A high numerical aperture, polymer-based, planar microlens array

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Abstract: We present a novel microfabrication approach for obtaining arrays of planar, polymer-based microlenses of high numerical aperture. The proposed microlenses arrays consist of deformable, elastomeric membranes that are supported by polymer-filled microchambers. Each membrane/microchamber assembly is converted into a solid microlens when the supporting UV-curable polymer is pressurized and cured. By modifying the microlens diameter (40–60 µm) and curing pressure (7.5–30 psi), we demonstrated that it is possible to fabricate microlenses with a wide range of effective focal lengths (100–400 µm) and numerical apertures (0.05–0.3). We obtained a maximum numerical aperture of 0.3 and transverse resolution of 2.8 µm for 60 µm diameter microlenses cured at 30 psi. These values were found to be in agreement with values obtained from opto-mechanical simulations. We envision the use of these high numerical microlenses arrays in optical applications where light collection efficiency is important.

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1. Introduction

Microlenses are used in optical communication [1,2], displays [3,4], optical sensors [5,6], photolithographic systems [7,8] as well as in biomedical imaging applications [9–11]. Recent advances in micromachining technology led to the development of a variety of microlens microfabrication approaches including photoresist-reflow and transfer methods [12,13], ink jet processes of UV curable polymers [14], hot embossing techniques [15], micromolding using silicon substrates [16,17], soft lithography-based replication processes by molding various materials against rigid or elastomeric molds [18–20]. Photoresist-reflow methods rely on the surface tension of the photoresist to form a smooth microlens surface. These methods require accurate control of the microfabrication parameters (photoresist thickness, hydrophobicity) and produce microlenses with small numerical aperture (NA) due to the small aspect ratio (thickness vs diameter) of the patterned photoresist. Ink-jet methods are serial processes that require an elaborate experimental setup for accurately dispensing small drops of the optical material onto a rigid substrate. The properties of ink-jet processed microlenses depend on the rheological properties of the dispensing material (viscosity,
surface tension), making the fabrication of microlenses with small diameters (<100 µm) and large aspect ratio (to achieve high NA), a challenging task. Hot embossing techniques produce microlenses with rough surfaces and suffer from post-embossing shrinkage. Fabrication of silicon molds requires isotropic wet etching of silicon and deposition of silicon oxide/nitride as the etchant mask. These fabrication steps are extremely time consuming and expensive. Soft lithography-based replication processes provide low-cost microlens arrays whose properties depend on the quality of the master mold. These processes take advantage of the excellent optical [21] and mechanical [22,23] properties of the polydimethylsiloxane (PDMS) elastomer. PDMS has low elastic modulus, minimum light absorption in the visible spectrum and extremely low autofluorescence, it is therefore an ideal optical material for microlens molding and replication processes [24,25].

In this work, we describe a novel array of high numerical aperture (NA~0.3), polymer-based, solid microlenses. Key element is the microfabrication of an ‘inflatable’, polymer-filled PDMS mold that consists of an array of circular microchambers enclosed by flexible membranes. When the mold is inflated, the microchamber/membrane array is converted into a microlens array. Using a UV-curable polymer as a filling medium, the microlens arrays can be subsequently solidified when the desired focal length is obtained. The proposed approach has three major advantages: a) the microlens focal length can be adjusted by regulating the pressure applied to the filling polymer during curing, b) the use of PDMS as the mold material enables large membrane deflections that result in microlenses with high NA, and c) the optical properties (e.g. index of refraction) of the microlenses can be varied as there is a large collection of commercially available curable materials. The novel microfabrication process is particularly useful for obtaining small diameter (<100 µm) microlens arrays with high light collection efficiency (high NA). We envision such microlens arrays to play a key role in various lab-on-chip detection systems for imaging micron-size objects (cells, viruses, etc.) [26,27].

2. Design and microfabrication of the microlens array

The inflatable PDMS mold has a two-layer architecture (Fig. 1): (i) the first layer (the ‘microlens’ layer) contains the circular microchamber/membrane array, and (ii) the second layer (the ‘support’ layer) contains an array of thick (~200 µm thick) square microwells aligned on top of the microchamber/membrane array. The main purpose of the second layer is to facilitate the handling of the thin first layer during the microfabrication process (see next paragraph for details). A microfluidic network patterned on the first layer is used to deliver the UV-curable polymer into the microchambers. The increase in pressure within the microfluidic network induces a uniform deflection of the PDMS membranes across the array. That results in the formation of an array of plano-convex microlenses with a pressure-dependent focal length and NA. When the pressure is stabilized within the network (typically in few seconds), the polymer is ready to be UV-cured to obtain the solid microlens array.

The microfabrication process of the microlens array involves (Fig. 2): i) the fabrication of two SU-8 master molds (for each of the two PDMS layers) using standard photolithographic processes, ii) the fabrication of the inflatable PDMS mold from the two SU-8 master molds using soft-lithography, and iii) the injection and curing of the UV-curable polymer into the inflatable PDMS mold.

The fabrication of the first SU-8 master mold (corresponding to the microlens PDMS layer) is performed in a two-step photolithographic process [25]. A 13 µm thick film of SU-8 photoresist is patterned on a silicon wafer to define the microfluidic network, followed by the patterning of a second, 40 µm thick, SU-8 film to form the circular microchambers. A 20:1 PDMS mixture is then spun at 1750 rpm and cured on the two-step SU-8 mold to obtain a ~52 µm thick PDMS layer. Such a PDMS composition results in a layer of low elastic modulus (<1MPa [28]), which is necessary to achieve large membrane deflections, and therefore high
Fig. 1. (A) A picture of a 9x11 PDMS-based, planar microlens array. The right inlet is used to fill up the microfluidic network with the UV curable polymer (the left inlet is not used in the depicted design). Scale bar, 1.5 mm. (B) A close-up view of 16 cured microlenses of different diameters. Each microlens sits beneath a square microwell. Scale bar, 200 µm. A magnified top view of a 60 µm in diameter microlens cured at 30 psi and a schematic diagram of its cross section are shown on the right (I and II respectively). Scale bar, 50 µm.

NA microlenses. By accurately measuring the thickness of SU-8 circular microchambers and the PDMS microlens layer, we estimated the PDMS membrane thickness to be 12.1 ± 1.4 µm (16 measurements were taken from different runs using a profilometer).

The second SU-8 mold (corresponding to the support PDMS layer) is fabricated by patterning a 50 µm thick SU-8 film. The design incorporates an array of 200 µm x 200 µm square microwells, each one sitting on top of a single microlens. A thick (~1 mm) PDMS layer (the support layer) is subsequently cured, peeled off and air-plasma bonded (90 W, 35 sec) to the PDMS microlens layer. Finally, the two-layer PDMS assembly is detached from the first SU-8 mold and bonded to a 175 µm thick glass slide to create the sealed inflatable PDMS mold. The use of the support PDMS layer is critical for peeling off the thin microlens layer as it provides structural integrity and eliminates the microlens membranes from tearing apart. The inflatable PDMS mold is then filled with a UV curable polymer, pressurized and cured.
3. Results

To obtain the optical properties of the proposed high NA, solid microlenses, we characterized an array of 40 µm and 60 µm diameter microlenses following the microfabrication process described above. A high index of refraction UV-curable polymer (Norland 60, index of refraction n = 1.56) was injected into the inflatable PDMS mold and cured (10 min, at 365 nm (Entela UV lamp)) under constant pressure to ensure uniform deflection across the membrane array. The effective focal length (EFL) of the cured microlens device was measured for a range of curing pressures (7.5-30 psi) using a custom-made optical setup (see Fig. 8). The EFL corresponds to the distance between the top surface of a microlens and the best-focused image formed when passing a laser beam (532 nm) through the microlens. We followed a 2-step sequence to determine the EFL: i) the top surface of a microlens was visually identified and set as the reference plane (plane I), and ii) the plane containing the image of the focused laser beam was brought into the imaging plane of the microscope objective (plane II) by vertically moving the microlens. The distance between these two planes corresponded to the EFL of the microlens. Plane II was identified by extracting the plane of the maximum light intensity through image analysis software (Metamorph®).

The EFL of both the 40 µm and 60 µm diameter microlenses exhibited a strong dependence on the curing pressure (Fig. 3). EFL changes up to ~200% were measured over the entire pressure range. For low pressures (< 7.5 psi), the circular membranes undergo small
These microlenses weakly focus the laser beam resulting in a large depth of focus (several mm’s) that makes it difficult to assign a single value to the focal length. High pressures (>30 psi) resulted in breakage of the microlens membranes. Experimental EFL data were also compared with opto-mechanical simulation values. The pressure-dependent microlens profiles were simulated using commercially available finite element analysis software (ANSYS). The deflected membrane profiles were imported into an optical design software (OSLO LT) to determine the corresponding EFLs. Simulations were performed for a membrane thickness of 10.7 µm and 13.5 µm to capture the upper and lower limit of the corresponding measured values. The elastic modulus and Poisson ratio of the PDMS membrane was set to 3 MPa [23] and 0.49 respectively. A refractive index of 1.41, 1.56 and 1.51 was used for the PDMS, the UV-curable polymer and the glass slide respectively. The experimental EFL values for both the 40 µm and 60 µm diameter microlenses were within the simulated upper and lower EFL bounds.

The numerical aperture (NA) of the microlenses (for use in air) was estimated from [29] where \( a \) and \( F \) represent the microlens radius and EFL respectively.

\[
NA = \sin \left[ \tan^{-1} \left( \frac{a}{F} \right) \right]
\]  

(1)

Based on the EFL values reported above, a maximum NA of \( \sim 0.17 \) and \( \sim 0.3 \) was obtained for 40 µm and 60 µm diameter microlenses cured at 30 psi respectively (Fig. 4). The light loss through a single microlens was obtained by measuring the decrease in the light intensity of white light passing through the microlens device. For microlenses cured at 30 psi, the light loss was found to be 0.86 dB (18%).
Fig. 4. Numerical Aperture (NA) versus curing pressure for (A) 40 µm and (B) 60 µm diameter microlenses. NA values are calculated using the EFL values presented in Fig. 3. 60 µm diameter microlenses (with lower EFL) have higher NA than 40 µm diameter microlenses (with higher EFL).

To characterize the surface profile of a single microlens from the array (Fig. 5(a) we used a white-light interferometer (Veeco NT9100). We obtain direct optical access to the array by immersing the microlens device in acetone for 10 minutes and manually detaching the support layer. A 25 nm thick, gold layer was subsequently evaporated on the microlens surface to acquire a clean interferometric image.
The PDMS membrane profile of a 60 µm diameter solid microlens showed a maximum deflection of ~6 µm when cured at 30 psi, corresponding to a microlens with an aspect ratio of 10:1 (Fig. 5(b)). The microlens profile (Fig. 5) allows us to determine the minimum microlens pitch (microlens center-to-center distance). For 60 µm microlenses cured at 30 psi, the membrane deformation extends up to ~40 µm from the center of the microlens, and therefore they can be placed as close as 80 µm apart. Microlenses of smaller diameter or cured at lower pressures will have smaller pitch. The depth of focus and the transverse resolution of such a microlens (60 µm diameter solid microlens, cured at 30 psi) were calculated by measuring its axial intensity profile and point spread function (PSF) respectively (Fig. 6). To obtain the axial intensity profile, we extracted the maximum intensity from imaging planes above and below the best focused plane in an optical setup similar to the one used for obtaining the EFL. The theoretical value of the depth of focus (DOF) was estimated to be ~6 µm [30]. Within that distance, the maximum intensity dropped by 5%. To obtain the PSF of the microlens, we measured the background-corrected in-plane intensity distribution (I(x,y) - I₀) at the best-focused plane and normalized that value by the background intensity (I₀). The transverse resolution of the microlens, defined as the full width at half maximum (FWHM) of the PSF [31], was found to be 2.8 µm.
Fig. 6. (A) Relative intensity (maximum intensity for a given axial plane normalized with the maximum intensity measured at the best focused plane) along the optical axis of a 60 µm diameter microlens as a function of the distance from the best-focused plane. The pictures depict the focused laser beam as imaged at the focal plane and at two out-of-focus planes. Scale bar, 10 µm. (B) The PSF of the same microlens represented as the in-plane intensity distribution (I(x,y) - I₀) at the best-focused plane, normalized with respect to the background intensity I₀.

Finally, we demonstrated that it is possible to use the fabricated microlenses to magnify and image micron-size resolution features patterned on a chrome mask (Fig. 7). 3 µm wide line features were clearly visible after placing the microlens device between the chrome mask and a 1x microscope objective (we used Olympus SZX16 stereo microscope). Minimum distortion was observed at the center region of the microlens.
4. Conclusions

We demonstrate a novel microfabrication process for obtaining polymer-based, planar microlens arrays with high numerical aperture. The microlens array comprises of polymer-filled circular microchambers enclosed by deformable, elastomeric membranes. Each microchamber is transformed into a solid microlens when the UV-curable polymer is pressurized and cured. By varying the curing pressure (7.5-30 psi), microlenses with a wide range of EFL (100-400 µm) and NA (0.05-0.3) have been fabricated from 40 µm and 60 µm diameter membranes. We have obtained a NA of 0.3 and transverse resolution of 2.8 µm for 60 µm diameter microlenses (cured at 30 psi). Smaller diameter (40 µm) microlenses have lower NA than larger diameter (60 µm) microlenses for similar curing conditions. We envision the use of these high NA planar microlenses in lab-on-chip detection systems for imaging micron-sized biological specimens. Moreover, the proposed microlens design is compatible with a wide variety of curable polymers and therefore it can be used to obtain microlenses with different optical properties.

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Appendix

Fig. 8. Schematic of the experimental setup for characterizing the optical properties (effective focal length (EFL), point spread function (PSF)) of the microlens device. A laser (532 nm) was used to obtain the EFL while a white light source was used to obtain the PSF.