

Discrete Out-of-Plane Coupling Components for Printed Circuit Board-Level Optical Interconnections

Jürgen Van Erps, *Student Member, IEEE*, Nina Hendrickx, *Student Member, IEEE*, Christof Debaes, *Member, IEEE*, Peter Van Daele, *Member, IEEE*, and Hugo Thienpont, *Associate Member, IEEE*

Abstract—We propose discrete out-of-plane coupling components as a versatile alternative to current approaches used to couple light in and out of the propagation plane in waveguide-based printed circuit board (PCB)-level optical interconnections. The out-of-plane couplers feature a 45° micromirror and are fabricated using deep proton writing as a rapid prototyping technology. Their fabrication is compatible with replication techniques and shows all the potential of low-cost mass fabrication. In a first configuration, we use the component in a fiber-to-fiber coupling scheme. Coupling losses as small as 0.77 dB were achieved. In a second configuration, the out-of-plane coupler is plugged into a laser ablated cavity in optical waveguides integrated on a PCB. Here a total link loss between out-of-plane fiber and in-plane fiber of 3.00 dB was achieved when using it at the transmitter side and 5.69 dB when using it at the receiver side.

Index Terms—Coupling components, deep proton writing (DPW), micromirror, polymer waveguides, rapid prototyping.

I. INTRODUCTION

IN THE future, the communication bandwidth inside data processing systems will be severely limited by the properties of galvanic interconnections [1]. These limitations stem from physical constraints imposed by RC -line time constants and transmission line effects such as frequency-dependent loss, crosstalk, and reflections. 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 [2]. Optical interconnects based on low-loss waveguides integrated on a printed circuit board (PCB) are a promising solution to overcome the interconnect bottlenecks while still relying on standard board technology [3], [4]. However, one of the most critical problems that remains unsolved is the coupling of light in and out of the optical guiding plane. A common approach is the use of 45° micromirrors to realize a 90° bending of the light. Various techniques are being applied for the fabrication of these micromirrors. Micromachining using a 90° V-shaped diamond blade [5], [6] can provide an excellent cut surface,

Manuscript received June 6, 2007; revised July 20, 2007. This work was supported in part by DWTC-IAP, FWO, GOA, IWT-SBO, the European Network of Excellence on Micro-Optics NEMO, and in part by the OZR of the Vrije Universiteit Brussel. The work of J. Van Erps and C. Debaes was supported by the Fund for Scientific Research-Flanders (FWO) under a research fellowship. The work of N. Hendrickx was supported by the Flemish IWT (Institute for the Promotion of Innovation by Science and Technology).

J. Van Erps, C. Debaes, and H. Thienpont are with the Department of Applied Physics and Photonics, Vrije Universiteit Brussel, 1050 Brussel, Belgium (e-mail: Jurgen.Van.Erps@vub.ac.be).

N. Hendrickx and P. Van Daele are with the Department of Information Technology, Ghent University, 9052 Zwijnaarde, Belgium.

Digital Object Identifier 10.1109/LPT.2007.906113

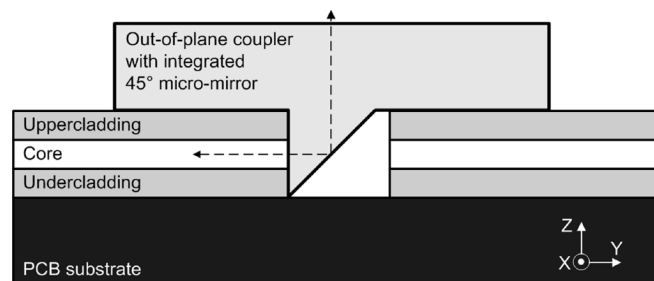


Fig. 1. Operation principle of a pluggable out-of-plane coupler with integrated 45° micromirror inserted into a cavity in a PCB: the light propagating in the optical waveguide is coupled out of plane by means of a 90° deflection on the micromirror, or vice versa, as illustrated by the dashed arrow.

but it is difficult to cut individual waveguides on the same substrate due to the physical size of the machining tool. Reactive ion etching [7], where the slope of the mirror is formed by 45° oblique etching, is limited by directional freedom. Gray-scale lithography [8] has a very narrow processing window, making it difficult for manufacturing. Other techniques are tilted X-ray exposure [9] and laser ablation, for which, e.g., KrF Excimer lasers are used [10]. All of the above technologies are used to write the micromirrors directly in the waveguides. In this letter, we present a completely different approach, where we propose the use of a discrete out-of-plane coupling component with an integrated 45° micromirror that can be readily inserted into cavities fabricated in optical PCBs, as illustrated in Fig. 1. This way, the light propagating in the PCB-integrated waveguides is coupled out-of-plane by a 90° deflection on the micromirror by total internal reflection (TIR), or, vice versa, the light emitted by surface-normal optoelectronic devices can be coupled into the PCB-integrated waveguides.

II. PLUGGABLE OUT-OF-PLANE COUPLERS

A. Fabrication Through Deep Proton Writing (DPW)

For the manufacturing of the discrete out-of-plane coupling components, we use the rapid prototyping technology of DPW [11]. It consists of a patterned 8.3-MeV proton irradiation of a polymer photoresist (PMMA), followed by a selective etching process to remove the exposed zones. The resist thickness of $500 \mu\text{m}$ was chosen to be compatible with the standard $250\text{-}\mu\text{m}$ pitch of the PCB-integrated waveguides allowing us to stack several out-of-plane couplers. However, this thickness could be increased (up to 2 mm) in the near future by transitioning to 16.5-MeV protons. During irradiation, the sample is moved according to a predefined pattern in steps of 500 nm with an accuracy of 50 nm, while depositing $2.5 \times 10^{12}/\mu\text{m}^2$ protons per step to achieve the highest quality optical surfaces.

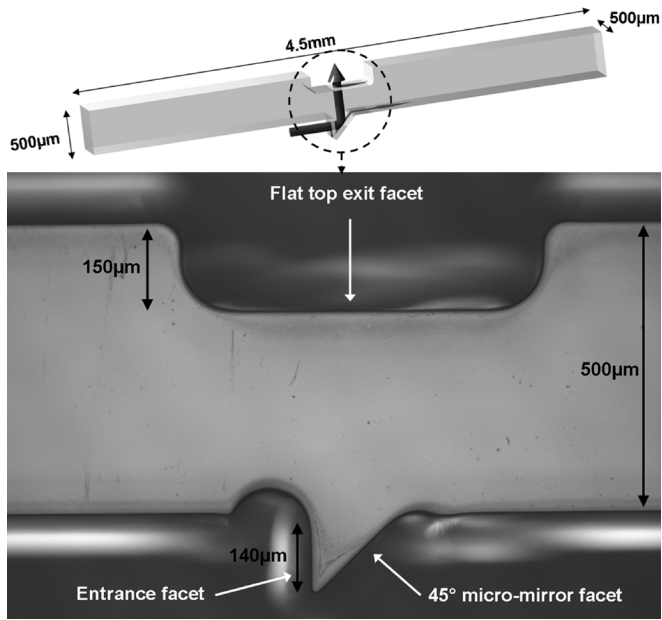


Fig. 2. Designed (top) and fabricated (bottom) DPW out-of-plane coupler with integrated 45° micromirror of $140 \mu\text{m}$ height.

Typical proton currents for the $125\text{-}\mu\text{m}$ proton beam diameter are 160 pA , resulting in total processing times of about 5 h (development included) for a component with dimensions of $4.5 \text{ mm} \times 0.5 \text{ mm} \times 0.5 \text{ mm}$. Fig. 2 shows the prototyped component with integrated 45° micromirror. Due to the finite beam size of $125 \mu\text{m}$, there is some rounding at the corners of the component but this does not affect its optical functionality.

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 electroplating. After removal of the plastic master, this metal mould can be used as a shim in a final microinjection moulding or hot embossing step [12]. This way, the component can be mass-produced at low cost in a wide variety of high-tech plastics.

B. Characterization of the Fabricated Components

To assess the quality of the optical surfaces of the fabricated out-of-plane couplers, namely the flat-top exit facet and the 45° mirror facet, we use a WYKO NT-2000 noncontact optical surface profiler. The measurement reveals that the optical surfaces have an average local root-mean-square (rms) surface roughness R_q of $12.5 \text{ nm} \pm 3.2 \text{ nm}$. We have averaged at least five measurements of an area of $58 \mu\text{m} \times 44 \mu\text{m}$ taken at randomly chosen positions. The peak-to-valley flatness R_t of DPW surfaces is measured to be as small as $2.2 \mu\text{m}$ over the total component thickness of $500 \mu\text{m}$. This is due to the proton scattering during the interaction with the PMMA [11]. We can conclude that the developed DPW surfaces have a very high quality: almost vertical and with a very low rms surface roughness.

C. Coupling Efficiency Measurements

To measure the coupling efficiency that can be achieved with the DPW out-of-plane couplers, we have first characterized the component in a fiber-to-fiber coupling scheme. Here, the input fiber is a silica multimode fiber (MMF) with a core diameter

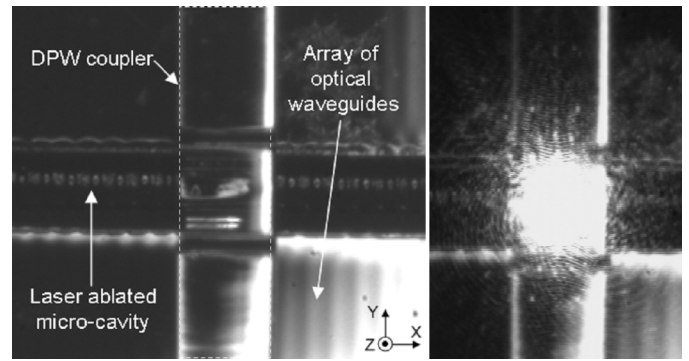


Fig. 3. Top view of the DPW out-of-plane coupler inserted in a microcavity on a PCB with optical waveguides. The axes definition refers to Fig. 1. The right picture shows the light spot coupled out-of-plane when the laser is turned on.

of $50 \mu\text{m}$ and a numerical aperture (NA) of 0.2 and the output fiber is a silica MMF with $100\text{-}\mu\text{m}$ core and 0.29 NA, mounted on a six axis parallel kinematics motion robot. This allows us to both position the fiber with an accuracy of 300 nm and to perform two axis scans to measure the tolerance for mechanical misalignments of the detector fiber. We measure coupling losses as low as 0.77 dB. The reference measurement consisted of an in-line butt coupling of both fibers.

In a second test, we plugged the component into a PCB with integrated multimode optical waveguides. The True-mode Backplane polymer waveguides have a cross section of $50 \mu\text{m} \times 50 \mu\text{m}$, an NA of 0.3, and a pitch of $250 \mu\text{m}$. A detailed description of the waveguide fabrication and characterization can be found in [13]. The microcavity that accommodated the DPW out-of-plane coupler was created using laser ablation. For the fabrication of the microcavity, the KrF excimer laser is tilted by 6° such that a vertical end-facet of the waveguides can be created. The DPW out-of-plane coupler is inserted manually in the cavity by means of a tweezer. Fig. 3 shows a top view of the DPW coupler inserted in the cavity and the light spot deflected by micromirror. When using the same detector fiber as in the first fiber-to-fiber coupling experiment, a total coupling loss of 5.69 dB was measured. This loss now includes the butt coupling from the input fiber to the PCB-integrated waveguide (in-plane, at the left side of Fig. 1), propagation in the waveguide over a length of about 5 cm, coupling towards the out-of-plane coupler and from the coupler to the detector fiber. No index-matching gel was used at any point. From [13], we know that the propagation loss of the PCB-integrated waveguides is 0.13 dB/cm and the average in-plane coupling loss is 1.77 dB. Hence, the mirror loss can be estimated to be 3.27 dB. The main reason for the relatively high coupling loss in this configuration is that for a large part of the NA, light is no longer satisfying the condition for TIR at the micromirror. The tolerance for mechanical misalignments of the detector fiber is $\pm 26 \mu\text{m}$ for an excess loss of 1 dB. The measured coupling efficiencies in the experiments described above can be even further increased by applying a metal reflection coating on the micromirror, especially in view of the large NA of the PCB-integrated waveguides.

Due to the large core and NA of the waveguides, the coupling loss will be much higher when using a mirror-based DPW coupler at the receiver (Rx) side—as described above—than when using it at the transmitter (Tx) side, since the divergence

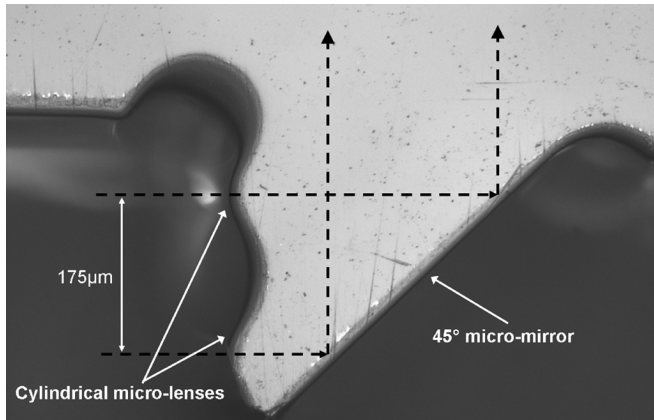


Fig. 4. First prototype of a DPW multilayer out-of-plane coupler with monolithically integrated cylindrical microlenses at the input facet. The light paths for each layer are indicated by the dashed arrows. The total height of the micromirror is $300 \mu\text{m}$.

of the vertical-cavity surface-emitting laser source can be much smaller than the divergence of the PCB-integrated waveguides. To show this, we have used the DPW coupler in a Tx configuration, where a standard single-mode fiber (SMF-28) was used at the flat top part of the coupler inserted in the microcavity on the PCB. The silica MMF detector fiber (with $100\text{-}\mu\text{m}$ core and 0.29 NA) was used to capture the light emitted by the PCB-integrated waveguides in-plane. Here, a total link coupling loss of only 3.00 dB was measured, confirming that the coupling loss at the Rx side is the most critical. The tolerance for mechanical misalignments of the source SMF is $\pm 16 \mu\text{m}$ for an excess loss of 1 dB.

D. Extension Towards Multilayer Couplers

The interest in multilayer optical interconnections on the PCB-level has grown recently [14] in view of their potential for higher integration densities and more flexible routing schemes. One of the big advantages of the discrete couplers presented in this letter is that the concept can be easily extended towards multilayer structures. A preliminary prototype of a two-layer out-of-plane coupler with monolithically integrated cylindrical microlenses at the input facet is shown in Fig. 4. The micromirror of this component is $300 \mu\text{m}$ high and the pitch between the upper and lower channel is $175 \mu\text{m}$. Due to the increased optical path length in comparison to the single-layer out-of-plane coupler and to avoid crosstalk between the upper and the lower channel, we decided to monolithically integrate cylindrical microlenses to ensure collimation (in one direction) of the beam emitted by each waveguide layer. Although the design is not yet optimized, first measurements have shown coupling losses of 1.63 and 1.24 dB for, respectively, the upper and the lower channel when using it in a similar fiber-to-fiber coupling scheme as the one described above. The crosstalk was smaller than -30 dB.

III. CONCLUSION

We have shown that we are able to prototype discrete out-of-plane coupling components for board-level optical interconnections using DPW. The resulting components feature

high-quality optical surfaces and are very versatile, since they can be readily inserted into cavities formed in PCB-integrated optical waveguides. A coupling loss of 0.77 dB was measured in a fiber-to-fiber coupling scheme. The prototyped out-of-plane couplers are compatible with mass fabrication at low cost in a wide variety of high-tech plastics.

When compared to the usual approach of integrating the micromirrors directly into the waveguides, which have to be compatible with standard high-temperature PCB manufacturing processes, the advantage of a discrete insert is that the couplers can be inserted at a later phase of the fabrication process. Finally, we have shown that the concept of discrete inserts can be easily extended towards multilayer structures, paving the way towards more complex routing components to guide the light from one layer to another. Cylindrical microlenses can be included in the coupler while ensuring perfect alignment with respect to the micromirror.

REFERENCES

- [1] D. A. B. Miller, "Rationale and challenges for optical interconnects to electronic chips," *Proc. IEEE*, vol. 88, pp. 728–749, Jun. 2000.
- [2] M. W. Haney, H. Thienpont, and T. Yoshimura, "Introduction to the issue on optical interconnects," *IEEE J. Sel. Topics Quantum Electron.*, vol. 9, no. 2, pp. 347–349, Mar. 2003.
- [3] R. T. Chen, L. Lin, C. Choi, Y. J. Liu, B. Bihari, L. Wu, S. Tang, R. Wickman, and B. Picor, "Fully embedded board-level guided-wave optoelectronic interconnects," *Proc. IEEE*, vol. 88, pp. 780–793, Jun. 2000.
- [4] S. Uhlig and M. Robertsson, "Limitations to and solutions for optical loss in optical backplanes," *J. Lightw. Technol.*, vol. 24, no. 4, pp. 1710–1724, Apr. 2006.
- [5] R. Yoshimura *et al.*, "Polymeric optical waveguide films with 45° mirrors formed with a 90° v-shaped diamond blade," *Electron. Lett.*, vol. 33, no. 15, pp. 1311–1312, 1997.
- [6] A. Glebov, J. Roman, M. G. Lee, and K. Yokouchi, "Optical interconnect modules with fully integrated reflector mirrors," *IEEE Photon. Technol. Lett.*, vol. 17, no. 7, pp. 1540–1542, Jul. 2005.
- [7] Y. Liu, L. Lin, C. Choi, B. Bihari, and R. T. Chen, "Optoelectronic integration of polymer waveguide array and metal-semiconductor-metal photodetector through micromirror couplers," *IEEE Photon. Technol. Lett.*, vol. 13, no. 4, pp. 355–357, Apr. 2001.
- [8] M. Immonen, W. Jianbo, and J. Kivilathi, "Fabrication of polymer optical waveguides with integrated micromirrors for out-of-plane surface normal optical interconnects," in *Proc. 4th IEEE Int. Conf. Polymers Adhesives Microelectron. Photonics (Polytronic 2004)*, 2004, pp. 206–210.
- [9] J.-S. Kim and J.-J. Kim, "Fabrication of multimode polymeric waveguides and micromirrors using deep X-ray lithography," *IEEE Photon. Technol. Lett.*, vol. 16, no. 3, pp. 798–800, Mar. 2004.
- [10] N. Hendrickx, J. Van Erps, G. Van Steenberge, H. Thienpont, and P. Van Daele, "Laser ablated micromirrors for printed circuit board integrated optical interconnections," *IEEE Photon. Technol. Lett.*, vol. 19, no. 11, pp. 822–824, Jun. 2007.
- [11] C. Debaes *et al.*, "Deep proton writing: A rapid prototyping polymer microfabrication tool for micro-optical modules," *New J. Phys.*, vol. 8, pp. 270–288, 2006.
- [12] M. Hecke and W. K. Schomburg, "Review on micro molding of thermoplastic polymers," *J. Micromech. Microeng.*, vol. 14, pp. R1–R14, 2004.
- [13] G. Van Steenberge, N. Hendrickx, E. Bosman, J. Van Erps, H. Thienpont, and P. V. Daele, "Laser ablation of parallel optical interconnect waveguides," *IEEE Photon. Technol. Lett.*, vol. 18, no. 9, pp. 1106–1108, May 1, 2006.
- [14] S. H. Hwang, M. H. Cho, S.-K. Kang, T.-W. Lee, H.-H. Park, and B. S. Rho, "Two-Dimensional optical interconnection based on two-layered optical printed circuit board," *IEEE Photon. Technol. Lett.*, vol. 19, no. 6, pp. 411–413, Mar. 2007.