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Fabrication of PDMS (polydimethylsiloxane) microlens and diffuser using replica molding

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Abstract

This paper reports the fabrication method of PDMS (polydimethylsiloxane) microlens array based on the replica molding process, casting a liquid PDMS into concave microlens molds. Concave microlens molds were fabricated through spin-coating processes suspended a liquid PMMA film on the micro-drilled hole, leading to the formation of the special curvature. Then, PDMS microlens arrays and diffusers were fabricated by replica molding and discussed in this study. The fabricated microlenses have both good surface roughness and high-quality optical properties. Therefore, diffusers were fabricated by two-step replica molding. A high-intensity He–Ne laser beam was uniformly spread through diffusers. Experimental tests demonstrated that all PDMS elements are successfully fabricated by replica molding process and operated during optical measurement.

Keywords: PDMS; Microlens; Diffuser; Replica molding

1. Introduction

Refractive microlenses have extensively applied to various fields such as optical communication, optical detectors, liquid crystal displays (LCDs), mobile phone panels and personal digital accessories (PDAs). These applications can be grouped into three generic areas: (1) beam shaping, (2) interconnections, and (3) imaging [1]. In order to satisfy the needs of photoelectric systems, many researchers have been exploring various ways to fabricate refractive microlens arrays on different lens materials. Various lens materials and corresponding technologies have been presented, like polymer [2–5], silica [6,7], diamond [8] and sol–gel [9,10]. For the modern science and technology, most of fabrication technologies for these materials must involve the photolithography process, leading to the high-priced charges.

In our previous work, a new approach to curved relief structures fabrication through soft replica molding was reported [3]. Unfortunately, this method has complex processes for polymeric curved relief structures fabrication. However, much attention has been given to a potential optical material (PDMS) in recently years. Moreover, PDMS has fascinating properties, such as low surface energy, thermal curing property, its refractive about 1.41 and soft nature. Although PDMS is a quite well material for molds, it may be a suitable material for lenses.

In this work, polymeric concave molds can be fabricated by spin-coating process. A liquid PMMA film was suspended on the micro-drilled hole, leading to the formation of the special curvature. After casting and curing the thermal curing material, PDMS microlenses can be easily fabricated. This fabrication process has no needs of photolithography, leading to reduce effectively the fabrication cost for microlens arrays. Additionally, diffusers can be also fabricated by a two-step replica molding process. Experimental test demonstrated that a high-intensity

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He–Ne laser beam can be uniformly spread through the made diffuser.

2. Experiment

Referring to the schematic depicted in Fig. 1, steps for fabricating PDMS microlens arrays and diffusers are described as follows:

(1) The footprint with designed shape and size for a required structure was defined on a metallic mask through which the excimer laser wrote the footprint directly onto a polycarbonate (PC) plate. By monitoring the power intensity and number of laser shots, depth of the holes drilled by the excimer laser could be well controlled. Fig. 1(a) shows the resultant PC plate with microholes that serves as the pedestal in the next step.

(2) A thin liquid polymethylmethacrylate (PMMA) film was then coated on the PC-based pedestal through spin-coating. As the liquid PMMA was rapidly spreading out, due to its own weight and viscosity, a film, suspended on the pedestals and with special curvature, was formed on the pedestal. The schematic is shown in Fig. 1(b). The effect of the liquid surface tension results in good surface uniformity, providing that the liquid PMMA is at reasonable thickness. After baking at 60 °C for 5 min, the liquid film was solidified and stuck fixedly on the pedestal.

(3) Soft PDMS microlens arrays were formed by the replica molding process. A liquid PDMS mixture (Sylgard 184, Dow Corning, the weight ratio of silicone elastomer to curing agent is 10 to 1) was cast onto the PMMA film obtained in Step 2 and then a glass or plastic substrate was covered on it. The schematic is shown in Fig. 1(c). After baking at 70 °C for 30 min, the solidified PDMS microlens arrays could be easily stripped from the PMMA film. The resulting PDMS microlens arrays are shown in Fig. 1(d).

(4) A PDMS diffuser was also fabricated by a two-step replica molding process. The second PDMS microlens arrays were attached by the second replica molding process on the opposite side of an underlay substrate with microlens arrays fabricated in Step 3. The position of the second arrays was relative to the original arrays shifted halfway along the diagonal on the opposite side of the underlay substrate. The resulting PDMS diffuser is shown in Fig. 1(e).

3. Results and discussion

The optical character of PDMS was measured by UV–Vis spectrophotometer. Fig. 2 shows a transmittance curve of PDMS as a function of incident wavelength. The PDMS transmittance is of approximately 85% at the wavelength range of 290–1100 nm. This wavelength range contains ultraviolet rays, visible light, and a part of infrared rays. Hence, PDMS is a suitable material for lenses.

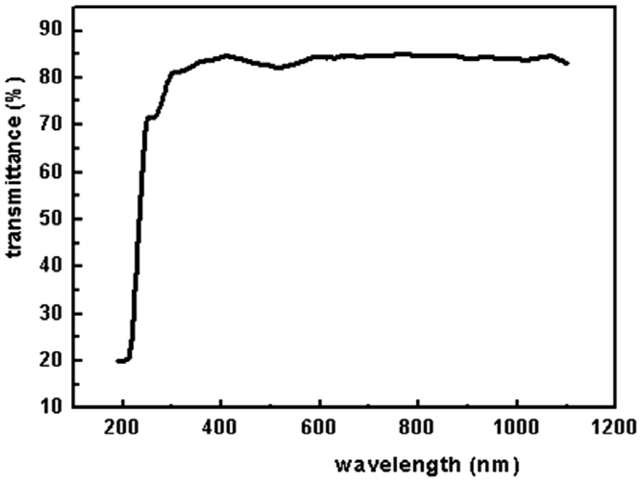

Fig. 2. Schematic for fabrication of PDMS arrays by replica molding processes.

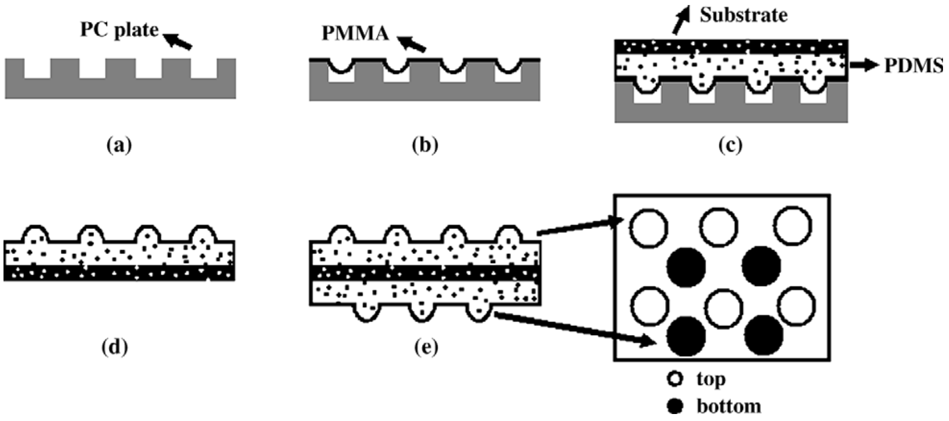

Fig. 1. Optical transmittance curve of PDMS as a function of incident wavelength.

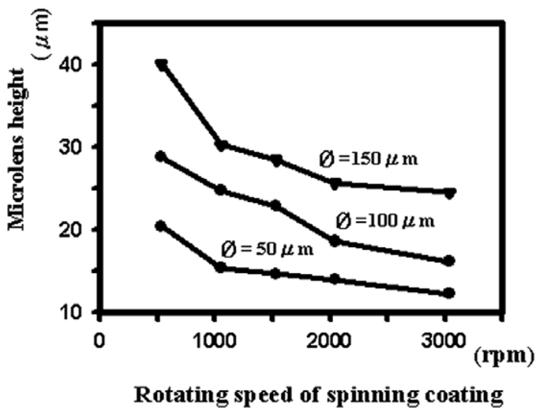

Fig. 3. Microlens height as a function of spin-coating rotating speed.

For the present fabrication method, heights of microlenses depended on diameters of holes micro-drilled by excimer laser and thicknesses of PMMA liquid films which were predominated by the rotating speed of the spin-coating process in Step 2. Fig. 3 shows this tendency that diameters of microholes and PMMA films were gradually decreased, leading heights of microlenses to decrease. Fig. 4 presents the characters of PDMS microlenses, including the shape of microlens (by three-dimensional confocal microscope), the focused spots of a 3 ∗ 3 PDMS microlens array, and surface roughness of a PDMS microlens (by atomic force microscope, AFM). Fig. 4(a) reveals this fact that microlenses with different diameters have different heights at spinning coating rotating speed of 5000 rpm. In Fig. 4(b), the profile of a microlens with a

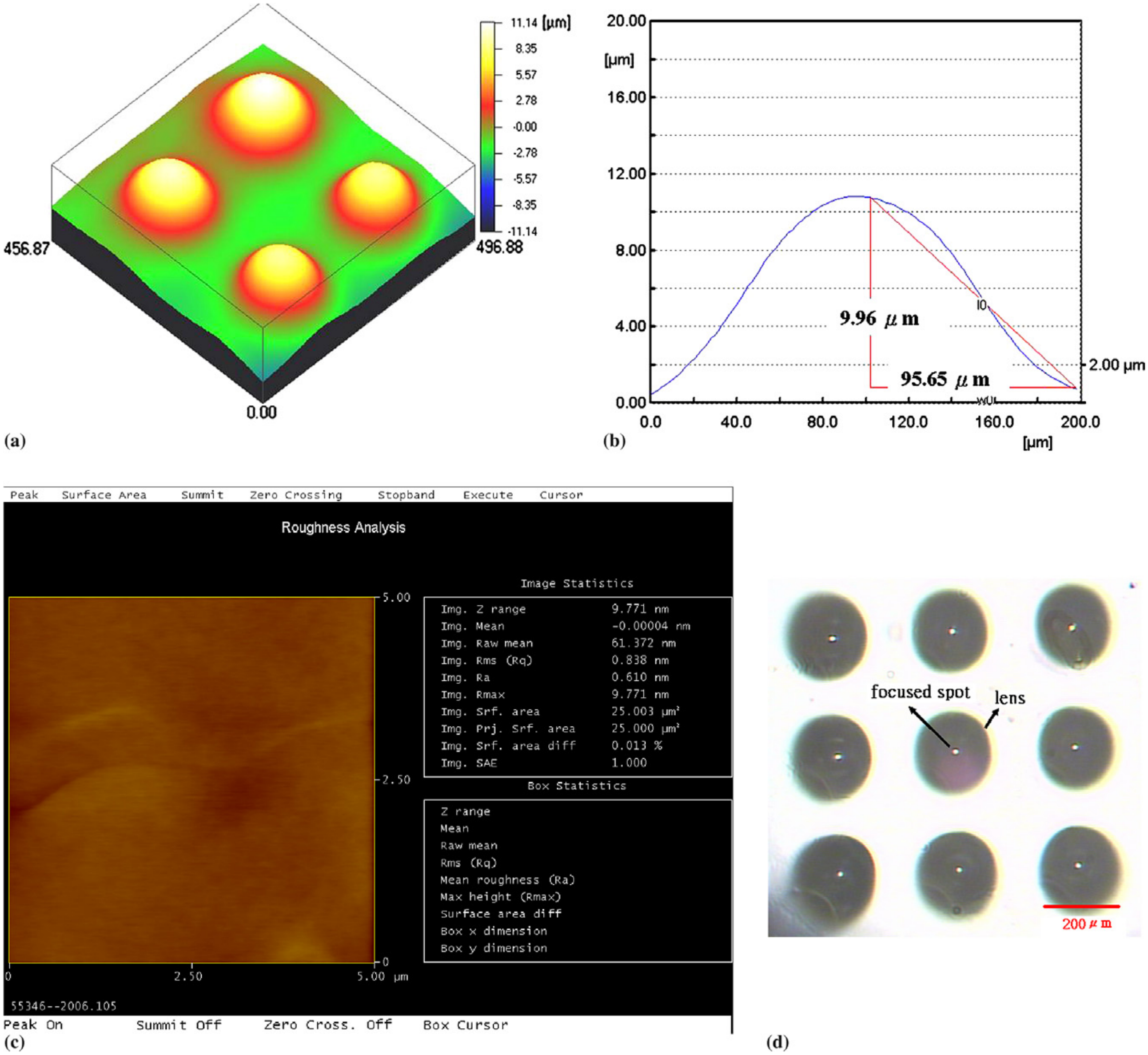

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               Image Statistics
Img. Z range              9.771 nm
Img. Mean                 -0.00004 nm
Img. Raw mean             61.372 nm
Img. Rms (Rq)             0.838 nm
Img. Ra                   0.610 nm
Img. Rmax                 9.771 nm
Img. Srf. area            25.003 μm²
Img. Prj. Srf. area       25.000 μm²
Img. Srf. area diff       0.013 %
Img. SAE                  1.000
                Box Statistics
Z range
Mean
Raw mean
Rms (Rq)
Mean roughness (Ra)
Max height (Rmax)
Surface area diff
Box x dimension
Box y dimension
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Fig. 4. Characters of PDMS microlenses: (a) 3D images of microlens arrays by confocal microscope, (b) 2D profile of a single microlens by confocal microscope, (c) images of surface roughness by AFM, and (d) focused spots of microlens.

diameter of 200 μm in this array is shown. Experimental images clearly demonstrated that the profile was a Gaussian distribution. Fig. 4(c) shows that the root mean square surface roughness was about 1 nm in areas of $5 * 5\ \mu m^2$ by AFM. Hence, PDMS microlens arrays with a high-quality surface could be obtained. Focusing properties of fabricated microlenses with diameters of 200 μm and heights of 10 μm were examined. Fig. 4(d) shows a very good focusing effect can be achieved.

However, the needs of micro-drilled holes which would lower the fill-factor of microlens arrays were disadvantages for present fabrication processes. In order to increase this fill-factor, adding another microlens array with the original microlens shifted halfway along the diagonal. This process can not only enhance the fill-factor in an underlay substrate but also be used as diffusers. To understand how efficiency for the made diffuser is, a schematic diagram of the experimental setup for measuring efficiency of components is shown in Fig. 5(a). The setup consisted of a laser diode as a light source, samples, screen and CCD camera, imagine display and recording system. As a laser beam propagated through the sample, an expended beam would be projected finally on the screen. A CCD camera can be acted as a detector and capture the image of intensity distribution of a laser beam. Therefore, optical intensity distributions can be clearly analyzed through a commercial optical software called beam profile. Three kinds of cases, including a laser beam without any elements, with microlens arrays attached to one side of an underlay substrate, and with the made diffuser, were respectively examined. Three kinds of resulting images are shown in Fig. 5(b)–(d), respectively. The intensity distribution for a high-intensity laser without any component is shown in Fig. 5(b). In Fig. 5(c), the original shape of the laser beam started to expand through the underlay substrate with microlens arrays, but the center of the expanded beam still kept a high-intensity. However, the laser beam passed through the made diffuser, a uniform intensity could be clearly observed in Fig. 5(d) and the center of the expanded beam was almost similar to other

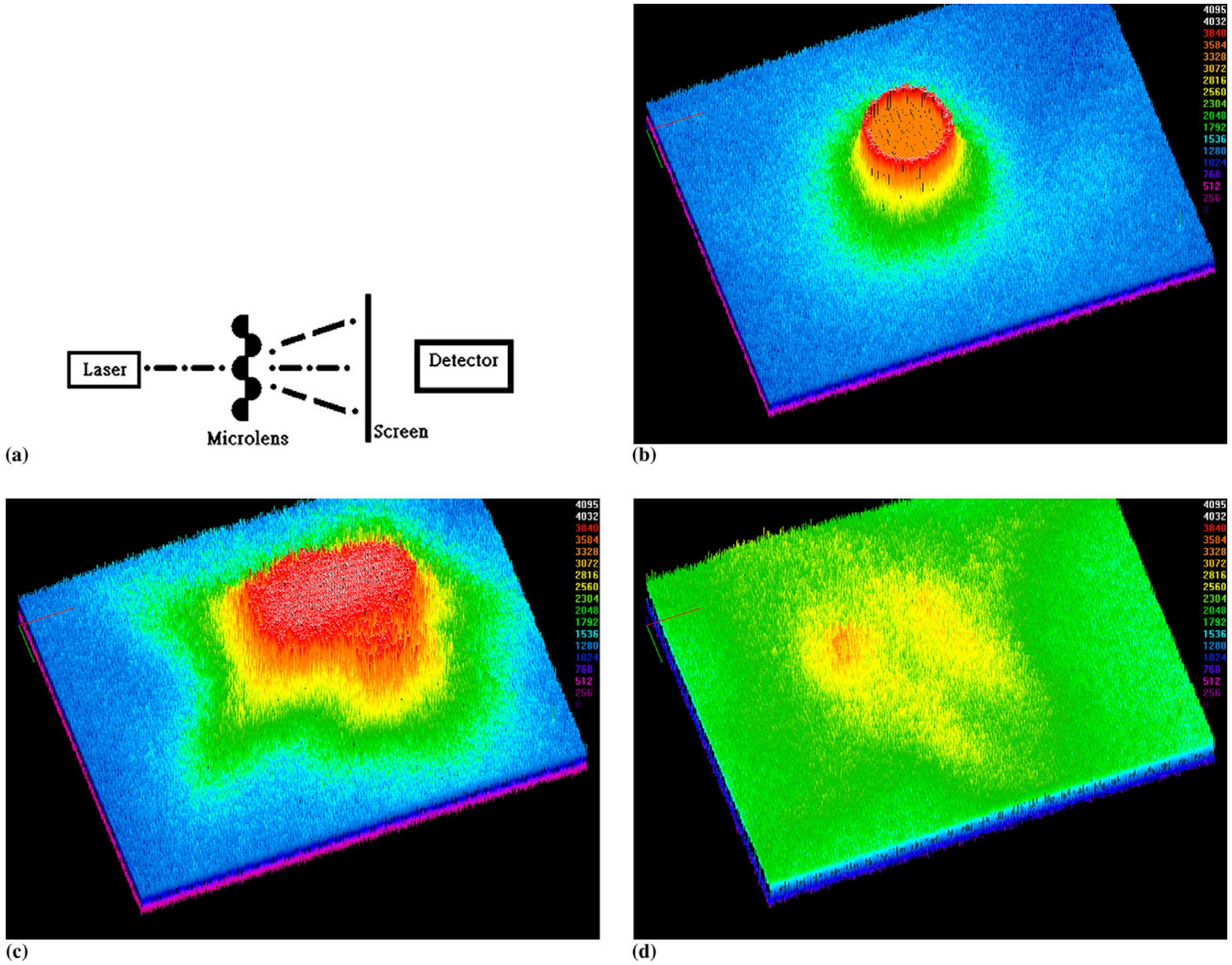

Fig. 5. Diffuser spot measurement: (a) schematic showing the experimental setup, (b) optical intensity of a laser beam without any component, (c) optical intensity of a laser beam with microlens arrays, and (d) optical intensity of a laser beam with diffusers.

area. Hence, the fabricated diffuser can effectively expand a high-intensity laser beam. Recently, diffusers have been popularly used as light-homogenizing devices in light emitting diode (LED) display panels, and LCD backlights [11].

With the fast development of flexible display, PDMS microlens arrays could be attached to a flexible plastic substrate and be used in the flexible display. Due to the soft nature of PDMS, these microlenses would be not damaged by stresses which existed in deformable devices. However, it would be difficult for general microlenses to bend the underlay substrate, due to stress destruction.

4. Conclusion

In this paper, we propose the application and fabrication of PDMS microlens arrays. Concave molds can be only fabricated by spin-coating process. Then, a liquid PDMS was cast onto molds by replication processes. Finally, PDMS microlens arrays were successfully fabricated. These microlenses have excellent optical characteristics as well as polymeric microlenses. Diffusers can be fabricated by a two-step replication process. Experimental test demonstrated that a high-intensity He–Ne laser beam can be uniformly spread through the made diffuser. This fabrication processes have no the needs of photolithography and all of processing steps of manufacture are executed in ambient environment and at low temperature.

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