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TECHNICAL PAPER

Rapid fabrication of semiellipsoid microlenses using 3D-printing and roll-to-roll imprinting process

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Abstract

A simple and rapid method for fabricating semiellipsoid microlens arrays (SEMA) is proposed. An elliptic-array substrate made of resin was first designed and fabricated by twice rollover method with a mold produced by 3D printing. Then droplets of UV curable resin were placed on the elliptic-array substrate and liquid lenses with semiellpsoid shape will be formed due to surface tension. Finally a SEMA can be obtained by curing the liquid lens with UV light. Numerical simulation was employed to predict the stable surface profile, and results show good agreement with the experiments. To massively and rapidly replicate SEMAs, a roll to roll (R2R) imprinting process is proposed,which uses a polydimethylsiloxane (PDMS) mold transferred from the preformed SEMA prototype. Measurements of surface profile are conducted, showing that the relative error of replicated microlens with theoretical is less than 1.59%.

1 Introduction

Aspheric lenses have been desired increasingly in many products for the advantage of correcting optical aberrations. As a typical aspheric lens, semiellipsolid microlens has been applied in enhancing optical fiber coupling efficiency (Hu et al. 2008) and micro-optical systems where astigmatism correction is required (Lee et al. 2006, 2007). Many methods for fabricating semiellipsolid microlenses have been reported. Muttahid-Ull Hoque and his team used a bi-axial scanning method to obtain the biconvex aspherical microlens for maximizing the coupling efficiency between an edge emitting laser and an optical fiber (Hoque et al. 2017). Luo et al. (2017) got a multi-focusing artificial compound eye with negative meniscus substrate by melting photoresist method. Thiele et al. (2017) fabricated an eagle eye for foveated imaging by 3D-printed technology. Other methods for fabricating aspheric lenses, including thermal reflow (Lian et al. 2014), photoresist inkjet-printing (Cadarso et al. 2011; Chen et al. 2013), lift-off and alignment exposure processes (Hung et al. 2012a), UV proximity printing (Hung et al. 2012b), mechanical manufacturing (Liu et al. 2011), etc., have been reported in the literatures. Though these methods have achieved good results and have been shown to be effective methods for aspheric microlens fabrication, they still needed to be improved in some aspects. One of the concerned issues needed to be investigated is the complicated technical processes, For example, thermal reflow processes firstly need a high-precision mask for further one or more series of lithography processes to get ellipse cylinders which will be heated to reflow or used as substrates for ink-jet droplets to form semiellipsolid microlens. By comparison, mechanical manufacturing technology can directly get aspherical surfaces, but it suffers from high costs and low efficiency, which prevents its application in massive fabrication. A novel method to get SEMA with high efficiency and low cost is therefore of important significance.

Recently, 3D printing technology has been rapidly developed over years as a promising alternative approach to conventional manufacture technologies due to its low cost, short process time and versatility in fabricating complicate parts (Ambrosi and Pumera 2016; Gill and Hart 2016; Yazdi et al. 2016). In this research, an approach to get precise semiellipsoid microlens by 3D printing and inkjet method was developed. Simulation and experiments were employed to study the relationships among the lens

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profile, the droplet volume and the contour shape. We then replicated the SEMA by a R2R process, which significantly improved the producing efficiency and would be useful in massive production.

2 Fabrication process

2.1 Elliptical contour substrate by 3D printer

Inkjet method is a main technique for fabricating microlenses, but as a microlens's performance depends on the microlens profile, the resin volume and substrate geometry that determine the microlens profile toned to be precisely controlled. Herein we designed a substrate with elliptical geometry with OA length of 1.2 mm, OB length of 0.6 mm, edge thickness d of 0.2 mm and the substrate height of 0.1 mm, as shown in Fig. 1a. 3d model of the elliptical substrate was first fulfilled by commercial software Solidworks (Dassault Systems S. A.), as shown in Fig. 1b, and then exported in STL format for further process.

Then we made a 3D elliptical substrate array mold by a 3D printer (Project3500 HDMAX, 3D system Inc). To massively obtain arrays of elliptical resin material at atmospheric pressure, PDMS was casted onto the printed mold and cured in room temperature of 300 K for 48 h. After demolding, the elliptical soft mold was achieved. UV resin (Tex Year, 1551M2) was first dripped on a slide, the soft mold was then imprinted onto the resin in the air, and the array of elliptical resin material was finally obtained after removing the PDMS mold. The imprinted elliptical contour was experimentally measured a microscopy, as shown in Fig. 2. The axial ratio of the printed elliptical is 1.995:1, while the design value is 2:1.The relative error of 0.25% (denoted by δ_1) demonstrates that the elliptical substrate can be precisely replicated.

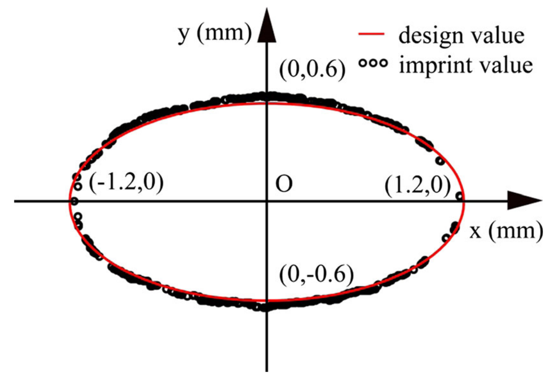

Fig. 2 Comparison between imprinted contour and designed contour

2.2 Droplet method for making semiellipsoid lens

After obtaining the array of elliptical substrate, a fixed amount of resin was dropped on the substrate, where semiellipsoid microlenses were formed under the influences of surface tension. The resin volume was precisely controlled by a precise dispensing device with resolution of 0.1 μl (BOSCOM, B-A6)through controlling outlet pressure, internal diameter of the pinhole, and spit time. In the experiments, the device outlet pressure was 60 Psi, internal diameter of the pinhole was 0.24 mm, and the spit time was 0.6, 0.7, 0.8, 0.9, 1 s respectively so that five kinds of semiellipsoid microlens were fabricated, as shown in Fig. 3.

3 Results and discussion

3.1 Theoretical calculation

To get deep understandings of the lens shape formed by surface tension, analytical and numerical procedures were developed. In the theoretical analysis, it is assumed that the microlenses are perfect semiellipsoid lenses. Coordinate system with origin located at the center of elliptical base

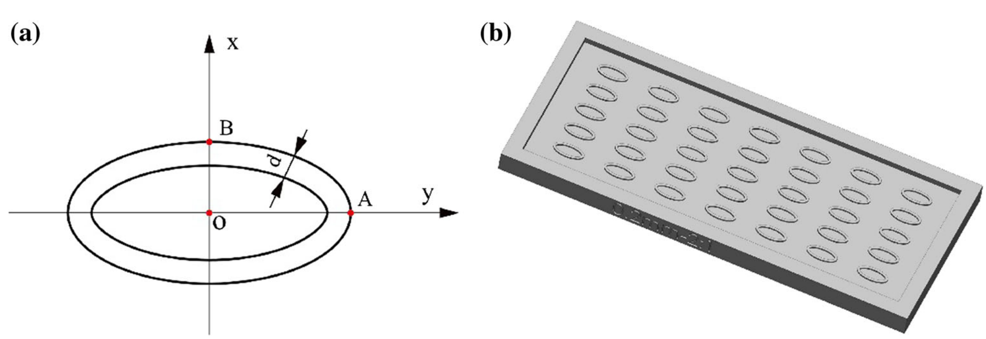

Fig. 1 **a** Diagram of the geometrical dimensions of the elliptical contour, **b** 3d model of the elliptical base

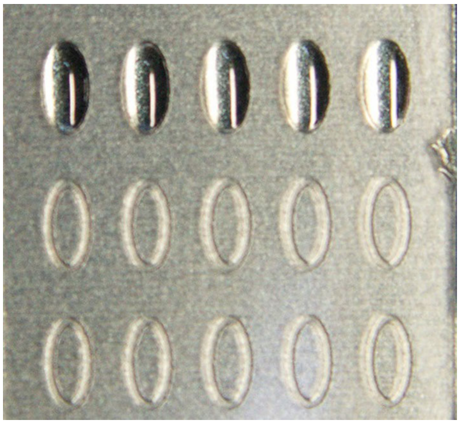

Fig. 3 Semiellipsoid lens by inkjet method

was defined, as shown in Fig. 4a. Liquid resin on this base naturally forms a semiellipsoid lens due to the influence of surface tension, therefore a coordinate system with origin located at the center of the ellipsoid is defined for convenience, as shown in Fig. 4b.

According to the ellipsoid definition, we can write the expression of semiellipsoid surface as:

$$\frac{x^2}{A^2}+\frac{y^2}{B^2}+\frac{z^2}{C^2}=1 \quad (z\geq 0) \tag{1}$$

where A, B and C are the length of three axes of the ellipsoid, given by $A = o'U$, $B = o'V$ *and* $C = o'W$. The ratio of the curvatures at Point C on the xz and yz plane can be calculated by second derivative, given by $\varphi = \frac{K_1}{K_2} = \frac{a^2}{b^2}$, where K_1 and K_2 are curvatures on the yz and xz plane, respectively, $a = oM$ and $b = oN$ are the lengths of the minor axis and major axis of an elliptical pattern, In our design, $\varphi = \frac{a^2}{b^2}$=4.

3.2 Experiments measure and simulation

The surface profiles of the five semiellipsoid microlens on the xz plane and yz plane were measured with an optical profiler (Form Talysurf PGI 2000S, Taylor Hobson Ltd.) to calculate the lens volume, the surface curvature and eventually the curvature ratio φ.

By using the measured lenses' heights and volumes presented in Sect. 1.2 as the initial conditions in a numerical fluid interface tool (Surface Evolver), the evolution of lens shape under the influence of surface tension could be obtained, as shown in Fig. 5. Therefore the numerical solution of semiellipsoid microlens could then be obtained to calculate the curvature ratios on the xz and yz plane.

Comparison between experiment data and emulational data is shown in Table 1. Good comparison agreement with relative error of 1% (denoted by δ_2) demonstrates that the numerical model can be used to predict the surface evolution. However, both experimental and emulational data are slightly lower than the theoretical value of $a^2/b^2 = 4$, because perfect ellipsoid shape can only remain when liquid volume is very little.

4 Roll to roll replication

In order to massively produce semiellipsoid microlenses, a SEMA array was made with the 3D printer and inkjet method. A belt-type PDMS mold with semiellipsoid microlens pattern was prepared by pouring PDMS onto the SEMA array. Then a soft mold was wrapped onto the roller mold.

In the previous research (Ye et al. 2014), we have developed a R2R process device for fabricating the microstructure in high speed and over large area. In this study, a PET film (A4300, TOYOBO, 188 μm thickness) was used as the flexible substrate. This PET film was coated with optical UV cured resin (Tex Year, 1551M2) in the coating module. Consequently the coated PET was transported to the imprinting module at a speed of 0.2 m/min in parallel, and the resin in the imprint module was cured by the LED UV light with intensity of 800 mw/cm^2 at the focus. After demolding from the imprinting roller, the SEMA was obtained. Figure 6 shows the microscopy image of a R2R fabricated microlens array.

For evaluating its reliability, the surfaces of the replication lens and mold lens were imaged by a camera. Surface profiles on the xz plane (major axis) and yz plane

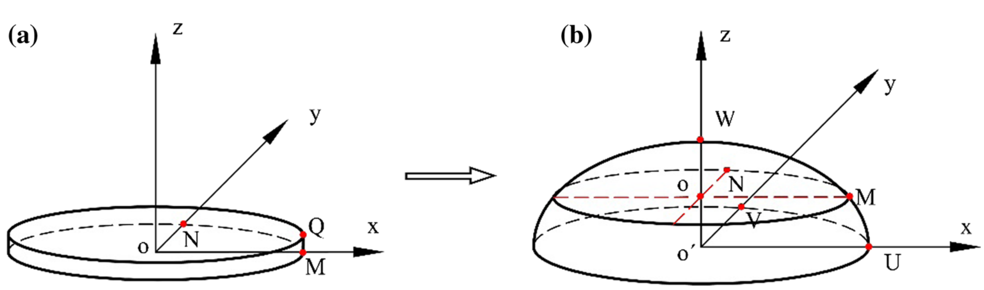

Fig. 4 **a** Coordinate system defined for the semiellipsoid microlens model, **b** Coordinate system with origin located at the center of the ellipsoid, the axis on the xz plane was defined as major plane, and on the yz plane was defined as minor plane

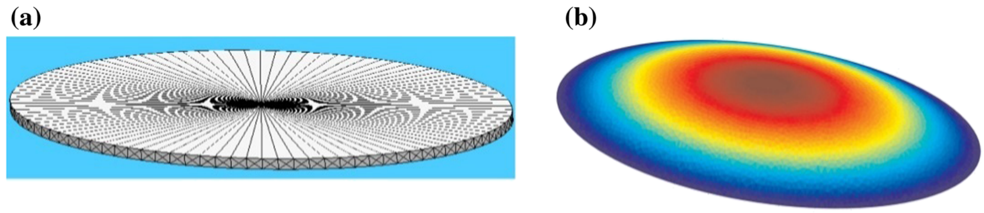

Fig. 5 Evolution of semiellipsoid microlens under the influences of surface tension, **a** initialized lens shape, **b** steady lens shape

Table 1 Comparison between experimental and simulational data

Resin spit time (s)	0.10	0.15	0.20	0.25	0.30
Experimental curvature radius on *xz* plane (mm)	26.828	15.536	13.627	11.596	10.988
Experimental curvature radius on *yz* plane(mm)	6.809	3.914	3.494	3.012	2.832
Simulation curvature radius on *xz* plane (mm)	26.856	15.588	13.631	11.812	11.051
Simulation curvature radius on *yz* plane (mm)	6.732	3.969	3.487	3.045	2.857
Curvature ratio in the experiment	3.94	3.97	3.90	3.85	3.88
Curvature ratio in the simulation	3.989	3.927	3.909	3.879	3.868

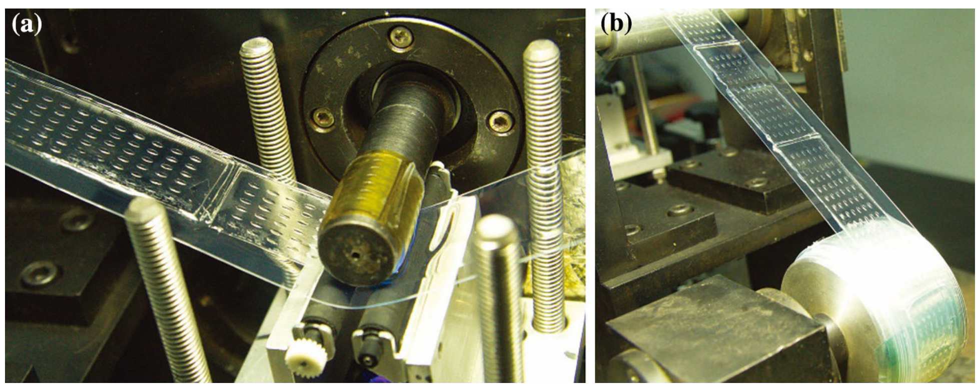

Fig. 6 The replicated SEMA with the R2R process

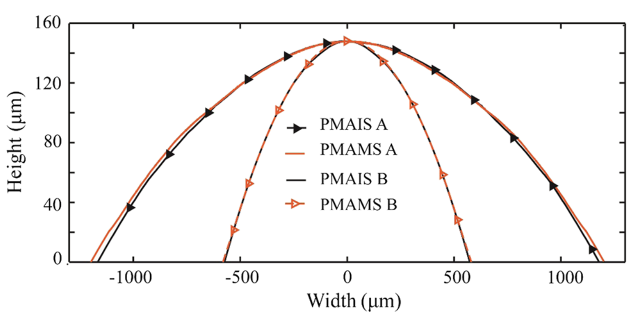

Fig. 7 Comparison between the profile of imprinted SEMA and molded SEMA (where PMAIS A is the profile of the major axiswith imprint SEMA, PMAMS A is the profile of the major axis with the molded SEMA, PMAIS B is the profile of the minor axis with imprinted SEMA, PMAMS B is the profile of the minor axis with molded SEMA). The curvature radius of the PMAIS A and PMAMS B is 13.459, 3.4646 mm, respectively

(minor axis) were extracted. Figure 7 showed the comparison between imprinted and molded surface profiles.

The relative error of two curve in major axis was $\delta_3 = \left|\frac{13.627-13.459}{13.627}\right| = 1.23\%$, and in minor axis was $\delta_4 = \left|\frac{3.494-3.4646}{3.494}\right| = 0.84\%$, which showed that the R2R production was effective and reliable.

Consequently, the max error of the final SEMA could be theoretically estimated by R2R process error and droplet process error. The elliptical substrate error was included in the droplet process error.

$$\delta = \sqrt{\delta_2^2 + \delta_3^2} = 1.59\% \tag{2}$$

The combined error δ is not very perfect for the profile accuracy, but fortunately, in real optical systems we usually use the ellipsoid crown only.

5 Conclusion

In the paper, we developed a simple and effective method for fabricating the SEMA. Firstly, 3D printing was applied to create a precise elliptical base with maximum of relative error of 0.25%. Secondly, the elliptical base was massively replicated by imprinting. UV curing resin was dropped on the elliptical base which precisely constrains the bottom shape of the ellipsoid microlens. A semiellipsolid shape can be naturally achieved under the influences of surface tension. Surface profiles of the semiellipsolid lens can be modulated by controlling volume of the resin. Experiments and theoretical calculations demonstrate that the curvature ratio can be expressed as $\frac{M}{N} = \frac{a^2}{b^2}$. Experimental results showed that the error of the solution is about 1% compared with theoretical one. Finally, a R2R imprinting process was employed to fulfill the SEMA replication. Compared with the replicated lens and original lens, the maximum of deviation is about 1.23%. And the combined error is 1.59%. The proposed fabrication method with 3D printing, droplet method and R2R process make it a promising candidate for future semiellipsolid microlens production.

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