Fabrication of multimode polymer waveguides with integrated micro-mirrors using Deep Lithography with Protons

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Abstract

We present Deep Lithography with Protons (DLP) as a promising, fast prototyping technology to fabricate multimode polymer waveguides to transfer optical signals between in-plane emitters and receivers. A free-standing waveguide, with a 500 µm by 500 µm cross-section, was realized in Poly(Methyl MethAcrylate) (PMMA). We have characterized the surface roughness by means of an optical non-contact surface profiler and experimentally measured the optical transmission efficiency of the micro-optical component using a Hexapod six-axis parallel-kinematics robot. The results are compared with non-sequential ray-tracing simulations.

Introduction

In the foreseeable future, the communication bandwidth inside data processing systems will be severely limited by the properties of galvanic interconnections. These limitations stem from physical constraints imposed by RC time constants, ohmic losses and cross-talk between the conductances of these galvanic interconnections. The International Technology Roadmap for Semiconductors (ITRS) now states that optics is a potential alternative route to circumvent the underlying problems of galvanic interconnects [1] and optics is also said to have the potential to continue to scale with future generations of silicon integrated circuits. Future deployment of photonic interconnects on Printed-Circuit-Boards (PCB) and in Multi-Chip-Modules (MCM) will immediately create the need for a seamless interface between these different optical interconnect approaches. To that aim the TONA department of the VUB recently started investigating the potentialities of dedicated optical waveguide structures that make it possible to efficiently couple and/or redistribute the light originating from micro-sized on-chip transmitters into multilayer waveguides embedded in the PCB or into optical fiber arrays. In this paper, we present the simulation, fabrication and experimental characterization of a basic rectangular waveguide with integrated micro-mirrors, as shown in Figure 1, allowing a point-to-point interconnection.

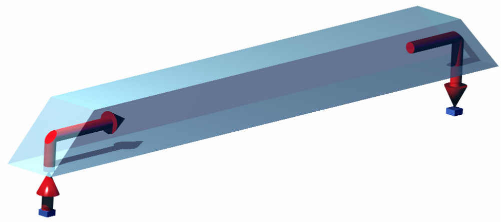

Figure 1: Basic rectangular waveguide with integrated 45° micro-mirrors for light coupling

Non-sequential ray-tracing simulations

Since the envisioned waveguide structures have a multimode character (due to their dimensions), non-sequential ray-tracing simulations give us an accurate view of the transmission efficiency of the waveguide. Figure 2 shows a ray-tracing through a free-standing PMMA waveguide with dimensions of 500 µm x 500 µm x 5 mm, and a mechanical holder structure with a base width of 500 µm, as it was actually fabricated.

The emitter used in the simulations is a standard single mode optical fiber SMF-28, with a numerical aperture of 0.13 and a core size of 8.3 µm (yielding a full width half maximum divergence angle of 8.79°), pigtailed to an INO FBS-CL broadband source (emitting light in the C+L band around 1550 nm). To calculate the irradiance distribution in the detector plane, we used Optis SPEOS to perform a non-sequential ray-tracing, thus including the Fresnel losses at the interfaces. Furthermore, we assumed perfect optical surfaces for our waveguide. This means that we are not taking into account the losses due to scattering.

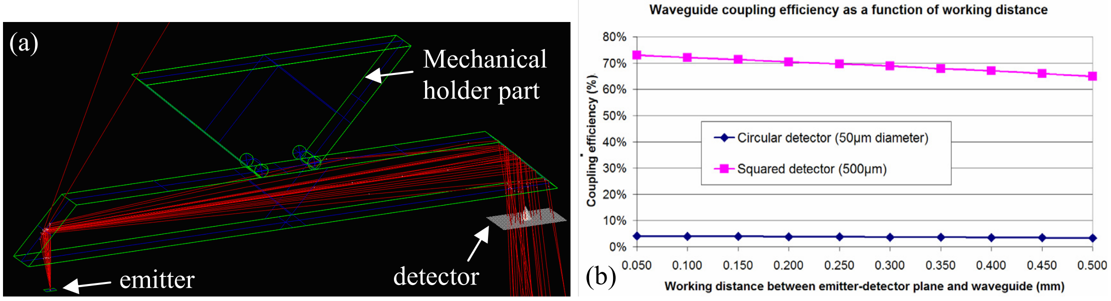

Figure 2: (a) Non-sequential ray-tracing simulation of an optical waveguide with 45° micro-mirrors interconnecting a laser source (left) and a detector (right) and (b) Simulation results: waveguide transmission efficiency as a function of working distance.

For a squared detector of 500 µm x 500 µm, we obtain transmission efficiencies above 70% for working distances up to 250 µm (see Figure 2 b), where the working distance is defined as the distance between the emitter-detector plane and the waveguide. The highest losses occur at the micro-mirrors (11.6% at emitter side and 7% at detector side). In the case of a fiber-to-fiber interconnection, the transmission efficiency drops to 4% if we take a 50 µm core-sized multimode fiber as detector. The mechanical holder structure introduces an additional loss of about 0.5% in this case.

Deep Lithography with Protons: the mastering process steps

For the fabrication of the waveguides, we use Deep Lithography with Protons (DLP) [2]. It is a unique technology for fast prototyping of micro-optical components. In general, the DLP process consists of the following basic procedures.

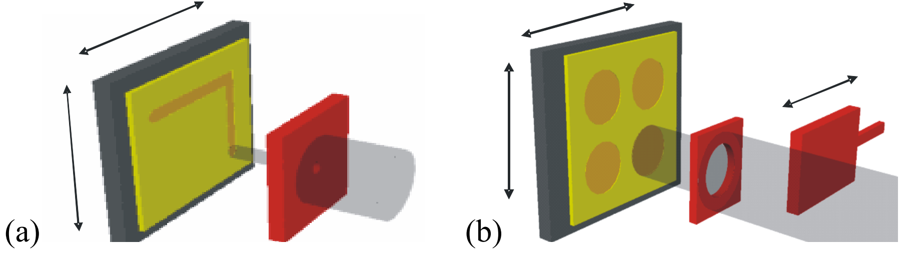

Figure 3: Irradiation step of DLP: Continuous (a) or point (b) irradiation of a PMMA sample

First a collimated, 8.3MeV proton beam is used to irradiate an optical grade Poly(MethylMethAcrylate) (PMMA) sample according to a predefined pattern by translating the PMMA sample, changing the physical and chemical properties of the material in the irradiated zones, as shown in Figure 3.

As a next step, a selective etching solvent is applied for the development of the irradiated regions. This allows for the fabrication of (2D arrays of) micro-holes, optically flat micro-mirrors and micro-prisms, as well as alignment features and mechanical support structures. On the other hand, an organic monomer vapor can be used to expand the volume of the bombarded zones through a diffusion process. This enables the fabrication of micro-lenses with well-defined heights. These processes are shown in Figure 4. If necessary, both processes can be applied to different regions of the same sample, yielding micro-optical structures combined with monolithically integrated micro-lenses.

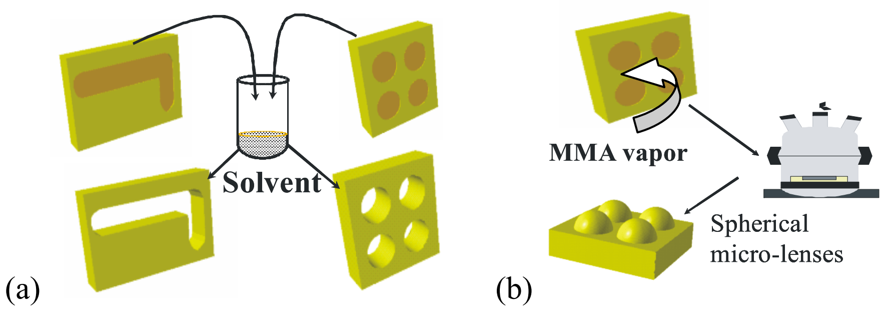

Figure 4: Chemical process steps of DLP: Selective etching process (a) and swelling process (b)

Experimental characterization

The surface profile of the polymer waveguide was measured using an optical non-contact surface profiler WYKO NT-2000, which is based on a Mirau interference microscope. The profiles along X and Y are shown on Figure 5.

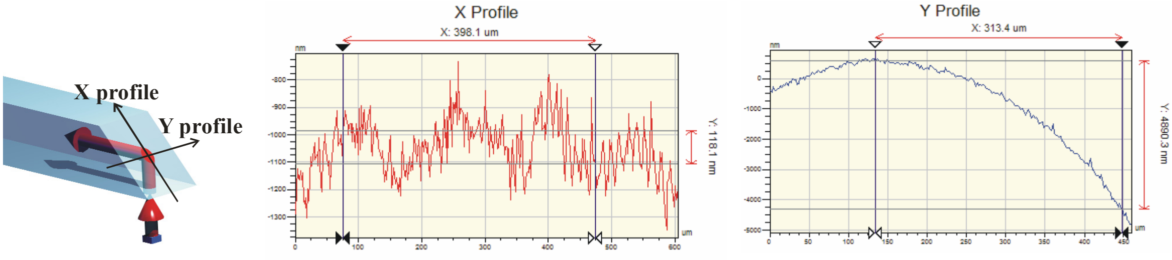

Figure 5: Surface roughness profiles along X and Y of the tapered facet of the waveguide, measured using an optical non-contact profiler

Because of the high accuracy of our positioning translation stages, we achieved an RMS surface roughness R_q = 118 nm over a length of 400 µm and a surface flatness of R_t = 4.89 µm over an area of 400 µm by 400 µm for the tapered facet of the waveguide.

The optical characterization of the coupling efficiency of the waveguides was performed using a Hexapod six-axis parallel-kinematics robot PI-206. In the experimental setup we used the same source as in the simulations (SMF-28), and a Thorlabs multimode fiber (MMF) with a core size of 50 µm and a numerical aperture of 0.22 as detector. Both fibers were fixed on a holder plate with V-grooves spaced 4.5 mm apart, as shown in the left part of Figure 6.

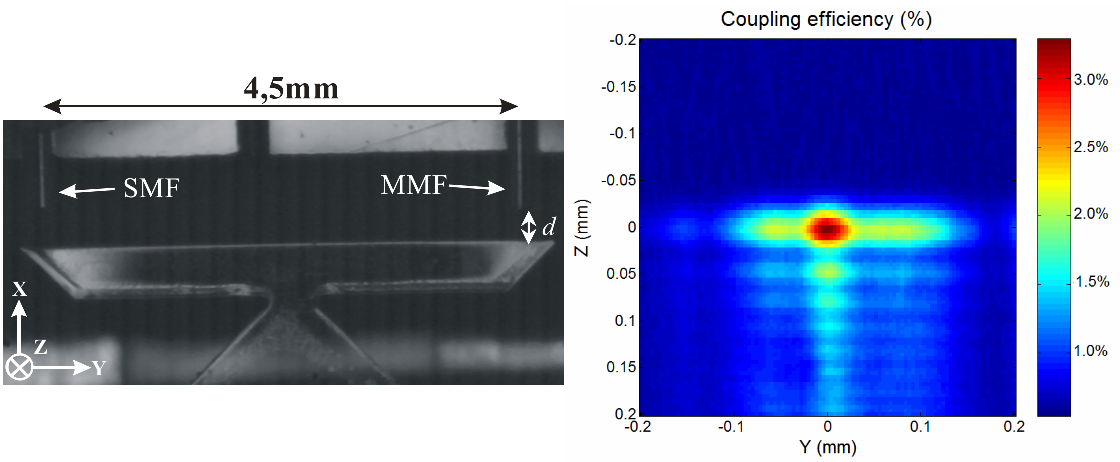

Figure 6: Waveguide in the experimental characterization setup to measure the optical transmission efficiency between source (SMF) and detector fiber (MMF) placed at working distance *d* of the waveguide (left) and plot of the YZ scan of the coupling efficiency (right).

The waveguide was mounted on the Hexapod robot, which enabled a six degrees of freedom alignment with a positioning resolution of 30 nm. We performed a scan of the transmission efficiency while moving the waveguide in the YZ plane. The maximal transmission efficiency measured was 3.3% (also shown on Figure 6), which is in pretty good agreement with the value resulting from the simulations, namely 4%.

Conclusion

We presented DLP as a promising, fast prototyping technology to fabricate multimode polymer waveguides to transfer optical signals between in-plane emitters and receivers. A free-standing waveguide, with a 500 µm by 500 µm cross-section, was realized in Poly(MethylMethAcrylate). We have characterized the surface roughness (R_q = 118 nm) and experimentally verified the optical transmission efficiency (3.3%) of the micro-optical component. In the future, we will integrate micro-lenses and scale down the waveguide dimensions to smaller cross-sections of e.g. 50 µm x 50 µm to improve the coupling efficiency. Furthermore, we will explore a larger variety of multimode polymer waveguides for flexible optical interconnect architectures while controlling the taper angle of the reflective surfaces and the length of the entire waveguide.

Acknowledgements

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[2] B. Volckaerts et al., “Deep Lithography with Protons: a generic fabrication technology for refractive micro-optical components and modules”, Asian J. of Physics, Vol. 10, No. 2, pp. 195-214, 2001.