The fabrication of cylindrical micro-lens arrays with Deep Lithography with Protons

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ABSTRACT

We report on Deep Lithography with Protons (DLP) as a promising, alternative technology for the fabrication of uniform, low-cost and replicable 1D cylindrical micro-lens arrays with high numerical apertures and chords ranging from 200µm to 1mm. After describing the different fabrication process steps, we will highlight the experimental characteristics of our cylindrical micro-lens arrays related to imaging and surface quality. Furthermore, we will illustrate the potentiality of DLP to offer suitable solutions for current problems in laser to fibre coupling by monolithically integrating these cylindrical micro-lens arrays with optical fibre-positioning U-grooves.

INTRODUCTION AND RATIONALE

Cylindrical micro-lenses and lens arrays are essential components to compensate the beam astigmatism of edge emitting lasers [1]. They also find use in industrial scanning and printing systems. In this paper we report on the fabrication of uniform, low-cost and replicable cylindrical micro-lens arrays with Deep Lithography with Protons (DLP or p-LIGA). The DLP process consists of the following basic procedures: a proton irradiation of a PMMA-layer in well-defined regions, followed by either a development of the irradiated regions with a selective solvent or by a volume expansion of the bombarded zones caused by a diffusion of an organic monomer vapour. If needed, both processes can be applied to different regions of a sample [2].

In this paper we only focus on the fabrication of cylindrical micro-lenses and therefor on the irradiation and the etching process. After discussing the fundamentals and the practical set-up of these processes, we will highlight the characteristics and some practical applications of the developed micro-lenses.

THE IRRADIATION PROCESS

The concept of the irradiation process is based on the fact that accelerated protons gradually lose their energy inside PMMA-plates. As a consequence, the molecular weight of the material located in the irradiated zones will be reduced and free radicals will be created. Therefore these zones achieve a higher solubility than the bulk material and they can be selectively etched using a special solvent.

When translating a 500µm thick PMMA-layer according to a curved pattern in a small-collimated proton beam with energy of 8.3MeV, we are able to precisely define the contours of high-quality cylindrical surfaces. For this purpose we use a closed-loop positioning system that consists of two inchworm-driven translation stages with a 50nm precision over a 2 inch travel range. Besides a precise positioning and movement of the sample, the second most critical parameter of the irradiation process is the dose that we have to deposit in the PMMA. We therefore developed a technique that allows a real-time measurement of the total amount of bombarding protons on the PMMA-plate. Its principle is based on the fact that the protons induce a current in the metal sample holder after they passed through the PMMA-plate. A precision-switched integrator trans-impedance amplifier that features resolutions of 1.6×10^6 particles instantaneously integrates this current. We obtain the final beam shape with the aid of a Nickel stopping mask with 30 high aspect-ratio cylindrical holes with diameters ranging from 20 µm to 1 mm. Up to now we have always generated circular proton beams with diameters of 200µm by selecting the 200µm aperture on the stopping mask [3].

Figure 1 shows a computer simulation of the absorbed dose distribution at the top and a cross section of a proton-irradiated curved zone inside a 500µm thick PMMA-plate. Here we assumed a "standard" irradiation procedure where we translate the sample with a step size of 0.5µm after each point bombardment with 3×10^8 particles. Due to this small step size and the relative large circular beam shape, the central parts of the irradiated zones absorb much higher doses than those near the edges (figure 1.b). Furthermore, the energy transfer of swift ions will remain more or less constant at the beginning of their trajectory (x = 0µm) (figure 1.c) and the ions that scatter in this region will deposit a low dose at the interface of the irradiated zone and the bulk material. At the end of their track however, due to the significant increase in energy transfer, straggled ions will deposit considerably more energy, hence causing the equal dose lines to diverge.

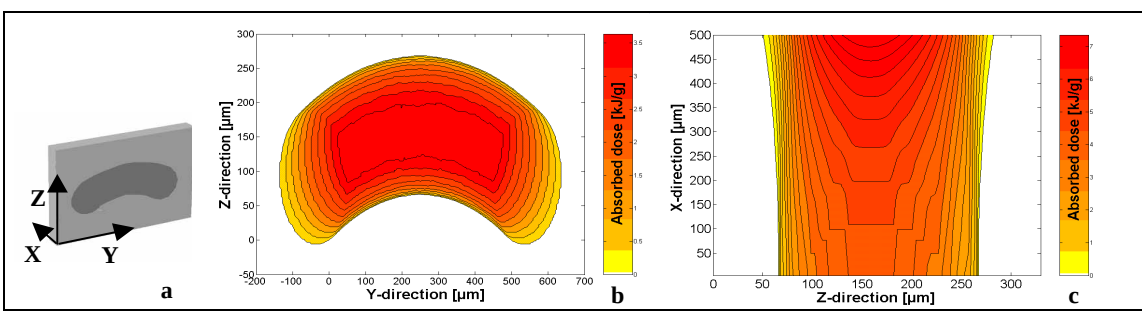

Figure 1: The absorbed dose profiles at the top surface (b) and a cross section at Y = 250µm (c) after a curved line irradiation.

THE ETCHING PROCESS

Once the PMMA-plate has been irradiated we can develop the bombarded regions by using a specific highly selective solvent, originally optimised for X-ray lithography. During this etching process, special care has to be taken to stabilise the temperature of the developer to an optimum temperature of 38°C. An ultrasonic stirrer enhances the removal of the etched material. After a development time of 60 minutes we place the sample in a stopping bath for 5 minutes. In a final step a water bath rinses all the residual chemicals from the sample.

When performing an irradiation using proton energies of 8.3 MeV and PMMA-samples with a thickness of 500µm, the protons will travel completely through the plate and the dose deposition (figure 1) will be such that the solvent will start to etch the material from both sides. In figure 2 we show the modelling results of the etching of a single cylindrical micro-lens with a chord of 500µm for three different timeframes. It can be seen that the development at the backside (i.e. the surface where the protons leave the PMMA-sample, here situated at the left-hand side of the figures) happens faster than at the front surface. This is due to the fact that the dose deposition at the backside is higher than at the front side of the sample. Moreover, due to the angular straggling of the protons, the size of the etched trench at the backside will be somewhat larger than at the front surface.

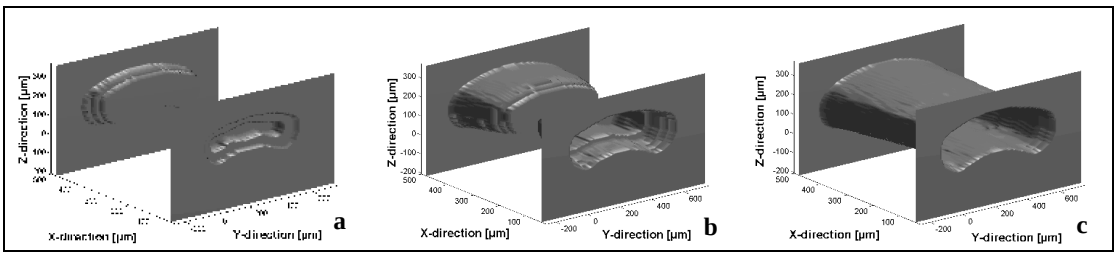

Figure 2: Simulation of the etching profile of a curved irradiated line after three arbitrary timeframes

CHARACTERISTICS OF CYLINDRICAL MICRO-LENSES

After applying the selective etching process to the irradiated curved zones, we produce bent optical surfaces. The flatness and the roughness of the resulting surfaces are determined by the magnitude of the straggling effect, by the precision of the movement of the translation stages and by the homogeneity of the deposited dose. At present we have improved both our irradiation and etching process to fabricate micro-lens arrays with high homogeneous curvatures ranging from 1mm to 2mm and chords from 200µm to 1mm (figure 3).

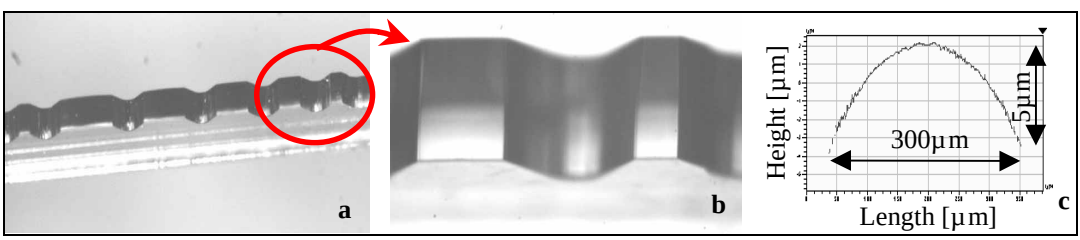

Figure 3: A close-up of a cylindrical micro-lens array with different chords and ultra-small heights.

During the characterisation of these components, we measured imaging qualities of 28.5 line pairs/mm and surface curvatures that are 250µm higher than the programmed design curvature. The latter deviation can be linked to a non-perfect flatness of the lens surfaces. Improved specifications are therefore expected in the near future after stabilising our proton beams and reducing the proton's scattering angle in the PMMA-plates by increasing the entrance energy.

THE FABRICATION OF A 1D OPTICAL FIBER CONNECTOR

Recently we have monolithically integrated these 1D cylindrical micro-lens arrays with U-grooves. As shown in figure 4, these grooves consist of rectangular etched-through zones combined with a special clenching mechanism that allows an accurate optical fiber positioning in front of the cylindrical micro-lenses. In the near future we will increase the mechanical stability of these components by creating fiber-positioning trenches with depths of 200µm in 500µm thick PMMA-plates. This allows us to lengthen these grooves while reducing optical fiber bends.

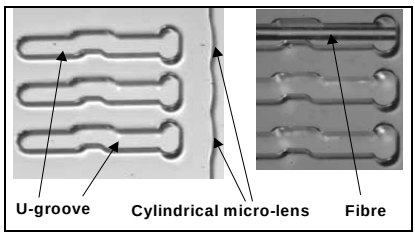

Figure 4: Top view of the monolithic integration of cylindrical micro-lenses with U-grooves and the positioning of optical fibres by mechanical alignment features.

CONCLUSIONS AND PERSPECTIVES

In this paper we have shown the potentialities of Deep Lithography with Protons for the fabrication of precise cylindrical micro-lens arrays. In the near future we will improve the optical surface quality of these micro-components by increasing the entrance energy and the stability of the proton beams. Furthermore we will integrate these lens arrays in both fiber-based and free-space optical interconnection modules. Finally it is important to notice that vacuum casting and injection molding techniques can replicate our developed micro-structures [4]. This allows to use DLP as a prototyping technology and to provide low-cost mass production by commercially available replication technologies.

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