

# A novel method for fabrication of self-aligned double microlens arrays

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## Abstract

Based on the excimer laser microdrilling and the spin coating scheme, a new fabrication method of polymeric, double microlens arrays on a thin plastic pedestal sheet is proposed in this study. On each through hole on the pedestal sheet, a double microlens pair, consisting of two microlenses with different parabolic surfaces, is sited. The two microlenses of each pair are located respectively on both ends of the through hole and arranged surface to surface and automatically share a common lens principal axis. The fabricated microlens arrays are made of PMMA that are formed on a PMMA pedestal sheet with thickness of 100  $\mu\text{m}$ . The diameter and height for the microlens on one layer are of 150  $\mu\text{m}$  and 28  $\mu\text{m}$ , respectively, and they are correspondingly of 130  $\mu\text{m}$  and 24  $\mu\text{m}$  on the other layer. Experimental results demonstrate that the double microlens arrays have a better focusing property than the single-layer microlens array. Simulation results indicate that, simply by changing the thickness of the pedestal sheet, the present fabricated double microlens arrays can serve the purposes for light collimating and diffusing. Due to its inherent simplicity in fabrication, the present method has high flexibility for making double microlens arrays with different lens configurations and various lens refractive indices. The facts that precise alignment and all processing steps are performed in ambient and at low temperature render the proposed approach a potential low-cost method for fabrication of double microlens arrays.

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## 1. Introduction

Refractive microlenses with lens diameters of a few to several hundred micrometers are very important components in today's high performance, compact optical systems including, for examples, optical communication, optical storage, video camera, optical scanner, high-definition projection display and optical and biomedical inspection instruments [1,2]. The use of refractive microlenses can be an effective solution in increasing optical coupling efficiency and tolerance. Thus, a need for custom-designed, low-cost, compact and lightweight microlenses is increasing. Since the 1990s, many researchers have been exploring various ways to fabricate refractive microlens arrays based on different lens materials [3–16]. Among these studies, several are concentrated on the glass-based lenses, which have been studied for a relatively long time. However, more are focused on

the polymer-based materials. The microjet technique [3], photoresist reflow method [4], ultraviolet curing of polymer [6], hydrophobic effect method [7], LIGA method [10] and soft replica molding method [15] are all newly developed methods for the polymeric lenses. With continuous improvement in material properties and advance in processabilities, a constant increase in the usage of polymeric microlenses is highly projected.

For applications in systems of scanning, optical coupling and interconnection, beam homogenizing, microlens projection lithography and the miniaturized imaging, microlens arrays are usually arranged based on spatial superposition to achieve particular purposes of light collimating, focusing, diffusing or imaging. However, packaging and alignment of stacks of miniaturized lens systems is a rather difficult task. The classical mounting techniques are not practical and expensive. Currently, the preferred method is manufacturing on the basis of a wafer-level packaging on which the stack of planar wafers containing microoptics and electronic devices are bonded on a mask aligner and then separated into individual systems or modules by the

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subsequent dicing steps. The whole process, however, consists of many steps and is usually more suitable for glass-based optics.

Motivated by the need of fabricating multi-layer microlens arrays that can be assembled more efficiently and simply, the present study proposes a new fabrication process that is able to make two microlens arrays assembled easily on a thin pedestal sheet, involving mainly the excimer laser microdrilling and the spin coating technique. Benefits of the new process include the self-alignment of the fabricated double microlens arrays and the ambient and low-temperature operation.

Following this section, details of the new fabrication processes for polymeric double microlens arrays is then described in Section 2. The demonstrated microlenses and the pedestal sheet are all made of PMMA. In Section 3, results examining the geometrical configuration of the lens' surface profile by a confocal surface measurement equipment and inspecting the surface characteristics of the polymeric films by an atomic force microscopy (AFM) are first reviewed. The focusing test result of the fabricated microlens arrays by a beam profiler analyzing system is then presented. Applications of the fabricated double microlens arrays for the purposes of light collimation and diffusion are further explored by extensive software simulation. Results demonstrate that the current double-layer microlens arrays, when compared to the single-layer microlens array, can effectively reduce the focal length and the size of the focused spot. Application of the current method to fabricating multi-refractive index microlens arrays is also discussed there. Major conclusions of this study are finally drawn in Section 4.

## 2. Fabrication

Referring to the schematic depicted in Fig. 1, steps for fabricating a self-aligned double microlens arrays with different surface profiles are described as follows:

- (1) The footprint with designed size for the microlens is defined on a metallic mask through which the excimer laser directly drills a through hole on a 100  $\mu\text{m}$  thick PMMA plate. This process defines the locations and the sizes of the footprint of the microlens arrays. Due to the beam focusing by the projection lens on the excimer laser beam delivering system, a converging, cone-like, through hole with different diameters on both ends of the PMMA plate (the side with the larger diameter was facing to the laser beam as the laser drilling process) was naturally formed. Fig. 1(a) shows the resultant PMMA plate with microholes that serves as the pedestal of the microlenses in the next step.
- (2) A thin liquid PMMA film is then coated on the first side of the PMMA-based pedestal through spin coating. As the liquid PMMA is rapidly spreading out, due to its own weight and the solution viscosity, a film, suspended on the pedestal and with special curvature, is formed on the pedestal. The liquid film is then cured thermally by baking at 60  $^{\circ}\text{C}$  for 5 min and it then sticks fixedly on the pedestal as shown in Fig. 1(b).
- (3) Shown in Fig. 1(c), by another lower speed spin coating process, the same liquid PMMA solution is then deposited

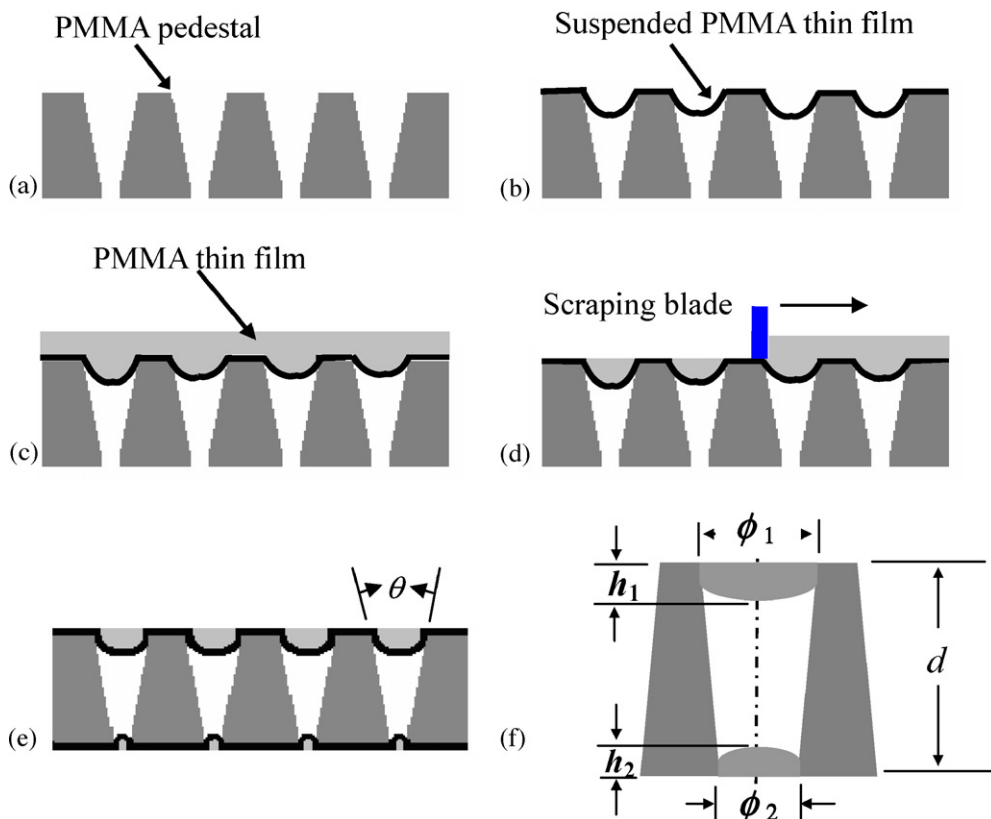


Fig. 1. Schematics showing fabrication steps for double-layer microlens arrays (a–f). Schematic showing a double microlens pair on which notations used are defined.

on the top of the coated thin film obtained in Step (2). To make sure the PMMA to be just filled in the cavities formed by the suspended film obtained in Step (2), the extra PMMA above the cavities is scraped away by a flat blade as shown in Fig. 1(d). The result is the first layer of a thin film microlens array.

- (4) Repeating Steps (2) and (3), the second layer of the thin film microlens array is formed on the other side of the PMMA plate. Schematic of the final, self-aligned, double microlens arrays is shown in Fig. 1(e).

### 3. Results and discussion

Fig. 2(a) shows the CCD image of the surface of the PMMA thin film, obtained up to and including Step (2), suspended on the PMMA pedestal. Only part of a  $14 \times 14$  cavity array is shown here. The diameter of each cavity is  $50 \mu\text{m}$  and its depth is about  $12 \mu\text{m}$ . A more detailed three-dimensional surface image of four adjacent cavities, scanned by a three-dimensional confocal surface measurement equipment manufactured by NanoFocus® C, is depicted in Fig. 2(b) and its corresponding two-dimensional surface profile of two neighboring patterns is presented in

Fig. 2(c). Fig. 2(d) shows the surface roughness on the concave side of the solidified PMMA film. Due to the measurement limitation of the atomic force microscopy in a concave surface, only several  $5 \mu\text{m} \times 5 \mu\text{m}$  regions on the film surface were scanned and the RMS values of the scanned surfaces were all within  $8 \text{ nm}$ , corresponding to a total integrated scattering within 5% for visible light. Although only the surface on the concave side could be available here, it is believed the roughness on the convex side, which serves as the final lens surface, is also within the same range of roughness because the whole film is solidified from liquid. To have good surface quality, the spin-coated PMMA film should be stayed in the liquid state for a reasonable time and with a certain film thickness so that the effect of the surface tension can modify the surface uniformity. These results demonstrate that microlens arrays with very good surface quality can be obtained by the present proposed method.

The focusing property of the fabricated microlenses was then examined experimentally. A schematic diagram of the experimental setup is shown in Fig. 3(a). This setup consists of a lamp as a white light source, beam focusing and expanding lenses, filter, microscope, CCD camera, image display and a beam profiler analyzer. The microlens array to be tested is placed

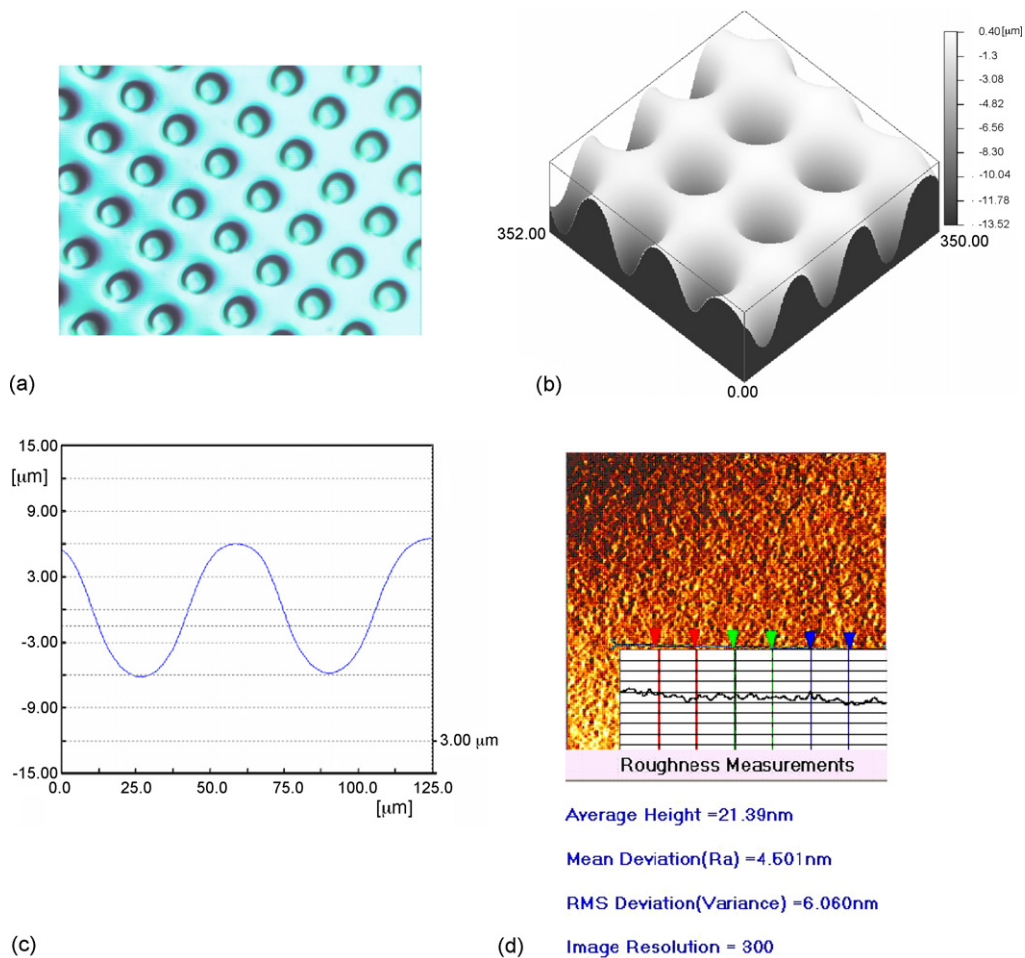


Fig. 2. (a) CCD image of the PMMA thin film surface obtained up to and including Step (2). Only partial patterns of a total  $14 \times 14$  concave patterns is shown. The diameter of the footprint is  $50 \mu\text{m}$  and the depth the suspending film is about  $12 \mu\text{m}$ . (b) Three-dimensional surface image for four adjacent patterns in (a). (c) Two-dimensional surface profile of two continuous patterns shown in (b). (d) Surface roughness on the concave side of the solidified PMMA film.

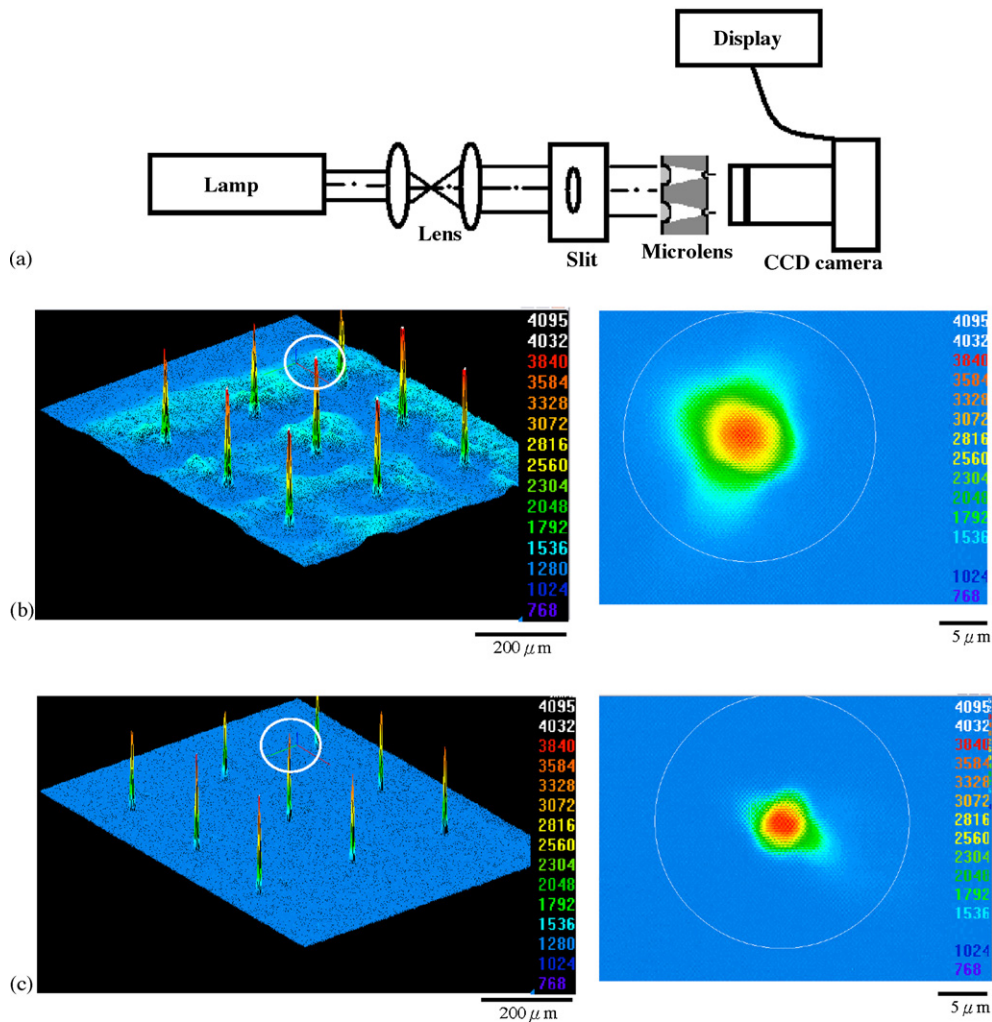


Fig. 3. Focused spot size measurement. (a) Schematic showing the experimental setup. (b) Three-dimensional image of focused spots from a single-layer microlens array (left); and, one (the circled one in the left) corresponding two-dimensional contour plot (right). (c) Three-dimensional image focused spots from a double-layer microlens arrays (left); and, one (the circled one in the left) corresponding two-dimensional contour plots.

between the filter and the CCD camera. In Fig. 3(b), the three-dimensional image for light from the lamp passing through a  $4 \times 4$ , single-layer microlens array, obtained up to and including the fabrication process Step (3), is presented. These microlenses are with diameter of  $\phi_1 = 150 \mu\text{m}$  and height of  $h_1 = 28 \mu\text{m}$ . It shows a very good focusing effect can be achieved. The spot size, measured according to the image size on the CCD, for this microlens array was about  $7 \mu\text{m}$ . The corresponding focusing image for double-layer microlens arrays is shown in Fig. 3(c). The diameter and height for the microlenses on the second layer are  $\phi_2 = 130 \mu\text{m}$  and  $h_2 = 24 \mu\text{m}$ , respectively. The measured spot size for this double-layer microlens array was reduced to about  $4 \mu\text{m}$ . Compared to Fig. 3(b), a significant reduction of the size of the focused spot was observed. The focusing function was apparently enhanced by the addition of the second layer of the microlens array.

For the present fabrication method, the height and the radius of curvature of the microlens depend on the diameters of the holes microdrilled by the excimer laser and the thickness of the PMMA liquid film which is predominated by the rotating speed

of the spin coating process [14,15]. Here three hole diameters,  $\phi_1 = 50 \mu\text{m}$ ,  $100 \mu\text{m}$  and  $150 \mu\text{m}$  are studied. As the speed in the spin coating process goes from 1000 rpm to 3000 rpm, Fig. 4 shows the film thickness in Step (2) can range from  $22 \mu\text{m}$  to  $12 \mu\text{m}$  and the height of the microlens varies between  $12 \mu\text{m}$  and  $30 \mu\text{m}$ . These results show the geometrical configuration of the microlens can be adjusted to a certain extent by the diameter of microdrilled hole on the pedestal sheet and the spin-coating parameters.

The optical properties of the microlens can be characterized by the lens' material properties and geometrical configurations. For an axial symmetrical plano-convex refractive lens, focal length ( $f$ ), height ( $h$ ), radius of curvature ( $R$ ) and the  $f$ -number ( $F^\#$ ) are related through the following formulas expressed as  $R = ((K + 1)h^2 + (\phi/2)^2)/(2h)$ ,  $f = ((R/n) - 1)$  and  $F^\# = f/\phi$ . In these formulas,  $\phi$  is the diameter of the microlens,  $K$  the aspherical constant and  $n$  is the refractive index of the material of the microlens [2]. The surface profile of the current fabricated microlens is not spherical, as shown in Fig. 2(c), but more like a parabolic shape. In addition to the ability of

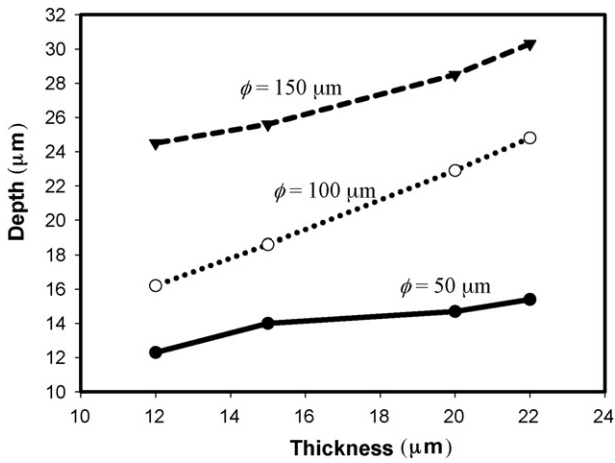


Fig. 4. Relations of the suspending depth and thickness of the film spin-coated on the pedestal for three different foot print diameters  $\phi = 50 \mu\text{m}$ ,  $100 \mu\text{m}$  and  $150 \mu\text{m}$ . The speed of spin coating varies from 1000 to 3000 rpm.

focusing light, the non-spherical microlens array is of particular interest for applications such as laser–material interaction, optically pumped microlasers and information processing or sensing [17]. To estimate characteristics of the microlens by the above-mentioned expressions, the shape of the microlens was approximated as a paraboloid, thus took  $K$  to be  $-1$ . The refractive index for the PMMA is 1.49. Fig. 5 shows the simu-

lation plots for focusing characteristics of the microlens using the software TracePro. As a parallel beam passing through a single paraboloid microlens with diameter of  $150 \mu\text{m}$  and height of  $28 \mu\text{m}$ , shown in Fig. 5(a), the obtained focal length is about  $307 \mu\text{m}$  and the size of the focused spot is about  $4.3 \mu\text{m}$ . As the second, smaller microlens, with diameter of  $130 \mu\text{m}$  and height of  $24 \mu\text{m}$  is placed in front of the microlens depicted in Fig. 5(a), a double microlens pair, schematically shown in Fig. 1(f), is formed. The distance between the two microlenses is  $d = 100 \mu\text{m}$ . Fig. 5(b) shows the focal length for this double microlens pair is reduced to  $202 \mu\text{m}$  and the corresponding size of the focused spot can further be down to  $2.4 \mu\text{m}$ . Compared to the sizes of the focused spot obtained by the experimental measurement, the simulation results show relatively smaller sizes, superior focusing effect, for both single- and double-layer microlens structures. This trend is expectable because the simulations were performed based on all ideal conditions that led to the best focusing performance. The estimated  $F^\#$  for the single layer microlens fabricated by the present method ranges from 0.8 to 1.6 [15].

Based on the simulation, Fig. 6 shows both the focal length and the size of focused spot as a function of the distance between the two microlenses,  $d$ . Here the geometrical configurations of the microlenses were the same as those in the case of Fig. 5(b). The range of  $d$  was arranged from the distance where the second lens was almost in contact with the first lens,  $d = 55 \mu\text{m}$ , to that

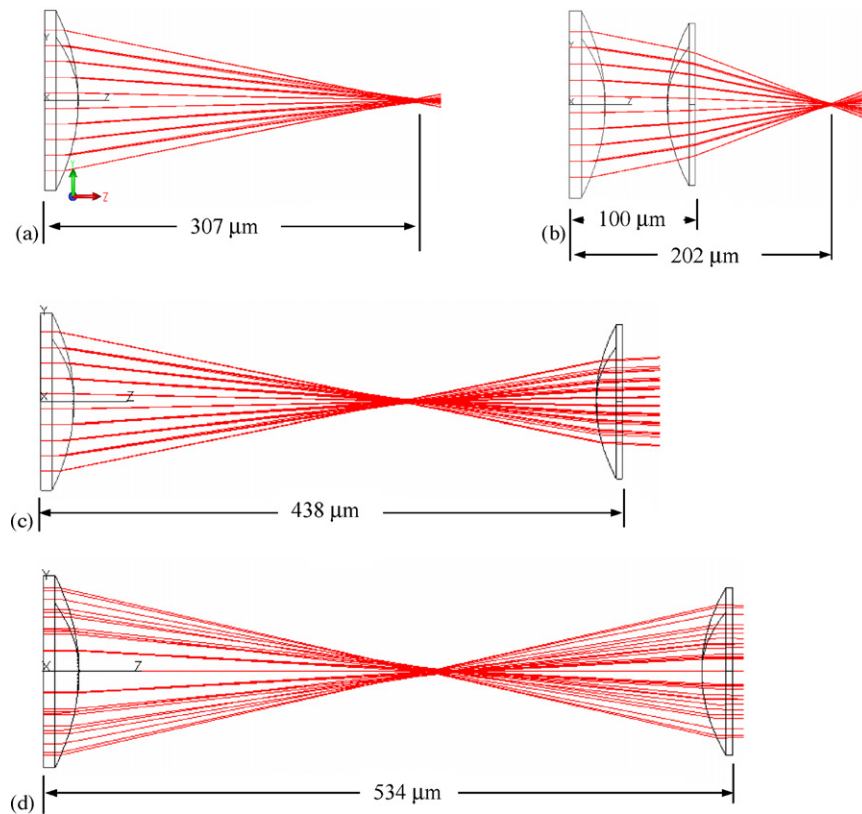


Fig. 5. Simulated focal lengths for a single microlens and a double microlens pair. (a) A single microlens with diameter of  $150 \mu\text{m}$  and height of  $28 \mu\text{m}$ , respectively. (b) A double microlens pair with lens' dimensions of  $\phi_1 = 150 \mu\text{m}$  and  $\phi_2 = 130 \mu\text{m}$  and lens' heights of  $h_1 = 28 \mu\text{m}$  and  $h_2 = 24 \mu\text{m}$ . The thickness of the pedestal is  $d = 100 \mu\text{m}$ . (c) A double microlens pair whose lens' dimensions are the same as those in (b), the thickness of the pedestal is  $d = 438 \mu\text{m}$ . (d) A double microlens pair whose lens' dimensions are the same as those in (b), the thickness of the pedestal is  $d = 534 \mu\text{m}$ .

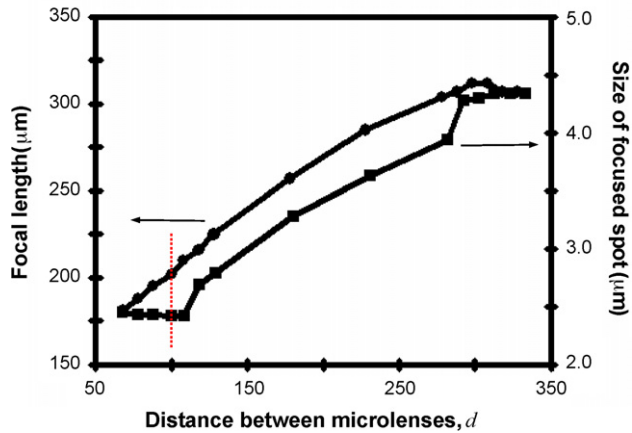


Fig. 6. Simulated focal length and size of the focused spot as a function of the distance between the two microlenses forming the double microlens pair.

the second lens was just beyond the focal length of the first lens,  $d = 330 \mu\text{m}$ . It shows that both the focal length and the size of the focused spot for this double microlens pair are monotonically increased with the distance  $d$ . For cross-reference, the situation when the distance  $d$  is  $100 \mu\text{m}$ , corresponding to the thickness of the PMMA pedestal sheet used in our experimental study, has been explicitly identified in Fig. 6. This simulation result also indicates that the adjustment of the focal length and the focused strength of a double microlens arrays can be accomplished by arranging the distance between the two microlens-array layers. Compared to the single-layer microlens array, the double microlens arrays can considerably reduce the focal length, enjoying the advantage for fabricating more compact optical devices for microoptical systems. In addition to the focusing purpose, when  $d$  is larger than  $330 \mu\text{m}$ , shown in Fig. 5(c), the double-layer microlens pair acts as a diffuser that can be employed for illumination purpose. Shown in Fig. 5(d), if the distance is arranged close to the sum of the two microlens' focal lengths, the double-layer microlens pair works to contract the beam size. Alternatively, if the light goes from the smaller lens to the larger lens, the configuration of Fig. 5(d) is for expanding the beam size. The double microlens arrays for the above discussed purposes can be achieved simply by changing the thickness of the pedestal sheet in the present proposed fabrication method.

In the present study, the foot print diameters on both ends of the through hole,  $\phi_1$  and  $\phi_2$  shown in Fig. 1(f), are different. The dimensional relations among  $\phi_1$ ,  $\phi_2$  and  $d$  are predetermined by the thickness of the pedestal sheet and the magnification factor of the projection lens set employed in the laser beam delivering system. Results shown in this study were fabricated based on a  $10\times$  projection lens set that resulted in the beam converging angle  $\theta$ , defined in Fig. 1(e), of  $11.4^\circ$ . For different options of the foot print diameter, a  $5\times$  or  $15\times$  projection lens set can be used. Foot print diameters,  $\phi_1$  and  $\phi_2$ , can also be produced to have the same value by the present excimer laser microdrilling systems. This can be simply accomplished by flipping over the already microdrilled pedestal plate, Fig. 1(a), and microdrilling, with suitable alignment, the same pedestal plate again.  $\phi_2$  can thus be enlarged to be equal to  $\phi_1$ .

With slight modification, the present method also allows for fabrication of a microlens consisting of two materials that might have different refractive indices. Therefore, it can be employed to fabricate both single- and double-layer arrays of microdoublet [18]. The fabrication process is described as follows. In Step (3), instead of using the same PMMA as that in Step (2), a different solution-based photopolymer, such as SU8 or AZ photoresists, can be coated upon the first generated PMMA film, that was formed in the Step (2). Materials for Steps (2) and (3) can also be deposited in a reverse order. With suitable combination of two refractive indices and appropriate control of the thickness of each layer, distortions in one material cancel out those that exist in the other and a microdoublet lens that minimizes optical aberrations can be fabricated.

#### 4. Conclusions

In this study, based on the excimer laser microdrilling on a thin polymeric sheet that serves as a pedestal for microlenses and the spin coating scheme, we propose a new method for fabricating plano-convex, polymeric, double microlens arrays. On each laser-drilled through hole on the pedestal sheet, a double microlens pair, consisting of two microlenses sitting, respectively, on both ends of the through hole with their convex surfaces facing to each other, is formed. Importantly, the two microlenses share a common principal lens axis. Furthermore, the two microlenses of the double microlens pair are allowed to have different geometrical shapes. The demonstrated microlenses are made of PMMA and formed on a PMMA pedestal sheet with thickness of  $100 \mu\text{m}$ . The foot-print diameters of the two microlenses for each double microlens pair are  $150 \mu\text{m}$  and  $130 \mu\text{m}$ , respectively, and their corresponding lens' heights are  $28 \mu\text{m}$  and  $24 \mu\text{m}$ . Compared to the single-layer microlens array, the experimental measurements show that the double microlens arrays can considerably reduce both the focusing spot size and focal length. Simulation results demonstrate that, in addition to the application for light focusing, the double microlens arrays can be employed for the purposes of light collimating and diffusing in the optical microsystems by simply changing the thickness of the pedestal sheet. Due to inherent simplicity of the present method, double microlens arrays with different lens configurations and various lens optical properties can be easily fabricated. Besides, the fact that all fabrication steps can be executed in ambient environment and at low temperature renders the present proposed method a potential approach suitable for low-cost mass production.

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