A platform approach towards hybrid photonic integration and assembly for communications, sensing, and quantum technologies based on a polymer waveguide technology

Moritz Kleinert, Madeleine Nuck, Hauke Conradi, David de Felipe, Martin Kresse, Walter Brinker, Crispin Zawadzki, Norbert Keil, and Martin Schell
Photonic Components Dept.
Fraunhofer Heinrich Hertz Institute
Berlin, Germany
moritz.kleinert@hhi.fraunhofer.de

***Abstract*—We present functionalities of photonic integrated circuits and a generic assembly approach for their hybrid integration with other components in the polymer waveguide platform PolyBoard. In addition to standard integrated optics capabilities, the PolyBoard approach allows for the realization of flexible interconnects, the fabrication of multilayer waveguide structures with low intra-layer coupling losses, and the integration of bulk optical crystals in on-chip free-space sections. These functionalities enable PICs with applications ranging from communications, via sensing, to quantum technology. The semi-automated assembly process presented in the second part of this paper ensures the compatibility of all individual functionalities and the scalability of the developed approaches towards production.**

Keywords—hybrid photonic integration; assembly; polymer waveguides

I. Introduction

Complex photonic integrated circuits (PICs) offer a great variety of functions on a small footprint, which makes them attractive for a broad array of applications, ranging from communications to sensing and analytics. While for many of these applications complex PICs have been successfully demonstrated as proof-of-concept or on a relatively small number of devices, the scaling of the prototypes towards production in small and medium numbers remains a challenge. This challenge is mainly posed by the complexity and required precision in many of the assembly processes. This is reflected in the fact that assembly and packaging accounts for ca. 80% of the total cost of an optoelectronic module [1]. This is especially true for hybrid photonic integration platforms, which combine different material systems in one chip. These platforms usually combine a passive material for waveguiding (e.g. SiO_2, Si_3N_4 or polymers) with active semiconductor components (e.g. InP, GaAs or Si) [2-4]. Compared with monolithic photonic integration platforms, the separation of waveguiding and photon generation and detection allows for a greater flexibility in the PIC design and for the independent optimization of the individual material systems. However, this comes at the price of further assembly steps to create an optical subassembly from the individual constituents.

Nevertheless, many applications greatly benefit from the use of a hybrid over a monolithic integration approach, such as narrow linewidth integrated tunable lasers [5] and on-chip integrated optical isolators [6]. Furthermore, novel application fields for PICs, such as quantum technologies, pose challenges that can only be addressed with hybrid PICs due to the broad spectral range required for some of the processes such as the generation of entangled photons via spontaneous parametric down-conversion (SPDC). In this paper, we will present the hybrid photonic integration platform PolyBoard of Fraunhofer HHI and introduce novel functionalities of the platform, such as flexible interconnects, multilayered structures and on-chip free-space sections. In order to make these features available for the use in PICs, an integrated assembly approach is presented and discussed in the second part of this paper.

II. Polymer-based Photonic Integration Platform

A. Core Functionalities

The hybrid integration platform PolyBoard of Fraunhofer HHI has been developed over the last years, with a focus on applications in optical communications and sensors. The passive waveguiding platform relies on single-mode polymer waveguides. The polymer material used for all presented functionalities is of the ZPU12 series manufactured by ChemOptics Inc. Fig. 1 (left) shows the diced end-face of a fabricated PolyBoard chip. The waveguide is implemented as a square-shaped channel waveguide with the waveguide core completely surrounded by cladding material. The platform features three different refractive index contrasts between the cladding and core materials ranging from $\Delta n = 0.005$ to $\Delta n = 0.030$. In order to ensure single-mode operation, the waveguides feature cross sections between 3.2 µm x 3.2 µm to 7.3 µm x 7.3 µm, depending on the refractive index contrast.

The mode field diameter in the case of the low refractive index contrast matches well to that of standard single-mode fibers, resulting in a fiber coupling loss of 0.1 dB per facet. For higher Δn values, the coupling loss increases towards 1.0 dB.

TABLE I. POLYBOARD WAVEGUIDE PARAMETERS AT 1550 NM

Δn	*Fiber coupling loss*	*Min. bend radius*	*Dimension*
0.005	0.1 dB	15.0 mm	7.3 µm x 7.3 µm
0.011	0.6 dB	6.0 mm	6.0 µm x 6.0 µm
0.030	1.0 dB	1.5 mm	3.2 µm x 3.2 µm

From the waveguide parameters given in Table I, the optimum refractive index contrast for a given application can be determined based on its specific requirements: E.g. a large number of optical functionalities on one chip is ideally realized in Δn = 0.030 due to the smallest bend radii that result in compact chips, whereas single optical functionalities such as optical filters are best fabricated with Δn = 0.005 because of the very low fiber-coupling loss.

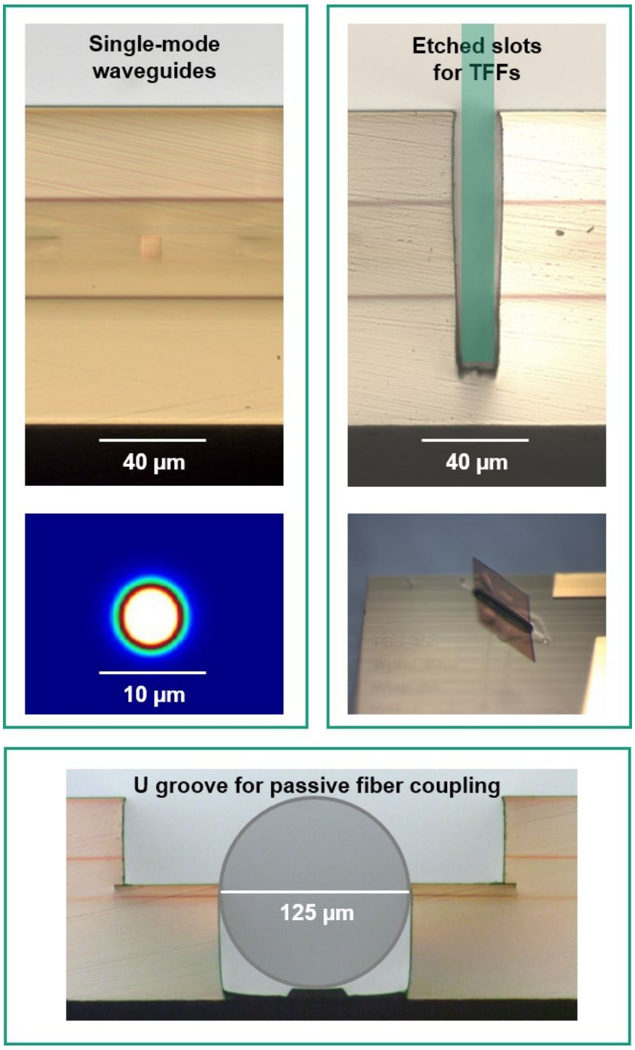

Fig. 1. Microscope image of the diced end-face of a single-mode waveguide and simulated mode profile for Δn = 0.005 (left column). Microscope image of a diced cross section of an etched slot for the integration of TFFs and photograph of a PolyBoard with inserted TFF (right column). The position of the inserted TFF is indicated in light green in the top picture. The lower row shows the cross section of a U groove for passive fiber-chip coupling. The position of the standard single-mode fiber is indicated in grey.

For the fabrication of the polymer waveguides, cladding and core polymer layers are spin-coated as liquid resins before being cured by UV light exposure and a hard bake. The waveguides, slots and U grooves (compare Fig. 1) are structured by reactive ion etching (RIE). The subsequent spin-coating of the layers allows for the deposition of metal structures buried in the layer stack, which enables efficient thermo-optical components [7]. The chip facet with a single mode waveguide (Δn = 0.005) shown in the left column of Fig.1 was diced out of the wafer. No further steps for the preparation of the end face were necessary, because in contrast to inorganic material systems, the polymers are not brittle and their refractive index contrast is close to that of optical fibers, thus overcoming the need for polishing and anti-reflective coating. The right column of Fig. 1 shows deeply etched slots for the insertion of thin-film filters (TFFs). They are based on dielectric layer stacks, enabling various spectral and polarization filter characteristics. The TFFs (green shaded area) are inserted perpendicularly to the waveguide layer with an input waveguide and appropriately placed output waveguides that collect the light in the reflected and transmitted bands of the filter. In this way, the design of the filter characteristic is independent of the specific PIC design. This enables the combination of well-proven temperature-insensitive dielectric coatings for filtering with integrated optics.

The lower row of Fig. 1 shows the cross section of a U groove used for fiber coupling of the PICs. The position of an inserted standard single-mode fiber with 125 µm diameter is indicated by the grey shaded area. The lateral position of the fiber relative to the waveguide is given by the lithographic resolution of the processes. The vertical position is defined by the wafer-scale etching process. On a 4” wafer a deviation of ± 1 µm from the target is achieved. This enables passive fiber-chip coupling, which greatly reduces the complexity of the alignment process.

B. *Fexible Interconnects*

The polymer layers of standard PolyBoard PICs are fabricated on silicon wafers and the final chips are separated by dicing. Hence, these devices are rigid due to the high mechanical stability of the crystalline silicon. This enables simple handling procedures. If, however, flexible interconnects are required, a different pre-treatment of the silicon substrate allows for the delamination of the completely structured chips from the wafer. This enables the fabrication of flexible optical and electrical interconnects as presented in Fig. 2.

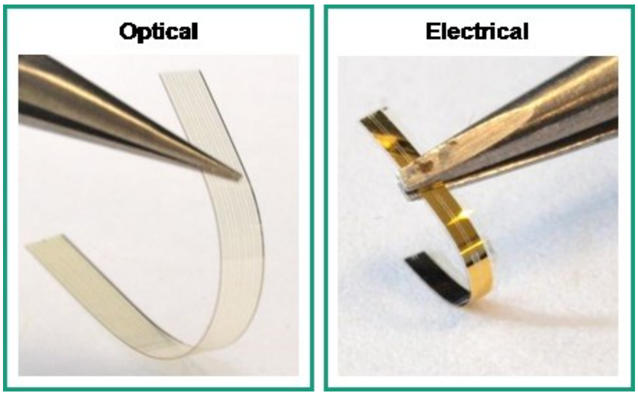

Fig. 2. Optical (left) and electrical (right) flexible interconnects based on the PolyBoard platform obtained by delamination from the wafer substrate.

Since the polymer layers are removed from the substrate after the finalization of all fabrication steps, the fabrication of the flexible interconnects is identical to the fabrication of standard PolyBoard PICs, except for the substrate pretreatment. This enables the use of accurate and scalable wafer-scale fabrication processes. The single-mode waveguide losses at 1550 nm obtained from flexible optical waveguides fabricated with this method amount to 0.8 dB/cm, which is close to the 0.7 dB/cm waveguide loss for rigid PolyBoard PICs. Hence, all integrated optical functionalities, such as multi-mode interference couplers (MMIs) and thermo-optical switches can directly be used in flexible optical interconnects. Besides optical waveguides, high-frequency electrical connections, e.g. co-planar electrical waveguides, can be fabricated in the standard PolyBoard platform and hence as flexible interconnects as well. Bandwidths in excess of 110 GHz have been demonstrated already [8]. These flexible single-mode optical and high-speed electrical interconnects allow for an additional degree of freedom in the assembly and packaging of PICs.

C. *Multilayer Structures*

Multilayer photonic integrated circuits are useful in a variety of applications ranging from LIDAR to crossing-free switch matrices. The spin-coating processes involved in the fabrication processes of the PolyBoard platform allow for a simple way of generating multilayer waveguide structures by alternating cladding layers and layers with structured waveguides as in Fig. 3 (top left). The main challenge for the application of these 3D structures is their connection to standard, quasi 2-dimensional PICs and the related assembly procedures. In polymer-based photonic integration platforms this can be solved by means of vertical MMIs as couplers between waveguide layers as presented in Fig. 3 (top right) [9,10]. These couple light from a lower single-mode waveguide (1.) via a vertical MMI section (2.) into an upper single-mode waveguide (3.). Compared with vertical coupling based on evanescent directional couplers, significantly higher distances in the order of several µm between the waveguide layers can be bridged in this approach. This results in a negligible cross-talk between waveguides in adjacent layers and hence the possibility to freely design the waveguide routing in the individual layers. By integrating these vertical couplers on a

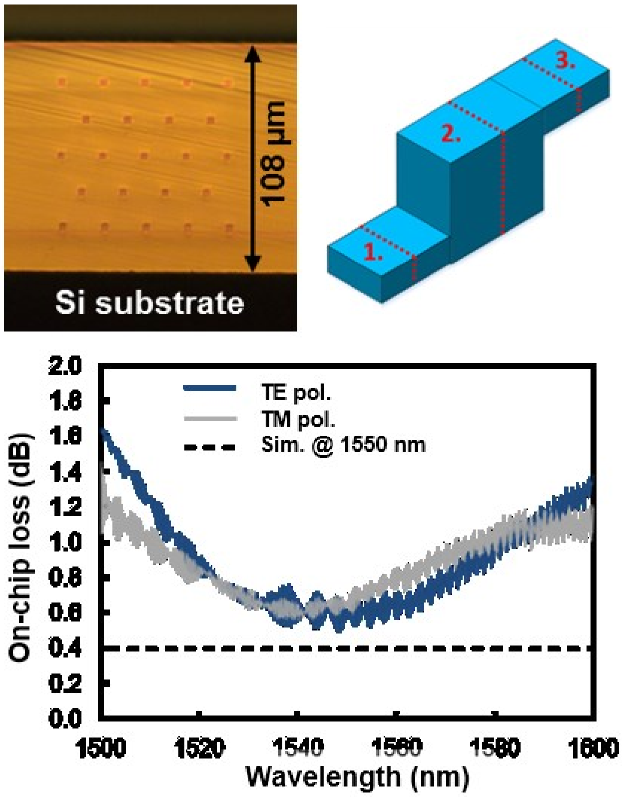

Fig. 3. Facet of a PolyBoard chip with 23 waveguides in five layers (top left) and schematic of a vertical MMI for the interconnection of waveguide layers (top right). The graph in the bottom shows the on-chip loss for a 1294-µm-long vertical MMI between two waveguide layers spaced by 7.2 µm.

multilayer PIC, facets with I/O waveguides in a single plane can be realized, because all waveguides can be routed to their respective layer on the chip. This allows for the use of standard assembly and packaging approaches that were developed for planar chips also for these novel multilayer PICs.

At the bottom of Fig. 3 the on-chip loss of a 1294-µm-long vertical MMI that connects two waveguide layers spaced by 7.2 µm is shown. This device was fabricated using the process described in [10]. The minimum loss of 0.6 dB for the TE polarization is obtained at the design wavelength of 1550 nm, which is close to the simulated optimum of 0.4 dB. Additionally, the polarization-dependent losses are below 0.2 dB across the C-band. This proves the feasibility of vertical MMIs for efficient interconnection in multilayer PICs.

D. *On-Chip Free-Space Sections*

While many optical functionalities can be realized efficiently in integrated optics, some still require bulk optical components, especially non-reciprocal und non-linear optical crystals. Recently, a combination of PICs with bulk crystals in the PolyBoard platform was developed. For this, a free-space section on the chip is formed by the same RIE processes as the U grooves presented in section II.A. At beginning and end of the free-space section graded index (GRIN) lenses with the same diameter as single-mode fibers are inserted into on-chip U grooves. These GRIN lenses create a collimated beam in the

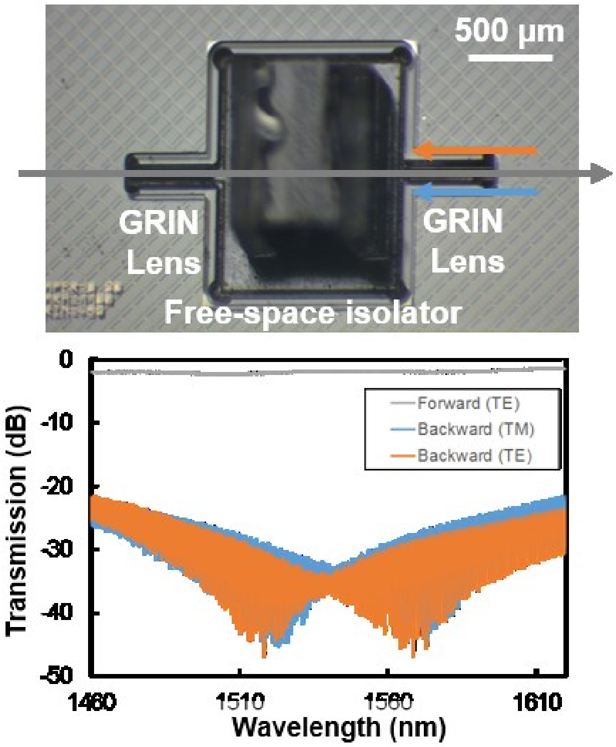

Fig. 4. Micrograph of a bulk optical isolator placed in a micro-optical bench formed by two GRIN lenses (top) and measured transmission and optical isolation of the device (bottom).

free-space section, hence avoiding large losses due to beam divergence. The sections can be as wide as some mm, which allows for the placing of bulk crystals.

In Fig. 4 (top) a PolyBoard chip with a micro-optical bench created by two GRIN lenses is shown. Here, an optical isolator for the TE polarization transmission, comprising of a Faraday rotator and two polarizers, is placed into the free-space section with 1 mm width. The transmission spectrum presented in Fig. 4 (bottom) shows the forward transmission of the TE polarization in grey. Excess losses of 1.4 dB to 2.0 dB compared to a straight reference waveguide are observed and recently, optimized structures yielded reduced on-chip losses of 0.7 dB. This demonstrates efficient light coupling from the single-mode waveguide through the crystal back into the single-mode waveguide. Orange and blue curves correspond to the backward transmission for TE and TM polarization, respectively. Across the complete wavelength span from 1460 nm to 1620 nm the isolation is greater than 20 dB for both polarizations with a maximum isolation greater than 30 dB.

Due to the proper isolation and the low losses, a structure as presented in Fig. 4 is useful for blocking unwanted reflections from within the PIC into integrated light sources such as lasers. So far this was only possible for reflections from external sources by optical isolators integrated in the module or external fiber. The micro-optical bench concept is not limited to non-reciprocal elements, but applies to all optical elements that can be placed in the free-space section. This concept is especially interesting for quantum communications, where well-proven setups exists on lab-scale optical benches, e.g. for the generation of entangled photons via SPDC [11]. The key element for this process is a non-linear optical crystal, such as periodically poled potassium titanyl phosphate (KTP), in which a short-wavelength pump photon decays into signal and idler photons at a longer wavelength. Such a crystal can be placed inside the on-chip free-space section in order to miniaturize the quantum communications setup into a PIC. In order for the entangled signal and idler photons to be in the infrared tele-communications bands, the crystal needs to be pumped with visible light. Hence, the waveguides need to be transparent across a broad wavelength range. In contrast to semiconductor-based material platforms such as Si, GaAs or InP, the polymers used in the PolyBoard platform meet this requirement and are therefore suitable for the fabrication of PICs for quantum communications based on non-linear optical crystals. Currently, this concept is being pursued within the UNIQORN project of the EU Quantum Flagship initiative [12].

III. Integrated Assembly Approach

In section II some basic PolyBoard functionalities as well as concepts that are unique to this integration platform were introduced and applications of these PICs in communications, sensing, and quantum technologies were discussed. However, in order to exploit the potential of the hybrid photonic integration for these applications, the assembly of the individual components that constitute the PIC need to be taken into account. For hybrid PICs from the PolyBoard platform, we propose a generic, semi-automated approach to the assembly,

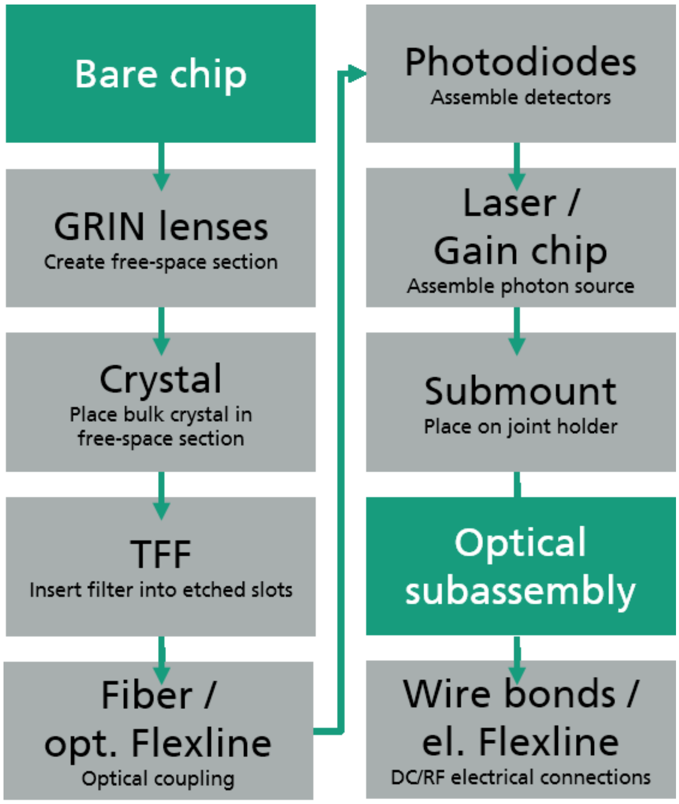

Fig. 5. Generic semi-automated assembly process of a hybrid photonic integrated circuit on the PolyBoard platform.

with scalability from prototypes (quantum technology) to production (sensing and communications).

To this end, the required processes are developed by HHI on a CL1500 assembly machine manufactured by ficonTEC. It comprises, among others, of one main axis with four degrees of freedom and three supporting axes with three translational and rotational degrees of freedom, which are equipped with interchangeable specialized pick-up tools for the handling of micro-optical elements. These are also able to apply epoxy and cure it with UV light. Fig. 5 shows a flow chart of the respective processes to obtain an optical subassembly. All functionalities of the PolyBoard platform are part of this process flow, which ensures the mutual compatibility of all features. If a specific PIC does not include one or several of these functionalities, the corresponding steps can be skipped without compromising the feasibility of the other steps. The assembly process starts out with the placing of the bare PolyBoard chip that was separated by dicing after the wafer-scale fabrication. Afterwards, these assembly processes follow:

- The GRIN lenses are placed into the on-chip U grooves and fixed with UV-curable epoxy. A picture of a 125-µm diameter GRIN lens handled during an assembly process is presented in Fig. 6 (top). This creates the collimated beam propagation in the free-space section.

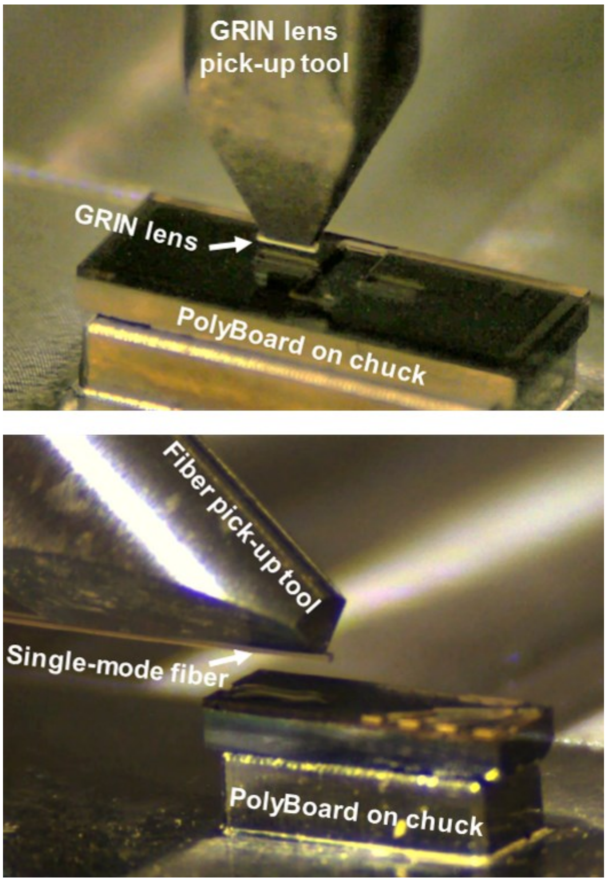

Fig. 6. Placing of GRIN lens into PolyBoard for generation of an on-chip free-space section (top) and single-mode fiber coupling to PolyBoard PIC with U groove (bottom).

- The bulk crystals are placed into the previously created free-space section and again fixed with UV-curable epoxy. These crystals can be, among others, optically non-reciprocal or non-linear.

- The TFFs are placed into etched slots and fixed with UV-curable epoxy [compare Fig. 1 (right)]. The slots are merely several micrometers wider than the TFFs, which feature typical thicknesses between 12 µm and 30 µm. The TFFs need to be placed perpendicularly to the waveguide layer plane into the slots in order to minimize the losses of the reflected band.

- Cleaved single-mode fibers are placed into U grooves for passive fiber-to-chip coupling [compare Fig. 6 (bottom)] or flexible optical interconnects are coupled to the facet of standard, rigid PolyBoard chips. In both cases epoxy is applied and UV cured.

- Photodetectors are attached with UV-curable epoxy either via 45° mirrors directly diced into the PolyBoard chips in case of backside illumination [13] or to the chip facet when using waveguide-integrated photodetectors. In the latter case, an active alignment is carried out in order to optimize the relative positions of PolyBoard and photodetector waveguides.

- Light sources (e.g. lasers or gain chips) are end-face coupled and fixed with UV-curable epoxy. The components are actively aligned in order to optimize the relative positions of both waveguides.

- The chip with its assembled components is placed on a submount, which provides mechanical stability. Thermally conductive glue ensures good heat dissipation.

- In an additional step, electrical connections to the submount or directly to the driving electronics are realized by wire bonds or flexible RF inter-connects.

The assembly process is semi-automated, meaning that all assembly steps are programmed and carried out by the machine, but the individual components need to be loaded manually, either on gel packs or, in the case of TFFs, on wafers. Picture recognition is used for the identification of the components as well as to acquire their orientation in the plane. Therefore, the components do not need to be specially prepared to be handled in the process. The machine, on which the current processes are being developed, is very versatile in order to cover all possible assembly steps required by any hybrid PIC in the PolyBoard platform. For production purposes the developed processes can be transferred to dedicated machines with higher throughput, ensuring the scalability of the presented concepts.

IV. Conclusion

Hybrid PICs offer great design flexibility and enable functionalities that cannot be realized efficiently in monolithic photonic integration platforms. In this paper, we presented flexible interconnects with single-mode waveguide losses of 0.8 dB/cm, multilayer PICs with intra-layer coupling losses of 0.6 dB and on-chip optical isolators with isolation ratios greater 30 dB as examples from the PolyBoard platform of Fraunhofer HHI. Hybrid PICs, and especially these novel features, require assembly processes that allow for the efficient and reliable fabrication of optical sub-assemblies from the individual constituents. In this paper we presented a generic, semi-automated assembly process flow covering all active and passive add-ons to the PICs. In order to enable a scaling from single prototypes towards production, the respective assembly processes are being developed on commercial equipment and can later be transferred to dedicated machines. This paves the way for the manufacturing of hybrid PIC assemblies for communications, sensing and quantum technology in volumes required by the respective application.

Acknowledgment

This work was partially funded by the German Federal Ministry of Education and Research under the project reference numbers 16FMD01K, 16FMD02, and 16FMD03 and the European Union's Horizon 2020 research and innovation programme under grant agreement No 780502 and No 820474.

References

[1] T. Hausken, "The cost of manufacturing optics", OPN, vol. 10/2014, October 2014.

[2] K. Wörhoff, R. G. Heideman, A. Leinse, and M. Hoekman, "TriPleX: A versatile dielectric photonic platform," Advanced Optical Technologies, vol. 4, no. 2, pp. 189–207, 2015.

[3] N. Grote et al., "Polymer photonic integration platform: Technology and components," in 17th Opto-Electronics and Communications Conference, Busan, South Korea, 2012, pp. 285–286.

[4] C. H. Henry and Y. P. Li, "Silica-based optical integrated circuits," IEE Proceedings - Optoelectronics, vol. 143, no. 5, pp. 263–280, 1996.

[5] Y. Fan et al., "290 Hz Intrinsic Linewidth from an Integrated Optical Chip-based Widely Tunable InP-Si3N4 Hybrid Laser," in Conference on Lasers and Electro-Optics, San Jose, 2017, JTh5C.9.

[6] H. Conradi et al., "High Isolation Optical Isolator: A new Building Block for PolyBoard Photonic Integrated Circuits," in 2018 European Conference on Optical Communication (ECOC), Rome, 2018, pp. 1–3.

[7] Z. Zhang and N. Keil, "Thermo-optic devices on polymer platform," Optics Communications, vol. 362, pp. 101–114, 2016.

[8] M. Kleinert et al., "Photonic integrated devices and functions on hybrid polymer platform," in Proc. SPIE Vol. 10098, San Francisco, 2017, 100981A.

[9] J.-M. Lee et al., "Vertical Coupling of Polymeric Double-Layered Waveguides Using a Stepped MMI Coupler," ETRI J, vol. 25, no. 2, pp. 81–88, 2003.

[10] M. Nuck et al., "Low-Loss Vertical MMI Coupler for 3D Photonic Integration," in 2018 European Conference on Optical Communication (ECOC), Rome, 2018, pp. 1–3.

[11] F. Laudenbach, S. Kalista, M. Hentschel, P. Walther, and H. Hübel, "A novel single-crystal & single-pass source for polarisation- and colour-entangled photon pairs,", Scientific reports, vol. 7, no. 1, p. 7235, 2017.

[12] M. Kleinert, H. Conradi, B. Schrenk, and H. Hübel, "UNIQORN-Making quantum photonics affordable," LASER FOCUS WORLD, vol. 55, no. 4, pp. 27-31, 2019.

[13] N. Keil et al., "Polymer PLC as an Optical Integration Bench," in Optical Fiber Communication Conference, Los Angeles, 2011, OWM1.