Hybrid polymer microlens arrays with high numerical apertures fabricated using simple ink-jet printing technique

Joo Yeon Kim,¹ Nils B. Brauer,² Vahid Fakhfouri,¹ Dmitri L. Boiko,^{2,4} Edoardo Charbon,^{2,5} Gabi Grutzner,^{3,6} and Juergen Brugger^{1,*}

¹Microsystems Laboratory, Ecole Polytechnique Fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland ²Aqua Laboratory, Ecole Polytechnique Fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland ³Micro Resist Technology GmbH, 12555 Berlin, Germany ⁴Centre Suisse d'Electronique et de Microtechnique CSEM SA, 2002, Neuchâtel, Switzerland ⁵Technische Universiteit Delft, Mekelweg 4, 2628 CD Delft, The Netherlands ⁶g.gruetzner@microresist.de ^{*}juergen.brugger@epfl.ch

Abstract: Microlens arrays fabricated by a direct ink-jet printing of UVcurable hybrid polymer are reported. A periodic pattern of polymer drops was ink-jet printed on the surface-treated glass substrate and cured in the UV-light. Using this simple technique, we demonstrated periodic arrays of almost semi-spherical microlenses of 50 μ m diameter size and a focal distance of 48 μ m. The optical characteristics of solitary μ -lenses and arrays comprising up to 64x64 microlenses are measured both in the near- and farfield zones. Large numerical aperture and short focal distance make the inkjet printing of microlenses very attractive for applications in optical interconnects, large 2D VCSEL arrays and pixelated imagine sensors utilizing CCD or SPAD arrays, offering thus an efficient, simple and a cheap alternative to the conventionally used photolithography technique.

©2011 Optical Society of America

OCIS codes: (130.0130) Integrated optics; (130.1750) Components; (130.3990) Micro-optical devices; (030.4280) Noise in imaging systems; (220.3630) Lenses; (220.4000) Microstructure fabrication; (160.5470) Polymers; (160.6060) Solgel.

References and links

- D. L. MacFarlane, V. Narayan, J. A. Tatum, W. R. Cox, T. Chen, and D. J. Hayes, "Microjet fabrication of microlens arrays," IEEE Photon. Technol. Lett. 6(9), 1112–1114 (1994).
- 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, Pure Appl. Opt. 8(7), S407–S429 (2006).
- Z. D. Popovic, R. A. Sprague, and G. A. N. Connell, "Technique for monolithic fabrication of microlens arrays," Appl. Opt. 27(7), 1281–1284 (1988).
- C. Croutxé-Barghorn, O. Soppera, and D. J. Lougnot, "Fabrication of refractive microlens arrays by visible irradiation of acrylic monomers: influence of photonic parameters," Eur. Phys. J. Appl. Phys. 13(1), 31–37 (2001).
- A. Tripathi, T. V. Chokshi, and N. Chronis, "A high numerical aperture, polymer-based, planar microlens array," Opt. Express 17(22), 19908–19918 (2009).
- M. He, X.-C. Yuan, N. Q. Ngo, J. Bu, and S. H. Tao, "Single-step fabrication of a microlens array in sol-gel material by direct laser writing and its application in optical coupling," J. Opt. A, Pure Appl. Opt. 6(1), 94–97 (2004).
- D. Wu, S. Wu, L. Niu, Q. Chen, R. Wang, J. Song, H. Fang, and H. Sun, "High numerical aperture microlens arrays of close packing," Appl. Phys. Lett. 97(3), 031109 (2010).
 W. Cheong, L. Yuan, V. Koudriachov, and W. Yu, "High sensitive SiO2/TiO2 hybrid sol-gel material for
- W. Cheong, L. Yuan, V. Koudriachov, and W. Yu, "High sensitive SiO2/TiO2 hybrid sol-gel material for fabrication of 3 dimensional continuous surface relief diffractive optical elements by electron-beam lithography," Opt. Express 10(14), 586–590 (2002), http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-10-14-586.
- V. Fakhfouri, N. Cantale, G. Mermoud, J. Y. Kim, D. Boiko, E. Charbon, A. Martinoli, and J. Brugger, "Inkjet printing of SU-8 for polymer-based MEMS a case study for microlenses," in *Proceedings of 21st IEEE International Conference on Micro Electro Mechanical Systems MEMS 2008* (Tucson, AZ, 2008), pp. 407–410.

- Y. S. Yang, D. H. Youn, S. H. Kim, S. Ch. Lim, H. S. Shim, S. Y. Kang, and I. K. You, "Preparation and characteristics of pmma microlens array for a blu application by an inkjet printing method," Mol. Cryst. Liq. Cryst. (Phila. Pa.) 520, 239–244 (2010).
- C. H. Tien, C. H. Hung, and T. H. Yu, "Microlens arrays by direct-writing inkjet print for LCD backlighting applications," IEEE J. Display Technol. 5(5), 147–151 (2009).
- S. Obi, M. T. Gale, C. Gimkiewicz, and S. Westenhofer, "Replicated optical MEMS in sol-gel materials," IEEE J. Sel. Top. Quantum Electron. 10(3), 440–444 (2004).
- P. Ruffieux, T. Scharf, H. P. Herzig, R. Völkel, and K. J. Weible, "On the chromatic aberration of microlenses," Opt. Express 14(11), 4687–4694 (2006), http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-14-11-4687.
- S. A. Akhmanov Y. E. D'yakov, and A. S. Chirkin, *Introduction to Statistical Radiophysics and Optics* (Nauka, Moscow, 1981), pp. 306–307.
- A. A. Grütter, H. P. Weber, and R. Dändliker, "Imperfectly mode-locked laser emission and its effects on nonlinear optics," Phys. Rev. 185(2), 629–643 (1969).

1. Introduction

Microlenses and microlens arrays are finding widespread application in optical interconnects, imaging sensors, photodetectors, offering a way to enhance light collimation and collection efficiency [1]. Several fabrication techniques of micro-optical components have been proposed so far [2]. These include for instance photoresist reflow [3], photopolymerization [4,5] and direct-laser [6,7] or e-beam writing [8]. However, most of these techniques require introducing numerous complex processing steps, making the fabrication quite expensive. The lens radius to the focal distance ratio for these techniques attain values of 0.3 [5] to 0.46 [7] (The numerical aperture defined by effective diameter is significantly lower, conditioned by reflections on the curved surface of microlenses). Recently, the ink-jet printing technique has been adapted as a direct fabrication method enabling microstructuring of high optical quality polymers.

In our previous work, the ink-jet printing technique has been optimized for microlenses fabricated in SU-8 polymer utilizing drop-on-demand (DOD) printing [9]. The drops of polymer material were deposited on a substrate in a controlled fashion, within predefined drop impact regions, enabling fabrication of large-area microlens patterns. Although the size of the in-flight droplets emanating the ink-jet head is defined by the orifice diameter of the head, the final size of the drops on a substrate is determined by the free energy balance between the droplet formulation, the substrate, and the surrounding atmosphere. With the conventional SU-8 polymer and various tested substrates, the size of the drops was quite large, yielding relatively low profile and long focal distance of the ink-jet printed microlenses. Other groups have reported on microlenses for display backlighting applications utilizing such materials as PMMA [10] or ultraviolet-curable epoxy [11].

In this work, we demonstrate DOD ink-jet printing of microlens arrays with very short focal distances 45-50µm, small curvature radius $R_c = 29$ µm and large ratio of the lens diameter to the focal length ($atan(D/2f) \sim 0.48$). The effective numerical aperture, limited by the total internal reflections, reaches NA = $atan(R_c/nf) \sim 0.37$. Such improvement, also in comparison to other techniques [5,7], has been achieved by using a hybrid polymer belonging to the ORMOCER[®] family of polymers [12] and a peculiar surface treatment of the substrate before deposition of microlenses. Measuring near- and far-field patterns of solitary microlenses and NxN microlens arrays, we analyze their optical characteristics and we evaluate performance of the ink-jet printing technique in fabrication of large uniform arrays of microlenses. We shall emphasize that our approach based on far-field measurements allows the dispersion of microlens displacement to be obtained in a single measurement as opposed to tedious statistical data treatment if standard tools are used for characterization of individual microlenses in array (e.g. SEM, optical microscopy, digital holographic microscopy or alphastep). The short focal distance of our microlenses and large numerical aperture make them particularly attractive for applications in large two-dimensional (2D) arrays of Vertical Cavity Surface Emitting Lasers (VCSELs) and in pixelated imagine sensors like charge-coupled device (CCD) cameras or single-photon avalanche diode (SPAD) arrays.

^{#142920 - \$15.00} USD Received 22 Feb 2011; revised 14 May 2011; accepted 14 May 2011; published 25 May 2011 (C) 2011 OSA 1 June 2011 / Vol. 1, No. 2 / OPTICAL MATERIALS EXPRESS 260

2. Fabrication technique

The hybrid inorganic-organic photo-curable polymer we used here belongs to the ORMOCER[®] polymers. This is a sol-gel material composed of a Si-O-Si network incorporating UV curable polymeric groups. It has been developed at the Fraunhofer Gesellschaft Institute and is now available from Micro Resist Technology GmbH.

Due to incorporation of inorganic domains, its optical transparency (after the UV curing) is higher than that of micro lenses fabricated in SU-8 so as the transparency window ranges over the wavelength range from 400 to 1600 nm. It has a relatively high refractive index as well as excellent thermo-mechanical properties. For the ink-jet printing application, the viscosity of polymer has been reduced by introducing a solvent.

Figures 1(a)-1(d) show a schematic diagram of the ink-jet printing setup and illustrates the main steps of fabrication process.

We use a 500 μ m-thick glass substrate cleaned with copious water and isopropyl alcohol (IPA), and dried using N₂ gas flow (Fig. 1(a)).



Fig. 1. Schematic diagram of the DOD ink-jet printing and the process flow used to fabricate microlenses. (a) Untreated (cleaned) glass substrate, (b) SAM-treated glass substrate (dark grey), (c) Ink-jet printing of a hybrid polymer and pre-bake, (d) UV-exposure and post-exposure bake, (e) SEM images of 64 x 64 ink-jet printed hybrid polymer microlens arrays (part of) on the SAM-treated glass with high magnification inset. The diameter and the height of the microlens are about 53 and 18 μ m, respectively.



Fig. 2. Contact angle of deposited water drop on quartz (qz), glass, SAM coated quartz (SAM-qz), SAM coated Si (SAM-Si) and SAM coated glass (SAM-glass).

A special provision is made to render its surface hydrophobic as the shape of the drops after deposition mainly depends on the wetting conditions. In particular, the surface of the glass substrate is functionalized by molecular vapor deposition (MVD) of fluorinated organosilane (trichloro(1H,1H,2H,2H-perfluorooctyl)silane, FOTS) forming self-assembled monolayer (SAM layer in Fig. 1(b)). After MVD deposition, the residue FOTS is removed by substrate cleaning with acetone, IPA and distilled water and drying it in N_2 flow.

Figure 2 shows the impact of such hydrophobic SAM on the water drop shape formation for various substrates including quartz, glass and Si. The highest contact angle is achieved in SAM-treated glass substrate which justifies our choice.

The piezo-actuated ink-jet nozzle of 50 μ m diameter (Microdrop GmbH, Germany) is used to generate droplets of polymer in the drop-on-demand mode enabling deposition of individual microdrops at desired locations (Fig. 1(c)). The amplitude and duration of the actuating electrical pulse at the nozzle are adjusted so as to produce solitary droplets defining position of microlenses on the substrate.

A regular pattern of microlenses is formed by translating the glass substrate using a computer-controlled motorized stage. After deposition of liquid polymer drops, the sample is baked at 95 °C for 30 min, UV exposed at 400 mJ/cm² of a deep UV source for 2 min, and post-baked at 130 °C for 30 min (Fig. 1(d)). In this way, large (up to 64x64) square arrays of 100 μ m pitch have been fabricated by printing microlens arrays row by row. Figure 1(e) shows the scanning electron microscope (SEM) image of a nominally uniform square array of microlenses obtained by ink-jet printing on the SAM-coated substrate. Note visible variations in the height of microlenses and their displacement from a regular pattern.

3. Results and discussion

The processed microlenses have a diameter of about $53 \pm 1 \,\mu\text{m}$ (measured from SEM image), thus exhibiting low droplet to nozzle diameter ratio of 1.1. Although the tilted-sample SEM image might result in overestimation of the height of microlenses, the low diameter ratio is in agreement with the semi-spherical shape of microlenses seen in Fig. 1(e). From the SEM image (Fig. 3(c)) estimated heights of microlenses are about 18 μm , yielding an estimate for the curvature radius $R_c = 29 \,\mu\text{m}$ and the focal length $f_{\mu} = R_c / (n-1) = 52 \,\mu\text{m}$ in the paraxial optics approximation. (The refractive index of the polymer after the UV exposure and bake up is n = 1.55 at the wavelength 633 nm.) We shall note that the height of microlenses obtained from the SEM image might be overestimated and predicted focal distance requires confirmation in direct measurements.

There exist many different techniques that can be applied for refractive index, lens profile and lens displacement measurements: surface profile scanning, interferometric methods or digital holographic microscopy (DHM) etc. In choosing a technique for characterization of our microlenses, several circumstances must be accounted for: The hemispherical shape of microlenses results in the total internal reflections (TIR) at the steep surface of microlenses nearby the aperture edges. This effect is clearly seen in the optical microscope image of the back-side illuminated microlens array in Fig. 3(a). It manifests as a dark ring surrounding the bright central part of each microlens. As a consequence, DHM in transmission mode is of limited use since the total height of microlens cannot be reconstructed correctly due to the uncertainty of the phase accrual in the TIR region. The consequence of this uncertainty is clearly seen in the DHM reconstructed lens profile as a false notch ring at the microlens edge (See the inset in Fig. 3(b)). The SEM image (Fig. 3(c)) reveals that no such notch ring exists in reality. The situation with DHM in reflectance mode is not better since the light from the steep edges is reflected out of the field of view of DHM CCD recorder so as again no information on the phase accrual nearby the aperture edges is available. Finally the profilometer (alpha step) measurements are of limited use as well for these microlenses. The microlenses deposited on the hydrophobic (SAM-treated) substrate reveal insufficient adhesion and detach during profile measurements.



Fig. 3. Microlens array. (a) Optical microscope image of back-side illuminated array. The zoomed image in the inset shows the dark ring caused by the total internal reflections (TIR) at the steep edges of a microlens surface. (b) Surface profile of the $2x^2$ microlense domain obtained from the phase accrual reconstruction in the transmission mode of DHM imaging. Note a large displacement of the microlens in the left bottom corner caused by imperfections of the ink-jet printing. The inset shows details of the reconstructed lens profile with false notch at the microlens edge (highlighted in red) due to the phase accrual uncertainty in the TIR region (c) SEM image used to measure the height of microlenses. No notch ring is available at the microlens edge.

Therefore, we have implemented a simple setup for optical characterization of microlenses, enabling measurements as the focal distances in solitary microlenses as the collective far-field intensity patterns of NxN microlens array. The optical characterization

methods we use here do not require expensive equipment and provide a direct measurement of the most important parameter of a lens, its focal distance. Finally instead of tedious measurements and subsequent statistical treatment of displacement of individual microlenses (e.g. there are 4096 microlenses in 64x64 array) we use a solitary far field intensity pattern to measure the variance of the displacement of microlenses over the array.

3.1 Optical characteristics of solitary microlenses

Figure 4(a) depicts the optical setup for measuring characteristics of solitary microlenses. The sample with imprinted microlens arrays is fixed on a motorized translation stage with microlenses being oriented towards the CCD camera. It is illuminated by an attenuated He-Ne laser beam (wavelength $\lambda = 633$ nm) reaching the 2 mm diameter in the sample plane and providing thus a uniform illumination of a microlens. The microlens under test is imaged on the CCD chip by 4-*f* optical length system composed of microscope objective O and lens F1. Its magnification (M = 37) has been calibrated such that the near-field (NF) image recorded by CCD camera (Fig. 4(b)) can be used to measure the diameter of the microlens. Increasing the distance between microlens array and microscope objective O allows the far-field (FF) intensity distribution in the focal plane of a particular microlens to be observed on the CCD



Fig. 4. (a) Schematic of the setups for optical characterization of solitary microlenses: O - 40x microscope objective (f = 4.1 mm, NA = 0.65), F1- lens (F1 = 150 mm). O and F1 form a 4-f optical length system of magnification M = 37. Near field (b) and focal-plane far field (c) intensity patterns and line scans of solitary microlens in 64x64 array. (d) Intensity distribution behind a microlens used to define the focal plane. (e) Histogram of measured focal distances.

Table 1. Optical Characteristics of Solitary Microlenses^a

Effective focal distance, f_{eff} [µm]	Lens diameter, D [µm]		Effective Numerical Aperture NA	Focal spot at 2% intensity, d [µm]	Focal spot at FWHM [µm]
48 ± 3	50.8 ± 0.6	0.48	0.37	2.7	2.1

camera (Fig. 4(c)). Figure 4(d) shows a typical intensity distribution behind a microlens, indicating the peak irradiance position in the focal plane. (In this example, the microlens exhibits a larger focal distance than the average focal length in the array). Readings of the motorized translation stage between the NF and FF imaging positions are used to measure the focal length. We have examined about 100 microlenses across a 64x64 array, using microlens trials from the center of array and nearby its corners.

The measured parameters of solitary ink-jet-printed hybrid polymeric microlenses are summarized in Table 1. Note that the large ratio of the lens diameter to its focal distance $(\operatorname{atan}(D/2f) \sim 0.48)$ and small focal spot of 2.7 µm size (2.1 µm at FWHM) make them highly attractive for practical applications. Because of almost hemispherical shape, the clear aperture of the microlens is limited by the total internal reflections and has a diameter $D_{eff} = 2R_c / n \sim 37$ µm. The effective numerical aperture limited by the total internal reflections is estimated as NA = $\operatorname{atan}(R_c / nf_{eff}) \sim 0.37$.

The measured diameter *D* of microlenses 50.8 ± 0.6 µm is in good agreement with the SEM image data. It reveals relatively small variations across the array. On the opposite, the effective focal length f_{eff} of 48 ± 3µm exhibits large dispersion (see Fig. 4(e)). In general, it is shorter than f_{μ} calculated in the paraxial optics approximation. Such focal shift can be caused by diffraction effects and spherical aberrations. Using the results of Ref [13], one can show that diffraction effects cause a shift of the peak irradiance from the paraxial focal plane at a distance f_{μ} to a plane at a shorter distance $f_{eff} = f_{\mu}(1 + 4\lambda f_{\mu} / D_{eff}^2)^{-1}$. For microlenses treated here, the estimated shift is about 4-5 µm, in agreement with experimental observations. The contribution of spherical aberrations to the focal shift is small, $0.067D_{eff}^2 / f_{\mu} = 1.2$ µm.

The focal spot is by a factor of 1.3 larger the diffraction limited one $d = 2.44\lambda f_{eff} / D$, which is about 2 µm for our microlenses. As the focal shift, the focal spot broadening can be attributed to the interplay of the diffraction effects, spherical aberrations and inhomogeneities of polymer after the solvent evaporation.

It is thus important to verify that the observed focal shift and broadening of the focal spot are not caused by microscopic inhomogeneities of the refractive index or surface roughness of microlenses. Such imperfections would otherwise introduce decorrelation effects. A coherent beam propagating through a microlens will become just partially correlated within a domain of effective correlation radius $r_{corr} < D_{eff} / \sqrt{2}$ and will exhibit shorter diffraction length $l_d = \pi D_{eff} r_{corr} / 2\sqrt{2}\lambda$ [14]. Respectively, the beam diameter d at the focus will be larger and the effective focal distance will be reduced down to $f_{eff} = f_{\mu} / (1 + f_{\mu}^2 / l_d^2)$ [14]. Thus the stronger decoherence effects are the smaller correlation radius r_{corr} and the larger focal shift $f_{eff} - f_{\mu}$ will be observed. On the other hand, the relationship $D/d \sim l_d / f_{\mu}$ [14] assumes that, in our microlenses, the diffraction length l_d of the beam is about 945 µm. Therefore, the contribution of decorrelation effects to the focal shift (~0.3µm) is negligible compared to the shift $f_{eff} - f_{\mu}$ observed experimentally, indicating that microscopic inhomogeneities in our microlenses are small and have no impact on measured characteristics. In a similar way we conclude that the measured focal shift cannot be attributed to the important gradient-index

(GRIN) lensing effects due to large-scale inhomogeneities of the hybrid polymer after the solvent evaporation.

Finally, focal length variation between individual microlenses (up to 6 μ m in Table 1) can be attributed as to the experimental uncertainty in defining the peak irradiance location as to the variations of the size of the liquid polymer drops, the lens height and refractive index after evaporation of the polymer solvent. We noticed that such focal length variations are smaller between the neighboring microlenses in the same printed row of the array.

The spreading of parameters and displacement of microlenses might be a limiting factor for application of large periodic arrays of ink-jet printed hybrid polymer microlenses (e.g. in pixelated SPAD array or CCD sensors). Instead of tedious characterization of individual microlenses, measurements of their displacement and subsequent statistical treatment of data, we have analyzed the far-field intensity pattern of the entire array to obtain the dispersion of microlens parameters in the NxN array.

3.2 Microlens arrays

In order to quantify the imperfections of ink-jet printing technique in application to large microlens arrays, we have examined the FF intensity patterns in nominally uniform NxN arrays of different size (5x5, 7x7, 10x10, 15x15, 20x20 and 30x30 arrays) fabricated on the same (SAM-treated) glass substrate. In the experimental setup (Fig. 5(a)), they are oriented towards the CCD camera to exclude the substrate impact. The sample is illuminated by a beam of He-Ne laser expanded by the 4-f optical length system with magnification M = 37. The iris diaphragm in front of the sample selects the central part of the beam with uniform intensity distribution and a flat phase front. To reduce the phase distortion, the sample and CCD camera acquiring the FF image are placed at the front and back focal planes of the lens F2 with the focal distance 150 mm.

In Fig. 5(b), the central lobe of highest intensity is located at zero spatial frequencies (the lobe with indexes (0,0)). It has important background contribution from illuminating beam and therefore it is unsuitable for estimation of the array parameters. As such, we use the lobes of the first diffraction order with indexes $(\pm 1, 0)$ and $(0, \pm 1)$ and of the second order with indexes $(\pm 1, \pm 1)$, as indicated in the figure. In particular, to assess the array imperfections, we compare the measured width of the first (1,0) and second (1,1) order diffraction lobes as well as the ratio of their intensities with the model predictions. Below we briefly introduce our model, which is based on superposition of wavelets from individual microlenses of the array. The array imperfections are accounted for by introducing stochastic phase and amplitude variations of individual wavelets. It has to be pointed out that analytically similar formulation of the superposition of partially correlated modes has been widely used to analyze in the time domain the emission of imperfectly mode-locked laser [15]. Following along the lines of Refs [14] and [15], the far field intensity distribution pattern observed in the focal plane of lens F2 in Fig. 5(a) can be represented in the form:

$$I(\Theta_x, \Theta_y) \propto \left| \sum_{n,m} (F_\mu(\Theta_x, \Theta_y) + \xi_{n,m}) \exp(i\Theta_x n + i\Theta_y m + i\phi_{n,m}) \right|^2,$$
(1)

where Λ is the array pitch, k_x and k_y are the transverse components of wavevector (spatial frequencies) along the square lattice directions of the array; $\Theta_{x,y} = k_{x,y}\Lambda$ so as the variables $\Theta_{x,y} / 2\pi$ measure the diffraction angle in terms of diffraction order. In Eq. (1), the summation runs over the array columns and rows so as the indexes *n* and *m* enumerate the columns and rows respectively; $\phi_{n,m}$ and $\xi_{n,m}$ account for the stochastic phase and amplitude



Fig. 5. (a) Schematic of the setup for optical characterization of NxN microlens arrays: O and F1 form the 4-f optical length system as in Fig. 2(a); lens F2 = 150 mm. (b) Far field image of the 30x30 entire array with superimposed line scan of the central lobe (logarithmic scale). (c) Left axis: measured (points) and modeled (curve) FWHM of the first diffraction order lobe (averaged over the (\pm 1,0), (0, \pm 1) lobes); right axis: ratio of the measured and modeled FWHM of the first diffraction order lobe as a function of array size *N* in *NxN* microlens arrays. (d) Measured (points) and numerically fitted (curve) intensity ratio of the (\pm 1, \pm 1) and (0, \pm 1) lobes.

variations due to microlens imperfections and misalignments of microlenses from the due locations. In Eq. (1), the background contribution of the illuminating beam is neglected so as the expression is valid for any diffractional order but the main lobe (0,0), which we omitted in this analysis.

For a nominally uniform *NxN* array without imperfections ($\phi_{n,m}, \xi_{n,m} = 0$), the summation in Eq. (1) yields well-known interference pattern for a screen with *NxN* pinholes,

$$I^{(0)}(\Theta_x,\Theta_y) \propto \left| F_{\mu}(\Theta_x,\Theta_y) \right|^2 \frac{\sin^2 N\Theta_x / 2}{\sin^2 \Theta_y / 2} \frac{\sin^2 N\Theta_y / 2}{\sin^2 \Theta_y / 2}, \tag{2}$$

The first and second order diffraction maxima are located at the spatial frequencies $(\Theta_x / 2\pi, \Theta_y / 2\pi) = (\pm 1, 0)$ (or $(0, \pm 1)$) and $(\pm 1, \pm 1)$. According to Eq. (2), the intensity ratio of the second and first order lobes is constant $I_{1,1}^{(0)} / I_{0,0}^{(0)} = 1$. At the same time, the measured intensity ratio of these lobes in *NxN* arrays reduces with the size of array *N* [Fig. 5(d)].

The envelope function amplitude $F_{\mu}(\Theta_x, \Theta_y)$ is a Fourier transform of the phase front after propagation through the lattice cell of the size $\Lambda \times \Lambda$. Each such cell comprises a

microlens of diameter *D*. Therefore $F_{\mu}(\Theta_x, \Theta_y)$ is complementary to the Airy diffraction pattern of a partially transmitting disk:

$$F_{\mu}(\Theta_{x},\Theta_{y}) \propto 1 - \gamma \frac{2J_{1}(\sqrt{\Theta_{x}^{2} + \Theta_{y}^{2}}D/2\Lambda)}{\sqrt{\Theta_{x}^{2} + \Theta_{y}^{2}}D/2\Lambda}$$
(3)

where γ is the complex amplitude, characterizing the contrast of microlenses. Note that this term is independent of the array size *N* and hence it cannot explain the measured intensity ratio of the FF lobes in Fig. 5(b).

Our analysis shows that the decay of the relative intensity in Fig. 5(d) is caused by misalignments of microlenses from the due locations. Indeed, random displacements of microlens at each lattice site (n,m) introduce in Eq. (1) a stochastic phase shift $\phi_{n,m} = k_x \delta x + k_y \delta y$ with δx and δy being misalignments along the principal lattice directions. It is convenient to make use of the variables $\Theta_{x,y}$ introduced in Eq. (1) so as the stochastic phase shift reads $\phi_{n,m} = \Theta_x \alpha_x + \Theta_y \alpha_y$ with $\alpha_x = \delta x / \Lambda$ and $\alpha_y = \delta y / \Lambda$ being random variables measuring the misalignments in the units of the lattice pitch ($|\alpha_{x,y}| \le 1$). For a Gaussian distribution of variables $\alpha_{x,y}$ with the standard deviation α_0 , one obtains the average value $\langle \exp(i\phi_{n,m}) \rangle = \exp(-(\Theta_x^2 + \Theta_y^2)\alpha_0^2 / 2)$. [The approach to calculate such average can be found in [14].] Therefore, after averaging Eq. (1) over the entire array, we find that the FF intensity pattern of $N \times N$ array with lattice defects is

$$I \propto \left| F_{\mu}(\Theta_{x},\Theta_{y}) \right|^{2} \left(e^{-(\Theta_{x}^{2}+\Theta_{y}^{2})\alpha_{0}^{2}} \left[\frac{\sin^{2}N\Theta_{x}/2}{\sin^{2}\Theta_{x}/2} \frac{\sin^{2}N\Theta_{y}/2}{\sin^{2}\Theta_{y}/2} - N^{2} \right] + N^{2} \right)$$
(4)

It can be seen that in the absence of random displacement of microlenses (when $\alpha_0 = 0$), this expression transforms in Eq. (2) so as the ratio of the diffraction lobe intensities is independent of the array size. At the same time, if there are random misalignments of microlenses, the array size impacts significantly the relative intensities of the FF lobes. In particular for the first and second order lobes one obtains:

$$\frac{I_{1,1}}{I_{1,0}} = \frac{\left|1 - \gamma \frac{2J_1(\sqrt{2\pi D} / \Lambda)}{\sqrt{2\pi D} / \Lambda}\right|^2}{\left|1 - \gamma \frac{2J_1(\pi D / \Lambda)}{\pi D / \Lambda}\right|^2} \frac{\left(e^{-8\pi^2 \alpha_0^2} \left[N^2 - 1\right] + 1\right)}{\left(e^{-4\pi^2 \alpha_0^2} \left[N^2 - 1\right] + 1\right)}$$
(5)

We use this feature to evaluate the misalignments α_0 . The numerical fit in Fig. 5(d) reports the amplitude contrast $\gamma = 0.56$ and the variance of the relative microlens position α_0 of 19% of the lattice pitch. Note that it is not evident from the SEM image in Fig. 1(e), which shows about 1/14 of the entire array, that the variance is so large.

The FWHM of the FF lobes in large NxN arrays (Fig. 5(c)) slightly exceeds the diffraction limited width predicted by the model (Eq. (4)). An analysis indicates that such broadening is due to systematic phase and/or amplitude variations within the array of the quadratic form $\exp(\xi_{n,m}), \phi_{n,m} \propto n^2 + m^2$. It can be attributed to the residual quadratic phase and amplitude variations across the illuminating Gaussian beam. All other defects, such as variations in the shape or refractive index of microlenses introduce in Eq. (1) the amplitude $\xi_{n,m}$ or phase perturbations $\phi_{n,m}$, which are independent of the spatial frequencies $\Theta_{x,y}$. They contribute only to a constant background of the FF.

These results of FF measurements indicate that practical application of the ink-jet printing technique might require improvement for better alignment of microlenses (e.g. with the pixels of SPAD arrays or CCD sensors). The technique reported in this section can be efficiently used to rapidly evaluate the average misalignments of microlenses across large arrays.

4. Conclusion

In conclusion, we have demonstrated a simple, yet powerful method to fabricate microlenses and microlens arrays using hybrid polymer and programmable drop-on-demand ink-jet printing technique. Fabricated microlenses on surface wetting controlled substrate have good optical quality and uniformity. Large numerical aperture and short focal distance make them very attractive for applications in optical interconnects, large 2D VCSEL arrays and pixelated imagine sensors utilizing CCD or SPAD arrays.

Acknowledgments

We acknowledge financial support from the EU funded project ACAPOLY (Academia and Company Collaboration and Technology Transfer in Advanced Polymers project with contract no 218075). Micro Resist Technology GmbH is gratefully acknowledged for providing the polymer material.

We thank Referee for valuable comment regarding the total internal reflection at the surface of microlens with high NA.