

High-Performance Laser Beam Homogenizer Based on Double-Sided Concave Microlens

Zefang Deng, Qing Yang, Feng Chen, Hao Bian, Jiale Yong, Guangqing Du, Yang Hu, and Xun Hou

Abstract—Microlens array (MLA) has attracted increasing interest as its application in micro-optical device and system. In this letter, we proposed a new approach that applies rotational displacement MLA to the laser homogenization system. These are nonregular arrays consisting of close-packed concave MLAs on two sides with specific rotation angle. And, the double-sided MLAs diffusers with new design parameter were successfully fabricated using single pulse femtosecond laser assisted chemical wet etching. Simulation and experimental results reveal the good homogenization performance of the double-sided MLAs. In addition, we fabricated diffusers with different rotation angles (θ), and when $\theta = 60^\circ$, the diffuser obtains the best optical performance.

Index Terms—Laser machining, microlens array, laser homogenizer.

I. INTRODUCTION

MICROLENSSES arrays (MLAs) are widely used in liquid crystal displays, extraction improvement for layered light-emitting devices, wavefront sensors, image recorders and focusing components in optical communication devices, and especially laser homogenization [1]–[5]. Homogenizer laser, which generally refers to laser beam with a uniform intensity profile, has attracted increasing interest in diverse applications, such as lithography and material processing [6]–[10], laser diagnostics [11], [12], high-performance illuminating and portable laser projection [13]–[15]. In the past decades, a series of other technologies and micro optical elements have been adopted to transform a Gauss laser beam into a flat top, including diffractive, reflective or refractive elements [16]–[18]. For example, Bokor et al. proposed the beam shaping technique based on reflection element consist of displaced parallel reflecting facets [19]. Fratz et al. designed and fabricated polarization-holographic optical elements for laser beam shaping [20], Zhan et al. reported an anamorphic beam concentrator consist of a tapered SiO₂-rod with skewed and curved

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The authors are with the State Key Laboratory for Manufacturing Systems Engineering, Shanxi Key Laboratory of Information Photonic Technique, Xi'an Jiaotong University, Xi'an 710049, China (e-mail: d1989217@stu.xjtu.edu.cn; yangqing@mail.xjtu.edu.cn; chenfeng@mail.xjtu.edu.cn; haobian@mail.xjtu.edu.cn; 449272783@qq.com; guangqingdu@mail.xjtu.edu.cn; hyxjtu@163.com; houxun@mail.xjtu.edu.cn).

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surface [21]. Among these, beam homogenizers based on microlens array (MLA) have attracted extensive attentions due to their distinct advantages. The MLAs could divide a non-uniform laser into lots of beamlets, and then each beamlet could be superimposed onto microdisplay with the help of an additional lens. Hence, the MLA diffusers exhibit independence from the incident intensity profile and large spectral range. However, a MLA diffuser assembly of microlenses with periodic distribution would give rise to interference pattern especially with the usage of highly coherent light.

Solution for reducing the contrast of the interference pattern has been developed by perturbing the spatial distribution of the microlenses. Double-sided MLAs with different design parameters have been proposed, such as microlens array on two sides with a lateral shift to each other [15], or chirped microlens arrays [22]. These diffusers could act as good homogenizer, but the previously proposed fabrications were mainly based on additional molds, which would increase the complexity and cost of the whole fabrication process [23], [24]. Efficiently and controllable method to fabricate double-sided MLA is still challengeable.

This letter presents a double-sided MLA with new design parameters, where the arrays of the microlenses on two sides were with a rotation angle to each other. The technology based on single femtosecond pulse irradiation and selective wet etching was utilized to rapidly fabricate the double-sided MLA diffusers. Within 60 min, about 2.78 million close-packed microlenses with quasi-periodic distribution could be fabricated. The performance of the double-sided MLA homogenizers was verified through simulation and experiment. Moreover, the microlenses on two sides with a rotation angle of 0°, 15°, 30°, 45°, 60°, 75°, and 90° were fabricated on the 10 × 10 × 2 mm³ silica glass block. We demonstrated these different fabricated parameters and show their influence on the optical properties of the diffusers.

II. METHOD & EXPERIMENTAL

In this letter, double-sided polished glass (BK7) blocks, with dimensions of 10 × 10 × 2 mm³, were utilized as the substrates. The substrate was mounted on a three-axis translation stage. Linearly polarized laser pulses at the central wavelength of 800nm with a duration of 50 fs and a repetition rate of 1 KHz were generated by an amplified Ti:sapphire fs-laser system. And the beam was focused onto the upper surface of the substrate using a (Nikon, NA=0.5, 50×) objective lens at normal incidence to form ablation craters. Through a

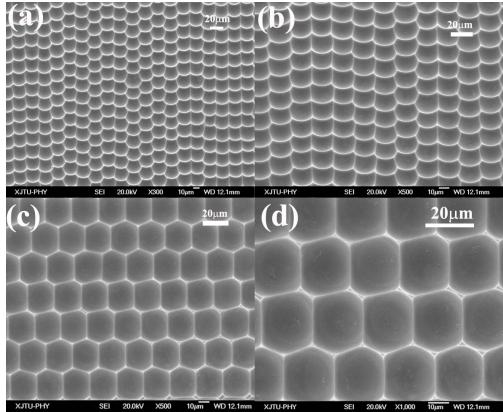


Fig. 1. The 2D morphology of fabricated MLA; (a) and (b) 25° tilted-view, (c) and (d) top-view (the other side of a double-sided MLA diffuser) SEM image of the quasi-periodic MLA.

progressive scanning process, moving the substrate at a speed of v mm/s ($10 \leq v < 40$, in our experiment conditions), serials of ablation craters with a separation space of $v \mu\text{m}$ were created at a laser repetition rate of 1 KHz. During the whole fabrication process, the surface of a substrate was monitored by a CCD camera. To obtain double-sided microlens array (MLA), the glass sheet was firstly irradiated by high-speed laser scanning on one side, and then be upturned over for the other side irradiation at the same scanning speed. In the case, the substrates were precisely realigned to the same direction or difference angles along the previous scanning direction by referring to the real-time high optical magnification imaging of previously fabricated craters array. Furthermore, we also demonstrated different angles (θ) between scans (ABS), which were $0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ$. For the subsequent use, the substrates were ultrasonic cleaned in de-ionized water to remove the laser ablation ejecta. Then, the substrates were treated with a 5% (w/v) hydrofluoric acid solution (HF) under ultrasonic waterbath at 60° . For about 40 minutes etching, quasi-periodic close-packed MLAs were generated on both sides of the substrate [25]–[27].

III. RESULTS AND DISCUSSION

Setting the scanning speed 18 mm/s, and the pulse energy $5 \mu\text{J}$ (energy density of $40\text{J}/\text{cm}^2$), quasi-periodic microlenses with an average size of $18 \mu\text{m}$ could be observed and the total area could easily cover a few square inches. Figure 1(a) shows the field emission scanning electron microscopy (FESEM, FEOLJSM-7000F) image of the MLA. An top-view and enlarge image of the concave microlenses is shown in Fig. 1(b), clearly demonstrating the irregular shape, smooth surface and high fill ratio (reach to 100%) of the fabricated MLA. The average roughness of the formed microlenses is approximately 8nm when measured using an atomic force microscopy.

The cross-section profiles of the fabricated microlenses were measured by a laser confocal scanning microscopy (LCSM, Olympus LEXT OLS4000). Figure 2(a) shows the cross-section profiles of several microlenses which were measured along the scanning direction. The profiles show a standard deviation of $0.3 \mu\text{m}$ ($3.2 \mu\text{m}$, average value) and $3.2 \mu\text{m}$ ($18 \mu\text{m}$,

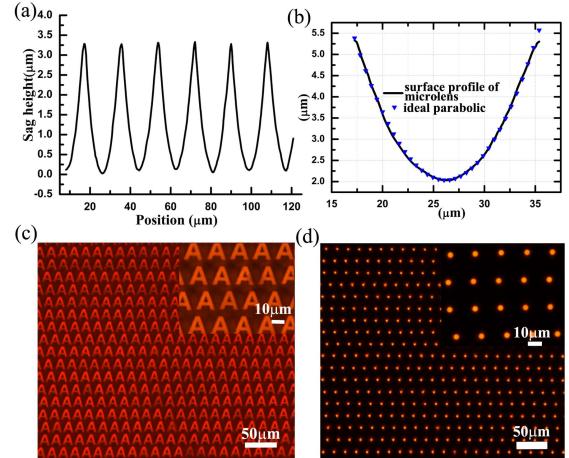


Fig. 2. (a) Cross-section profile of the diffusers with a mean lens width of $18 \mu\text{m}$. The curve in graph (b) is the cross-section profile of single microlens, while the marks is its parabolic fittings correspondingly. Test of the (c) imaging and (d) focal properties of the fabricated MLA.

average value) in the sag height and diameter of aperture, respectively. The deviations are associated with the slight variation in laser pulse energy and substrate flatness. Precision polish for substrate and series of measures taken to laser system, such as maintaining the local temperature around the laser, may effectively decrease these deviations. Figure 2(b) shows the measured cross-section profile of a single microlens (black curve) and their theoretical fitting conic section (circle mark). The root-mean-square (RMS) error between the microlens and fitting conic section is less than $0.03 \mu\text{m}$, so the surface of the fabricated microlenses can be regarded as parabolic. As a result, the surface profile of the fabricated microlenses can be expressed as $h(x) = A(x - x_0)^2 + y_0$, where A is equal to 0.042, x_0 and y_0 are associated with the position of the microlenses.

To investigate the basic optical properties of the MLAs, imaging experiments were carried out by an optical microscope setup comprising a tungsten light source, 3D translation stage, an objective lens and a CCD camera. A quasi-periodic array of miniaturized “A” letters (Fig. 2(c)) were observed when positioning a projection mask, which was a black sheet with a transparent letter “A” on it, between the tungsten light source and a substrate. The clear images of “A” are uniform. Figure 2(d) shows a quasi-periodic array of bright focal spots. It is clear that the brightness and size of the spots are also uniform.

The performance of the double-sided MLA diffuser is optically analyzed by ray tracing. Figure 3(a) shows the optical simulation mode. It includes a laser source, double-sided MLA diffuser ($\theta = 0^\circ$), imaging lens with a square aperture ($f = 75\text{mm}$), and a diffuse screen placed 500mm away from the imaging lens. As a source a coherent Gaussian ray at 632.8nm was used; the beam shape of the laser was circular with a diameter of 0.5mm. The diffuser was modeled by the basic measured parameters of the fabricated microlenses, such as the aperture diameter, sag height, and the cross-section profile. The concave MLAs diffusers were obtained by arranging paraboloids (see Fig. 3(b)) at a specific pattern, equidistance spacing between every two adjacent units in each

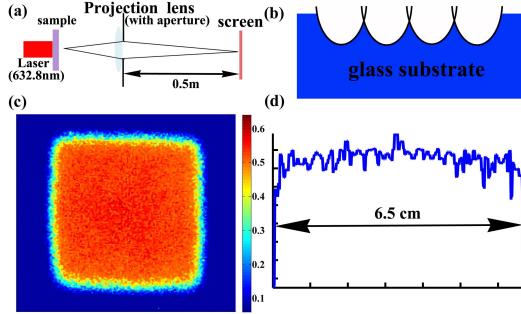


Fig. 3. (a) Schematic diagram of optical setup to simulate the intensity distribution; (b) the model to generate diffuser with a given set of realistic MLA parameters; (c) the output of intensity distribution on the screen radiated by the double-sided diffuser; (d) cross sectional distribution of the output pattern. The incident laser parameters are: $\lambda = 632.8\text{nm}$, coherent Gaussian beam, beam radium 0.5mm, divergence angle 1.5mrad.

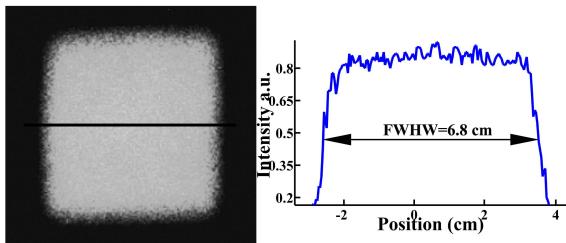


Fig. 4. Illumination patterns and the cross sectional distribution of it.

row and equidistance spacing between neighbor rows and random variation in the starting position between every two adjacent rows, and then removing the material surrounded. The simulated results of the output intensity distributions is shown in Fig. 3(c), meanwhile, the normalized intensity at the central horizontal line of the output pattern is shown in Fig. 3(d). The incident Gaussian beam spot becomes homogeneous as the rays propagate the double-sided MLA diffuser, and the beam spot size is $6.5 \times 6.4\text{cm}^2$.

Then, the illumination patterns were experimentally measured using a similar projection system portrayed in Fig. 3(a). The monomode He-Ne laser at the wavelength of 632.8nm was used as the light source, and the diameter of the beam was about 1mm. The detector screen was replaced by a piece of print paper, and a CCD camera was used to capture the output pattern. Figure 4 shows the measured output pattern and relatively cross-sectional intensity distribution of the double-sided MLA diffuser. After shaped by the fabricated double-sided MLA diffusers, the output beam is nearly flat-top, and the size of beam spot is $6.8 \times 6.7\text{cm}^2$, which agrees well with the simulation result. We have compared the illumination patters of the diffuser with different rotation parameters. In general, the ripples (Fig. 4) decrease as the increase of the rotation angles, and reach a minimum value at 60° , and then it would increase with the rotation angle. We also measured the transmittance of the double-sided diffusers at 632.8 nm wavelength. The results show that the transmission rates of double-sided microlens array diffuser range from 83% to 85%, which could be considered as independent on the angles between scans.

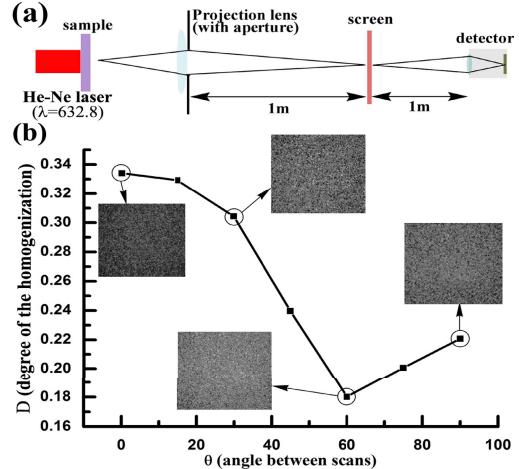


Fig. 5. (a) Schematic view of experiment setup for the quality of homogenization measurement; the graph (b) shows a change of the degree of homogenization (D) with the ABS (θ). Illustration: illumination patterns from the diffusers with different ABS.

In addition, in order to characterize the quality of the homogenization of the double-sided MLA diffusers with different scanning angles, a possible method has been proposed to describe the degree of the homogenization [22], [28], [29]. It is the rate of standard deviation to the mean value of the intensity pattern. The degree of the homogenization D could be expressed as $D = \sigma/I_{\text{mean}}$, where

$$\sigma = \sqrt{\frac{1}{M-1} \sum_i^M (x_i - I_{\text{mean}})^2} \quad (1)$$

and

$$I_{\text{mean}} = \frac{1}{M} \sum_i^M x_i \quad (2)$$

For a perfect flat top D equals 0. Otherwise D increases when the degree of the homogenization becomes poorer. The quality of the homogenization was tested through the experimental setup shown in Fig. 5(a). The source light was the above-mentioned He-Ne laser. The laser beam passed the double-sided MLA diffusers, and then the diffused light was projected to a screen 1m away. The illumination patterns on the screen were measured by a CCD camera placed 1m away from the screen. The CCD camera was equipped with an imaging lens of focal length $f = 12\text{mm}$ and its f-number was set as 4. The illumination patterns of double-sided MLA diffuser with different rotation angles (equal to θ) were measured, and the quality of homogenization were calculated by equations (1) and (2). Figure 5(b) shows the evolution of degree of the homogenization, D , versus the angle between scans, θ . The minimum value of D is 0.18, which was obtained at the ABS of 60° .

Finally, as reported in previous literatures [15], [30], and [31], a vibrating diffuser would greatly improve the quality of homogenization. We compared the illumination pattern of double-sided MLA diffusers under motionless mode with the vibration mode (with a vibration frequency of 5 Hz). Figure 6 shows the illumination patterns and relative intensity

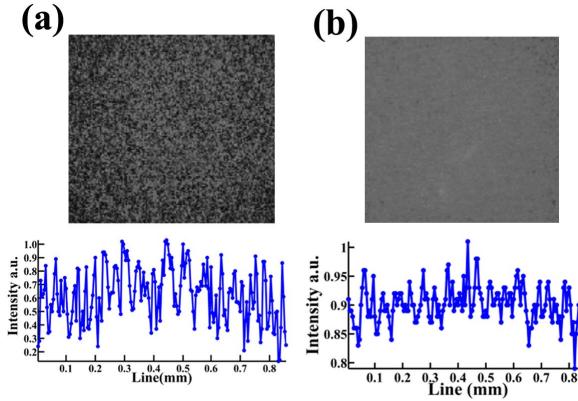


Fig. 6. Images and sampling of intensity fluctuation (on the white line in the patterns) from the double-sided microlens diffuser ($\theta = 0^\circ$) with (a) motionless mode, and (b) the vibration mode of a frequency 5 Hz, respectively.

distribution of the pixels along the white line indicated in illumination pattern (measured through the experiment setup in Fig. 5(a)). The calculated D (degree of homogenization) of motionless mode and vibrating mode were 0.33 and 0.04, respectively.

IV. CONCLUSIONS

In conclusion, we proposed a double-sided microlens array (MLA) with a new design parameters, where the microlens array on two sides are with a rotation to each other, and fabricated this double-sided MLA diffusers using single pulse femtosecond laser assisted chemical wet etching. For mass production, this method shows great potential to fabricate quasi-periodic close-packed microlenses with parabolic surface on glass sheet. The choice of optical glass as a material and concave structures allow the use of the diffuser in high power laser applications. Double-sided MLA diffusers with different rotation angles were successfully fabricated. The homogenizing performance of the diffusers were simulated and experimentally measured, and the results revealed that the illumination of the double-sided MLA diffusers maintained a quite well uniformity. When the rotation angle is 60° , the degree of homogenization reaches a minimum value.

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