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Miniaturized, focusing fan-out elements: design, fabrication and characterization

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Abstract.

We present miniaturized, focusing fan-out elements. The new micro-optical elements were fabricated using different technologies: double-sided injection moulding in polycarbonate, double-sided photolithography with subsequent transfer in quartz and direct laser writing in photoresist. The fan-out elements were characterized by measuring their efficiency and uniformity, the surface profiles of the microlenses were measured with a Twyman–Green interferometer. The overall performance of the combined, hybrid elements is demonstrated with intensity distributions recorded in the focal planes.

Keywords: Focusing fan-out, injection moulding, reactive ion etching, direct laser writing, optical interconnects

1. Introduction

Fan-out phase gratings are micro-optical elements which split an incoming beam into an array of light beams with equal power. The diffracted beams are then focused by a Fourier transform lens. These elements are used, for example, in optical interconnects, in multidetector systems and in parallel optical processing [1–3]

We present different concepts for the fabrication of hybrid elements which combine the fan-out and focusing function. The combination of the refractive and diffractive function results in a monolithic element with miniaturized dimensions, which therefore has high potential for applications in optical microsystems. To achieve this functionality, we used two different designs and different fabrication technologies. The hybrid elements were fabricated by injection moulding in polycarbonate, double-sided photolithography with subsequent etching in quartz, and direct laser writing in photoresist. Single elements, as well as large arrays of elements, have been fabricated.

2. Design considerations

The combination of the fan-out and the focusing function can be made in two conceptually different ways. Either the two functions are implemented on the two opposite sides of one substrate (see figure 1(*a*)), or the fan-out function is superimposed on the focusing function of a plano-convex microlens (see figure 1(*b*)). The first concept was used for the elements fabricated by injection moulding in polycarbonate, and by double-sided photolithography with subsequent transfer into quartz. The second possibility was used for elements fabricated by direct laser writing in photoresist.

In case (*a*), the diffraction orders are generated by the grating and propagate parallel to the optical axis after the lens, when the grating plane is in the back focal plane of the lens. For case (*b*), the diffraction orders are divergent after the element with respect to the optical axis, because the fan-out grating is on top of the curved surface. For an application, where the spots have to be aligned relative to a reference, for example a detector, the properties of the two concepts in terms of alignment tolerances are different. With concept (*a*), the longitudinal alignment of element and detector is not critical. Concept (*b*) can be advantageous for a system which has lateral alignment errors between the spots and the reference, because these errors can be compensated by longitudinal adjustment of the element relative to the reference.

3. Fabrication of the elements

For the fabrication of the hybrid elements three different technologies were applied.

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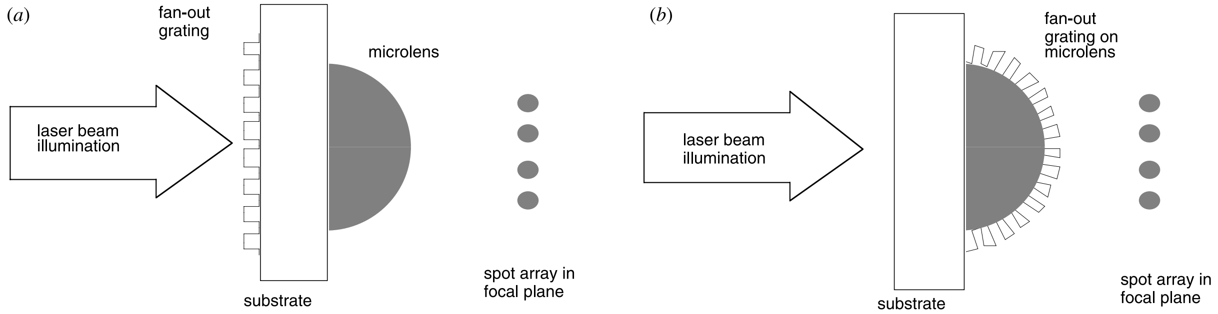

Figure 1. Schematic diagram of the two different concepts for hybrid elements: (*a*) the fan-out structure is on the back side of the microlens; (*b*) the fan-out structure is on top of the refractive surface.

3.1. Injection moulding in polycarbonate

The plano-convex microlens originals in photoresist were fabricated by photolithography and a subsequent melting process [4]. The diffractive fan-out gratings in photoresist were obtained by standard binary-mask lithography on another substrate. Two metal masters were made from the photoresist originals—one for the diffractive fan-out structures and the other for the refractive microlenses. With these masters, double-sided replications in polycarbonate were fabricated by injection moulding. The process was executed at the IMM in Mainz. The alignment of the structures on the two sides of the element is limited by the mechanical tolerances of the metal masters and is of the order of 20 μm. This technology is well suited for low-cost mass production.

3.2. Double-sided photolithography with subsequent transfer into quartz

The diffractive fan-out structures and the refractive microlenses were fabricated by photolithography onto both sides of a quartz wafer. Subsequently, these photoresist elements were transferred into quartz by reactive ion etching (RIE) using two independent etch steps. The photoresist microlenses, with a height of about 60 μm, resulted in microlenses with a height of 40 μm after the transfer into quartz.

3.3. Direct laser writing in photoresist

Plano-convex photoresist microlenses, again made using photolithography and subsequent melting, were spin coated with an additional photoresist layer. Afterwards, a continuous relief fan-out phase grating was written directly into the photoresist using the laser writer at CSEM Zürich [5, 6]. This technology can be used for rapid prototyping of photoresist elements. A possible replication of these elements would have the advantage that no alignment is necessary for the replication step, because the two optical functions are on one single surface.

4. Comparison of the fabrication methods

Each of the three different technologies, which were used for the fabrication of the hybrid, focusing fan-out elements, has its advantages and limitations. The best choice of technology to apply depends strongly on the specifications imposed by the application for which the element will be used later. Besides, the compromise between quality and cost is of importance. Double-sided photolithography with subsequent transfer into quartz produced the elements with the best overall performance. However, compared to the other two fabrication technologies, it is relatively expensive, and the transfer of deep photoresist microlenses into quartz is not yet a standard process. For the production of a large number of elements at low cost with satisfactory quality, the injection moulding technology is well suited. An alternative possibility is to use direct laser writing to produce an element in photoresist and, subsequently, fabricate a nickel shim by electroforming. Using this nickel shim, elements can be replicated by hot embossing [7]. The advantage of this approach is that only one surface needs to be replicated and, therefore, only one metal master needs to be made. Consequently, no aligning is necessary during the replication step. An advantage of laser writing technology compared to the other two technologies is that a prototype in photoresist can be fabricated relatively quickly. A disadvantage of this technique is that, for the performance of the element, the homogeneity of the additional photoresist layer is critical. The homogeneous deposition of this additional resist layer on the curved surfaces of the convex microlenses is not trivial. The double-sided photolithography provides an accurate alignment of the two optical functions of about 1 μm, whereas the injection moulding process allows an alignment with a tolerance of about 20 μm, limited by the mechanical positioning of the two metal masters during the process. The accuracy of the alignment was not critical for our periodic fan-out structures. However, for diffractive aspheric correction of the microlenses, for example, the alignment accuracy will become critical.

5. Characterization

5.1. Injection moulding in polycarbonate

The original is a binary Dammann grating in photoresist, which generates 4×4 equal diffraction orders. The grating period is 64 μm with a minimum feature size of 1 μm. An SEM micrograph of an element fabricated by injection moulding is shown in figure 2. We measured a diffraction efficiency of 73% and a uniformity error $([I_{\max} - I_{\min}]/[I_{\max} + I_{\min}])$ of 2.6%. 1% of the incoming light was found in

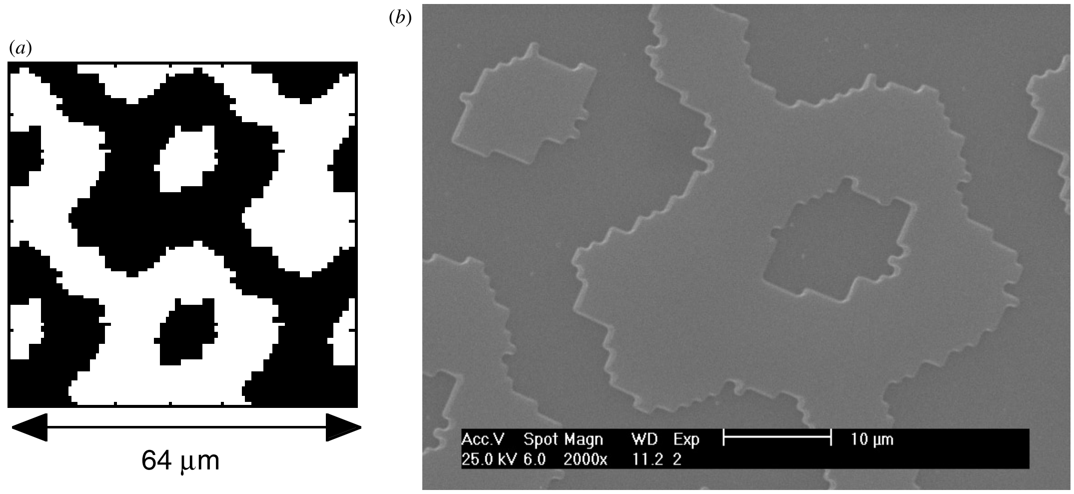

Figure 2. (*a*) Calculated phase element and (*b*) SEM image of fabricated binary fan-out structure, which generates a 4 × 4 equal intensity fan-out. The SEM micrograph shows an element which was fabricated by injection moulding in polycarbonate.

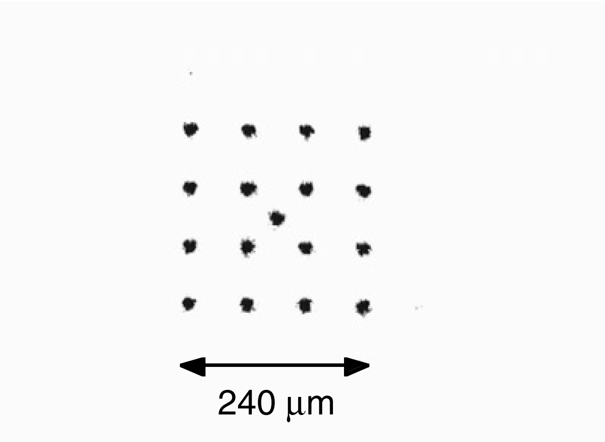

Figure 3. Intensity distribution of miniaturized, focusing fan-out element in the focal plane. The element was fabricated by injection moulding. The diameter of the microlens is 990 μm and the grating period of the fan-out is 64 μm ($\lambda = 632.8$ nm, NA $= 0.12$).

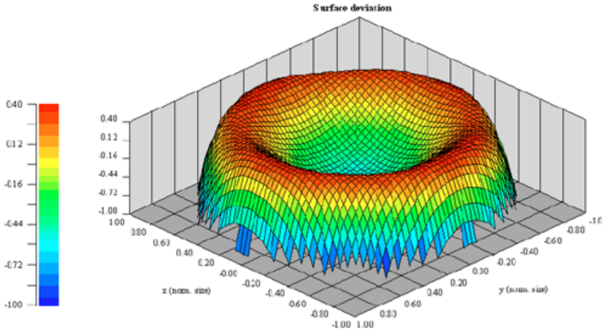

Figure 4. Surface deviation from a sphere for a replicated microlens (990 μm diameter), measured with a Twyman–Green interferometer. The rms value is 0.3λ.

the zeroth order. The theoretical values are 76% for the efficiency, 0.7% for the uniformity and 0% in the zeroth order. The replicated fan-out elements had an efficiency of 62%, typically, with a uniformity error of 20%; 6% of the light was in the zeroth order. The fan-out performance of the separate fan-out and the monolithic, hybrid elements was comparable. The pitch of the replicated microlens arrays, measured with a knife edge, was reproduced to within less than 1% between two neighbouring microlenses. The accumulated relative pitch error over six microlenses (990 μm diameter, gap 10 μm) and over 10 microlenses (350 μm diameter, gap 5 μm) was, in both cases, 0.4%.

We characterized the surface profile of the replicated microlenses with a Twyman–Green interferometer. The surface deviation of the microlenses from a sphere was typically 0.2λ (rms) for lenses with 610 μm diameter, and 0.35λ (rms) for lenses of 990 μm diameter. The measured surface deviation of a microlens with 990 μm diameter is shown in figure 4. Subsequently, we performed a ray-trace analysis using the measured surface profile. The original photoresist microlenses with a diameter of 610 μm which were used for the fabrication of the metal master had a surface deviation of 0.11λ (rms). The intensity distribution in the focal plane (4 mm after the microlens) of a hybrid element with 990 μm diameter is shown in figure 3. The measured spot size is about 18 μm (NA $= 0.12$), compared to about 17 μm obtained from a ray-trace simulation. The spot size is mainly determined by the spherical aberration of the microlens. In terms of unwanted stray light between the diffraction orders, the elements with larger diameters performed better.

5.2. Double-sided photolithography and subsequent transfer into quartz

We used a binary 4 × 4 fan-out grating in photoresist, which had the same parameters as the photoresist originals for the injection moulding process: 64 μm grating period, a measured efficiency of 73%, and a uniformity error of 2.6%, with 1% in the zeroth order. The quality of the refractive photoresist microlenses was characterized with a Twyman–Green interferometer. A typical surface deviation from the

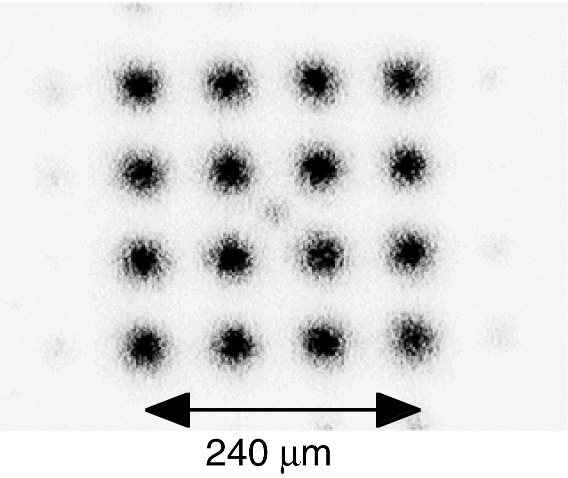

Figure 5. Intensity distribution in the focal plane of a miniaturized, focusing fan-out element. The element is in quartz, the diameter of the microlens is 610 μm and the grating period of the fan-out is 64 μm ($\lambda = 632.8$ nm, NA $= 0.17$).

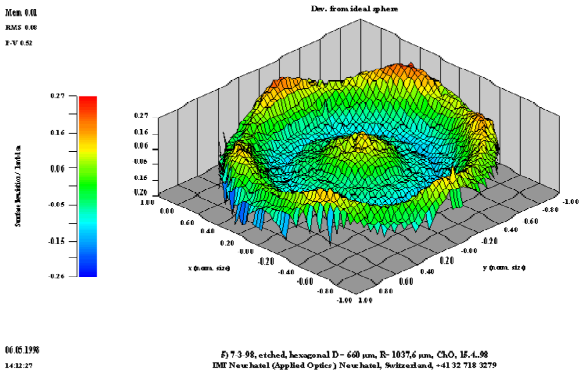

Figure 6. Surface deviation from sphere for a microlens with 610 μm diameter, etched in quartz. The measurement was done with a Twyman–Green interferometer. The rms value for the deviation is 0.08λ.

sphere of about 0.1λ (rms) was found. The alignment of the refractive and diffractive structures on the two sides of the substrate was made using a mask aligner with an accuracy of about 1 μm.

After the first etch step before the transfer of the microlenses, the fan-out has been characterized. The efficiency was 75% (theoretically 76%), the uniformity error was 7% (theoretically 0.7%) and 0.5% of the light was in the zeroth order (theoretically 0%). For the combined elements with diameters of 990 and 610 μm, the uniformity error was the same as for the separate fan-out elements. For the elements with a diameter of 350 μm, the uniformity error and stray light between the diffraction orders increased. Figure 5 shows the measured intensity distribution in the focal plane of a focusing fan-out element in quartz with a diameter of 660 μm. The measured surface deviation from a sphere for a microlens with 660 μm diameter is shown in figure 6. The rms value for the surface deviation is 0.08λ.

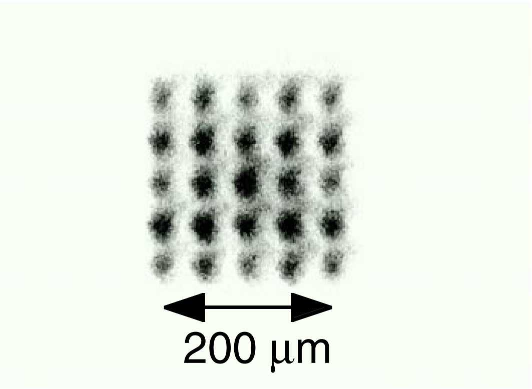

Figure 7. Intensity distribution of focusing fan-out element in the focal plane. The element was fabricated by direct laser writing in photoresist on photoresist microlenses. The diameter of the microlens is 990 μm and the grating period of the fan-out is 51.2 μm ($\lambda = 632.8$ nm, NA $= 0.14$).

5.3. Direct laser writing in photoresist

An additional layer of photoresist was spin coated onto the photoresist microlenses. The additional layer had a thickness of about 2–3 μm. The photoresist microlenses were characterized with a Twyman–Green interferometer before and after the deposition of the additional photoresist layer. Subsequently, a continuous relief 5×5 fan-out phase grating was written into the photoresist with the laser writer. We used a reduced writing speed of $v = 10$ mm s^{-1} and a spot size of 1.3 μm (FWHM). The grating period of the fan-out was 51.2 μm. Since it was difficult to achieve a homogeneous layer of photoresist on the microlenses with the spinning procedure, the fan-outs showed a large uniformity error. Figure 7 shows the measured intensity distribution in the focal plane of a focusing fan-out element with a diameter of 990 μm which generates 5×5 diffraction orders.

6. Conclusion

We have presented miniaturized, focusing fan-out elements. The new micro-optical elements were fabricated using different technologies: double-sided injection moulding in polycarbonate, double-sided photolithography with subsequent etching in quartz, and direct laser writing in photoresist. For the fabrication, two different concepts were used: either the two optical functions are implemented on the two opposite sides of one substrate, or the fan-out function is superimposed on the focusing function of a plano-convex microlens.

We have demonstrated that the three different technologies can be successfully employed for the fabrication of miniaturized focusing, fan-out elements, although each technology has certain advantages and limitations. The small size of the combined elements makes it necessary to use fan-out gratings with small grating periods. This causes a relatively large uniformity error for the fan-out elements presented in this work. The characterization showed that the quality and overall performance of the elements fabricated by injection moulding is satisfactory. The advantage of this technology is the possibility of mass production at low cost.

The focusing and the fan-out functions on the two opposite sides are aligned to within about 20 μm. The quartz elements showed the best optical performance. However, the transfer of deep photoresist microlenses into quartz is not a standard process. The direct laser writing technique has the advantage that a prototype can be fabricated relatively quickly. For a replication of the hybrid elements only one surface has to be replicated and therefore no alignment is necessary. Critical for the performance of the elements is the homogeneity of the additional photoresist layer.

References

[1] Nussbaum Ph, Völkel R, Herzig H P, Eisner M and Haselbeck S 1997 *Pure Appl. Opt.* **6** 617–36

[2] Berger Ch, Collings N, Völkel R, Gale M and Hessler T 1997 *Pure Appl. Opt.* **6** 683–9

[3] Wang M R, Sonek G J, Chen R T and Jannson T 1992 *Appl. Opt.* **31** 236–49

[4] Hutley M C 1997 Refractive lenslet arrays *Micro-Optics: Elements, Systems, and Applications* ed H P Herzig (London: Taylor and Francis) pp 127–52

[5] Gale M T and Rossi M 1997 Continuous-relief diffractive lenses and microlens arrays *Diffractive Optics for Industrial and Commercial Applications* ed J Turunen and F Wyrowsky (Berlin: Akademie) ch 4

[6] Gale M T, Hessler Th, Kunz R E and Teichmann H 1996 *OSA Tech. Digest* **5** 335

[7] Gale M T 1997 Replication *Micro-Optics: Elements, Systems, and Applications* ed H P Herzig (London: Taylor and Francis) pp 153–77