Micro-lens Array Fabrication by Two Photon Polymerization Technology

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Abstract: This paper presents the design and fabrication of micro-lens arrays (MLAs) by Two Photon Polymerization (TPP) technology. First, a computer program is developed to construct a solid MLA model with a specified focal length and lens diameter. A TPP laser scanning path for MLA fabrication is then generated. MLAs are fabricated by TPP, with quality assessed by SEM. Finally, good quality 5×5 MLA squares with dimensions 108×108 are successfully manufactured.

Keywords: Micro-lens array; Two photon polymerization; Vertical slicing method

Introduction

The fabrication process using Two Photon Polymerization (TPP) technology is extremely simple and easy to manipulate, thus decreasing total fabrication time. TPP is the ideal choice for the fast fabrication of small scale micro-lens arrays (MLAs). However, layered manufacturing methods [1] result in defects on the surface of the micro-lens, and a vertical slicing method is adopted to prevent such defects.

In recent years techniques have been developed to improve the fabrication of MLAs, including roller embossing [2], gray-scale photolithography [3, 4], thermal reflow [5], and ink-jet methods [6, 7]. However, these methods all entail complex fabrication processes requiring expensive equipment for mold-fabrication, masking, and the precise alignment control of each lens. TPP technology using a femtosecond-laser can be used to fabricate micro-lenses or more sophisticated microstructures in polymers [8]. Due to its low cost, the 532nm green laser is used here rather than the femtosecond-laser, with experimental results showing excellent performance in the fabrication of high resolution products [9].

The Hardware Setup of TPP Micro Fabrication System

Figure 1 shows the complete hardware setup of the TPP micro-fabrication. A low-cost frequency-doubled

Nd:YAG laser (130kHz, 26mW, 532nm) is been used as an irradiation source for the TPP micro fabrication system. The laser beam is tightly focused into the resin with an oil immersion objective (N.A.=1.3, 100x). A commercial resin Photomer (model 3015, Henkel Corp.) is used with 0.3% of a highly-sensitive additive two-photon photo-initiator. The resin is placed on top of the cover slip with dimensions of $18\text{mm} \times 18\text{mm}$ and a thickness of $170\mu\text{m}$, and then is mounted on a three-dimensional piezo stage (PI P-545 with a $200\mu\text{m}$ range in each axis, a 1nm closed-loop resolution and $\pm 0.1\%$ linearity).

The principle for the setup of the TPP micro fabrication system is summarized in Figure 2. The laser beam passes through an attenuator which provides control of the laser energy. The beam passes through a beam expander, coupled with an inverted microscope, and is finally focused in the resin by the oil immersion objective lens. The sample is mounted on a piezo stage for 3D positioning. A camera behind a dichroic mirror is used to monitor the TPP fabrication process.

Design of Micro-lens Arrays

A spherical lens is used, with parameters as shown in Figure 3. According to the optical theory of spherical lenses [10, 11], the relation between the focal length f , the spherical radius R , and the refraction rate of the lens material n can be expressed as

$$R = f \times (n - 1) \quad (1)$$

Figure 1. Hardware setup of TPP micro-fabrication.

Figure 2. Schematic diagram of the TPP micro-fabrication system.

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Photomer 3015 was used as the TPP resin, with a refraction rate n of 1.541. The lens thickness t is independent of the focal length f . However, the length thickness determines the size D of the lens and is an important parameter for designing MLAs.

Figure 3. The design parameters of a spherical lens.

The lens diameter of the lens is determined by the size and the number of lenses in the MLA. Given a spherical radius R of the lens, the relation between the lens size D and the lens thickness t can be determined from the Pythagorean theorem as

$$R^2 = (R - t)^2 + \left(\frac{D}{2}\right)^2 \quad (2)$$

Our goal is to manufacture a 5x5 lens array of about $100\mu\text{m} \times 100\mu\text{m}$, with a $40\mu\text{m}$ focal length. From Equation (1), the spherical radius $R = 40 \times (1.541 - 1) = 21.64\mu\text{m}$. For the desired 5x5 MLA, we chose a lens size D as $20\mu\text{m}$. From Equation (2), given $R = 21.64\mu\text{m}$ and $D = 20\mu\text{m}$, the lens thickness t can be calculated as $2.44\mu\text{m}$.

Manufacturing of Micro-lens Arrays

The proposed program was used to determine the experimental manufacturing parameters: voxel size, voxel overlap ratio, layer thickness, display offset, slicing sequence and the face hatching for slicing. User-designated parameters are shown in Figure 4. The program was used to plan the slicing contour of the vertical and horizontal slicing methods. The distance of two voxels can be obtained by the voxel size and overlap ratio. Figure 5 illustrates the voxel distance and layer thickness, which affect the quality of TPP products, and must be properly designed to obtain firm structures and smooth surfaces.

Figure 6 shows the slicing contour of the vertical slicing method. First, the 3D CAD model is built using commercial CAD software. Second, the model is sliced vertically to obtain the contours. Lastly, the contours are divided into points through which the piezo stage will move along the paths.

Figure 4. User interface of slicing and planning.

Figure 5. Voxel distance and layer thickness.

Figure 6. Planning process of the solid model: (a) CAD model, (b) slicing contours, and (c) laser scanning path through points.

Results and Discussion

The horizontal slicing method [12] is used, with laser power, exposure time, and layer thickness respectively set at 1.12mW, 3ms, and 0.011 μ m. The cascaded surface shown in Figure 7(a) displays obvious defects. The fabrication time in this experiment is 2.55 minutes. The vertical slicing method was then used in an attempt to improve on these results, with laser power, exposure time, and layer thickness respectively set as 1.8mW, 1ms, and 0.1 μ m, and results shown in Figure 7(b). The required fabrication time is 0.72 minute. To reduce the edge defects of MLA in Figure 7(b), the laser power and exposure time are changed to 1.01mW and 10ms. As shown in Figure 7(c), the reduced laser power and prolonged exposure time produce better lenses. The increased exposure time increases the fabrication time to 5.35 minutes. All lenses fabricated by the various methods or parameters have the same voxel distance of 0.21 μ m. The manufacturing parameters for Figure 7(a), 7(b) and 7(c) are also listed in Table 1.

A 5x5 MLA was also produced using the parameters shown in Figure 7(b), with a manufacturing time of about 20 minutes. Figure 7(d) and 7(e) show the top view and 45-degree view of the MLA.

Table 1. MLA manufacturing parameters.

Manufacturing parameters	Micro-lens		
	Figure 7(a)	Figure 7(b)	Figure 7(c)
Laser Power [mW]	1.12	1.8	1.01
Exposure time of each voxel [ms]	3	1	10
Voxel distance [μ m]	0.21	0.21	0.21
Layer thickness [μ m]	0.011	0.1	0.1
Total fabrication time of a single lens [min]	2.55	0.72	5.35

A simple experiment is carried out to roughly measure the focal length of the manufactured MLAs, with the measurement setup shown in Figure 8. The cover slip with MLAs is mounted on the microscope table with a ZEISS 25x objective lens. First the vertical position of the interface between the cover slip and the MLAs is determined by focusing the laser on the underside of the cover slip. The vertical position of the focal point of the MLAs is then determined. The parallel light source on top of the microscope is activated such that the parallel lights will pass through the MLAs and focus on the lens focal points. The vertical position of the focal point can be obtained by adjusting the table such that focal images can be seen clearly, as shown in Figure 9. The distance between the underside of the cover slip and the position of the focal spot is the focal length [13, 14].

The designed focal length of the 5 $\times$ 5 array is 40 μ m and the experimental measured value is 30.5 μ m. The purpose of this simple experiment is to show that the MLAs can focus light in parallel. The difference between designed and measured focal lengths may result from many reasons including the large shrinkage of the TPP products (about 8.25%), or size errors in the manufactured MLAs. Such size errors may be caused by the oval-shaped voxel which increases the thickness of the micro-lens. The voxel is about three times taller than it is wide, thus increasing the thickness of micro-lens, which changes and shortens the focal length. In Figure 9, the focal condition is better on the left side than on the right side, and this may be caused by the slight tilt of the cover slip.

Figure 7. SEM images of the micro-lens and MLA: (a) Using the horizontal slicing method ($D=20\mu\text{m}$, $t=2.44\mu\text{m}$), (b) using the vertical slicing method ($D=20\mu\text{m}$, $t=2.44\mu\text{m}$) with an exposure time of 1ms, (c) using the vertical slicing method ($D=20\mu\text{m}$, $t=2.44\mu\text{m}$) with an exposure time of 10 ms, (d) top view of 5×5 MLA with a size of $108\mu\text{m} \times 108\mu\text{m}$ and a $2\mu\text{m}$ lens gap, (e) 45-degree view of the 5×5 MLA.

Figure 8. Focal length measurement.

Figure 9. Focal spot images of the 5×5 MLA.

Conclusion

A 5×5 micro lens array is designed and manufactured using two-photon polymerization (TPP) technology. A low-cost frequency-doubled Nd:YAG laser (130kHz, 26mW, 532nm) is used, and the resin is Photomer 3015 with 0.3% highly sensitive photo-initiator. Both horizontal slicing and vertical slicing methods are used to manufacture the MLA. The vertical slicing method is shown to produce fewer edge defects in the MLA and reduce surface roughness without overexposing the top of the lens. Compared with the horizontal slicing method, the vertical slicing method is also faster and can more easily obtain the desired structure using TPP technology.

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