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Novel micro-optical components made from optical adhesives

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ABSTRACT

Using a drop-on-demand print head allows for PC-controlled production of various types of microlenses as well as lens arrays. The possibility to place microlenses on arbitrarily shaped substrates allows for novel optical elements like beam splitters or non-planar scattering discs. Another interesting possibility opened by pre-shaped substrates is the production of concave lenses, which are key elements for aberration correction in micro-optical systems.

Keywords: microlenses, lens arrays, drop-on-demand printing, optical adhesives, micro-system technology

1. INTRODUCTION

During the last years the interest in micro-optical systems has been growing steadily. This development is driven mainly by the demand for increasing bit-rates in information processing. Surely the optical fiber is the key element in optical data transmission. However, micro-optical elements are needed to couple light from laser diodes into the fiber as well as out of the fiber to a receiver.

An alternative concept for optical data transmission are free-space optical interconnects[1]. They rely on classical imaging using microlenses or holographic optical elements to connect multiple light emitters and receivers e.g. on different cards in a computer. They also allow for easy reconfiguration of the connections. Arrays of microlenses may serve as a means to redirect beams to different receivers.

Another important field of application for microlenses is sensors, for instance for wavefront analysis, or in confocal scanning microscopes[2]. Single microlenses and arrays of microlenses may also be used as beam shaping or homogenizing elements.

Generally the world of micro-optics differs considerably from that of well known macro-optics. Problems arise in manufacturing and handling such minuscule components. In particular the small size of the various elements causes difficulties in hybrid assembling due to increased sensitivity to damage by handling, cementing, bonding and welding and a decreased range of tolerances for positioning on the order of 0.1 to 1 microns. In addition to the conventional production[3] and handling of individual microlenses there are several technologies which avoid these problems.

One approach, as is done in macro-optics, is making both refractive and diffractive micro-optical elements from plastics by molding. Here the production of the master model requires the largest amount of effort because of the high precision needed. Though this method is good for mass production, it is too expensive for prototypes or small numbers of devices. Elements with practically any shape may be produced.

Another approach is the production of microlenses from a film of photoresist. After UV-exposure or using the LIGA process, small cylinders of the resist are etched and formed by melting on the substrate. Finally convex lenses are formed by heating the sample leading to a reflow of the material[4]. Like the above process, this involves rather sophisticated equipment and a large number of steps. The necessity of an exposure of the resist limits the process to planar substrates only. The shape of the

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microlenses is controlled by the surface tension restricting the amount of possible lens forms. Another restriction is the thickness of the film which can be exposed.

An alternative technology using a drop-on-demand (DOD-) microjet print head was first published by D. J. Hayes and W. R. Cox[5]. By dispensing very small drops of adhesives they generated convex refractive microlenses. In contrast to the above techniques this one does not need extremely sophisticated equipment. Furthermore, it is completely data driven and involves two steps, only placing the material and curing it when required. This allows for rapid prototyping of various optical elements[6]. For instance, there are no problems in applying the droplets directly onto the tips of fibres[7], thus reducing manufacture and assembly to one step.

The DOD technology allows placement of microlenses onto arbitrarily shaped targets. We exploit this feature in different ways, for example, in producing arbitrarily shaped scattering discs. Another application is in beam splitters, where a microlens is placed in the centre of a conventional lens. From our experiments, using a preshaped substrate it seems probable that we can offer concave lenses, which are an essential complement to convex lenses in imaging systems and may be used to correct lens aberrations.

2. TECHNOLOGY

A scheme of the apparatus for the production of microlenses is given in fig. 1. In this set-up we used a piezo-driven DOD-print head[8] with a 100 μm nozzle. Each voltage pulse from the controller induces a shock wave inside the nozzle and leads to the ejection of a single drop of adhesive. Its temperature and, thus, also viscosity are held constant by the print head controller. The lenslet position is determined by an x-y-table. A computer program controls both the number of drops forming an individual lens and positioning of the table.

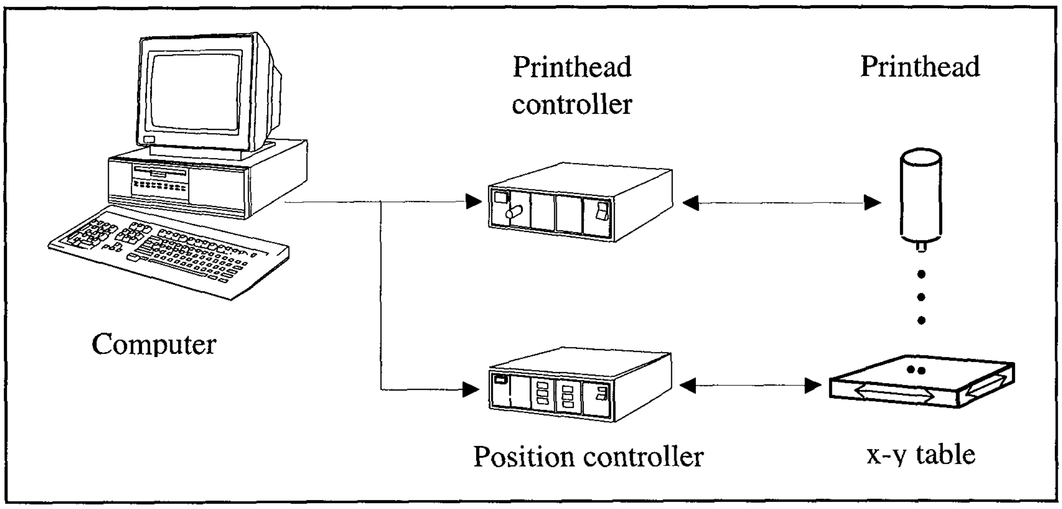

Fig. 1: Scheme of the apparatus for the production of microlenses

As the basic material for the lenses we used the UV-curable optical adhesive NOA 61. Since this material is designed especially for optical applications. It has a high transmission over the whole visual spectral range and its properties are well characterized. As a precondition for its use in a DOD print head it has also relatively low viscosity.

The lens shape is controlled completely by surface tension. This guaranties a high surface quality, but limits the achievable shapes of the lenses to spheres, cylinders or ellipsoids[6]. The state of the art is using planar substrates for making only convex lenses. Their numerical aperture is determined by the surface contact angle between adhesive and substrate.

To overcome these limitations on the shape of the lens we have used preshaped substrates. For instance we have successfully obtained concave lenses when we placed the drops in small cylindrical holes. Hole diameters as small as 100 μm were produced by classical micromachining. To obtain concave lenses by this procedure the surface contact angle between adhesive and substrate must not exceed 90°. Finally the hole may be filled to its upper end with another suitable adhesive to obtain a duplet lens.

3. RESULTS

In a first step we measured the surface shape of the individual lenses using a Talysurf 120L profilometer. The results are the diameter of the lens, its radius of curvature and the deviation of the surface from the best sphere. Typical values for NOA 61 on a glass substrate are presented in table 1. Since the curvature of the lenses is controlled primarily by surface tension the numerical aperture remains nearly constant. The remaining slight decrease is due to the influence of gravity, which tends to flatten larger lenses.

number of drops	diameter d (mm)	volume V (nl)	height h (μm)	radius of curvature r (mm)	focal length f (mm)	numerical aperture NA
1	0.163	0.375	35.9	0.105	0.188	0.398
3	0.24	1.14	50.6	0.166	0.297	0.375
5	0.288	1.89	56.7	0.203	0.363	0.369
11	0.394	4.29	70.8	0.304	0.543	0.341
20	0.496	7.86	82.2	0.421	0.753	0.313
100	0.786	40	154	0.587	1.049	0.351

Tab. 1: Data of convex microlenses made from NOA 61 on a planar glass substrate

In addition we investigated the quality of individual lenses interferometrically. Two different methods were used. First the deviation of the surface shape from a sphere was measured with a Twyman-Green interferometer. The result is a r.m.s. deviation from the best sphere by 0.5 λ or 3 λ peak-valley at 633 nm, respectively. A typical result is displayed in fig. 2. The form of the deviations indicates a slight ellipticity of the lens circumference. Consequently most errors concentrate at the edge of the lens.

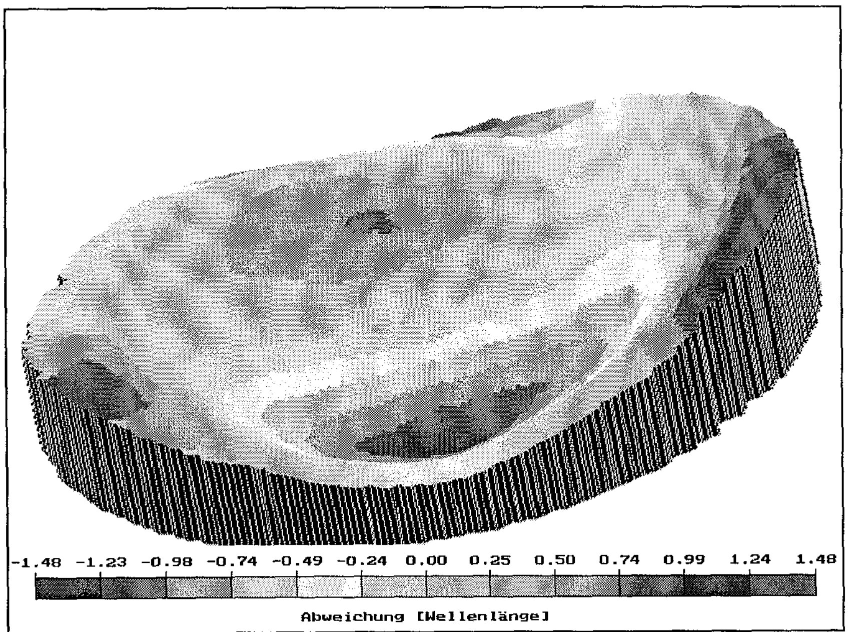

Fig. 2: Evaluation of the surface shape of a convex microlens. The lens was made from a single drop of NOA 61 on a glass substrate. The results were obtained using a Twyman-Green interferometer.

The imaging properties of the convex lenses were also evaluated with a shearing interferometer. The results of this method contain direct information on the wavefront aberrations. To exclude the errors induced by the boundary the lens was stopped down to 70% of the full aperture. The resulting r.m.s. deviations amount to 0.15 λ or 3 λ peak-valley. The corresponding point spread function has a width of 3 μm. If the aperture is reduced further to 50% the peak-valley deviation drops to 0.6 λ which corresponds to 0.12 λ r.m.s.. If we take into account the high NA of the lenslets and the simple production method, these results are surprisingly good.

Similar investigations were carried out on concave lenslets produced on a preshaped PMMA sample. Data for three different lenslets are given in table 2. One difference that is not fully understood compared to the production of convex lenses is the surface contact angle at the edge of the hole is not clearly defined. If the adhesive in the hole reaches the rim, the surface curvature will also depend on the amount of material deposited which gives an additional degree of freedom to control the lens shape.

hole diameter d (mm)	surface sag below rim h (μm)	radius of curvature r (mm)	focal length f (mm)	numerical aperture NA
0.75	229	0.469	-0.838	0.408
1.05	349	0.655	-1.171	0.409
1.55	320	1.268	-2.267	0.323

Tab. 2: Data for concave lenslets produced from NOA 61 on a PMMA sample with premachined holes.

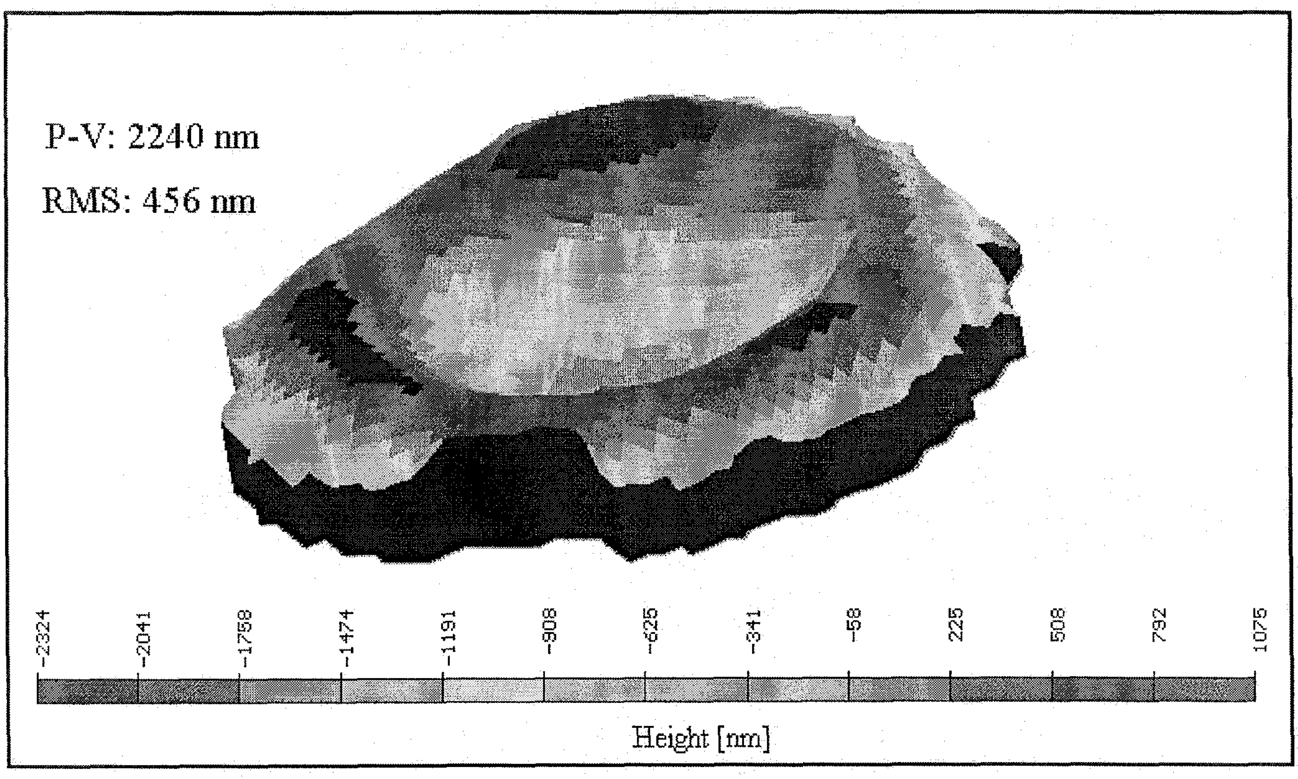

Fig. 3 Interferometric evaluation of the surface shape of a concave microlens at wavelength $\lambda = 633$ nm. The lens was made from NOA 61 on PMMA. The hole diameter was 0.75 mm.

The investigation with the Twyman-Green interferometer revealed, that the primary errors of the surface are symmetric around the optical axis. Thus spherical aberration is dominant. A typical picture of the deviations is given in fig. 3. The respective deviations are 0.7 λ r.m.s. or 3.5 λ peak-valley. These errors exceed those of the convex lenses. The reason is the larger N.A. on the one hand and the influence of shrinkage of the adhesive on the other.

The use of uniform arrays of microlenses for beam homogenization or for confocal microscopy[2] is already well established. Performance is usually limited by the reproducibility of the lens shapes and positions. Table 3 presents results on the reproducibility of different lens parameters.

	lenses made from 5 drops				lenses made from a single drop			
measured quantity	volume	diameter	radius	height	volume	diameter	radius	height
standard deviation within one array	0,7%	0,7%	1,1%	0,6%	0,1%	1,2%	1,9%	0,7%
standard deviation between different samples	4,8%	3,5%	8,2%	6,1%	4,6%	2%	8,7%	6,6%

Tab. 3 Reproducibility of lens shapes. The lenses were made from NOA 61 on glass.

The position error was measured for an array of lenses made from 5 drops each. The average spacing was 261 µm with a standard deviation of 5 µm. The position error is not due to the errors of the table but due to irregularities in the motion of the drops between the print head and the sample.

In addition to regular arrays, arrays with arbitrary sizes and distributions of lenses, may be produced using the DOD technique. Such elements may be used to achieve predefined non homogeneous beam shapes. Different sized lenses also allow for varying focal length. For instance, this variation may be used to monitor the surface profile of a certain object using the confocal geometry. An example of such an inhomogeneous array is displayed in fig. 4.

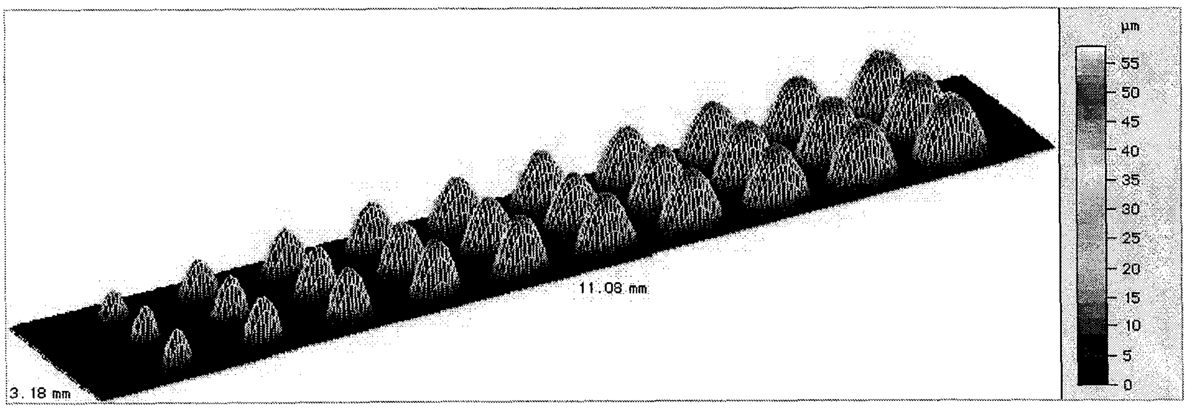

Fig. 4 An array of microlenses with different sizes of the individual lenses (NOA 61 on glass).

Another application which uses the possibility to print lenses onto variously shaped substrates, is to place a lenslet on a conventional lens. We demonstrate this possibility in fig. 5.

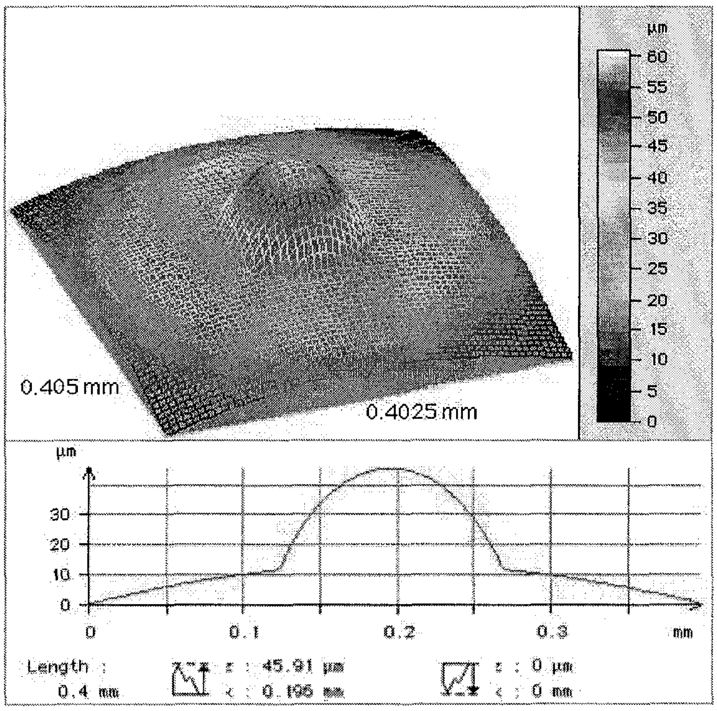

Fig 5 Lenslet made from NOA 61 placed on a conventional glass lens with a radius of curvature of 1.5 mm.

Such a configuration may be used for beam splitting. A typical application could be in a laser range finder. There the lenslet would couple the beam from the transmitting laser into the optical path. The size of the coupling lens has to be small to avoid vignetting in the path back to the receiver.

4. SUMMARY

The drop-on demand printing of micro-optical components is a promising technology for the rapid production of samples or small numbers of components. It enables production of a variety of different components in particular convex, concave and cylindrical lenses. The production of multiple-component lenses is possible if suitable materials are found. One of the main advantages is the possibility to place the components on substrates of almost any form and size. The use of this technology is limited only by the quality, the exact shape produced and by the precision of placement.

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