Arrays of microlenses with variable focal lengths fabricated by restructuring polymer surfaces with an ink-jet device

Ramon Pericet-Camara¹, Andreas Best¹, Sebastian K. Nett¹,², Jochen S. Gutmann¹,²*, Elmar Bonaccurso¹*

¹Max-Planck-Institute for Polymer Research, Ackermannweg 10, 55128 Mainz, Germany
²Institute of Physical Chemistry, University of Mainz, Welderweg 11, 55099 Mainz, Germany
*Corresponding authors: bonaccur@mpip-mainz.mpg.de, gutmann@mpip-mainz.mpg.de

Abstract: We report of a method for fabricating two-dimensional, regular arrays of polymer microlenses with focal lengths variable between 0.2 and 4.5 mm. We first make concave microlenses by ink-jetting solvent on a polymer substrate with a commercial drop-on-demand device. Solvent evaporation restructures the surface by a series of combined effects, which are discussed. In the second step we obtain convex elastomeric microlenses by casting the template made in the first step. We demonstrate the good optical quality of the microlenses by characterising their surfaces with atomic force microscopy and white light interferometry, and by directly measuring their focal lengths with ad-hoc confocal laser scanning microscopy.

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OCIS codes: (220.0220) Optical design and fabrication; (220.4000) Microstructure fabrication; (230.0230) Optical devices; (230.3990) Microstructure devices.

References and links

1. Introduction

Arrays of microlenses are found in the vision organs of many animal species such as certain insects or crustaceans [1]. As well, they are present in many common devices in photonics and optoelectronics [2]. Microlenses are found in commercial CCDs, LCD projectors, flat panel displays, or as beam collimators for optical fibers. There is a wide list of methods to fabricate arrays of microlenses [3]. Molding and casting optical materials are very common [4-6]: In these techniques, the fabrication of a template has to be accomplished previous to the manufacturing of the microlenses. For template production, various techniques such as photolithography [7], ion exchange [8] or LIGA processes [9] are used. Arrays of microparticles have been used recently as template to fabricate microlenses [4, 10], as well as irradiation of sol-gels with UV light [11]. Fabricating microlenses by these techniques is in general time-consuming, since multiple steps are required. As well, the means are not always easily accessible, being expensive or complex.

Microjet devices have also been used for producing microlenses, by depositing polymer solutions [12], as well as UV-curable optical adhesives, forming structures from plano-convex to convex-convex configuration [13, 14]. Yang et al. were able to tune the position and the radius of curvature of similarly deposited lenses by means of electrowetting [15, 16]. The viability of ink-jet etching on soluble polymeric surfaces has been already established by other authors to be applied in the manufacturing of microelectronic devices [17, 18]. Ink-jet restructuring of polymer surfaces for the fabrication of microlens arrays is based on off-shelf materials and low-cost experimental apparatus, is highly flexible, and suitable for mass production.

Herein, solvent droplets are deposited onto a polymeric surface by a drop-on-demand ink-jet apparatus. After the complete evaporation of the solvent, a spherical cavity is left behind [19]. Several physical effects concur to form this cavity. When the droplet is deposited on the surface, the bottom of the drop pushes the underlying surface due to the Laplace pressure. As well, the droplet is pinned at the three-phase-line due to the surface tension. At the same time, the liquid diffuses into the substrate to a certain depth, swelling it, and dissolving part of the polymer. Since the evaporation rate is higher at the rim of an evaporating droplet with pinned three phase contact line (TPCL) [20], the solvent flows from the centre to the edge, carrying dissolved polymer, and depositing it there. This phenomenon is known as the coffee-stain effect [21, 22]. The final crater presents at its edge a rim of previously transported and deposited polymer, and bears a spherical shape that may be characterized by its diameter, depth, and radius of curvature [see Fig. 1(a)]. Recently, it has been shown that aspherically shaped craters may be produced by
using mixtures of solvents [23] instead of pure solvents. In this work we focus only on spherically shaped cavities, and we verified this by fitting each cavity profile with a circle, like in Fig. 1(a).

![Fig.1. (a). Profile of a single crater in the direction of the red line at the lower picture. From this profile, the structural parameters of a microvessel such as diameter w, depth d and radius of curvature R are obtained. The dashed black line corresponds to the fit of the lens profile to a circle with radius R. (b) Average depth d and diameter w of the craters of five arrays as a function of deposited drops of toluene on the polystyrene surface. Error bars are the standard deviation of the data.]

2. Experimental part and results

In this work, toluene droplets are deposited onto extruded poly(styrene) plates of 220 kDa molecular weight, purchased from Goodfellow Ltd. A Nano-Plotter® NP 2.0 (GeSiM GmbH, Germany) is used in order to dispense the solvent droplets onto the polymeric surface in non-contact regime. This apparatus allows to define various parameters of the dispensing procedure, established by the user through the implemented software. It consists of a mobile pipette dispenser and a working plate. The dispenser is a piezoelectric driven microdosage head whose positioning is fully controlled along the plane parallel to the underlying surface. The droplets are deposited forming square arrays on the polymer plane. A section of them is imaged in Fig. 2(a) using a µSurf® white-light confocal profilometer (Nanofocus AG, Germany). With this device, physical parameters of the microlenses such as diameter, depth or height, and radius of curvature are measured from the surface profile. In the upper picture of Fig. 2(a), the polystyrene surface is imaged after droplet deposition. The lenses in the same row (X-direction) are produced with the same number of droplets. However, the number of deposited droplets increases along the y-direction. The pitch size between the craters is kept at 250 µm.

A good control of the physical parameters of the resulting craters in the fabrication process is wanted in order to obtain microlenses with variable focal lengths. In this paper we show that we can produce lenses of different focal lengths by varying the depth of the vessels and keeping their diameter constant. The depth of the craters is varied by introducing a delay between depositing droplets of equal volume. When a droplet is deposited at the same place of a previous one of the same size, the diameter of the crater does not change significantly. Indeed, the following droplets are actually deposited at the bottom of the previously formed vessel, which acts as a focusing tool. Thus, the dissolved polymer is removed from the bottom rather than from the side, keeping the diameter nearly constant. For 50 measured vessels, the average value of the diameter was 49 µm with a standard deviation of only 6 µm. Instead, the depth of the crater increases after every deposited droplet. This behavior is clarified by viewing Fig. 1(b). It can be observed that a higher number of deposited drops does not vary significantly the diameter of the crater. However, the depth is increased notably in the studied range. A similar process, namely removing polymer from the center and piling-up at the rim
of a drop has been previously employed by Kawase et al. [17] to etch via holes of constant
diameter through thin polymeric films, but in that case the holes were of cylindrical and not
spherical shape. Similarly, Bonaccorso et al. [19] showed that spherical cavities with different
depths can be produced in bulk polymer.

The production of convex microlenses from the concave ones fabricated in the first step is
of special interest, since those are the most commonly used in optic and optoelectronic
devices. The arrays of concave microlenses are employed as a template to obtain convex
microlenses by casting an elastomeric silicone polymer, Sylgard 184 (Dow Corning, MI). This
polymer is spread onto the template at ambient temperature. Then, it is placed in the oven at
80 ºC during 30 min. After that, both elements, the template and the sample, are separated
mechanically. We obtain a substrate bearing arrays of microlenses with the same physical
parameters as the concave ones, but negative depth, that is, with the same absolute height [Fig.
2(b)].

![Fig. 2. (a). Arrays of microlenses imaged by a confocal profilometer. The upper picture shows concave microlenses obtained by ink-jet printing. The number of deposited drops is increased in the y-direction. Below, convex microlenses obtained by template casting from the concave ones. (b). The graphs present the profile of the arrays along the full and dashed green lines shown in the upper image.](image)

Surface topography images of individual microlenses were realized by using a Nanowizard® (JPK Instruments AG, Germany) atomic force microscope in intermittent-contact mode, in order to test the optical properties of the employed materials. Pictures of different sizes from the surface of four microlenses were obtained. The root mean square roughness and peak-to-peak values of the surfaces are below 7 nm and 380 nm respectively in any of the studied samples. The value of the surface roughness is comparable to the ones obtained employing other techniques[3]. This shows that the surface of the microlenses is of very good optical quality. The manipulation of the samples does not damage the structure of the surface. Indeed, no scratches were found in all the acquired images.

In order to characterize optically the convex microlenses, cross-sectional scans of the light
reflected and transmitted by the microlenses in the X-Z plane are obtained by means of laser
scanning confocal microscopy. We use a LSM 510 module and an Axiovert 200M inverted
microscope (Carl Zeiss AG, Germany). The technique is similar to the one used in Gu et al.
[24]. Our specific setup is shown in detail in Fig. 3. While the confocal scan of the reflected
light shows a cross section of the microlenses, the transmission image displays how light rays
propagate through and are focused by the microlenses. Merging both reflection and
transmission scans into one image may be useful in order to have a full characterization of the
arrays. Here, we only analyze the transmitted light with this technique, since the structural profiles are studied with an especially dedicated confocal profilometer.

The focal power of the fabricated convex microlenses is studied here in detail. First, fits of the concave microlens profile to a circle equation are realized [see Fig. 1(a)]. From these fits, the radius of curvature of the craters is obtained as a parameter, and implemented as $R$ in

$$\frac{1}{f} = \frac{n-1}{R}$$

which yields the focal length $f$ of a plano-convex thin lens. In Eq. (1), $n$ is the refractive index of the lens material. The value of $n$ implemented here is the one specified by the manufacturer of the silicone polymer, namely $n = 1.43$ for a wavelength of $\lambda = 633$ nm. The calculated values for a single array are displayed in Fig. 4(a) as a function of the number of deposited droplets. One can observe that the theoretical focal length of the ink-jet fabricated lenses decreases with increasing number of deposited droplets up to approximately seven drops, where the values of the focal length level off to a plateau around $f = 0.21$ mm. To check the accuracy of these values experimentally, a simultaneous reflection/transmission confocal microscopy scan picture at the X-Z plane is shown in Fig. 4(b). Here, two He-Ne laser beams illuminate the microlens array sample: the one with a wavelength of 543.5 nm is transmitted through the microlenses, bundled to the focal point, and collected with a photomultiplier. On the other hand, the 632.8 nm wavelength laser beam is reflected from the surface of the microlens arrays and collected as well with a second photomultiplier. Figure 4(b) shows the transmitted laser beams through an array of microlenses. The regions of the focused light around the beam waist show the highest intensity. The experimental focal point is obtained by fitting the intensity profile of the transmitted laser beam to a Gaussian curve [see Fig. 4(c)], and it is defined at the position of the peak maximum. We would like to point out here the two different ways in which we have obtained the focal length of the microlenses. In the first, the value is calculated from the physical parameters of the vessels, namely the radius of curvature of the crater, where we have assumed a given value of the refractive index $n$ of the lens material. On the other hand, the images obtained from laser scanning confocal microscopy show the "real" focusing of the light bundled by the microlenses, and the experimental focal point is extracted from the position at which we find the maximum intensity. Even though the calculated and the experimental focal lengths agree well, a slight deviation is observed. The experimental value of the refractive index $n_{\text{exp}}$ of Sylgard 184 has been calculated from the experimental focal lengths, and it results $n_{\text{exp}} = 1.38 \pm 0.04$ @ 543.5 nm. The difference between the values of the refractive index may have its origin in the preparation of Sylgard.
184. A slight variation of the proportions between the base and the curing agent may yield a refractive index dissimilar to the one provided by the manufacturer.

Fig. 4. (a) Focal lengths $f$ of an array of microlenses as a function of the number of deposited drops. Red triangles are the calculated values and the empty diamonds correspond to the experimental data. (b) Confocal reflection/transmission scan image in the X-Z plane of a convex microlens array. The vertical green lines are the transmitted laser beams. The reflection scan image has been merged with the transmission one, and can be distinguished at the bottom of the picture as a bright green horizontal line. (c) Intensity profile along the Z-axis of a transmitted laser beam through a microlens obtained with 4 deposited droplets. This beam is pointed at (b) by the white arrow at its experimental focal point. The black line is the experimental intensity and the red one is the fit to a Gaussian peak. The position of the maximum of this fit determines the experimental focal length of the microlens.

3. Conclusion

In summary, we report here of a method to fabricate arrays of spherical microlenses with variable focal length in the micrometer range. Concave microlenses are directly fabricated by an ink-jet printing device, which deposits solvent droplets on a polymer substrate. Several combined physical effects take place while the solvent evaporates and restructures the surface to form spherical cavities. The structural properties of these cavities, such as diameter, depth and radius of curvature, are determined by controlling the parameters of deposition of the droplets, and are also dependent on the proper combination of solvent and polymer. The depth of the cavities is increased by multiple drop deposition, provided that a delay of 2 s between every deposition is introduced to allow the evaporation of the solvent in between. In this way, the diameter is kept constant while the radius of curvature of the cavity decreases. The surface bearing the concave microlenses serves as a template to produce convex ones. These are fabricated by casting a silicone elastomer on the template. The focal lengths of the produced microlenses are between 4.5 mm and 0.2 mm, which results in a high refractive power. The accuracy of the focal length values calculated from the microlens structural parameters is confirmed by comparing them with the ones obtained from the cross-sectional scan images of the microlens transmitted laser light obtained by laser scanning confocal microscopy. As well, the surface shows roughness in the nanometer range, which conveys high optical quality to the lenses.