

Photonic Integration

Using Industry Ready Photonic Wire Bonds & Facet Attached Micro-Lenses

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Abstract— Photonic wire bonds and facet-attached micro-lenses are 3D freeform structures that enable high design flexibility while maintaining low loss, reproducibility, high reliability and packaging compatibility. These attributes are crucial for high-volume production of compact optical integration platforms in advanced photonics packaging.

Index Terms — Photonic wire bonding, Facet attached Micro Lenses, hybrid multi-chip packaging

I. INTRODUCTION

The rapid advancements in optoelectronic devices have driven a growing demand for developing photonic integrated circuits (PIC) that leverage cutting-edge active and passive components, which are often fabricated on different material platforms. For instance, a PIC module could involve hybrid integration of an indium phosphide (InP) based device such as a laser and a lithium niobate-based device such as a ring modulator. However, for packaging and assembling such a hybrid multi-chip module there remains significant technical and commercial challenges that consequently hinders the full commercialization of photonic systems.

The fundamental issue behind photonic integration is to achieve low optical loss when coupling photonic chips and components. This requires both careful matching of mode fields and precise alignment of photonic chips down to hundreds of nanometers precision to ensure efficient light transmission. One solution for assembly of such photonic systems is to use so-called active alignment techniques where the optical coupling efficiency is continuously monitored and optimized during the alignment process. However, this becomes particularly complex for photonic chips with a mode field size below 2 μm , such as semiconductor-based photonic chips with high-index contrast waveguides. Additionally, when chips with different mode field

sizes are involved, further complexity arises as elements such as micro-lenses are needed.

Furthermore, in industrial mass production, processes such as mode matching and alignment must be fast and reproducible as speed and yield are critical to cost-effectiveness. Moreover, the reliability of packaged assemblies under various environmental conditions must be ensured, with requirements differing across applications such as tele- and data- communication, 3D sensing, e.g. Lidar as well as quantum applications. Hence, despite photonic devices used for such specific applications are made with sophisticated processes from sometimes exotic material platforms, the optical packaging or integration process remains in most cases the biggest cost driver.

Current industry-ready solutions that facilitate optical connectivity for high volume applications have focused on single mode fiber alignment and integration to PICs, either with spot size converters for mode field matching and butt coupling [1-4] or etched U- and V- grooves [5,6] for precise fiber positioning. Both methods require a degree of active alignment to ensure low losses and require a significant amount of chip space for implementation, when compared to the space required by the photonic integrated circuit. To reduce the amount of chip real estate required for mode field matching, glass interposers and microlens arrays [7-8] have shown significant benefits which enable the production of co-packaged optics (CPO). However, the implementation of these solutions increases the complexity of the manufacturing process steps and is currently only available commercially for fiber arrays. The implementation of wafer level features [9] for alignment and mode field matching of fiber arrays can significantly reduce the production complexity and has the advantage that it can be performed at wafer level.

The industry also requires solutions to integrate active and

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passive chips with low losses and reduced complexity of production steps. While there exist many solutions, none have the full benefits which is associated with 3D printing for photonic integration. This solution allows passive alignment of chips with optical integration performed by additive manufacturing using two-photon polymerization to perform alignment offset compensation, mode field matching and low loss coupling. Furthermore, the solution takes no additional chip real estate, reduces the complexity of manufacturing and can be used for almost every use case: fiber to chip integration, CPOs, active and passive chip integration and hybrid multi module photonic integration. For further comparison of the respective advantages of 3D printing to other industry ready solutions, please see Table 1.

Vanguard Automation provides a fully automated solution, the Vanguard Symphony, which comprises two systems: the Vanguard Sonata 1000 for the fabrication of photonic wire bond (PWB) and facet-attached micro lenses (FaML), and the Vanguard Reprise 1000 for postprocessing optical assemblies. The Vanguard Symphony platform also includes Vanguard's Brightwire3D software, offering sub-100 nm precision in detecting coupling interfaces as well as on-the-fly design of optimal PWB trajectories, alongside dedicated photoresists tailored to meet strict industrial reliability requirements (Vanguard VanCore series). To maintain alignment accuracy, the lithography objective in Sonata 1000 is immersed in an index-matching medium, separated from the photoresist with a thin membrane. Both the photoresist and the immersion medium have a carefully designed refractive index, matching the numerical aperture of the objective. This configuration enables the lithography system to operate effectively as an immersion lithography setup with a laser focus depth of 250 μm . For application operating at 1550 nm, we control the diameter of the photonic wire bond within the range of 1.8 μm to 1.9 μm along PWB trajectory with a circular cross-section to ensure the single-mode propagation (see **Fig.S1**). In combination with standard processes as well as engineering service and support, Vanguard's solution enables customers to advance quickly from prototyping phases to high-volume production.

Photonic wire bonds (PWB) (see **Fig.1a**), which can be considered as the optical equivalent to metal wire bonding in electronics, are free-form waveguides that efficiently connect integrated photonic chips to each other or to optical fibers. A photonic wire bond contains tapered waveguides that can maximize the mode field overlap for each individual coupling interface, and a single moded waveguide that enables compensating for the misalignment between two components. A typical PWB process fabrication process flow, as shown in **Fig.2** involves following steps: firstly, photonic chips or fibers are fixed to a common submount using standard pick-and-place machinery with moderate precision; then the interconnect regions are immersed embedded into a photosensitive resist and the actual position and direction vector for each facet is detected using 3D machine vision techniques with sub-100 nm accuracy; next the optimal trajectory of a PWB connection is calculated

on the fly according to the recorded facet information and then fabricated using two-photon lithography; finally, unexposed resist is removed in a development step and followed by applying a low-index cladding material to embed the structures. Since the shape of PWB can be adapted to the facet information and mode field of the coupling interfaces, PWBs have intrinsic design flexibility and can overcome vertical and lateral offsets of up to $\pm 30 \mu\text{m}$ without impeding the optical performance. In the data center, telecommunication, and artificial intelligence markets, the advantages associated with innovative PWB processes have been utilized by Vanguard's technology users to advance the concept of hybrid integration [10-17]. PWB have been utilized for self-injection-locked Kerr soliton microcombs and lasers with sub-100Hz linewidth [12,13]. In the field of quantum applications, PWB has been successfully tested in ultra-low temperature experiments [16-17].

In addition to PWB, Facet-attached Micro Lenses (FaML) (see **Fig.1b**), that are directly fabricated on the facets of individual optical components based on real-time detected facet information, offer a complementary technology that relax the alignment tolerances up to $\pm 15 \mu\text{m}$ by serving as beam expanders. FaML has demonstrated improved efficiencies for High-Bandwidth Coherent Driver Modulators (HB-CDM) [18]. FaMLs have emerged as a versatile platform for electro-optical engines, including transceivers, co-packaged optics, laser engines, and sensing devices [18]. The precise alignment and printing of the facet-attached micro-optical elements at the wafer-level not only facilitates scalability but also opens new possibilities to address new applications [19,20]. FaMLs were successfully utilized in LiDAR applications for beam shaping elements [19, 23-24] and in quantum applications to increase the effective collection area of superconducting nanowire single-photon detectors (SNSPD), thereby overcoming a fundamental design conflict of such devices [25].

Vanguard Automation's comprehensive technology portfolio, which integrates PWB and FaML elements, offers a streamlined solution for customers aiming to incorporate these technologies into high-volume production. Initially, Vanguard's technology can be employed in hybrid approaches alongside conventional methods, such as active alignment, to improve coupling efficiencies and yield without requiring significant changes to existing production processes [12]. In subsequent phases, beam-expanding micro-lenses can be integrated into products to ease positioning tolerances for photonic integrated circuits (PICs) and optical components like InP lasers and fibers, making passive assembly a feasible process [26]. Ultimately, the full potential of Vanguard's technology can be utilized by incorporating PWB, enabling standard pick-and-place assembly of hybrid multi-chip systems with relaxed placement tolerances while maintaining high coupling efficiency, yield, and manufacturing speed, along with dense packaging.

This paper highlights the latest advancements from Vanguard Automation and Sumitomo Electric, addressing the critical

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aspects in advancing scalable, high-volume production: broad compatibility with various material platforms, reproducibility, long-term reliability in Telcordia testing and seamless integration with existing packaging technologies.

II. MATERIAL PLATFORM COMPATIBILITY

Vanguard's technology is compatible with a wide variety of material platforms while delivering high performance. These platforms range from silicon, silicon nitride, and indium phosphide to thin-film lithium niobate, and support different foundries (**Fig. 2**). Silicon on insulator (SOI) and silicon nitride (SiN) are the most widely used photonic chip platforms, where Vanguard's technology has consistently delivered low insertion loss. The insertion loss for fiber-to-SOI (AMF, Singapore) connections, illustrated in **Fig. 2b**, is averaged over 160 connections, while fiber-to-SiN (AIM, USA) connections are averaged over 18 connections. Both measurements were performed at a wavelength of around 1550 nm, with the fiber array loss (0.2 dB per fiber, as specified by the manufacturer) subtracted. Across the wavelength range of 1530 nm to 1580 nm, the insertion loss variation remains within 0.2 dB. The corresponding transmission spectra is reported in **Ref. [27]**.

Moreover, PWBs have been successfully employed to couple with indium phosphide (InP) based devices. For passive devices, as shown in **Fig. 2a** and **Fig. 2b**, a PWB connection from SMF 28 to edge-couple InP dies, fabricated by the Fraunhofer Heinrich-Hertz-Institute (HHI, Berlin, Germany), was achieved with a transmission loss of 2 dB at 1550 nm single wavelength subtracted fiber loss and on-chip loss. This result aligned perfectly with simulations that accounted for the physical geometry of the InP waveguides and the corresponding PWB cross section at the coupling interface. The InP dies used in the experiment were part of multi-project wafers fabricated under the JePPiX platform [28], utilizing HHI's E1700 InP platform with a 2 μm wide waveguide. Simulations of PWB cross sections coupling with varying waveguide widths indicated that the coupling loss could be further reduced by using 3 μm wide waveguides from the E1700 platform in future designs. The successful integration of PWB with HHI InP dies has been applied to package an InP-based optical phased array (OPA) to operate, allowing operating the active OPA with an off-chip laser source [29]. Moreover, for active InP-based devices, Sumitomo demonstrated that PWB connectivity with polarization maintaining fibers (PMF) to lasers did not affect the laser's performance (**Fig. 2c**).

Thin-film lithium niobate (TFLN) represents a promising technology platform for high-speed photonic integrated circuits. In the scope of the ELENA project [30], Vanguard and CSEM optimized the edge coupler of TFLN chips design and fabrication process to facilitate the PWB interfacing (**Fig. 2a** and **Fig. 2b**). Our initial result shows that the insertion loss of

fiber-to-TFLN can reach down to 2.18 dB at 1550 nm with removal of the on-chip loss and fiber loss [31]. The latest result with fiber to TFLN chip from CSEM foundry [32] is down to 1.78 dB. In **Fig 2b** we present the averaging insertion loss of fiber-to-TFLN which averages 8 PWB connections and has a broad spectral range of 1530 nm to 1580 nm (**Fig. S2**), with fiber loss and on-chip loss subtracted. Other eco-partners of Vanguard have achieved a coupling loss of 1.8 dB for fiber-to-TFLN. These results confirmed the potential of PWB as a generic solution for interfacing TFLN at the foundry platform.

Furthermore, PWB can be expanded to connecting more than two components. For example, in the work of Ref. [33], a spectrally sliced optical arbitrary waveform measurement (OAWM) module has been demonstrated, where the optically packaged multi-chip receiver module relies on in total 26 3D-printed PWB for internal optical chip-chip and fiber-chip connections.

The high compatibility across different material platforms demonstrates that Vanguard's technology portfolio offers a unique advantage: utilizing a single coupling PDK to interface with various optical components. This makes it adaptable for use in both academic and commercial foundries, removing the need for these foundries to develop intricate spot size converters. By employing straightforward inverse tapered edge couplers fabricated through stepper lithography, Vanguard's technology notably minimizes the chip space required for advanced couplers, paving the way for a new, more universal standard in optical coupling.

III. REPRODUCIBILITY

Integrating Vanguard's technology into optical interconnects enhances the coupling efficiency of light and reduces the overall power consumption. Constantly achieving reproducible low coupling loss is crucial for cost-effectiveness and scalability, particularly when moving towards high-volume production. High reproducibility demands stable machinery, material sets with quality-controlled characteristics, a precise fabrication process with specified alignment tolerance, optical components with clearly defined specifications.

We demonstrate reproducible performance for fiber-to-fiber connectivity with an average loss of 1.1 dB across 105 channels and 95% of the values below 1.5 dB (see **Fig.4d**). The PWB fiber taper design is optimized by Lumerical FDTD simulation to maximize the coupling efficiency. **Fig.4a-4b** illustrate the simulation model and corresponding electric field distribution for the optimized PWB fiber taper. In the experiment shown in **Fig 4c**, we evaluate the dependence of coupling loss on fiber taper displacement for a complete fiber-to-fiber connectivity. The simulation results align well with experimental data, wherein lateral displacements of the fiber taper from the detected fiber core position were intentionally introduced

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during fabrication of the fiber-to-fiber assembly. This also rules out the possibility of taper misalignment exceeding 1 μm .

Moreover, we have achieved 100% yield with losses below 2dB for fiber-to-Si PIC connectivity with an average insertion loss of 1.44 dB across 160 connections (see **Fig. 4e**). Importantly, the insertion loss remains constant despite lateral offsets between fiber and Si PIC interface is more than 20 μm and vertical offsets is up to 40 μm (**Fig. 4f**). This result highlights PWB's unique advantage to overcome component misalignment. We remark that other users of Vanguard's technology have also achieved a reproducible yield with PWB: 99% yield with the coupling losses below 2.3 dB, and an average of 1.7 dB in laser-to-SiN PIC connections across 96 connections.

IV. RELIABILITY

Vanguard's PWB and FaML have been tested in various environmental conditions including standard Telcordia damp-heat and temperature cycles with long-term monitoring, shown good reliability [13,14,15,18]. **Fig. 5a** shows that PWBs in fiber-to-fiber assemblies have less than 0.5 dB variation over 2000 hours in a damp heat environment. A typical failure mode in reliability testing for fiber-based assemblies is the degradation of fiber arrays such as damage to the connectors or broken jacket bundles, which can be easily detected with a fault locator. Another prevalent failure mode involves the presence of air pockets between the grooves of the fiber array and fibers, which can result in fiber delamination. To enhance assembly performance in reliability testing, it is essential to implement robust quality control measures, careful optical fibers handling processes, and avoid direct contact of the connectors and jacket bundles with metal surfaces. Furthermore, optimizing the gluing process is critical to prevent the relative movement of photonic components under reliability test conditions.

Similarly, our results for FaMLs have proven to be stable in reliability test. **Fig. 5b-5c** presents that FaMLs printed on a SiN chip closely matching the theoretical simulations for MFD even after 590 hours of exposure to damp heat environment (see **Fig. 5b-5c**). Additionally, Sumitomo Electric has tested FaMLs printed with InP laser diodes under high-power conditions for over 5000 hours, observing less than 0.5 dB of power fluctuation. In this instance, the FaML is directly printed in-situ to the laser diode surface, which has a mode field diameter of only 3 μm (**Fig. 6**) [26]. A common concern is that the FaML on the laser diode facet may degrade due to heat from absorbed light; however, the results confirm that Vanguard Automation's VanCore resist series is highly transparent at telecommunication wavelengths, even at 200 mW, and can endure operation at this power level throughout its lifespan.

Vanguard's technology has also been proven to be compatible with the existing industrial standard packaging processes in the

work from Sumitomo Electric. FaMLs printed on InP modulator chip and mounted into industry standard hermetic packages (Gold Box), showing no degradation in temperature cycles from -40 to 85 $^{\circ}\text{C}$ up to 500 cycles, mechanical vibration test (20-2000 HZ) and mechanical shock test (up to 1500 G), and after a die bonding process at 320 $^{\circ}\text{C}$, all in accordance with Telcordia GR-468- CORE specifications [18]. For non-hermetic packaging, **Fig. 7** presents an example of the coupling from a SiN PIC to polarization maintaining fiber (PMF) arrays with FaML under reflow process (260 $^{\circ}\text{C}$, 60 s, 1 time). Here, the coupling loss deviation is less than 0.1 dB and remains unchanged after reflowing thermal stress, indicating that the printed structure maintains uniformity and stability during and after exposure to thermal stress. This scenario is particularly relevant for CPO package application, where detachable, low-profile, and reflow-tolerant fiber to chip coupling is essential.

V. CONCLUSION

In conclusion, Vanguard's Photonic Wire Bonding (PWB) technology stands out as a powerful photonic packaging and integration approach for advanced photonic multi-chip modules, effectively merging the complementary strengths of various optical integration platforms. The specific advantages of PWB are the achievable high yields, the compatibility of the process with large channel numbers and high connectivity density which promotes compactness with reduced cost while retaining high performance and exceptional design flexibility, as shown in the comparison in **Table 1**. However, it is essential for the industry to continuously improve yield and reliability on multiple photonic integration platforms to promote the technology adoption. Stable high-quality photonic components are crucial for high reproducibility. For instance, photonic PICs require highly reproducible well-defined mode field distribution and chip facets with reasonable roughness to meet performance standards. We are actively collaborating with various academic and commercial foundries to develop optimized parameters and photonic design kits (PDKs) for edge coupler designs and geometry layouts that are tailored to PWB implementation. Furthermore, as previously discussed, the gluing process and component quality are pivotal for achieving long-term reliability. Together with industrial partners, we are advancing the development of a reliable, reproducible, and automated assembly process to enhance the robustness of the final products. Most importantly, market demands are driving the rapid adoption of automated wafer-level processes, and here we are actively adapting our methods to be compatible with standard industrial processes such as wafer readers.

Vanguard's solution portfolio is completed by facet-attached micro lenses (FaMLs), allowing for low-loss coupling and facilitate wafer-level probing of optical devices, ensuring high alignment tolerances. For instance, POET Technologies, in collaboration with Vanguard Automation, integrates 3D printed micro-lenses onto its silicon optical interposer to maximize coupling efficiency while maintaining the hallmark wafer-level passive-assembly process of its technology. The micro-lenses

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from Vanguard Automation are one crucial component in POET's wafer-level assembly process capability to offer significant scale and cost benefits to customers in the AI and datacom industries [19-20].

The fully automated Vanguard Symphony solution has already used by both research and industrial clients focused on next-generation photonic integration and packaging. Our results confirm that Vanguard's PWB and FaML technologies are viable industrially ready solutions and exceptionally suited for compact optical integration. The widespread applicability across diverse material platforms, offering the unique advantage of using only one coupling PDK to couple to other types of optical components, means Vanguard's technology portfolio is compatible with all academic and commercial foundries. Consequently, foundries can avoid having to create complex spot size converters to perform mode field matching. Additionally, Vanguard's technology enables low-loss connectivity and high yield production through stable machinery, consistent materials, and reproducible processes, reliable in harsh environments. Moreover, these technologies are compatible with existing industrial packaging standards, simplifying the transition to mass production. With design flexibility for multi-component assemblies and outstanding low-loss performance, Vanguard's solutions significantly reduce development efforts and foster seamless integration into competitive markets.

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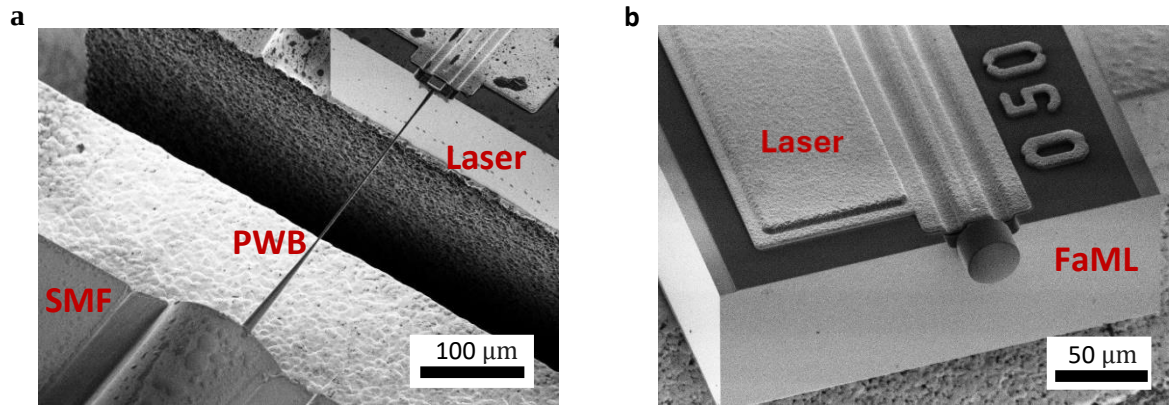


Fig. 1. **a.** Scanning electron beam microscope image of PWB connecting a single mode fiber array with an array of indium phosphite based lasers from Sumitomo. **b.** Scanning electron beam microscope image of a FaML on an indium phosphite based laser from Sumitomo.

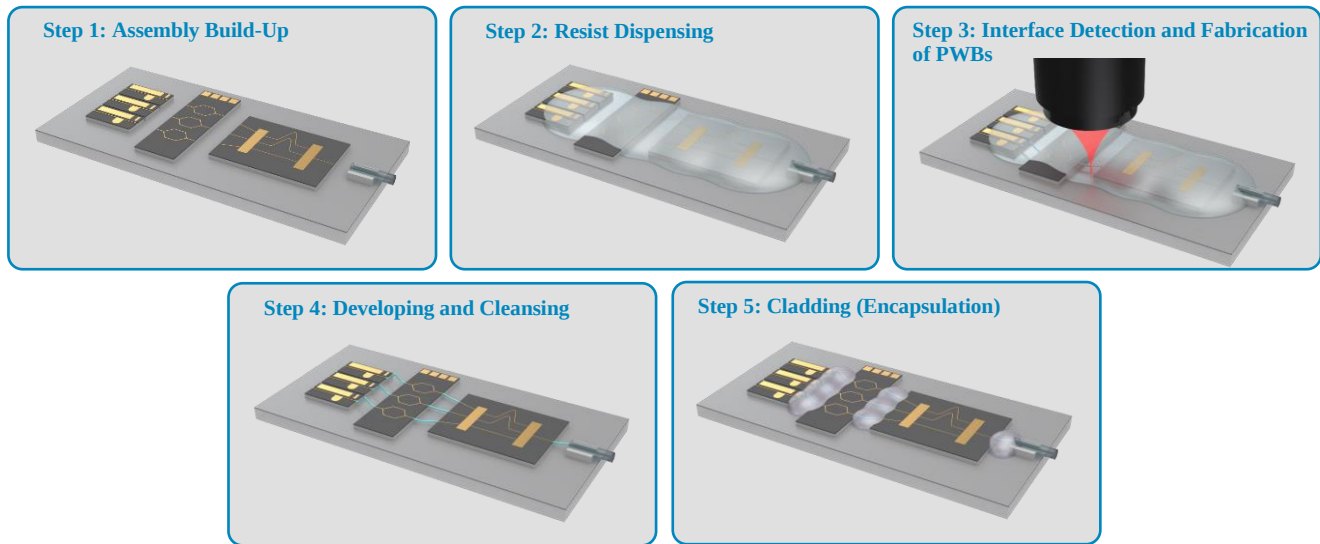


Fig. 2. PWB fabrication process flow. **Step 1:** Photonic chips and fibers are fixed to a common submount using standard pick-and-place machinery with moderate precision. **Step 2:** The interconnect regions are then embedded into a photosensitive resist, and the actual positions of waveguide facets and coupling structures within the resist are detected using 3D machine vision techniques with sub-100 nm accuracy. **Step 3:** The shape of the photonic wire bond (PWB) waveguide is designed according to the recorded facet positions and defined using two-photon lithography. **Step 4:** Unexposed resist material is removed in a development step. **Step 5:** Finally, the structures are embedded in a low-index cladding material.

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Optical connectivity solutions	Compatibility					Losses	Pitch	MFD	Yield	Reliability
	Chip to Chip	Fiber to Chip	Edge coupling	Surface coupling	Evanescent coupling					
Photonic Wire Bonding	X	X	X		X	< 1.5 dB	Minimum 10 μ m	2 μ m...12 μ m	95%	2000 Hours damp heat
Facet Attached Micro Lenses	X	X	X	X		< 1.5 dB	Minimum 30 μ m	2 μ m...40 μ m	95%	5000 Hours damp heat
Glass Interposers [27-28]	X	X	X	X	X	< 1.5 dB	<30 μ m	Minimum 6.5 μ m	-	-
V-groove attach [33]		X	X			< 1.5 dB	250 μ m	NA	-	2000 Hours damp heat
Wafer alignment features [34]		X	X			< 1.5 dB	127/250 μ m pitch	NA		4000 Hours damp heat
Spot size converters	X	X	X			< 1.0 dB	Dependent on fiber array pitch		99%	2000 Hours damp heat

Table. 1 Comparison of the most common optical connectivity solutions for flexibility and typical best case loss values, yield and reliability and typical MFD.

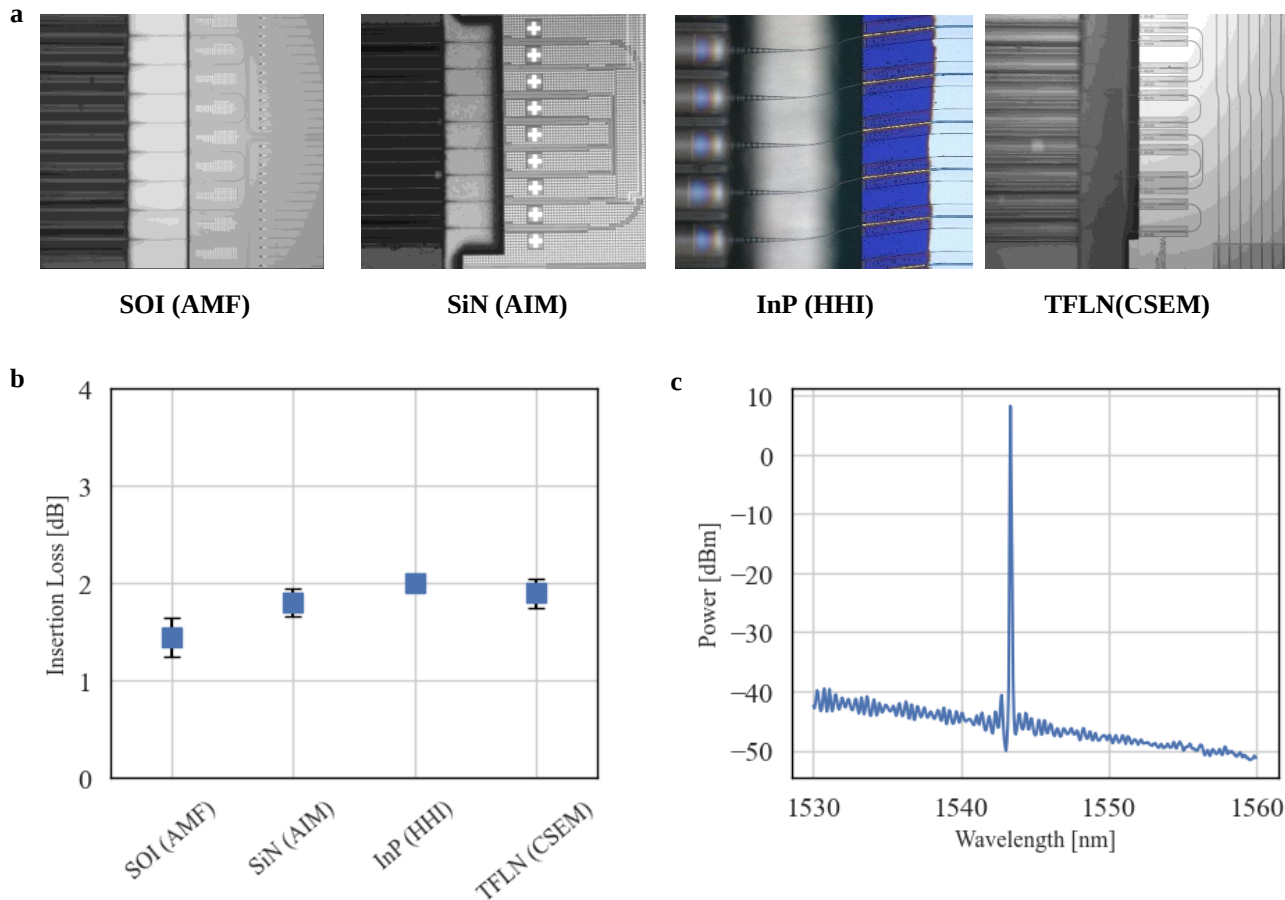


Fig. 3 Material platform compatibility. **a.** microscopic images of Fiber-to-X assemblies. **b.** average coupling loss over several connections for individual chip platform at 1550 nm. **c.** spectra from a PMF-InP laser connectivities from Sumitomo.

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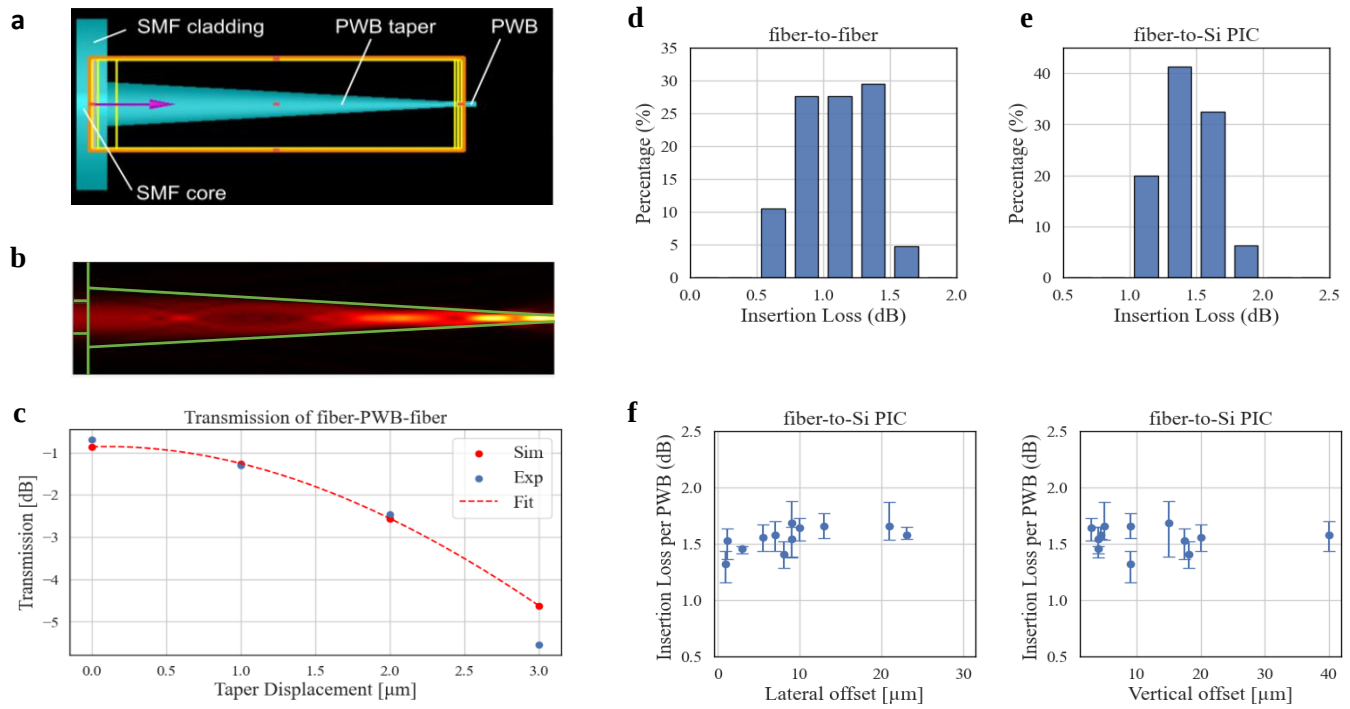


Fig. 4 a. Lumerical model for SMF-PWB interface. **b.** Electric field distributions for the fiber PWB taper. **c.** Simulated and experimental transmission as a function of taper displacement losses for fiber-to-fiber connection. **d.** Statistics on insertion loss of fiber-to-fiber connection using PWB, 105 connections with an average of 1.1 dB, 95% yield below 1.5 dB. **e.** Statistics on insertion loss of fiber-to-Si PIC connections using PWB, 160 connections with an average of 1.44 dB, 100% yield below 2 dB. **f.** Insertion loss per PWB as a function of offset between fiber and Si PIC in fiber-to-Si PIC assemblies. Each data point stands for the insertion loss per assembly for 8 channels: maximum, minimum and average.

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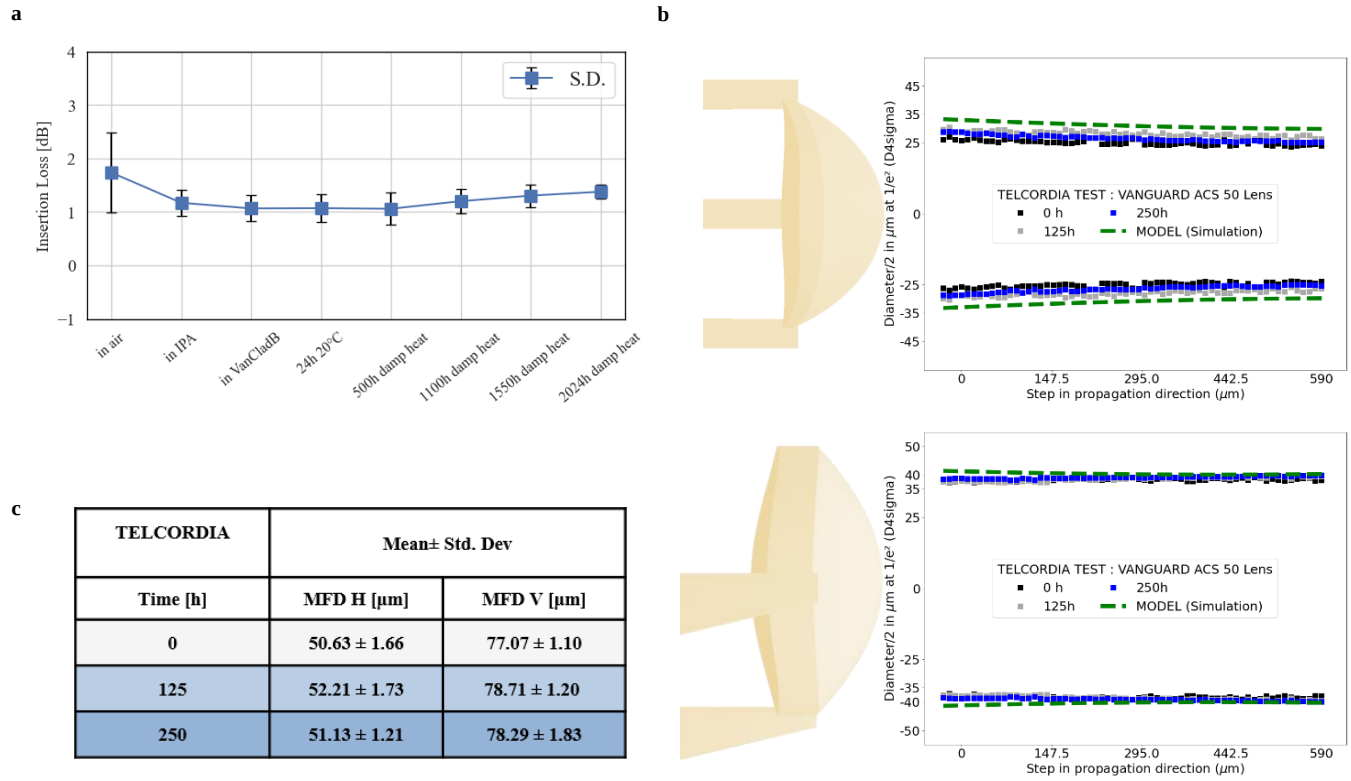


Fig. 5. a. Telcordia damp heat test (85°C, 85% relative humidity) result of fiber-to-fiber connections, monitored for 2000 hours. Each data points represents an average of 10 PWBs. **b.** FaML on SiN chip on Telcordia damp heat test for 250 hours. **c.** Table of the mode field diameter change over 250 hours in Telcordia damp heat tests.

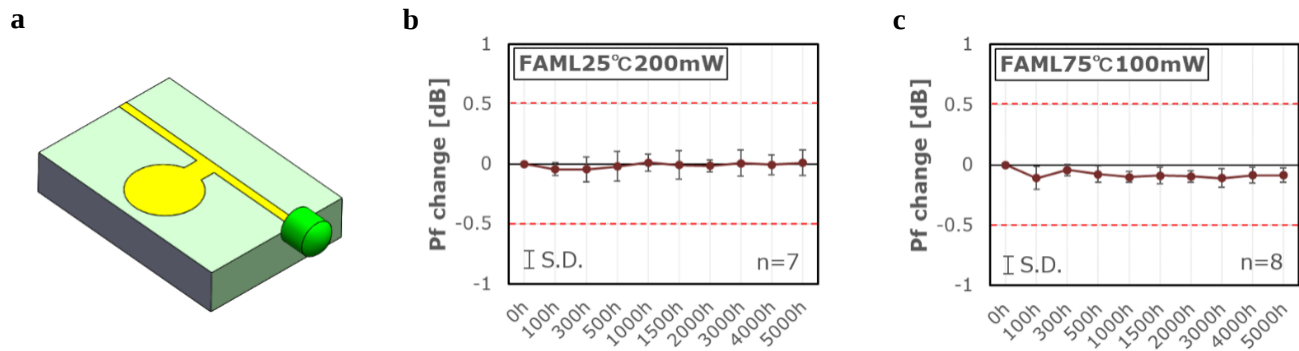


Fig. 6. High power operation test result of InP laser with printed FaML. **a.** Illustration sketch of a FaML printed on InP laser. **b.** Power fluctuation over 7 InP lasers with printed FaMLs, monitored for 5000 hours at 25 ° C at 200 mW. **c.** Power fluctuation over 8 InP lasers with printed FaMLs, monitored for 5000 hours at 75 ° C at 100 mW.

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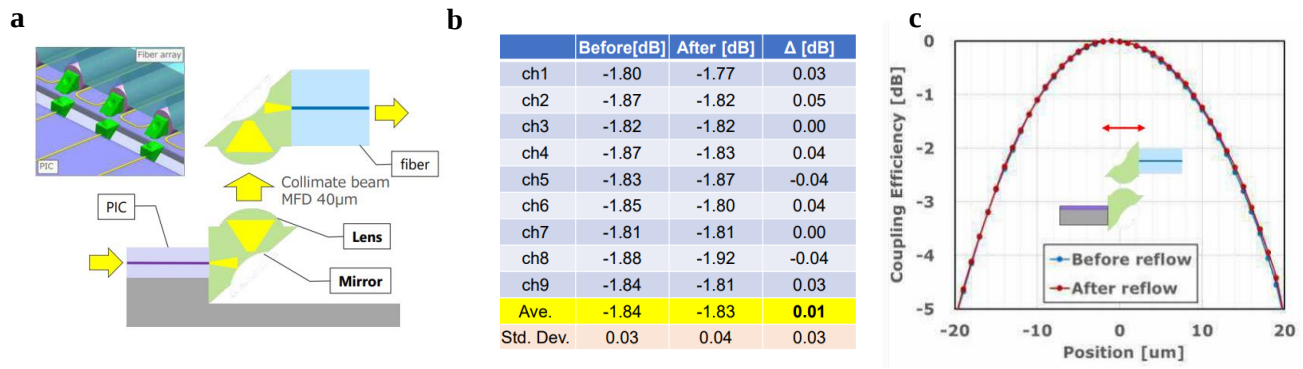


Fig. 7. Reflow stability of FaML printed on SiN PICs and PMF arrays. a: illustration of the concept for coupling a SiN PIC to PMF arrays with 3D- printed beam expanding vertical lenses. b. measured coupling efficiency before and after Nitrogen reflow process condition (260 ° C, 60 s, 1 time). c alignment tolerance before and after reflow remains no change