

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

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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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References and links

1. M. F. Land, "Microlens arrays in the animal kingdom," *Pure Appl. Opt.* **6**, 599 (1997).
2. K. Iga, Y. Kokubun, and M. Oikawa, *Fundamentals of Microoptics: Distributed-Index, Microlens, and Stacked Planar Optics* (Tokyo, 1984).
3. H. Ottevaere, R. Cox, H. P. Herzig, T. Miyashita, K. Naessens, M. Taghizadeh, R. Volkel, H. J. Woo, and H. Thienpont, "Comparing glass and plastic refractive microlenses fabricated with different technologies," *J. Opt. A* **8**, S407 (2006).
4. H. Yabu and M. Shimomura, "Simple fabrication of micro lens arrays," *Langmuir* **21**, 1709 (2005).
5. C. Y. Chang, S. Y. Yang, L. S. Huang, and T. M. Jeng, "A novel method for rapid fabrication of microlens arrays using micro-transfer molding with soft mold," *J. Micromech. Microeng.* **16**, 999 (2006).
6. C. Y. Chang, S. Y. Yang, L. S. Huang, and K. H. Hsieh, "Fabrication of polymer microlens arrays using capillary forming with a soft mold of micro-holes array and UV-curable polymer," *Opt. Express* **14**, 6253 (2006).
7. M. H. Wu, C. Park, and G. M. Whitesides, "Fabrication of arrays of microlenses with controlled profiles using gray-scale microlens projection photolithography," *Langmuir* **18**, 9312 (2002).
8. B. Messerschmidt, T. Possner, and R. Goering, "Colorless Gradient-Index Cylindrical Lenses with High Numerical Apertures Produced by Silver-Ion Exchange," *Appl. Opt.* **34**, 7825 (1995).
9. P. Ruther, B. Gerlach, J. Gottert, M. Ilie, J. Mohr, A. Muller, and C. Ossmann, "Fabrication and characterization of microlenses realized by a modified LIGA process," *Pure Appl. Opt.* **6**, 643 (1997).
10. H. J. Nam, D. Y. Jung, G. R. Yi, and H. Choi, "Close-packed hemispherical microlens array from two-dimensional ordered polymeric microspheres," *Langmuir* **22**, 7358 (2006).
11. D. J. Kang, J. P. Jeong, and B. S. Bae, "Direct photofabrication of focal-length-controlled microlens array using photoinduced migration mechanisms of photosensitive sol-gel hybrid materials," *Opt. Express* **14**, 8347 (2006).
12. B.-J. de Gans, P. C. Duineveld, and U. S. Schubert, "Inkjet printing of polymers: State of the art and future developments," *Adv. Mater.* **16**, 203 (2004).
13. B. P. Keyworth, D. J. Corazza, J. N. McMullin, and L. Mabbott, "Single-step fabrication of refractive microlens arrays," *Appl. Opt.* **36**, 2198 (1997).
14. R. Danzebrink, and M. A. Aegerter, "Deposition of micropatterned coating using an ink-jet technique," *Thin Solid Films* **351**, 115 (1999).

15. S. Yang, T. N. Krupenkin, P. Mach, and E. A. Chandross, "Tunable and latchable liquid microlens with photopolymerizable components," *Adv. Mater.* **15**, 940 (2003).
16. T. Krupenkin, S. Yang, and P. Mach, "Tunable liquid microlens," *Applied Physics Letters* **82**, 316 (2003).
17. T. Kawase, H. Siringhaus, R. H. Friend, and T. Shimoda, "Inkjet printed via-hole interconnections and resistors for all-polymer transistor circuits," *Adv. Mater.* **13**, 1601 (2001).
18. B. J. de Gans, S. Hoeppener, and U. S. Schubert, "Polymer-relief microstructures by inkjet etching," *Adv. Mater.* **18**, 910 (2006).
19. E. Bonaccorso, H. J. Butt, B. Hankeln, B. Niesenhaus, and K. Graf, "Fabrication of microvessels and microlenses from polymers by solvent droplets," *Appl. Phys. Lett.* **86**, 124101 (2005).
20. C. Stupperich-Sequeira, K. Graf, and W. Wiechert, "Modelling and simulation of micro-well formation," *Math. Comput. Model. Dyn. Syst.* **12**, 263 (2006).
21. R. D. Deegan, O. Bakajin, T. F. Dupont, G. Huber, S. R. Nagel, and T. A. Witten, "Capillary flow as the cause of ring stains from dried liquid drops," *Nature* **389**, 827 (1997).
22. R. D. Deegan, O. Bakajin, T. F. Dupont, G. Huber, S. R. Nagel, and T. A. Witten, "Contact line deposits in an evaporating drop," *Phys. Rev. E* **62**, 756 (2000).
23. S. Karabasheva, S. Balushev, and K. Graf, "Microstructures on soluble polymer surfaces via drop deposition of solvent mixtures," *Appl. Phys. Lett.* **89**, 031110 (2006).
24. E. Gu, H. W. Choi, C. Liu, C. Griffin, J. M. Girkin, I. M. Watson, M. D. Dawson, G. McConnell, and A. M. Gurney, "Reflection/transmission confocal microscopy characterization of single-crystal diamond microlens arrays," *Appl. Phys. Lett.* **84**, 2754 (2004).

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 irregularities of the surface, pulling it upwards 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 apherically 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).

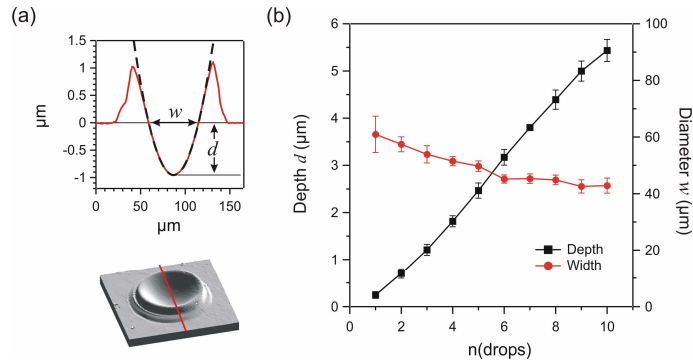


Fig.1. (a). Profile of a single crater in the direction of the red line at the lower picture. From this profile, the structural parameters of a microvessel such as diameter w , depth d and radius of curvature R are obtained. The dashed black line corresponds to the fit of the lens profile to a circle 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 °C 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)].

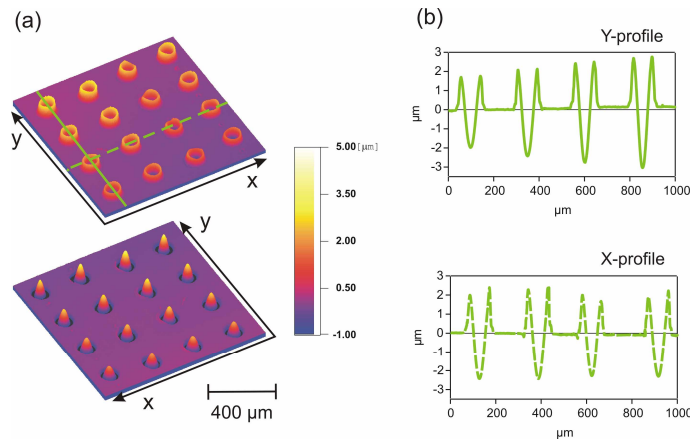


Fig. 2. (a). Arrays of microlenses imaged by a confocal profilometer. The upper picture shows concave microlenses obtained by ink-jet printing. The number of deposited drops is increased in the y-direction. Below, convex microlenses obtained by template casting from the concave ones. (b). The graphs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

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.

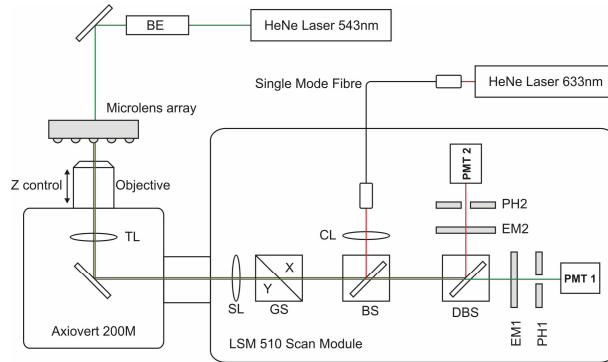


Fig. 3. Scheme of the Laser Scanning Confocal Microscopy setup. Abbreviations: BS = beamsplitter, DBS = dichroic beamsplitter, GS = galvanometric scanner, BE = beamexpander, PMT = photo-multiplier, PH = pinhole, EM = emission filter, TL = tube lens, SL = scan lens, CL = collimator lens.

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

$$\frac{1}{f} = \frac{n-1}{R} \quad (1)$$

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_{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.

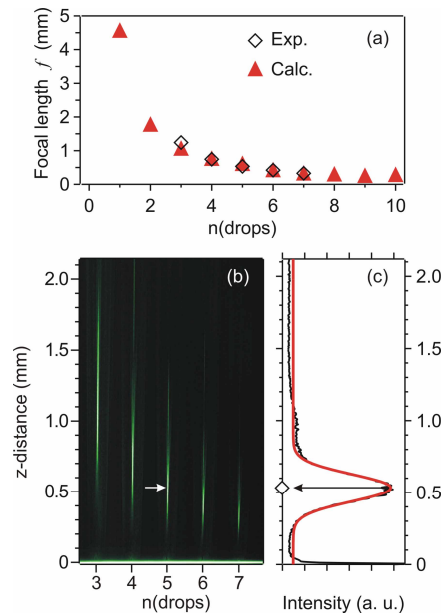


Fig. 4. (a). Focal lengths f of an array of microlenses as a function of the number of deposited drops. Red triangles are the calculated values and the empty diamonds correspond to the experimental data. (b) Confocal reflection/transmission scan image in the X-Z plane of a convex microlens array. The 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.