Lens-on-lens microstructures

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Received 18 September 2015; revised 22 October 2015; accepted 22 October 2015; posted 22 October 2015 (Doc. ID 249778); published 10 November 2015

Microtools with multiple focal lengths play an important role in three-dimensional imaging and the real-time detection of unconfined or fluctuating targets. In this Letter, we present a novel method of fabricating lens-on-lens microstructures (LLMs) using a two-step femtosecond laser wet etching process. A 3 × 3 LLM array was made with a diameter of 129.0 μm. The fabricated LLM has two focal lengths, 80.4 and 188.7 μm, showing excellent two-level focusing and imaging abilities. Its size and focal length can be controlled by adjusting laser power and etching time. Its surface roughness remains about 61 nm. This simple and efficient method for large-scale production of LLMs has potential applications in diverse optical systems. © 2015 Optical Society of America

OCIS codes: (220.0220) Optical design and fabrication; (230.0230) Optical devices; (220.3630) Lenses; (140.3330) Laser damage.

http://dx.doi.org/10.1364/OL.40.005359

Microtools are crucial optical devices because of their extensive applications in optical sensing technology, optical waveguides, optical fiber coupling, artificial compound eye structures, micro-manufacturing, biochemical systems, and lab-on-a-chip systems [1–7]. In the recent years, microtools with special structures have played more important roles than simple lenses in many applications; an example of the former type is the Fresnel microlens, which can be integrated with other optical components, owing to its nearly flat surface [8]. An ellipticone-shaped microlens offers great advantages in efficient coupling between high-power laser diodes and single-mode fibers [9]. Cylindrical microlens arrays can increase the luminous current efficiency of the OLED panel and make the spectrum of the OLED panel more insensitive to the viewing angle [10].

In this Letter, based on the femtosecond laser wet etching technology [11,12], we propose a two-step femtosecond laser wet etching method to fabricate a concave lens-on-lens microstructure (LLM). The fabricated LLM has two focal lengths, which has potential applications in optical storage [13,14], extended depth of focus of a laser beam [15], real-time detection of the unconfined or fluctuating targets [7], etc. By adjusting laser power and etching time, we obtained LLMs with both changeable size and focal length.

A convex LLM array was simply achieved on polydimethylsiloxane (PDMS) and polymethylmethacrylate (PMMA) surfaces through a replica molding process. The morphology and three-dimensional (3-D) profiles of the LLMs were measured by a scanning electron microscope (SEM) and confocal laser scanning microscope (CLSM). The optical performance of the LLMs was also tested, and the results presented below show the excellent imaging and focusing abilities of the LLMs.

The fabrication process of the LLMs, as shown in Fig. 1, includes first femtosecond laser irradiation, first buffered HF wet etching, second femtosecond laser irradiation, second buffered HF wet etching, and replica molding. First, a square-arranged crater array was induced on polished silica glass chips using femtosecond laser pulses (800 nm, 50 fs, 1 KHz) with a power (P) of 5 mW focused through an objective lens, which had a numerical aperture of 0.5 [Fig. 1(a)]. The laser power and irradiation time could be controlled by a variable density filter and a fast mechanical shutter. Then, the irradiated sample was put into a 3% hydrofluoric (HF) acid solution at room temperature. After buffered HF wet etching, the irradiated craters were transformed into concave microlenses [Fig. 1(b)]. An ultrasonic bath was necessary to ensure conformity and high speed by removing the bubbles generated at a liquid—solid interface during the chemical etching process. Subsequently, the femtosecond laser with a lower power (3 mW) irradiated the center of the bottom of the concave microlenses for the second time [Fig. 1(c)]. Then, the sample was treated again with a 3% HF acid solution at the same temperature [Fig. 1(d)]. Finally, the concave LLMs were formed. Further, convex LLMs on PDMS and PMMA surfaces could be obtained by a simple replica molding process [Figs. 1(e) and 1(f)].

To investigate the formation process of the LLMs, a series of SEM pictures were taken at different times during the process, as shown in Fig. 2. Figure 2(a) shows the SEM image of an untreated crater irradiated by the femtosecond laser, which reveals that some nanostructures exist in the crater. These structures are considered to be Lewis bases that accelerate the...
buffered HF etching velocity in the crater [16,17]. After the buffered HF wet etching process, a fine concave microlens was formed, as shown in Fig. 2(b). At the beginning of the wet etching process, the etching velocity in craters was higher than that in the other areas; with the progress of the etching process, the nanostructures in the craters were gradually consumed, and then the etching velocity in the whole area became identical. Thus, owing to the same etching velocity between the surface of the glass and the bottom of the microlens, the depth of the microlens did not increase during etching, whereas the diameter of the microlens still increased. After the first microlens was generated, a new crater at the center of the first microlens was irradiated by the femtosecond laser, as shown in Fig. 2(c). Then, the second buffered HF wet etching process was continued for several minutes. Finally, a perfect LLM was created. Figure 2(d) shows the excellent spherical morphology of the LLMs. The whole formation process was complete in 3 h.

Figure 3(a) shows the SEM picture of the concave LLM array, which clearly shows its perfect uniformity and spherical morphology. Figure 3(b) shows the 3-D morphology of the concave LLM, as observed by a CLSM. The cross-sectional profiles of the LLMs are presented in Fig. 3(c). The depth of the concave LLMs is 31.734 μm, and the half-width of the first microlens is 64.500 μm. Correspondingly, the depth of the second microlens is 12.048 μm, and the half-width of the second microlens is 29.356 μm. The curvature radius of the concave microstructures can be calculated by

\[ R = \frac{b^2 + r^2}{2b}, \]

where \( b \) and \( r \) present the depth and half-width of the microlens, respectively. According to Eq. (1), we can calculate the curvature radius of the second microlens immediately. Because the depth of the first microlens is not known, we cannot calculate its curvature radius directly; however, we can calculate its depth, according to the geometrical relationship in Fig. 3(c). The calculation yields the curvature radius of the first microlens and the second microlens as 98.107 and 41.788 μm, respectively. The focal length of the first microlens and the second microlens of the LLMs can be calculated by

Fig. 1. Schematic of the fabrication process for LLMs. (a) First femtosecond laser irradiation on silica glass chip. (b) First buffered HF wet etching. (c) Second femtosecond laser irradiation at bottom of the first microlens. (d) Second buffered HF wet etching. (e), (f) Replica molding process of the convex LLMs on PMMA or PDMS surfaces.

Fig. 2. Formation process of the LLMs. (a) SEM picture of the crater irradiated by the femtosecond laser. (b) First buffered HF wet etching. (c) SEM picture of the femtosecond laser irradiated crater in the bottom of the first microlens. (d) SEM picture of the LLMs.

Fig. 3. Characterization of both concave and convex LLMs. (a), (b) SEM image and 3-D morphologies of the concave LLMs. (c) Cross-sectional profiles of the LLMs. (d), (e) SEM image and 3-D morphologies of the convex LLMs, respectively. (f) Cross-sectional profiles of the convex LLMs.
where $f$ is the focal length, $R$ is the curvature radius, and $n$ is the refractive index of the material. We used K9 glass, which has a refractive index of 1.52. Using Eq. (2), we obtained focal lengths of 188.7 and 80.4 μm for the first microlens and the second microlens, respectively. In addition, the arithmetic-mean surface roughness value, $R_a$, is measured in an area of $128 \times 128$ μm$^2$ by a CLSM, and the result is 61 nm.

The convex LLMs were obtained on PDMS and PMMA materials by the replica molding process. Figure 3(d) shows the SEM image of the convex LLMs. It can be seen that the replicated convex LLMs have perfect morphology and good uniformity, which is very close to the mold. Figure 3(e) shows the 3-D morphology of the replicated LLM. Form the cross-sectional profile of the convex LLM in Fig. 3(f), we can see that the half-width of the first microlens is 63.539 μm, and the whole sag-height of the convex LLM is 31.096 μm. The half-width and sag-height of the second microlens are 28.339 and 11.496 μm, respectively. Compared with the mold, the deviation of size is less than 5%. Using the replica molding process, we can realize the efficient replication of the convex LLMs.

Figure 4 shows the focusing and imaging ability of the convex LLMs. The schematic shown in Fig. 4(a) demonstrates the rays that pass through the convex LLMs and focus on the focal planes. Figures 4(b) and 4(c) represent the simulation results of focusing ability on the focal planes $f_1$ and $f_2$, respectively, which were obtained from TracePro (simulation software). It can be seen that a ring-shaped light distribution is obtained [Fig. 4(b)]. The reason for the formation of this ring is that parallel light is focused on the focal plane $f_1$ through the small lens, but light passing through the large lens gives rise to a ring distribution on the focal plane $f_1$, as shown in Fig. 4(a).

Figures 4(d) and 4(e) show the real focused images on $f_1$ and $f_2$ that are consistent with the simulation results. We also tested the imaging ability of the LLMs. A mask with letter “A” was put between the light source of the microscope and the LLMs, and images were observed by using a CCD camera, which was equipped on the microscope. The results for $f_1$ and $f_2$ are displayed in Figs. 4(f) and 4(g), respectively, which indicate that the LLMs have excellent imaging ability.

In the experiment, the size of the LLM and its focal length were controlled by adjusting the laser power and etching time. Figure 5(a) shows the change of the diameter of the LLM as a function of etching time and femtosecond laser irradiation power. In Fig. 5(a), the black line represents the first microlens that is irradiated by a laser power of 5 mW and subjected to etching for 100 min, at the beginning. Then, a new crater is irradiated in the bottom of the first microlens. The inserted images show the formation process of the LLM and indicate that its size can be controlled. Figure 5(a) shows that selecting different combinations of parameters results in the formation of...
LLMs with different sizes (e.g., the middle and right inserted pictures). Figure 5(b) shows the focal length of the microlens, which is influenced by the laser power and etching time. We measured the focal length of the microlens at different laser powers and etching time. It can be seen that the focal lengths at the same etching time for different laser powers have a linear relationship, and the least-squares fittings at different etching time have approximately the same slope. In Fig. 5(b), the focal length of the microlens ranges from 30 to 140 μm. Therefore, we can design and fabricate LLMs with different sizes and focal lengths, according to the relationships in Fig. 5. To design the convex LLMs, we selected two sets of parameters: (1) 5 mW (laser power of the first irradiation), 100 min (the first etching time), 3 mW (laser power of the second irradiation), and 40 min (the second etching time); and (2) the corresponding values of parameters: 5 mW, 100 min, 3 mW, and 60 min. After the replication process, we obtained the convex LLMs, as shown in Fig. 6.

To summarize, in this Letter, we demonstrate a method to fabricate an LLM with two focal planes, which has potential applications in optical storage, extended depth of focus of a laser beam, real-time detection of the unconfined or fluctuating targets, etc. Using this method, we can fabricate LLMs with different sizes and focal lengths, which can be controlled by adjusting the parameters (femtosecond laser power and etching time) carefully. The convex LLM can be easily replicated by the concave mold. Its focusing and imaging abilities are confirmed to be excellent. Our approach provides a simple and efficient method to large-scale production of LLMs for different applications in diverse optical system.

Funding. National Natural Science Foundation of China (NSFC) (51335008, 61275008, 61475124); Special-funded programme on national key scientific instruments and equipment development of China (2012YQ12004706).

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