

100% Fill-Factor Aspheric Microlens Arrays (AMLA) With Sub-20-nm Precision

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Abstract—Substitution of a single aspheric microlens (array) for a complex multilens system results in not only smaller size, lighter weight, compacter geometry, and even possibly lower cost of an optical system, but also significant improvement of its optical performance such as better imaging quality. However, fabrication of aspheric microlens or microlens array is technically challenging because conventional technologies used for macro-sized aspheres like single-point diamond milling, and those for spherical microlens like thermal reflow, are not capable of defining a complicated lens profile in an area as small as several to tens of micrometers. Here we solve the problem by using femtosecond laser micro-nanofabrication via two photon polymerization. Not only well-defined single lens, but also 100% filling ratio aspheric microlens array were readily produced. The average error of the lens profile is only 17.3 nm deviated from the theoretical model, the smallest error reported so far.

Index Terms—Aspherical lens, femtosecond laser, high fill-factor, microlens array.

I. INTRODUCTION

AN ASPHERIC lens or asphere is a lens whose surfaces profile neither a portion of a sphere nor of a circular cylinder, from which spherical aberration can be eliminated and other optical aberrations reduced [1]. Hence, replacement of a complex multilens system by a single aspheric lens or by an aspheric microlens array results in not only smaller size, lighter weight, a more compact geometry, and even possibly lower cost of an optical system, but also significant improvement of its optical performance such as better imaging quality. An asphere is generally fabricated by grinding and polishing, [2], i.e., a blank is first ground to roughly the right form by point-contact contouring, and then several techniques are used to polish the optic to its final shape. Single-point diamond turning [3] is the most important approach to reach the end, in which a computer-controlled lathe uses a diamond tip to cut the desired profile into a piece of glass or another optical material. These methods are apparently not applicable to aspheric or inverse aspheric lenses to be used for molding of diameters from

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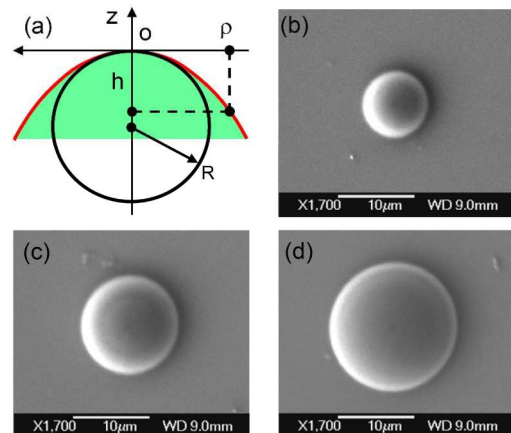


Fig. 1. Single microlenses by two-photon photopolymerization of the epoxy-based negative resin SU-8. (a) Illustration of aspheric lens geometry, and (b)–(d) top-view SEM images of spheric microlenses with different radii 4, 6, and 8 μm , respectively.

several to tens of micrometers. These devices are, however, highly desired in many micro-optical systems and applications [4]. On the other hand, due to the difficulty in precise control of a complicated surface profile, e.g., that defined by a parabolic function, techniques that are currently used for production of spheric microlens or microlens array like thermal reflow [5], gray scale lithography [6], and soft lithography [7] do not work for this purpose, either. The production of a high-quality aspheric microlens array or AMLA is now an open problem. In this letter, we solve the problem by direct laser writing based on two-photon polymerization of resins [8], [9]. Due to the capability of pinpoint writing with nanometric accuracy of the technology, not only an arbitrary lens profile was achieved for individual lenses, but also the lenses were spatially arranged into regular array with 100% filling ratio, as is not accessible by any other microfabrication technologies.

II. EXPERIMENTS

Fig. 1 shows geometry of aspheric lens and scanning electron microscope (SEM) images of single microlenses with different radii of 4, 6, and 8 μm , all fabricated by two-photon photopolymerization of the commercial epoxy-based negative resin SU-8 (2075, MicroChem). The resin has been widely used for fabrication of high-quality three-dimensional (3-D) photonic crystals [10] and micro-optical devices [11], [12] by two-photon polymerization due to its high transmittance for light from the visible to the near-infrared wavelengths, low polymer volume shrinkage, good mechanical properties (Young's modulus, $E \sim 4\text{--}5$ GPa and biaxial modulus of elasticity ~ 5.2 GPa), and high thermal stability (the degradation temperature $\sim 380^\circ$), making it a good material for micro-optical components. For direct laser

writing, femtosecond pulses from a mode-locked Ti-sapphire laser (Spectra-Physics Tsunami: central wavelength at 790 nm, pulse duration of 120 fs, repetition rate at 80 MHz) were tightly focused by a $\times 100$ oil immersion objective lens with a high numerical aperture ($NA = 1.45$) into the resin. The laser power measured before the objective lens is only 6 mW. The laser focal spot was scanned laterally by steering a two-galvano-mirror set and along the optical axis by a piezostage. The photoresist samples were prepared by spin-coating SU-8 films on a glass slide that was cleaned with acetone and absolute ethanol. After evaporation of the solvent in a soft-bake step by 30 min at 95 °C, a 20- μm -thick film resulted. On irradiation by the femtosecond laser, the photoinitiator (mixed triarylsulphonium/hexfluoroantimonate salt in propylene carbonate solvent) generated, through two-photon absorption, spatial distribution acid with a spatial concentration following the distribution of the light intensity square. In a postexposure bake from 65 °C to 95 °C for 10 min, the latent image was converted into a crosslinked solid skeleton by a chain reaction. The written structures were then developed in the SU-8 developer (1-Methoxy-2-propylacetate) for 60 min, leading to a positive image of the scanned pattern. The heights at the vertex of the lenses are 1.6, 2.4, and 3.2 μm , respectively. Their surfaces are smooth, and the surface roughness, according to atomic force microscopy (AFM) measurement, is < 10 nm.

III. RESULTS AND DISCUSSION

For a lens made with spherical surfaces, parallel light rays that pass through the central region of a spherical lens focus farther away than light rays that pass through the edges of the lens. The result is the occurrence of many focal points, producing a blurry image [1]. An aspheric lens eliminates the spherical aberration and reduces other optical aberrations compared to a simple lens. With the optical axis as the z -axis and the coordinate origin coinciding with the vertex, a rotationally symmetric aspheric lens profile is described well in cylindrical coordinates. The lens profile is parameterized as [Fig. 1(a)]

$$z(\rho) = \frac{\rho^2/R}{1 + \sqrt{1 - (1+k)\rho^2/R^2}} + \sum_{i=1} C_i \rho^{2(1+i)} \quad (1)$$

where ρ is the radius of base circle of a lens, R the vertex radius, k the conic constant, and C_i is the $2(1+i)$ th aspherical deformation constants. The length height h is related with R and ρ by $R = \rho^2/2h$. By systematically investigating the effects of various terms, a best combination of coefficients and, hence, a best-form aspheric lens is obtained. For example, to design a spherical-aberration-free lens, the spherical aberration can be taken as the merit function, and a smaller value of the merit function means a lens with a better optical quality (i.e., with a lesser spherical aberration). Due to the high precision point-by-point prototyping strategy [15], [16], femtosecond direct laser writing is a promising tool to satisfy the requirement of the complex lenses' fabrication. As a proof-of-concept, we take the parabolic shape, meaning that $k = -1$ and $C_i = 0$ in (1), as an example. Shown in Fig. 2(b) is the 90°-tilted SEM images of a parabolic lens with the radius $\rho = 10 \mu\text{m}$ and heights $h = 10 \mu\text{m}$. For comparison, an elliptical lens is also shown in Fig. 2(a). The shape difference is evidently discerned from the SEM images: the elliptical lens looks round while the parabolic lens appears sharper. From Fig. 2(c) and (d), we find that

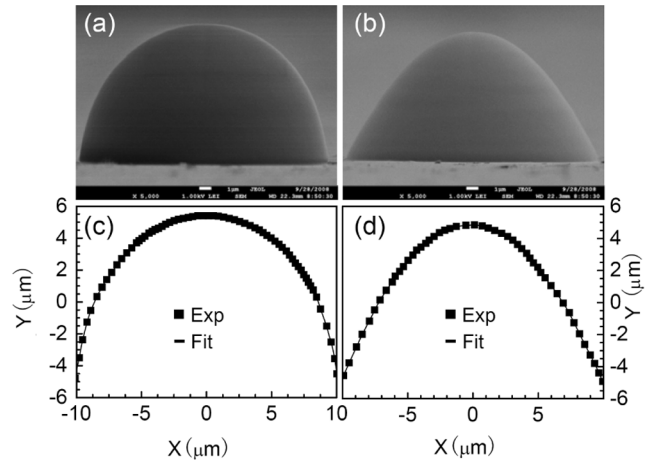


Fig. 2. Single aspherical microlens. (a) and (b) 90°-tilted SEM images of an elliptical and parabolic lenses. (c) and (d) The measured profile (the square symbol) and the theoretical curves (the lines).

the measured line of the lens profile agrees well with the theoretical elliptical and parabolic curves. The relative error is less than 0.2%, far smaller than that from other approach, e.g., 8% in thermal reflow [5]. The achievement of such a high overall fabrication precision, around 20 nm, arises from four factors: 1) The small size of voxels consisting of a structure, < 100 nm [13], and relatively low shrinkage rate of the SU-8 upon polymerization; 2) high reproducibility of the shape and size of voxels, for example, laser pulse energy fluctuation, generally $< 5\%$, leads to fluctuation of size of voxels less than 5 nm; 3) high positioning accuracy of voxels due to the use of high precision moving stage (< 1 nm) and mirror steering (several nanometers); and 4) the small voxels written in way of spatially overlapping with each other to produce a smooth surface with surface roughness around 10 nm [14]. These four points guarantee that the two-photon photopolymerization is appropriate for fabrication with high precision of micro-optical devices. The small error is considered caused by ambient vibration and the remained resin shrinkage.

Compared with single aspheric microlens, even more interesting and useful is their array. Shown in Fig. 3(a) is an SEM image of 100% fill factor square array of the microlens. For comparison, the solid model of a square microlens and 3-D geometry of a gapless square microlens array are shown in Fig. 3(c). The fill factor defined as the percentage of lens area to the total area is one of the important parameters for microlens arrays. Since there is no gap between the lenselets in design and the computer pattern is faithfully converted into a physical structure, the laser technology possesses intrinsic capability to realize 100% filling ratio. It is well known that 100% fill factor microlens arrays are expected to ultimately utilize the entire incident light and enhance the image brightness of liquid-crystal displays and raise the out-coupling efficiency in organic light-emission diodes (OLEDs). The entire arrays are composed of aspheric lenslets with $\rho = 5 \mu\text{m}$, $h = 1.5 \mu\text{m}$, and each lens was written with annular way [17], by which a surface smoother than the common raster scan is attainable. Transmission measurement revealed that the optical absorption by the microlens array was negligible, e.g., 1.5- μm -thick polymerized SU-8 film gives a transmittance of $> 99\%$ in the

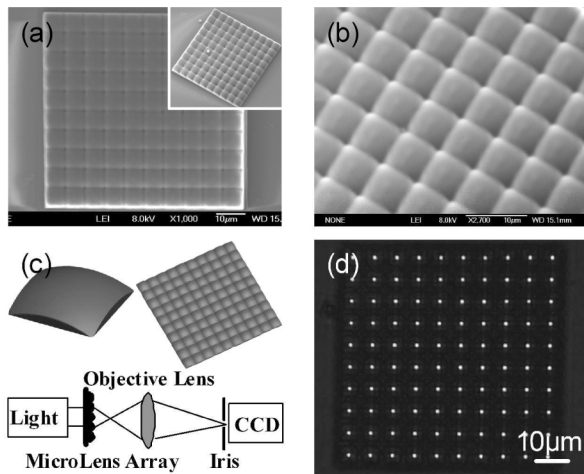


Fig. 3. The 100% fill-factor square microlens arrays. (a) and (b) Top-view SEM images of the gapless square microlens arrays and its locally magnified tiled view. (c) Solid model of a square microlens, 3-D geometry of 100% fill-factor square array, and the optical characterization system for microlens array. (d) Focal spot image was obtained at the focal plane under illumination by a halogen lamp.

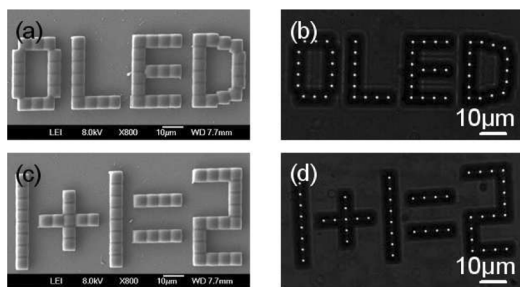


Fig. 4. Various arrangements of microlenses. (a) and (c) Top-view SEM images of the patterns of "OLED" and "1 + 1 = 2," which are composed of square microlenses. (b) and (d) Measured focal spots.

wavelength range from 360 to 1100 nm. AFM measurements showed the surface profile consistency of lenses in the array is also less than 0.2%. To investigate the focusing capability of the microlens arrays, they were illuminated with white light from a halogen lamp. A square array of bright focal spots was observed behind the objective lens, as shown in Fig. 3(d). The focal spots are quite sharp and uniform.

For femtosecond laser two-photon fabrication, there is no need for mask and all models are designed by computer programs. Therefore, it is convenient to fabricate different microlens arrays to meet customized needs. Shown in Fig. 4(a) and (b) are SEM images of letter patterns of "OLED" and "1 + 1 = 2," as they are composed of square microlenses, and all lenslets demonstrate good lens functions [right images in Fig. 4(c) and (d)]. This manifests that we can not only fabricate single lens but also they can be spatially arbitrarily positioned. It is worth mentioning that although Guo *et al.* [17] utilized the two-photon technology for fabrication of the microlens array (2 × 2), their lenses are spherical, and the issues of arbitrary definition of lens surface profile and filling ratio were not addressed.

IV. CONCLUSION

Aspheric microlens and lens array with 100% filling ratio were fabricated by femtosecond laser direct writing through pin-point two-photon photopolymerization. The relative error of the lens profile is less than 0.2%. The lenses or lens array structures could be further converted into optics consisting of hard materials like silica by some finishing steps like reactive ion etching. This work shows the simpleness, rapidness, and high precision of the femtosecond laser technology for the fabrication of complicated micro-nanoscaled functional optical devices.

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