Direct Fabrication of Microlens Arrays on PMMA With Laser-Induced Structural Modification

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***Abstract*— Reported here is the direct fabrication of the convex microlens arrays on poymethylmethacrylate using laser-induced structural modification. Based on single femtosecond pulse *in situ* modification, sixty thousand convex microlenses, whose diameters was <12 μm, could be fabricated per minute, exhibiting much higher efficiency than conventional laser direct writing technique. The formation mechanism was mainly attributed to photodecomposition, which would result in the scission of polymer chains. The shape of microlenses could be tuned by the laser power. In addition, the good optical performance of the microlens was revealed by its ability of high resolution imaging. This technique may open up a new way of preparing low-cost and large-area convex structure which is widely used in many advanced microdevices, such as lab-on-chips and biomimetic compound eyes.**

***Index Terms*— Convex microlens arrays, femtosecond laser, single pulse structural modification.**

I. Introduction

IN RECENT years, polymers are widely used to fabricate microlens arrays (MLAs) due to their low cost, and easy formability [1]–[5]. The polymer MLAs have become important in applications such as communication performance, display technologies and photovoltaic devices [6], [7]. Over the past few decades, the polymer MLAs has been readily fabricated through typical techniques including photo-resist reflow method [8], gray-scale photolithography [9], micro-jet fabrication [10], LIGA process (German acronym for Lithography, Electroforming, and Molding) [11], and so on. However, these techniques require multi-stepped procedures or limit by alignment accuracy. Currently, femtosecond (fs) laser processing has become a promising technology to fabricate three-dimensional (3D) microstructures [12]–[14]. The conventional fs laser direct writing (FLDW) based on laser ablation is a feasible method to fabricate convex microlenses but it suffers the disadvantage of poor surface quality during material removal [15]–[17]. Furthermore, the efficiency of FLDW based on two-photon photopolymerization (TTP) is limited due to point-by-point scanning [18], [19]. For example, it would take dozens of minutes to fabricate a microstructure. We notice that approaches mentioned above are inefficient, which are not suitable for the fabrication of large area convex MLAs. It is still challenging to develop a high-efficient and low-cost strategy for fabricating the polymer MLAs. In this Letter, we introduce a high-efficiency process for generation of large-area convex MLAs in a commercial PMMA sheet by a high speed fs laser scanning method, which is based on single fs pulse in-situ modification without any masks or duplicated templates. About sixty thousand convex microlenses could be fabricated per minute. The fabrication process is based on a swelling of material locally modified by single fs laser pulse. The optical properties of the fabricated MLAs are demonstrated by an imaging test. In addition, the shape of the microlenses could be tuned by the pulse energy. The fs laser pulse in-situ induced microstructures holds great promise for the development of many advanced microdevices such as lab-on-chips and biomimetic compound eyes.

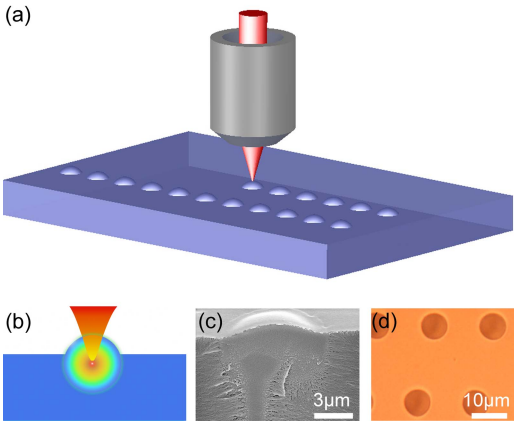

Fig. 1. (Color online) (a) Schematic illustration of the fabrication PMMA MLAs. (b-c) The cross section of a microstructure showed the morphology revolutions and formation mechanism. (d) The morphology of the sample surface was captured by the CCD camera.

II. Experiments & Discussion

The fabrication of convex PMMA MLAs was schematically illustrated in Fig. 1. The substrate with dimensions of 20mm×20mm×1mm was cut from a commercially

Manuscript received May 20, 2015; revised June 23, 2015; accepted July 14, 2015. Date of publication July 31, 2015; date of current version September 23, 2015. This work was supported in part by the National Science Foundation of China under Grant 51335008, Grant 61275008, and Grant 61176113, in part by the Special-Funded Program on National Key Scientific Instruments and Equipment Development of China under Grant 2012YQ12004706, and in part by the Collaborative Innovation Center, Suzhou Nano Science and Technology. *(Corresponding author: Feng Chen.)*

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Digital Object Identifier 10.1109/LPT.2015.2459045

available PMMA sheet. The substrate was fastened on a three-dimensional (3D) stage which could be controlled by a computer program. The fs laser (800nm central wavelength, 1kHz repetition rate, 50fs pulse width) was focused by an objective lens (10×, NA=0.3, Nikon) and subsequently irradiated on the surface of the PMMA at the perpendicular direction. The diameter of the focal spot was about 40.54μm. Then a high speed scanning process was implemented to create a line patterned microlens [20]. In the rapid scanning process, the average distance of the adjacent microlenses could be adjusted by the scanning speed, and the interval between two adjacent laser scanning lines could be set by the computer. For these convex MLAs, well-separated features are found with periods as small as 12μm. Based on this scale, the distance between adjacent lateral scanning lines and the scanning speed were respectively set at 20μm and 20mm/s to prevent the overlap of adjacent modification regions each other. Hence, a microlens could be generated by a single fs pulse. But it would be difficult to fabricate well-aligned structures under our experimental conditions by fs laser scanning method based on single fs pulse in-situ modification. Moreover, the shape of the microlens could be tuned by laser power. Figs. 1(b) and (c) show the cross section of a microlens. The results revealed that there was no internal microvoid during the fabrication process. The irreversible swelling of the modified area on the material was related to volume increase [21]. When the energy of single fs pulse is below the damage threshold of PMMA material, laser initiated nonlinear absorption was dominated by multiphoton and avalanche ionization. The nonlinear absorption would result in energy transformation from electrons to lattice [22]. The swelling, which was arised from the scission of polymer chains, was formed at the regions where laser exposed [23]. The transformation area occurred under the conditions of partial stress confinement. The pressure gradient caused the separation of the transformation region, which would lead to the formation of swelling [24]. The morphology of swelling had good stability. At threshold energies, ablation started from formation of a pore at the center of the dome. As pulse energy increases, the pore size increased and the annular protrusion decreased. [21]. Ablation caused material ejection is attributed to the plasmas produced by coulomb explosion [25]. The plasmas went out of the focal spot and formed a damage crater on the sample surface. So we could obtain swelling surface by adjusting pulse energy. In addition, it may open up possibilities for refinements in splash reduction and profile control of swelling surface. After laser modification, the samples were cleaned ultrasonically in alcohol and deionized water, respectively. The morphology of the sample surface was captured by the CCD camera, as shown in the Fig. 1(d).

Figure 2 shows scanning electronic microscope (SEM, US-8010) images of the convex MLAs taken from different view angels. Thousands of convex microlenses were produced on a PMMA sheet, as shown in Fig. 2(a). It is clear to find that the fabricated MLAs have a high quality and good uniformity, and the diameter of each microlens is about 3.95μm, which was extracted from the SEM image in Fig. 2(b). Furthermore, the distance between the adjacent convex structures was 20μm. One thousand microlenses could be generated per second because the repetition rate of the laser is 1 kHz. It is generally known that the surface profile and surface roughness are critical factors for the imaging performance of the lens. Fig. 2(c) and 2(d) demonstrate the ability of our technique to generate smooth, dome-like convex MLAs on the surface of PMMA substrate.

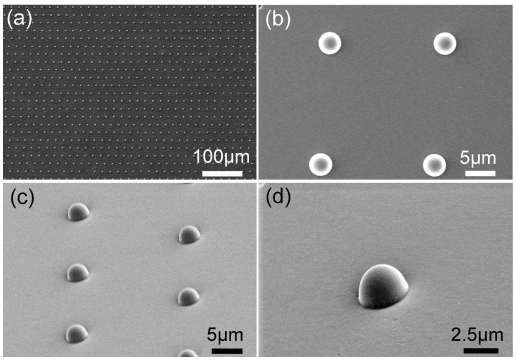

Fig. 2. Scanning electronic microscope (SEM) images of the MLAs at different view angles. (a-b) Top-view SEM images. (c-d) 60° tiled-view SEM images. The MLAs formed by focusing 1.25mW femtosecond pulse on the PMMA surface.

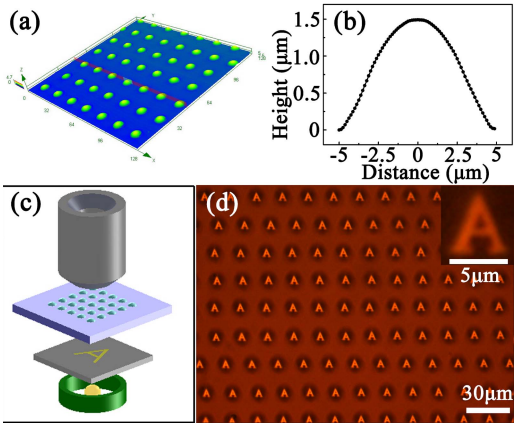

Fig. 3. (Color online) (a) A laser confocal scanning (LCSM) 3D profiles of the convex MLAs. (b) Cross section of a measured microlens and its spherical fitting. (c) Schematic diagram of the imaging system. (d) Imaging performance of the convex MLAs.

To get further insight into the surface profile of the convex microlenses, the 3D profile and cross section of the convex microlenses were investigated by a laser confocal scanning microscopy (LCSM, Olympus LEXT OLS4000), as shown in Figs. 3(a) and (b). The height (h) and the diameter (D) of the convex microlens are 1.6μm and 11.1μm, respectively. The focal length (f) and numerical aperture (NA) of the convex microlenses can be calculated by the following equations [24]: $f=(r^2+h^2)/2h(n-1)$, $NA=D/2f$, where r is the radius of the microlenses, which equals to D/2, and n is the refractive index of the material (n=1.49 for PMMA). A theoretical focal length and numerical aperture were calculated as 80.21μm and 0.069. The imaging properties of the convex MLAs were performed by a commercial imaging system, as shown in Fig. 3(c). During the experiments,

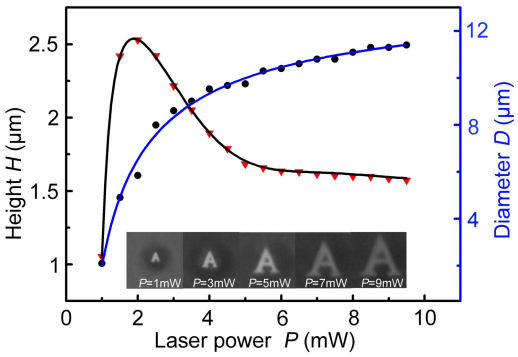

Fig. 4. (Color online) Laser Power dependency of the height and diameter of the convex microlens. The insertions present the images of a letter 'A' generated through the fabricated microlenses. The fabricating laser power are 1, 3, 5, 7, 9 mW, respectively, from left to right.

the MLAs was positioned on the motion stage, a mask with a transparent letter 'A' was placed between the illumination light and the MLAs. The clear and uniform images of the letter 'A' were obtained by a CCD camera, as shown in Fig. 3 (d). In addition, the high-performance imaging quality of the MLAs also demonstrated the good surface smoothness and excellent cross-sectional profiles of the microlenses. The imaging quality of the MLAs is obviously more superior to the microlenses obtained by nanojoule energy fs laser that focus into the internal material and form a microvoid [26], [27].

In our experiment, laser pulse energy played a significant role in controlling the size and shape of the convex microstructures. Figure 4 shows the dependence of the height and diameter of the convex structure on laser powers. It is clear that the height of the convex structure increases with the growth of the average laser power varies from 1mW (the corresponding laser fluence was 39mJ/cm^2 and laser intensity was 0.78 TW/cm^2) to 2mW (the corresponding laser fluence was 79mJ/cm^2 and laser intensity was 1.58 TW/cm^2). Subsequently, the height decreases with the increase of the laser power, and the decreasing trends slowed down when the laser power exceeded 5mW (the corresponding laser fluence was 198mJ/cm^2 and laser intensity was 3.96 TW/cm^2). In addition, it demonstrated that the diameter of the convex structure increases with the growth of the laser power, and the increasing trends slowed down when the laser power exceeded 5mW. The dependences of size and shape on the laser power can be explained as follows: as the laser power is less than 2mW, all the absorbed energy was used for the scission of polymer-chains. As a result, the height and diameter increase with increasing laser power. During the experiments, we found that laser scanning was accompanied by plasma generation when laser exceeded 2mW. Once the laser power exceeded the 2mW, photodecomposition consume a part of energy and other energy was taken away by the produced plasma, which resulted in that the height decreases with increasing laser power. The results indicated that the profile of the convex structure could be easily tuned by changing the laser power in the range from 1mW to 9.5mW (the corresponding laser energy was 377mJ/cm^2 and laser intensity was 7.55 TW/cm^2). But, when the laser power is higher than 9.5mw, ablation craters would be created instead of swelling dome. Although the smoothness of the fabricated microlens increases with the decrease of the laser power, a lower laser power can not induce swelling in the material [24]. The insets in Fig. 4 presented the clear images of a letter "A" generated through the fabricated microlens. In addition, the images of letter "A" were captured by adjusting the objective to the best focusing distance. The corresponding laser powers, from left to right, are 1mW, 3mW, 5mW, 7mW and 9mW, respectively. The focal lengths of these convex microlenses were 5.35 μm, 36.31 μm, 59.32 μm, 75.34 μm, 83.92 μm, respectively. According to the focal length formula, the obvious increase of microlens radius will lead to the increase of focal length, which agreed well with the images in the insets to allow for the relationship between focal length and image distance when the object distance remain a constant. As we know, the performance of microlenses is related to the morphology. And the morphology was changing with laser power. It is found that the image was clearest when the average laser power was 3mW (the corresponding laser fluence was 119mJ/cm^2 and laser intensity was 2.38 TW/cm^2), and the image would become blurry when the laser power increased, owing to the scattering of incident light caused by the laser induced rough surface.

III. Conclusion

In summary, we presented a high-efficiency process to fabricate large-area convex MLAs. The experimental results showed that convex MLAs, which were composed of several million lens units, could be easily fabricated on PMMA within an hour. The formation mechanism of the microstructures is associated with the separation of the transformation region resulting from the pressure gradient of laser-exposure regions. The smooth surface and excellent optical performance of the convex MLAs were well demonstrated by SEM images and imaging properties of MLAs, respectively. In addition, the size and shape of the microlens could be easily tuned by the laser power. And the clear images could be obtained when the average laser power was 3mW. Moreover, these large-area convex MLA is a promising candidate for broad applications in lab-on-chips and biomimetic compound eyes.

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