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Research Note

Fabrication of high numerical aperture micro-lens array based on drop-on-demand generating of water-based molds

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ABSTRACT

This letter presented a simple fabrication method of micro-lens arrays with high numerical aperture based on a new drop-on-demand generating of water-based mold. The micro-droplet array which acted as the water-based mold was generated on the polypropylene substrate using a drop-on-demand generator, and then a replication process was followed for fabricating the micro-lens arrays with high numerical aperture. A spherical-like micro-lens array with the numerical aperture of 0.62 was fabricated. The surface of the formed micro-lens was demonstrated super smooth ($R_a \sim 0.5$ nm, $R_q \sim 0.7$ nm, $R_{max} \sim 13.2$ nm, $2 \times 2\ \mu m^2$ scanned area) by the atomic force microscope, which can reduce the optical noise. The qualities of imaging and light gathering characteristics of the MLAs were evaluated by the optical microscope.

1. Introduction

Micro-lenses (μ-lenses) and micro-lens arrays (MLAs) are acquiring a key role in several application fields, such as micro-optical sensors [1,2], digital display units [3], biomedical instruments [4,5] and optical communications [6]. For some applications [7,8], MLAs with a high numerical aperture (NA) which can generate low focal lengths and high-resolution images are required. Although various techniques have been proposed to pursue a high NA, mainly including self-assembly [9], thermal reflow and the boundary confined method [10], glass microspheres trapped on microholes with a thin polymer layer method [11], femtosecond laser enhanced local wet etching method [12], controllable dielectrophoretic force in template holes [13], inkjet printing the polymer on the hydrophobic surfaces [14] and so on, most of these methods involved complex processing steps or tools, leading to a poor cost-effectiveness or process reproducibility.

Recently, inkjet printing has been adapted for the fabrication of μ-lenses using various materials because of the potential applicability of flexibility and cost-effectiveness in the micro-optical system. Several research groups have directly printed the polymer droplet on the hydrophobic surfaces [15,16] and the polymeric mesas or micro-holes [17,18] to pursue the high NA MLAs with large contact angles and they did work effectively. However, it is difficult for the surface treatment to reduce the surface energy for a further increased contact angle of the polymer on a planar surface because most of the polymer used for inkjet printing has a low surface tension. Although the boundary confinement effect of the micro-mesas or micro-holes can raise the contact angles of the polymer droplet, the fabrication of the polymeric mesas or mciro-holes array involves the complex lithography process and printing process, leading to a poor process reproducibility. Furthermore, the traditional inkjet printing equipments have the disadvantages of high production and maintenance costs due to their complex structures.

In this letter, we demonstrated a simple and high throughput approach for fabricating high NA MLAs based on a new drop-on-demand (DOD) generating of water-based molds [19,20]. A glycerol solution micro-droplet array which acted as the water-based mold was generated on the polypropylene (PP) substrate by the DOD droplet generator. We used a PZT stack actuator as driving source to provide an enough microfluidic pulse inertia force to eject the glycerol solution [21]. Then polydimethylsiloxane (PDMS) was used to transfer the water-based mold to the MLAs with a solid state. The NORLAND1625 (NOA1625) optical adhesive was chosen as its material of the final formed high NA MLAs due to the good optical performance and higher refractive index after curing. The formed spherical-like μ-lenses with perfect curvature and high quality surface have greatly increased the NA of the MLAs and reduced the optical noise.

2. Experiment set-up

Fig. 1(a) shows the assembly of the DOD droplet generator which consists of four parts: (1) PZT stack actuator, (2) connector, (3) clamper, (4) glass micro-nozzle. The manufacture cost of the generator

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has significantly decreased as the simple structure of the generator, which have neither micro-moving parts nor embedded micro electric circuits. As is shown in Fig. 1(a), the PZT stack actuator is constructed of several disc-shaped piezoelectric ceramic pieces, whose thickness is in the range of 0.02–1 mm. It is an approximate linearity between applied voltage amplitude and the displacement of the actuator. So, when the actuator is applied with a higher pulse driving voltage, the actuator will cause a larger displacement instantaneously and consequently provides a greater pulse inertia force for the micro-nozzle and liquid inside. Fig. 1(b) shows the typical waveform of the driving signal. The droplet formation process in the droplet generator is shown in Fig. 1(c). When being applied with a pulse voltage, the PZT actuator connected to the solid wall of the glass micro-nozzle stretches and exerts a periodicity disturbing on the solid wall; in consequence, the boundary flow obtains a movement along with the solid wall. Then the viscous force V_1 within the fluid transfers the movement and the microfluidic body obtains a velocity. When the applied pulse voltage decreases rapidly to zero in magnitude, the PZT actuator contracts and the liquid inside the micro-nozzle obtains a pulse inertia force F_1 relative to the micro-nozzle. When the inertia force F_1 is larger enough in magnitude, the inertia force F_1 exceeds the viscous force V_2, a droplet of the liquid will be thrown out of the micro-nozzle drop by drop in the direction of the inertia force F_1 [22,23].

Fig. 2 illustrates the process of fabricating high NA MLAs based on the DOD droplet generating of the water-based mold. The PP substrate which was ultrasonic cleaned in deionic water for 15 min and dried in ambient air was prepared as the substrate of the micro-droplet array. The 70 vol% glycerol solution was selected to be the ink materials for generating the micro-droplet array because the evaporation of the droplet out of the micro-nozzle can be avoided effectively and the viscosity of the 70 vol% glycerol solution measured by the rotational viscometer NDJ-1, 4 # rotors, 12 rpm/min at 25 °C was 25 mPa s, which was suitable for the ejecting. As is known that PDMS is a kind of most widely used silicon-based organic polymer which has the features of optically clear, inert, non-toxic and typically non-flammable. Furthermore, PDMS is commonly used in the replication process due to its good plasticity. In our work, the PDMS (Dow Corning SYLGARD 184) was used to transfer the shape of the micro-droplet array to the MLA with a solid state due to the immiscibility of the liquid PDMS and the glycerol solution. Firstly, the 70 vol% glycerol solution was DOD printed on the PP substrate to form the micro-droplet array, as shown in Fig. 2(a). For the liquid PDMS preparing, the PDMS base and curing agent were mixed in a weight ration of 10:1, and well mixed by a stirrer at a speed of 800 rotations per minute for 10 min. After the PDMS solution was degassed by a vacuum drying oven, the degassed mixture was then poured onto the micro-droplet array slowly, as shown in Fig. 2(b). As

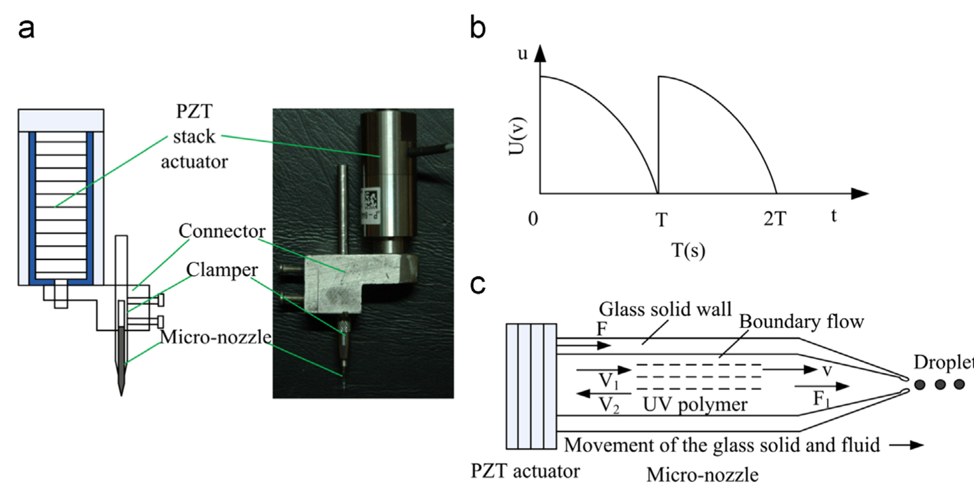

Fig. 1. (a) The drop-on-demand droplet generator. (b) Typical waveform of the pulse driving voltage signal applied to the PZT stack actuator for droplet generation. (c) Liquid driving principle of the droplet generator.

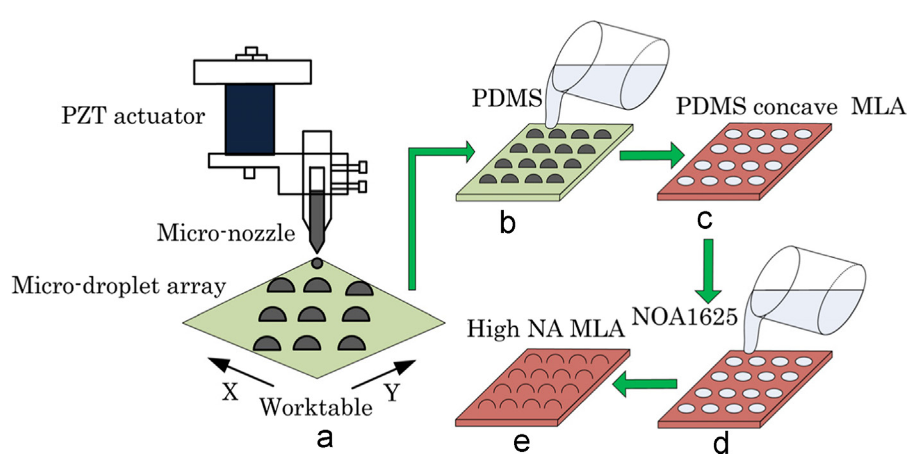

Fig. 2. Schematic illustration for fabricating high NA MLAs by using the DOD droplet generating of the water-based mold. (a) Fabricate the micro-droplet array on PP substrate using the DOD droplet generator. (b) Pour the liquid PDMS on the micro-droplet array and cured in drying oven of 60 °C for 12 h. (c) Strip off the cured PDMS concave MLA from the PP substrate. (d) Pour the liquid NOA1625 on the PDMS concave MLA and cured by UV irradiation for 50 min at room temperature. (e) Strip off the cured MLA from the PDMS concave MLA.