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Gaussian beam shaping based on aspheric cylindrical lenses*

SHI Guang-yuan (史光远), LI Song (李松), HUANG Ke (黄科), YI Hong (易洪), and YANG Jin-ling (杨晋陵)**

Electronic Information School, Wuhan University, Wuhan 430072, China

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We propose a specific aspheric cylindrical optical system to transform Gaussian beam to flat-top and rectangular beam. The Gaussian beam shaping system is composed of dual orthogonal aspheric cylindrical lenses. The principle of shaping Gaussian beam is studied theoretically. The mapping function of arbitrary rays in an incident plane and an image plane is deduced based on the law of energy conservation, and the real ray tracing method is adopted to design the shaping system. Finally, the lens system is processed by single point diamond turning techniques. Testing results indicate that the system achieves the theoretical expectation, and the uniformity of flat-top and rectangular beam is 88.2%. The method is not only simple but also practical.

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Ever since the invention of the laser, it has been recognized that the typical intensity distribution and shape of a Gaussian beam are often undesirable for practical applications, especially in those fields requiring uniform illumination of an extended rectangular area, for example, lidar technology, pattern recognition, lithography, optical data storage, materials processing and nonlinear optics[1-3].

In recent years, some new laser shaping techniques, including refractive optical system[4-7], diffractive optics[8] and liquid crystal spatial light modulator[9], are developed to redistribute the irradiance and shape of the input beam. Among them, the refractive optical system has the excellent shaping performance and the high energy efficiency, and it is suitable for high power laser. The single aspheric lens can transform the Gaussian beam to the flat-top beam at a certain distance[10,11]. Based on this theory, in this paper, we use the dual orthogonal aspheric cylindrical lenses to transform the shape of laser beam and meanwhile to redistribute its irradiance from Gaussian shape to uniform one on two axis directions.

The principle of beam shaping by a single aspheric cylinder lens is shown in Fig.1. Assume that the input collimated laser beam is injected from the left, and the irradiance with single-mode Gaussian distribution is generated to exist in plane A. In plane B which is at a specified distance away, the irradiance on Y axis direction is uniform, while the irradiance on X axis direction remains Gaussian distribution. According to geometrical optics, due to the presence of aspheric cylindrical lens on the right of plane A, the radiation on y axis direction within any section of $[0, y]$ ($y \leq y_{\max}$) in the plane A can be assumed to strike the plane B within the corresponding section of $[0, Y]$ ($Y \leq Y_{\max}$). Therefore, it is reasonable to seek one path $Y(y)$ for each ray with height of y in plane A which corresponds to Y in plane B.

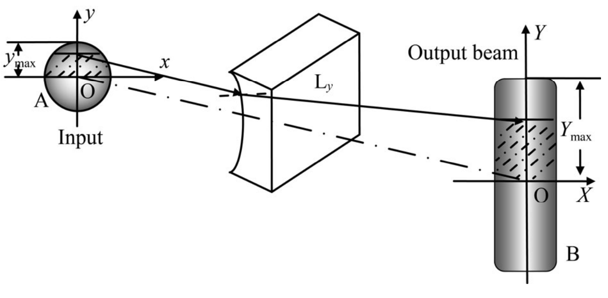

Fig.1 Schematic diagram of principle for beam shaping by a single aspheric cylinder lens

In plane A, the total power of input beam $P_A(y)$ within the section of $[0, y]$ ($y \leq y_{\max}$) on y axis direction is given by

$$P_{\mathrm{A}}(y) = P\left[1 - \exp\left(\frac{-y_{\max}^2}{2\omega_0}\right)\right]^{-1} \exp\left(\frac{-y^2}{2\omega_0^2}\right) , \qquad (1)$$

where ω_0 is the waist of Gaussian beam, and P is the total power of input beam within $y_{\max}$.

Assume that the pupil radius of plane B is $Y_{\max}$ and the irradiance must be constant on Y axis direction. Considering the energy loss coefficient τ caused by lens, the

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** E-mail: shigy1988@163.com

total power of output beam $P_B(Y)$ is given by

$$P_{\mathrm{B}}(Y)=(1-\tau)P\left(\frac{Y}{Y_{\max}}\right)^2 . \tag{2}$$

Assuming $P_A(y)=P_B(Y)$, we can get the relationship between coordinate y of arbitrary rays in incident plane A and coordinate Y in exit plane B according to Eqs.(1) and (2), so the mapping function is given by

$$Y(y)=\pm(1-\tau)Y_{\max}\left[1-\exp\left(\frac{-y_{\max}^2}{2\omega_0^2}\right)\right]^{1/2} \cdot \left[1-\exp\left(\frac{-y^2}{2\omega_0^2}\right)\right]^{1/2} , \tag{3}$$

where the sign ±, which implies two solutions to the problem, represents a choice of power for the optical element. The sign – would require the positive power element, so all rays must be refracted across the optical axis. The sign + would choose the negative power element, so the input rays and the output rays are on the same side of the optical axis. In addition, this function indicates that the aspheric cylindrical lens can expand the beam size from $y_{\max}$ to $Y_{\max}$, and transform the beam irradiance from Gaussian distribution into uniform distribution on Y axis direction.

As shown in Fig.2, this design method employs two aspheric cylindrical lenses L_x and L_y which form a combination of two separate cylindrical lenses with their symmetry axes perpendicular to each other. The beams with Gaussian distribution on X and Y axis directions are reshaped by lenses L_x and L_y, respectively. We can design the aspheric cylindrical lens L_x with the refractive power significantly different from that of lens L_y in each axis. As a result, the intensity distribution of output beam is flat-top, and its shape is rectangle.

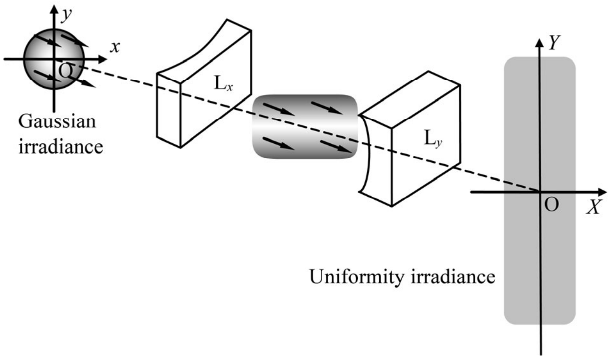


Fig.2 Schematic diagram of beam shaping system with two aspheric cylinder lenses L_x and L_y

The method of automatic optimization design for Gaussian beam shaping by using ZEMAX software is introduced, and the ZEMAX programming language (ZPL) is used to compile the macro order to extend the optimization function[12].

To design a specific beam shaper, the parameters of input beam are as follows: the waist of Gaussian beam is 5 mm, the wavelength is 632.8 nm, the target beam has flat-top irradiance, the shape of beam profile is rectangle, and the size is about 100 mm×800 mm at the distance of 2 000 mm.

Here are some steps to complete this beam shaper by ZEMAX method. (I) In the ZEMAX lens data editor, set the surface type as "Toroidal" to establish the aspheric cylindrical lens and select the radius, conic and high-order coefficients of lens as variables. Then, set the aperture style as "Gaussian" to simulate the irradiance of input beam. The diameter of entrance pupil must be more than 4 times larger than the waist of Gaussian beam in order to avoid the diffraction effect[13]. (II) According to Eq.(3), calculate the coordinate of every ray on the exit plane for the related incident ray. ZEMAX software is used to optimize the system by establishing the operation of "REAY" in the merit function editor, where the operation of "REAY" stands for the mapping relationship of the ray coordinates in incident plane and in exit plane. To get the desired result, more than 500 sampling rays are essential. However, it is a time-consuming job to input 500 operations one by one. To solve this problem, by using ZPL, the ray coordinates can be calculated automatically, and all the operations can be generated simultaneously. (III) The lenses L_x and L_y need to be optimized, respectively, and then the ZEMAX non-sequential mode is applied to simulate the characteristics of the beam shaping system.

The basic parameters of the shaper are shown in Tab.1. The second and the forth surfaces are even asphere, and the aspheric coefficients are shown in Tab.2.

Tab.1 Basic parameters of the shaper

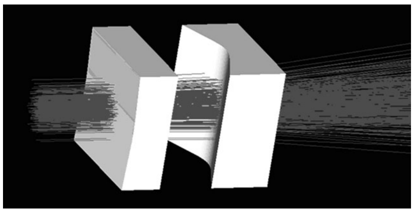
Surface type	Diameter (mm)	Radius (mm)	Conic	Thickness (mm)	Glass
Stop	30	–63.826	13.277	10	Silica
1	30	0	0	5	Air
2	30	–7.935	–2.985	10	Silica
3	30	0	0	2 000	Air

Tab.2 Aspheric coefficients of the shaper

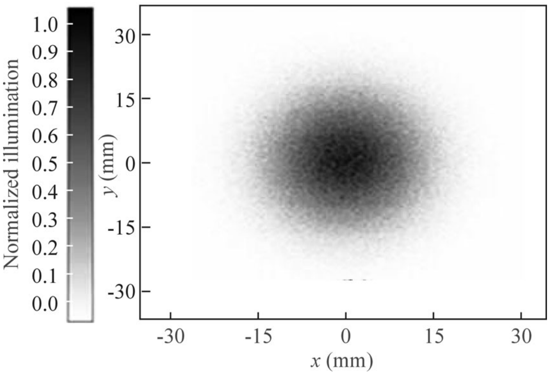
Surface type	4th order term	6th order term	8th order term	10th order term	12th order term
2	8.315×10^{-5}	-6.497×10^{-7}	3.742×10^{-9}	-1.161×10^{-11}	1.593×10^{-13}
4	1.624×10^{-5}	-1.493×10^{-7}	7.433×10^{-9}	-1.952×10^{-11}	2.105×10^{-13}

The design result of the shaper system at the distance of 2 000 mm is shown in Fig.3. Fig.3(a) is the layout of optical system, Fig.3(b) and (c) show the energy distributions of input beam and output beam, and Fig.3(d) and (e) show the energy distributions of output beam on Y axis and X axis. As shown in Fig.3(c)–(e), the shape of beam profile is rectangle, and the size is about 100 mm×800 mm.

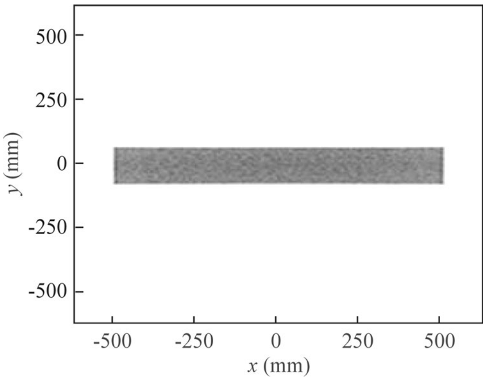
The photo of experimental setup is shown in Fig.4. The waist of laser beam is converted to 5 mm by beamexpanding telescope, and then the collimated beam propogates through the beam shaper. Finally, the illuminance of output beam is tested by the MINOLTA CL-500A illuminometer, and the tested data can be analyzed by digital image manage software. Two plane-concave cylindrical lenses in the shaper both have negative refractive power, which can avoid the ray to be focused to damage devices. As shown in Fig.4, the Gaussian beam transforms to the flattened and rectangular beam, the central energy distribution is quite uniform, and the edge shows slight energy attenuation.



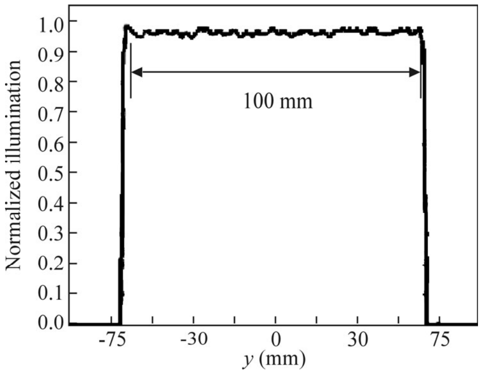
(a) Layout of optical system



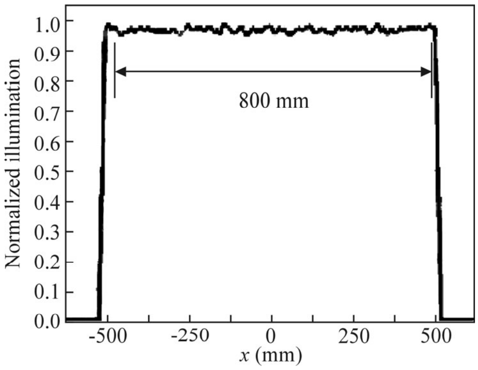
(b) Energy distribution of input beam



(c) Energy distribution of output beam



(d) Energy distribution of output beam on *Y* axis



(e) Energy distribution of output beam on *X* axis

Fig.3 The design results of the shaper system

Fig.4 Photo of the experimental setup

Define the relative uniformity γ as[14]

$$\gamma = 1 - \frac{\sqrt{\sum\left(E_{\mathrm{i}} - \bar{E}\right)/N}}{\bar{E}}, \tag{4}$$

where N is the sampling grid of 10×80 within the rectangular region of 100 mm×800 mm, E_{i} is the normalized illuminance for every sampling point, and $\bar{E}$ is the average illuminance for all the points. According to Eq.(4), the relative uniformity is about 88.2%. Fig.5 shows the intensity distribution of output beam. Due to the surface errors of lens and some differences between actual beam profile and ideal Gaussian distribution, there are some gaps between experiment result and theoretical design. Generally, the experimental result indicates that the beam shaper can achieve the theoretical expectation.

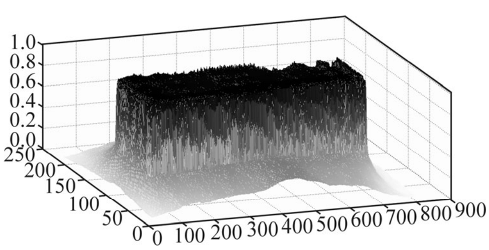


Fig.5 The intensity distribution of output beam

In summary, the Gaussian beam shaping system based on dual orthogonal aspheric cylindrical lenses is presented in this paper, which can transform the Gaussian beam to the flat-top and rectangular beam. The principle of beam shaper is analyzed in detail. Using ZEMAX software greatly simplifies the process of design. In fact, this system can be also applied to get various dimensional rectangular spots by choosing appropriate parameters of two aspheric cylindrical lenses. The method with significant engineering application value is not only simple but also practical.

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