

Deep Lithography with Protons for the fabrication of optical waveguides with integrated out-of-plane coupling structures

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Abstract

We present Deep Lithography with Protons (DLP) as a promising, fast prototyping technology to fabricate a waveguide-based micro-optical component with monolithically integrated 45° micro-mirrors acting as out-of-plane couplers, splitting the optical signal in 3 separated paths. For the first time, two different proton beam sizes are used during one irradiation and a $20\mu\text{m}$ collimating aperture is chosen to accurately define the out-of-plane coupling structures. We measured the surface roughness ($R_q=27.5\text{nm}$) and the flatness ($R_t=3.17\mu\text{m}$) of the realized components and experimentally measured the optical transmission efficiency of the micro-optical splitter component. The results are in excellent agreement with non-sequential ray-tracing simulations performed for the design.

Introduction

In the 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. Optics is a potential alternative route to circumvent the underlying problems of galvanic interconnects and 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. The proposed micro-optical branching component realizes a 1-to-3 branching of an optical signal through integrated 45° micro-mirrors, as shown in Figure 1. This component allows for optical interconnects, such as splitting the output of an optical fiber equally into multimode waveguides integrated in a printed circuit board or coupling the light to and from surface-mounted optoelectronic devices.

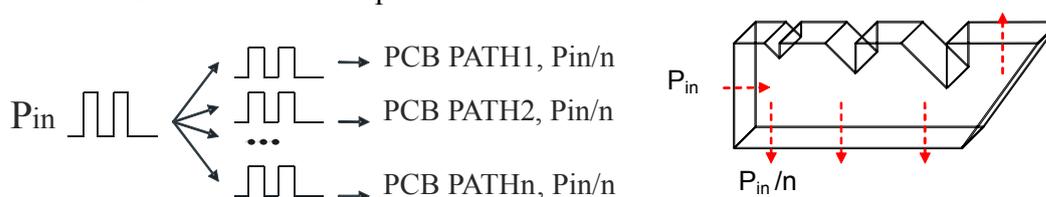


Figure 1: Working principle and schematic view of the component

Non-sequential ray-tracing simulations

The amount of light coupled out at each coupling structure can be varied by changing the dimensions of the micro-mirror. Therefore, we simulate the behaviour of the multimode branching waveguide using non-sequential ray-tracing software to optimize the geometrical dimensions of the out-of-plane coupling structures and the resulting coupling efficiency. When using a multimode fiber with a numerical aperture of 0.22 and a core diameter of $50\mu\text{m}$ as an input, the resulting geometrical dimensions of the micro-mirrors in order for each of them to couple out 20% of the optical power, are $123\mu\text{m}$, $155\mu\text{m}$ and $212\mu\text{m}$, placed at respectively, 4mm, 10mm and 16mm from the input facet. Under these conditions, the cross-section of the waveguide is refilled uniformly after each micro-mirror, as shown in Figure 2.

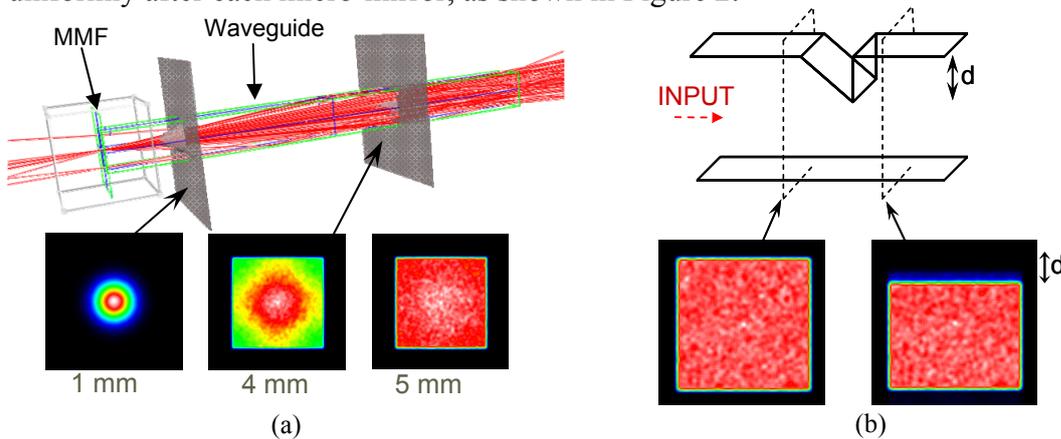


Figure 2: Non-sequential ray-tracing simulation of (a) the filling of the waveguide at the input side and (b) the cross-sectional energy distribution just before and after a coupling structure

Deep Lithography with Protons: the mastering process steps

For the fabrication of the waveguide with out-of-plane coupling structures, we use Deep Lithography with Protons (DLP) [1]. It is a unique technology for rapid prototyping of micro-optical components. In general, the DLP process consists of the following basic procedures, as illustrated in Figure 3. First, we translate an optical grade PMMA [Poly(MethylMethAcrylate)] sample in a collimated 8.3MeV proton beam according to a predefined pattern. Due to the proton interactions with the sample, the physical and chemical properties of the material change locally in the irradiated zones. As a next step, a selective etching solvent is applied for the development of the irradiated regions.

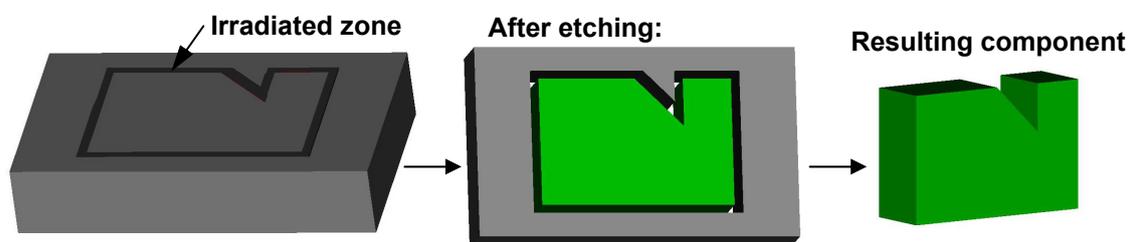


Figure 3: DLP fabrication process – irradiation and selective etching

The compatibility of DLP with standard replication techniques such as injection moulding and hot embossing makes our prototypes suitable for low-cost mass production [2]. For the first time, two different proton beam sizes are used during one

and the same irradiation. We namely use a $140\mu\text{m}$ diameter beam for the patterning of the outer contour of the branching component and a $20\mu\text{m}$ diameter proton beam to irradiate the out-of-plane coupling micro-mirrors.

Characterization of the fabricated components

The resulting waveguide with mechanical holder structure for easier handling is shown in Figure 4 (a). An example of an out-of-plane coupling mirror is shown in Figure 4 (b). The geometrical dimensions and the surface profile of the fabricated component were measured using an optical non-contact surface profiler WYKO NT-2000 (Veeco), which is based on a Mirau interference microscope. The measured dimensions of the micro-mirrors, respectively $126\mu\text{m}$, $150\mu\text{m}$ and $215\mu\text{m}$, are in correspondence with the designed values mentioned earlier. The profiles along X and Y are shown in Figure 4 (c) and (d). The measured local RMS surface roughness for the $140\mu\text{m}$ -beam irradiated parts of the branching waveguides averages 30nm over an area $60\mu\text{m} \times 48\mu\text{m}$ and the flatness is $3.17\mu\text{m}$ over a length of $500\mu\text{m}$. For the out-of-plane coupling mirrors, patterned by means of the $20\mu\text{m}$ proton beam, we measure $R_q = 27.5\text{nm}$ over an area of $60\mu\text{m} \times 48\mu\text{m}$ and a flatness $R_t = 3.14\mu\text{m}$ over a length of $500\mu\text{m}$. The values mentioned for R_t are measured along the depth of the component (the Y-axis in Figure 4), and the higher value in this direction is due to the scattering of the protons when interacting with the polymer.

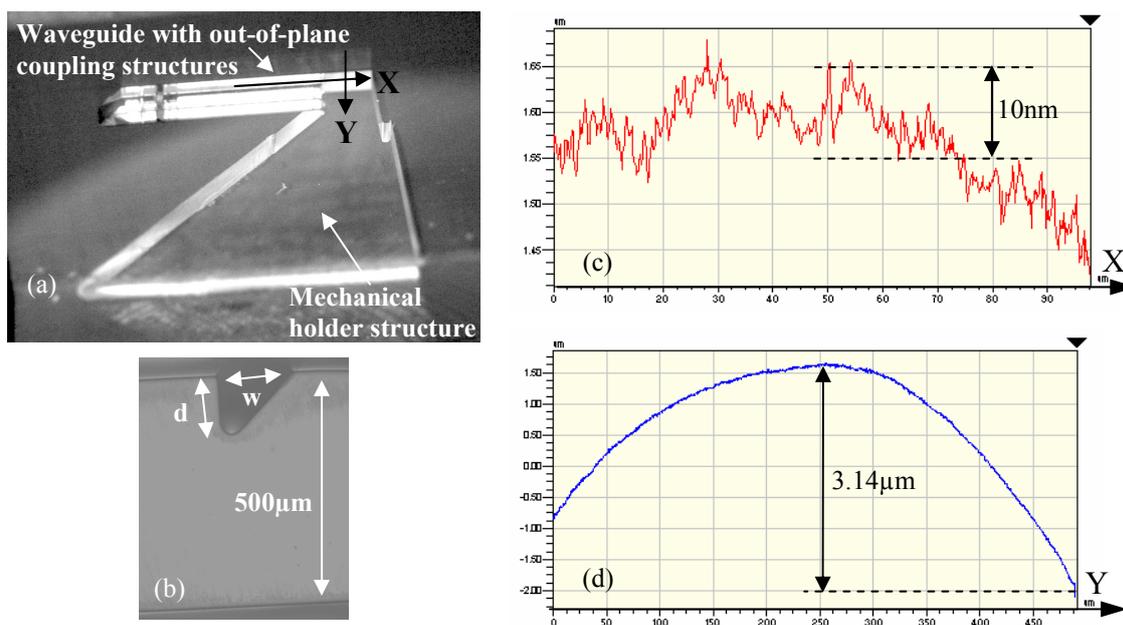


Figure 4: (a) Resulting branching component with mechanical holder structure and (b) zoom of an out-of-plane coupling micro-mirror with dimensions $w = d = 126\mu\text{m}$; (c) Surface roughness along X and (d) surface roughness profile along Y

For the characterization of the optical coupling efficiencies of the different out-of-plane coupling micro-mirrors, we use a Thorlabs multimode fiber as a source, having the same specifications (N.A. 0.22, core diameter $50\mu\text{m}$) as used during the simulations. It is pigtailed to a laser diode with wavelength 635nm . To ensure perfect alignment of the input fiber with respect to the branching waveguide's input facet, the fiber is mounted on a Newport UltraAlign XYZ-tip-tilt translation stage. We measure the power coupled

out by each micro-mirror separately by using a Newport 818-SL power detector. The experimentally measured coupling efficiencies of the out-of-plane coupling structures are respectively 22.7%, 21.8% and 21.8%, which is in agreement with the targeted 20% during the design. Moreover, the far field intensity pattern of the light coupled out corresponds to the simulation results, including the scattering effect due to the rounding of the bottom of the micro-mirrors, as shown in Figure 5.

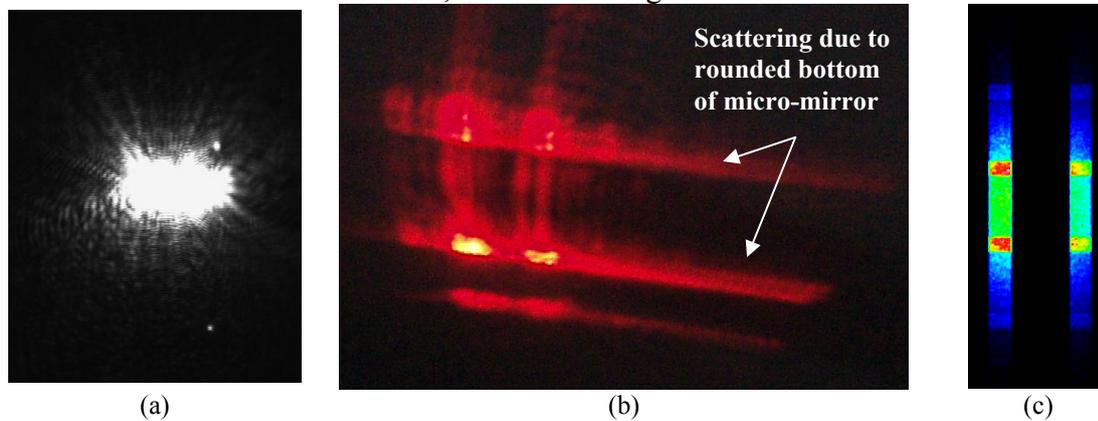


Figure 5: Intensity distribution of the light coupled out by a micro-mirror – near-field pattern (a) and far-field pattern (b); When compared to the simulated distribution (c), the horizontal lines observed in (b) are due to the rounding at the bottom of the micro-mirror (as can be seen in Figure 4(b) – resulting from the finite proton beam size used during irradiation)

Conclusion

We designed and simulated a waveguide with integrated out-of-plane coupling micro-mirrors using non-sequential ray-tracing. For the fabrication of the resulting component, we used Deep Lithography with Protons where, for the first time, we used two different beam sizes (140 μ m and 20 μ m) during one irradiation. We achieve optical surfaces with a repeatable RMS surface roughness of 30nm and the optical coupling efficiencies measured experimentally for the three out-of-plane coupling micro-mirrors (22.7%, 21.8% and 21.8%) are in excellent agreement with the targeted value of 20%. Since the energy distribution of the light coupled out by each micro-mirror is relatively large and asymmetrical, in the future, we will need optics to focus this light into an optical fiber or a PCB-integrated waveguide. Another approach that we will further explore is to downscale the cross-sectional dimensions of the waveguide.

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