Microlens fabrication in PMMA with scanning excimer laser ablation techniques.

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Abstract.

Laser ablation is a versatile technique for fabricating microstructures on polymer surfaces. Due to the nature of the process, the fabrication of the microstructure can take place in a very late stage of a heterogeneous assembly. This makes laser ablation very attractive for fabricating micro-optical components on opto-electronic assemblies in comparison to other fabrication techniques like injection molding and embossing.

In this paper we will report on the first experimental results of microlens fabrication with excimer laser ablation techniques. By scanning the polymer surface along multiple circular paths with a circular beam of a pulsed excimer laser, one is able to obtain a lens shape with arbitrary focal distance and diameter. Important issues as choice of ablation parameters, selection of scanning path and performance of the resulting laser ablated lens will be discussed.

Introduction.

An increasing number of opto-electronic applications makes use of 1D or 2D arrays of optical beams. Often these beams need to be collimated or focussed by microlens arrays.

Fabrication technologies for these micro-optical components are embossing and injection molding (both mass-production oriented), lithography, deep proton lithography[1], micro-jet printing, LIGA, laser ablation, …

In literature several methods are described to realize microlenses with excimer laser ablation. In general, they are based on the use of complex mask patterns for fabrication of Fresnel[2] or refractive microlenses[3] and CGHs[4] (Computer Generated Holograms) by direct ablation, or involve the use of selected polymer materials in a process[5] based on ablation or irradiation and diffusion of doping agents in order to achieve a curved surface.

The approach we propose here is based on direct ablation and requires little post-processing. The whole fabrication process is an essentially non-contact method and can be performed on a multitude of polymer materials or layers. It can be applied in a final step of the fabrication of an opto-electronic heterogeneous assembly.

Microlens fabrication approach.

The lens fabrication method we propose in this paper, uses a simple circular aperture for the excimer beam and a high precision translation stage carrying the PMMA substrate, which is able to make circular movements. The pulse energy and the pulse frequency (number of pulses per second, f) remain constant during the process. While the excimer laser is firing pulses, the translation stage makes subsequent circular movements with different radii and speeds. The relationship between ablation parameters and eventual lens profile is explained hereafter.

- Profile of the ablated trench.

In the ablation set-up we use a projection lens to image the circular aperture on the mask onto the PMMA substrate with a certain demagnification. We assume that the intensity of the laser light is constant on the sample within the illuminated area (diameter ρ). A circular movement of the table will result in the ablation of a closed trench. If R is the radius of the circle, v the speed of the table movement and d the depth of ablation per pulse, the resulting ablated profile can be described as

$$depth(s) = \frac{1}{\pi} \cdot a\cos\left(\frac{\left(\frac{\rho}{2}\right)^2 - R^2 - s^2}{-2 \cdot R \cdot |s|}\right) \cdot \Phi\left(R + \frac{\rho}{2} - |s|\right) \cdot \Phi\left(\frac{\rho}{2} - R + |s|\right) \cdot \Phi\left(R - \frac{\rho}{2} + |s|\right) + \Phi\left(\frac{\rho}{2} - R + s\right) \cdot \Phi\left(\frac{\rho}{2} - R - s\right) \cdot \Phi\left(\frac{\rho}{2} - R\right) \cdot \frac{2 \cdot \pi \cdot R \cdot f \cdot d}{v}$$

by considering the overlap of the aperture with the circle of movement (Φ is the heaviside function). This function is illustrated in FIG. 1 for several values of R and ρ. In FIG. 2 we compare the calculated profile with the experimental results for a particular value of R and ρ. The latter are measured by a Tencor profilometer. One can observe that the measured values deviate from the theoretical curve at the edges. This is likely due to the inability of the contact needle to measure steep edges. The influence of lower laser pulse intensity at the edges of the mask can play a role as well. This will be further investigated in the near future.

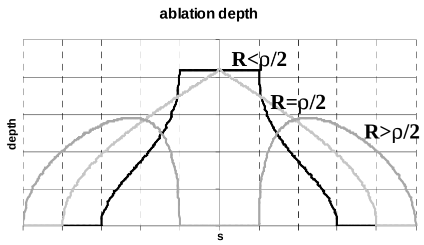

FIG. 1: Profile of ablated circular trenches for different values of R.

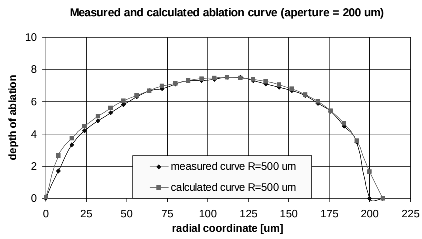

FIG. 2: Comparison of the theoretical and experimental profile.

- Approximation of the desired lens shape

In a next step we assume that a microlens shape can be approximated by executing several of the circular paths mentioned above at variable speeds. This idea is illustrated in FIG. 3.

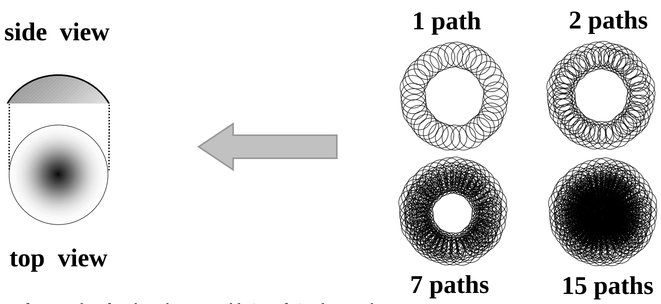

FIG. 3: Approximation of a curved surface by subsequent ablation of circular trenches.

The overlap of the subsequent pulses determines the depth per channel and the overlap between the neighboring channels can be chosen to achieve a smooth surface profile.
A least squares method has been applied to optimize the radii and stage velocity.

- Laser ablation of the microlens.

In a last stage, the optimal radii and speeds are used as input to create the control code for the translation stage of the laser ablation unit. Before execution, the trenches with a depth larger than a certain d_{max} are split up in several trenches with the same radii but smaller depths, and the order of the circle movements are randomized to minimize effects of a non-planar surface on the ablation process.

Experimental set-up and results.

The experiments were carried out with a Lumonics Pulse Master 848 (ArF 193 nm wavelength) and by means of an optical set-up (Optec's Micromaster) as in FIG. 4.
A Molectron J3 pyroelectric joulemeter, put at far distance from the image plane, was used for energy density measurements. The PMMA sample is about 250 μm thick and is attached to the translation stage by a vacuum line.
After ablation of the microlens in PMMA, the surface of the sample is cleaned by pressed air and H_2O and the microlens area is exposed to a number of excimer pulses with low energy (near ablation threshold of the PMMA). Then the cleaning step is repeated. This procedure allows us the clean the surface of the microlens in an efficient way. Another benefit of the post-illumination of the sample is masking the possible creation of a ripple due to the discrete nature of the process. Since the laser fires discrete pulses, the bottom of the trench that is created during the circular movement of the table will have a step-like nature. Though, when the rotational move is slow enough, the subsequent pulses will hit the sample in practically the same area. If those regions only differ about Δ in distance, then we can assume that there is no ripple when Δ is small enough so the lens can not resolve it ($\Delta < 1.6$ μm in the focus plane). This limit translates in a maximum velocity of the table.
On the other hand, we do not like to write the lens to full depth at one go since this can heavily influence the ablation of a neighboring, overlapping channel. A maximum depth will be determined that is allowed to be ablated in one time. This results in a minimum velocity of the table.
Both speed limits can in practice be rather close to each other. The minimum value is easy to implement in the generation of control code for the laser ablation process by simply chopping trenches in several pieces with a much smaller depth. Handling the maximum value however is not that evident: given a certain aperture and a required depth, it is very much possible the table has to move faster than allowed by Δ. This is in particular the case when using large apertures and requiring small depths. To a certain extent we can solve this problem by limiting the pulse energy, introducing an offset in depth (bury the microlens deeper into the PMMA sample) and by post-processing the microlens as described above. In the fabricated microlens shown below, neither of these solutions except for the post-processing has been performed.

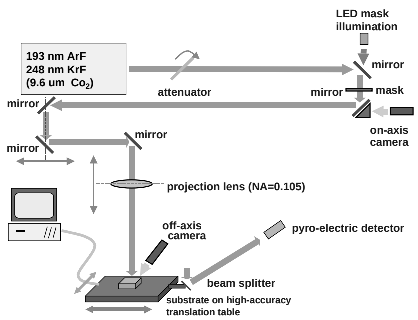

FIG. 4: Laser ablation set-up.

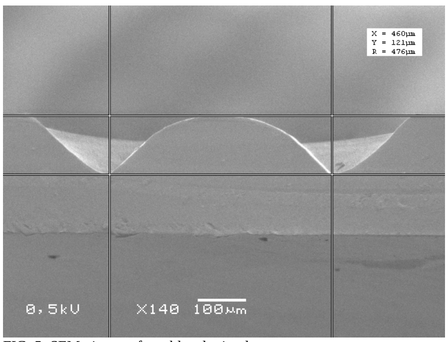

FIG. 5: SEM picture of an ablated microlens.

In FIG. 5 a SEM picture is shown of laser ablated microlens with a diameter of 460 μm and a radius of curvature equal to 280 μm. We used the excimer laser firing pulses with an intensity of 270 mJ/cm^2 at 20 Hz. The beam aperture had an on-substrate size of 200 μm and 39 trenches were used to write the lens. FIG. 6 illustrates a close-up on the surface profile of the lens and FIG. 7 illustrates the surface morphology of the microlens before and after exposure to sub-threshold pulses (post-processing).

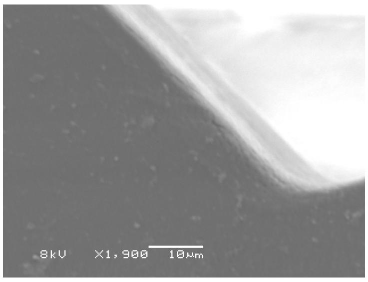

FIG. 6: Close-up on a cross-cut of the microlens.

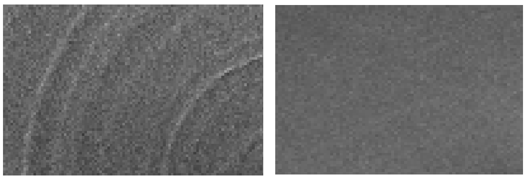

FIG. 7: Microlens surface with and without exposure to near-threshold pulses. Both surfaces were cleaned with pressed air and H_2O.

Conclusions.

The scanning aperture method has been successfully implemented in the fabrication of a microlens with laser ablation techniques. Further research is now being performed to analyze and evaluate the surface in terms of optical quality and the performance of the lens in an optical set-up. The algorithm is also being optimized to calculate faster and to take limitations on variable parameters (e.g. sample stage velocity) into account.

Acknowledgements.

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