# Rapid Fabrication of Large-Area Concave Microlens Arrays on PDMS by a Femtosecond Laser

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ABSTRACT: A fast and single-step process is developed for the fabrication of low-cost, high-quality, and large-area concave microlens arrays (MLAs) by the high-speed line-scanning of femtosecond laser pulses. Each concave microlens can be generated by a single laser pulse, and over 2.78 million microlenses were fabricated on a 2×2 cm^2 polydimethylsiloxane (PDMS) sheet within 50 min, which greatly enhances the processing efficiency compared to the classical laser direct writing method. The mechanical pressure induced by the expansion of the laser-induced plasmas as well as a long resolidifing time is the reason for the formation of smooth concave spherical microstructures. We show that uniform microlenses with different diameters and depths can be controlled by adjusting the power of laser pulses. Their high-quality optical performance is also demonstrated in this work.

KEYWORDS: femtosecond laser, concave microlens array, single pulse ablation, optical performance
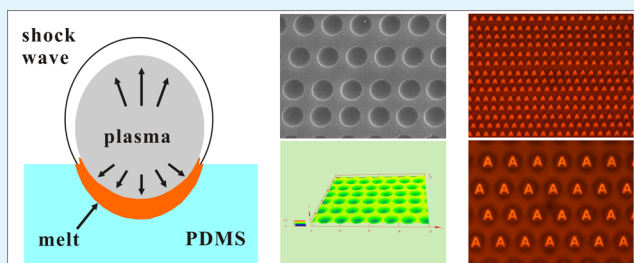
1. INTRODUCTION

Microlens arrays (MLAs), which generally refer to two-dimensional (2D) arrays of small lenses with diameter ranging from several micrometers to nearly millimeter,[1] have diverse applications in micro-optical systems, high-definition displays, photovoltaic devices, biochemical systems, and artificial compound eyes.[2−8] In the past several years, various methods have been explored for fabricating MLAs, including thermal reflow,[9] droplet method,[10] hot embossing,[11] gray scale photolithography,[12] and so on. However, concave or negative MLAs are not availably fabricated by those well-establized techniques, which have extensive applications such as compound refractive lens for focusing X-rays, diffusers, and carriers of DNA chips.[13,14] Recently, some techniques have been proposed to manufacture concave MLAs. For example, Yuan et al. reported a concave refractive microlens array (MLA) in solgel glass fabricating by a proximity-effect-assisted reflow technique.[14] Yi et al. fabricated a 5×5 concave microlens array by using an ultraprecision diamond turning machine equipped with four independent axes.[15] Ding et al. introduced an low-cost approach for fabricating large-area concave MLAs by liquid trapping and electrohydrodynamic deformation of the liquid in a microhole array.[16,17] On the other hand, the concave MLAs could be produced by the convex MLAs using the reversal replication technique.[8]

Recently, femtosecond laser has become a popular tool to fabricate arbitrary three-dimensional (3D) microstructures. The classical femtosecond laser microfabrication needs to remove the materials by the top-down process, which suffers from the debris problems.[18] Femtosecond-laser-induced two-photon polymerization (TPP), a popular femtosecond laser direct writing (FLDW) method, allows for the bottom-up process, which can be used for fabricating more complex 3D microstructures in polymers, such as MLAs.[19,20] However, these laser direct writing processes are low efficiency. Although Sun et al. has proposed an improved TPP process that increases the processing speed, it is still impossible to fabricate large-area MLAs with millions of lenses in a few hours.[1,21] To meet the requirement of their wide applications, a fast, simple and cost-effective method to fabricate high-quality and large-area MLAs is still needed.

In this paper, we present a rapid single-step process to fabricate large-area concave MLAs by a high speed femtosecond laser scanning method. Each microlens can be formed by a single femtosecond laser pulse. Within 50 min, about 2.78 million microlenses with a diameter of 8.68 μm and depth of 0.95 μm are fabricated on a 2×2 cm^2 polydimethylsiloxane (PDMS) sheet. The mechanism of heat and mass transfer under laser irradiation as well as a long PDMS solidification time is proposed and used to explain the formation process of microlenses.

2. METHOD AND EXPERIMENTAL SECTION

PDMS is an Optical transparent polymer which has many advantages to fabricate MLAs, such as flexibility, biocompatibility, thermal stability and nontoxicity. The preparation process of the PDMS sheets is

shown in ref 22. In this experiment, the PDMS mixture was solidified in an oven at 120 °C for 2 h.

The large-area MLAs were fabricated by a rapid femtosecond laser scanning process on PDMS film, as demonstrated in Figure 1a.[23,24]
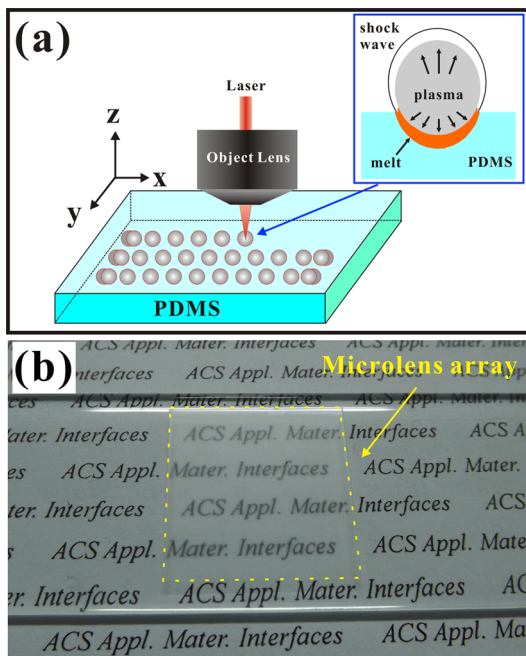

Figure 1. (a) Schematic of the fabrication process. The inset shows the formation mechanism of a microlens irradiated by a single femtosecond laser pulse. (b) The digital photo of the fabricated MLA.

The PDMS samples were irradiated by a 50 fs regenerative amplified Ti:sapphire laser system (Coherent Libra-usp-he) at the center wavelength of 800 nm with a repetition rate of 1 kHz. The laser beam was focused with an objective lens (10×, NA = 0.30, Nikon) on the samples. The femtosecond laser exposure spots were generated point-by-point for using a pulsed laser system. Each spot was ablated by a single pulse and formed a microlens. In the rapid scanning process, the average distance of the adjacent microlenses was tuned by the scanning speed in the transverse direction as well as the interval of the adjacent scanning lines in the perpendicular direction. Finally, the as-prepared samples were cleaned by acetone, alcohol and deionized water in a sonic bath for 10 min, respectively.

The morphology of the fabricated microlenses was characterized by a JSM-7000F scanning electron microscopy (SEM, JEOL, Japan). The 3D profile and surface roughness of the fabricated MLA was measured by a LEXT-OLS4000 laser confocal microscopy (Olympus, Japan). The optical performance of the MLAs was investigated by a modified optical microscope system. The simplified setups were shown in panels a and c in Figure 3.

3. RESULTS AND DISCUSSION

3.1. Morphology Features of the As-Prepared Microlens Arrays.
Figure 1b is the digital photo of the MLA fabricated by a femtosecond laser at laser power of 20 mW. The scanning speed is set at 12 mm/s and the interval of adjacent laser scanning lines is 12 μm. Due to the fast speed, the irradiated spots separate with each other, which will lead a single pulse to give rise to a microlens. Because the repetition rate is 1 kHz, 1000 microlenses will be generated every second. The processing efficiency is more than 1×10^5 times the popular FLDW process.[1] A large-area MLA (2.78 million microlenses) with good transmittance has been produced in the middle of the PDMS sheet covering 2×2 cm^2 area (Figure

1b). The total machining process only lasts about 50 min, which declares that high-speed scanning provides an extremely efficient approach to the development of the large-area MLAs.

Figure 2a shows the SEM image of the MLAs, which demonstrates the good uniformity of the large-area MLAs. The
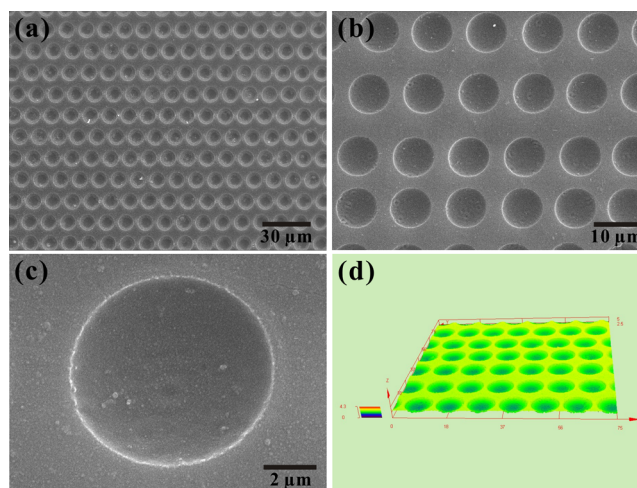

Figure 2. (a−c) SEM images of the fabricated MLA under different magnifications. (d) 3D profile of the fabricated MLA. The MLA was scanned at laser power = 20 mW, and the distance of the adjacent ablated spots was set as 12 μm.

magnified images are shown in Figure 2b, c. A concave crater can be induced by a single laser pulse irradiation. With a high speed scanning process, the microlens array structure is rapidly generated. The 3D profile is investigated by a laser confocal scanning microscope and the result is shown in Figure 2d. The measurement results show that the diameter (D) and depth (h) of the concave microlens are 8.68 and 0.95 μm, respectively.

On the basis of geometry and optical theory, the radius of curvature (R), focal length (f), f-number ($f_\#$) and numerical aperture (NA) can be estimated using the following formulas[13,25]

$$R = (h^2 + r^2)/2h, \quad f = R/(n-1), \quad f_\# = f/2r,$$

$$NA = D/2f \tag{1}$$

where r is the radius of the concave microlenses ($D/2$), n is the material refractive index. Given $D = 8.68$ μm, $h = 0.95$ μm, and $n = 1.41$ for PDMS. We have $R = 10.39$ μm, $f = 25.34$ μm, $f_\# = 2.92$, and NA = 0.17, respectively. Such low values of f, $f_\#$, and NA are within the expectation because the small diameters of microlenses impose small value for radius of curvature and small amount of light was collected.[26]

3.2. Formation Mechanism of the Concave Microlens Structures.
The surfaces of the fabricated microlenses are very smooth which are obviously different from conventional femtosecond laser ablated craters. The formation mechanism of a microlens is presented here by analogy with Ben-Yakar's theory.[27] When the fluence of incoming single femtosecond laser pulse is exceeded the damage threshold of PDMS material, part of the incident laser energy is absorbed initially by electrons through the nonlinear effects such as multiphoton and avalanche ionization. Meanwhile, the electrons transfer some energy to the lattice. As the electrons and ions thermally equilibrate, high-pressure and high-temperature plasmas form above the surface.[28] Then plasmas expand and burst out of the

9383

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focal spot. At the same time, the ablated materials are removed from the surface, forming an ablated crater, as shown in the inset of Figure 1a. The ablated crater has a good concave curved shape and forms an original microlens. Recent studies indicate that a transient shallow molten zone exists below the expanding plasma.[29,30] The mechanical pressure exerted by the spherical plasma shock wave onto the molten PDMS as well as a long solidification time can make the surface of the concave crater smoother. The longer resolidification process of molten PDMS than glasses or semiconductors provides enough time for the melted liquid polymer to be smoothed by the surface tension, avoiding the nanoroughness or periodic nanostructures in the conventional laser-induced craters.[31−33] In this way, a microlens can be fast fabricated by a single femtosecond laser pulse and the MLA can be fabricated by rapid scanning process. The mass transfer under the spherical plasma shock wave and heating effect are the main reason for forming smooth concave microlenses.

3.3. Optical Property.

To demonstrate the optical performance of the MLAs, imaging experiments are carried out by an optical microscope system.[17,34] The artificial concave MLAs are fixed on a movable sample stage and are illuminated by a tungsten light through a projection mask, which is a black plastic sheet with a transparent letter "A" on it (Figure 3a). An array of bright false and reduced images of "A" on the false focal plane of the MLAs is clearly captured by an objective lens and a CCD camera which are placed on the other side of the MLAs, as shown in Figure 3b. The clear images of "A" are uniform in size and shape, which indicate the uniformity of the structures and the fine imaging property of the MLAs.
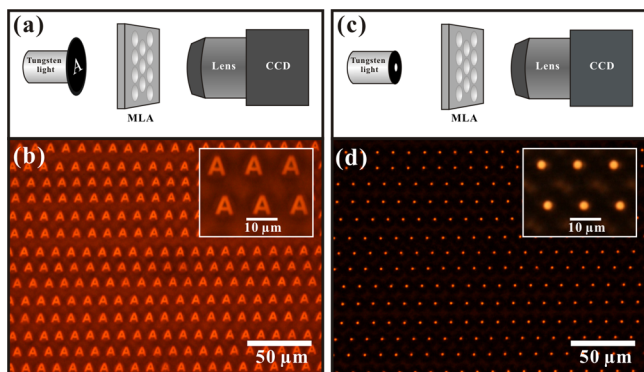

Figure 3. Test of the (a, b) imaging and (c, d) focal properties of the fabricated MLA. (a, c) Simplified setups of the optical system for the measurements. (b, d) Imaging and focal images of the MLA.

Imaging performance of the spot light source is also tested, and the setup is schematically shown in Figure 3c. The mask "A" is removed. This leads to an array of bright spots observed on the false focal plane of the MLAs (Figure 3d). The brightness and size of the spot-like virtual images are quite uniform. This result indicates that the MLAs perform good consistency of focal lengths. The fine optical property makes the MLAs possible to be employed as functional optical devices.

3.4. Control of the Shape and Size of the Concave Microlenses.

Laser power (P) is an important parameter to control the profile of the microlens. Figure 4 shows the dependences of the diameter and depth of the formed concave microlens on the laser power. It can be seen that the diameter and depth of the microlenses are closely related to the laser
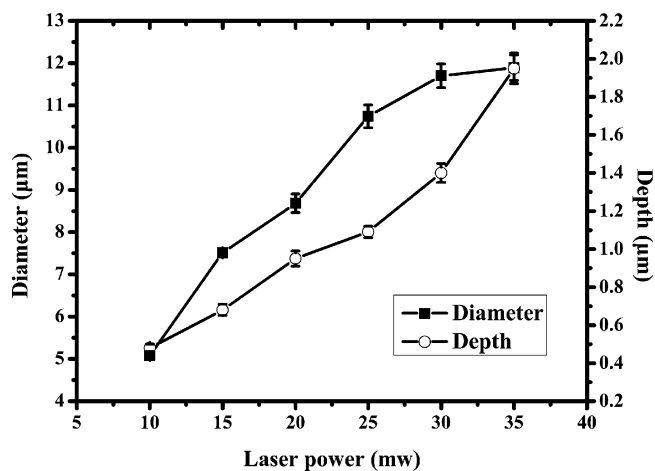

Figure 4. Dependences of the diameter and depth of the concave microlens on laser power.

power and the values increase with the increase of the laser power. The results agree well with the fact that the higher laser power leads to the more violent ablation process. Figure 5
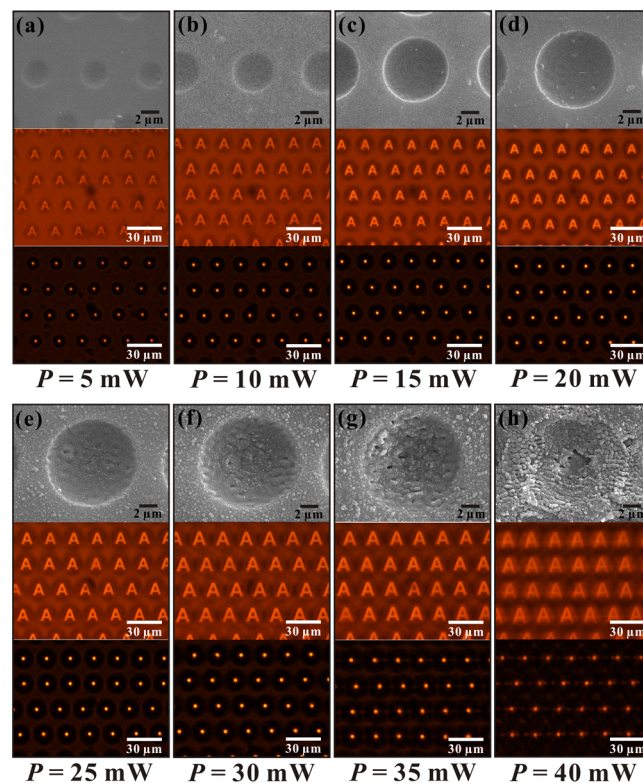

Figure 5. SEM images and optical performances of the MLAs fabricated at different laser power. (a) 5, (b) 10, (c) 15, (d) 20, (e) 25, (f) 30, (g) 35, and (h) 40 mW.

shows SEM images and optical performances of the MLAs fabricated at laser power of 5−40 mW. The size of the microlens gets bigger with the laser power increasing. Meanwhile, higher laser power will increase the surface roughness (R_a) of microlenses (The R_a is 10, 11, 10, 12, 14, 16, 20, and 34 nm for P = 5, 10, 15, 20, 25, 30, 35, and 40 mW, respectively). If the laser power is higher than 35 mW, the rough ripple structure becomes evident because the transient

molten-zone-induced smooth process only partly weakens the great micro/nanostructures formed from the large laser power ablation. The image quality of MLA will be degenerated for the scattering effect of rough structures on the incident light (Figure 5h). Although the smoother surface can be obtained at a low laser power, too low laser power is also difficult to form a usable MLA. When the power is no greater than 5 mW, the as-prepared microlenses will be too small and too shallow, resulting in a weak imaging performance (Figure 5a). The fundamental imaging performances in Figure 5b−g show that the single femtosecond laser pulse ablation is an effective way to fast fabricate high-quality and large-area concave MLAs. In addation, the size controllability makes the fabricated MLA applications more extensive and in-depth.

4. CONCLUSIONS

In this paper, we presented a single-step process to fabricate large-area concave MLAs by a single femtosecond laser pulse ablation method rapidly. About 2.78 million microlenses are fabricated on a 2×2 cm^2 PDMS sheet, taking only 50 min. The mechanical pressure induced by the expansion of the laser-induced plasmas onto the molten PDMS as well as a long PDMS solidification time is responsible for the formation of high-quality MLAs. The MLAs show fine optical property, and the diameter and depth of the as-prepared microlenses can be conveniently tuned by the femtosecond laser power. The most proper laser power range is from 10 to 35 mW in our experiments. Moreover, the convex MLAs can be also mass replicated by serving the concave MLAs as molding templates.

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Notes
The authors declare no competing financial interest.

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