

Rapid optical μ -printing of polymer top-lensed microlens array

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Abstract: Microlenses have wide applications for light beam focusing or shaping in microoptical systems. However, it remains challenging for conventional microfabrication methods to rapidly fabricate arrays of microlenses with complex profiles like lens-on-lens structures. In this paper, we present the rapid fabrication of polymer microlenses with lens-on-lens structures by using a digital optical μ -printing technology. An improved dynamic optical exposure method is developed to directly and precisely fabricate polymer top-lensed microlenses (TLMLs). Arrays of TLMLs with either elongated focal depth or two separate foci have been numerically investigated and experimentally demonstrated.

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1. Introduction

Microlens is one of fundamental micro-optics and plays increasingly irreplaceable roles in the miniaturization of various optical systems [1–4]. Recently, microlenses with complex profiles or configurations attracted increasing attention because of their enhanced light-beam shaping ability. For instance, a microlens with the profile defined by a double-axial hyperboloid was demonstrated to shape asymmetrically divergent output beam [3]. A microlens with two aspheric surfaces was fabricated to achieve a diffraction-limited focus spot for high-density optical storage systems [4]. Particularly, a special kind of microlenses with lens-on-lens structures has attracted remarkable attention because of its extraordinary beam reshaping abilities as well as the promising applications in diverse optical systems, such as optical storage and unconfined fluctuating target counting systems [5–10].

However, conventional methods, such as hot embossing [11], microdroplet jetting [12], and femtosecond laser ablation process [13,14], cannot be used to directly fabricate lens-onlens structures. Two-photon polymerization (TPP) showed great flexibility on the fabrication of arbitrary form microlenses [3,15–17]. However, due to the single-spot scanning nature, it has low efficiency and typically needs a few hours to fabricate extensive arrays of microlenses [13]. One of the promising solutions to overcome such a technical bottleneck is the digital mirror device (DMD)-based dynamic optical exposure technology, which has been demonstrated to exert around a million of pixels to rapidly fabricate arrays of microlenses [18,19]. However, the microlenses demonstrated in previous works are conventional one with single-lens component. It is still in a loose sense whether the technology can efficiently fabricate lens-on-lens structures.

In this paper, we present an improved dynamic optical exposure technology to directly print microlenses with lens-on-lens structures, i.e. top-lensed microlenses (TLMLs). With an in-house DMD-based optical μ -printing platform [20,21], the relation between the exposure dose of UV light and the cured depth of photopolymer is studied. Then, a dynamic exposure scheme using the bitmap of corrected exposure doses is developed to facilely tailor the



profiles of microlenses pixel by pixel and thereby precisely print arrays of top-lensed microlenses with either elongated depth of focus or dual foci.

2. Design and fabrication

Figure 1 shows the designs of TLMLs whose diameters are 290 and 180 μ m, respectively. The curvatures of the upper and bottom parts of the first microlens, as shown in Fig. 1(a), are 0.0065 and 0.002 μ m⁻¹, respectively, while the upper and bottom parts of the second microlens are with the curvatures of 0.045 and 0.006 μ m⁻¹, respectively. Ray tracing method (COMSOL Multiphysics 5.1) was used in simulation of the propagation of light beams through such microlenses, as the diameters of microlenses are far longer than the operation wavelength in visible range [22,23]. Figure 1(b) shows a 2D plot of light field traced by 10000 incidence rays passing through the first TLML in which the intensity represents the relative number of refracted rays at each point on a meridional plane. It can be seen that the depth of focus along the optical axis is elongated to as long as 570 μ m. If the curvature difference between the upper and bottom parts of the microlens is further increased, as the second TLML shown in Fig. 1(c), two separate focal points can be achieved. It can be seen from the simulation results in Fig. 1(d) that two separate foci with the distance of 215 μ m was achieved.



Fig. 1. Schematic design and simulation results of TLMLs. (a) shows a TLML with elongated depth of focus and (b) is its simulated distribution of light field. (c) shows a TLML with dual foci and (d) is its simulated distribution of light field.

The optical μ -printing setup consists of a high-power UV light source (OmniCure 2000 System, Lumen Dynamic Group Inc.), a DMD (DLi4120 0.7" XGA, Texas Instruments, USA), projection optics, and a high-precision motorized X-Y stage (M-687, Physik Instrumente GmbH & Co.) [20,21]. The motorized stage can enable the precise location of exposure for fabrication of large-area microstructures through seamless pattern-stitching process. The 3D model of designed microlens is sliced into 100 layers of image data in commercial image-data analysis platform (Tecplot Inc., USA). The light beam from UV light source is homogenized, collimated, and then illuminates the DMD chip. As a spatial light modulator, DMD chip can dynamically create optical patterns for dynamic exposure processes according to the image data.

EPON resin SU-8 (Monmentive Ltd.) was used to fabricate the polymer microlenses because of its good transparency as well as excellent mechanical property and chemical resistance. OPPI SbF₆ (Hampford Research Inc.), tributylamine (Meryer Chemical Technology Co., Ltd.), and TINUVIN 234 (Sigma-Aldrich Ltd.) were used as photo-initiator, inhibitor, and photo-absorber, respectively. These compositions were dissolved by using cyclopentanone in a weight ratio of SU-8/ OPPI/ tributylamine/ TINUVIN-234 = 100:2.1:0.014:0.15. A thin layer (~1 μ m) of SU-8 photoresist was polymerized on a glass substrate to act as a buffer layer for promotion of the adhesion between glass and MLAs. Another relatively thicker layer of SU-8 photoresist was then spin-coated upon the buffer layer for fabrication of microlenses. The photoresist was soft baked to remove solvent. The sample was dynamically exposed by optical patterns generated by the DMD. The intensity of

UV light irradiated upon the photoresist was 41.15 mW/cm². Based on the additive property of optical penetration depth, the photoresist was activated layer by layer by the patterns of predefined microstructures. Thereafter, the exposed photoresist was cured by a post-bake process. After that, the sample was developed by using 1-Methoxy-2-propyl acetate (J&K Scientific Ltd.) for 10 min.

To fabricate a complex microlens with predefined profile, it is critically important to know clearly the relation between the exposure dose and cured depth so as to determine individual time for each sliced image for dynamic exposure process. In order to reveal such a relation, a series of micrometer-scale pillars with different heights were fabricated with linearly increased exposure time. The optical microscopic image and laser-scanning confocal 3D image of the fabricated pillars were shown in Figs. 2(a) and 2(b), respectively. The height of pillars varied from 17.1 μ m to 84.53 μ m with the increase of exposure time from 22 to 60 s. The top-left inset of Fig. 2(c) shows that the dependence of the height of pillars (i.e. the cured depth of resin) on the accumulative exposure dose when the UV light intensity is 41.15 mW/cm². It can be seen that the relation between the cured depth and exposure dose is not linear.



Fig. 2. Optical microscopic image (a) and laser-scanning confocal 3D image (b) of the fabricated SU-8 micro-pillar array for calibration of exposure time. (c) Dependence of cured depth on the natural logarithm of exposure time. The inset is the curve of cured depth verses exposure time.

According to Beer Lambert law, such a nonlinear relation caused by the absorption of UV light in SU-8 resin and TINUVIN 234 can be written into a linear equation as

$$d = \gamma \hat{t} + \gamma \ln(t_{th}) \tag{1}$$

where \hat{t} is the natural logarithm of exposure time, γ is the slope of the linear relationship, and t_{th} is the threshold of exposure time. For a specific UV light intensity, the slope γ mainly depends on the ratio of the contents of photo-initiator to that of UV light absorber, and a larger ratio results in a deeper slope γ . The threshold of exposure time t_{th} is the minimum time required to initiate the curing of photoresist, which mainly depends on the ratio of the contents of photo-inhibitor. Higher concentration of photo-inhibitor leads to longer threshold time. From the fitting result of the date shown in Fig. 2(c), it can be induced that γ is 56.25 and threshold time t_{th} is 15.75 s.

3. Results and discussion

In the experiments, three groups of microlens arrays without and with lens-on-lens structure, called ML-0, TLML-1 and TLML-2, respectively, were fabricated, whose exposure time is less than 36 seconds. Figures 3(a)-3(c) are their images taken by scanning-electron microscope (VEGA3, TESCAN company) operated at 20 kV. The magnifications of the machine used to take Figs. 3(a)-3(c) are 276, 134, and 260, respectively. Figures 3(d)-3(f) show the comparison of the designed (dash curves) and five measured (solid curves) profiles

of each kind of microlens, which were measured by a laser-scanning confocal microscopy (Keyence VK-X200K). The measured heights are 32.9, 40.1, and 35.1 μ m, respectively. The diameters of the three kinds of microlenses are 184.1, 296.83 and 178.02 μ m, respectively, while the diameters of the top lenses of TLML-1 and TLML-2, as shown in Figs. 3(b) and 3(c), are 120.1 and 50.8 μ m, respectively.



Fig. 3. SEM images (a)-(c) and cross-sectional profiles (d)-(f) of the fabricated ML-0, TLML-1 and TLML-2, respectively. The designed profiles (dash curves) have been added to compare with five measured ones (solid curves) of microlenses in (d) to (f). Scale bars are 100 μ m.

For the profile of a microlens, it can be approximated by using the equation [24],

$$z(r) = -\frac{cr^2}{1 + \sqrt{1 - (1+k)c^2r^2}}$$
(2)

where *r* is radial coordinate, *c* is the curvature of microlens, *k* is conic constant. The profile is hyperbolic when k < -1; it is parabolic when k = 1; it is elliptic when -1 < k < 0; it is spherical when k = 0; it is oblate ellipsoidal when k > 0. The fitted results of the parameters of the measured profiles of the fabricated microlenses were given in Table 1. The bottom lenses of TLML-1 and TLML-2 are oblate ellipsoidal, whose conic constants are 11.31 and 2.33, respectively, while their upper-lenses are hyperbolic, whose conic constants are -3.5455 and -4.8393, respectively.

Table 1. Fitted results of the curvature *c* and the conic constant *k*.

	Curvature c	Conic constant k
ML-0	0.0048	4.1033
TLML-1 (U.)	0.0064	-3.5455
TLML-1 (L.)	0.0019	11.3146
TLML-2 (U.)	0.0462	-4.8393
TLML-2 (L.)	0.0058	2.3341

The ability of the microlenses on focusing of an incoherent light beam was tested by using an own-established setup. The light beam from an LED with the central wavelength of 532 nm was collimated by a home-made expander using an objective $(20 \times)$ and a lens (f = 100 mm) and an aperture (placed at the focal position of the objective). The light illuminated the glass slice and then passed through the microlens from bottom to top so as to avoid the influence of the glass substrate on testing results. A digital camera was mounted on a motorized stage so that a LabVIEW program can be used to automate the capturing of images every 5 µm from the microlens to 1750 µm away. By extracting the light intensity at the

determined location of focus in each image, the distributions of optical intensity alone the optical axis were shown in Figs. 4(a)-4(c). The images of light patterns taken at the six positions indicated in Figs. 4(a)-4(c) are given in Figs. 4(d)-4(f), respectively.

With the measured profiles, numerical simulations have been carried out by using raytracing method to compare with measured results. To compare with experimental results, rays emitted from a spherical surface with the curvature of $3 \times 10^{-4} \,\mu\text{m}^{-1}$ were used in the simulation. The refractive index of SU-8 is assumed to be 1.59. The simulated distributions of optical intensity alone the optical axis were also given as dash curves in Figs. 4(a)-4(c) to compare with measured results.

It can be seen from Fig. 4(a) that the measured focal position of the fabricated ML-0 is at 400 μ m, which is close to the simulated focal position at 394.4 μ m. To test the imaging quality of the fabricated microlenses, a mask with the character 'M' was put on a position before light enters the microlens. The image projected by the fabricated ML-0 is shown in the inset of Fig. 4(a).



Fig. 4. (a), (b) and (c) are the measured (solid curves) and simulated (dash curves) light intensity distributions along the optical axes of ML-0, TLML-1, and TLML-2, respectively. The insets are the images projected by the microlenses, in which the scale bars are 25 μ m. (d), (e) and (f) are the measured transverse optical images, in which the scale bars are 100 μ m, at different positions indicated in (a), (b) and (c), respectively.

For TLML-1, the measured first focal position is at 410 μ m, and its second focus is at 910 μ m, as shown in Fig. 4(b). The depth of focus at half maximum is 767.11 μ m, which shows the ability of the TLML to elongate the focal depth. The simulated two foci locate at 366.1 μ m and 992.9 μ m, respectively. Simulation revealed that the elongated focal depth attributes to the close location of the two foci and a smooth transition between the upper and bottom lenses make a more flat distribution of light between the two foci. The upper and lower inset in Fig. 4(b) shows imaging pictures at the first and second foci respectively. Figure 4(e) shows the cross-sectional intensity distributions in Figs. 4e(1-3) result from the upper and bottom lenses, respectively. With the propagation of light, the first focal point by the upper lens diverges and while the bottom lens takes more effects to converge the light and maintain the light intensity. The spider-web like segmented look of the images may attribute to the structure of LED's emitting area and the TLMLs' astigmatism aberration [25].

Two separate foci can be achieved by increase of the difference between the curvatures of the upper and bottom lenses. Figure 4 (c) shows the TLML-2's distribution of optical intensity alone the optical axis. The measured first and second foci are at 80 μ m and 360 μ m, separately. The simulated positions of the first and second foci are close to measured results as 88.7 μ m and 363.1 μ m, respectively. Compared with the symmetric on-axis distribution of the first focus, the distribution of the second focus is not symmetric, which may result from the spherical aberration caused by the shape of oblate ellipsoid of the bottom lens. It can be improved by using an improved design of the bottom lens with elliptical or parabolic profile [26].

It can be seen that the image projected by the lower part of TLML-2 is clearer than that projected by the counterpart of TLML-1 because of its smaller spherical aberration. The relative magnitudes of spherical aberration can be deduced from Fig. 4e(5) and Fig. 4f(5), in

which Fig. 4f(5) shows a sharper light spot than that of Fig. 4e(5). The image produced by the upper part of TLML-2 is also clearer and with higher contrast than that produced by the counterpart of TLML-2 because of its smaller spherical aberration, which can be estimated from the comparison between Fig. 4e(2) and Fig. 4f(2). Moreover, the lower part of TLML-1 produced the largest image because the longest focal length (which leads to the smallest reduction ratio).

4. Conclusion

In conclusion, we have presented a fast and facile method for fabrication of top-lensed microlenses. Arrays of complex microlenses with different focal structures have been experimentally demonstrated. A lens-on-lens structure with upper-lens of hyperbolic profile and oblate ellipsoidal bottom-lens has been fabricated to achieve the elongated focal depth. With the increase of the difference between the curvatures of top and bottom lenses, TLMLs with two separate focal points have also been demonstrated. Such TLMLs have great potentials in light beam focusing or shaping for diverse micro-optical applications ranging from optical storage to real-time fluctuating target counting in microfluidic systems.

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