Industrial photonics packaging for high volume applications

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ABSTRACT

Commercial introduction of emerging integrated photonics technologies requires a long and complex multi-layer product development, industrialization, and qualification cycles at all levels of value chain from initial product design, material sourcing, component-system-module manufacturing, and testing, through marketing and delivery of new products to the market. Scalable assembly and packaging of electronic-photonic integrated modules is important and may take more than a half of the entire product’s costs. In this paper, we will report on some of our industrial processes for scalable photonics packaging, as well as challenges and results obtained from our research and innovation projects.

Keywords: Hybrid Integration, Integrated Photonics, Micro-Optics, Photonics Packaging, Wafer-Scale Assembly.

1. INTRODUCTION

Integrated photonics has emerged as the technology of the future for advanced optical applications [1]. Massive amounts of data are being created and distributed all around the world, and this trend is likely to increase. Most of the data traffic is happening within the datacentre, where low power, high reliability and fast data transmission really matters for the future of internet communications. Advancing datacentre network architecture is driving high demand for photonics packaging of optical transceivers and co-integration of photonics and electronics. This market is relatively mature; however, “silicon” photonics technology is expanding into additional fields from 3D imaging to chip-based sensors for healthcare, and from artificial intelligence and deep learning to smart fabrics, and quantum communications infrastructure. The area of biomedical sensors is particularly emerging, and it might enable us to provide medical assistance anytime and anywhere, new diagnostic tools, and improved public health at reduced healthcare costs. Other applications encompass quantum photonics, LIDAR, and agri-photonics, which may provide us with higher security, better food quality, remotely controlled vehicles and machines in hard-to-reach areas, easily deployable and remotely accessible environmental sensors in metropolitan and marine environments, compact and low cost quantum clock sensors for monitoring the industrial processes, and resilient devices for monitoring atmospheric conditions, which can provide early warnings for impeding catastrophes and reduce effects of climate change. All these emerging areas have seen market growth, which is a driving factor for photonics packaging [2].

The characteristics of photonics packaging technologies are set by the individual application/product requirements. At the moment, there is no single material platform that can efficiently generate, guide, manipulate and detect light at a low cost while also being compatible with standard processes used in the semiconductor industry. Therefore, hybrid photonic packaging and integration of photonic and electronic integrated circuits is necessary to satiate consumers’ demand for more. This activity is challenging and may take more than half of the entire product’s costs.

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For example, different material platforms may have different optical, electrical, thermal, and mechanical properties, so once they are assembled on the common substrate, each of these hybrid chip materials will react differently to moisture, mechanical and temperature stresses particularly at the interface region between the two chips causing potential delamination. Therefore, for each scenario, a thermo-mechanical model needs to be developed to ensure that packaged products can operate efficiently at a low power consumption. The lack of standardization represents another issue because it makes it difficult for different modules and systems in package to be efficiently assembled to communicate together seamlessly. To keep not only the material costs but also the production costs low, a suitable scaling strategy must be considered. It includes integration, optical, electrical, thermal, and mechanical aspects of the packaged products. This is important as the markets for these new and emerging products grow rapidly. In this paper, we will report on some of our industrial processes for scalable photonics packaging, as well as challenges and results obtained from our research and innovation projects. This includes complex hybrid integration, wafer-scale assembly, photonic-electronic integration, spot-size converters (SSCs), and aligned 3D printing of micro-optical lenses.

2. OPTICAL PACKAGING AND HYBRID INTEGRATION

Hybrid integration of active and passive photonic chips via edge coupling has been proven successful for producing working photonic modules. However, this technique is unsuitable for integration on a wafer scale. Flip-chip assembly, on the other hand, adds on integration complexity but fosters high integration density, cost effectiveness and volume production. In the following paragraphs, we will showcase some of our recent results obtained using both edge coupling and flip-chip assembly techniques, and we will discuss our recent work in the area of optical interface building blocks such as SSCs and 3D printed microlenses.

2.1 Edge coupling

Within the EU Horizon 2020 project, TERAWAY [3], which aims to develop a disruptive generation of photonics-based terahertz transceivers for applications in 5G networks, a complex hybrid integration was performed. This work was done as a collaboration between different partners, in particular PHIX Photonics Assembly, Fraunhofer HHI, and National Technological University of Athens. Figure 1 shows the state-of-the-art prototype assembly of one of the modules, consisting of active (InP lasers, InP antenna array and InP phase modulator chips) and passive photonic components (SiN filters and beam forming networks and polymer motherboard chip), fiber arrays and DC/RF printed circuit board (PCB). Optical integration of photonic chips based on indium phosphide (InP) and silicon nitride (SiN) platform to the polymer photonic motherboard was performed by edge coupling utilizing active alignment, followed by UV-curing of the optical adhesive. Where possible, alignment loops were used to simplify the alignment approach. However, electrical driving was required to realize alignment for some of the active devices. The detailed description of the assembly processes was described in Ref. [4] and will not be further discussed in this manuscript.

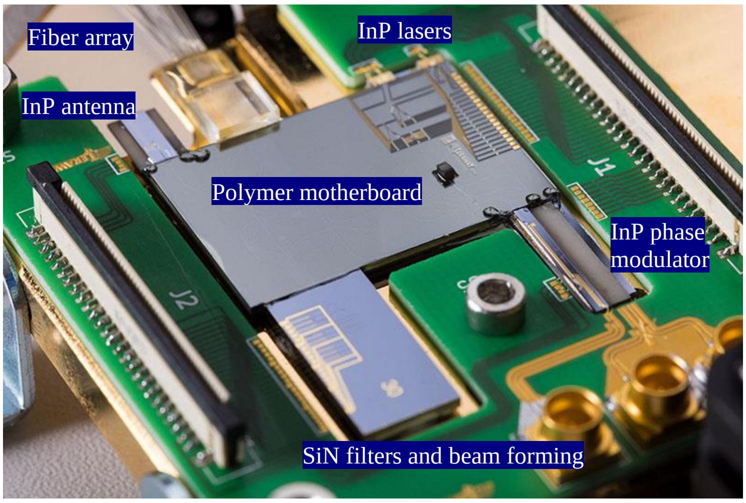

Figure 1. (a) State-of-the-art assembly performed by PHIX within the EU-project TERAWAY consisting of a fibre array to PolyBoard™ and 4 PICs from different technologies (InP, PolyBoard™ and SiN) using edge-coupling and wire bonding for DC and RF connections [4].

2.2 Flip-chip assembly

Within the EU Horizon 2020 project PHOTO-SENS [5], which aims to develop a plug and play photonic biosensing platform for use in aquaculture, we performed hybrid integration of light sources, and photodiodes (PDs) on 4-inch silicon nitride wafer (Figure 2). Waveguide grating couplers were used to couple light in and out of the wafer while electrical bond pads were used to make electrical connection with other photonic components. A single mode VCSEL operating at 850 nm wavelength and two 1×4 arrays of gallium arsenide (GaAs) p-i-n PDs were integrated using flip-chip bonding technique. Photodiodes were top-side illuminated to operate at 850 nm wavelength with a signal-ground pad configuration, and were solder bumped using gold-tin alloy. NTC thermistor was directly mounted onto the wafer and was used for temperature stabilization of the hybrid PICs. Bonding of optoelectronic components was achieved using an automated Finetech flip-chip bonding machine, on which the assembly process for different components was optimized. Two different solder ball (pad) reflow methods were investigated: conductive heating and laser assisted heating. It was found that the conductive heating technique was not suitable for wafer level bonding of photonic components because the whole wafer had to be reheated every time a photodiode array was placed onto the wafer. Therefore, laser assisted heating technique was adopted in which a laser beam was focused on the back of the wafer substrate to locally reflow specific solder bumps within a limited area. This allowed successive PD arrays to be transferred onto the wafer without compromising the bonds that have already been made. Four different components (one VCSEL, two PD arrays, and one NTC) were populated onto every single die of the wafer. The assembly process flow of these components was dictated by the required bonding temperatures. Firstly, VCSELs were populated via thermocompression Au-Au bonding at a temperature of 330 ^{o}C, followed by the PD arrays using solder reflow temperature of 300 ^{o}C. Finally, NTC thermistors were attached using electrically conductive adhesive and post baking at 150 ^{o}C. Leveraging advanced pick-and-place tooling and machine vision system for accurate alignment, each photonic component was accurately attached to the substrate within 30 seconds achieving alignment precision of less than 300 nm: therefore, providing the assembly of 30 functional hybrid PHOTO-SENS PICs within a time frame of one hour.

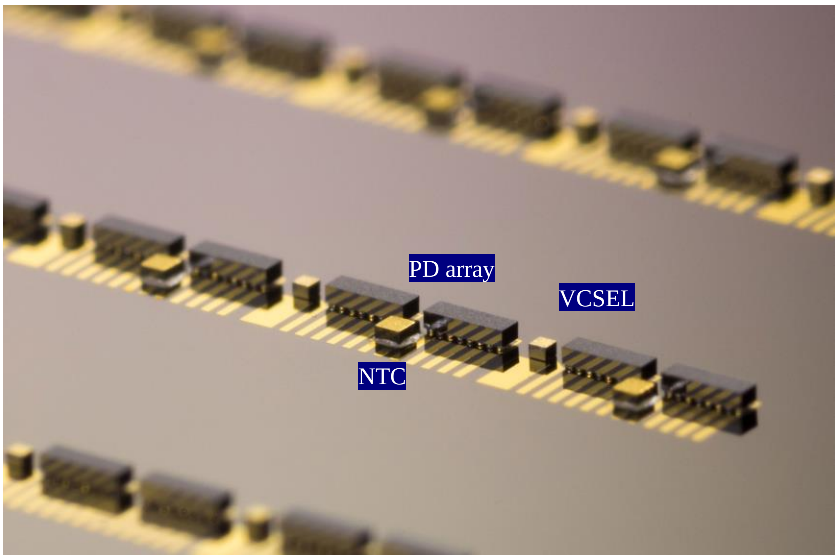

Figure 2. Wafer level flip-chip assembly of VCSELs, PDs and NTCs performed by PHIX within the EU project PHOTO-SENS [5].

2.3 Spot-size converters

One of the critical steps in photonic assembly represents coupling between the two dies. A major factor contributing to the coupling losses of light between an optical fiber and the waveguide located on a PIC is mode field and polarisation mismatch (elliptical or circular polarisation). Various building blocks such as SSCs, photonic wire bonds, 3D printed lenses, vertically curved and suspended waveguides, out-of-plane and adiabatic couplers are being studied to enable efficient and reliable transfer of optical signals in a variety of applications [6-12]. Efficient optical coupling requires good alignment as well as inherent matching between the mode fields that are guided within the waveguides. Choosing the optimal mode size of a SSC for coupling into a PIC seems straightforward in theory (by matching their mode fields), however, the situation is different in practice because it is also important to consider the potential misalignment between the waveguides which are located on different dies that are being attached. To illustrate this, let us consider a PIC with the mode-field diameter (MFD) in x and y direction of $MFD_{x/y}$ = 3.0 × 1.0 µm (typical for InP platform), which needs to be attached to a SSC with an alignment accuracy of 250 nm. Since the vertical y-component of the MFD is relatively small, a misalignment is dominant over x-direction, reaching a coupling loss of up to 1.2 dB at an alignment accuracy of 250 nm (Figure 3a). However, due to a small MFD in y-direction (MFD_y), the losses increase quickly, approaching 3 dB at an alignment accuracy of 400 nm. Therefore, the use of SSC with circular MFD instead (2.0 × 2.0 µm) can be a good alternative. In the case of SSC with circular MFD, coupling losses are higher when there is no misalignment, however, this is very difficult to achieve in practise and since the misalignment-related losses increase more slowly (Figure 3b), this could be an alternative approach for achieving a low loss coupling. Then, what is the best choice? This will depend on the level of alignment tolerances that is achievable. For the two cases described above, the use of SSC with MFD of 3.0 × 1.0 µm is a better choice when alignment accuracy is greater than 350 nm (Figure 3c), however for a misalignment above 350 nm an SSC with MFD of 2.0 × 2.0 µm would be a better option. The situation gets more complicated when we also consider other degrees of freedom such as rotational angles and a gap between the dies in z-direction. For example, in the case of a SSC with the MFD of 3.0 × 1.0 µm, a coupling gap of only 2 µm between a PIC and a SSC could lead to an additional coupling loss of 3 dB. This value is significant because a 'yaw' rotational angle between two 2-mm wide dies of only 0.05° may lead to such gaps. Therefore, low loss coupling to a particular PIC requires careful consideration of various parameters that may affect the coupling efficiency [12].

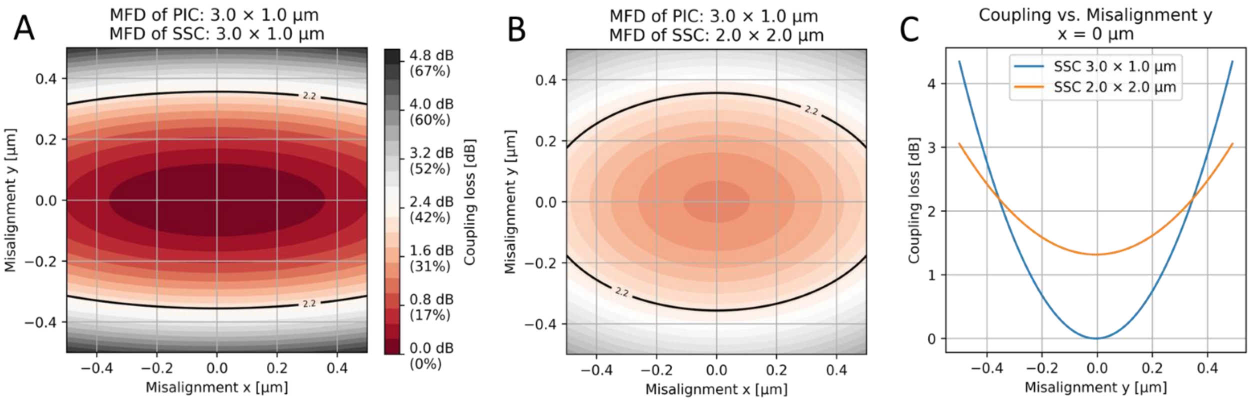

Figure 3. (a) Gaussian overlap calculation of the coupling losses between two waveguides, one located on a PIC and the other one located on a SSC (MFD in the plot title). The x- and y-axes show misalignment between the two waveguides, while the contour plot shows the insertion loss at a given misalignment. (b) Similar plot as in Figure 3a but considering different MFD of the SSC. Figures 3a and 3b use the same color scale. (c) Coupling losses between PIC and SSC as a function of waveguide misalignment in y-direction for two different geometries of SSC.

2.4 Micro-optical lenses

Optical lenses can be 3D printed on the facet of optical fibers or on top of the optical waveguides with diameters ranging from several micrometers to below 1 µm [9]. Using Quantum X align tool from Nanoscribe, we were able to 3D print microlenses on top of the fiber arrays and PIC grating couplers with high precision (Figure 4). Lens arrays can focus or collimate optical signal, enabling mode field conversions or large distance free space coupling. The machine is capable of fabricating three-dimensional micro and nanostructures in photo-sensitive materials based on two-photon polymerization (2PP) direct laser writing. Two-Photon Polymerization (2PP) is a non-linear two-photon absorption process based on the simultaneous absorption of two photons in a photoresist [9]. This process introduces a change in the photoresist from monomer state to polymer state through polymerization by activating so-called photo-initiators located inside the resist. It is necessary for two photons of near-infrared light to be absorbed simultaneously to have a sufficiently high light intensity that is provided by a femtosecond pulsed laser beam. Typically, the laser is focused into the photoresist and polymerization is triggered only in the focal spot volume, where the light intensity exceeds the threshold of polymerization. The smallest printable 3D volume is called voxel, which is similar to a 2D pixel. It enables printing structures by moving the laser focal spot along a trajectory in all three dimensions. This technology is able to print structures with small, medium and large feature sizes in 3D as well as 2D patterns. The alignment accuracy is up to to 100 nm (xy direction) / 500 nm (z direction). It optimizes the printing on standard and customized fiber arrays and photonic chips with superior quality (surface roughness of 10 nm and shape accuracy of 200 nm). This 2PP microfabrication technology with real voxel tuning enables an eight-lens array printed within 10 min. In order to manufacture 2PP 3D printed microlens, accurate design, printing and process quality control are necessary. Optical design of a lens is generated using optical design platforms such as Zemax. These design files are then transferred to Nanoscribe desk software nanoPrintX to create printing projects that are uploaded onto Quantum X align machine. Afterwards, a substrate with a drop of photoresist IP-S is loaded on the machine and the printing project can be started. The lenses are developed after removing the remaining photoresist by immersing it in PGMEA (propylene glycol monomethyl ether acetate) for 15 min and IPA for 3 min. To make sure that the printed lenses are in shape with their design, a confocal microscope measurement with a high numerical aperture objective lens is required to check the shape accuracy and the surface roughness (Figure 5). Periscope lenses and custom designed lenses usually require further optical analysis, horizontal beam profile measurement, working distance and coupling loss considerations. The minimum coupling loss between an optical fiber array and a PIC chip is 0.5 dB.

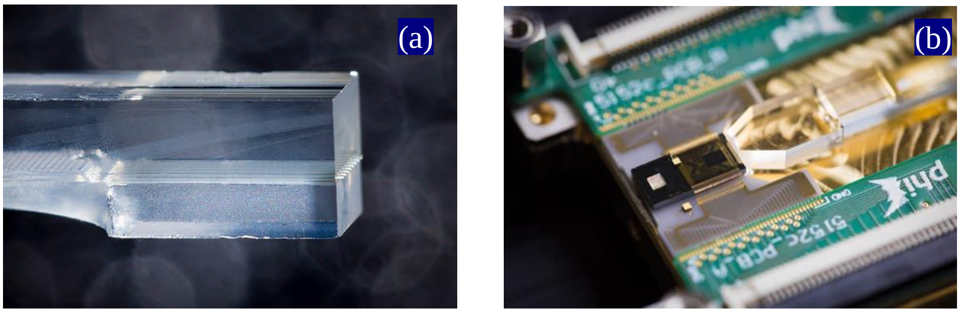

Figure 4. (a) 3D printed microlens array on the facet of an optical fiber array. (b) 3D printed microlens array on top of a photonic chip. A SSC is located in between an optical fiber array and a photonic chip [12].

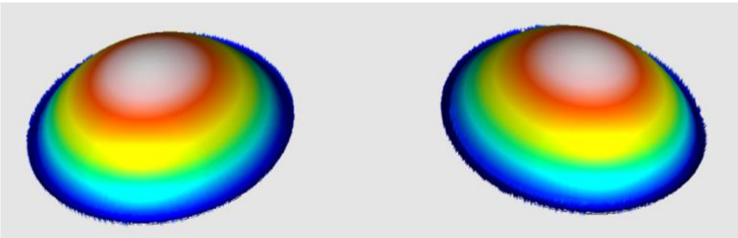

Figure 5. Confocal microscope image of collimating lenses with a diameter of 80 μm.

3. ELECTRICAL CONNECTIONS

Electrical packaging represents a crucial part of any large-scale semiconductor manufacturing line and it’s necessary for providing reliable and secure electrical interconnections between various photonic-electronic components inside and/or outside the package, and with the package itself. This is a very broad field which is rapidly evolving due to high customer and competitor demands for products with increased functionality and performance, higher reliability, lower power, and reduced costs. In the following paragraphs we will present and discuss some examples of electrical packaging that was performed in the context of EU funded projects, such as wire-bonding, ribbon bonding and flex-line attachment.

Electrical wire bonding is a standard technique in semiconductor industry, and it is typically used to interconnect photonic-electronic devices with their packages. PHIX Photonics Assembly uses automated wire bonding tools to realize electrical connectivity (DC and RF signals) of photonic integrated components. In each of the EU projects presented above, the bond pad requirements were meticulously considered during the design and fabrication phase of integrated photonic components. A fully automatic wedge wire bonder was utilized to achieve the electrical interconnections of the prototypes (Figure 6a). The wire bonder was equipped with a camera, which was employed to pinpoint the exact position of the components and determine the bond pad positions, along with a microscope for visual inspection of the wires. A gold wire with diameter of 17 µm was used to perform wedge-wedge bonding. At a minimum bond pad size of 60×60 µm^2, a pitch of as little as 100 µm can be achieved. Wire bonding is usually used for carrying DC or low speed RF electrical signals; however, depending on the transceiver co-design and the length of the wires some wire bonded transceivers may reach frequencies between 50 GHz and 60 GHz. Ribbon bonding is an alternative to wire bonding technique (Figure 6b), and it is mainly used for high-speed RF applications typically in the range between 20 GHz and 100 GHz [12]. Ribbon bonding combines the flexibility of wire bonding with the electrical characteristic of the ribbon (a typical wire bonding machine can be relatively easily reconfigured to carry out ribbon bonding) and has a potential for achieving further miniaturization in size of electrical bond pads and higher interconnects density due to a different shape of the wires. New materials, such as thin film lithium niobate, barium titanate and poled polymers, are being investigated to provide high-frequency (>100 GHz) modulation. The RF flex lines represent another possibility for high-speed electrical interconnects, and they will be further discussed.

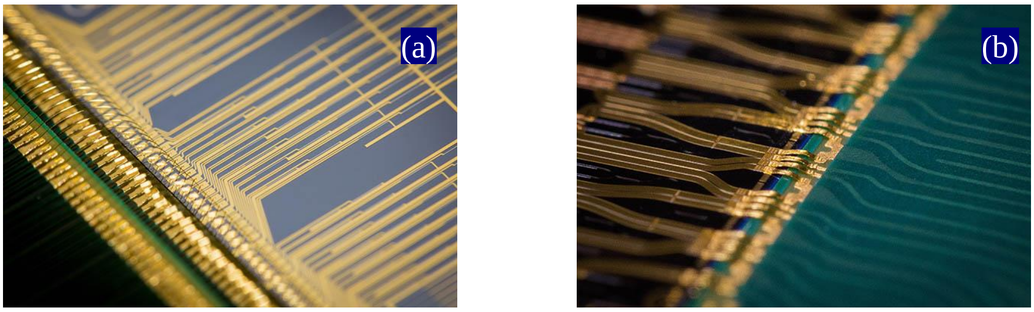

Figure 6. An image of (a) wire-bonding and (b) ribon bonding used for making electrical connection between a photonic chip and a PCB [12].

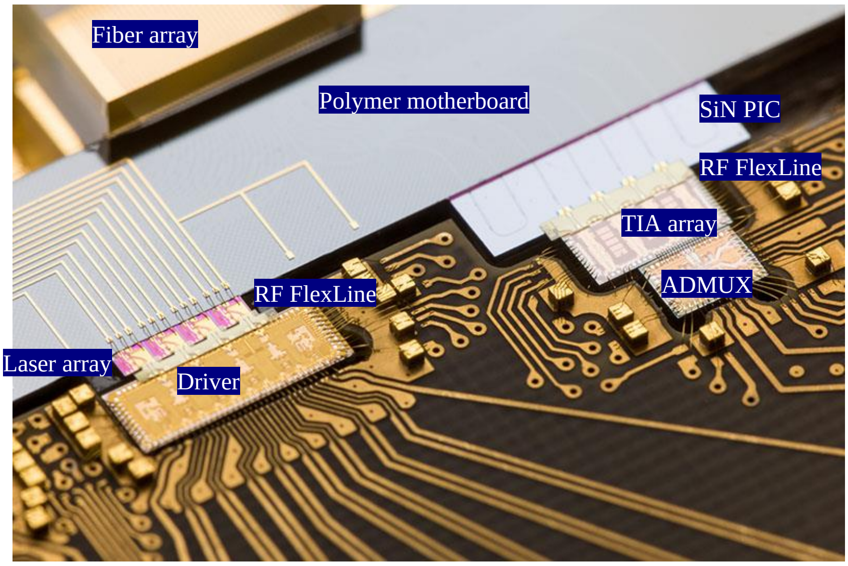

Figure 7. Hybrid PIC showcasing the RF FlexLine technology that was used to interconnect the InP externally modulated lasers with electronic drivers (left) and TIA array with silicon nitride PIC (right) within the EU funded project POETICS [13].

Within the EU Horizon 2020 project POETICS [13], which aims to bring optical interconnect technology to the next level facilitating further growth of datacenters and 5G wired infrastructure, several interconnect technologies were investigated aiming at high-speed interfaces. A particularly promising and innovative approach based on RF FlexLines (Figure 7) was proposed and manufactured by a consortium partner Fraunhofer-HHI. The RF FlexLines are made of flexible polymer material and thin film gold electrodes which are reinforced with electroplating. The length and dimensions of the bond pads (pad size and pitch) can be adjusted based on target application requirements according to the hosting components pad size and pitch. From a signal integrity perspective, FlexLines offer advantages compared to ribbon/wire bonding because their cross-section can be customized to achieve specific characteristic impedance and provide proper shielding between electrical channels (a 1 mm long FlexLine was able to carry electrical signals at a frequency of 110 GHz with insertion losses of 1.7 dB). However, attaching very short FlexLine (approximately 200-400 µm long) to very small high-frequency bond pads (with 40 µm passivation opening) poses a considerable challenge. Within POETICS, RF FlexLine technology was used to interconnect the RF contacts of photonic components such as externally modulated lasers (EMLs) and photodetectors (PDs) with the RF contacts of the electronic components such as drivers and transimpedance amplifiers (TIAs). Gold bond pads make the Flexline suitable for thermosonic bonding.

4. PHOTONIC PACKAGES: MECHANICAL AND THERMAL CONSIDERATIONS

Mechanical and thermal stability of hybrid photonic integrated modules is of paramount importance because changes in operating temperature or module handling can lead to significant alterations in module's performance. This section describes measures taken to establish a system that is both mechanically and thermally stable.

4.1 Mechanical stability

Within EU Horizon 2020 project POETICS [13], a photonics Bene switch (16×16) was fabricated on a silicon nitride platform, and then integrated with fiber arrays and electronics, and finally packaged utilising PHIX characterization package (Figure 8). A 6 mm thick gold-plated copper mount was used as a mechanically stable carrier on which PCB and optical assembly were placed. Copper material possesses very high thermal conductivity, and therefore was used to provide good thermal conduction from optical assembly to the cooling system. Accurate alignment of electrical interfaces of the subassembly and the PCB is crucial to minimize the physical distance between components and associated parasitics. Optical subassemblies were mounted on an AlN/Si submount to elevate the overall thickness of the subassembly by approximately 1.5 mm. Printed circuit board (PCB) with the same thickness (1.5 mm) was fabricated to match this configuration. Mechanical assembly involved mounting the PCB boards and stiff fiber array strain reliefs on a mechanical carrier. PCB and the strain reliefs were attached and secured onto a metal carrier through openings created inside the metal holder, PCB, and strain reliefs. Subsequently, the preassembled optical subassembly was meticulously aligned with the PCB tracks and then bonded onto the housing using thermally conductive adhesive. Finally, the fiber arrays were attached to their respective strain reliefs using a combination of shrink tubing and hot glue (Figure 8).

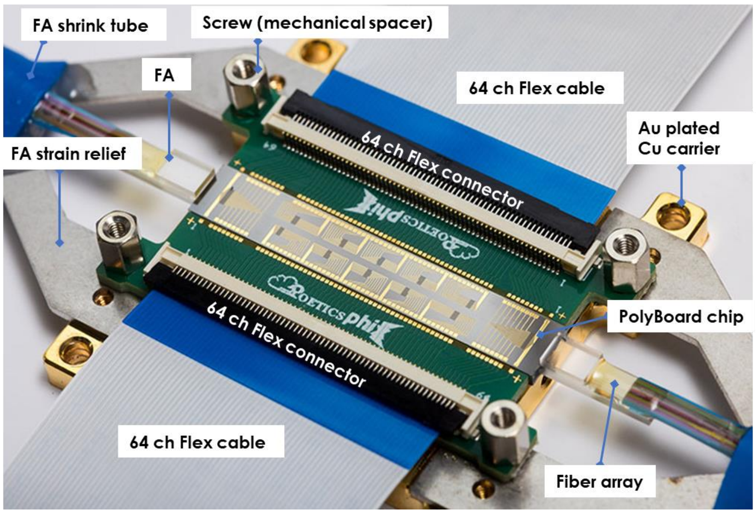

Figure 8. A photograph of an optical switch prototype manufactured within EU funded project POETICS and packaged using PHIX characterization package. The optical subassembly, combined with the electrical boards, was securely mounted on an Au-plated copper carrier. The image also highlights the integration of fiber array strain relief [13].

4.2 Thermal management

Thermal management sub-systems play a crucial role in highly integrated photonic integrated circuit modules, as excess heat and unstable temperatures can significantly impact performance and reliability. However, thermal management needs to be optimised, otherwise it may significantly increase the overall power budget. Both active and passive thermal sub-systems can be integrated into various packages. Active thermal control utilizes a thermoelectric cooler (TEC) based on the Peltier effect, while passive thermal subsystems use metal heat sinks within the package or thermal paths leading to a rack mount or case.

A comprehensive thermal analysis for POETICS project prototypes has been conducted based on the heat dissipation of the modules. The selected cooling systems were then determined, taking into account the targeted operational temperature of the modules. Figure 9 showcases the developed multi-chip module (MCM) which consists of the optical (multi-chip) module, thermal management subsystem, and a mechanical stand (shelf). The maximum heat dissipation (load) of an MCM prototype was found to be equal to 20.24 W when all channels were activated at targeted operational temperature of 50 °C. This operational temperature is achievable in an air-conditioned room; however, if operation at a lower temperature is required, such as 35 °C, an additional cooling system needs to be implemented. Thermal management system consisted of thermoelectric cooler (TEC) – Peltier element, fan driven heat sink, and thermal sensor (thermistor). TEC was positioned between the optical module and the fan-driven heat sink. The cold part of the TEC was bonded to the optical module, and its hot part was connected to the heat sink. Depending on the applied current, the TEC transfers the heat from the cold side to the hot side (i.e., from the optical module to the heat pipe). To reach the required operational temperature (~35 °C), the Peltier consumed 2.62 W of power (driven by 1.689 A and 1.551 V). A fan-driven heat sink with a low thermal resistance (0.72 K/W) was mounted under the Peltier element, while a thermistor was placed on the copper mount close to the active photonic chips.

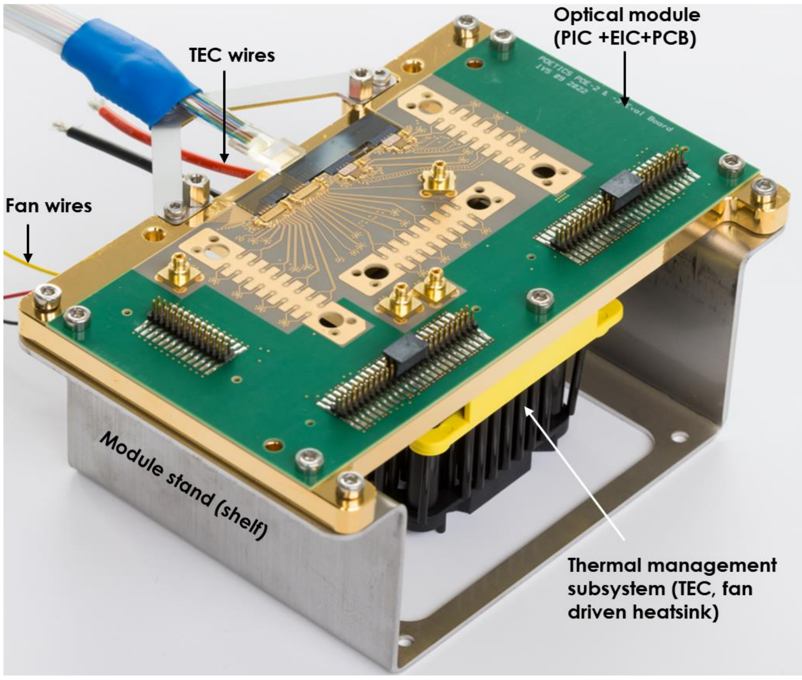

Figure 9. A photograph of the MCM prototype. The optical subassembly, combined with the electrical boards, is securely mounted on an Au-plated copper carrier. The image also highlights the integration of fiber array strain relief and the thermal management subsystems [13].

4.3 Package solutions

PHIX photonics assembly provides packaging solutions for all maturity stages of targeted technology. Our standard package types, listed in Ref. [12], are a starting point for chip characterization, device prototyping and small to medium volume production. Additionally, we provide custom packaging solutions for higher volume production opto-electronic components and devices. Figure 10a shows an optical switch packaged using PHIX characterization package. This is an open package, which is convenient for rapid prototyping and testing of modules during the product development phase. This package type provides both optical and electrical interfaces with which end users can power and read out photonic-electronic chips without having to probe it manually. Furthermore, its open architecture allows for easy visual inspection of the PIC's behavior during operation and provides high flexibility for customization. However, most industrial packages comprise a photonic chip encapsulated inside the package in hermetic or non-hermetic fashion. The addition of desiccant materials may help increase the lifetime of the module. PHIX Butterfly package and Large Area Gold Box are used in applications that are more mature due to their compact and closed architecture. Although both packages are robust enough for high volumes, it is often required to design custom housing for those products. Figure 10b shows integrated and packaged ultraviolet laser in a hermetically sealed nitrogen environment using 14-pin butterfly package. The white substance on the bottom of the glass lid is a getter material which absorbs any remaining volatile gases and moisture in the package. The laser was based on hybrid integration of aluminum-oxide platform and InGaN amplifier operating at the wavelength of 405 nm. This work was published in Ref. [14], and one of the packaging challenges was epoxy free fiber attached to the photonics chip enabling applications at ultraviolet wavelengths.

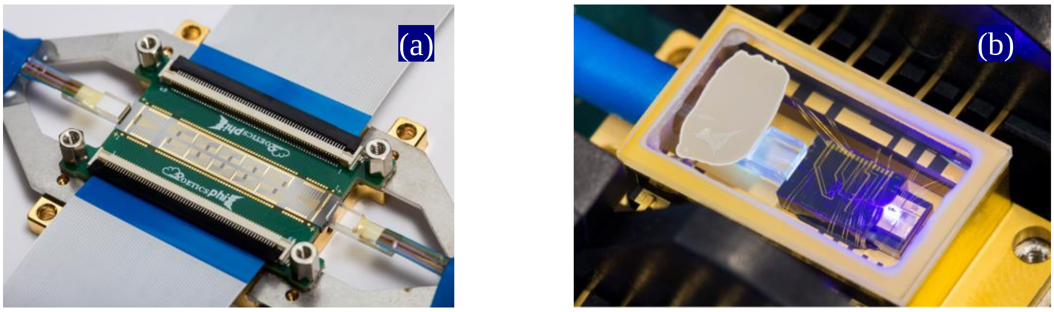

Figure 10. (a) Photonics Bene switch (16×16) integrated with fiber arrays and electronics and packaged using PHIX characterization package [13]. (b) Hybrid integrated and packaged ultraviolet laser in a hermetically sealed nitrogen environment. The white substance on the bottom of the glass lid is a getter material which absorbs any remaining volatile gases and moisture in the package [14].

5. SUMMARY

Integrated photonics has emerged as the technology of the future for advanced optical applications. Governments across the world are investing significant resources to boost R&D, industrial manufacturing, and workforce development [15]. Several Chip Acts have been recently announced across the globe. The US Science and Chips Act allocated US$ 278 billion for the next decade, out of which US$ 2.5 billion are allocated for advanced packaging programs and US$ 52 billion for production, R&D, and workforce development. Similarly, China allocated US$ 143 billion to support semiconductor packaging programs, while Europe allocated US$ 43 billion to secure the supply chain and enhance production capabilities in semiconductor manufacturing [15]. Recently, within Europe, the photonixFAB project, with a total budget of €47.6 million, was launched to enable photonics product innovation and commercialization with a path to high-volume manufacturing [16].

In this paper, we reported some of the industrial processes for scalable photonics packaging in the context of research funded projects. An obvious way to avoid packaging and assembly cost is to minimize the number of parts to be assembled. That is being addressed through the increased use of integration at the platform level in the front end. Unfortunately, all the functions needed in optical applications cannot be integrated yet, so parts made with appropriate technologies are combined using heterogeneous integration, which may raise production costs. Reliability, upgradeability, and technological compatibility of products with the current technology (already in existence for the semiconductor industry) play a very important role in meeting the end-user expectations. Security of the supply chain and standardization is a must, and it would require changes to be made at all levels of the supply chain (e.g., design, fabrication, packaging, testing, materials, equipment) to support migration towards emerging photonic technologies. However, photonics industry, currently producing several million products a year, is still a relatively small business compared to the semiconductor industry. Nevertheless, there are several consumer markets and application areas that are blooming, from communication to healthcare, and from sensing and agrifood to artificial intelligence and quantum technologies. This poses a huge challenge for companies in all areas of the supply chain because some of the promising markets cannot grow due to the immaturity of the supply chain for photonics manufacturing, and quite contrary, at the same time, the investors are relatively reluctant to invest in photonics manufacturing because the markets are still relatively small and the return on investment is not high enough. In the coming years, it is likely that most of the photonics manufacturing supply chain will be suitable for small to medium volumes. Therefore, in order to succeed in rapidly growing and emerging markets, companies would require strategic collaborations and partnerships to align user requirements, technological needs, feasibility, and economic viability.

6. ACKNOWLEDGEMENT

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