The fabrication of 2D fibre alignment μ-optic structures using Deep Lithography with Protons

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Abstract

In this paper we present here a promising technology for the fabrication of deep mechanical fibre alignment structures with a lithographic defined circular shape, accurately ordered in massive 2D arrays. The fabrication process consists of irradiating PMMA-resist layers with high-energetic proton beams, followed by a selective development of the irradiated circularly shaped zones. To increase the coupling efficiency, we can additionally integrate uniform spherical micro-lenses created by swelling the proton-bombarded zones with a monomer vapour.

Introduction and rationale

The improvement of the optical performance of multiple fibre connectors (1D and 2D arrays of single-mode optical fibre) is still a challenge. It currently represents a bottleneck for the development of high fibre count network products and does not allow to simplify installation and shrink costs of fibre optic network deployments. Therefore, promising fabrication techniques like mechanical drilling [1, 2], laser ablation [3, 4] and stacking anisotropic-etched Si V-grooves [5] have been extensively investigated during the last decades. Notwithstanding these important efforts, until today none of the above mentioned techniques allows for the fabrication of reliable, low cost fibre insertion blocks that guarantee sub-micron positioning accuracies. In this paper we describe the perspectives of Deep Lithography with Protons to meet the stringent requirements of these 2D fibre coupling devices. We hereby present the basic process steps that lead to the fabrication of the individual connector components, namely 2D micro-holes and 2D micro-lens arrays.

Deep Lithography with Protons: The basic concepts

The DLP-technology consists in irradiating a Poly(MethylMetAcrylate) (PMMA) plate with a high-energetic circular micro-beam of protons originating from a cyclotron. During this irradiation the protons exchange energy with the high molecular chains of the plastic PMMA plate they are traveling through. As a result, the polymer chains break and chemical active centers are created. These changes can be exploited in the next process steps to shape the plastic plates in highly-efficient 2D fibre couplers. For the fabrication of the micro-hole and micro-lens arrays, we initially point irradiate the PMMA plates while stopping the beam after a critical number of particles have impinged on the sample, followed by a high-resolution sample translation towards the next point position (figure 1a). Two further chemical treatments of the irradiated plates can be done; the irradiated zones can be selectively etched or swollen in specific solvents, resulting in high-quality arrays of circular micro-holes or micro-lenses, respectively (figures 1b, 1c). These fabricated micro-structures in PMMA, can furthermore be mass-produced at low-cost by a suitable replication method [6].

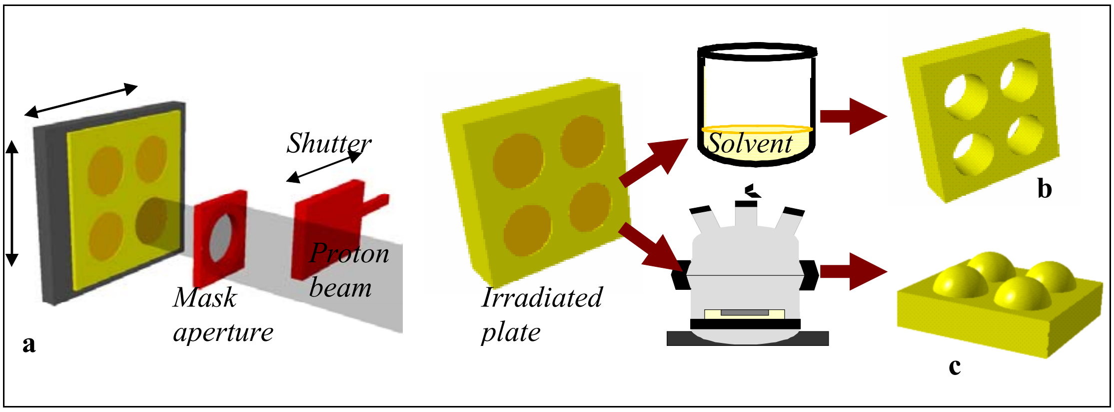

Figure 1: The 3 basic process steps of DLP ; A proton point-irradiation of a free-standing PMMA-plate (a), followed by a selective development (b) or swelling (c)

The fabrication of accurate, user-friendly and field-installable 2D arrays of fibre insertion holes

Optical simulations show that a small transversal misalignment of only a few micrometers between 2 single-mode fibres in a mechanical splice decreases the coupling efficiency drastically [7]. Therefore it is our aim to fabricate fibre connectors featuring pitches and circular fibre holes with a sub-micron accuracy. We fulfill the need for accurate pitches by moving the PMMA plate during the irradiation process from point-to-point with the aid of a closed-loop translation stage that ensures a precision of 50nm. As expected, this stage allows for pitches with an accuracy better than the 0.5µm measurement resolution of our optical non-contact profilometer [8].

The quality of the profile of the developed micro-holes is restricted by the quality of the mask aperture that shapes the proton beam impinging on the PMMA-plate. For the moment we use a 125µm mask aperture which corresponds to the cladding diameter of a standard optical single-mode fibre. After the first irradiation sessions, we developed an array of 5x5 micro-holes with diameters of 130±1.5 and 136±0.6µm in the 2 transversal directions at the front side of the PMMA plate (figure 2). The slightly larger diameters are a direct effect of the proton beam divergence and the thermal degradation of the bulk material that closely surrounds the irradiated spot on the sample. We will overcome these effects in the future by selecting a smaller aperture on our metal stopping mask. Due to a tilted position of the mask in the proton beam, we obtained on these first test samples unacceptable elliptical-shaped apertures. We will improve this shape in the future by implementing scintillation-based beam monitors in our beam-line that allow for a real-time adjustment of the mask aperture during the irradiation [9].

To allow for an easy manual fiber insertion in the micro-holes, it is also extremely important to create conical hole profiles with larger diameters at the backside of the connecting. Because of the multiple proton scattering during the beam propagation through the PMMA-plate, the proton beam will diverge inside the plate. This scattering effect results for the moment in a diameter enlargement of 30µm over a sample thickness of 500µm.

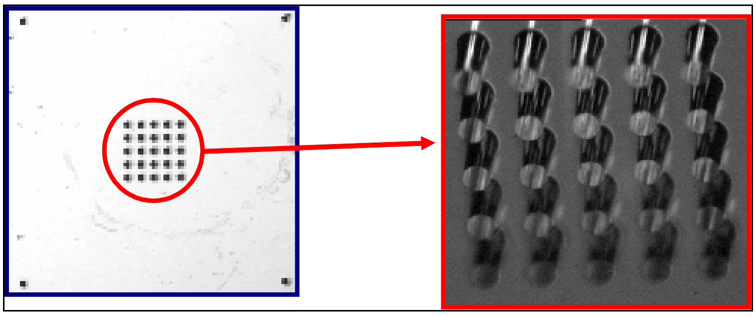

Figure 2: Recently developed 2D arrays of micro-holes: front surface (left) and side view through the sample thickness (right)

Improvement of the fibre coupling efficiency by integrating 2D spherical micro-lens arrays

We aim to design a tolerant fibre connector insensitive to different types of installation defects like longitudinal misalignments, dust, low-quality cleaved facets, etc. Hereby we make use of the generic character of the DLP technology that permits to fabricate besides positioning holes, 2D arrays of spherical micro-lenses. For this purpose, we bring the point-irradiated plate in an MMA monomer vapor. As a result of the decreased molecular weight, the monomers diffuse in the irradiated zones of the PMMA plate at an elevated temperature of 70 degrees C, resulting in a local swelling. The in-diffused monomers polymerize with the chemically active centers formed during the interactions between the protons and the PMMA molecules [10]. This reaction allows for the fabrication of 2D matrices of stabilized, spherical lens surfaces that we will use here to improve the coupling efficiency of a fibre connector.

During the last months, we extended the swelling process by resizing the diameter of the micro-lenses from 200µm down to 115µm and by extending the dimensions of the lens array (figure 3a). After a dedicated calibration of the swelling process for different crucial process parameters, like proton fluence, reaction temperature, and diffusion and stabilization time, it is currently possible to fabricate uniform lens arrays with different pre-defined focal numbers.

We depict in figure 3b a 5x5 spherical micro-lens array with a lens sag of 10.5±0.3µm and a pitch of 250µm. We integrated additional alignment holes in the corners of the plate which permit to align the micro-lenses right in front of the developed micro-hole array.

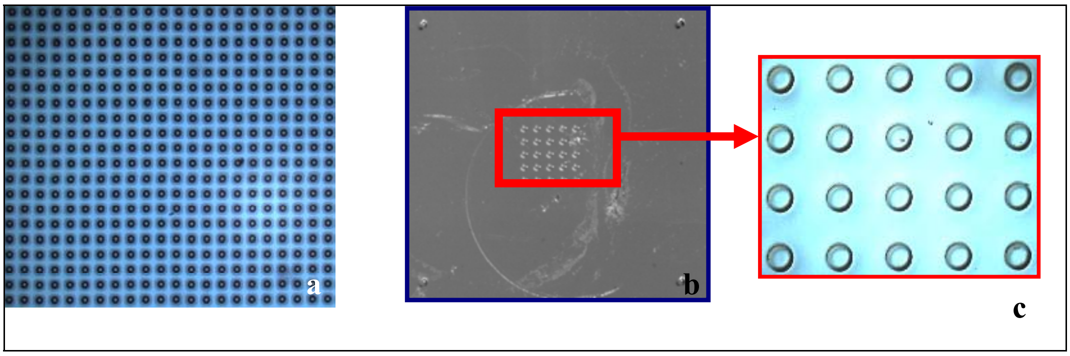

Figure 3: Spherical micro-lenses with DLP : Part of a 80x80 lens array (a) and a 5x5 lens array with additional alignment holes (b & c)

Conclusions and future perspectives

We presented in this paper Deep Lithography with Protons as a promising technology for the fabrication of connectors for 2D arrays of optical, single-mode fibres. After describing the major concepts of the fabrication processes, we discussed the impact of the proton interactions on the different characteristics of the fabricated micro-hole and micro-lens plates. In the future, we will monolithically integrate both plates using our in-house vacuum casting technique [6]. Afterwards, we intend to test the resulting components on their coupling losses in a dedicated optical set-up. Furthermore, from a more fundamental point of view, we will increase the initial energy of our proton beams to intensify the conical profile of the fiber insertion holes in thicker and therefore more stable PMMA-plates.

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