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One-Dimensional Reflective Diffuser for Line Beam Shaper with Microlens Array Homogenizer

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A laser beam shaping architecture based on a microlens array homogenizer has been exploited, in which the interference effect due to the coherency of the laser source deteriorates the uniformity. Moving diffusers have been considered as an effective way of averaging out the interference pattern. Because the uniformity is required in the line direction only, a one-dimensional reflective-type diffuser with a well-controlled diffusion angle has been proposed and prototyped. The diffuser is attached onto a rotating cylinder for movement in operation. The experiment demonstrates the effectiveness of the scheme, and a line beam with a uniformity of up to 92% has been achieved.

Keywords: laser beam shaping, one-dimensional reflective diffuser

1. Introduction

A line beam shaper has been successfully used as an efficient tool for processing a large-area substrate with a fine feature structure, such as when annealing the thin film transistor liquid crystal display and solar panel.[1,2] The architecture shown in Fig. 1 has been proposed for the line beam shaper, in which the microlens array serves as the homogenizer. The first microlens array dissects the incident laser beam into several parts, and the second microlens array, together with the condenser lens following it, maps each lenslet on the first microlens array onto the target line, as shown by the light path in Fig. 1. Therefore, each part of the illumination on the first microlens array will illuminate the whole line on the target plane, which will result in a uniform illumination on the target plane even if the incident light beam on the first microlens array is not sufficiently uniform. The finer the pitch of the microlens array, the better the uniformity is. Because the uniformity is required in the line direction only, the lens arrays shown in Fig. 1 are both composed of cylindrical lenslets. However, in this architecture, the interference between the light from the sectional area of the microlens array could deteriorate the line beam uniformity, especially for the highly coherent laser source.[3,4] One effective approach to resolve this issue is to use a moving diffuser to reduce the coherency of the laser source or to average out the interference pattern.[5,6] In those works, more than one transmissive diffuser with a large diffusion angle was used. The mechanism for eliminating the interference pattern is the relative motion between two diffusers. The effect of interference reduction is prominent, but the structure might not be suitable for cases where efficiency and energy concentration are the major concerns. This concept is adopted for the proposed line beam shaper, but a dedicated diffuser has been designed and fabricated to meet the special requirement of the system, especially regarding the concerns of efficiency and line beam shaping.

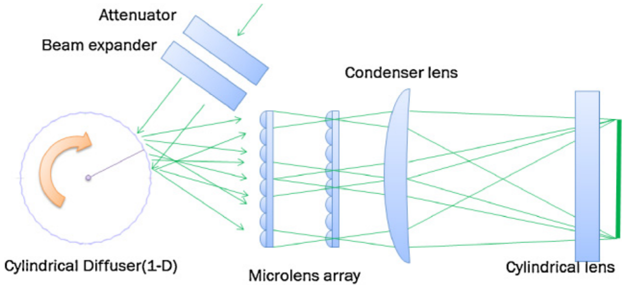

Fig. 1. (Color online) Line beam shaper with microlens array homogenizer and rotating 1D reflective diffuser.

The diffuser can be transmissive or reflective, where the latter type can provide better efficiency, which is important for laser processing systems, although there is the sacrifice of light path complexity. In addition, for the case of line laser beam, the interference issue needs to be resolved in the line direction only, and the other direction should be undisturbed by the diffuser so as to maintain collimation for the ease of focusing. As a consequence, a one-dimensional (1D) reflective diffuser is proposed, and the moving mechanism is rotation on a cylinder, as indicated with a curved arrow in Fig. 1.

2. Design and Fabrication of 1D Reflective Diffuser

On the basis of the schematic light path shown in Fig. 1, the efficiency can be largely reduced or the light path can be difficult to control if the diffuser causes scattering. Therefore, a random microstructure with a concave reflective surface for inducing light diffusion is proposed, as shown in Fig. 2(a). To maintain the light diffusion in the same plane in a continuous movement, the 1D diffuser is attached onto a cylinder, as shown in Fig. 2(b).

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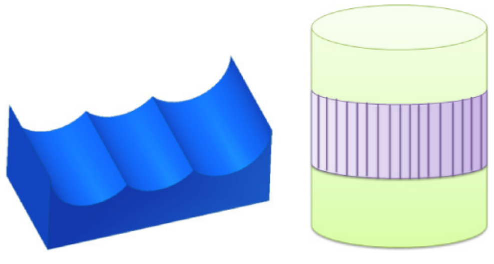

(a) (b)

Fig. 2. (Color online) (a) Structure of 1D reflective diffuser. (b) Cylinder with attached 1D diffuser.

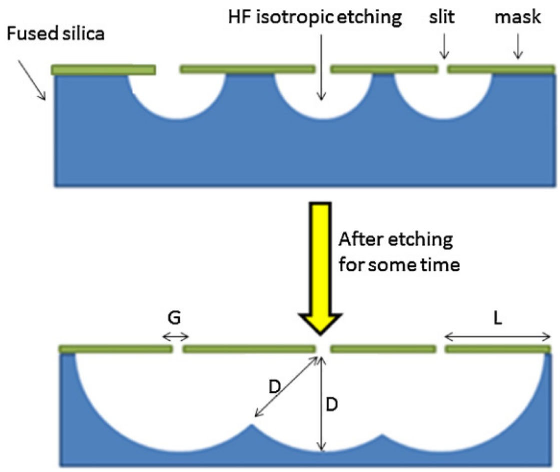
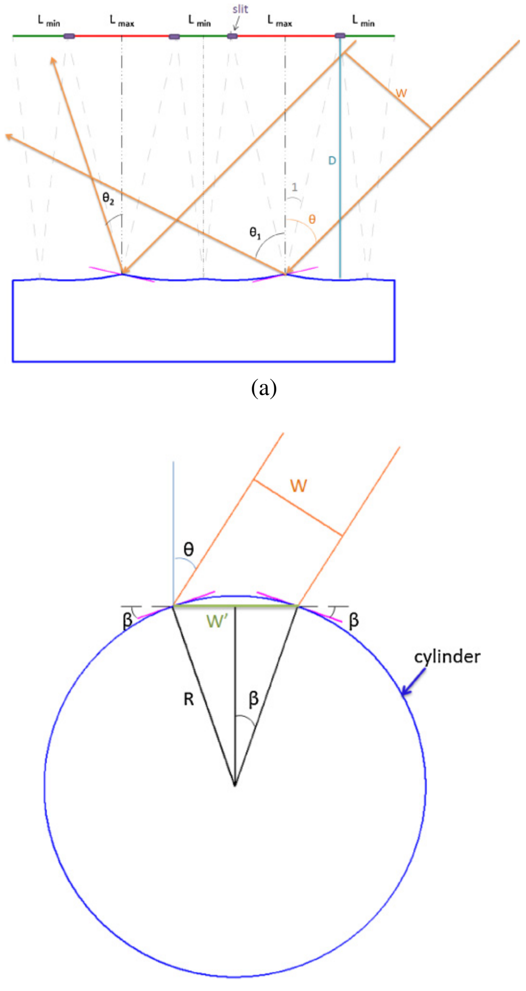


Fig. 3. (Color online) Etching process for the reflective diffuser.

The mold for making the diffuser is prepared by HF isotropic etching on fused silica through a mask, and the width of each cylindrical mirror depends on the distance between the mask and the substrate, denoted as D, and the pitch between two adjacent slits on the mask, denoted as L, as shown in Fig. 3. The pitch between two adjacent slits is varied and randomly allocated with a value between 20 μm ($L_{\min}$) and 30 μm ($L_{\max}$). The widths of the slits labelled G are all 2 μm.

The diffusion angle will be defined by the cylindrical concave mirror with the greatest curvature. The larger the diffusion angle, the more effective it is for eliminating the interference effect, but the more the energy loss as well. For designing and estimating the diffusion angle, Fig. 4(a) illustrates the geometry of the diffuser in the etching process with the parameters of the incident light beam, including beam width W and incident angle θ. The maximum reflection angle θ_1 will occur at the boundary where $L_{\min}$ is assigned to the right of $L_{\max}$. The minimum reflection angle θ_2 will then occur at the boundary where $L_{\min}$ assigned to the left of $L_{\max}$. The diffusion angle, if the diffuser is on a flat substrate, becomes $(\theta_1 - \theta_2)$. $\angle 1$ in Fig. 4(a) is an auxiliary angle, and the evaluation of θ_1 and θ_2 can be carried out using the following relationships:



(a)

(b)

Fig. 4. (Color online) Geometry of the 1D diffuser (a) on a flat surface and (b) on a cylinder.

$$\angle 1 = \sin^{-1}\frac{L_{\max}}{2D}, \tag{1}$$

$$\theta_1 = \theta + 2\angle 1, \tag{2}$$

$$\theta_2 = \theta - 2\angle 1. \tag{3}$$

Because the diffuser will be attached onto a cylinder with a radius of curvature R, the diffusion angle will be increased; the geometrical relationship is illustrated in Fig. 4(b).

In Fig. 4(b), β is the tilt angle of the tangential line at the two extreme edges of the laser beam. The minimum reflection angle $\theta_{\min}$ and maximum reflection angle $\theta_{\max}$ can be evaluated with the following relationships:

$$W' = \frac{W}{\cos\theta}, \tag{4}$$

$$\angle\beta = \sin^{-1}\frac{W}{2\cos\theta \times R}, \tag{5}$$

$$\theta_{\max} = \theta_1 + 2\beta, \tag{6}$$

$$\theta_{\min} = \theta_2 - 2\beta. \tag{7}$$

The diffusion angle α with the cylindrical diffuser can then be given as

Table 1. Parameters used for diffuser and system design.

L (μm)	D (μm)	R (mm)	W (mm)	θ (deg)
25 ± 5	500	45	8	45

$$\begin{aligned}\angle\alpha &= \angle\theta\max - \angle\theta\min \\ &= 4\left(\sin^{-1}\frac{L_{\max}}{2D} + \sin^{-1}\frac{W}{2\cos\theta\times R}\right). \qquad (8)\end{aligned}$$

All the parameters used for the diffuser and system design are listed in Table 1. On the basis of these values, the diffusion angle α is evaluated to be 35.7°. The greater the diffusion angle, the better the interference reduction effect is, but the less the energy efficiency.

Among the parameters, L is restricted to the minimum pitch of the mask producing machine. D is limited by etching time and the thickness of the substrate. If D is large, the substrate would be too thin and the substrate could be easily broken. R cannot be too large with the consideration of the maximum size of the diffuser that can be made as well as the weight and inertial of the cylinder that the rotating motor can support. The beam width W is determined by the size of the microlens array. The incident angle θ should not be too small or there might be mechanical interference between the optomechanics of the incident and reflected light paths.

Figure 5 shows the light path simulation upon reflection using the 1D diffuser with LightTools™. It indicates a diffusion angle of 32.7° with an incident angle of 45°. The difference between the values evaluated from ray tracing simulation and using Eq. (8) is due to the estimation of the diffusion angle being based on the worst case scenario.

After the etching process on a fused silica substrate as shown in Fig. 3, the mold is then made by the electroforming process. The final diffuser structure is then hot embossed with the mold on a PET substrate, and a reflective layer is coated onto the microstructure. Figure 6 shows the cylinder with the attached 1D diffuser.

3. Experiment on Line Beam Shaper with Rotating 1D Diffuser

The experimental setup corresponding to the schematic configuration in Fig. 1 is shown in Fig. 7, marked with the components and dimensions.

The laser source has a power of 500 mW with a wavelength of 532 nm. The specifications of the microlens array, condenser lens, cylindrical lens, and CCD camera for capturing the line beam are listed in Tables 2 to 5, respectively.

Figure 8 shows the line beam quality from the setup under various conditions for comparison, including the case of no diffuser, with a diffuser but without rotation and with a rotating diffuser. The scales of energy distribution for the three cases are not the same owing to the tuning of the exposure time to avoid saturation of the CCD by the peak intensity in the distribution pattern. The evaluation of the uniformity (U) is based on the definition described by Eq. (9), where $I_{\max}$ and $I_{\min}$ denote the maximum and minimum intensities, respectively, of the energy distribution in the line direction:

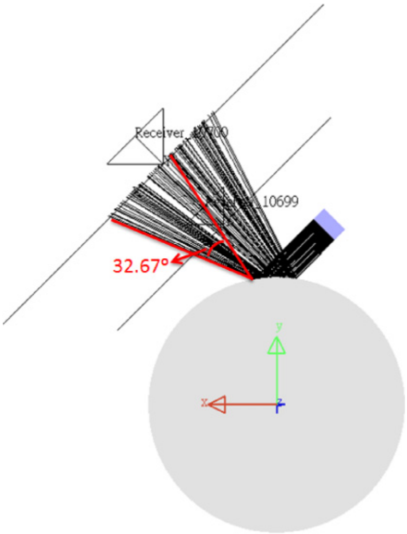


Fig. 5. (Color online) Light path diagram of laser beam reflected from the 1D diffuser on a cylinder.

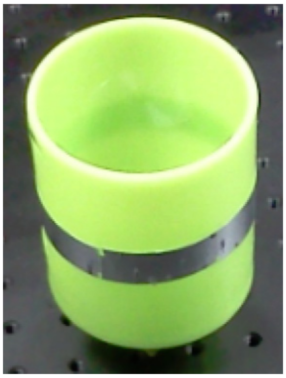


Fig. 6. (Color online) Prototype of cylinder with attached 1D diffuser.

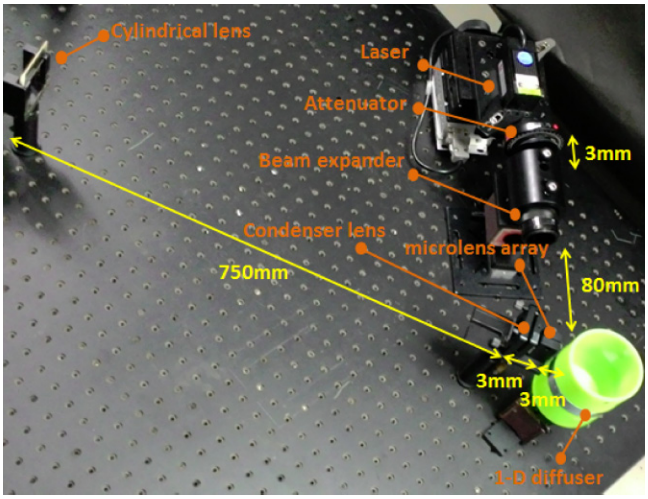


Fig. 7. (Color online) Experimental setup.

Table 2. Microlens array specifications.

Type	Plano convex
Material	Fused silica
Pitch (µm)	1015
Radius of curvature (µm)	6500
Array size (mm^3)	10 × 10 × 1.2

Table 3. Condenser lens specifications.

Type	Plano convex
Diameter (mm)	25
Center thickness (mm)	3.2
Radius (mm)	387.6
EFL (mm)	750
Material	BK7

Table 4. Cylindrical lens specifications.

Type	Plano convex
Height (mm)	30
Length (mm)	60
Center thickness (mm)	6.8
Radius (mm)	25.8
EFL (mm)	50
Material	BK7

Table 5. CCD camera specifications.

Type	Beamage-CCD12 (Gentec-eo)
Pixel count ($\times 10^6$)	1.4
Pixel dimension (μm^2)	4.65 × 4.65
Signal to RMS noise	1000 : 1
Max full frame rate (Hz)	~10
Wavelength range (nm)	350–1150
Max average power (W)	1

$$U = 1 - \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}. \tag{9}$$

A uniformity of up to 92% has been achieved with a rotating speed of 2500 rpm, which demonstrates the effectiveness of eliminating the interference effect by using the proposed 1D rotating diffuser. The uniformity has met the requirement of 90% for the target application, and the experiment shows that the uniformity can be further improved with a larger diffusion angle of the diffuser and a higher rotating speed of the cylinder.

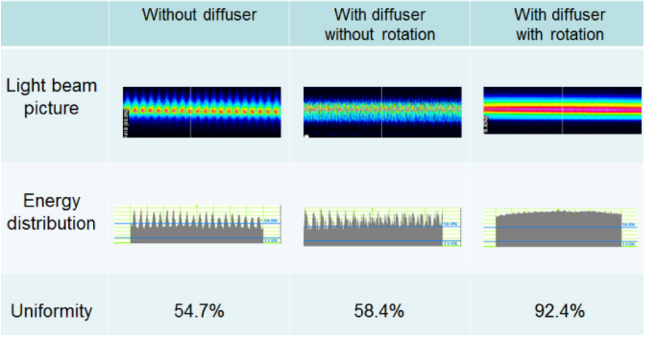


Fig. 8. (Color online) Intensity distribution and uniformity of the line beam under various conditions.

The efficiency evaluation is based on the measurement of the total power with an integrating sphere. The efficiency of the 1D diffuser is 85% calculated by dividing the reflected power by the incident power. The overall efficiency is 76% calculated by dividing the total line beam power by the laser power. The efficiency has been higher than the claimed transmission of 70% of a commercial system[7)] and can be improved with better coating of the reflective diffuser.

4. Conclusions

A one-dimensional reflective diffuser composed of a random pitch cylindrical mirror has been designed and fabricated as the element to average out the interference pattern and improve the uniformity for the line beam shaper with a microlens homogenizer used with a highly coherent light source. The reflective diffuser with a well-controlled diffusion angle helps to maintain the efficiency while performing light diffusion and its one-dimensional microstructure maintains the collimation of the laser beam in the other direction. These features make the diffuser and the associated architecture a highly efficient and compact solution for line beam shaping.

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