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Prototyping of pluggable out-of-plane coupling components for multilayer board-level optical interconnections

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Abstract

Board-level optical interconnects offer a possible solution to the bandwidth problems that electrical interconnects are facing in the near future. The integration of the optical interconnection to the board level is done by integrating one or more optical layers on a printed circuit board (PCB). We present Deep Proton Writing (DPW) as a generic rapid prototyping technology for the fabrication of a micro-optical coupling component incorporating a 45° micro-mirror that can be readily inserted into a multilayer optical waveguiding structure integrated on a PCB. Micro-cavities are ablated into the optical layers to accommodate the discrete out-of-plane coupler. The advantage of using a discrete component is that micro-lenses can be incorporated to increase the coupling efficiency with a guaranteed perfect alignment of the lens and the micro-mirror. In case lenses are integrated in the coupling component, the layer thickness of top and bottom optical layer has to be in accordance with the designed value and the alignment of the component with respect to the waveguide is critical. In the case the lenses are not used and a metallized mirror facet is used for out-of-plane coupling, there is quite a large tolerance on the thickness of the layers and the alignment accuracy of the component. The surface quality of the fabricated components was characterized and the coupling efficiency of the out-of-plane coupling components was be measured in a fiber-to-fiber coupling scheme. The coupling component is prototyped in PMMA material, which is not compatible with standard PCB manufacturing. This should however not be considered as a limiting factor since the DPW process is compatible with mass replication technologies such as hot embossing or micro-injection moulding and the master as such can be replicated in a variety of high-tech plastics.

Key words: coupling structures, deep proton writing, micro-optics, optical interconnects, polymers, waveguides

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 [1]. 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 [2],[3] 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 [4] where the slope of the mirror is formed by 45° oblique etching is limited by directional freedom. Temperature controlled RIE [5] is not limited by directional freedom but this method has the disadvantage of being material dependent. Other techniques are tilted X-ray exposure [6] and laser ablation, where generally a KrF Excimer laser is used, depending on the material in which the waveguides are defined [7].

All the above technologies are used to write the micro-mirrors directly in the waveguides. In this paper, we present a completely different approach, where we propose the use of a pluggable out-of-plane coupling component with an integrated 45°

micro-mirror that can be readily inserted in into cavities fabricated into printed circuit boards (PCB) containing multilayer optical waveguides.

Multilayer optical waveguides

Truemode Backplane™ Polymer is used as for the optical layer. It is an acrylate-based highly cross-linked polymer material that shows excellent optical and thermal properties. Each optical layer consists of a cladding-core-cladding stack, where the cladding material has a slightly lower refractive index than the core material. The light can in this way be trapped inside the core layer through total internal reflection. The numerical aperture (NA) of the waveguides is 0.3. Multimode waveguides are patterned into the core layer with either photolithography or laser ablation. In case photolithography is used, the waveguide core features are transferred to the core layer by UV-exposure through a suitable mask which has to be used in proximity mode because of the sticky character of the material. In case laser ablation is used, material is removed on both sides of the resulting waveguide core with a KrF excimer laser beam. The waveguides have a cross-section of 50µm×50µm and have a pitch of 125µm or 250µm.

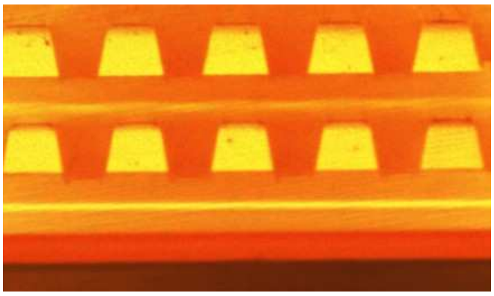

Figure 1: Cross-section of a two-layer optical waveguiding structure

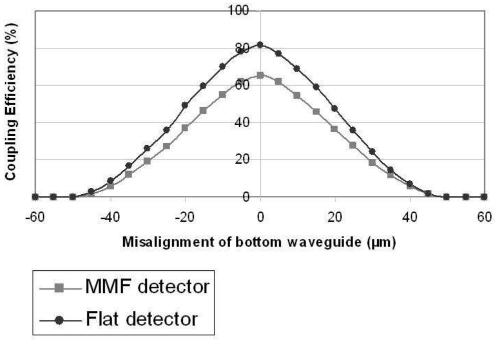

Figure 2: Tolerance for mechanical misalignment of the upper waveguide layer with respect to the lower layer, results from optical simulations.

A multilayer optical structure consists of a stack of optical layers, as shown in Figure 1. Each layer contains multimode optical waveguides which have to be aligned with respect to each other accurately. The alignment is done with the help of Au alignment marks which are evaporated on the substrate through a suitable mask. The achievable alignment accuracy between waveguides in top and bottom layer in a two layer optical structure is better than 5µm. This value is in accordance with the required accuracy obtained from a numerical study, as can be seen in Figure 2.

The coupling component described in the next section is to be plugged into a laser ablated micro-cavity. There is always a certain degree of tapering during the ablation, which also causes the slightly trapezoidal form of the waveguide cores. The KrF excimer laser beam is therefore tilted for the ablation of the micro-cavity to compensate for the tapering. This ensures that the ablated micro-cavity has one vertical wall and one with the double tapering angle. The vertical wall is used as output facet; the coupler is subsequently inserted into the cavity.

Out-of-plane coupling components

As mentioned in the introduction, we are investigating the use of pluggable micro-optical components that can be used to couple the light to or from PCB-integrated waveguides by inserting it into cavities fabricated in the board. We have previously shown that this type of out-of-plane coupling components is capable of achieving high coupling efficiencies for single layer waveguide structures [8]. In this paper, we extend this out-of-plane coupler towards multilayer structures. This can be easily done by increasing the size of the micro-mirror. A schematic working principle is shown in Figure 3. Two cylindrical micro-lenses ensure the collimation (in one direction) of the beam emitted by the PCB-integrated optical waveguides, increasing the coupling efficiency.

Another type of extension of the component, allowing routing of signals between the different layers of optical waveguides, is also possible thanks to the versatility of the Deep Proton Writing fabrication technology. We refer to [9] for more details.

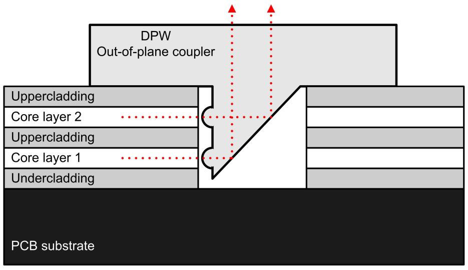

Figure 3: Multilayer out-of-plane coupling component with integrated cylindrical micro-lenses inserted in a cavity formed in the PCB-integrated waveguides. Light paths are indicated by the dotted arrows.

In the following sections, we describe in detail the design, fabrication and characterization of the pluggable multilayer out-of-plane coupling components.

Fabrication using Deep Proton Writing

For the fabrication of the pluggable multilayer out-of-plane coupling component, we make use of our in-house generic rapid prototyping technology of Deep Proton Writing (DPW) [8]. It consists of the following processing steps.

First a collimated 8.3MeV proton beam is used to irradiate an optical grade 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 (see Figure 4). 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 an in-diffusion process. This enables the fabrication of spherical (or cylindrical) micro-lenses with well-defined heights. These processes are illustrated in Figure 5. If necessary, both processes can be applied to different regions of the same sample, yielding micro-mechanical structures combined with monolithically integrated micro-lenses.

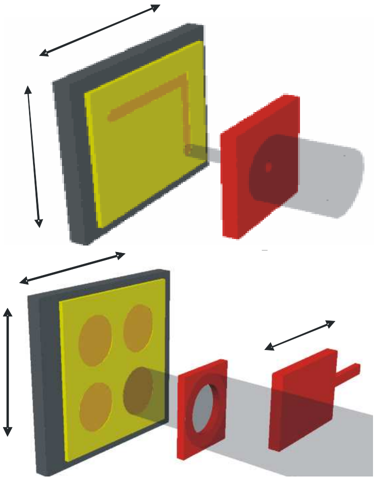

Figure 4: Irradiation step of DPW: Semi-continuous (top) or pointwise (bottom) irradiation of a PMMA sample

We use high molecular weight PMMA with a thickness of 500µm, which allows the 8.3MeV protons to completely traverse the sample. During the irradiation step, the PMMA sample is semi-continuously translated perpendicularly to the beam in steps of 500nm using high-precision translation stages with an accuracy of 50nm. Optimal surface roughness results are obtained by using a proton dose of 50pC per step of 500nm, with a proton current of 160pA. This current is monitored by measuring the charge that the protons induce on a target located directly behind the sample. The deposited dose at each position can then be determined by integrating this proton current during the irradiation using a precision-switched integrator trans-impedance amplifier that aims at compensating any current fluctuations of the proton source.

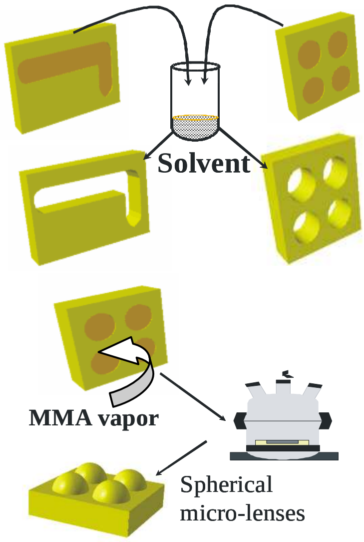

Figure 5: Chemical process steps of DPW: Selective etching process (top) and swelling process (bottom)

After the exposure step, the irradiated zones can be selectively etched in a so-called GG developer (diethylene glycol monobutyl ether 60%, morpholine 20%, 2-aminoethanol 5%, and DI water 15%) during 1h at 38°C, resulting in micro-components with high-quality optical surfaces, as will be discussed in section 3.3. An ultrasonic stirrer is used to enhance the etching process. The resulting component is shown in Figure 6. The total dimensions of the pluggable out-of-plane coupler are 4.5mm x 0.5mm x 0.5mm.

It is obvious that DPW is not a mass fabrication technique as such. However, one of its assets is that, once the master component has been prototyped with DPW, a metal mould can be generated from the master by applying electroplating. After removal of the plastic master, this metal mould can be used as a shim in a final micro-injection molding or hot embossing step [11]. This way, the master components can be mass produced at low cost in a wide variety of high-tech plastics. It is especially important to ensure compatibility of the polymer used with standard PCB fabrication processes – the lamination and solder reflow processes in particular. The PMMA material used for the prototypes has a glass transition temperature T_g around 100°C, which is too low to withstand the temperatures reached during these processes. By replication of the prototype in e.g. cyclo-olefin copolymers (COC), the T_g -and thus standard PCB process compatibility- can be greatly improved.

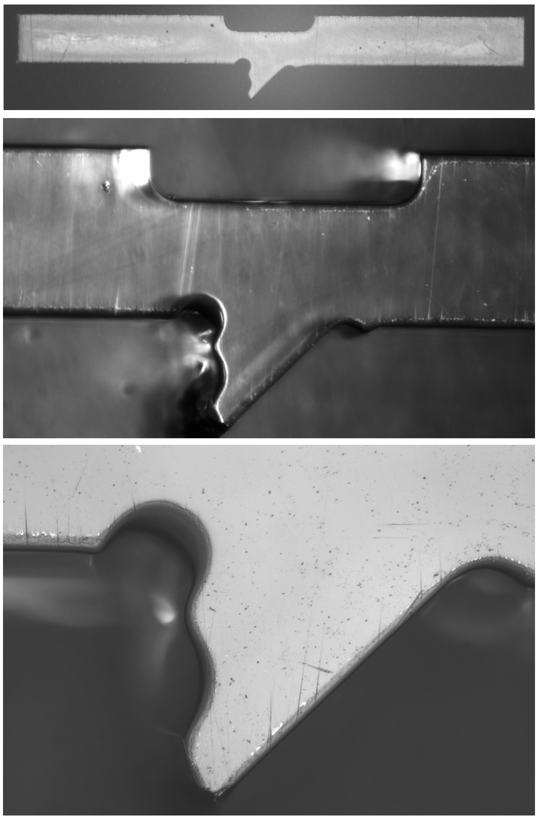

Figure 6: Fabricated multilayer our-of-plane coupling component: overview (top) and zoom on the micro-mirror with integrated cylindrical micro-lenses at the input facet (middle, bottom)

Total Internal Reflection

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. PMMA has a refractive index of 1.4834 at the targeted datacom wavelength of 850nm. To investigate the reflection of light on a PMMA-air interface, we use the Fresnel equations to calculate the reflectance for various incidence angles θ_i, measured from the surface normal [12]. The result is shown in Figure 7 (top), where R_s is the reflectance component perpendicular to the plane of incidence and R_p the component parallel to that plane. We see that we satisfy the TIR condition for incidence angles larger than the critical angle θ_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, especially taking into account the NA of 0.3 of the PCB-integrated waveguides. This means that we have a high risk of having light rays inciding on the mirror with an angle θ_i smaller than θ_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 [13], the reflectance at a PMMA-Au interface shown in Figure 7 (bottom) is obtained. We now have a high reflectance, albeit polarization dependent, regardless of the angle of incidence. The use of gold instead of other metals is preferred, since it has the lowest absorption.

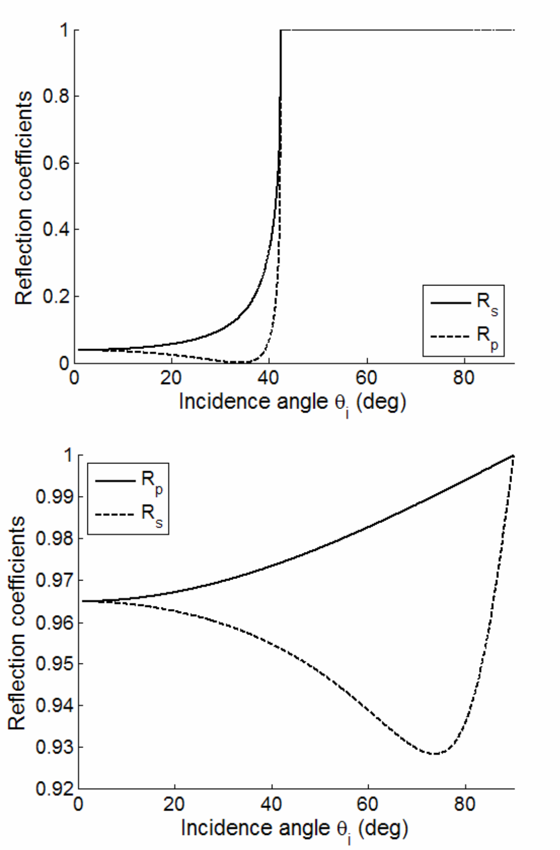

Figure 7: Fresnel reflection coefficients for various angles of incidence in the case of a PMMA-air (top) interface and a PMMA-Au interface (bottom)

Experimental characterization

For the characterization of the critical optical surfaces of the component, namely the flat top exit facet and the 45° mirror facet, we use a WYKO NT-2000 non-contact optical surface profiler (Veeco). Since the entrance facet with the cylindrical microlenses is not accessible with the microscope objective, this surface was not measured, but its surface roughness will be analogous to the two others. The surface roughness analysis reveals that the flat top part has an average local RMS surface roughness R_q of 14.1nm ± 2.7nm measured over an area of 60µm by 46µm. We averaged at least 5 measurements of randomly chosen positions. Applying the same measurement method to the 45° angled facet reveals an RMS roughness R_q of 17.1nm ± 4.2nm. The global mirror surface as well as an example of a locally measured surface profile of the micro-mirror can be seen in Figure 8.

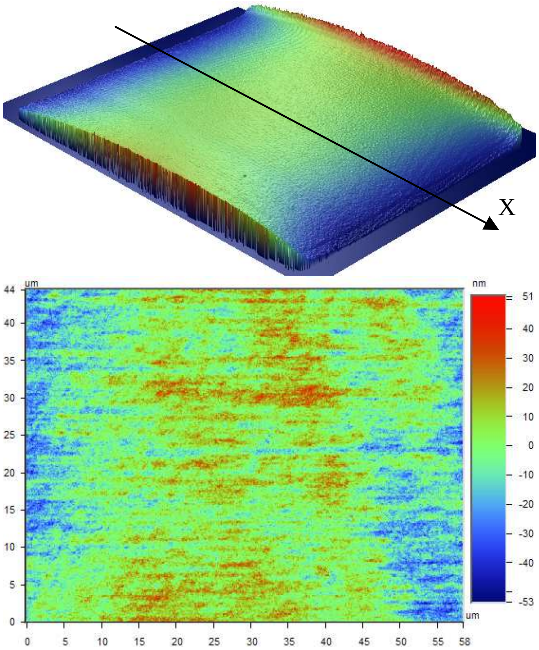

Figure 8: Non-contact optical surface profile measurement of the micro-mirror: overview image (400µm x 500µm, top) and local image (60µm x 48µm, bottom) with resulting RMS roughness R_q=14.98nm.

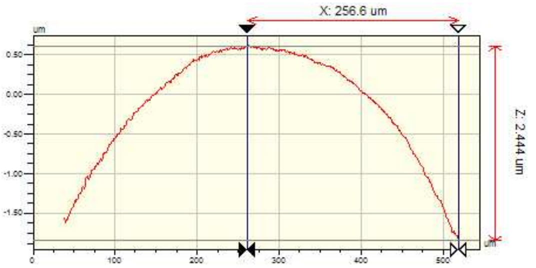

Figure 9: Cross-sectional profile along X showing the flatness of our optical surfaces. R_t=2.444µm over the total depth of the component (500µm).

The top part shows an overview image of the entire micro-mirror surface, whereas the bottom part shows a local measurement for RMS roughness determination, after removing the sample tilt from the measurement. The overview image shows that the surfaces created by DPW are not completely flat (vertical), due to the scattering of the protons during the interaction with the PMMA. It can be clearly seen by taking a cross-sectional profile along X through this surface, as shown in Figure 9. The flatness R_t or peak-to-valley difference along the depth of 500µm of the component is measured to be smaller than 2.5µm. As a conclusion, we can say that our developed DPW surfaces have a very good and reproducible optical quality: almost flat with a very low RMS roughness.

We first test our DPW multilayer out-of-plane coupling component in a fiber-to-fiber coupling scheme, as illustrated in Figure 10. For the input, we use a multimode fiber (MMF) with a core diameter of 50µm and a numerical aperture (NA) of 0.2. The detector MMF has a core size of 100µm and a NA of 0.29 and is mounted on a PI F-206 six-axis parallel motion kinematics Hexapod system. This allows us not only to position the detector with an accuracy of 300nm, but also to perform a two-axis scan to check the tolerance for mechanical misalignments of our detector fiber. The resulting 2D scan of the output fiber is shown in Figure 11.

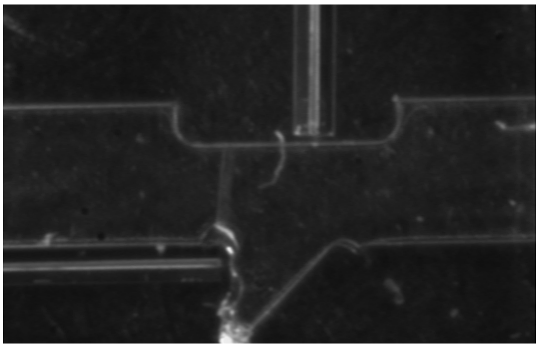

Figure 10: Fiber-to-fiber coupling efficiency measurements (shown in upper channel position)

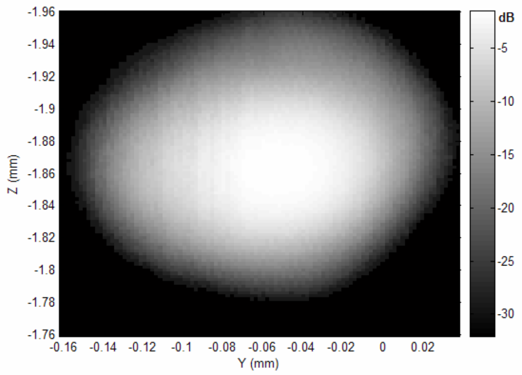

Figure 11: 2D tolerance scan of the spot coupled out by scanning the output MMF

The maximum coupling efficiency measured when using a source wavelength of 850nm was 70% and 75% for respectively the upper and the lower channel position. The reference measurement consisted of a in-line butt coupling of the input and output fiber. In Figure 12, we show a normalized cross-section of the 2D tolerance scan of Figure 11. This plot shows that the -1dB tolerance range for mechanical misalignment of the output MMF is ±26µm. Coupling efficiency measurements when the component is plugged into a multilayer printed circuit board will be performed in the near future.

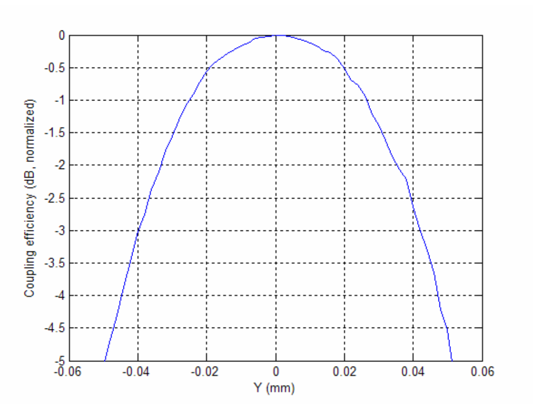

Figure 12: Normalized cross-section of the 2D scan of Figure 11. The -1dB tolerance range for detector multimode fiber misalignments is shown to be ±26µm.

Conclusions

We have shown that Deep Proton Writing is a versatile fabrication technology allowing the rapid prototyping of dedicated pluggable out-of-plane coupling components for multilayer optical waveguides integrated on PCBs. The quality of the fabricated optical surfaces is very high, with average RMS roughness below 20nm and flatness of 2.5µm over a total length of 500µm. Cylindrical micro-lenses can be monolithically integrated into the component to increase the overall coupling efficiency. Coupling efficiencies up to 75% have been measured in a fiber-to-fiber coupling scheme, which can be further increased by applying a metal reflection coating on the micro-mirror.

Acknowledgements

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