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Fabrication of multi-scale micro-lens arrays on hydrophobic surfaces using a drop-on-demand droplet generator

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ABSTRACT

A simple method was demonstrated for the fabrication of multi-scale polymer microlenses (μ-lenses) and microlens arrays (MLAs) using a drop-on-demand (DOD) droplet generator. A ultraviolet (UV) curable polymer used as the ink was DOD printed on the hydrophobic surfaces with different wetting conditions and cured by a UV lamp. The high quality μ-lenses and MLAs with good geometrical uniformity were fabricated. The shapes of the μ-lenses and MLAs were controlled by the different surface wetting conditions, and these shape changes affected the optical properties of the μ-lenses and MLAs, such as the numerical aperture (NA), focal distance (f) and the f-number ($f_{\#}$). The surface roughness of the μ-lens was measured by a white light interferometer (VSI mode) and atomic force microscope (AFM) and proved satisfactory. The influences of the surface wetting conditions on imaging and light gathering characteristics of the MLAs were evaluated by an optical microscope.

1. Introduction

Since the early 2000, industry has shown a considerable interest in the use of micro optical devices. Among them, micro-lenses (μ-lenses) and micro-lens arrays (MLAs) are acquiring a key role in several application fields, such as micro optical sensors, optical storage devices, digital display units, biomedical instruments and optical communications. Recent advances in micro-machining technologies have led to the development of μ-lenses and MLAs including photo-resist reflow [1–3], gray-scale photolithography [4], photo-polymerization [5], reactive ion etched μ-lenses [6], LIGA process [7], direct-laser [8] or e-beam writing [9], and so on. However, most of these techniques require multiple process steps that are quite complex and sophisticated, making the fabrication quite expensive. For example, a high processing temperature and an etch-transfer process are required in the photo-resist reflow method for the fabrication of μ-lenses, and it is difficult to match the desired shape precisely due to the gray-levels with sharp edges in the gray-scale photolithography method. Also, the LIGA method has high dependence on the mask and complex process steps. The direct-laser or e-beam writing is time-consuming and requires expensive facilities.

Recently, microjet techniques have been adapted for the fabrication of μ-lenses [10] using various materials because of the potential applicability of flexibility and cost-effectiveness to micro-optical system. Among them, polymer μ-lenses attracted considerable research because of their potential applicability to micro-optical system and the advantages of simplicity, low fabrication costs, flexibility, and maturity. The droplet generating of the microjet techniques can be divided two types: the continuous mode [11] and the drop-on-demand (DOD) mode [12,13]. Among them, the DOD mode, in which the droplets are generated individually at the desired times and positions allowing surface pattern generation, is more appropriate to be used in μ-lens manufacturing applications. To the best of our knowledge, the types of DOD droplet generator used for the fabrication of the μ-lens mainly include displacement piezoelectric droplet generator [14–16] and pneumatic droplet generator [17]. The displacement piezoelectric droplet generator can precisely control dispensing liquid and microjet droplets. However, the disadvantages are the high production and maintenance costs due to their complex structures. Besides, the micro-nozzle structure is complex and the cleaning of the micro-nozzle is not convenient. Although the pneumatic droplet generator is simple and convenient, the precisely control of dispensing liquid is difficult to achieve and the dimension of the generating droplet is mostly above 150 μm. Therefore, it is necessary to introduce a more convenient and efficient μ-lens fabrication method which is simple, less time-consuming and fabrication costing.

In our previous work, a simple and easy μ-lens fabrication method had been demonstrated using UV curable polymer based on a simple DOD droplet generator [18]. The UV curable polymer was dispersed into uniform fine droplets based on microfluidic pulse inertia force [19] and ejected onto the substrates out of a

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glass micro-nozzle. Although the dimension of the μ-lens primarily depended on the inner diameter of the micro-nozzle and parameters of the droplet generator, the final shape of μ-lens was determined by the free energy balance between the droplet formulation, the substrate, and the surrounding atmosphere. The μ-lenses with different shapes are required for some applications. For example, long focal length MLAs with small numerical aperture (NA) are required in Shack–Hartmann wavefront sensors for detecting small tilting of light wavefront because long focal length MLAs can lead to larger lateral displacement on an image sensor than short focal length MLAs [20,21]. Also, the MLAs with high NA are required in some optoelectronic devices for ensuring high resolution and high signal-to-noise-ratio optical imaging and detection [22,23].

Therefore, in this work, the fabrication of multi-scale μ-lenses was described using a UV curable polymer directly printed on the different hydrophobic surfaces with different surface wetting conditions based on the DOD droplet generator. We used a PZT stack actuator as driving source to provide an enough microfluidic pulse inertia force to eject UV curable polymer. The multi-scale μ-lenses with controllable shape that resulted from different surface wetting conditions of substrates were fabricated and characterized.

2. Materials and methods

2.1. Ink materials

UV curable polymer is a preferred class of material for the fabrication of μ-lens, because of their good characters such as thermal and chemical durability, excellent optical performance, high adhesion, photo curing rapidly, low volume shrinkage, and so on. The UV curable polymer used in our experiment is acrylic-based modified resin component liquid, which includes efficient membrane material and additives such as corrosion inhibitors, binding agents, waterproofing agents, anti-aging agent and so on, purchased from Dongguan East Pivot Electronics Co., Ltd. (Guangdong, China), which has a viscosity of 50 mPa s and a refractive index of 1.5 at a wavelength 620 nm. Furthermore, it is much cheaper than the SU-8, AZ-4500 series photoresist, and ORMOCER® polymer group. The baking before cuing the UV curable polymer is not required due to no inorganic solvent in the polymer and the volume shrinkage during the curing process is low.

2.2. Substrates with surface treatment

Glass substrates with surface treatment were prepared for the fabrication of multi-scale μ-lenses. In order to obtain μ-lenses with different contract angles, substrates with different surface wetting conditions were prepared in this work. Firstly, the substrate was cleaned by the concentrated sulfuric acid and acetone. Then the substrates with surface treatment were prepared by sol–gel processing. The amino acrylic resin was taken as the forming film resin, xylene as the solvent. They were stirred and mixed with the SiO_2 nanoparticles (NPs) at a high speed shearing mode, in which the proportion of SiO_2 NPs (mass fraction) ranged from 0 to 10%. After letting it settle for 5–10 min, the SiO_2 NPs hydrophobic sol suspension was sprayed on the glass substrate uniformly, then a low-energy 1,1,2,2-Tetrahydroperfluorodecyltrimethoxysilane (FDTS) concentration was diluted into 0.5–2% by the hydrofluoro ether solvent was sprayed uniformly on the glass substrate which was treated by the SiO_2 NPs hydrophobic sol. The final hydrophobic substrate was acquired after the treated substrate was put in the hot oven (approximately 150 °C) for 20 min [24]. The SiO_2 NPs, concentrated sulfuric acid, acetone, amino acrylic resin, xylene, FDTS, and hydrofluoro ether solvent were purchased from SICONG Co., Ltd. (Fujian, China).

2.3. The DOD droplet generator

2.3.1. Structure of the DOD droplet generator

Fig. 1 shows the assembly of the droplet generator based on microfluidic pulse inertia force. The structure of the generator consists of four parts: (1) PZT stack actuator, (2) connector, (3) clamper, (4) glass micro-nozzle. The micro-nozzle is clamped by the micro-nozzle clamper, which is fixed with the PZT stack actuator by the connector. The manufacture cost of the generator has significantly decreased as the simple structure of the generator, which have neither micro moving parts nor embedded

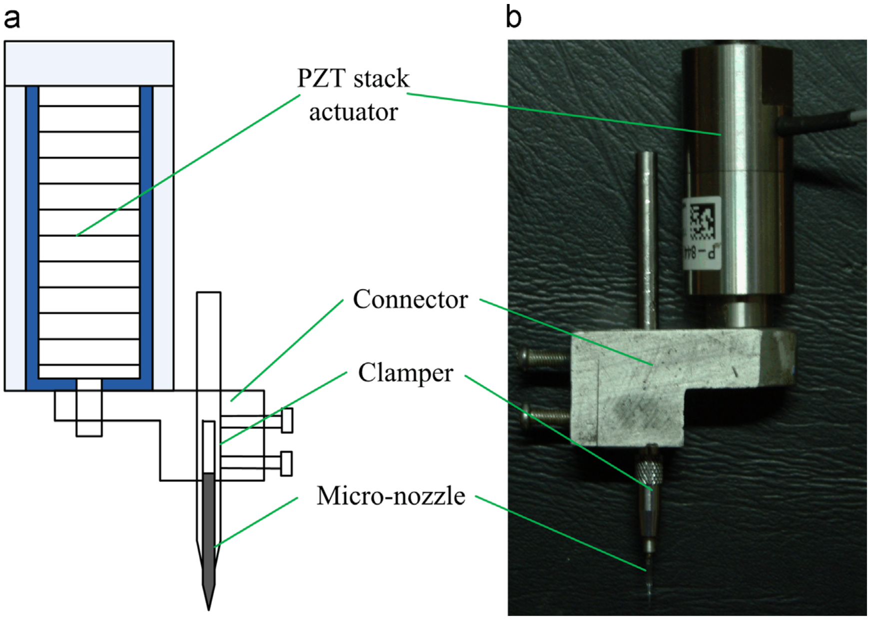

Fig. 1. The droplet generator; (a) sketch of the droplet generator; (b) photo of the droplet generator.