Wafer-scale in-plane micro-optical interconnects for fiber arrays

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***Abstract*— A novel wafer-scale, compact, in plane solution for interconnecting optical devices with fibers and fiber arrays in a self-aligned "plug-and-play" style is presented. In particular, micro-optical structures on glass wafers, as well as on SiN waveguide grating couplers were designed, optimized, and fabricated. The micro-optical structures are based on re-directing light (reflection) elements, combined with integrated comp like fiber self-alignment structures, fabricated using wafer scale reflow and replication processes. Successful assembly of a 12-fiber ribbon is demonstrated. Excess losses of these structures as low as 0.35 dB are obtained.**

***Keywords*— Wafer-scale integration, microoptics, packaging, optical interconnections, optical fiber arrays**

I. Introduction

Photonics packaging remains one the most challenging steps in the in the optoelectronic system industry and is therefore oftentimes responsible for more than 80% of the total cost of a of a fully assembled device [1]. Moreover, space is becoming more and more an issue especially with the trend for increased data throughput and the related demand for multi-fiber connectivity. This leads to an increasing need for miniaturized, compact, cost effective, optical interconnects to fiber arrays. In fact, it is essential to have such interconnectors to photonic integrated circuits (PIC), to waveguides in electro optical boards [2], but also to active optical devices (e.g. lasers, LEDs and detectors).

The conventional methods of coupling light into a device from an optical fiber or a fiber array normally require active alignment in a serial process which is extremely time consuming and costly. Several advanced types of fiber to waveguide connectivity solutions have already been reported based on diffractive gratings [3], reflective curved mirrors [4], microlenses on 45°-angled fibers [5], facet mirrors of V-grooved silicon optical benches [6], V-grooves with integrated optical micro-systems [7], etc. However, most of these solutions are for single fibers only, offering low coupling efficiency, needing active alignment and/or requiring complicated manufacturing methods. Moreover, additional components are usually required (e.g. lens/micro mirror arrays, fiber bundles) that adds up to the complexity and cost of the packaging, as well as making the final product bulky.

In an earlier work [8] we already reported on a compact, folded, single fiber, interconnect, based on total internal reflection (TIR) and combined with integrated self-alignment structures [8].

Here, we present the extension and advancement of this compact wafer-scale solution for interconnecting optical devices with fiber arrays and in combination with SiN waveguide grating PICs. The technology is based on micro-optical reflection elements combined with fiber self-alignment structures, resulting in comb-like structures. The accuracy and performance are obtained using a single reflow process which results in automatically smooth mirror walls which are the key for low optical losses as well as precise fiber alignment. In the following, we describe the realization and measurements of such micro-optical interconnects, including their design, their characterization and the assembly of a fiber array.

II. Concept and Design Considerations

A. Concept

The proposed compact "plug-and-play" interconnects are based on micro-optical structures preferably employing total internal reflection (TIR). They are based on reflection elements, fabricated from reflowed cylindric structures. In addition, to easily enable passive fiber array coupling and packaging, these reflecting elements are combined with integrated fiber alignment walls. The final micro-optical interconnect as it is foreseen for a fiber array of four fibers coupled into waveguide gratings is sketched in Fig. 1.

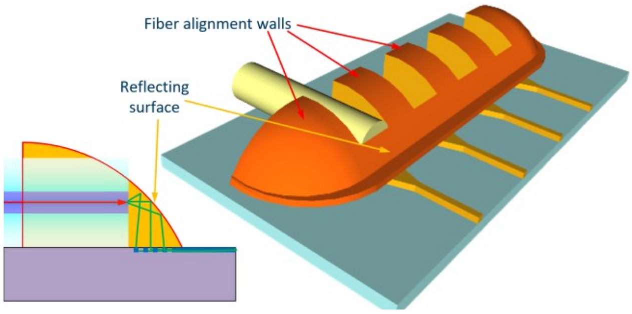

Fig. 1. 3D visualization of the proposed "plug-and-play" micro-optical interconnect for an optical fiber array of four fibers into waveguide gratings together with the corresponding optical path

The resulting comb like micro-optical interconnect provides passive alignment and assembly of the fiber arrays through the fiber alignment walls, whereas the reflecting surface points the light with high precision and with the desired angle into the corresponding optical input of the device.

B. Folded interconnect design

To redirect the light from a standard glass fiber to the optimal optical input of the particular device, several constraints and requirements were taken into account. For example, the geometry of the micro-optical structures was designed to cover single mode fibers (SMF) on the input (i.e. SMF-28 E9, operating at 1550 nm with a beam size of 10.5 µm and a numerical aperture NA = 0.13), and multimode fibers (MMF) on the output (i.e. MMF G50, operating at 1550 nm with a core size of 50 µm and a numerical aperture NA = 0.20). Most important is that the height of the reflecting micro-optical elements must be compatible with the location and core size of the fibers to result in the proper entry point and input angle (e.g. 100-degree for waveguide grating couplers). Furthermore, the beam divergence at the exit of the glass fiber should preferably comply with the TIR requirements at the reflecting optical interface to avoid application of an additional reflection layer.

The main geometrical constrains of such a designed micro-optical element for the example of using an MMF G50 as source are sketched in Fig. 2.

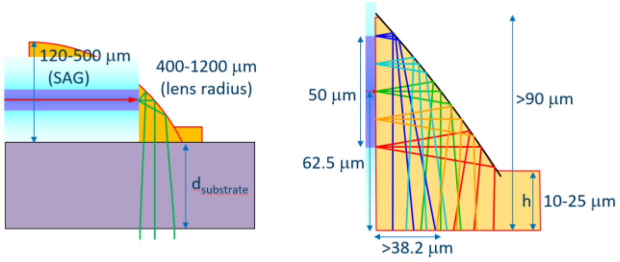

Fig. 2. Left: Schematics of folded micro-optical interconnects directly replicated on a glass wafer. Right: Ray trace within micro-optical element and main geometrical constrains for the G50 fiber approach

In order to satisfy the above requirements for waveguide grating inputs, we designed micro-optical interconnects with a structure radius of around 1100 µm, a lens sagita (SAG) of 440 µm while having a socket height h of around 15 µm. Other more compact versions with smaller radii (300 µm) and SAG (160 µm) resulting in smaller footprint were also realized.

In addition, to provide “plug-and-play” precise fiber array self-alignment features (fiber walls) are designed into the reflecting elements (see Fig. 3). Here the design of the distance between the walls is crucial, as it has to be wide enough to accommodate the fiber inside and tight enough to have as little alignment mismatch as possible. Accuracy within 1 µm is achievable. They will be realized in the same mask-aligner process step, as the alignment of the reflecting elements to the input of the device. Again, precision around 1 µm is achieved.

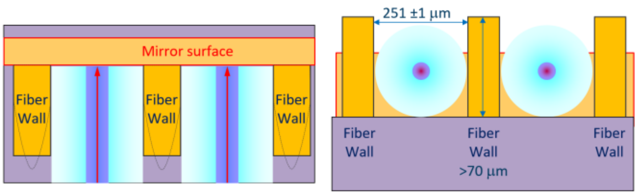

Fig. 3. Top view (left) and front view (right) of the folded micro-optical interconnect with the integrated fiber walls for self-alignment

To ease fiber assembly even further, these alignment structures had been designed as funnels and combined with stress release structures in other implementations.

III. Fabrication of the Fiber Array Interconnects

One of the most cost-effective fabrication technologies for volume production of micro-optical components is based on UV wafer-scale replication into chemically stable polymers or hybrid organic-inorganic solgel using standard semiconductor equipment [9]. The process as used for our micro-optical interconnects consists of two main phases (Fig. 4):

First (step 1), a master with the micro-optical structures is fabricated. For generating the reflective micro-optical element, photolithography and a reflow process are applied [10]. The resulting structure looks like the top part of a cylinder with round ends having a spherical cross section (master in Fig. 4). This master is then used to produce the replication tool (mould or stamp).
To obtain master structures with prism like, aspherical or even more exotic (freeform) mirror surfaces other technologies such as direct laser writing, grayscale, or other 3D micro-fabrication methods could be applied.

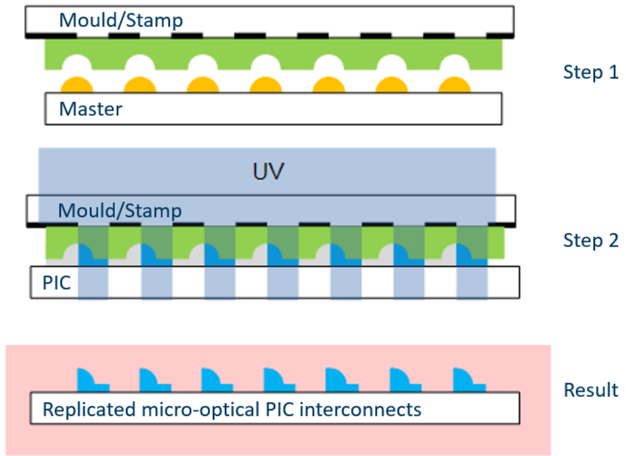

Fig. 4. UV replication process steps to define the alignment elements and the final shape of reflecting surface of the in-plane micro-optical PIC interconnect.

The resulting replication tools can then (step 2) be used to mass manufacturer the micro-optical elements by replication into a UV curable polymer or hybrid solgel directly onto the optical elements. In particular, the UV casting process enables the replication of micro-optical structures at wafer-level (possible also on single dices) with a precise control of the alignment in respect of the optical input (below +/- 1 µm) and of the height (+/- 2 µm) of the replicated elements, using a modified MA6 mask-aligner from Süss Microtec. A residual layer (h in Fig. 2) both defines and precisely limits the achievable height. As the UV exposure is done through a specifically designed Cr-photomask (the orange area in the left part of Fig. 3) that defines the final top-view of the wafer's replicated structures, the replication of the self-alignment fiber walls occurs in the same process step (together with the reflecting micro-optical element).

Such replicated final micro-optical interconnect structures on a SiN waveguide grating, together with one fiber inserted is shown in Fig. 5.

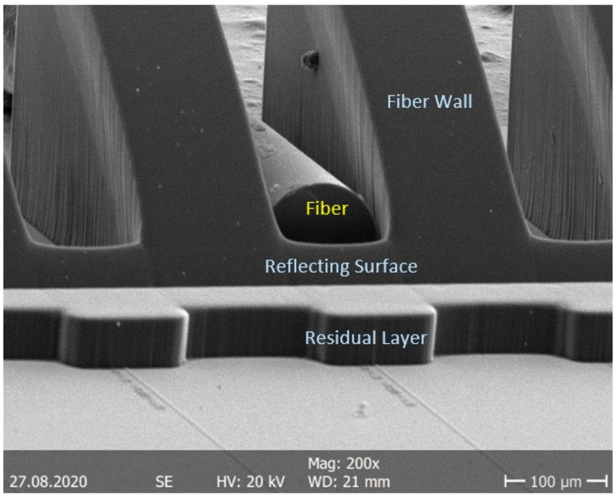

Fig. 5. Scanning Electron Microscope (SEM) image of the in-plane micro-optical interconnect having a single fiber inserted.

IV. Results of Fiber array interconnects

A special flexible setup was built to be able to characterize the reflecting micro-optical element integrated onto glass substrates or waveguide PICs with integrate grating couplers (Fig. 6). The setup consists of an input and an output fiber each on a three-axis micro stage together with a substrate holder. The setup can principally handle most commercially available optical fiber types (SMF-28 E9, MMF G50, H200, etc.) and cover a wide wavelength range (400 nm – 1700 nm) using the corresponding source and detector. It further can flexibly adjust angles (0-90°) of input and output fiber.

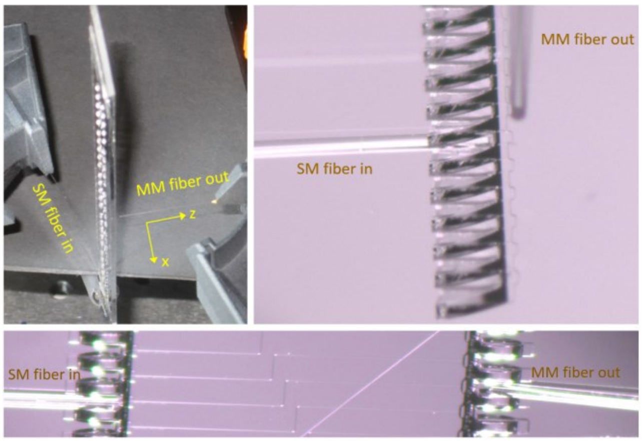

Fig. 6. Right angled optical characterization setup used to measure the beam quality, beam deflection angle and excess loss of the reflective micro-optical elements on a glass substrate (top row), as well as the straight fiber-PIC(waveguide)-fiber arrangement to measure fiber-to-fiber transmisssion (bottom row).

In order to characterize the optical beam quality, the beam deflection angle, as well as the optical excess loss of the reflecting micro-optical surface element, the measurement setup had been arranged in a 90-degree configuration (see Fig. 6 top). After inserting the input fiber between the fiber walls the horizontal beam profile (x-axis) can be measured at different positions along the beam propagation axis (z-axis). Results showed negligible excess loss into a MM G50 fiber (<0.3 dB) and agreed very well with the predicted output beam deflection of 100°. Both results clearly prove the quality of the replicated reflecting surfaces.

To measure the optical transmission loss through a PIC with waveguide grating structures as optical in and outputs the setup was arranged such that in- and output fibers were facing each other (see Fig.6 on the bottom). Additional losses of 3-5 dB per coupling into the MM G50 fibers and 8-10 dB for the SMF-28 input side were obtained compared to the ones taken without the micro-optical interconnect. These relatively high losses are due to a positional offset of the micro-optical microstructure in respect to the optimal grating position caused by material shrinkage during the replication process of the micro-optical elements. This will be overcome in future by anticipating the shrinkage in the initial master structure design.

V. Fiber array Assembling

In the final step, one of the glass substrates with the fabricated and characterized micro-optical interconnects was assembled to a 12er fiber array. The ribbonized fiber patch cord had an MT style connector on one side. The fibers were then introduced into the micro-optical interconnects using a similar setup as for the characterization of the replicated structures. The principle is visualized in Fig. 7, with the fibers half-way and fully inserted into the funneled fiber walls, demonstrating the "plug-and-play" working principle. In a final step the fibers are glued in place.

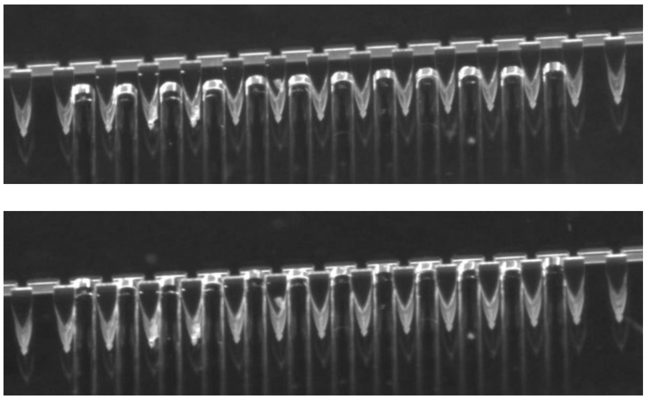

Fig. 7. Picture of fiber array assembly process, partly inserted between the fiver walls (top); and fully pushed against reflecting mirror structure (bottom).

One of such assembled patch cord is shown in Fig. 8 together with the light coming out on the backside of the glass substrate when illuminating the MT-connector with a white light source.

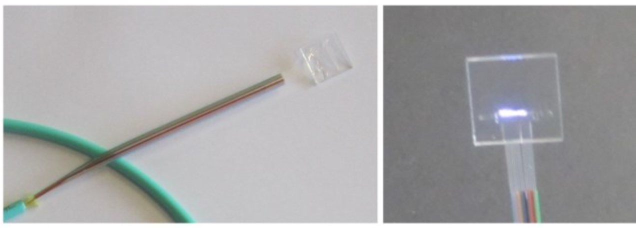

Fig. 8. Patchcord assembled into the micro optical interconnect on a glass substrate (left) with its optical output on the substrate back side (right).

Conclusions

In this paper, we presented an innovative "plug-and-play" style micro-optical interconnect for fiber arrays. Fabricated by UV wafer-scale replication, these structures are compact, they facilitate fiber alignment, and can reach excess losses as low as 0.35 dB. making them very suitable for optoelectronic packaging. Overall, our wafer-scale parallel replication process allows fabrication of thousands of interconnects at once at very low costs.

First integration of such micro-optical elements onto SiN waveguides showed successful fiber-to-fiber optical transmission in and out of the device thus demonstrating that the presented micro-optical interconnects can be implemented for standard industrial PIC production. Furthermore, it can be applied to waveguides in electro-optical boards, or waveguide based active devices. First assemblies with fiber arrays were successfully concluded.

The implementation of such a replication technology will enable the production of reflecting micro-optical interconnects with extreme compactness, thus providing significant technical advantages and degrees of freedom for both component suppliers and device/system integrators

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REFERENCES

[1] Fuchs, E. R. H., Bruce, E. J., Ram, R. J. & Kirchain, R. E. Process-based cost modeling of photonics manufacture: the cost competitiveness of monolithic integration of a 1550-nm DFB laser and an electroabsorptive modulator on an InP platform. Journal of Lightwave Technology 24, 3175–3186 (2006).

[2] K. Schmidtke, et al., "960 Gb/s Optical Backplane Ecosystem Using Embedded Polymer Waveguides and Demonstration in a 12G SAS Storage Array," IEEE J. Lightwave Technol., 2013, 31, (24), pp. 3970-3974.

[3] Gordillo, O. A. J. et al. Plug-and-play fiber to waveguide connector. Opt. Express, OE 27, 20305–20310 (2019).

[4] Gehring, H., Eich, A., Schuck, C. & Pernice, W. H. P. Broadband out-of-plane coupling at visible wavelengths. Optics Letters 44, 5089 (2019).

[5] K.-W. Jo, M.-S. Kim, J. H. Lee, et al., "Optical characteristics of a self-aligned microlens fabricated on sidewall of a 45º- angled optical fiber", IEEE Photon. Technol. Lett. , 2004, **16,** (1), pp. 138-141.

[6] S. H. Hwang, J. Y. An, M.-H. Kim, et al., "VCSEL array module using (111) facet mirrors of a V-grooved silicon optical bench and angled fibers," IEEE Photon. Technol. Lett., 2005, **17**, (2), pp. 477-479

[7] R. Krähenbühl, J. Kunde, A-C Pliska, et al., "Compact 90º releasable multifiber optical connectivity solution", IEEE Photon. Technol. Lett., 2007, 19, (8), pp. 580-582.

[8] R. Krähenbühl, Angélique Luu-Dinh, and Rolando Ferrini, "Wafer-scale Folded Micro-optical Interconnects", 45th European Conference on Optical Communication (ECOC 2019).

[9] M. Rossi, H. Rudmann et al., ''Wafer-scale micro-optics replication technology'' Proc. of SPIE, 2003, vol. 5183, pp. 148–154

[10] S. Haselbeck, H. Schreiber, J. Schwider, et al., "Micro-lenses fabricated by melting photoresiston on a base layer" Opt. Eng., 1993, **6** pp. 1322–4

[11] Y. Bellouard, et al." Femtoprint: A femtosecond laser printer for micro- and nano-scale systems", CLEO_AT.2012.ATu3L.3.