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A laser beam shaper for homogeneous rectangular illumination based on freeform micro lens array*

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An effective design method of freeform micro lens array is presented for shaping varied laser beams into prescribed rectangular illumination. The variable separation mapping is applied to design concave freeform surfaces for constructing a freeform lens array. Several dedicated examples show that the designed freeform optical lens array can achieve a prescribed rectangular illumination pattern, especially without considering the initial states of incident laser beams. Both high collection efficiency and good spatial uniformity can be available simultaneously. Tolerance analysis is also performed to demonstrate that this optical device can well avoid fabricating difficulty in actual applications.

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Laser sources, characterized by the advantages of identical directional propagation, good energy concentration and low spatial wastage, are extensively applied in different research fields[1-6]. During the utilization of laser beams, the inherent characteristics of intensity distribution, beam location and cross section have to be taken into account as separate influence factors. Nowadays, the beam shaping of homogeneous rectangular illumination with freeform optical lens is demonstrated to be a challenging research topic[7,8]. It is becoming a preferred route to apply freeform surfaces to illumination design due to the high degree of design freedom. Freeform surfaces will make it possible to produce uniform rectangular illumination patterns to perfectly match the target. It is more likely to obtain a volume-miniaturized design with similar optical performance. During conventional designs, the freeform optical surface that meets a predefined mapping is always designed to redirect the light beam which has a fixed pattern and intensity distribution. It indicates that the source, the freeform optical element and the target are in fixed one-to-one correspondence with each other[9-13]. In other words, these designs have an obvious limitation of design flexibility. In practical applications, a design, which is less sensitive to the initial states of the laser beam, will be more preferred. To realize this purpose, we present a laser beam shaping device integrated by freeform micro optical lens array to achieve prescribed uniform illumination without considering the initial states of incident light source. Laser beams characterized by different spatial distributions or discontinuous cross sections can be flexibly employed as an incident light source. It will be demonstrated that the optical characteristics of the proposed design are satisfactory.

The proposed beam shaper is composed of a micro freeform lens array and a subsequent regular lens. The freeform lens array is constructed by multiple micro optical units. Each unit has an entrance planar surface and an exit freeform surface. As shown in Fig.1, the well-collimated laser beam firstly transmits through the front planar surface without any refraction, then is redirected by the rear freeform surface, and finally focused by the regular lens onto the target plane. The entrance surface of the optical unit is planar, which means that the propagation direction and the intensity distribution will be identical to those of the incident collimated beam. The key problem becomes a mathematical solution that can accurately define the freeform surface. Assume that an arbitrary ray of the incident beam intersects the freeform surface at point $P(x,y,z(x,y))$, and is finally refracted to

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point T on the target plane. $P(x,y,z(x,y))$ is the exact coordinate to be solved. The unit normal vector $\boldsymbol{N}$ of the freeform surface at point P should be firstly determined. In the Cartesian coordinate system, the unit normal vector at point P is given by

$$\boldsymbol{N}=\frac{1}{\sqrt{z_x^2+z_y^2+1}}(-z_x,-z_y,1)\,, \tag{1}$$

where z_x and z_y are the first-order partial derivatives of the coordinate z with respect to x and y, respectively. According to the Snell's law, a set of first-order partial differential equations (PDEs) can be deduced:

$$\begin{cases} z_x=-O_x\big/\left(O_z-n\right) \\ z_y=-O_y\big/\left(O_z-n\right) \end{cases}, \tag{2}$$

where $\boldsymbol{O}=(O_x,O_y,O_z)$. The unit vector $\boldsymbol{O}$ can be determined by the variable separation mapping of the freeform micro optical element, as shown in Fig.1. Assume that the freeform surface has a square aperture with an area of $W_x\times W_y$, and the final illumination region is a rectangular one with an area of $L_x\times L_y$. The energy separation grids on the freeform surface and the target plane are proportionally divided according to the longitude and latitude directions, respectively. Actually, the boundary of the target pattern is no longer limited by the aperture of freeform micro optical device. That implies an improvement to the conventional micro lens design. Based on the Snell's law and the convergence of the regular lens, the unit vector $\boldsymbol{O}$ at the target point $T_i(t_{xi},t_{yi},t_{zi})$ on the target plane is defined by

$$\boldsymbol{O}=\frac{1}{\sqrt{t_{xi}^2+t_{yi}^2+f^2}}(t_{xi},t_{yi},f)\,, \tag{3}$$

where $t_{zi}=l$, l is the distance between the entrance surface of the freeform optical unit and the target plane, and f is the focal length of the regular lens. By substituting Eq.(3) into Eq.(2), a set of discrete data points can be solved numerically with the fourth-order Runge-Kutta formulas. Then the freeform surface is constructed to pass through these data points. According to the aperture of the incident collimated beam, a freeform lens integrated with the calculated micro surface could be established. Based on the variable separation mapping method, one-to-one correspondence should be established between the freeform unit and the target plane to realize prescribed illumination. The proposed variable separation mapping is shown in Fig.1. According to the mapping relation, we should choose the concave freeform surfaces with the convex connection to construct the freeform unit. This can well avoid fabrication difficulty in actual applications.

Several dedicated examples and the corresponding tolerance analysis are provided to verify the effectiveness of the proposed design. The optical construction and the actual function of the proposed laser beam shaper are illustrated clearly in Fig.2. A cross-shaped well-collimated laser is employed as the incident light source. The freeform optical lens array has multiple optical units that can divide the incident beam into several sub-beams. A regular lens is located closely behind the freeform optical lens array. Homogeneous rectangular illumination on the target can be finally available on the target plane. Fig.2 also shows the 3D rainbow-colored illumination map with normalized luminance levels. Actually, the incident laser source of any irregular beam profile can be well shaped into prescribed rectangular illumination by this device. In Fig.3, a laser source with the beam profile of two letters "O" and "E", i.e., the abbreviated form of "Opto-Electronics", is specifically created as the system source. Target rectangular illumination can be also achieved after beam shaping. Fig.3(a) shows the rainbow-colored rectangular illumination on the target plane. By comparison between Fig.2 and Fig.3, it is not difficult to validate that a definite freeform lens array can present similar optical performance while employing varied laser source.

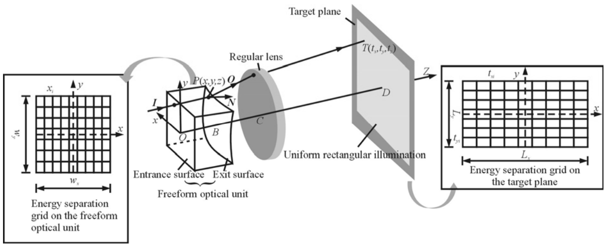


Fig.1 The variable separation mapping of the proposed design

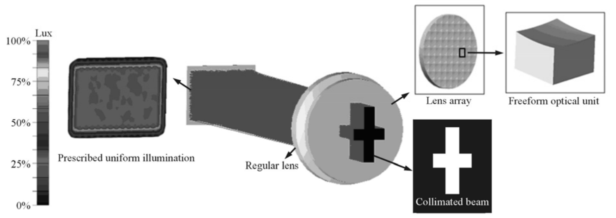


Fig.2 The optical construction and design verification of the laser beam shaper

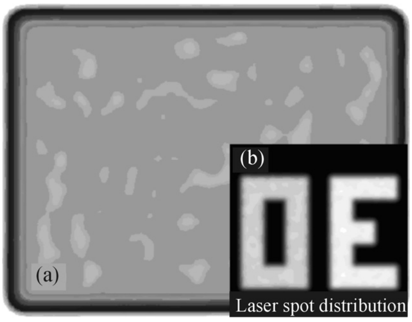
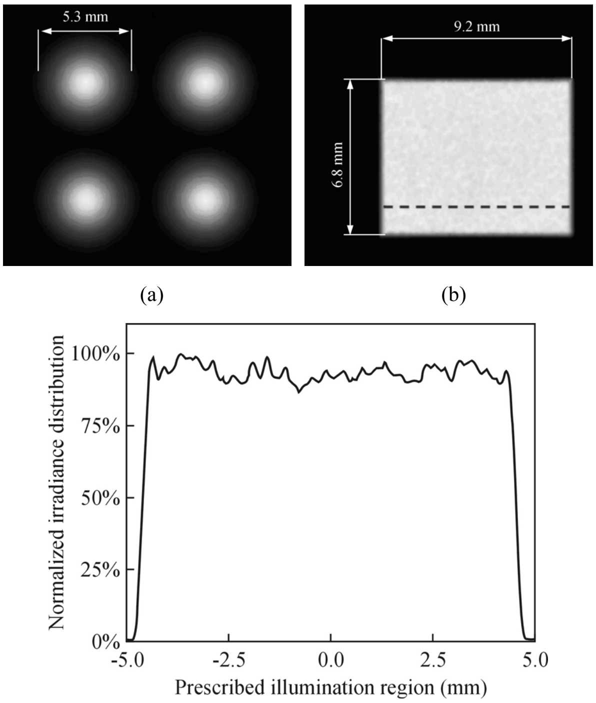


Fig.3 (a) The rainbow-colored rectangular illumination on the target plane; (b) The specifically created laser source with beam profile of two-letter abbreviations of "Opto-Electronics"

As illustrated above, it is possible to shape any irregular beam profile into rectangular illumination with good optical performance by the lens array. Uniform intensity distribution is a common feature of the above examples. However, whether the device can be used for complex beam shaping (e.g., discontinuous beam distribution or non-uniform beam distribution) is still unknown. To further develop the potentials, another kind of laser beam with Gaussian intensity distribution and discrete circular sub-beams is employed as the light source, as shown in Fig.4(a). The whole beam spot is composed of four independent regions, each of which is a non-uniform circular one with a radius of 2.65 mm. This represents a tough challenge for conventional optical device to achieve rectangular illumination. However, the proposed design provides an effective solution. After the corresponding simulation experiment, the final system transmission efficiency is 96.3% on the target plane. The normalized irradiance distribution along the reference lines on the target illumination region shows that homogeneous rectangular illumination is available at the same time. If the illumination spatial uniformity is defined as the minimum value divided by the maximum one, the system uniformity is 87.3% within the effective lighting area. It demonstrates that the designed beam shaper can achieve prescribed rectangular illumination without considering the initial states of laser source.

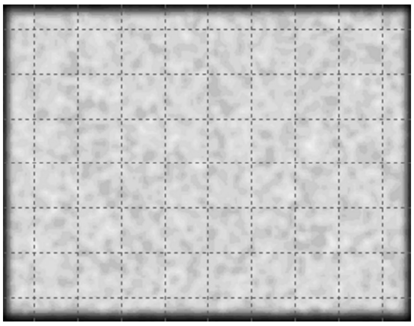


(a) (b)

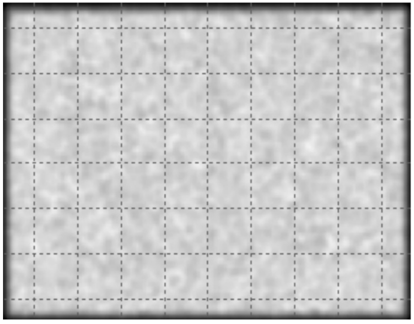
(c)

Fig.4 (a) The pattern of the compound collimated light source; (b) The result of homogeneous rectangular illumination on the target; (c) The normalized irradiance distribution along the reference lines on the target illumination region

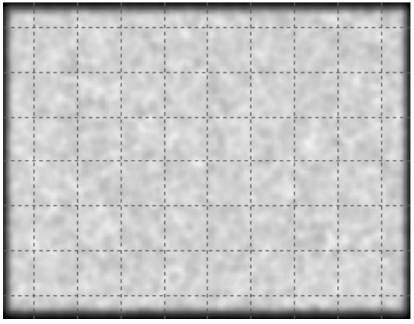
Tolerance analysis is an essential tool to verify optical devices. Position tolerance and rotation tolerance are both analyzed here. In Fig.5, the system optical values of collection efficiency and spatial uniformity do not show any obvious change while the distance between the light source and the optical device varies from 1 mm to 8 mm. The system transmission efficiency gradually decreases, and finally drops to 91.6%. It implies that the designed device has a good position tolerance. However, rotation tolerance of the device is not as stable as the position tolerance. While the incident beam rotates a certain angle around the axis, the optical values are also recorded and analyzed. As shown in Fig.6, the collection efficiency is stable at 91.6% and the spatial uniformity has no visible decrease while rotation deviation is within the range from 1° to 5° around the axis. While rotation deviation reaches 8°, some light and dark patterns can be obviously observed, which may influence the spatial uniformity of the device. Nevertheless, it can be concluded that the designed beam shaper is well acceptable for actual applications.



(a) Position deviation at 1 mm on axis

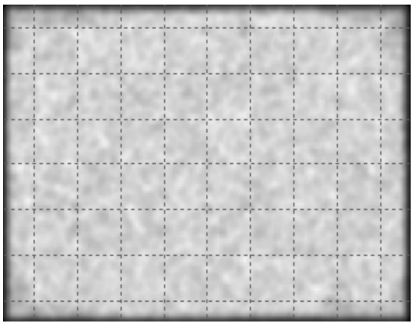


(b) Position deviation at 5 mm on axis

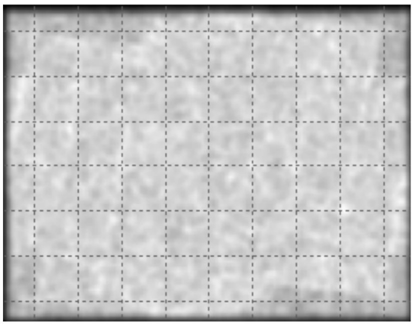


(c) Position deviation at 8 mm on axis

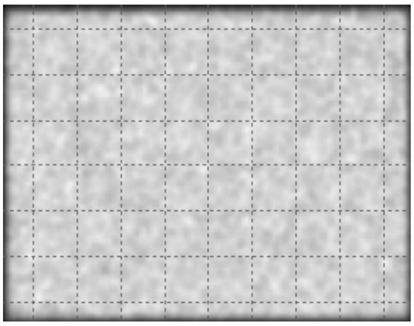
Fig.5 Position tolerance of the designed freeform optical lens array



(a) Rotation deviation at 1° around axis



(b) Rotation deviation at 5° around axis



(c) Rotation deviation at 8° around axis

Fig.6 Rotation tolerance of the designed freeform optical lens array

This paper presents a kind of freeform micro optical array to achieve prescribed uniform illumination without considering the initial states of laser source. To verify the design, laser sources with irregular emitting surfaces, Gaussian intensity distribution and circular discrete sub-beams are employed as the light source, respectively. The concave freeform surfaces with the convex connection are derived and calculated to construct the lens array, which can well avoid fabrication difficulty in actual applications. Simulation results show that the prescribed rectangular illumination can be achieved with high efficiency and good uniformity. Further, the designed device is also verified to have acceptable tolerance potential for actual applications.

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