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Fabrication of polymer compound microlens by lens-on-lens microstructures

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ABSTRACT

We proposed a novel method for fabricating polymer compound microlenses (PCMLs) using micro-inkjet technique and subsequent curing process. Two different types of PCMLs with sandwich microstructure (PDMS-Glycerol-PDMS), concave and convex PCMLs, have been designed and fabricated in experiments. Convex PCML has two real images and two foci. The concave PCML has one real and one virtual focal planes, which can generate one real image and one virtual image respectively. Moreover, the diameter of concave PCML can be controlled by adjusting the curing time and temperature. The proposed method is simple, efficient and suitable for realizing large-scale high numerical aperture PCMLs array, which has potential applications in diverse optical systems such as optical storage and three-dimensional imaging.

1. Introduction

In recent years, microlenses with multiple focal lengths play an important role in three-dimensional imaging and the real-time detection of unconfined or fluctuating targets. Microlenses with special structures have played more important roles than simple lenses in many applications, such as achieving illumination uniformity by Fresnel microlens [1], improving coupling efficiency of high-power laser diodes and single-mode fiber by an elliptic cone-shaped microlens [2], achieving two focal plane by polydimethylsiloxane (PDMS) lens-on-lens microstructure [3]. Due to the low cost and easy formability, polymers are widely used to fabricate microlens [4,5]. Many researchers unceasingly explores in this domain, the methods for fabricating the microlens are gradually matured, such as photo-resist reflow method [6,7], gray-scale photolithography [8], micro-inkjet fabrication [9,10], and femtosecond laser direct writing [3,11,12]. Moreover, the laser direct writing technology can also be used to fabricate convex microlenses, but there are some problems in surface quality, profile and fabricating efficiency, which should be improved [13,14]. We have also noticed that the approaches mentioned above are multistep process and inefficient, which are not suitable for the fabrication of the lens with compound microstructure. Therefore, it is still a challenge to develop a high-efficient and low-cost strategy for fabricating the PCML array.

In this paper, based on the micro-inkjet technique, we proposed a simple method for fabricating PCMLs array with excellent multiple imaging abilities. Two different microstructures, including concave PCML and convex PCML, have been fabricated successfully. The fabricated PCML is sandwich microstructure (PDMS-Glycerol-PDMS), in which the middle layer (glycerol) can be used to modulate the surface profile of the PCML. For realizing the PCMLs with different surface profile, the substrates should be placed in different way to solidified PDMS. The solidification temperature and time should also be optimized to realize PCML with desired diameter. Experimental results show that the fabricated convex PCML has two real images, and the concave PCML has one real image and one virtual image due to the central concave surface. The top small lens diameter of PCML can be controlled by adjusting the solidification temperature and curing time. The fabricated PCMLs array can also be fabricated with potential applications in optical storage [15,16], extended depth of focus of a laser beam [17], real-time detection of the unconfined or fluctuating targets [18].

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2. Experimental

The fabrication process of the PCML is shown in Fig. 1. Commercial silica glass was chosen as the base material, on which thin Teflon film was prepared by spin-coating method. The speed of the Vacuum Spin Coater (MTI VTC-100) was 1500 rad/min and the spin time was 60 s, respectively. Then thin Teflon film was put into a tube furnace annealing at 380 °C for 10 min. Next, in step II, glycerol droplets were produced by a syringe (2.5 μl, Eppendorf) with precision of 0.1 μl. As shown in Fig. 1, the glycerol droplets array can be formed on the top of Teflon film and the distance between adjacent droplets can be controlled by a three-dimensional stage (Prior Scientific Inc.) with precision of 100 nm. In step III, the glycerol droplets were covered with PDMS droplets as encapsulation layer and outer lens. The schematic compound structure is shown in step III, in which the glycerol droplet is wrapped by PDMS droplet. For guaranteeing precision, the needle of the syringe must be as close as possible to the glycerol droplets. Because of the large contact angle (as shown in Fig. 1) of glycerol droplet against Teflon film, it is easy to realize the suspended glycerol droplet in the PDMS by inverting the substrate over 40 min. Then the PDMS was solidified for realizing the PCMLs. However, in the step IV, there are two ways to solidify the PDMS as shown in Fig. 1 for fabricating convex PCML and concave PCML. Normal solidification (PDMS droplets on the top of glass) can form concave PCML. Inverted solidification (PDMS droplets on the bottom of glass), can form convex PCML.

In the inverted solidification process, the slow evaporation of the glycerol leads to concave surface of the PDMS droplet. As shown in Fig. 2(a), the outer PDMS flows into the concave bottom and condenses into a smaller PDMS droplet with spherical surface due to gravity and surface tension. Because of the poor fluidity of PDMS, for generating convex PCML, the solidification spent more time at low temperature. The fabricated convex PCML is shown in Fig. 2(c). The fabricated convex PCML shows clear interface between glycerol and PDMS. The convex PCML was solidified at 90 °C for 50 min. Since the evaporation of glycerol leads to concave surface, the concave PCML can be realized by normal solidification with the droplets on the top of substrates. As shown in Fig. 2(b), during the solidification process, the high temperature leads to evaporation of glycerol and progressively smaller glycerol droplet results in concave surface. And the PDMS cannot flow into the top concave surface because of gravity. That is the solidification temperature and time relate to the size of concave surface. Using the normal solidification, the fabricated concave PCML can be seen in Fig. 2(d) with clear interface between glycerol and PDMS. The concave PCML was solidified at 110 °C for 20 min. Therefore, the PCML with

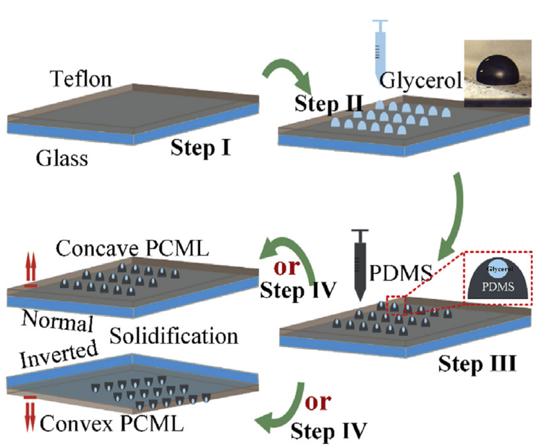

Fig. 1. The schematic diagram of the fabricating process.

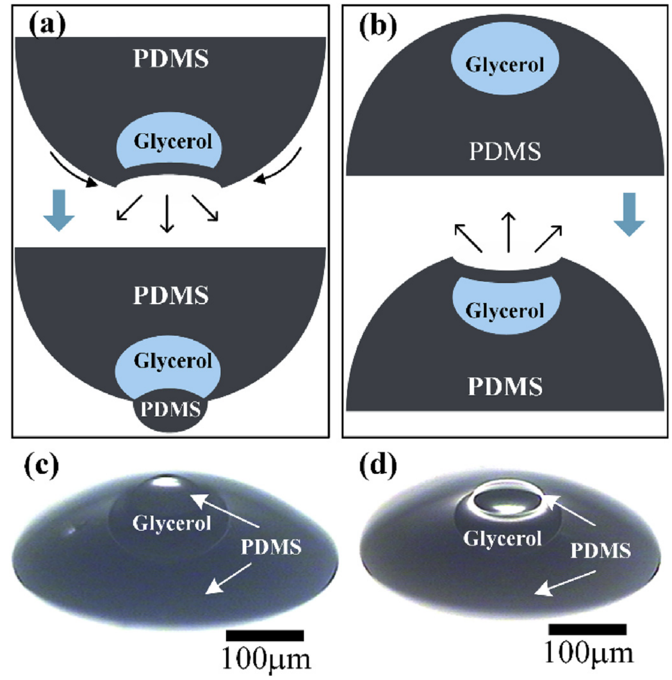

Fig. 2. The schematics of convex surface (a) and concave surface (b) PCMLs. The fabricated PCML with convex surface (c) and concave surface (d).

concave or convex surface can be fabricated by choosing different solidification method. From Fig. 2(c) and (d) we can see that the sandwich microstructure of PCML can be considered as a new kind of polymer triplet microlenses (PDMS-Glycerol-PDMS).

3. Results and discussion

By using micro-inkjet technique, PCMLs array were fabricated with 1 mm interval between single PCML. For characterizing the imaging ability of the PCMLs array, a letter “F” printed in a paper was placed in front of the PCMLs array, and a CCD camera was used behind the PCMLs array to capture the images. By modulating the position of the CCD camera, images can be observed. As shown in Fig. 3(a) and Fig. 3(b), there are two real images in different focal plane generated by convex PCMLs array. These images indicate that the convex PCMLs array have excellent imaging ability that has potential applications such as optical storage, three-dimensional image and real-time detection. Moreover, we also investigated the imaging abilities of the concave PCMLs array. As shown in Fig. 3(c) and (d), the inverted images and erect images can be obtained which represent the virtual focus imaging ability and real focus imaging ability. The experimental results indicate that the concave PCMLs array also have excellent imaging ability. But, from the images array, we can see that the uniformity of the PCMLs is still a problem by using the micro-inkjet technique. PDMS and glycerol are viscous liquid, it is still difficult to transmission under high pressure. Therefore, how to control the volume of glycerol and PDMS precisely is the key point in preparing PCMLs array.

For investigating the relationship between curing temperature and top surface profile, PCMLs were fabricated with the same curing time (30 min) and different curing temperature, as shown in Fig. 4. When the curing temperature were 80 °C and 90 °C, the convex PCMLs can be realized, as shown in Fig. 4(a) and (b). The obtained central erect images proved the top convex surface. However, with the temperature increasing, the top surface of PCML trends toward a plane surface as shown in Fig. 4(c) whose curing