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Polymeric microlens array fabricated with PDMS mold-based hot embossing

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Abstract

This study presents a simple, flexible and cost-effective process to fabricate microlens arrays. The polymeric microlens arrays are fabricated using a polydimethylsiloxane (PDMS) mold-based hot embossing process. The desired profile of the lens is achieved with the use of air pressure to deform the PDMS membrane. The deformation of the PDMS membrane is determined by numerical simulation. Simulation results show that the sag height of the PDMS membrane varies nearly linearly along with the change of the negative pressure. The shape of the PDMS membrane is transferred to the PDMS mold with UV curing and casting processes. Then, PDMS is used as a mold insert, and polycarbonate microlens arrays with different sag heights are fabricated with the hot embossing technique. The surface profile of the fabricated microlens keeps spherical with the variation of the sag height induced by the negative pressure. For the negative pressure −3600 and −5900 Pa, sag heights with 40 and 65 μm are obtained and the corresponding focal lengths are changed from 1.0 to 0.6 mm. Good uniformity and imaging quality of the microlenses is confirmed by the experimentally evaluated and measured optical properties of the replica.

Keywords: microlens array, PDMS membrane, PDMS mold, hot embossing

(Some figures may appear in colour only in the online journal)

1. Introduction

The microlens array is a key component in the fields of optical sensors, optical communications, and lighting devices and displays [1]. Many methods for the manufacture of microlens arrays have been extensively investigated, including photoresist reflow [2], laser ablation [3], etching [4] and grayscale photolithography [5]. However, most of these techniques require expensive equipment and involve complicated processes. Recently, inkjet printing [6] and electrostatic-induced lithography [7] have been optimized as direct fabrication methods to develop polymer-based microlenses. The shape of the microlens can be well controlled by the adjustment of process parameters. These methods provide a one-step fabrication process without photolithography and etching. Compared with the direct fabrication process, the replication process offers an efficient, low-cost and mass production method to produce precise microstructure arrays. Popular replication methods include injection molding [8], hot embossing [9] and UV molding [10]. Researchers have done very comprehensive studies on air pressure assisted embossing. By changing the air pressure and the temperature, the shape of a microlens can be controlled effectively [11–13]. We can utilize this approach to control the profile of a microlens by changing the air pressure. For any replication technique, a mold with negative features of the final desired patterns is required. The mold considerably affects the replication process. Choosing an appropriate mold material is important, because it affects the quality of the final microstructures and complexity of the process.

In recent years, casting or imprinting processes using polydimethylsiloxane (PDMS) molds have been proposed for fabricating microlens arrays and other microstructures [14–18]. Compared with the conventional electroformed metal mold, the PDMS mold can be fabricated by a casting process without

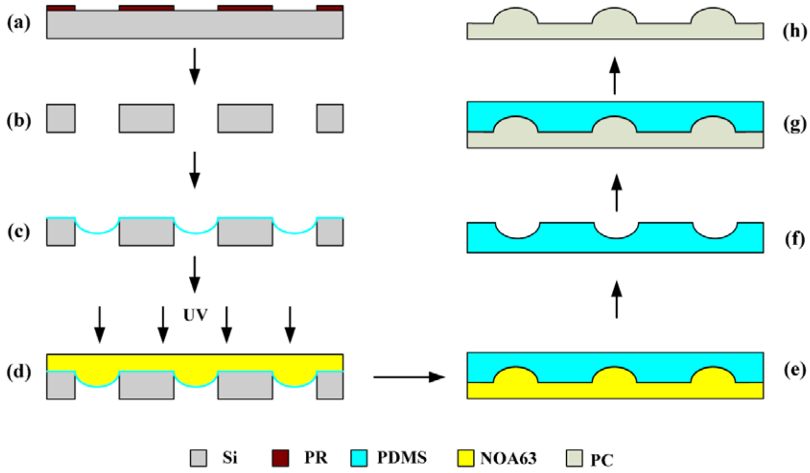

Figure 1. Fabrication procedure of the microlens array: (*a*) microhole patterning; (*b*) Si etching; (*c*) PDMS membrane deforming; (*d*) UV curing the male NOA63 mold; (*e*) PDMS pouring and curing; (*f*) the female PDMS mold manufactured from the male NOA63 mold; (*g*) hot embossing microlens array using the PDMS mold; (*h*) the final PC microlens array after demolding.

the requirement for expensive facilities. Moreover, the surface energy of the PDMS is low, which results in a low adhesion and friction coefficient between the polymer and the mold, and is thus easy to demold [19]. Researchers have also shown that using PDMS mold-based hot embossing can be used to fabricate complex structures with high aspect ratios effectively [20, 21]. Although the process cannot be fully automated, PDMS mold-based hot embossing is a rapid and simple method with low start-up costs and an easy fabrication process. These features show the potential of PDMS for use as a soft mold to hot emboss microlens arrays in thermoplastics.

In this study, PDMS is used as a mold insert, and plastic microlens arrays are fabricated by using the hot embossing technique. The PDMS mold is fabricated by soft photolithography techniques. Instead of a photoresist or glass mother mold, air pressure is used to deform the PDMS membrane until the desired profile of the lens is achieved. During this process, one Si substrate with a microhole array is fabricated, and then the PDMS membrane is bonded to the Si substrate. The membrane is deformed by negative pressure, and the deformation is observed through a microscope in real time. After UV curing and casting processes, the shape of the PDMS membrane can be transferred to the PDMS mold. Polycarbonate (PC) is used as a lens material in this study. PC is a suitable material for optical components because of its high refractive index (1.56) and high level of light transmission (>90%) in the visible and near-infrared region [22]. PC is also a popular thermoplastic with high formability for hot embossing. The microlens arrays can be replicated using this method on the PC substrate. The morphology of the fabricated microlens is assessed, and the optical properties are experimentally evaluated.

2. Fabrication procedures

To fabricate the plastic microlens arrays, standard photolithography, soft photolithography, and hot embossing techniques are used. The photomask film used in lithography is generated by importation of the computer-aided design file into a photoplotter (EIE RP224 + SXT). The fabrication procedure of the microlens array involves four steps (figure 1): (i) fabricating the Si mold with the microhole array; (ii) achieving the desired profile of the lens with a negative pressure-deformed PDMS membrane; (iii) transferring the shape of the PDMS membrane to the PDMS mold by UV curing and casting processes; and (iv) fabricating the PC microlens arrays by PDMS mold-based hot embossing.

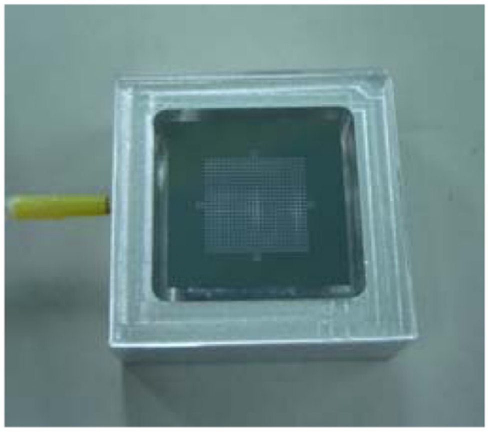

Figure 2. Photograph of the designed chamber.

Especially, a layer of photoresist (AZ 4620) is coated onto the Si substrate. After standard lithography (Suss MA6/BA6), the photoresist is developed into a mask for Si etching (figure 1(*a*)). Si is etched by inductively coupled plasma dry etching process (Alcatel 601E). After the photoresist is removed, the Si mold with a microhole array is obtained (figure 1(*b*)). PDMS (Dow Corning Sylgard 184) is used to fabricate the elastomeric membrane in this study. After the curing agent and the PDMS prepolymer with weight ratio of 1:10 are mixed, the PDMS mixture is degassed with a mechanical vacuum pump at 0.08 MPa for 10 min to remove air bubbles. The PDMS mixture is spun onto another Si substrate at a speed of 2,500 rpm and heated at 80 °C to cure for 10 min. Then, the PDMS membrane (20 μm thick) is peeled off from the Si substrate. The PDMS membrane can be bonded to the Si mold after oxygen plasma treatment (PVA TePla GIGAbatch 310M plasma system).

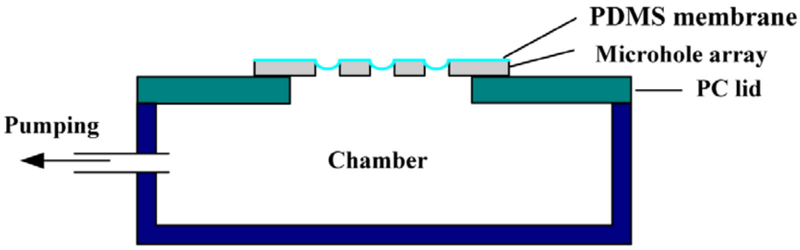

Figure 3. Schematic showing the use of air pressure to deform the PDMS membrane.

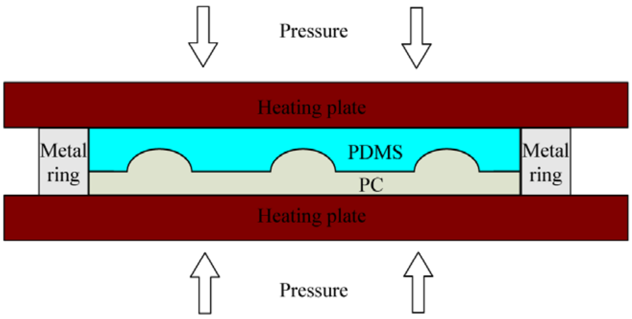

Figure 4. PDMS mold-based hot embossing with a metal ring.

As demonstrated in figures 2 and 3, a chamber with an outlet connection is designed and fabricated to generate the negative pressure. A PC with a blowhole at the center is used as the lid. The Si mold was subsequently mounted onto the blowhole and sealed together with a 3M adhesive transfer tape. The PDMS membrane is deformed by the air pressure in the chamber, the negative pressure is controlled by a digital syringe pump (RISTRON RSP04-C) and the deformation is observed through a microscope in real time (figures 1(*c*), 3 and 6). A photocurable polymer (Norland Optical Adhesive 63 NOA63) is poured onto the deformed PDMS membrane. UV light is used to cure the NOA63 polymer for 10 min. The male NOA63 mold is formed (figure 1(*d*)). The mixed PDMS is poured onto the male NOA63 mold and then heated at 80 °C to cure for another 10 min (figure 1(*e*)). Then, the female PDMS mold is peeled off from the male NOA63 mold (figure 1(*f*)). The female PDMS mold is used to hot emboss the PC substrate (figure 1(*g*)). A Suss bonding system (Suss SB6E substrate bonder) is used in this step. The PDMS mold and the PC substrate are placed on the bottom hot plate and heated together to a temperature of 180 °C, which is 40 °C higher than the glass transition temperature (T_g) of the PC. After the desired temperature is reached, the top hot plate is pressed down with a force of 1 kN. The force is applied until the system is cooled to room temperature. Then, the applied force is reduced and the top hot plate is removed. After demolding, the PC microlens array is obtained from the female PDMS mold (figure 1(*h*)).

Briefly, the embossing process mainly depends on three critical parameters: embossing temperature, embossing time and embossing pressure. Embossing temperature depends on the plastic substrate and should be higher than the glass transition temperature of the plastic substrate. Compared with the conventional mold, PDMS mold-based hot embossing needs a higher temperature to further raise the mobility of the thermoplastic. The embossing temperature should be approximately 40 °C above the T_g of the plastic to ensure the quality of replica [20].

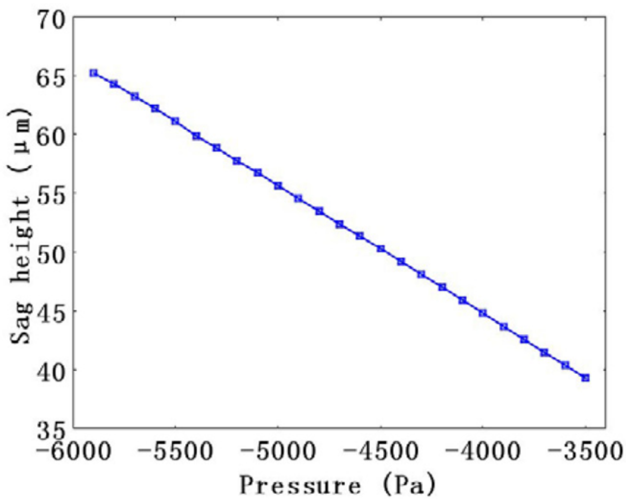

Figure 5. Sag heights of the PDMS membrane corresponding to different negative pressure.

The thickness of the replica depends on the embossing temperature and the embossing time as well as the embossing force. A thinner microlens sheet corresponds to a longer embossing time. The embossing pressure should high enough to overcome the viscous force of the substrate. However, due to the softness of the PDMS mold, excess embossing force will result in large deformation of the PDMS mold [21]. Deformation of the mold will affect the quality of the fabricated microlens array.

To ensure the quality of the replica, we put a metal ring between the two heating plates (figure 4). Then, the thickness of the microlens sheet could be controlled. The excess embossing force and the deformation of mold could be eliminated. When the embossing temperature (180 °C) is reached, the embossing force is loaded. We maintain the embossing temperature for 6 min to release the stress both of the mold and PC substrate. Then the mold and PC substrate are separated by cooling the temperature down to 20 °C.

3. Results and discussions

In order to determine the negative pressure used to deform the PDMS membrane, numerical simulation is implemented using the Structural Mechanics and Moving Mesh modules of COMSOL Multiphysics (Version 3.5). PDMS is a nearly incompressible material, with Young's modulus and Poisson's ratio equal to 4×10^6 Pa and 0.5, respectively. In the simulation, the displacement of the PDMS membrane with size $440 \times 440 \times 20\,\mu$m on the Si hole with radius equal to $210\,\mu$m is computed for different

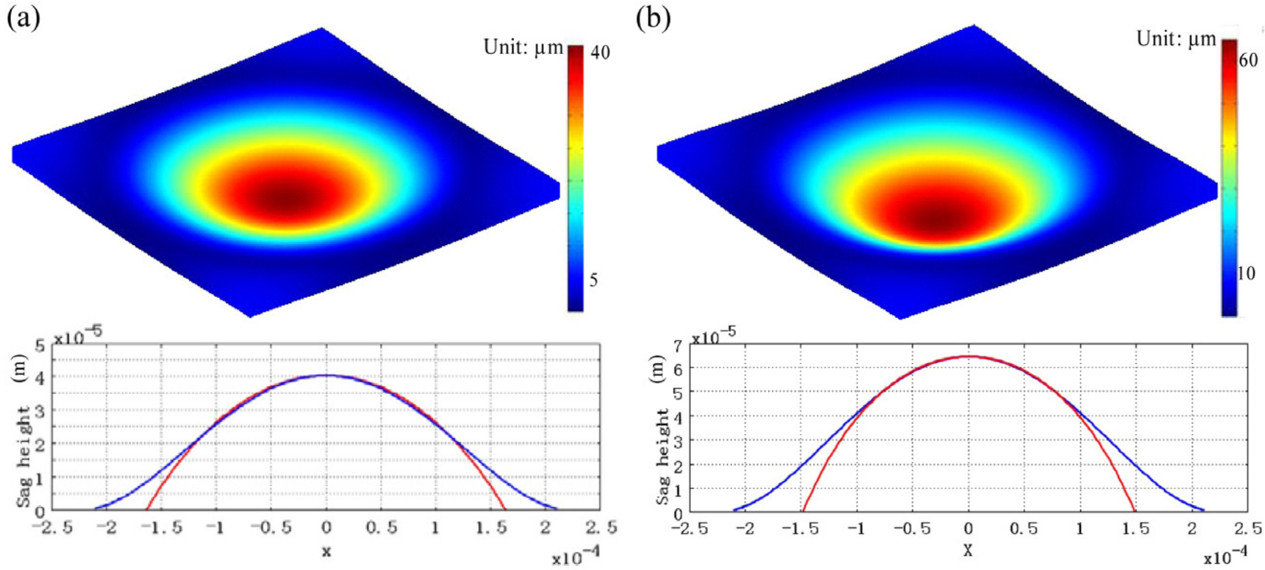

Figure 6. (*a*) Deformed PDMS membrane with negative pressure equal to −3600 Pa, the corresponding displacement of the symmetrical axis of the membrane upper surface (blue curve), and the fitted circular arc (red curve); (*b*) deformed PDMS membrane with negative pressure equal to −5900 Pa and the corresponding displacement of the symmetrical axis of the membrane upper surface (blue curve), and the fitted circular arc (red curve).

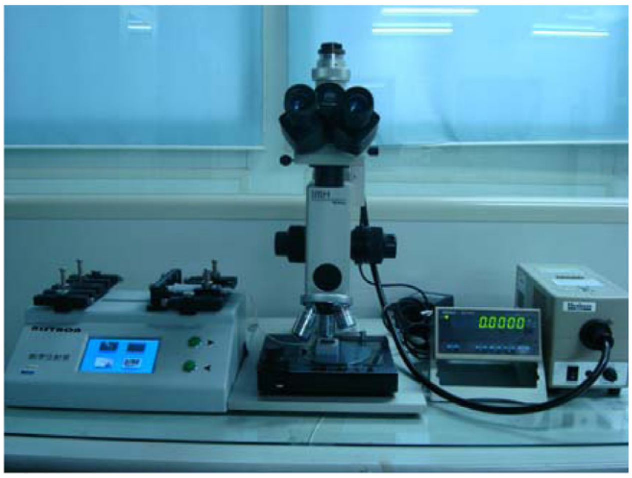

Figure 7. Experimental setup used to observe the deformation of the PDMS membrane.

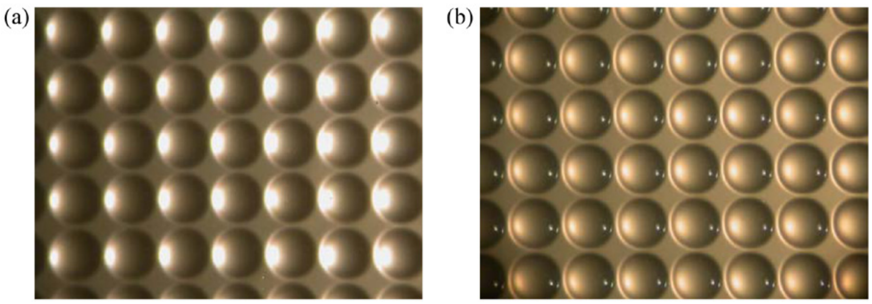

Figure 8. Optical microscope images of the fabricated microlens arrays. The sag height of the microlens is (*a*) $h = 40\,\mu$m and (*b*) $h = 65\,\mu$m.

negative pressure. The sag heights of the PDMS membrane corresponding to negative pressure from −5900 to −3500 Pa are computed as shown in figure 5, where the reference atmospheric pressure is set to 0. Figure 5 shows that the sag height of the PDMS membrane varies nearly linearly along with the change of the negative pressure. For negative pressures of −3600 Pa and −5900 Pa, the PDMS membrane is deformed with displacement of the symmetrical axis of the membrane upper surface, as shown in figure 6, and the corresponding sag heights of the deformed PDMS membrane are $40.38\,\mu$m and $65.18\,\mu$m.

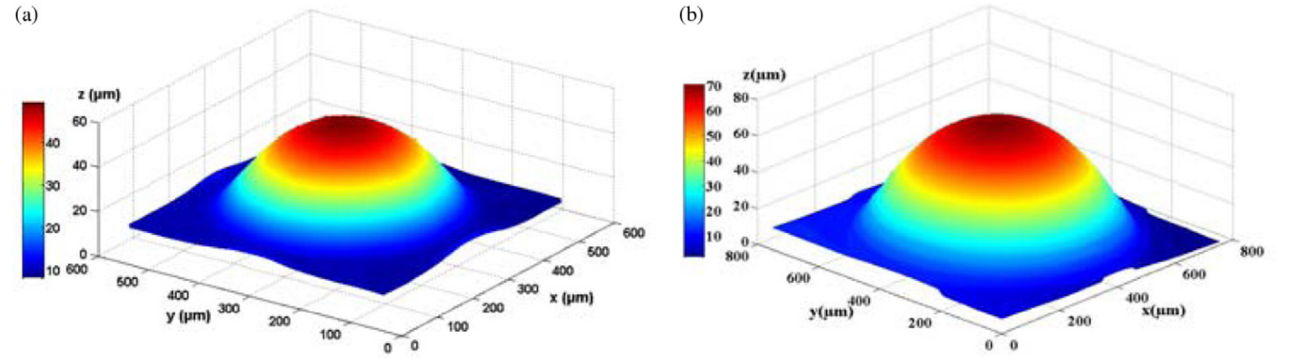

Figure 9. 3D surface profiles of the fabricated microlens measured with the use of LSCM. The sag height of the microlens is (*a*) $h = 40\,\mu$m and (*b*) $h = 65\,\mu$m.

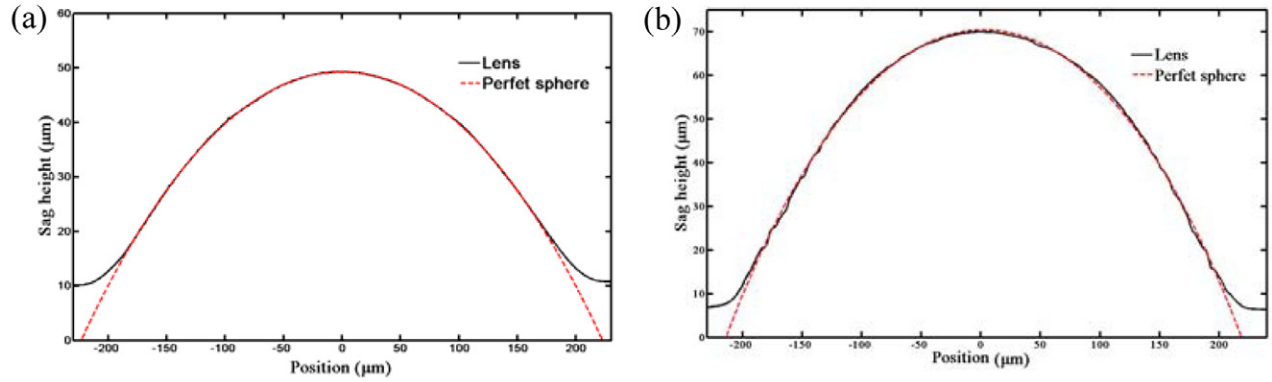

Figure 10. Cross-sectional profile comparison of the fabricated microlens and the theoretical sphere surface. The sag height of the microlens is (*a*) $h = 40\,\mu$m and (*b*) $h = 65\,\mu$m.

Based on the numerical simulation results, the PDMS membrane is deformed by the negative pressure, and the deformation along the *z*-axis direction can be measured in real time (figure 7). In this work, corresponding to different negative pressure obtained from the simulation results, microlens arrays with different sag heights are fabricated. The surface profiles and the focal length of the fabricated microlens arrays are measured, and the optical properties of the replica are experimentally evaluated.

The 3D morphology of the microlenses is assessed by using a stereoscopic microscope (MEIJI EMZ-TR) (figure 8) and a laser scanning confocal microscope (LSCM; Olympus LEXT OLS4000) (figure 9). From the figures, we observed a high degree of uniformity of the fabricated microlens arrays. The 3D profiles also show a nearly spherical shape. Figure 10 shows the 2D surface profiles obtained from the results of the laser scanning confocal microscopy measurement. The cross-sectional profile of the fabricated microlens is similar to the theoretical sphere surface. However, a small deviation still exists, which is probably caused by the variations in the thickness of the PDMS membrane during the deforming process. For the operability of the process, the PDMS membrane must meet a certain thickness. Thickness affects the deformation of the membrane at the junction of the Si mold and causes uneven deformation. This is consistent with the computed displacement distribution on the symmetrical axis of the membrane upper surface (figure 6).

Basing on the measurements obtained previously, we can determine the focal length of the lens. The relationship

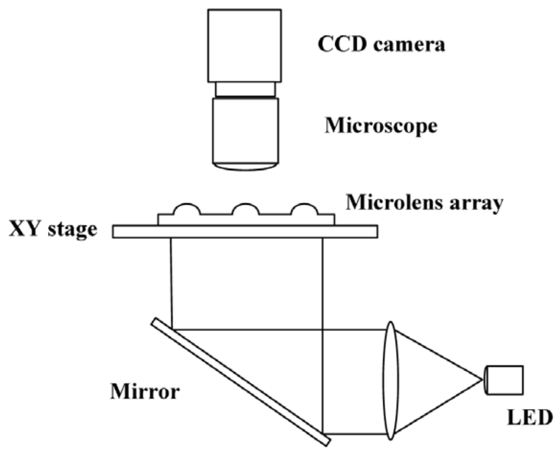

Figure 11. Schematic to measure the focal length of the fabricated microlens array.

between the focal length (f), the curvature radius (R), and the refractive index (n) of the fabricated microlenses can be expressed with the following equations [23]:

$$f = \frac{R}{n-1}, \tag{1}$$

$$R = \frac{h^2 + \left(\frac{d}{2}\right)^2}{2h}, \tag{2}$$

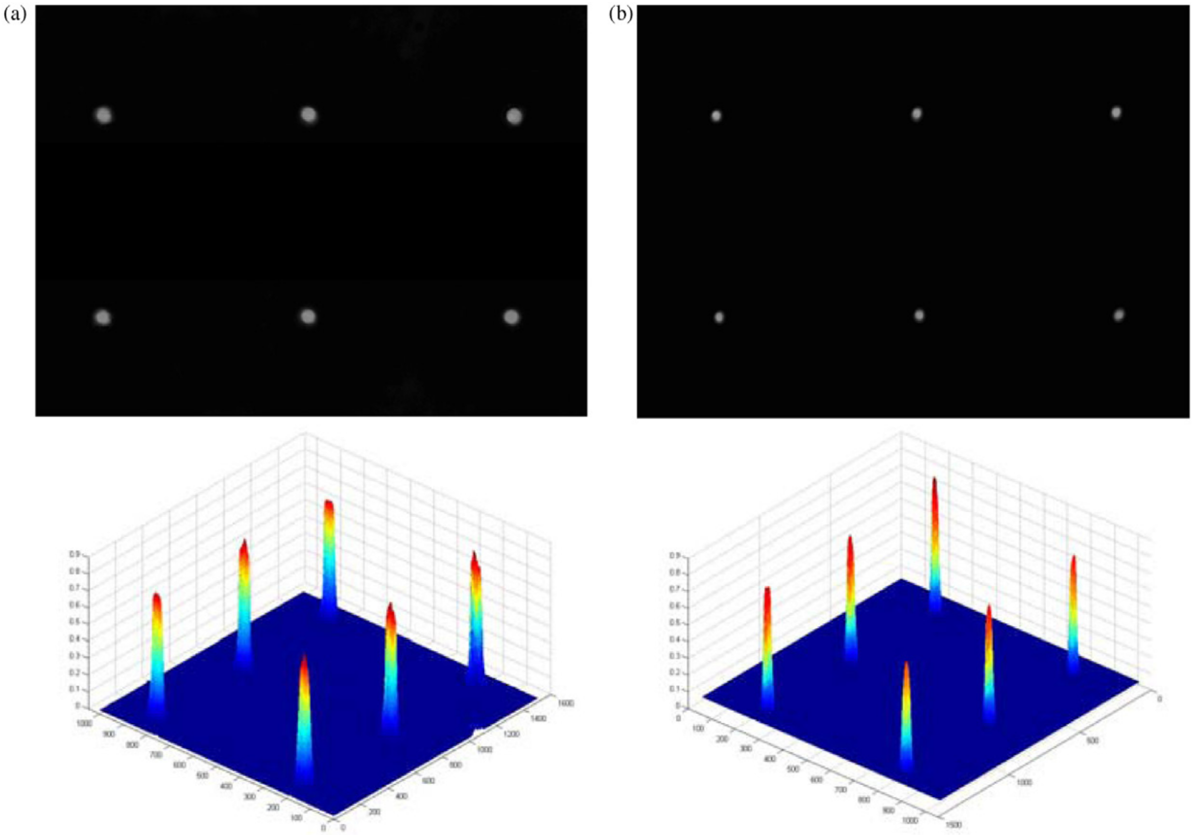

Figure 12. Focused spot pattern of the microlens arrays and the intensity profile transferred from the focused spot. The sag height of the microlens is (*a*) $h = 40\,\mu$m and (*b*) $h = 65\,\mu$m.

where h is the lens sag height, d is the lens diameter and n is the refractive index of PC ($n = 1.56$). The microlenses have a diameter of $420\,\mu$m, and corresponding to different deformations of the PDMS membrane, the sag heights are $h_1 = 40\,\mu$m and $h_2 = 65\,\mu$m. Then, the focal lengths of the microlens are $f_1 = 1020\,\mu$m and $f_2 = 664\,\mu$m. We measured the deformation of the PDMS membrane along the z-axis direction with pressure and the sag height of the replicated microlenses. We observed only a small deviation (approximately 3%) in height, which is probably caused by the variations in the thickness of the PDMS membrane. From figures 8–10, we can confirm that the shape of the PDMS membrane is transferred to the final PC replica. The experimental results are in good agreement with the numerical simulation results and prove that the PDMS mold does not significantly affect either the shape or the dimension of the microlenses.

The focal length of the lens is also measured with a microscope (Union Optical IMH non-contact depth measurement unit) and bottom-emitting parallel light (figure 11). First, the microscope is vertically moved to determine the focal plane of the lens. The smallest spot point of light can be observed at this plane. The microscope is then moved to focus on the vertex of the lens. The distance between the light-focusing point and the vertex of a microlens is the focal length. The measured focal lengths are in good agreement with the results obtained with the calculation of equation (1). Figure 12 shows the focused spot patterns of the microlens arrays. The images of the focused spots are then grayscaled and analyzed with MATLAB to calculate the intensity profiles of each light spot. The images show that the pitch and intensity of the focused spots are uniform.

To evaluate the optical imaging performance of the fabricated microlens array, a coverslip with the letter M is placed between the light source of a stereoscopic microscope (MEIJI EMZ-TR) and the microlens array. The images are captured by a charge-coupled device camera (figure 13(*a*)). The images show the perfect imaging properties of the microlens array, in which every lens can form a sharp image. Figure 13(*b*) is recorded by a digital microscope system (KEYENCE VHX-1000). On the surface of the microlenses, we can clearly observe the images formed by the light source of the microscope. These images show that the microlenses have excellent consistency and surface smoothness.

As previously mentioned, the experimental results indicate the good quality, uniformity and imaging properties of the fabricated microlens arrays. The experimental results are in good agreement with the simulation results. However, several aberrations exist between the numerical and experimental results. On the basis of our analysis, these aberrations are caused by microfabrication errors, e.g. the variations in the thickness of the PDMS membrane, as well as the inevitable fabrication errors of lithography, etching, and PDMS demolding. The measurements show the possibility of using the present molded microlens array for optical applications. This technique shows great potential for the efficient replication of the low-cost microlens arrays with mass production.

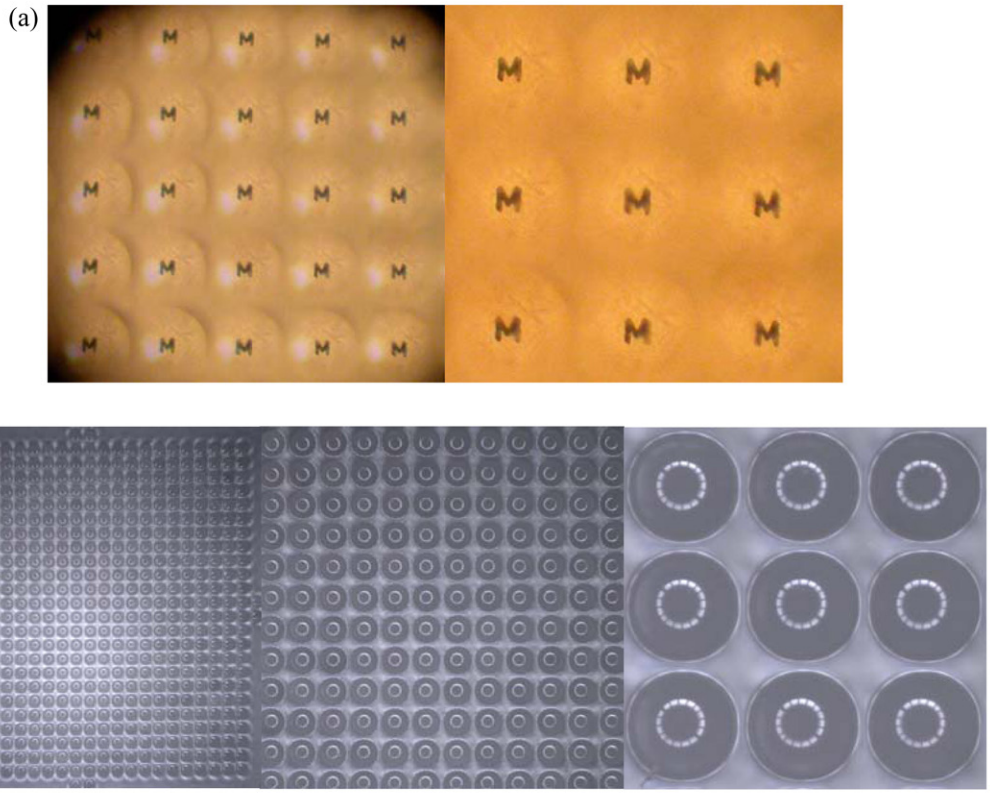

Figure 13. Images captured by the microscope systems for the fabricated microlens array: (*a*) captured by the stereoscopic microscope and (*b*) captured by the VHX-1000 digital microscope.

4. Conclusion

In summary, we have shown a simple and flexible method to fabricate polymeric microlens arrays with PDMS mold-based hot embossing. We have replicated 24 × 24 microlens arrays with a diameter of 420μm and a separation of 20μm. The sag height can be controlled by modification of the deformation process of the PDMS membrane. The deformation process of the PDMS membrane has been determined by numerical simulation. The deformation along the *z*-axis direction has been measured in real time. Corresponding to the simulation results, microlens arrays with the sag heights of 40μm and 65μm have been fabricated. Deviation of the obtained sag height is 3%. The surface profiles and the focal length of the fabricated microlenses have been measured. Good agreement between experimental and simulated results has been obtained. The optical imaging performance has demonstrated that the fabricated microlens arrays have good consistency and surface smoothness. The shape of the microlens array can be varied with the change of the number, diameter and arrangement of the microholes. The limitation of the proposed process is on the sag height, whose maximal value should be less than the radius of the microhole to keep the spherical deformation of the PDMS membrane. This fabrication process for microlens array can be extended to achieve the aspherical deformation of the PDMS membrane, so as to obtain the controllable aspheric microlens.

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