

# **Plastic Microlens Arrays by Deep Lithography with Protons: fabrication and characterization**

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*In this paper we focus on the fabrication of individual plastic refractive microlenses with Deep Lithography with Protons (DLP). We give a detailed description of the microlens fabrication technique and the calibration procedure that goes along with it. We highlight the geometrical and optical characteristics of these DLP microlenses and we demonstrate the reproducibility of the fabrication process. We also illustrate the prototyping flexibility of DLP by making arrays featuring microlenses with different sags, pitches and diameters.*

## **1. Introduction**

The efficient integration of arrays of opto-electronic devices into photonic data handling systems calls for the development of high-quality, high-precision, low-cost refractive micro-optical structures like 2D arrays of spherical and cylindrical microlenses, micro-prisms integrated with mechanical positioning structures such as 2D fiber array holders. The vast domain of applications where these Micro-Opto-Mechanical Structures (MOMS) can be used is the major driving force behind our interest in their fabrication. Today different technologies exist that allow the fabrication of individual high-quality micro-optical refractive components. However, technologies that allow to fabricate 3D monolithic modules that combine various types of micro-optical components and structures are scarce. Deep Lithography with Protons (DLP) is one of those rare candidate technologies to fabricate 3D MOMS [1].

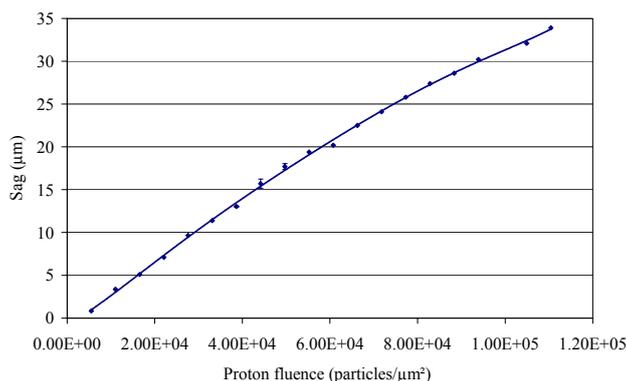
## **2. Deep lithography with protons: basic principle to fabricate microlenses**

The concept of the DLP process is based on the fact that protons, which penetrate a sample made of linear high-molecular-weight PMMA, will split the long polymer chains [2]. As a consequence the molecular weight of the material located in the irradiated zones will be reduced and free radicals will be created, resulting in material properties that are very different from those of the bulk. The irradiated zones therefore feature a higher solubility than the non-irradiated zones for specific solvents and can be selectively etched [3]. What is more, we can also swell the irradiated domains using a monomer vapor. Indeed, because of the lower molecular weight of the PMMA material in the irradiated zones of the sample, the diffusion velocity for small molecules will be much larger than in the non-irradiated bulk material. This selective diffusion process will cause a considerable expansion of the irradiated volume, which for circular footprints will result in hemi-spherical surfaces. After diffusion into the PMMA sample the monomers will bond to the irradiation-induced free radicals and as a consequence will be fixed in the sample. This process, the details of which are described hereafter, permits the fabrication of stable spherical microlenses with well-defined sags [4].

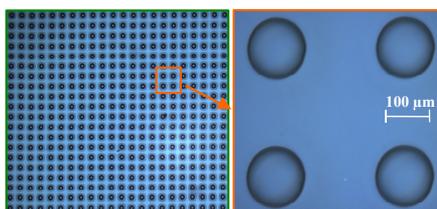
## **3. Calibration of the microlens fabrication**

To calibrate our DLP fabrication method we irradiated a 10x10 array of 125  $\mu\text{m}$  diameter microlenses whereby we increased the proton fluence from  $0.5 \cdot 10^4$  particles/ $\mu\text{m}^2$  to  $1.1 \cdot 10^5$  particles/ $\mu\text{m}^2$  in steps of  $5.5 \cdot 10^3$  particles/ $\mu\text{m}^2$  with increasing column number. The sample was

placed in a 70 °C temperature-controlled reactor. Next 10 ml MMA was injected with a syringe and we allowed swelling to take place during 40 minutes. Finally the microlenses were stabilized through UV exposure as this results in the highest-quality microlenses. The sags increase from 5.1 to 34 μm for proton fluences spanning the range from 1.7 10<sup>4</sup> particles/μm<sup>2</sup> to 1.1 10<sup>5</sup> particles/μm<sup>2</sup> (see Figure 1). From this figure we can conclude that the sag of the microlenses increases linearly with the proton fluence. The uniformity of the microlens characteristics in each column of the array under study is better than 2%. Using this calibration curve for the swelling of 125 μm diameter lenses, we demonstrated the uniformity of DLP. We therefore irradiated an array of 80x80 identical microlenses with a proton fluence of 3.04 10<sup>4</sup> particles/μm<sup>2</sup>, a diameter of 125 μm and a pitch of 250 μm (see Figure 2). From the calibration curve we can expect for this proton fluence a microlens sag of 10.5 μm.



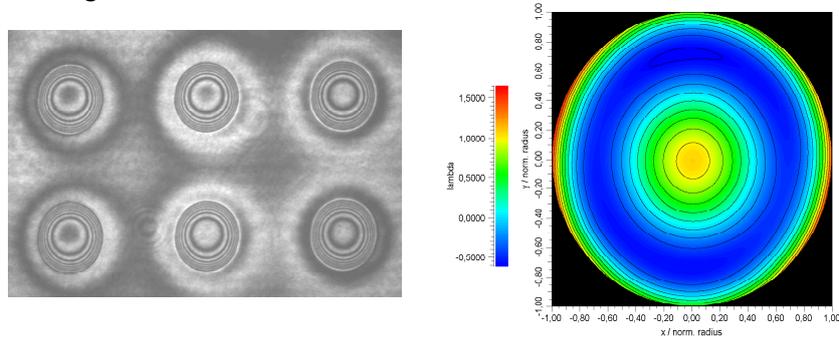
**Figure 1: Microlens sag (μm) as a function of the proton fluence (particles/μm<sup>2</sup>) (swelling: 40 min @ 70 °C, stabilization: 40 min UV exposure)**



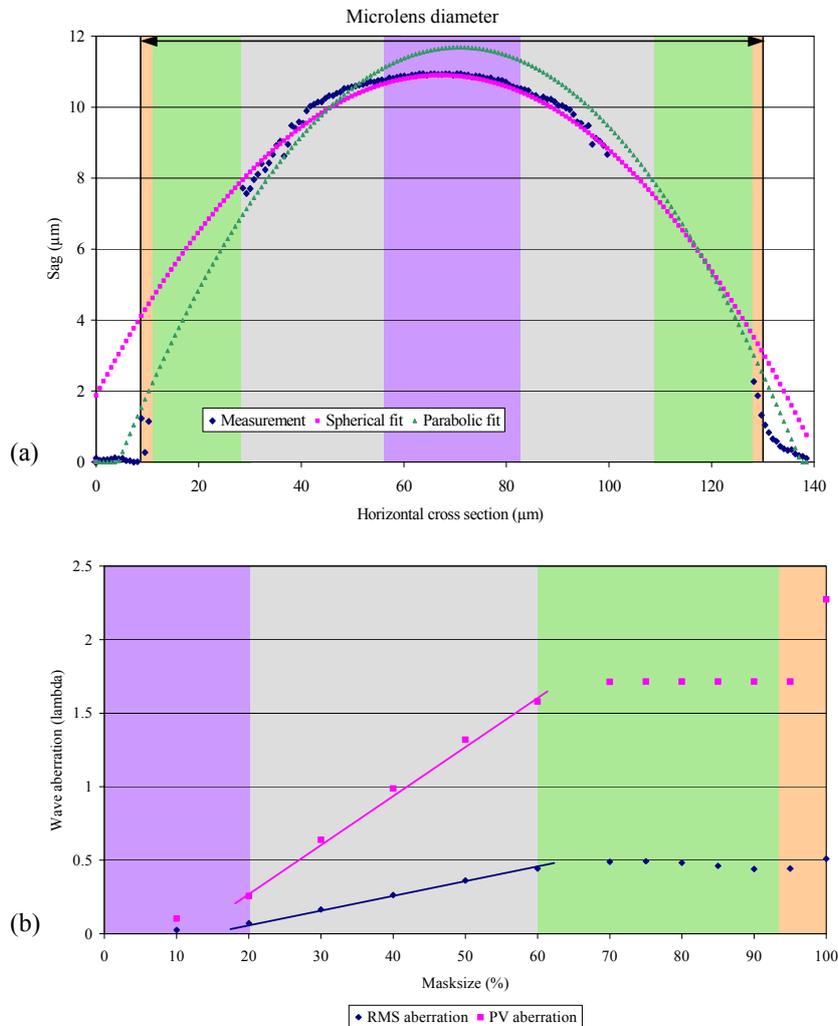
**Figure 2: Part of a 80x80 microlens array with 125 μm diameter lenses**

For 50 randomly chosen microlenses we measured the sag and the diameter of the microlenses along the x and the y direction with a non-contact optical profiler. We found that the microlenses have an average sag of 10.47±0.28 μm, while they feature a diameter of 119.81±0.59 μm and of 123.94±0.28 μm along the x and y direction respectively. From the latter measurement values we can conclude that the microlenses are very uniform over a very large array (2.7%). These microlenses however have a footprint that is slightly elliptical (ellipticity of 1.04). The use of a Mach-Zehnder interferometer with plane wave illumination allows a visual inspection of the uniformity of the microlens array as shown in Figure 3a. However a quantitative characterization of the microlens uniformity in the array can only be performed by evaluating each lens individually. By performing such a characterization we find a focal length of 398.60±10.53 μm. A study of the aberrations with spherical wave illumination reveals that the microlenses have an RMS and PV aberration of 0.532±0.031 λ and 2.51±0.33 λ respectively. Figure 3b displays the measured wave aberrations for one of the microlenses of the array. To investigate the main origin of the aberrations of a 125 μm diameter microlens (its cross-section is shown in Figure 4a) we plotted the RMS and PV wave aberrations as a function of the chosen mask size during a measurement (see Figure 4b). We observe that for mask sizes up to 60% of the lens diameter the wave aberrations increase linearly with increasing mask size. However the aberrations do not increase for mask sizes beyond 60% and up to 95% of the lens diameter. This leveling off can be ascribed to the aberration compensating effect of the

aspherical lens profile of the microlens under test. Finally for the last 5% of the lens diameter the aberrations of the microlens make a sudden jump. This effect is due to the fact that these measurements include the rim region of the lens which shows higher aberrations because of the local defects or irregularities in the irradiation mask.



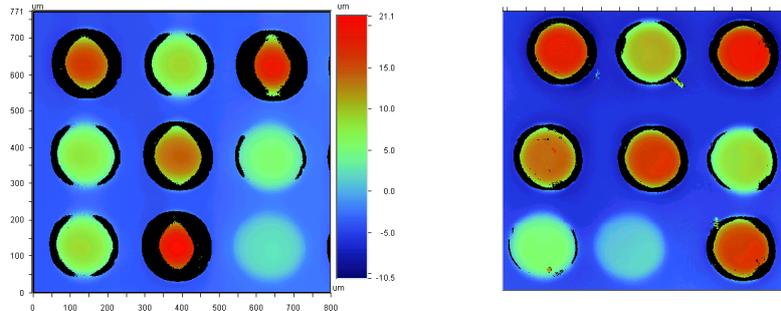
**Figure 3: (a) Part of the microlens array measured with a Mach-Zehnder interferometer and a plane wave illumination; (b) Wave aberrations (RMS  $0.51 \lambda$ , PV  $2.37 \lambda$ , distance between lines  $0.2 \lambda$ ) for one of the refractive microlenses ( $D=125 \mu\text{m}$ ;  $h=10.5 \mu\text{m}$ ) measured with a Mach-Zehnder interferometer**



**Figure 4: (a) Cross-section of a DLP microlens ( $D=125 \mu\text{m}$ ;  $f=406 \mu\text{m}$ ) fitted to a perfect sphere and a parabola; (b) The influence of the mask size on the RMS and PV wave aberrations ( $\lambda$ ) for this microlens**

#### 4. Flexible prototyping of various microlens arrays

Using the calibration curve of the microlens swelling process as derived in section 3, we now demonstrate the prototyping flexibility of DLP for the fabrication of microlens arrays. As a first example we fabricated a 3x3 array where every 200  $\mu\text{m}$  diameter lens featured a different sag ranging between 5 and 24  $\mu\text{m}$ , while the lens pitch was fixed at 250  $\mu\text{m}$  (see Figure 5a). As a second example we show in Figure 5b a similar 3x3 array of microlenses with a diameter of 200  $\mu\text{m}$  but this time with pitches varying between 230 and 300  $\mu\text{m}$ .



**Figure 5:** (a) 3x3 microlens array with different sags, constant diameter ( $D=200\ \mu\text{m}$ ) and pitch ( $P=250\ \mu\text{m}$ ) measured with a non-contact optical profiler (WYKO NT2000); (b) WYKO plot of 3x3 array of 200  $\mu\text{m}$  lenses with different sags and various pitches

#### 5. Conclusions

We have introduced Deep Lithography with Protons as a flexible technology for prototyping individual plastic refractive microlenses and 2D arrays of these lenses. In this paper we mainly focused on the fabrication and characterization of these microlenses featuring a wide range of numerical apertures, diameters and pitches. What is more, these microlenses can also be integrated with other DLP fabricated micro-optical components. An important drawback however for using DLP to produce micro-optical components, is the time consuming irradiation and chemical processes. Recently we have remedied this issue by showing that DLP can be made fully compatible with the LIGA replication technique when low-cost mass fabrication of 2D and 3D micro-optical components in general and microlens arrays in particular are needed.

#### 6. Acknowledgement

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