Fabrication of high quality and low cost microlenses on a glass substrate by direct printing technique

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The fabrication of high quality and low cost microlenses on a glass substrate using a simple, rapid, and precise direct microplotting technique is shown in this paper. The fabrication method is based on the use of a microplotter system, which is significantly different from the existing inkjet, roll-to-roll printing, and reactive ion etching technology and could work with higher viscosity materials. By optimizing the parameters of voltage, dispense time, and concentration of the polymer solution, high quality microlenses with a diameter of 20 μm could be obtained. The geometrical and optical characteristics of the microlenses are analyzed by measurement of the surface profile and the imaging properties in the near-field and far-field zones as well as the diffraction pattern. We think that the fabricated microlenses could be attractive for enhancing the light extraction efficiency of light emitting diodes.

OCIS codes: (350.3950) Micro-optics; (220.3630) Lenses; (220.4000) Microstructure fabrication.

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1. Introduction

Microlenses are small lens with a diameter of less than 1 mm and often as small as 10 μm, which are commonly composed of small lenses with one plane surface and one spherical or aspherical surface on a supporting substrate [1]. As an important micro-optical element, microlenses play an important role and exhibit various wide applications in optical fields, such as integral optics systems [2], optical data storage [3], optical communication [4], and wavefront sensing [5]. In particular, microlens arrays on top of light-emitting diodes (LEDs) could contribute to enhancing the light extraction efficiency [6,7], as the microlens arrays could increase the effective photon escape cone of the LEDs. Recently, significant progress has been achieved in fabricating the microlenses using several approaches such as hot embossing [8], laser beam written microlenses [9], deep lithography with protons [10], microcompression moulding [11], and a soft-lithography technique [12]. In addition, inkjet technology [13], roll-to-roll printing [14], and reactive ion etching [15] have also been used to manufacture micrometer-sized lenses. Nearly all of these approaches effectively have made important contributions to fabricating high quality microlenses. However, in comparison with the above techniques, the microplotter system is significantly different from existing inkjet technology and other technology and could work with higher viscosity materials [16]. Rather than ejecting droplets over a distance to a surface, the microplotter acts like a pen plotter, directly dispensing droplets or true continuous features. This dispensing is driven by the patented ultrasonic pumping action at the core of the microplotter. Moreover, some of the above approaches require complex fabrication processes of dry etching, wet etching, or optical lithography technology, which show some potential issues of high cost and nonuniformity. Thus, it is essential to develop a low cost and straightforward technology for high quality microlens fabrication in order to meet the requirements of large scale production.

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In this paper, we report a novel technology of fabricating high quality microlenses on the surface of a glass substrate by using the microplotter system [17]. The total microlens fabrication using the microplotter system could be finished within 1 min, which demonstrates a significant enhancement on fabrication efficiency. The microplotter could deposit controllable and high quality microlens arrays on glass substrate directly without using complex etching and costly optical lithography processes, which would be considered as a potential technology for realizing low cost and large scale production. Moreover, using the microplotter could also avoid any degradation on the performance of microlenses.

2. Design and Fabrication Process

The fabrication technique of the high quality microlenses is based on a microplotter system. The core part of this system is a dispenser, which is constructed by a piezoelectric element and hollow tapered glass needle. The main features of this microplotter system have a high resolution of 5 μm for the deposition patterns, and the glass needle can input more than 0.6 pl volume of the solution at one time. The main working principle of this microplotter system is described as follows: first, when an appropriate AC current is applied to the piezoelectric element, it causes vibration along its axis and generates the ultrasonic field. Second, the ultrasonic field results in the pumping action within the needle under certain driving frequencies (400–700 kHz), and then the fluid is sprayed out of the end of the needle. Third, the microlenses could be formed on the surface of the glass substrate. The position of the dispenser could be controlled by a high precision positioning software system on a personal computer. This position system with three positioning stages can make the glass needle have accurate movements and deposition patterns. The operator can monitor the total deposition process in real time using an attached charge-coupled-device (CCD) camera. For a given glass needle, the size of the microlenses is mainly related to the amplitude of the AC voltage applied to the piezoelectric element and the concentration of the deposited solution.

The fabrication process of the microlenses on the glass substrate by using the microplotter system is shown schematically in Fig. 1. Before depositing the patterns on the glass substrate, three steps were taken to clean the glass substrate. We placed the glass substrate in the warm acetone bath for 10 min of washing. Subsequent to the washing process, we removed and placed the glass substrate in the alcohol for 5 min. Then, we transferred the glass substrate to a container with deionized (DI) water for a rinse, and we dried the glass substrate using a nitrogen gun. We optimized the parameters of the voltage, the dispense time (the contact duration of the glass needle and substrate), and the concentration of the solution. The optimized voltage and the dispense time are 4 V and 0.6 s, respectively. The solution used for pattern deposition is composed of a hardener (Araldite M accelerator 960) and epoxy resin (Araldite 506) with a ratio of 1∶10 (hardener∶epoxy = 1∶10). The total experimental process for the microlens deposition on the glass substrate consisted of four steps. The first step was moving the dispenser to a fluid well with the mixed solution of hardener and epoxy and loading the dispenser with solution by dipping the sharp end of the glass needle into the fluid well. The solution can rise up into the glass needle through capillary action. The second step was positioning the glass needle over the starting coordinate of the glass substrate, adjusting the desired position, and lowering the glass needle close to the surface of the glass substrate. About this step, the accurate z positioning of the glass needle is necessary in order to generate the high quality of the microlenses. If the glass needle is positioned too high (>2 μm) above the surface of the glass substrate, the fluid contact may not be formed, and the microlenses could not be deposited. This step could actually be controlled and accomplished by the positioning software system. The third step was the microlens deposition process by sending the AC voltage to the dispenser. The final step was the baking process. After the microlens deposition, the samples were put inside the oven for baking at 70°C for 1 h. To avoid the effect of thermal expansion and enable a gradual solidified process, the temperature was gradually increased at the rate of 5°C/ min. (Note: the 1 h baking includes the time of temperature increasing. The temperature was increased from room temperature (23°C to 70°C). This treatment helps to solidify the microlenses and maintain their shapes; otherwise these microlenses would be destroyed under high temperature. We found that these microlenses could maintain their shapes well even after the baking treatment.

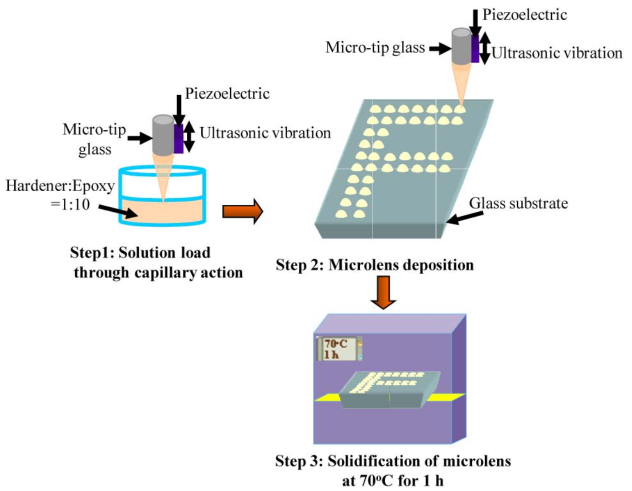

Fig. 1. Schematics of the microlens fabrication process. Step 1: the microtip glass dips into the solution, and solution should start rising up the inside of the tip glass through capillary action. Step 2: the microtip glass detects the surface of the substrate and starts to print the microlens. Step 3: the samples are put inside the oven for baking at 70°C for 1 h.

3. Results and Discussion

The single microlens or microlens arrays could be manufactured by using the microplotter. In order to verify the reproducibility of the microlens production, a lens array with “F” patterns was successively manufactured, as shown in Fig. 2. In fact, the arbitrary patterns of the lens array could be manufactured by setting the parameter of the Microplotter. Figure 2 shows different magnification pictures of the microlens array formed on the glass substrate. The fabricated microlens arrays were transparent as a result of the characterization of the epoxy materials and smooth surface, which could be capable of producing a high quality image at their center. The microlens sizes were measured by optical microscopy. The diameters were found to 20 μm. As can be seen from Fig. 2, all the microlenses present a well-defined hemispherical shape and are practically the same, which indicates high reproducibility.

To demonstrate the focusing performance of the fabricated microlenses, the optical image measurements at the focal plane of the microlenses and at other planes are necessary. The focused light spot of the far-field image at the focal plane and near-field image at other planes were measured by a micro-optical measurement system, which is composed of a microscope, a visible laser light source, and a CCD system. For the focused light spot measurement, by increasing the distance between the microscope objective and microlens array, the far-field intensity distribution in the focal plane of the microlens array can be detected on the CCD. As can be clearly seen from Fig. 3(a), the sharp focal spot images are clearly observed. The pitch of the focused light spot is uniform, and the spots have uniform and symmetrical intensity distribution, which indicates that beam profiles should exhibit a Gaussian distribution. The measurement results show the focused spots have the size of 4.00 μm. The near-field image also presents a clear and symmetrical distribution, as shown in Fig. 3(b). To study the shape of the microlens arrays which were fabricated, we use the surface profiler to measure the geometrical properties of microlenses arrays. The radial scan of the profile is shown in Fig. 4. It shows that the lens-to-lens variation is almost unchanged. The diameter and height of the microlenses are about 20 and 8.8 μm, respectively. The microlenses were also characterized by surface roughness measurement. Surface roughness is an important parameter for microlens arrays because a smooth surface can minimize the reflection or refraction of light that is passed through the microlenses. The actual scanned area for each microlens measurement on the curved surface was 3 μm × 3 μm.The average surface roughness of the microlenses was about 2.35 nm. The surface roughness appearance is because of the different densities of mixed epoxy and hardener. Maybe the stirring time for the process of the mixed solution is not enough.

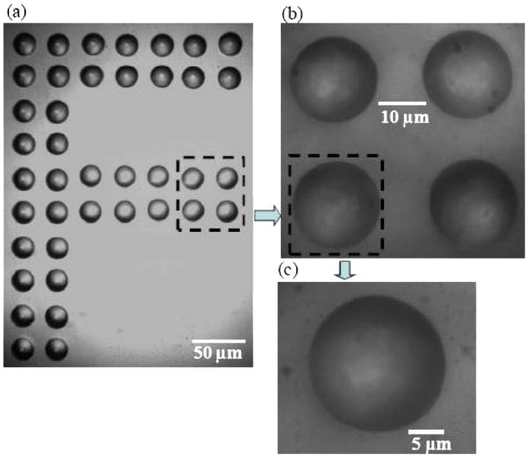

Fig. 2. Microscopic images of the fabricated microlens array under different magnifications.

The diffraction picture of the microlenses is shown in Fig. 5. For this diffraction picture collection, the microlens was inserted between a glass plate coated with UV ink and a UV laser source with an operation wavelength of 325 nm. By adjusting the distance between microlenses and the glass plate, the diffraction picture could be generated on the glass plate after UV laser illumination on the back side of the microlenses for 2 s. Then the glass plate was dipped into

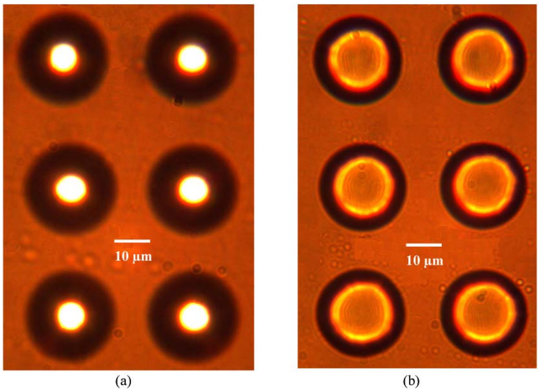

Fig. 3. Optical microscope image of the backside illuminated microlens array with a visible laser light source. (a) Light spot of far-field image at the focal plane and (b) near-field image at other planes.

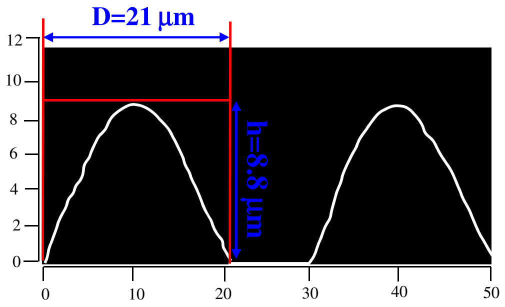

Fig. 4. Surface profiles of the microlenses.

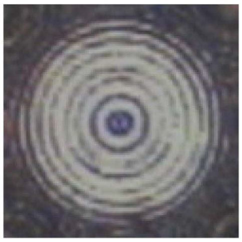

Fig. 5. Diffraction pattern of one particular microlens.

the acetone solution for 5 s. Bright and dark circular rings can be observed. Circular rings are attributed to the diffraction of the UV laser beam on the lens itself.

4. Conclusion

In this paper, we fabricated high quality polymer microlenses by using the microplotter printing technology, which shows the advantages of a simple, rapid, and low-cost fabrication method. The fabricated microlenses show good optical characteristics with surface smoothness. The sharp focal spot images are also clearly observed. The fabricated microlenses could be used for realizing a high power LED.

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