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PIXAPP Photonics Packaging Pilot Line – development of a silicon photonic optical transceiver with pluggable fiber connectivity

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***Abstract*— This paper demonstrates how the PIXAPP Photonics Packaging Pilot Line uses its extensive packaging capabilities across its European partner network to design and assemble a highly integrated silicon photonic-based optical transceiver. The processes used are based on PIXAPP's open access packaging design rules or Assembly Design Kit (ADK). The transceiver was designed to have the Tx and Rx elements integrated on to a single silicon photonic chip, together with flipchip control electronics, hybrid laser and micro-optics. The transceiver used the on-chip micro-optics to enable a pluggable fiber connection, avoiding the need to bond optical fibers directly to the photonic chip. Finally, the packaged transceiver module was tested, showing 56 Gb/s loop-back modulation and de-modulation, validating both the transmitter and receiver performance.**

***Index Terms*— Electrooptic modulators, Chip scale packaging, Demodulation, Electronic packaging thermal management, Electronics packaging, High-speed electronics, High-speed integrated circuits, Intensity modulation, Modulation, PIC, PIC packaging, Photonics, Semiconductor device packaging, Silicon photonics, Telecommunications, communication systems.**

I. INTRODUCTION

Recent decades have seen the growth of integrated photonics supported by the ever-growing information communication technology needs, as well as lidar systems, biomedical and other industrial sensing applications. The silicon Photonic Integrated Circuit (PIC) platform was created on the foundation of established CMOS (complementary metal–oxide–semiconductor) fabrication technology for silicon electronics. This native compatibility with CMOS technology, together with the ability to build compact, highly integrated photonic subsystems are the main driving forces behind Si-photonics. In recent years, the field has further grown out of the Silicon to include other integrated photonics platforms such as SOI [1], [2], InP [3], Si_3N_4 [4] and Ge [5]. These more optic-centered

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platforms allow for a better integration of active elements such as lasers, and are transparent in optical windows that silicon is not.

A. PIC elements and MPWs

A wide array of Si-photonic elements has been demonstrated, and while there continues to be improvements in component performance, the technology has matured to the stage that design kits exist. These are provided as certified "building blocks" in the multi-project wafer (MPW) runs offered by various silicon foundries [6]. These include strip/rib waveguides and crossings, one-dimensional (1D) and two-dimensional (2D) grating-couplers (GCs), broadband edge-couplers, multi-mode-interference (MMI) splitters, broadband edge-couplers, integrated lasers, arrayed waveguide gratings (AWG), multiplexers/de-multiplexers, thermally tunable micro-ring resonators, high-speed Ge photodiodes, thermo-optic phase shifters, electro-absorption modulators (EAMs), etc.

Hundreds of the unique PIC designs, together containing thousands of Photonics elements can be laid out in a single wafer. Researchers, graduate students, and Small & Medium Enterprises (SMEs) now routinely design PICs through these Multi-Project Wafer (MPW) runs which enable them to develop new devices and share costs without having to individually invest in expensive dedicated wafer runs. These PICs, a few millimeters wide, can easily contain hundreds of electrical and optical connections on a very small footprint, all of which require interfacing with other elements of the system.

The challenge for integrated photonics is no longer in fabricating photonic chips, but in fabricating photonic devices, i.e. the coupling of light and electrical signals between the 2D PIC and the 3D world outside.

B. PIC packaging

Developing an operational PIC and demonstrating its functionality in a laboratory environment requires building a first prototype that allows accessing its inputs and outputs. PICs - being tightly integrated devices and at most a few millimeters long – need to be electrically and optically interfaced, which can be done in a variety of ways as shown in Figure 1. They also need to be placed in a dedicated mechanical housing, that often needs to be thermally cooled. These four domains – electrical, optical, mechanical and thermal - make the core of what is known as photonic packaging. The challenges associated with photonic packaging are often underestimated and remain technically challenging [7]. The optical alignment tolerances can be sub-micron and must be carefully considered to account for the polarization requirements and thermal expansion. Small misalignments can cause large optical losses which necessitates photonics packages to be well made and accounting for all of these issues already at a lab stage [8]–[12].

However, bridging the gap from laboratory to an industrial product commonly brings in significant other issues related to reliability, which reflect in high financial cost of packaging which, at small volumes, can easily amount to about 50% of overall product cost.

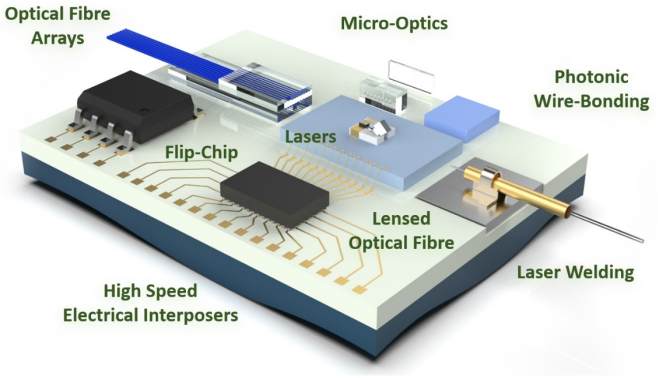

Figure 1. Various packaging technologies available through PIXAPP

A fragmented ecosystem is another reason why PIC packaging is costly. It is difficult for an SME to get a comprehensive and large volume photonic packaging service at a single company. A lack of design rules and standardization leads to SMEs holding multilateral talks with companies doing specific packaging technologies, each with its own set of processes which are not always mutually compatible.

C. PIXAPP

Technical and economic challenges of Photonic Packaging exist for all device designers, whether they are multinational companies, SMEs, or Researchers. To address those issues, the EU funded PIXAPP (Photonic Integrated Circuit Assembly and Packaging) Pilot Line was established. PIXAPP's goals are to (1) be a single point of contact for PIC Packaging, (2) Offer generic Packaging Solutions for PICs, and (3) Create a credible strategy to future full-scale PIC Manufacturing. The Pilot Line helps SMEs and industrial organizations bridge the so-called "Valley of Death", moving them from Technology Readiness Levels 5 (prototyping) to 9 (manufacturing). Different technological solutions are offered through PIXAPP in what are called building blocks – which are validated and scalable packaging processes.

To prove that multi-party assembly of photonic devices can be achieved at medium volume, to industry timescales, and at accessible cost-points, PIXAPP developed several showcase "demonstrators". These demonstrators were designed to stress-test the packaging and assembly capabilities of the pilot-line before opening the pilot-line to external users.

In this paper, we present the assembly of the Datacommunications (Datacom) Demonstrator that was established within PIXAPP using a variety of different building blocks. The goal of this demonstrator was to show how it is made in PIXAPP's distributed network, taken from design right through to testing.

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II. The Datacom specifications

The planned Datacom Demonstrator has a 200G transmitter side consisting of four channels each operating at 50Gb/s. The same was chosen for the receiver side, giving the module a total of 8 channels. An On-Off Keying (OOK) modulation format was chosen as it reflects bandwidth performance, a key figure for high-speed electronic packaging. The more advanced modulation formats usually involve more high-speed electronics [13], an added complexity which was not in scope of this packaging demonstration.

The agreed specifications for the PIXAPP Datacom demonstrator were as follows:

- single-chip transceiver
- SOI PIC platform
- 1310 nm laser integration
- Parallel Single-Mode 4 channel (PSM4) – for both Tx and Rx
- Relaxed Fiber-to-PIC tolerance through a pluggable connector
- 50Gbits (OOK) per channel

Furthermore, the packaging of this module was to address some key packaging challenges, and introduce non-standardized novel technologies:

- High degree of 3D integration including 2×EICs; µOptics; Micro Optical Bench (MOB)
- Hybrid laser integration using Micro-Optical Bench (MOB) [14]
- Pluggable Fiber-to-PIC connection using micro-lenses on chip and on a fiber array cable
- High speed lines and interconnects such as LTCC electrical interposer and ribbon bonds
- Design optimized for passive cooling

The Datacom Demonstrator's tasks were divided among different packaging partners to demonstrate how the distributed network could be used. These tasks and its division could generally be divided to system, optical and electrical packaging, and are shown in the Table 1.

TABLE 1
DATACOM DEMONSTRATOR TASK DIVISION AMONG PARTNERS – PARTNER ENTITY'S FULL NAME ARE LISTED IN THE APPENDIX, TABLE 3.

	Partner	Task
System	**TYN**	System design
	ARG	System Design, and Electrical interconnects simulation
	IMEC	PIC design and fabrication
	ARG	Mechanical housing design and fabrication
	TYN	Thermal behaviour of laser and EICs
Optical	**TYN**	Zemax/Lumerical simulation
	CORD	MOB assembly and Laser Integration
	EBL	MOB assembly and 1310nm laser development
	ARG	MOB-to-PIC fixing
	KIT	Pluggable connector design and simulation
	IMEC	Pluggable connector design and simulation
	IMEC	Microlenses on PIC fabrication
	IMEC	Microlenses on MPO fiber array fabrication
	KIT	Microlenses on MPO fiber array fabrication
	TYN	MPO receptacle housing fabrication
	ARG	MPO receptacle to PIC fixing
Electrical	**VTT**	LTCC design and fabrication
	ARG	PCB design and fabrication
	ARG	PCB and LTCC interconnecting
	TYN	Solder ball Jetting
	TYN	Stud bumping
	ARG	Flip chip die bonding
	ARG	PIC to LTCC interconnects
Tests	**III-V**	S parameters - Electrical structures testing
	IMEC	Data transmission - Final modules testing

III. Flow of the Demonstrator Assembly

Adequate sequencing of packaging tasks is crucial for the success of the overall packaging and assembly. For example, elevated temperature reflows during electrical packaging can damage epoxy bonds during optical assembly. After assessing different options of the assembly, the assembly process was agreed to proceed as shown in the schematic under Figure 2. For clarity of visualization, simulation building blocks are not shown. The packaging took place over 6 countries through 7 packaging partners, the geographical extent of different assembly strands are shown in Figure 3.

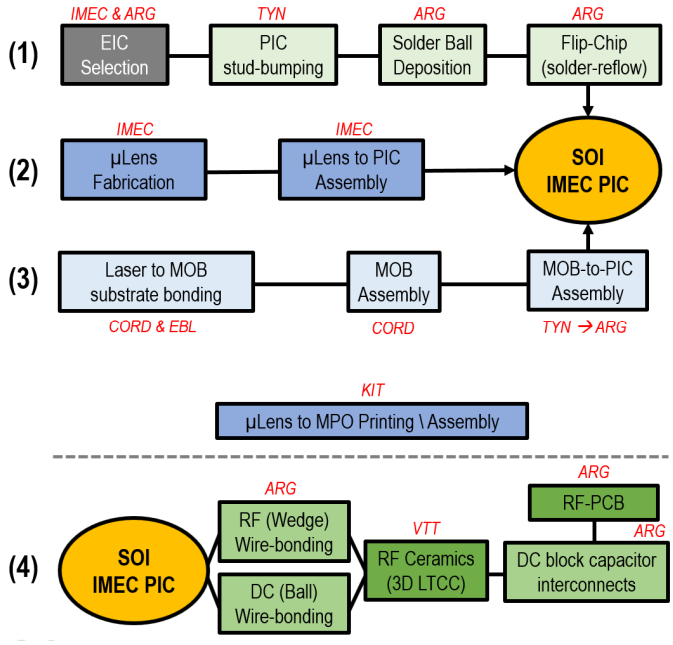

Figure 2. Flow of Datacom Demonstrator assembly. The assembly was performed in 4 assembly strands: (1) Flip-Chip integration (2×EICs), (2) Microlenses for pluggable optical connector, (3) Laser Integration (MOB), (4) High speed LTCC, PCB, and interconnects. The KIT-led building block was technically a part of strand 2, but as it did not influence the flow of the integration, it is pictured outside of the strands.

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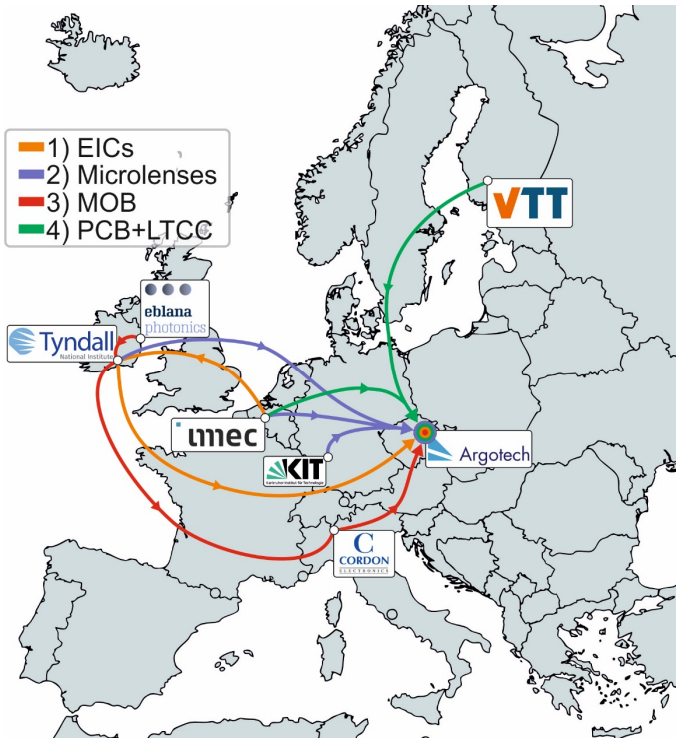

Figure 3 Assemby sequence process flow through the PIXAPP packaging partners, for 4 different assembly strands shown in Figure 2.

IMEC designed and fabricated PICs in SOI platform [15], which is shown in the Figure 4. They implemented the requirements for optical and electrical elements on the PIC (strands 1-3, shown in Figure 5), and designed sufficient clearances for the tooling used to achieve different packaging steps.

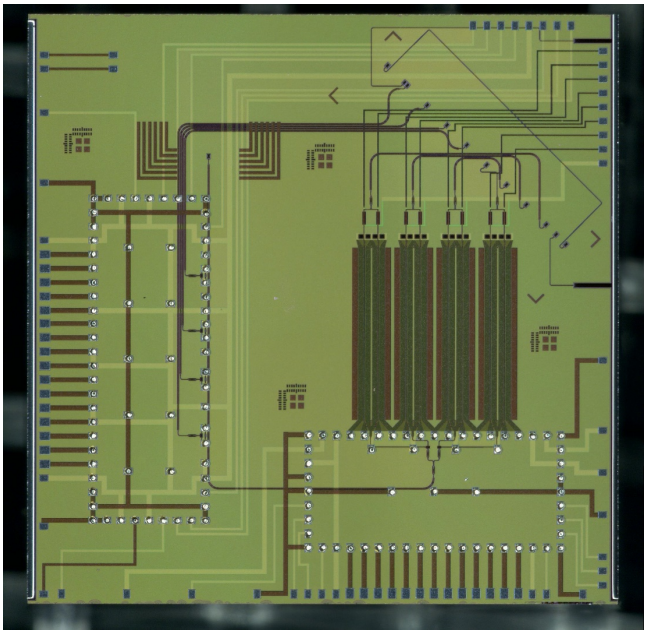

Figure 4. Datacom PIC designed and fabricated by Belgian foundry IMEC

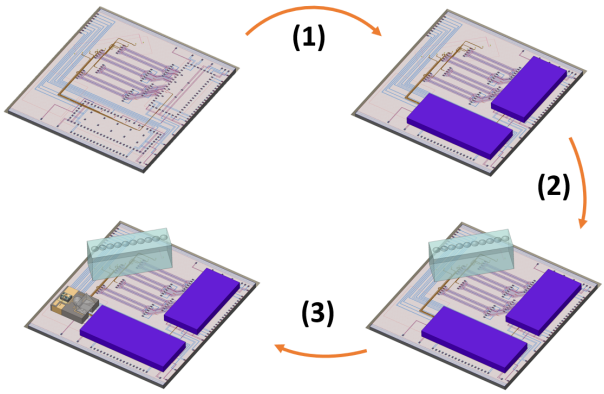

Figure 5. Schematic of packaging the first 3 assembly strands on PIC. The (1) deals with EICs, (2) with microlenses and (3) with the MOB.

A. Strand (1) - EICs

The first strand of the assembly dealt with Flip-Chip die bonding - the Electronic Integrated Circuit (EIC) integration. Each PIC contained 2 EICs, for the transmitter side a Driver for the Mach Zehnder Modulators (MZMs) and for the receiver side a Trans Impedance Amplifier (TIA), both in 4 channel configurations. High speed IMEC developed EICs were chosen due to their small footprint and high-speed performance. For reliable electrical connection between EICs and the PIC, the PIC was solder jetted and EICs were gold stud-bumped and were subsequently coined (flattened to have a similar height). The Driver has 69 and TIA 70 connections, which in total gives 139 bond-pads that were prepared for flip-chip die bonding by stud bump and solder jetting.

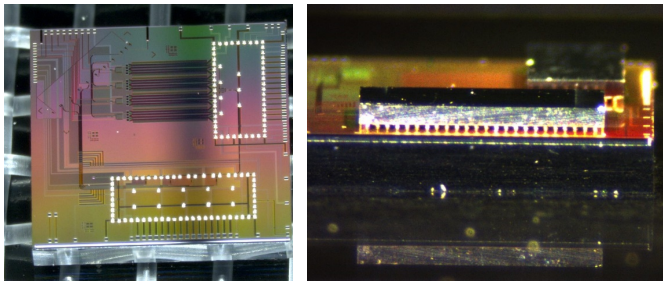

Figure 6. Datacom PIC with solder showing as a white glow deposited on bondpads (left), and side view of die-bonded TIA and MZM Driver (right).

The flip-chip process was then performed with a die bonding machine where at the temperature of 245ºC the solder was reflowed, and a conductive contact was established between bondpads on the PIC and on the EICs (see Figure 6).

B. Strand (2) - Microlenses

One of the goals in this demonstrator was to establish a pluggable fiber connection to/from the optical transceiver. The PIC has 8 grating couplers which are emitting light at 10º in the air, and with a Mode Field Diameter (MFD) of 9.2 µm at the wavelength of 1310 nm. The same MFD is on SMF28 fiber, a common fiber for telecommunications, which was chosen for

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coupling the light to the PIC. The connector system was developed by use of precision-fabricated components and microlenses, that were placed on PIC and on a Multi-fiber Push On (MPO) Fiber Array (FA). The microlenses serve 2 purposes. Firstly, they can collimate diverging beams and couple the light to PIC from a distance. That way they protect the PIC from being damaged under forces due to (un)plugging. Secondly, they can expand the MFDs so that small misalignments created by plugging and unplugging result in a much smaller loss of optical power, and therefore maintain a good quality high-speed optical data link.

Polymer based microlenses were designed by IMEC in Belgium and, through their proprietary technology [16], deposited on a 980 µm thick silica glass block. The glass block was then deposited on a PIC, ensuring epoxy extends only within the allowed perimeter on the PIC. On the MPO FA side, KIT in Germany 3D printed polymer lenses on individual fibers of the MPO FA patch cable (see Figure 7) using two-photon polymerization [17]. These freeform lenses match and couple the light to IMEC's expanded MFD. The flexibility of design and fabrication of these lenses allowed the MPO connector to come perpendicularly to the PIC's surface. This proved to be successful with a working distance of 2 mm. Additional loss per interface (IMEC+KIT microlenses) showed to be about 1.5 dB, with respect to direct Fiber to GC coupling. It is caused mainly by reflection losses at the 2 polymer lens-air interfaces; lens fabrication (shape and positioning) inaccuracies which lead to a mismatch in terms of optimal coupling angles and MFDs; as well as lens aberrations. The lenses expanded MFDs to 30 µm at a distance of about 2 mm, as shown in Figure 8, achieving more than 3x the original MFD. A mechanical connector for plugging an MPO FA was made at Tyndall in Ireland with MPO receptacles, components that are used in MTP version of MPO Fiber Array (FA) connectors, that were kindly provided by US Conec.

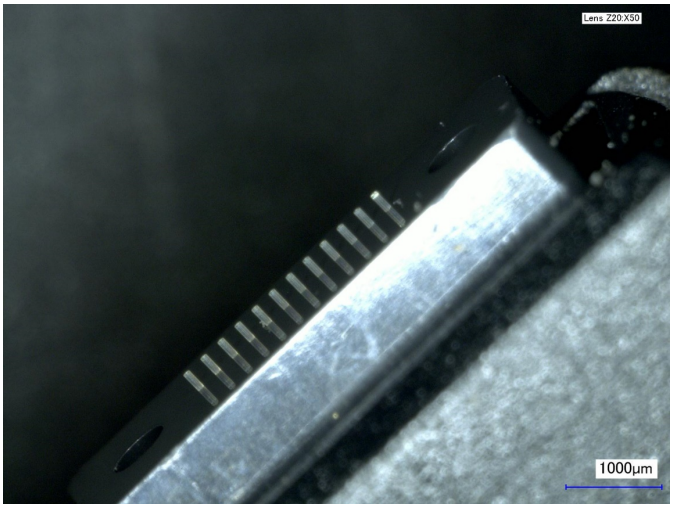

Figure 7. Freeform lenses fabricated by two-photon polymerization on the facet of an Multi-fiber Push On (MPO) connector.

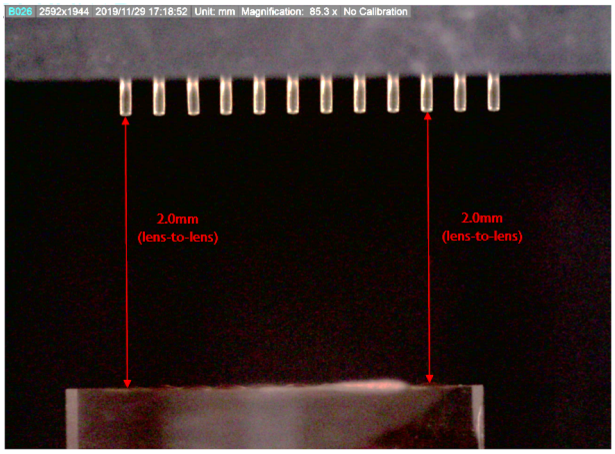

Figure 8. Datacom Demonstrator PIC with micro-lens block (bottom) and lensed MPO connector (top). Working distance of 2 mm between the two lens surfaces.

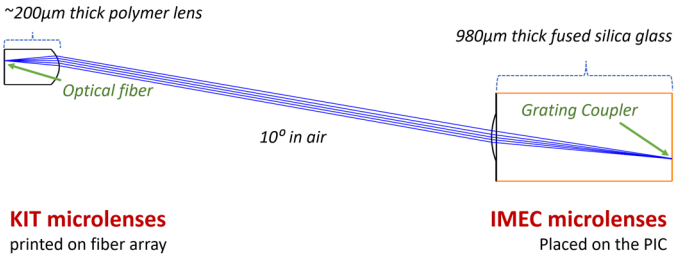

Figure 9. A schematic graph showing the light path between MPO connector's free-form lenses (KIT lenses, left) and PIC's micro-lens block (IMEC microlenses, right), as shown in Figure 8. Ray model only for illustration purpose, the design was optimized using the Gaussian beam propagation method.

C. Strand (3) - MOB

A Micro-Optical Bench (MOB) is a subassembly hosting a laser on a separate, dedicated substrate [14]. It was used as a hybridly integrated source on the PIC. The laser output light is focused by a ball lens, and then enters the prism which reflects it downwards at a 10º angle, through an opening in the substrate. The light is focused and reflected at an angle for optimal coupling to the GCs on the PIC.

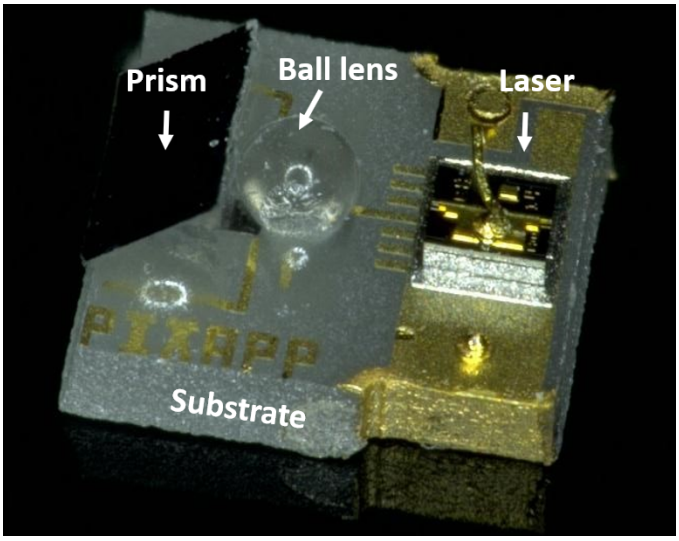

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Figure 10. Micro-Optical Bench (MOB) supports a laser, whose output is focused via ball lens and directed at 10º angle to couple to the GC, on the surface of the Datacom PIC.

The benefit of an MOB is in its very small footprint and in ability to be independently placed on the PIC, to which it has to be bonded. The MOB was designed in Tyndall and was thermally simulated to ensure sufficient heat dissipation that can lower laser's output power (see Figure 11). It was assembled at Cordon Electronics in Italy as shown in the Figure 10, with lasers and guidance from Eblana Photonics in Ireland.

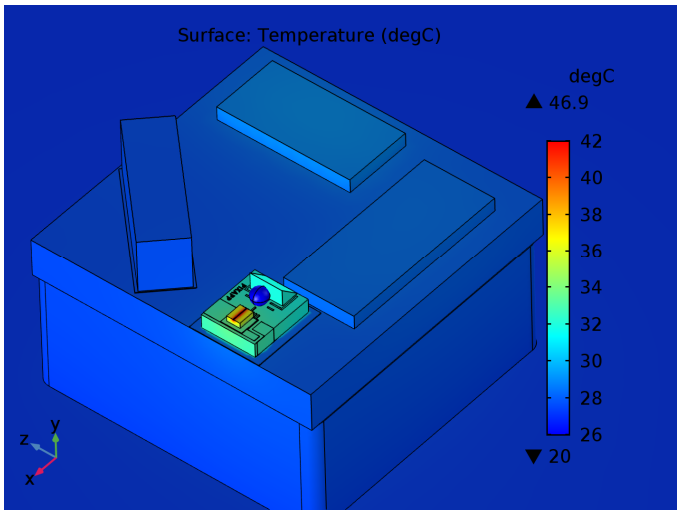

Figure 11. Tyndall performed steady state heat dissipation simulation of the PIC, and its top-surface elements, positioned on aluminum submount. TIA and Driver produce significant heat, but due to low thermal conductivity of substrate and epoxy, high power laser on the MOB heats up the most averaging 36ºC, and reaching up to 77ºC in the laser's active region. MOB's height and the amount of low conductivity epoxy holding it significantly impact laser performance. Simulations indicated that no active cooling is necessary.

Tyndall and Argotech both placed MOBs on PICs using a UV curable glue, as shown in Figure 12, with former partner developing the process and the latter adopting it for production at scale. The complete coupling losses (from laser output – ball lens - prism to GC) were measured with multiple MOBs on test structures to be in the range of 8.9-9.5dB. Higher loss was mainly due to discrepancies between the mode size, shape and angle required by GCs. Placement and gluing process introduced additional loss on the order of 0.5 dB (±1µm).

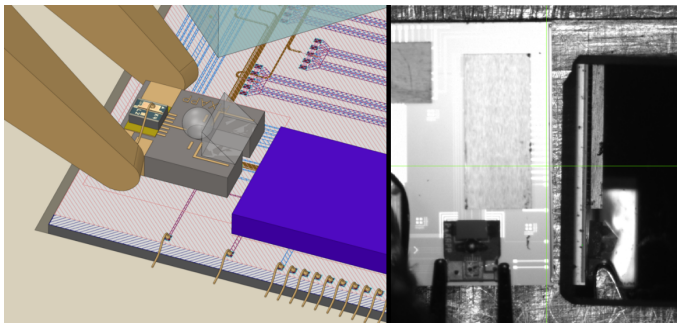

Figure 12. MOB placement 3D design (left), and microscope image (right). Besides sequencing packaging steps in a way that is the least hazardous to other packaging processes, the successful packaging of complex systems requires establishing clearances for the tooling – such as for the MOB placement shown.

With the first 3 assembly strands completed, all on-PIC components were integrated, as shown in Figure 13.

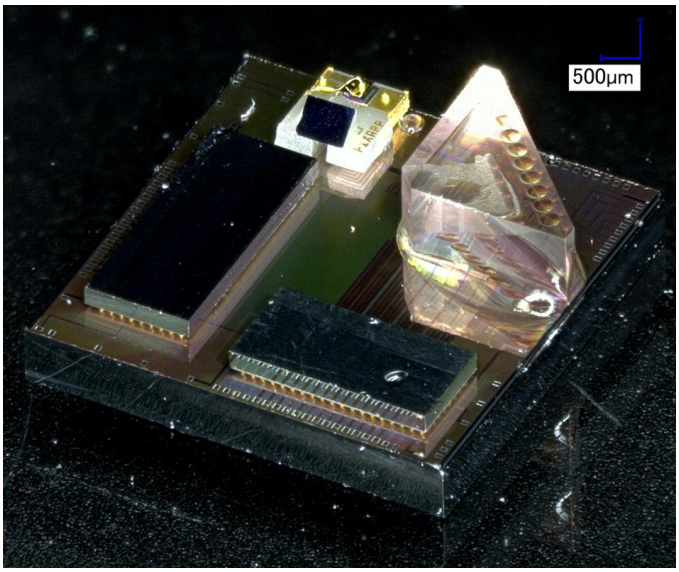

Figure 13. Microscope photo of a fully assembled Datacom PIC. On-PIC elements involve 2 EICs, IMEC's microlens array, and an MOB.

D. Strand (4) – PCB, LTCC and other electrical interconnects

The PIC has a footprint of 5.1mm x 5.1mm, and with 139 flip-chip electrical connections for the 2 EICs, that required a significant amount of electrical interfacing - much of it high speed. High bandwidth for 50G operation required careful design of the electrical lines leading away from the PIC and to the electrical connectors on the PCB. Connectors chosen are solderless, surface mount SMA connectors by Rosenberger (RPC 1.85). They were selected for their high-speed performance and the ability to be easily taken off and reused on multiple test structures and final modules.

The PIC required 75 closely placed bond pads and precision-made electrical waveguides that would fan out high speed electrical signal with minimal losses. Closely spaced RF bondpads and carefully designed fan-outs were the factors entailing an electrical interposer. VTT in Finland develops interposers in Low Temperature Cofired Ceramic (LTCC) technology [18]. Their laminated multilayer structures of high precision allow 3D guiding of multiple high-frequency electrical lines to be brought close to the PIC (and to fan-out from it) with a reduced pitch spacing, what normally would not be possible with PCB.

Argotech designed and simulated the complete mode propagation in all 8 GSSG lines, from the connector pads on the PCB, through the interposer, and onto the bondpads of the PIC. Their design was translated into LTCC fabrication design for VTT, and a PCB design which was finalized again by Argotech, and subsequently fabricated by an external supplier.

Upon fabrication of both the PCB and LTCC, the two were joined together in mechanical housing, and were electrically interfaced with DC blocking capacitors [19]. Image of that assembly is shown in Figure 14.

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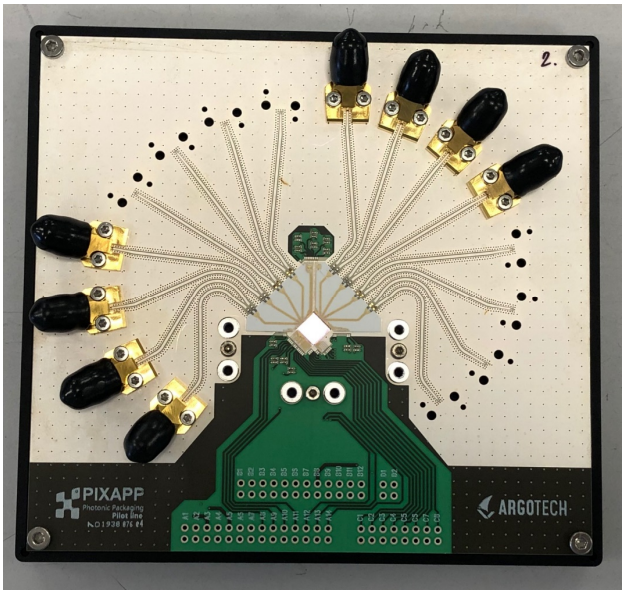

Figure 14. Datacom Demonstrator's housing with several Rosenberger connectors being attached to the PCB, that is connected to the LTCC interposer close to the central opening where the PIC comes in. This PCB-LTCC assembly was assembled together, and the PIC was placed in the centre once assembled PIC (passing through strands 1-3) was ready.

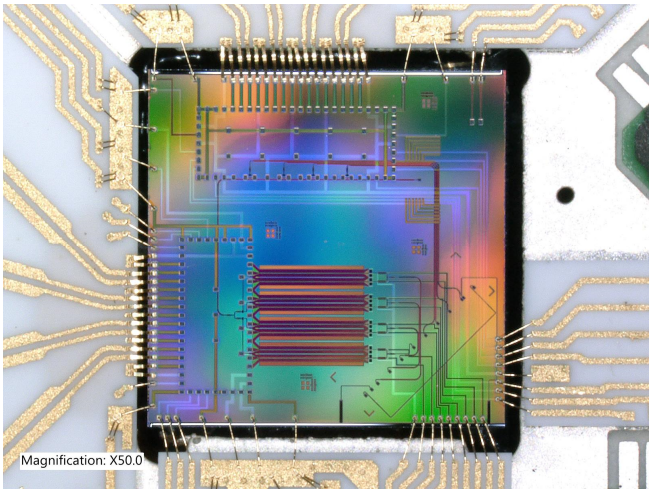

Figure 15. Datacom test PIC (centre) used for verifying DC wire- and RF ribbon-bonding to the LTCC (around). This PIC is without on-PIC elements, and was used to test the electrical integration processes, as well as to asses the electrical line's signal losses.

The PIC is then placed on a dedicated submount in-between LTCC interposer, and it's 75 bondpads were wirebonded (DC signal) and ribbon bonded (RF signal) to the interposer, as shown in Figure 15.

For operation, a pluggable optics had to be placed on top of the PIC, ensuring free space connection to the on-PIC microlenses. A 2.2mm thick top (connector-holding) plate was placed on the mount, just about a millimeter above the PIC. The plate was positioned and secured, with central opening in it being over the PIC's microlens. The Tyndall-made connector using US Conec components, shown in the Figure 16, and with the MPO FA containing microlenses already plugged into it, was placed on the top plate, and subsequently fixed with an epoxy. The complete module is shown in the Figure 18.

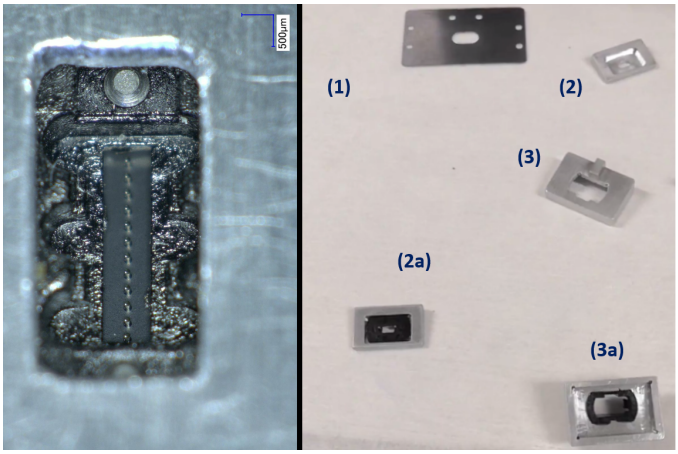

Figure 16. Left - KIT-made microlenses on an MPO FA patch-cord slotted in, and visible through the MTP/MPO receptacle from US Conec. Right – Tyndall made connector parts used in Datacom Demonstrator with top plate (1) on top of which goes MPO connector (2 and 3) that contains MTP/MPO receptacle and holder (2a and 3a).

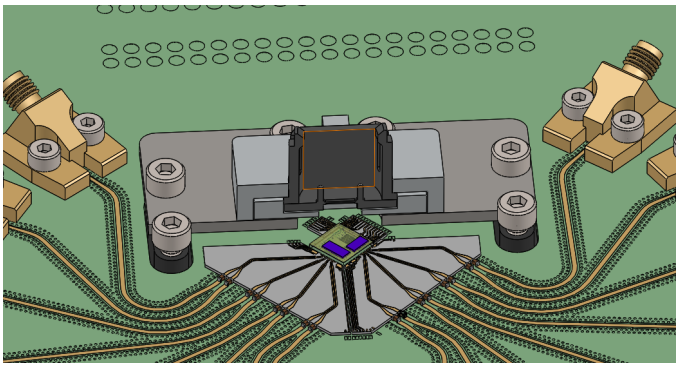

Figure 17. Scheme of the Datacom Demonstrator. Rosenberger RPC 1.85 connectors on the PCB are shown at the extreme left and right, from which electrical lines are going over PCB and LTCC to reach the PIC, a cross sectional view of the top (connector-holding) plate with the connector.

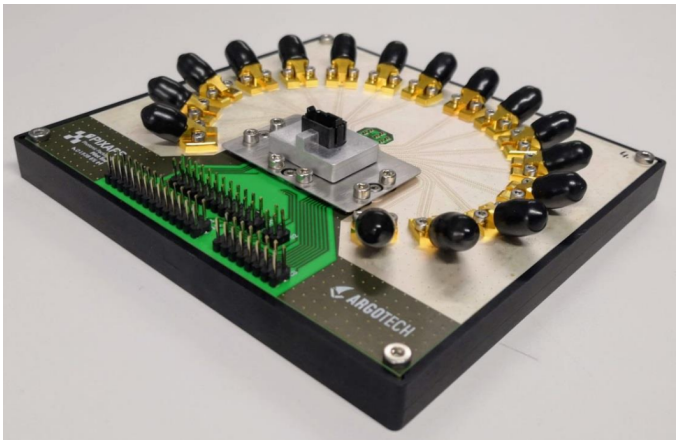

Figure 18. Fully assembled Datacom Demonstrator.

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IV. Testing

The testing of Datacom Demonstrator took place at IMEC in Belgium. The results presented here are from a version of the demonstrator that had IMEC lenses both on PIC and on MPO connector, instead of KIT 3D printed ones. This change was made to ensure longer working distance between FA and PIC, mitigating the risk of a connector touching the PIC.

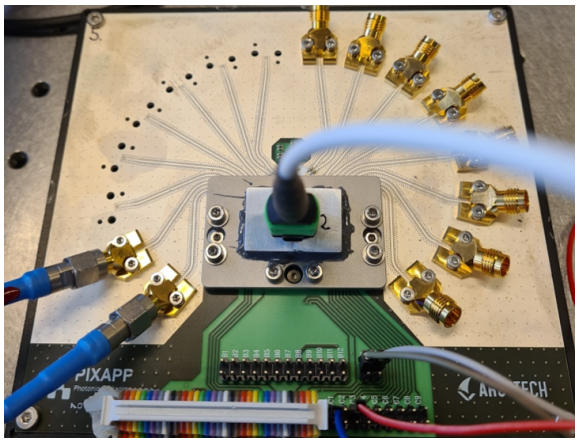

Figure 19. Datacom Module with RF cables connected to the transmitter side only, and the MPO FA with microlenses being plugged in the centre.

Firstly, the optical power emitted by the module's laser was evaluated. The laser was saturating between 80mA and 100mA, and the optical spectrum of the laser was measured showing peaks at 1308.2nm and 1310.2 nm respectively. That was a longer wavelength than what was found optimal for the modulator itself, which was 1289 nm. With the Mach-Zehnder Modulator biased both for heater and electrodes at maximum transmission point, and at a laser bias current of 80mA, the light emitted was between -12.1dBm and -13.2dBm.

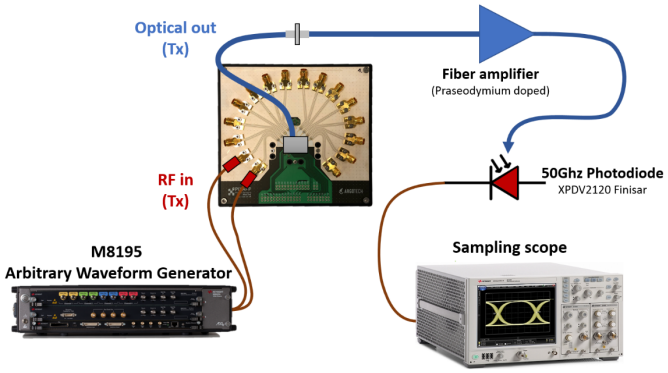

Figure 20. Measurement setup for high-speed time-domain tests of the transmitters.

With module connected as shown in the Figure 19 and the setup as shown in schematic Figure 20, the high-speed time-domain transmission test was conducted and the eye diagrams showed good performance for both 28Gb/s and 56Gb/s. Resulting open eye diagrams are presented in the Figure 21. The corresponding transmitter losses are shown in Table 2.

Table 2.
Transmitter losses

Component	Loss [dB]
Micro optical bench	2.0
Input grating coupler	2.6
Waveguide routing from GC to splitter	1.7
Splitter loss	6.10
Modulator loss at quadrature point	7.30
Waveguide routing from MZM to GC	0.67
Output grating coupler	2.57
TOTAL	**22.94**

The average insertion loss value of the full electrical transmission line, excluding the PIC, for 42GHz (~ 56Gb/s) was about 3dB, which was close to the value of 2.5dB obtained from RF simulation. When PIC line is considered, the loss value increased for 2dB to a total of about 5dB, which nearly doubled the insertion loss of the full electrical line. Variations in linewidths, effects of ground pattern and matching circuits at the end of LTCC lines make LTCC-only measurements less reliable at high frequencies. However, longer than desired PIC lines also caused significant increase in losses. Therefore this 2dB increase in losses reflects combined PIC and LTCC line performance. Typical LTCC microstrip line losses have been 0.29 dB/cm at 10 GHz, and PCB line was measured to be about 1 dB at 42 GHz.

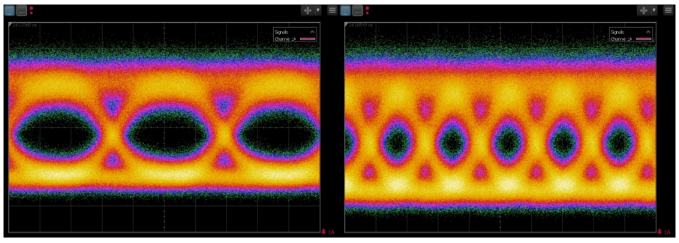

Figure 21. 28Gb/s transmitter eye diagram (left) and 56Gb/s eye diagram (right).

The final test on the Demonstrator involved connecting the transmitter part of the PIC to the receiver one, as presented in the Figure 22. The back-to-back measurement, involving modulation and de-modulation, was shown to be successful.

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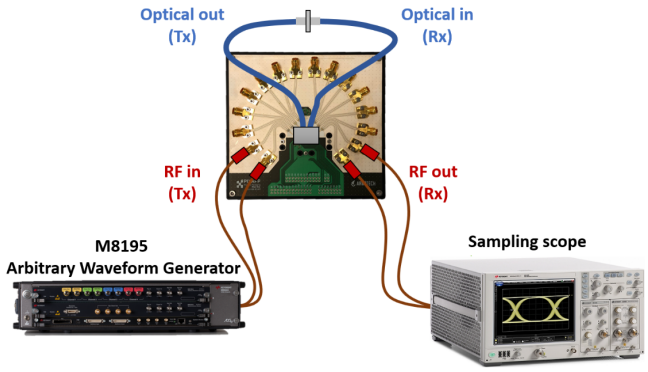

Figure 22. Measurement setup for high-speed time-domain measurements of the transmitter's (Tx) modulation and receivers's (Rx) demodulation simultaneously.

As shown in Figure 23, at 28Gb/s open eyes can still be clearly observed, however, at 56Gb/s the signal-to-noise ratio is reduced due to the non-optimum laser wavelength with respect to the central wavelength of the modulator.

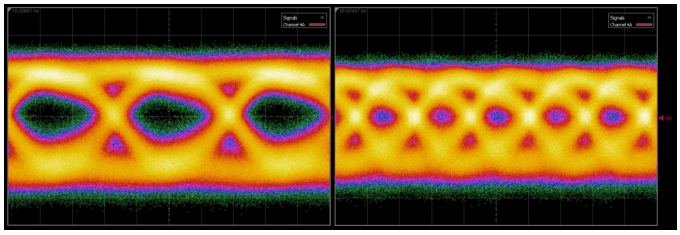

Figure 23. 28Gb/s loopback (transmitter + receiver) eye diagram (left), and 56Gb/s eye diagram (right).

V. Conclusion

In this paper we presented how the Pilot Line enables complex assemblies to be made with building blocks - packaging technologies that are scalable and suitable for volume manufacturing. The use of these building block processes was showcased by the development of a truly one-chip optical transceiver package, which was assembled using inputs from across the PIXAPP supply chain. The demonstrator covered the key PIC packaging processes from the PIC design phase, to optical, electrical, thermal and to the mechanical packaging – successfully integrating different technologies together into a functional module.

Results showed successful 56Gb/s per channel, OOK high-speed data modulation and de-modulation - resulting from carefully designed and packaged electrical and optical lines. PIXAPP is an important step forward in linking the fragmented value chain, greatly enhancing industrial competitiveness, and Europe's leading position in advanced photonics technology. The Datacom Demonstrator showed successful distributed packaging through PIXAPP - it validates how Pilot Line's building blocks and interdisciplinary coherent technology chain unite multiple European companies and Research Centers.

VI. Appendix

Table 3.
Abbreviations and full names of PIXAPP partners involved in Datacom Demonstrator work.

Abbreviations	**Full name**	**Country**
TYNDALL, TYN	Tyndall National Institute	Ireland
ARGOTECH, ARG	Argotech A.S.	Czech Republic
IMEC	IMEC - Interuniversity Microelectronics Centre	Belgium
CORDON, CORD	Cordon Electronics Italia	Italy
EBLANA, EBL	Eblana Photonics Ltd.	Ireland
KIT	Karlsruhe Institut of Technology	Germany
VTT	VTT Technical Research Centre of Finland Ltd	Finland
III-V Lab, III-V	III-V Lab	France

VII. Acknowledgment

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References

[1] P. Dong, Y. K. Chen, G. H. Duan, and D. T. Neilson, "Silicon photonic devices and integrated circuits," *Nanophotonics*, vol. 3, no. 4–5. Walter de Gruyter GmbH, pp. 215–228, Aug. 01, 2014, doi: 10.1515/nanoph-2013-0023.

[2] T. Komljenovic *et al.*, "Heterogeneous silicon photonic integrated circuits," *Journal of Lightwave Technology*, vol. 34, no. 1. Institute of Electrical and Electronics Engineers Inc., pp. 20–35, Jan. 01, 2016, doi: 10.1109/JLT.2015.2465382.

[3] M. Smit, K. Williams, and J. Van Der Tol, "Past, present, and future of InP-based photonic integration," *APL Photonics*, vol. 4, no. 5, May 2019, doi: 10.1063/1.5087862.

[4] T. Sharma *et al.*, "Review of recent progress on silicon nitride-based photonic integrated circuits," *IEEE Access*, vol. 8. Institute of Electrical and Electronics Engineers Inc., pp. 195436–195446, 2020, doi: 10.1109/ACCESS.2020.3032186.

[5] D. Marris-Morini *et al.*, "Germanium-based integrated photonics from near- to mid-infrared applications," *Nanophotonics*, vol. 7, no. 11. De Gruyter, pp. 1781–1793, Nov. 01, 2018, doi: 10.1515/nanoph-2018-0113.

[6] S. Y. Siew *et al.*, "Review of Silicon Photonics Technology and Platform Development," *J. Light.*

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Technol., 2021, doi: 10.1109/JLT.2021.3066203.

[7] P. O' Brien, L. Carrol, C. Eason, and J. S. Lee, "Packaging of silicon photonic devices," in *Topics in Applied Physics*, vol. 122, Springer Verlag, 2016, pp. 217–236.

[8] L. Carroll *et al.*, "Photonic packaging: Transforming silicon photonic integrated circuits into photonic devices," *Applied Sciences (Switzerland)*, vol. 6, no. 12. MDPI AG, 2016, doi: 10.3390/app6120426.

[9] J. S. Lee *et al.*, "Meeting the Electrical, Optical, and Thermal Design Challenges of Photonic-Packaging," *IEEE J. Sel. Top. Quantum Electron.*, vol. 22, no. 6, pp. 409–417, Nov. 2016, doi: 10.1109/JSTQE.2016.2543150.

[10] C. Li, K. S. Chee, J. Tao, H. Zhang, M. Yu, and G. Q. Lo, "Silicon photonics packaging with lateral fiber coupling to apodized grating coupler embedded circuit," *Opt. Express*, vol. 22, no. 20, p. 24235, Oct. 2014, doi: 10.1364/oe.22.024235.

[11] N. Pavarelli *et al.*, "Optical and electronic packaging processes for silicon photonic systems," *J. Light. Technol.*, vol. 33, no. 5, pp. 991–997, Mar. 2015, doi: 10.1109/JLT.2015.2390675.

[12] B. Snyder and P. O'Brien, "Packaging process for grating-coupled silicon photonic waveguides using angle-polished fibers," *IEEE Trans. Components, Packag. Manuf. Technol.*, vol. 3, no. 6, pp. 954–959, 2013, doi: 10.1109/TCPMT.2012.2237052.

[13] X. Liu, "Challenges and Opportunities in Future High-Capacity Optical Transmission Systems," in *Optically Amplified WDM Networks*, Elsevier, 2011.

[14] M. Duperron *et al.*, "Hybrid integration of laser source on silicon photonic integrated circuit for low-cost interferometry medical device," Feb. 2017, doi: 10.1117/12.2250921.

[15] "Europractice Si-Photonics iSiPP50G," Aug. 2021. https://europractice-ic.com/mpw-prototyping/siphotonics/imec/.

[16] N. Mangal, B. Snyder, J. Van Campenhout, G. Van Steenberge, and J. Missinne, "Expanded-Beam Backside Coupling Interface for Alignment-Tolerant Packaging of Silicon Photonics," *IEEE J. Sel. Top. Quantum Electron.*, vol. 26, no. 2, Mar. 2020, doi: 10.1109/JSTQE.2019.2934161.

[17] P. I. Dietrich *et al.*, "In situ 3D nanoprinting of free-form coupling elements for hybrid photonic integration," *Nat. Photonics*, vol. 12, no. 4, pp. 241–247, Mar. 2018, doi: 10.1038/s41566-018-0133-4.

[18] M. Lahti, K. Kautio, M. Karppinen, K. Keränen, J. Ollila, and P. Karioja, "Review of LTCC technology for millimeter waves and photonics," *Int. J. Electron. Telecommun.*, vol. 66, no. 2, pp. 361–367, 2020, doi: 10.24425/ijet.2020.131886.

[19] M. Zoldak, L. Halmo, J. P. Turkiewicz, S. Schumann, and R. Henker, "Packaging of ultra-high speed optical fiber data interconnects," in *Optical Fibers and Their Applications 2017*, Feb. 2017, vol. 10325, p. 103250R, doi: 10.1117/12.2271032.

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Peter O'Brien is Director of the European Photonics Packaging Pilot Line, leads the new European Photonics Academy and head of the Photonics Packaging & Integration Group at the Tyndall Institute at University College Cork in Ireland. Prof. O'Brien previously founded and was CEO of a start-up company manufacturing specialty photonic systems for bio-imaging applications, which he sold in 2009. Prior to this, he was a post-doctoral scholar at the California Institute of Technology and a research scientist at NASA's Jet Propulsion Laboratory. He received his degree and PhD in Physics from Trinity College Dublin and University College Cork respectively.

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