Prototyping micro-optical components with integrated out-of-plane coupling structures using Deep Lithography with Protons

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ABSTRACT

We present Deep Lithography with Protons (DLP) as a rapid prototyping technology to fabricate waveguide-based micro-optical components 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 20µm collimating aperture is chosen to accurately define the out-of-plane coupling structures. We fully optimized the DLP process for this 20µm proton beam and we measured the surface roughness (Rq=27.5nm) and the flatness (Rt=3.17µm) of the realized components. Finally, we 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.

Above that, we present a pluggable out-of-plane coupler incorporating a single micro-mirror for the 90° coupling of light to or from polymer multimode waveguides integrated on a printed circuit board (PCB). This millimeter-sized mass-reproducible component can then be readily inserted into laser ablated cavities. Non-sequential ray-tracing simulations are performed to predict the optical performance of the component, showing coupling efficiencies up to 78%. These results are then experimentally verified using piezo-motorized positioning equipment with submicron accuracy in a multimode fiber-to-fiber coupling scheme, showing coupling efficiencies up to 56%. The fabricated coupling components are suitable for low-cost mass production since our micro-optical prototyping technology is compatible with standard replication techniques, such as hot embossing and injection molding, has been shown before.

Keywords: deep lithography with protons (DLP), micro-optics, optical interconnect, out-of-plane coupling, passive optical splitters, polymer multimode waveguides

1. 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. Optical interconnects based on low-loss integrated waveguides are a promising solution to overcome the interconnect bottlenecks at board and module level. However, one of the most critical problems is coupling the light in and out of the optical plane. A common approach is the use of 45° micro-mirrors. Various techniques are being applied for the fabrication of these micro-mirrors. Micro-machining techniques using a 90° V-shaped diamond blade can provide an excellent cut surface, but it is difficult to cut individual waveguides on the same substrate due to the physical size of the machining tool. Reactive ion etching RIE where the slope of the mirror is formed by 45° oblique etching is limited in directional freedom. Temperature controlled RIE is not limited in directional freedom but this method has the disadvantage of being material dependent. Another technique is the use of laser ablation, where a KrF Excimer laser is used, depending on the material in which the waveguides are defined.

In this paper, we present Deep Lithography with Protons as a generic rapid prototyping technology for the
fabrication of two types of micro-optical components with integrated 45° micro-mirrors. The first type is an optical tap waveguide, splitting an optical signal in three separated paths and the second type is a pluggable out-of-plane coupler for PCB-integrated multimode waveguides.

2. DESIGN AND SIMULATIONS

2.1. Optical tap waveguide

The proposed micro-optical branching component realizes a 1-to-3 branching of an optical signal through integrated 45° micro-mirrors, as shown in Fig. 1, enabling for example the splitting of the output of an optical fiber equally into multimode waveguides integrated in a Printed Circuit Board (PCB) or the coupling of light to and from surface-mounted optoelectronic devices. This type of component would enable a seamless integration of the different optical interconnect approaches used on PCB- and Multi-Chip-Module (MCM) level.

The branching waveguide has a square cross-section of 500µm × 500µm, corresponding to the thickness of the PMMA sample used for the fabrication (see section 3.1.1). To split the optical signal propagating in the waveguide, we will use 45° micro-mirrors that will couple a desired amount of the propagating light out of the waveguide by total internal reflection (TIR). Due to the large cross-sectional dimension of the waveguide, we first have to determine the propagation distance needed before the waveguide’s cross-section is uniformly filled. This is the minimal distance from the input facet of the waveguide after which we can place an out-of-plane coupling structure. To determine this distance, we use commercially available non-sequential ray-tracing simulation software from Breault: ASAP. For a multimode fiber (MMF) with a numerical aperture of 0.22 and a core diameter of 50µm as an input, this distance is 4mm. From this point the change in uniformity is below 1%. This can be seen from Fig. 2, showing the irradiance distribution in the waveguide after 500µm (1), after 2mm (2) and after 4mm (3). The amount of light coupled out at each coupling structure can be varied by changing the dimensions of the micro-mirror. We optimize the geometrical dimensions of the out-of-plane coupling structures in order for each of them to couple out 20% of the optical power. The irradiance distribution before (3) and after (4) a micro-mirror of width and depth $d$ is also shown in Fig. 2. From the irradiance plot in (4), it is
clear that once the light propagating in the branching waveguide has encountered a micro-mirror, again a certain propagation distance is necessary to uniformly refill the waveguide’s cross-section. According to our simulation results, the dimensions of the micro-mirrors should respectively be 123\,\mu m, 155\,\mu m and 212\,\mu m and they should be placed at respectively 4\,mm, 10\,mm and 16\,mm from the input facet of the branching waveguide. Under these conditions, each micro-mirror couples out 20\% of the optical power and the cross-section of the waveguide is refill uniformly after each micro-mirror.

2.2. Out-of-plane coupler

Instead of writing the micro-mirrors directly in the waveguides, we propose as in this section a second type of component which uses an 'external' micro-mirror. The targeted component is a pluggable out-of-plane coupler that can be readily inserted into laser ablated cavities integrated at the endpoints of optical waveguides integrated on a PCB. A schematical representation is shown in Fig. 3. We design the out-of-plane coupler in view of the demonstrator on which it will be used in the future, existing of 50\,\mu m x 50\,\mu m multimode waveguides on a PCB substrate, in which laser ablated cavities have been created. Referring to Fig. 3, the core layer, the upper- and the undercladding layer have a thickness of 50\,\mu m each. The cavities are ablated down to the PCB substrate and are thus 150\,\mu m deep. The component is characterized by three important dimensions: \(d_0\), the height of the component, \(w_0\), the thickness of the component and \(d_1\), the dimension of the micro-mirror. The thickness is fixed to 500\,\mu m by the resist used for the fabrication process (cfr. section 3). Since we need a 45\degree facet, the height and the width of the mirror are the same and equal to \(d_1\). In order to avoid damage of the point of the micro-mirror when inserting it in a laser ablated cavity, we decide to choose \(d_1\) equal to 140\,\mu m. The parameter \(d_0\) should be chosen as small as possible because due the relatively large numerical aperture (0.30) of the PCB-integrated waveguides the spot size at the top surface of the out-of-plane coupler increases quickly with \(d_0\). Without micro-optics to collimate or focus the beam it becomes increasingly difficult to couple that light distribution efficiently in e.g. an optical fiber or surface-mounted optoelectronic devices. For reasons of mechanical stability, we choose \(d_0\) equal to 350\,\mu m. A smaller value would lead to an over-fragile component.

For the non-sequential ray-tracing simulations (Fig. 4), we do not take into account the scattering that occurs due to surface roughness (in other words: we assume perfect optical surfaces), but we do incorporate the Fresnel losses occurring at the different interfaces in our system. We use different sources for the simulation of the reflection at the 45\degree micro-mirror in our out-of-plane coupling component. The first one is a multimode fiber (MMF) with a core size of 50\,\mu m, cladding diameter of 125\,\mu m and a numerical aperture (NA) of 0.22. The second device used as a source is the light emitted by a Truemode\textsuperscript{TM} polymer waveguide integrated on a printed circuit board, having a square cross-section of 50\,\mu m x 50\,\mu m and a numerical aperture of 0.30, as resulting form the difference in index of refraction between the Truemode\textsuperscript{TM} waveguide core (\(n_{\text{core}} = 1.5563\) at 850nm) and the Truemode\textsuperscript{TM} cladding around it (\(n_{\text{clad}} = 1.5266\) at 850nm). Just for comparison purposes, we also simulate the micro-optical coupling structure with a single mode fiber (SMF) as a source, where we take the specifications of standard Corning SMF-28\textsuperscript{TM} optical fiber: a core size of 8.3\,\mu m, a cladding diameter of 125\,\mu m and a 0.13 numerical aperture. For all the simulations, we have set an air gap of 10\,\mu m between the exit plane of the source.
Figure 4. Non-sequential ray tracing through the system, with a Truemode™ waveguide as a source and a multimode fiber as detector. No reflection coating applied on the micro-mirror.

fiber or waveguide and the entrance facet of the out-of-plane coupler, and we use a wavelength of 850nm, unless it is specified otherwise.

The propagation of light in the PCB-integrated waveguides as well as the reflection at the micro-mirror facet is based on the phenomenon of Total Internal Reflection (TIR), which can confine light in a material with refractive index $n_1$ surrounded by another material (or air), with a lower index of refraction $n_2$. Our micro-component will be fabricated in a polymer, more specifically PMMA (see section 3), having a refractive index of 1.4834 at a wavelength of 850 nm. To investigate the reflection of light on a PMMA-air interface, we use the Fresnel equations to calculate the reflectance for various incidence angles $\theta_i$, measured from the surface normal. We know that there is TIR for incidence angles larger than the critical angle $\theta_c$, which equals 42.39° for a PMMA-air interface. However, for light reflection on a 45° micro-mirror, we are very close to this critical angle. This means that we have a high risk of having light rays inciding on the mirror with an angle $\theta_i$ smaller than $\theta_c$ and thus not satisfying the TIR condition. To avoid this, we investigate the use of a metal reflection coating on the PMMA mirror facet. If we use gold (Au) for this purpose, having a complex index of refraction of 0.188 + 5.39i at a wavelength of 827nm, a high reflectance is obtained, albeit polarization dependent, regardless of the angle of incidence. The thickness of the metal layer is chosen to be 5µm, satisfying the requirement that the layer thickness should be large in comparison to the absorption depth of the metal used. The use of gold instead of other metals is preferred, since it has the lowest absorption. That the application of a metal reflection coating on the mirror facet is necessary to avoid problems with total internal reflection is clearly visible in Fig. 4, where one can see that quite a few rays are refracted out of the component instead of being reflected upwards by total internal reflection. To minimize the Fresnel losses due to the air gap between the different materials, we also investigate the use of index matching gel.

Last but not least, we use two types of detectors in our simulations. The first one consists of a flat, sufficiently large detector, such that it can capture all the rays reflected over 90° by the micro-mirror. The term 'flat' refers to the fact that no numerical aperture has been assigned to the detector. The second type of detector is a multimode fiber with the same specifications as the MMF defined above, which corresponds to the fiber used for the experiments as will be described in section 5.2. The distance between the exit facet of the out-of-plane coupler and the detector plane is fixed at 10µm for all simulations. The results of our simulations are summarized in Table 1 and Table 2 for a large, flat detector (with dimensions 300µm x 300µm) and for a multimode fiber as detector, respectively.

From our simulations, we can draw the following conclusions. First of all, the use of a metal reflection coating on the micro-mirror significantly increases the efficiency in our system. The largest gain (almost 20%) is obtained in the case of the Truemode™ waveguide, since it has the largest numerical aperture. The smaller the N.A., the smaller the TIR loss at the mirror and thus the smaller the gain when applying a coating on the micro-mirror. The use of index matching gel improves the efficiency by about 6.5% for all sources. Combining the use of index matching gel and the application of a coating on the micro-mirror would boost the system performance even further. However, the spot at the detector plane is quite large. This means that coupling this light distribution
Table 1. Non-sequential ray-tracing results: efficiency when using a large ‘flat’ detector of 300µm x 300µm.

<table>
<thead>
<tr>
<th>Source</th>
<th>Total Internal Reflection</th>
<th>w/ Au coating</th>
<th>w/ index matching gel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multimode Fiber</td>
<td>78.5%</td>
<td>92.5%</td>
<td>84.9%</td>
</tr>
<tr>
<td>Truemode™ Waveguide</td>
<td>73.0%</td>
<td>92.5%</td>
<td>79.2%</td>
</tr>
<tr>
<td>Single Mode Fiber</td>
<td>87.1%</td>
<td>92.6%</td>
<td>94.2%</td>
</tr>
</tbody>
</table>

Table 2. Non-sequential ray tracing results: efficiency when using a multi-mode fiber as detector.

<table>
<thead>
<tr>
<th>Source</th>
<th>Total Internal Reflection</th>
<th>WithAu coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multimode Fiber</td>
<td>63.4%</td>
<td>73.5%</td>
</tr>
<tr>
<td>Truemode™ Waveguide</td>
<td>41.7%</td>
<td>49.9%</td>
</tr>
<tr>
<td>Single Mode Fiber</td>
<td>79.7%</td>
<td>85.0%</td>
</tr>
</tbody>
</table>

into a fiber will not be straightforward and will result in much lower efficiencies than those mentioned in Table 1. From the simulation results in Table 2, we can conclude that if we do not make use of index matching gel, the maximum achievable efficiency for our system is 63.4% when using an MMF as a source versus 41.7% for Truemode™ waveguides. The ray tracing of this latter system is shown in Figure 3. Remark that in the latter case, the attenuation in the Truemode™ polymer due to material absorption is not taken into account. For a comparison with the experimentally obtained values, we refer to section 5.2. Also in this case the efficiency can be improved by applying a reflection coating on the micro-mirror.

3. FABRICATION USING DEEP LITHOGRAPHY WITH PROTONS

For the fabrication of both types of micro-optical components with out-of-plane coupling structures, we use Deep Lithography with Protons (DLP). It is a unique technology for the rapid prototyping of a wide variety of micro-optical, micro-mechanical and micro-fluidic components with plenty of applications in photonics. In general, the DLP process consists of the following basic procedures, as illustrated in Fig. 5. First a collimated 8.3MeV proton beam is used to irradiate an optical grade PMMA sample according to a predefined pattern by translating the poly(methylmethacrylate) (PMMA) sample perpendicularly to the proton beam, changing the physical and chemical properties of the material in the irradiated zones. 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. As a following step, an organic monomer vapour can be used to expand the volume of the bombarded zones through an in-diffusion process. This enables the fabrication of spherical or cylindrical micro-lenses with different heights. If necessary, both processes can be applied to different regions of the same sample, yielding micro-optical structures combined with monolithically integrated micro-lenses. The compatibility of DLP with standard replication techniques such as injection moulding and hot embossing makes our prototypes suitable for low-cost mass production.

3.1. Optical tap waveguide

In this specific case, we will use DLP to write an optical waveguide and out-of-plane coupling mirrors in one processing step. For the first time we have used two different proton beam sizes during a single irradiation session. In particular, we have used a 140µm diameter proton beam for the patterning of the outer contour of the branching component and a 20µm diameter proton beam to shape the three out-of-plane coupling micro-mirrors. To be able to do this, we first have to optimize the DLP process for different beam parameters and align the pointing position of the proton beam before and after switching the proton beam diameter. Both steps will be discussed in detail in the next sections.
Position-controlled PMMA sample

Mask

Proton beam

Position-controlled PMMA sample

MMA in-diffusion

Micro-lenses

Selective etching of irradiated zones

Micro-holes

Prisms, waveguides, mirrors,…

Figure 5. Deep Lithography with Protons: basic processing steps. After a patterned irradiation we can either apply a binary chemical etching to remove the irradiated regions or we can in-diffuse a monomer vapor to create micro-lenses through a swelling process.

3.1.1. Optimization of the DLP process for different beam diameters

For the irradiation, we use high molecular weight PMMA with a thickness of 500µm, which allows the 8.3MeV protons to completely traverse the sample. PMMA is a positive resist, which means that protons impinging on it will cause scissions in the long polymer chains. This material degradation allows us to selectively remove the irradiated zones during the etching process. This means that we have to irradiate the entire contour of the designed component. Therefore, the PMMA sample is quasi-continuously translated perpendicularly to the beam with steps of 500nm using Burleigh inchworms with an accuracy of 50nm. We monitor the total amount of protons hitting the sample by integrating the proton current induced in a probe located directly behind the target. This measurement is based on a precision-switched integrator trans-impedance amplifier and it is conceived to compensate for any fluctuations in the proton current caused by instabilities of the cyclotron. While the 140µm beam is perfectly suited to pattern the contour of the branching waveguide, it does not allow to write the small features of the out-of-plane coupling micro-mirrors. For this reason, we used the 20µm diameter collimating aperture of our final stopping mask for the first time. This means we have to optimize fabrication parameters for this 20µm proton beam to achieve the optimal surface quality for our micro-optical components. The three main fabrication parameters are: deposited proton dose during the irradiation step, and temperature and etching time of the development step. The latter two remain unchanged in comparison with a 140µm proton beam irradiation, since the entire sample is to be developed at once. The etching takes place in a GG developer (diethylene glycol monobutyl ether 60%, morpholine 20%, 2-aminoethanol 5%, and DI water 15%) during 1 hour at 38°C, while using an ultrasonic stirrer. As criterion for optimal surface quality, we use minimal local RMS roughness (Rq) and minimal peak-to-valley flatness (Rt). Both Rq and Rt are measured using a WYKO NT-2000 non-contact optical profiler (Veeco). The graph in the left part of Fig.6 shows the surface Rq and Rt as a function of the deposited dose during the irradiation step. Rq was measured over a length of 500µm and Rq was calculated by averaging several measurements over an area of 46µm x 60µm. From this graph, we can conclude that the best results are obtained when we irradiate the sample with a dose of 8pC per step of 500nm at a beam current of 4pA. The right part of Fig.6 shows an RMS roughness Rq of 27.5nm and a flatness Rt of 3.17µm of a surface created with the optimal dose of 8pC per step of 500nm. Notice that Rt represents the flatness in the direction of the proton path. In this direction, the Rt is much higher because of the proton scattering that occurs during
the proton-POMMA interaction. In the direction perpendicular to the proton beam, the flatness $R_t$ is determined by the surface roughness $R_q$. These results for the 20 $\mu$m proton beam should be compared to an optimal RMS surface roughness $R_q$ of 33.6 nm and peak-to-valley flatness $R_t$ of 3.79 $\mu$m for a deposited dose of 60 pC per step of 500 nm at a proton current of 200 pA when using the 140 $\mu$m diameter collimation aperture.

3.1.2. Switching mask apertures during irradiation

Irradiation of the entire contour of the waveguide with this 20 $\mu$m proton beam is not feasible, because the irradiation time increases rapidly with decreasing beam diameter to achieve the same amount of material degradation. As shown in section 3.1.1, the proton current decreases from 200 pA for the 140 $\mu$m beam to 4 pA for the 20 $\mu$m beam. To overcome this issue, we switched from the 140 $\mu$m aperture to the 20 $\mu$m aperture during the irradiation. The 140 $\mu$m proton beam is then used for patterning the contour of the branching waveguide, while the out-of-plane coupling micro-mirrors are written using the 20 $\mu$m proton beam. Of course, this requires a perfect alignment of the beam positions in order to make sure the out-of-plane coupling micro-mirrors are defined at the correct position with respect to the patterned waveguide contour, as illustrated in the left part of Fig. 7. The right part of Fig. 7 shows a WYKO plot of a sample in which we have performed point irradiations while repeatedly switching collimation apertures (140 $\mu$m $\rightarrow$ 20 $\mu$m $\rightarrow$ 140 $\mu$m $\rightarrow$ etc.). By determining the centers of the different holes, we can check if the measured values of $d_1$ and $d_2$ correspond to the desired values of respectively 300 $\mu$m and 0 $\mu$m (i.e. the 20 $\mu$m holes should, according to the design, be positioned on the same vertical line as the 140 $\mu$m holes). We measured values of $79 \mu$m $\pm$ 5 $\mu$m and $227 \mu$m $\pm$ 5 $\mu$m for $d_1$ and $d_2$ respectively. This shows that there is a proton beam misalignment in both Y and Z directions when switching from one aperture to another when the X-axis is defined along the proton beam path. This misalignment is due to the fact that the collimation mask can only be moved up and down and not left and right. Our collimation mask, consisting of a 300 $\mu$m thick Nickel plate, contains apertures ranging from from 300 $\mu$m down to 20 $\mu$m. To ensure good beam homogeneity and circularity of the irradiated holes, the mask is tilted until it is positioned perpendicularly to the proton beam. If a rotational error exists between the axis of movement Z and the axis formed by the line interconnecting the apertures in the mask, a misalignment of beam pointing when switching apertures is inevitable. This misalignment can not be compensated because no motorized Y movement of the mask is presently installed in the DLP irradiation setup. The fact that the 20 $\mu$m aperture is located as far as 25.5 mm under the 140 $\mu$m aperture increases this misalignment even further.

However, the misalignment of the 140 $\mu$m and 20 $\mu$m holes we measured is repeatable, meaning that we can compensate for this misalignment. To determine the sample-to-sample repeatability of the misalignment that occurs when switching apertures over two irradiations, we measure $d_1=77\mu$m $\pm$ 2 $\mu$m and $d_2=174\mu$m $\pm$ 75 $\mu$m. This shows that the misalignment is only really repeatable in the X direction. For our application this is not a real problem, since only the depth of the out-of-plane coupling structures is critical, whereas the position of the
3.1.3. Fabrication of the designed branching waveguides

Before fabricating the branching waveguide with three integrated out-of-plane coupling micro-mirrors, we fabricated a simplified version, featuring only one micro-mirror (and a tapered end facet). Both designs are shown in Fig. 8, where one can clearly observe the displacement of the out-of-plane coupling structures with respect to the branching waveguide’s contour to compensate for the proton beam misalignment when switching collimation apertures, as described in section 3.1.2. Notice also that for the final design, shown in the right part of Fig. 8, the third micro-mirror has been placed at the opposite side of the branching waveguide. The reason for this is the fact that due to the large cross-sectional dimension of the waveguide, the distance needed for uniform refilling is quite large (6mm, as explained in section 2.1) and would lead to unacceptably long irradiation times. It has however no implications on the optical functionality of coupling out 20% of the optical power, since we use this part of the cross-section that is still uniformly filled after the second micro-mirror. Both designs incorporate a mechanical holder structure for easy handling of the fabricated components. Parts of these triangular mechanical holder structures (indicated by a point-dashed line in Fig. 8) are milled using a micro-machining system, since no optical surface quality is needed and irradiation time needed is already high. Non-sequential ray tracing simulations show us that there is no energy leakage in this mechanical holder structure, since it is positioned directly after the input facet of the branching waveguide, where the light is still concentrated around the input fiber’s axis (as can be seen in the left part of Fig. 2).

3.2. Out-of-plane coupler

For the fabrication of the pluggable out-of-plane coupler, we have to stepwise irradiate the entire contour of the designed component. As for the waveguide contour of the component described in the previous section, the PMMA sample is quasi-continuously translated perpendicularly to the beam in steps of 500nm using Burleigh inchworms with an accuracy of 50nm. We have chosen to use here the proton beam collimating aperture of 125µm, which causes some rounding in the corners of the component, as shown in Fig. 9, but this does not

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**Figure 7.** Left: Switching proton beam diameters during the irradiation step requires a perfect alignment accuracy to ensure the patterning of the micro-mirrors (20µm beam) at the correct position with respect to the waveguide contour (140µm beam). Right: Non-contact optical profiler plot of a sample in which we tested the repeatability of the aperture switching and the shift occurring during switching.

**Figure 8.** Irradiation designs of the branching waveguides with respectively one (left) and three (right) integrated out-of-plane coupling structures, including compensation for aperture switching misalignment.
Figure 9. (a) Contour of the out-of-plane coupler as written by a 125\(\mu\)m proton beam and (b) the resulting component after etching.

Figure 10. DLP fabricated prototype of a branching waveguide with one out-of-plane coupling micro-mirror: overview (a), zoom on micro-mirror and tapered end facet (b) and zoom on micro-mirror (c).

affect its optical functionality in any way. Therefore, no aperture switching is necessary during the irradiation. We fabricated two out-of-plane couplers, with exactly the same design.

4. CHARACTERIZATION OF THE FABRICATED COMPONENTS

4.1. Optical tap waveguide

The two fabricated prototypes of branching waveguides, incorporating respectively one and three out-of-plane coupling structures, are shown in Fig. 10 and Fig. 11. The stereomicroscope images of the entire components are accompanied by highly magnified views of the micro-mirrors. Using the WYKO NT-2000 non-contact optical profiler, we have measured the geometrical dimensions of these micro-mirrors, resulting in \(d=126\mu\)m for the one shown in Fig.10 and \(d=120\mu\)m, 150\(\mu\)m and 215\(\mu\)m for respectively the first, second and third micro-mirror shown in Fig.11. These measured values are all in close correspondence to the designed values of 123\(\mu\)m, 155\(\mu\)m and 212\(\mu\)m, as resulting from our simulations in section 2.1. This indicates that we have successfully compensated the proton beam pointing misalignment when switching collimation aperture during the irradiation step. The measured values for the RMS surface roughness \(R_q\) are respectively 27.5nm and 33.6nm, as mentioned in section 3.1.1. Due to the finite size and the circular shape of the proton beam, we observe some rounding at the bottom of the out-of-plane coupling micro-mirrors. Feedback into the simulation software reveals that this rounding leads to a negligible amount of scattering visible as a broadening of the far field intensity profile, which is also visible during experimental characterization (cfr. section 5.1).

4.2. Out-of-plane coupler

Fig. 12 shows microscope images of the fabricated out-of-plane couplers, and close-ups on the micro-mirror. For the characterization of the critical optical surfaces of the component, namely the flat top exit facet, the entrance facet and the 45° mirror facet, we use a non-contact optical surface profiler. Since the entrance facet is not accessible with the microscope objective of the non-contact profiler, this surface was not measured, but its surface roughness will be analogous to the two others. The surface analysis reveals that the flat top part has an average local RMS surface roughness \(R_q\) of 34.19nm ± 4.90nm (for component 1) and of 25.10nm ± 1.29nm (for component 2), measured over an area of 46\(\mu\)m x 60\(\mu\)m. We averaged 5 measurements of randomly chosen positions. Applying the same measurement method to the 45° angled facet reveals an RMS roughness of 29.24nm ± 3.96nm and of 29.21nm ± 3.96nm for component 1 and 2, respectively. We can conclude that our developed surfaces have a very good and reproducible optical quality.
**Figure 11.** DLP fabricated prototype of a branching waveguide with three out-of-plane coupling micro-mirrors.

**Figure 12.** Stereo-microscope (a) and high-resolution microscope (b, c) images of the fabricated out-of-plane coupling components.
5. EXPERIMENTS

5.1. Optical tap waveguide

The final step consists of measuring the optical coupling efficiency of each of the out-of-plane coupling structures of the branching waveguide. As a source, we use a multimode fiber with the same specifications as used for the simulations (N.A. of 0.22, core diameter of 50\,\mu m), pigtailed to a laser diode emitting at a wavelength of 635\,nm. To ensure a perfect alignment of the input fiber with respect to the branching waveguide’s input facet, the fiber is mounted on an XYZ-tip-tilt stage with a precision of 0.5\,\mu m. We measure the power coupled out by each micro-mirror separately by using a power detector. For the branching waveguide with one out-of-plane coupling micro-mirror, we measure a coupling efficiency of 22.7\%, which is in close correspondence with the targeted value of 20\% during the design. For the final component, incorporating three out-of-plane coupling structures, this correspondence could only be observed for the first and the third micro-mirror, for which we measured coupling efficiencies of 21.8\% and 21.8\% respectively. Since the second micro-mirror and the tapered end facet of the branching waveguide are positioned closely together and are bending the light out of the waveguide in the same direction, we were not able to separately measure the optical power coupled out by each of them individually.

Besides the coupling efficiency, the far-field intensity pattern of the light coupled out was also characterized. The shape of this far-field pattern, as shown in the left part of Fig. 13, corresponds to the far-field pattern resulting from the simulation, shown in the right part of Fig. 13. The horizontal lines that can be observed in the left part of Fig 13 are caused by scattering due to the rounding of the bottom of the micro-mirrors, as described in section 4.1.

5.2. Out-of-plane coupler

For the experimental characterization of the out-of-plane coupler, we need high-accuracy positioning equipment. For this purpose, we mount the detector MMF on a Hexapod six-axis parallel kinematics robot PI F-206, which allows us not only to position the detector with a repeatability of 300\,nm, but also to perform a two-axis scan to check the mechanical misalignment tolerance of our detector fiber. The fibers used for the experiments have the same specifications as those used in the simulations discussed in section 2.2. The source MMF is connected to a laser diode emitting at a wavelength of 850\,nm. The detector MMF is connected to a power detector. For the active alignment, we use Volpi microscope objectives, mounted on a CCD camera. We measure a maximal MMF to MMF coupling efficiency of 47.5\% (-3.25\,dB). This is in pretty good agreement with the simulated efficiency of 63.4\% (-1.98\,dB) in Table 2, considering the fact that we did not take scattering losses due to surface roughness into account for the simulations. The measured coupling efficiency increases to 56.5\% (-2.49\,dB) if we apply index matching gel between the exit facet of the source MMF and the entrance facet of the out-of-plane coupler.

6. FUTURE PERSPECTIVES

As can be seen from the irradiance map in Fig. 14, the energy distribution of the light coupled out by a micro-mirror is relatively large and asymmetrical, with dimensions of 500\,\mu m by \(d\), where \(d\) is the geometrical dimension.
of the micro-mirror under consideration, as defined in section 2.1. We will therefore need micro-optics to focus this outcoupled light into an optical fiber or PCB-integrated waveguide, both having cross-sectional dimensions in the order of 50µm for their core in case they are multimodal. We have performed additional non-sequential ray-tracing simulations to investigate the possibilities of two different optical lens systems.

In the first configuration, we use one spherical microlens to focus the light coupled out of the waveguide, as shown in Fig. 15. The required lens diameter in this configuration lies around 855µm to fulfill the 99% transmission criterion, and for a radius of curvature of 427.5µm, we achieve coupling efficiencies not higher than 10%, according to our simulations when using a multimode fiber with a core of 50µm as a detector. Therefore, we investigate as a second configuration a so-called anamorphic lens system, which consists of two cylindrical microlenses of which the optical axes are positioned perpendicularly to one another. Because this system is better suited to focus the asymmetric energy distribution of the light coupled out, simulations show that the achievable coupling efficiencies rise to 40% for an optimal choice of lens parameters.

Another approach that we will follow in the future to improve the coupling efficiency when coupling into a multimode fiber or a PCB-integrated waveguide, is to downscale the cross-sectional dimensions of the branching waveguide to e.g. 50µm. Not only would it then be perfectly matching the dimensions of the input and output fiber/waveguide, making the use of micro-optics for focusing unnecessary, but it would also strongly affect the design of the branching component. The propagation distance needed to uniformly refill the waveguide’s cross-section behind a micro-mirror decreases from 6mm to 600µm. This allows the output waveguides or fibers to be much more densely packed, as would generally be the case in 1D arrays of PCB-integrated MM waveguides, where pitches of 250µm or less are common.1 The concept of out-of-plane coupling micro-mirrors remains valid as long as the branching waveguide retains a multimode character. When its cross-sectional dimensions would be scaled down further, yielding single mode behaviour, other concepts should be used to couple the light out of the waveguide, e.g. grating couplers.14

As far as the out-of-plane coupler is concerned, we will investigate the application of a gold reflection coating on the micro-mirror of the out-of-plane coupler and the use of micro-optics to improve the coupling efficiency of the component. We will further characterize the out-of-plane coupler by testing it on a real demonstrator testbed, i.e. a PCB-integrated waveguide board in which cavities have been fabricated using laser ablation.
7. CONCLUSION

We designed and simulated an optical tap 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$\mu$m and 20$\mu$m) during a single irradiation session. We achieve optical surfaces with a repeatable RMS surface roughness around 30nm and the optical coupling efficiencies measured experimentally for 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.

We have also shown that Deep Lithography with Protons allows us to fabricate high-quality micro-optical out-of-plane couplers, with a very low surface roughness on its optical surfaces. These couplers are furthermore highly versatile components, since they can be inserted into laser ablated cavities on printed circuit board-integrated optical waveguides. We have thoroughly analyzed the component’s functionality through non-sequential ray-tracing simulations showing coupling efficiencies up to 78.5% which can be improved to 92.5% by applying a metal reflection coating on the micro-mirror. We have experimentally characterized the out-of-plane coupler in a fiber-to-fiber coupling scheme. The resulting coupling efficiencies up to 56% are in pretty good agreement with the simulated values when coupling the light into a multimode fiber as detector, considering that perfect optical surfaces have been assumed for the simulations.

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