation between these two vectors and here we define \( \theta_d \) as the angle deviation. The expression of \( \theta_d \) is

\[ \theta_d = \cos^{-1} \left( \frac{N_1 \cdot N_2}{|N_1| \cdot |N_2|} \right). \]

To ensure the continuity of the joint position, a threshold \( \theta_{\text{th}} \) is introduced to control the angle deviation \( \theta_d \). For example, if we set \( \theta_{\text{th}} \) as 5 deg, then, \( \theta_d \) must be smaller than 5 deg strictly.

Based on the energy-mapping method, a series of incident and refractive vectors can be calculated. According to Snell’s law the incident vector, refractive vector, and normal vector on the freeform surface can be connected. That is

\[ 1 + n^2 - 2n(O \cdot I) = |N|, \]

where \( I \) and \( O \) are denoted as the unit incident vector and refractive vector, respectively. \( N \) represents the unit normal vector at the intersection point of the incident ray and freeform lens surface. Here, the emergence medium is air and the refractive index of air equals 1. \( n \) indicates the refractive index of the incidence medium, namely the encapsulating material of the freeform lens.

According to Eq. (18), we can calculate the normal vector and then the tangential plane. The following point is calculated by computing the intersection of the incident ray and the tangent plane. In a similar way, we can obtain all the points of the profile curve.

2.3.3 Constructing freeform lens model

After the coordinates of all points are obtained, such points are imported into the software Rhinoceros to generate the freeform lens model, which can be imported into optical analysis software Tracepro in an ACIS file format to conduct a ray tracing simulation. The ray tracing is based on a Monte Carlo algorithm and its simulation results can be an effective evaluation factor for the optical performance of the designed freeform lens. Actually, if the LED light source is no longer an ideal point source, the illumination will deteriorate on the target surface under the initial freeform lens. The feedback method has been demonstrated as an effective way to achieve uniform illumination for an extended source.
next section, we will discuss the proposed iterative feedback method as applied in our combined design method in detail.

2.4 Iterative Feedback Optimization

If the LED light source becomes an extended source, the illumination will deteriorate dramatically and the light spot will spread outside the target zone. Therefore, we introduce an iterative feedback function to optimize the freeform lens. The optimization steps are as follows:

1. Calculate the 2-D contour curve of the freeform lens for uniform illumination on the target surface based on the point light source.

2. Establish an optical model to conduct ray tracing, in which the light source is an extended source, and obtain the illumination distribution on the target surface. Verify whether or not the illumination uniformity satisfies the requirement. Here, we define illumination uniformity $U_E$ as

$$U_E = \frac{E_{\text{min}}}{E_{\text{max}}},$$

where $E_{\text{min}}, E_{\text{max}}$ are the minimum and maximum illumination values among the certain zone, respectively.

If $U_E$ exceeds the preset value, stop optimization and export curve coordinates. If not, extract the illumination values along the central horizontal axis and continue to the next step.

3. Calculate the energy feedback function $E_f^{25}$

$$E_f(i) = 2(1 + \varepsilon)E_{\text{average}} - E_a(i), \quad i = 0, 1, 2, \ldots, N$$

and $|\varepsilon| \leq 0.1$.

4. According to the computed radius of each ring, we can obtain the 2-D contour curve of the freeform lens and conduct the corresponding simulation. Verify whether the illumination uniformity along the central horizontal axis satisfies the requirement. If $U_E$ exceeds the preset value, stop the optimization and export the curve coordinates. If it does not, go back to the last step.

The whole design process of the combined mapping method is shown in Fig. 3.

3 Design Examples and Analysis

To demonstrate the effectiveness of the proposed combined method, we designed two types of freeform lens applied for an ideal point light source and extended source, respectively. In the example related to the extended source, the freeform lens designed by energy mapping was set to be a counterpart and the illumination uniformity was inferior to that of the lens design by the proposed combined method. In the example related to the extended source, our energy

![Fig. 3 The design flowchart of the combined method.](image-url)
feedback function shows high-efficient optimizing ability. Optimization was only conducted one time to achieve the preset illumination uniformity, which is due to the appropriate values of $\varepsilon$, $k$ used in the energy feedback function and grid optimization coefficient.

For our examples, the design parameters are shown in Table 1. The distance between the LED light source and the target surface is 2 m and the radius of the light spot is 3.5 m. The emitting angle of the designed light source is 120 deg. Here, silicone with a refractive index of 1.54 is used as the encapsulating material, due to its excellent characteristics such as transparency, high resistance to temperature and weather, electrical insulation, and so on. The central apex height of the freeform lens is 10 mm. In the example related to the point source shown in Fig. 4(a), the LED light source is actually a blue GaN chip with a size of 350 $\mu$m $\times$ 350 $\mu$m, covered with a down-converted yellow phosphor. In the example related to the extended source shown in Fig. 4(b), the light source is a circular luminous surface with a diameter of 6 mm with a multichip configuration coated with yellow phosphor. In the white LED light source, blue light emitted by GaN chip is combined with down-converted yellow light to generate white light with a different correlated color temperature. To simplify the simulation, the phosphor layer was overlooked and only the blue LED chip with the emitting wavelength of 455 nm was employed in the optical ray tracing. The simulation results are also applicable for white LEDs. 26

3.1 Design Example for Point Light Source Based on the Combined Method

The design example was based on a point light source for uniform illumination. We conducted the related computation using energy and the combined mapping method. In our design, the incident angle range $[0, \pi/2]$ is divided into 1000 subintervals. The specific designing angle range is based on the illumination distribution of the energy-mapping method. Since the illumination peak is induced by the large surface error in the central region, the freeform surface around the axis needs to be redesigned by the intensity-mapping method. The minimum exiting angle $\theta_{\text{min}}$ used in the central region is 0.1, and the corresponding illumination area on the target screen is the circular area with a radius of 350 mm. In the intensity mapping design, the central angle range around the normal axis is redivided into 10 evenly distributed sub-intervals and the central positions of the contour profile are calculated by the corresponding algorithm to replace the original points.

The corresponding optical simulations based on the energy-mapping method and the combined mapping method were conducted and the illumination results are shown in Figs. 5(a) and 5(b), respectively. Here, we define the ratio between the minimum and maximum illumination values within the circle with the radius of 2.5 m as the illumination uniformity on the target surface and the ratio between the received energy and the light output power as the energy efficiency on the target surface. In Fig. 5(a), the illumination uniformity and the energy efficiency on the target surface are 78.25% and 95%, respectively, for the energy-mapping method. In Fig. 5(b), the corresponding values are 89.76% and 94.69%, respectively, for the combined mapping method. The illumination uniformity for the combined method was 87.5% and 95%, respectively. The simulation results are also applicable for white LEDs. 26

<table>
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<th>Table 1 Freeform lens design parameters.</th>
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<tr>
<td>Distance between lens and target surface</td>
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<td>Radius of light spot</td>
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<tr>
<td>Lens refractive index</td>
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<td>Central height of freeform lens</td>
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Fig. 4 (a) The point source model and (b) extended-source model of freeform lens design.

Fig. 5 Illumination performance of freeform lens based on (a) the energy-mapping method and (b) the combined method.
mapping method is 11.51% higher than that for energy-mapping method, whereas the energy efficiency for both methods remains almost the same, which demonstrates that the combined mapping method is a valid approach to eliminate the illumination aberration of the central position. Based on the combined mapping method, the illumination peak caused by the energy method disappears and the illumination curve is very flat. Figure 6 shows the light intensity distributions for different mapping methods. Both mapping methods present the same highest light intensity at viewing angles of ±55 deg and a half-peak boundary at viewing angles of ±60 deg. The only difference lies in the center where the energy-mapping method shows a hump, whereas the combined mapping method appears smooth. The smoothness of the light intensity distribution based on the combined mapping method also demonstrates the effectiveness in uniform illumination design.

In Fig. 5(a), the illumination uniformity around the peripheral region is higher than that of the central region for the energy method and shows no difference with the combined method. The illumination peak in the central region is the main cause of illumination uniformity deterioration on the target surface. In the energy method, we always assume that the normal vector in the initial position is vertically upward. However, there exists an unavoidable error between the assumed normal vector and the real vector in the initial angle interval, which is the cause of the appearance of an illumination peak. In the energy-mapping method, the angle range is divided according to the equal-energy principle, leading to the extremely large angle intervals on both sides, as shown in Fig. 7. Due to the Lambertian distribution of the LED light source, the central intensity has the highest value and is more sensitive to the surface error. The surface error leads the light ray among the initial angle interval to concentrate at the central position, which causes the irradiance peak in the central region. The irradiance peak is more obvious when the divided angle intervals are insufficient. If we enlarge the number of divided angle intervals, or add fitted points to the lens profile, the illumination aberration phenomenon will be improved. However, the phenomenon will not vanish totally, for the error could not be eliminated completely. Much larger angle intervals would enlarge the calculation and are not beneficial for computing. For the intensity method, arbitrary angle division is allowed, which could compensate the drawback of equal-energy division, especially in the central region. In this design example, the incident angle $\theta_1$ in the central region was redivided into 10 evenly distributed subintervals and then the positions of the contour profile were calculated correspondingly. The evenly distributed subinterval (0.01) has a smaller interval length than the original central one based on the energy-mapping method (0.03). The smaller subinterval causes less surface error in the profile calculation and contributes to the high illumination uniformity in the central region. In addition, though large angle intervals also exist in the edge area, the illumination distribution shows less aberration compared to that in the central region. The reason is that light intensity in this zone is near zero and large surface error has little influence on the incident ray; therefore, there is no need to redesign the profile in the edge area.

3.2 Freeform Lens Design for Extended Light Source

The design example was based on an extended light source, which was a circular luminous surface with the diameter of 6 mm. The simulated illumination results are shown in Fig. 8. Due to the extended size of the LED light source, the freeform lens based on the point light source is not suitable for the application. In Fig. 8, the illumination distribution is not uniform and shows a trend in which the illumination value in the middle is higher than that on both sides. The illumination uniformity is 74.22% and the energy efficiency is 88.76%.
For improving the illumination distribution, an iterative feedback optimization is needed. The steps for the iterative feedback optimization are shown in Sec. 2.4. The uniformity value is required to be over 90%. The baseline controlling coefficient $\epsilon$ is set as zero. When the illumination value is higher than the average value, the optimization factor $k$ is set as 1. Otherwise, $k$ is set as zero. The determination of $k$ means that the part of energy in the middle could be distributed to both sides to achieve uniform illumination on the target surface. According to the optimization principle, the optimization factor versus a divided grid was calculated, as shown in Fig. 9(a). Based on the optimization factor, the new lens profile could be computed, shown in Fig. 9(b). Compared with the initial lens profile, the new profile is larger and is 0.7 mm wider.

Based on the new lens profile, we constructed a new freeform lens suitable for the extended light source using the combined method and optical simulation. The simulation results are shown in Fig. 10(a) and the illumination uniformity is 95.32%, exceeding the preset value 90% and 21.1% higher than that of nonoptimized lens profile. The energy efficiency is 87.29%, which is almost the same as that of the nonoptimized lens. Only one optimization was conducted to achieve the preset uniformity, which means that the proposed optimization algorithm was efficient. The high efficiency is due to the appropriate values of the baseline controlling coefficient $\epsilon$ and the optimization factor $k$. The proposed method, which inherits the superiority of the energy-mapping method, exhibits an excellent ability on freeform design for an extended light source.

To be compared with the combined mapping method, an example based on intensity mapping method has also been set to obtain a freeform lens. First, the near-field light intensity of the extended light source can be obtained based on the ray tracing result and considering the circular symmetry of the light source, it can be expressed as

$$I_S(\theta) = a_0 + a_1\theta^2 + a_2\theta^4 + a_3\theta^6 + a_4\theta^8 + a_5\theta^{10}. \quad (24)$$

The values of the polynomial coefficients are 1.002, −0.1436, 0.02196, −0.4659, 0.3242, −0.06008, respectively. Then the profile of the freeform lens can be obtained based on the corresponding algorithm as shown in Fig. 9(b) and the ray tracing based on the new freeform lens was conducted. As shown in Fig. 10(b), the illumination uniformity and energy efficiency are only 64.36% and 83.81%, which are lower than the optimized results of the combined method. On one hand, the near-field and mid-field intensity distributions vary with different distances and are hard to describe, which limits the design accuracy. On the other hand, the rays emitted from a certain point on the freeform lens surface come from different positions of the extended source and will not be refracted toward the same position on the target surface, which causes design difficulties for the intensity mapping method.

Figure 11 shows the light intensity distributions before and after optimization. The viewing angles of peak intensity
and half-peak boundary are almost the same before and after optimization. The great difference lies in the center. After optimization, the combined mapping method shows a lower intensity in the center, which can be attributed to the fact that central energy is distributed toward the edge area. In contrast with the mapping method, the intensity mapping method shows an opposite trend in the energy redistribution, which causes the deterioration of illumination uniformity on the target surface. The uniformity deterioration demonstrates the failure of the intensity mapping method in the freeform lens design for extended sources.

4 Conclusions

In this paper, we propose a composite method combining the energy and intensity mapping methods to overcome the limitations of a conventional energy method. This method takes advantage of arbitrarily divided subintervals of intensity mapping to compensate the drawback of irregular sampling in the energy-mapping method, thus eliminating the hot spot in the central region. The design example has demonstrated that the illumination uniformity increases from 78.25% to 89.76% with a high-energy efficiency of 94.69%, almost the same as the 95% of the conventional method. In the extended-source-design example, the baseline control coefficient ε and optimization factor k are appropriately chosen to achieve effective and fast feedback optimization. Optimization is only conducted one time to reach the preset uniformity value, which increases from 74.22% to 95.32% while only adding 1.47% energy loss. Furthermore, not only can this method be applied in the design of circular uniform illumination, but also can be well extended to noncircular uniform illumination, which will be studied in further research.

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References


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