Review

Photonic Integrated Circuits for NGPON2 ONU Transceivers (Invited)

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Abstract: The development of photonic integrated circuits (PIC) for access network applications, such as passive optical networks (PON), constitutes a very attractive ecosystem due to PON's potential mass market. The implementation of PIC solutions in this context is expected to facilitate the possibility of increasing the complexity and functionalities of devices at a potentially lower cost. We present a review addressing the prominent access network market requirements and the main restrictions stemming from its specific field of application. Higher focus is given to PON devices for the optical network unit (ONU) and the implications of designing a device ready for market by discussing its various perspectives in terms of technology and cost. The discussed PIC solutions/approaches in this paper are mainly based on indium phosphide (InP) technology, due to its monolithic integration capabilities. A comprehensive set of guidelines considering the current technology limitations, benefits, and processes are presented. Additionally, key current approaches and efforts are analyzed for PON next generations, such as next-generation PON 2 (NGPON2) and high-speed PON (HSP).

Keywords: photonic integrated circuits (PIC); access networks; passive optical network (PON); next-generation passive optical network 2 (NGPON2); high-speed PON (HSP); super-PON

1. Introduction

Telecommunication network infrastructures can be described by three main network segments, i.e., core or backbone, metro/regional, and access networks, as depicted Figure 1. Long-distance communications with high aggregate traffic are attained with core and metro networks, while access networks entail service provider to end-user fiber-optic telecommunications technology. These systems are subject to significant growth in capacity requirements with operators looking for feasible cost-effective solutions. The potentiation of cost-effective solutions can be reached with the improvement of current network technologies, as they become widely used, e.g., coherent systems in future optical access networks [1,2].

DSLAM: digital subscriber line access multiplexer; ATM: asynchronous transfer mode; DSL: digital subscriber line; POTS: plain old telephone service; IDSL: ISDN digital subscriber line; ISDN: integrated services digital network; G. SHDSL: single-pair high-speed digital subscriber line; IAD: integrated access device; OLT: optical line terminal; RN: remote node; ONU: optical network unit.

Figure 1. Diagram of a telecommunications network infrastructure, based in [3].

Photonic integrated circuits (PIC) are considered an evolving technology offering a sustainable (efficient and cost-effective) alternative to data transmission interfaces [4]. The implementation of integrated photonics can thus enable savings and new functionalities, increasing the transmission capacity [5]. In the access network context, PIC can offer compelling performance improvements compared to traditional bulk technology [6], like bi-directional optical sub assembly (BOSA). Upgrades in terms of weight and volume, reduced power consumption, high mechanical and thermal stability, and assembly simplification for high subsystem integration are expected under PIC solutions [6–9].

By combining the need of providing enhanced passive optical network (PON) technologies and taking advantage of photonic integrated solutions benefits, a comprehensive description of PIC design challenges for the optical network unit (ONU) side of next-generation PON is delivered in this study (see optical access network branch in Figure 1). The paper is organized into four additional sections. The historical PIC evolution addressing current developments and expectations are described in Section 2. Section 3 addresses the PON standards and next-generation PON timeline. The implementation of PIC solutions for PON is introduced in Section 4, discussing the technology impact on reach (Section 4.1), the adopted band and wavelength selection criteria (Section 4.2), photonic packaging (Section 4.3), and control complexity, power dissipation and form factor issues (Section 4.4). The study is concluded in Section 5.

2. PIC Evolution

Photonic integrated solutions are a promising technology for the 21st-century optical systems, under the current demand for flexibility/reconfigurability in optical communication networks [5,10]. Differentiated examples of PIC solutions include the implementation of photonic integrated optical transforms for data compression applications in different integrated platforms, e.g., indium phosphide (InP) [11,12], silicon nitride (SiN) [13], and new organic-inorganic hybrid materials [14]; SiN-integrated photonic dispersion compensator enabling extended reach pulse-amplitude modulation with four amplitude levels (PAM-4) transmission as a low-cost interface for data center interconnects (DCI) [15]; development of state-of-the-art sub-hertz fundamental linewidth (<1 Hz) photonic integrated Brillouin laser, narrow enough to move demanding scientific applications to the chip-scale [16–18]; and a new soft-packaging flexible platform approach for photonic integrated processors, based on the spatial light modulation operation principle [19,20]. Moreover, new concepts of PIC-to-PIC interconnects with integrated fan-in/fan-out multicore fiber applications for optical dense networks have been

reported [21]. Photonic integration appears as a dominant technology in high bandwidth optical communication systems [9], offering increased valuable solutions in several innovative fields, such as bio-photonics [22], sensing [23], and space technology [24]. Nevertheless, PIC technology is still more expensive than standard microelectronics, which can restrict its application into some niche markets [5].

PICs are the equivalent of electronic integrated circuits (EIC) in the optical domain. As an alternative to transistors and other electronic components, PICs contain optical elements, such as modulators, detectors, attenuators, multiplexers, optical amplifiers, and lasers embedded in a single chip using a waveguide (WG) architecture [19]. The photonic integration technology is going through a similar evolution path as microelectronic integration, however, with a time delay of about 20 to 30 years [25]. Historically, the invention of the transistor in 1948 [26,27] launched microelectronic integration developments; analogously, the invention of the semiconductor laser in 1969 [28] was the breakthrough of photonic integration technology. Transistor and laser technologies were primarily implemented as discrete components. Microelectronics integration technology started with Kilby in 1959 [29] and matured with the complementary metal-oxide-semiconductor (CMOS) [30] in the 1970s. A first PIC comprising a laser integrated with a modulator was reported in 1987 [31], marking the start of PIC exponential development, typically associated with Moore's law [25]. Moore's law forecasted a double in the number of components per integrated circuit about every two years, with a new technology generation introduced approximately every three years and an expected compound annual growth rate (CAGR) under the dozens [32]. Optical communications evolution has brought the advent of improved PIC, presenting an economic and sustainable alternative to data transmission [4]. PIC technology offers compelling performance advances in terms of small weight and volume, low power consumption, high mechanical and thermal stability, and the ease for assembling a substantial number of complex systems [9].

Consequently, the current PIC-related contexts are evolving at a good rate with an overall worldwide concertation set of efforts aiming to reach a sustainable PIC ecosystem model [33,34]. From the 2000s when the first consortia started to consolidate the concepts around photonics multi-project wafer (MPW), the way for groundbreaking photonic integration developments was paved. State-of-the-art PIC-based consortia, such as JePPiX [35], TriPlEX [36], and ePiX [37], pioneered the effort in Europe and globally, followed by private and public-private arrangements, like AIM photonics [38], Compoundtek silicon photonics, and others [39]. They are working to replicate in optics what happened in the 80s–90s with electronics, e.g., the Marconi GaAs MPW runs and others [40]. The traction gathered by these consortia allowed a fast development of integrated optics simulators and of the process design software (PDS) market, supported by software suites running process design kits (PDK) from almost all available fabs.

The development of a generic common language for the photonic design was an important breakthrough that allowed integrated photonics to be regarded as a promising short-term technology. During these developments, many integrated and hybrid solutions emerged [41–43]; nonetheless, the majority were bulky, expensive, and typically non-replicable, making these approaches unfeasible to be integrated into further complex systems and subsystems. For instance, devices such as optical amplifiers [44], lasers [16,45], and modulators [46], are not supplied by the different integrated platforms due to limitations of semiconductor integration technology. Thus, it restricted the investment of the different labs and research institutes in the development of their concepts/testing to validate their contributions/solutions while waiting for the necessary developments of the technology. In the 90s, few basic building blocks (BB) were made available in a packaged version, e.g., the semiconductor optical amplifier (SOA) based Mach-Zehnder interferometer (MZI) [47], though with an expensive associated cost of several tens of thousands of euros.

Different materials are suitable to produce PICs, nonetheless, only a few have been selected by actors in the ecosystem and, therefore, have gained traction into foundries, software suppliers, design houses, and fabless companies [48]. Current main photonic integration platform technologies

offering access to generic processes and manufacturing through multi-project wafer (MPW) runs are silicon (Si) [49,50], indium phosphide (InP) [51–53], and silicon nitride (SiN) [48,54]. The selection of the integrated photonic platform to realize PICs is driven by the functional requirements of the devices to be developed and the underlying available components (active/passive) for the different platforms [33,55,56]. An overview of the key characteristics between the different available integrated platform technologies is provided in Table 1 [33,56,57]. BB components, such as lasers, optical amplifiers, and detectors, pose design challenges for their implementation in a SiN-based monolithic integrated platform; this constrain can be overcome with hybrid and/or heterogeneous processes, as presented in Table 1. Similarly, hybrid/heterogeneous processes are employed for lasers and optical amplifiers BBs in Si-based technology.

Table 1. Key features from three available photonic integration platforms, i.e., indium phosphide (InP), silicon (Si), and silicon nitride (SiN) monolithic technologies.

Building Block (BB)	InP	Si	SiN
Passive components	✓✓	✓✓	✓✓✓
Lasers	✓✓✓	○ ○ H	○ H
Modulators	✓✓✓	✓✓	✓
Switches	✓✓	✓✓	✓
Optical amplifiers	✓✓✓	○ H	○ H
Detectors	✓✓✓	✓✓	○ H
Footprint	✓✓	✓✓✓	✓
Chip cost	✓	✓✓	✓✓
CMOS compatibility	○ ○	✓✓	✓
Low-cost packaging	○	○ ¹ /✓✓ ²	✓✓

Performance: ✓✓✓ very good; ✓✓ good; ✓ modest; ○ challenging; ○ ○ very challenging.
 H: hybrid/heterogeneous processes to overcome the design challenges associated with the monolithic integrated technology. ¹ End-fire coupling (low reflection); ² vertical coupling (medium reflection).

Several advantages and/or limitations can be highlighted from the referred technologies. High gain, speed, and low loss are three of the main attributes of photonic devices' improved performance. As InP is a direct bandgap material, it presents the best available gain performance, however, with higher associated losses due to electrical doping from current injection which requires the inclusion of optical amplifiers [55]. Regarding systems-on-chip (SOC) complexity, InP platform has a good maturity with chips comprising up to hundreds of components. Silicon-based photonic processes are complementary metal-oxide-semiconductor (CMOS)-compatible, allowing its integration to be run in a CMOS foundry which provides well-controlled and more rapid scalability to the fabrication environment [42]. Nevertheless, as components in silicon substrates usually have higher dimensions than in InP and since silicon photonics lack light sources and amplifiers, InP-based platforms provide a higher potential for volume scaling and integration [25]. Despite the high processing technology maturity of silicon photonics, as an indirect bandgap material native gain is difficult to realize under this platform. The platform features are in-between InP and ultra-low loss SiN technologies, with some active detection elements but no light source solutions, and medial optical losses (amid InP and SiN) [55]. Regarding wavelength properties, Si/SiO₂- and InP-based platforms are mainly used in near-infrared (NIR), while silicon nitride can operate from visible to NIR [48].

Ultra-low loss SiN planar lightwave circuits (PLC) with propagation loss below 0.1 dB/m have been demonstrated by University of California, Santa Barbara (UCSB) and LioniX[®] research [58], orders of magnitude lower than other reported platforms. As a result, high-performance passive components are enabled by this platform, though electrical pump for gain is unavailable due to the insulating nature of SiN/SiO₂ glass WGs [55]. However, the demonstration of optical gain using erbium-doped WG distributed Bragg reflector (DBR) and distributed feedback (DFB) laser arrays integrated within ultra-low loss SiN [59] shows potential for the platform's active component integration. Silicon is

among the most mature photonic integrated platforms, leveraging from existing technologies like silicon electronics and micro electro-mechanical systems (MEMS) industries and enabling foundry services robustness and product commercialization. InP platforms can be seen as one of the options that stem out from the alternatives since it integrates monolithically high-quality lasers, receivers, amplifiers, and passives [33,35,60]. Si and SiN are more prone to be used for passive and filtering components, with the need to recur to hybrid packaging [61] when incorporating lasing and gain.

Some of the available foundries/players under the InP, Si, and SiN integrated technologies are described below:

- i. InP: Fraunhofer Heinrich-Hertz-Institut–Fraunhofer HHI (Berlin, Germany); Smart Photonics (Eindhoven, The Netherlands); Global Communication Semiconductors, LLC (Torrance, CA, USA); and fabless solution providers, e.g., the INTENGENT III/V Photonics Company (Ontario, Canada), VLC Photonics (Valencia, Spain), Bright Photonics (Eindhoven, The Netherlands), and PICadvanced (Aveiro, Portugal);
- ii. Si: Acacia Communications, Inc. (Maynard, MA, USA); Luxtera Inc. (Carlsbad, CA, USA); Intel Corporation (Mountain View, CA, USA); Cisco Systems Inc. (San José, CA, USA); Mellanox Technologies (Sunnyvale, CA, Israel/USA); Finisar Corporation (Sunnyvale, CA, USA); Hamamatsu Photonics K.K. (Shimokanzo, Iwata City, Japan); International Business Machines Corporation (IBM, Armonk, NY, USA); GlobalFoundries Inc. (Santa Clara, CA, USA); NeoPhotonics Corporation (San José, CA, USA); Oclaro Inc. (San José, CA, USA); CompoundTek (Singapore); and the American Institute for Manufacturing Integrated Photonics (AIM Photonics, Albany, NY, USA);
- iii. SiN: Ligentec (Ecublens, Switzerland); Lionix (Enschede, Netherlands); Institute of Microelectronics of Barcelona IBM-CNM, “Silicon Nitride Technology,” (Barcelona, Spain).

Furthermore, several reference institutions with state-of-the-art research in integrated photonics contributed to the technology developments, namely the University of California, Santa Barbara (UCSB) with the available California NanoSystems Institute (CNSI) Nanostructure Cleanroom Facility (NCF); the Kavli Nanoscience Institute (KNI) laboratory at the California Institute of Technology (Caltech), the Fraunhofer Heinrich-Hertz-Institut (HHI); the ePIXfab, INTEC department–Photonics Research Group at Ghent University; the Nanophotonics Technology Center (NTC) at the Universitat Politècnica de València (UPV); etc.

Beyond the generic availability of design/fabrication, it is necessary to further develop and invest in packaging technologies to reach simpler, standardized, and efficient approaches, thus making it accessible for users and/or companies. Currently, the technology-associated limitations are mainly related to the lack of general design rules that ease the encapsulation and allow successful testing of the manufactured photonic chips [6]. This last integration step (packaging) is imperative for labs and companies that are trying to enter/grow in the integrated photonic technology and market. A consortium model aiming to establish PIC packaging processes under European commission Horizon 2020 funding is currently being conducted [62] to facilitate the development of this PIC technologic branch through the development of standard technologies to provide access to affordable, mature, and scalable packaging solutions [63].

3. Passive Optical Networks

From the 80s onwards, PONs [64] have evolved greatly with the simplification of network management, pushing network traffic multiplexing closer to the user with the minimization of stranded capacity [65]. Since then, PON architecture remained one of the most predominant access network options. PONs have been under mass deployment, with more than 900 million broadband subscribers reported in 2017 [66]. This infrastructure has subsidized PONs establishment relevance for a long time [65]. PON basic technology includes: (i) the equipment at the edge of Metro/Access, i.e., the optical line terminal (OLT); (ii) the user end terminal, i.e., the optical networks unit (ONU); and (iii) the optical

distribution network (ODN) that connects the OLT to the ONUs (see optical access network branch in Figure 1).

PON emerging technical requirements are very unique, being the surviving solutions particularly sensitive to price and related costs, both capital expense (CAPEX) and operating expense (OPEX) [67]. Nevertheless, PON poses several advantages, such as the simplification of infrastructure management, as it is based on a fully passive ODN [65]. A completely passive ODN made of buried glass with cabinets to ensure connections and splitting anticipates long-term expectation of 20 years or even more. Its architecture derives from the technical approach to be deployed at the PON ends. Several technologies are competing to be implemented in the access space, with the most common based on a passive splitter tree topology. The OLT (interface from the operator side) feeds one trunk fiber that splits into several arms, each arm is divided into another set of arms, and so on, generating a tree structure, which, depending on the technology, can range from low (8 to 16) to high (64 to 256) terminal counts.

Optical access standardization has evolved rapidly, with IEEE 802.3 and *International Telecommunication Union - Telecommunication Standardization Sector* (ITU-T) Q2 groups playing dominant roles in the process [68]. The most common technologies are Gbit-capable PON (GPON) and Ethernet PON (EPON) [69], typically supporting up to 64 users in the same OLT trunk fiber. At the end users lays an ONU (the user terminal for the fiber). For each end technology, a different ONU is typically required. Currently, it is very common to have combined interfaces that allow multiple technologies to be handled within the same device, the so-called “combo” solutions [70]. Figure 2 illustrates some of the main existing characteristics of the ITU-T related technologies.

Figure 2. Recent *International Telecommunication Union-Telecommunication Standardization Sector* (ITU-T) based optical technologies standards evolution.

Some operators are engaging in the 10 G-capable symmetric PON (XGSPON) and 10 G-capable EPON (10GEPON). Moreover, a number of more aggressive and disrupting operators are investing in deploying NGPON2, merging the traditional concepts of time-multiplexed single-channel per direction PON combined with wavelength division multiplexing (WDM) [71]. This approach allows for further developing network flexibility concepts and the smooth evolution of offered data rates [70], i.e., up to 40 or 80 Gbit/s aggregated rates. An example of a PON with coexisting technologies supported by the current ITU-T standard series [71] is depicted in Figure 3.

PON: passive optical network; NGPON2: next generation PON; GPON: Gbit-capable PON; XGSPON: 10 Gbit-capable symmetric PON; OLT: optical line terminal; λ MUX: wavelength multiplexing.

Figure 3. Diagram describing a PON architecture with three coexisting technologies.

New trends are emerging and triggering discussions in the fora, mostly focused on either an architecture innovation, like the Super-PON, which is on the standardization path in IEEE and ITU-T, or on the efforts to move to high-speed PON (HSP) towards higher data rate technologies, such as 25 Gbit/s and 50 Gbit/s [72].

Current low-cost laser and receiver technologies face some challenges to deliver higher data rates without increasing packaging or electronic costs. Namely, the current methods used for interconnecting devices with drivers and boards are typically based on wire bonding and flex printed circuit board (f-PCB). The latter has limited high-frequency performance and tough mechanical design challenges to meet the right soldering robustness, with an expected high impact on the electrical performance of assemblies and sub-assemblies.

Among PON future technologies, high interest has been given to the research/development of long-reach/high-speed transmission, where optical amplifiers, electrical domain digital signal processing (DSP) to enhance the link budget, and/or transceiver technology are predicted to be key factors [73]. Generically, for N subscribers, a PON requires a single transceiver at the central office, which results in a total of $N + 1$ transceivers overall [67]. For NGPON2, the OLT transceiver should contain four transmitters (Tx) and four receivers (Rx) with an internal wavelength mux/demux optical module. In the ONU, a 10 Gbps transceiver with both tunable Tx and Rx is required [70]. By employing wavelength-selective branching devices in ODN, losses can be diminished, nevertheless at the cost of wavelength transparency waiving. Furthermore, by increasing the number of wavelengths, a high number of transceivers at the OLT is expected, raising power consumption, port density, and cost [73]. Similar to what happened with integrated circuits' contribution to electronics development, PIC technology is one of the most attractive solutions to tackle the referred issues. Thus, integrated photonics can have a key role in the deployment of more flexible PON networks, as they can incorporate different optical components with various functions in a potentially cost-effective way without increasing the assembly process complexity [7,8].

4. PIC for Next-Generation PON

Photonic integration can provide advantageous solutions to PON by limiting the number of optical and electrical interconnections and thus overcoming some of the bulk packaging restrictions, such as bandwidth, power dissipation, and cost [65,74]. Nevertheless, complexities can arise with the use of this technology, namely fiber interfacing difficulties, number of electrical connections, and possible high-density of components per device, which demands a high power dissipation

management [70]. The development of PIC solutions for access networks has already been reported, e.g., with an InP monolithic transceiver PIC for NGPON2 applications [75], the proposed layout has the potential to be implemented as an OLT and with filter redesigning as an ONU. A photonic integrated apparatus for tunable multi-wavelength transmission was patented in 2017 [76], the time and wavelength division multiplexing (TWDM)-PON transmitter system proposed is tailored to support current and next-generation access technologies. Monolithically integrated dual electro-absorption modulated laser (DEML) solutions with application in PON and claims of small footprint and low-cost external-modulator-free Tx can likewise be found in the literature [46]. More recently, a theoretical analysis of polarization-independent receiver (PI-Rx) based in a 3×3 symmetric coupler with applications for access networks was reported [77]. An example of a BOSA transceiver solution implemented in ONU side of a PON with a representation of a 10 Gbit small form-factor pluggable (XFP) evolution from discrete optical component to PIC technology is depicted in Figure 4.

Figure 4. Diagram describing the evolution of photonic integrated circuits (PIC) for PON, specifically the implementation of a bi-directional optical sub assembly (BOSA) transceiver solution in PON ONU side, i.e., XFP with discrete optical component packaging (current PON products) and with PIC approach technology (next-generation products).

Several steps and guidelines for PIC implementation in PON are addressed in this section, along with the technology impact on reach (Section 4.1); the adopted band and wavelength selection criteria (Section 4.2); the integrated photonics packaging (Section 4.3); and the issues related with the control of complexity, power dissipation, and form factor (Section 4.4).

4.1. Technology and Impact on Reach

A major requirement for future PON technologies is the need for coexistence with current deployed PON systems [65,70]. For example, GPON has already been deployed on a scale of millions, thus any new PON technology must be capable of coexisting with this large base [65]. A PON framework of three coexisting technologies, i.e., GPON, XGSPON, and NGPON2, is depicted in Figure 3 from Section 3. Here, the same ODN conveys several technologies allowing the migration and evolution of the network without forcing clients to shift technology. This approach leads to reduced CAPEX and supports pay-as-you-go approaches since it allows keeping using the legacy operating technologies untouched, opening an evolution path for other technologies to follow [7].

The longer the required reach, the more difficult it gets to find the laser technology able to support the demanded distance. As an example, for a 10 Gbit/s with a short-reach like 10 km, almost all standard laser technologies can be used. If addressing the 2.5 Gbit/s market, a medium-reach like 40 km and further are still not a major limiting factor to the laser choice. However, if requiring a common GPON ODN which ranges 20 km including splitters and the handling of dispersion penalty, it poses challenges to most of the 10 Gbit/s solutions. To achieve that target, the laser must be designed to perform a low penalty, typically below 1 dB to 2 dB, at the required distance. To meet those specs,

specially designed direct modulated lasers (DML) are required, or even the migration to external modulated laser (EML) technologies [7,8].

Furthermore, in most recent standards, ODN should support 128 users and a 20 km reach. These requirements have the penalty of a 21-dB attenuation stemming from splitting losses plus 4 dB due to fiber losses and around 3 dB insertion loss (IL) of co-existence elements, leading to an ODN total loss greater than 28 dB. If we target 10 Gbit/s with avalanche photodiode (APD) receivers allowing a -26 dBm to -30 dBm receiver sensitivity, it leads to a minimum laser output power of 4 dBm. A possible alternative to overcome this requirement is to use an amplification stage in the path which removes the passivity of the ODN, however, it reduces the potential usage of EML-based solutions since its typical power does not exceed the 0 dBm.

4.2. Band and Wavelength Selection Criteria

To improve reach, several techniques are available and many stem from the laser (e.g., low dynamic chirp or frequency modulation efficiency), laser driving (pre-chirping or equalization), and wavelength selection (e.g., O-band instead of C and L bands) [2,70]. O-Band has been used for supporting upstream and was adopted by some of the standards like GPON and XGSPON. O-band, besides presenting low or null dispersion, only introduces slightly higher attenuation than C-band. These facts greatly reduce the pressure on the O-band components industry, impacting positively on the cost and yield. The current spectral allocation from O to L-band is depicted in Figure 5.

PON: passive optical network; XGSPON: 10 Gbit-capable symmetric PON; GPON: Gbit-capable PON; NGPON2: next generation PON; PtP: point-to-point; WDM: wavelength division multiplexing; RF: radio-frequency; multi- λ : multi-wavelength.

Figure 5. Spectrum allocation in ITU-T based standards for PON and trends for channel spacing.

If a certain technology is deployed in greenfield, a viable approach is to implement standards that are not back-compatible, i.e., does not support legacy technologies. In this scenario, the use of O-band is an option for future PON. The drawback of this option is that the operator has to guarantee that the PON evolution is on top of the new technology deployed. To cope with the maturity of the technology and promote an easier and simplified entry into the market, initial PON technologies, like GPON, were set in large bandwidths for better yield in laser choice with the upstream in the O-band [7,67]. The wavelength range of 20 nm to 30 nm per traffic direction was reserved for this technology, which allowed it to easily mature while still being competitive. This strategy proved to be solid since it resulted in the current GPON BOSA to sit in the few dollars range (as of today).

Furthermore, PON technology evolution can be achieved by data rate multiplication and more efficient use of the bands to promote further network evolution scenarios. Following this path, XGSPON

standard was conceived with slightly smaller bandwidths for both upstream and downstream, which resulted in a four-times higher bitrate than GPON [70,78].

To further exploit the available bands (see Figure 5), dense wavelength division multiplexing (DWDM) can be a route to explore. The possibility of including tunability allows network active transformation and management. Even considering the associated price to pay, it is an important solution under the requirement of tightly controlled lasers. Furthermore, with this capability, a projected OPEX reduction is expected, since clients can seamlessly migrate to any of the available wavelengths while the network grows smoothly and systematically.

The most evident barrier for the spread of this technology is the laser and receiver requirements, which should be attained under a potential low cost and simultaneously have a high grade of stability [7,8]. Figure 5 presents the bands for the different steps of the network evolution, i.e., from the legacy technologies wide bands to the next generation tighter bandwidths.

A representation of the typical distribution of lasers, stemming from a single wafer run, is depicted in Figure 6A. Each of the lasers collected from the wafer will have its emission wavelength and thus they can be used in a more specific/tighter wavelength range. To accomplish this feature, a tuning process is required, e.g., temperature, current, etc. Each wafer run may present different statistics due to material deposition doping and processing, see Figure 6B. Nonetheless, the wafer uniformity wavelength map is in general scarcely reported by the foundries, some works suggest these claims [79,80]. Tight control of the doping process may reduce this variation and greatly improve the yield and temperature control mechanisms. The finer the required tuning, the more complex the laser selection process. The qualification of a laser to operate in a certain wavelength range results from setting its maximum allowed wavelength at initial temperatures. The broad requirements of the technology in terms of the client locations may require industrial temperature ranges (-40 to 85 °C), which bring extra requisites to the laser wavelength choice or thermal control mechanisms. Directly modulated lasers have good optical output power and are easy to drive and modulate. However, the inherent high wavelength fluctuation when modulated or the inherent chirp can result in propagation limitations. Laser design/control efforts are being made to minimize these effects and currently, there are already some devices in the market able to cope with some of the most stringent standard requirements [81], e.g., the NGPON2. With an external cavity, EMLs result in a much lower chirp, however, having typically a more complex tunability mechanism when compared to the simple current or thermal tuning of the DML [7].

Figure 6. Representation of a generic statistical distribution of lasers over their initial wavelength (λ) in a set of three wafer runs. Different wafers may result in different central λ s. (A): distribution of initial λ of wafer #2; (B): example of an initial λ s distribution for three different wafers.

4.3. Integrated Photonics Packaging

Photonic packaging technology has achieved a higher significance under optical communication systems' recent developments [82] by covering the optical and electronic connections in/out of the PIC. Packaging process developments are of great importance for the next generation of optical components [6]. Being one of the most complex segments of the integrated component viability, it can pose several challenges, such as limitations in terms of volume, cost, RF performance, power dissipation, and its high-volume manufacturing capability [83], which can highly impact the cost of the solution.

Currently, packaging is seen as one of the most significant bottlenecks in the development of commercially relevant PIC devices [60,84]. The packaging design flow is divided into three main areas: the optical design, the electrical design, and the thermal management of the module. A first open-access PIC assembly and packaging pilot line of Europe's leading industrial and research organization teams (i.e., PIXAPP) are dedicating efforts to the development of a photonic packaging platform to gather state-of-the-art technologies and procedures [62]. This highly interdisciplinary team provides single-point access to PIC assembly and packaging for users. The project key objectives include: (i) custom solutions through standard packaging technologies; (ii) training and education as a future workforce; and (iii) link the PIC ecosystem through the development of packaging standards and roadmaps [17]. Considering the typical wavelength gain band of an active device, ranging from 20 nm to 30 nm for the O- to L-bands, and the technology wavelength map presented in Figure 7, several approaches may be required to merge in a single device the upstream/downstream signals. There are several network standards, like XGSPON, which require upstream/downstream wavelengths spaced by more than 200 nm. A 200 nm spacing brings higher challenges and may require hybrid integration, which poses additional packaging challenges [7].

PON: passive optical network; XGSPON: 10 Gbit-capable symmetric PON; GPON: Gbit-capable PON; NGPON2: next generation PON; PtP: point-to-point; WDM: wavelength division multiplexing; RF: radio-frequency; PIN: positive-intrinsic-negative photodiode; APD: avalanche photodiode; US: upstream; DS: downstream; OTDR: optical time domain reflectometry.

Figure 7. Diagram describing transmitter and receiver technologies with potential use in access networks. Typical gain and lasing media profiles are presented, with 20 nm to 60 nm bandwidths for common current materials, PINs with different doping materials, and APDs. (A): transmitter/(pre-) amplification side; (B): receiver side.

In the same technological space, NGPON2 requires only 60 nm between the upstream and downstream, thus a fully monolithic approach may be achievable by changing slightly the doping or applying regrowth. Figure 7 provides a representation of the gain curve for a generic material doping, the abstraction of a laser for the transmitter side, and three types of available receiver techniques/devices. On the transmitter side tunability limitation of a laser is depicted and corroborated by the limited gain media in which the laser light is generated, see Figure 7A. This constraint results in 20 nm to 30 nm tunability range, considering laser operation with significant output power. Simple tuning based on thermal effects usually results in an available tuning range of 3 nm to 4 nm. A combination of a tunable device with an external cavity supported by a convenient control mechanism results in a wider tuning range. On the receiver side several techniques are described, such as a positive-intrinsic-negative photodiode (PIN), APD, and coherent [7,8], see Figure 7B. The PIN is one of the cheapest and simplest detecting techniques presenting a wide light wavelength detection range. Its profile can be changed by the type of materials and doping used. PINs can be easily integrated into e.g., InP PIC, which is already available for bandwidths exceeding >35 GHz and operational wavelength ranges covering the common fiber telecommunication bands [33,60,85]. APDs are tougher to integrate, however, from the system point of view, they result in improved sensitivity due to their intrinsic avalanche gain. The referred receiving technologies are wide wavelength band, however, with a coherent detection scheme tunable reception can be achieved. Depending on the arrangement, a different number of associated PINs (from dual-polarization differential with 8 PINs to quasi-coherent single photodetector) simultaneous gain and filtering (stemming from the local oscillator beating with the signal) can be implemented [7,77,86].

To achieve the optical interface between the PIC and the fiber, there are several challenges to be surpassed, such as the mode adaptation between the WG in the PIC and the cylinder-shaped fiber core [87]. Spot size convert (SSC) modules in the PIC, lensed fibers connected through V-grooves, holders, and other techniques are used to achieve consistent solutions. The PIC packaging interfacing of the electrical connections between the PIC and the PCB is usually carried out by wire-bonding [34]. As bandwidth grows, the trend is to replace the bonding wires by flip-chip solutions to reach higher thermal and electrical performance. Furthermore, packaging should be a gateway to solve power dissipation, which is expected to increase significantly with density [7]. Packaging solutions based on holders with high thermal conductivity and inherent thermal monitoring is an attractive solution to overcome this constraint.

4.4. Control Complexity, Power Dissipation and Form Factor

The different PON standards and technologies have their own requirements in terms of complexity control, especially for tunable devices. When wavelength control is not essential, simpler actuation systems with lower power are required [88]. Nonetheless, once the wavelength spectrum becomes more crowded, the options have to be restricted and the requirements for more complex control increase [7]. A summary of the technology and expected power for its optoelectronic interfaces versus the complexity and requirements for a certain interface is depicted in Figure 8. A general sweep, from low data rate with large wavelength range and short-reach to higher data rate with tighter wavelength range and longer reaches, are also presented in the Figure 8. Additionally, the technologies with an approximate relative power requirement classification (from low to high power) are also identified. The x-axis represents the optical requirements, ranging from low data rate and short-reach to long-reach DWDM and high data rate. The red arrows describe the complexity steps from the system requirements.

SR: short-reach; LR: long-reach; DSP: digital signal processing; WDM: wavelength division multiplexing; UDWDM: ultra-dense WDM; DWDM: dense WDM; LUT: look-up table; ADC: analog-to-digital converter; DAC: digital-to-analog converter; CFP: centum form-factor pluggable; XFP: 10 Gbit small form-factor pluggable; SFP: small form-factor pluggable.

Figure 8. Diagram of requirements in terms of control, complexity, and power for different technologies.

Potential form factor solutions able to cope with the required power dissipation are also presented in the far right of Figure 8. Technology evolution poses increasing challenges in the control complexity and required power. As the demanded power grows, a change in the form factor is needed. Form factors have two major characteristics: minimum volume and maximum dissipated power [89].

An approximate chart of the average pricing for GPON, XGSPON, and NGPON2 evolution versus time is presented in Figure 9. GPON faced a strong price drop with its increased manufacturability, pushed by the worldwide broad adoption of the technology by the operators. XGSPON is following the same steps, which for the user can be the motto to have 10 Gbit solutions sooner. Technically, XGSPON generically adopted the physical layer characteristics of IEEE 802.3av 10GEPON systems, e.g., differing in the burst mode timing requirements [70,78]. Moreover, to jump-start the market, initial implementations of XGSPON systems relaxed the timing requirements to fully adopt 10GEPON standards [70]. With this rapid price erosion model, the profit margins in the supply chain depreciate very fast. As NGPON2 is based on the limited tunability of DWDM lasers and receivers, it poses some challenges for its adoption by manufacturers, vendors, and operators. This fact has delayed its deployment process. NGPON2 technology differs from the traditional model since it goes out of the O-band, making the laser control and manufacturability more stringent. Thus, it results in a potentially slower cost reduction and more sustainability from the supply chain point of view [7].

PON: passive optical network; GPON: Gbit-capable PON; XGSPON: 10 Gbit-capable symmetric PON; NGPON2: next generation PON.

Figure 9. Representation of average price evolution of PON technology for GPON, XGSPON, and NGPON2 bulk type BOSA (not PIC based). Pricing was empirically collected along the years from several providers and averaged in the graph.

The indicative pricing evolution of the traditional bulk type BOSA for the three technologies is depicted in Figure 9. Early, broad and late adoption notes refer to perception and predictions estimated by the authors given the present standing of the technology. Pricing is indicative and may not represent all realities/contexts, and is based on, per vendor and per order, 100 pieces at the early adoption stage, 100k pieces at broad adoption, and 1M pieces at late adoption stages, see Figure 9.

A reduction in physical volume, number of sub-assemblies, and calibration steps are expected with the migration to PICs. These steps may greatly reduce the price of the subassemblies based on PICs when compared with traditional bulk BOSA [7,8]. As identified above, by having upstream/downstream on approximately the same wavelength band, NGPON2 can be a great applicant for monolithic PIC. In such a case, ONU and OLT can coexist in the same PIC platform without further processing. XGSPON, besides being already stressed in price, may require O-band and L-band integration, which can entail extra processing and packaging steps, thus increasing the limitations of PIC viability in this wavelength range. DWDM is also included in the wavelength plan of NGPON2 and is already an ITU-T standard being used for implementing several telecommunication systems, which also poses a good opportunity for the use of the PIC technology.

5. Conclusions

PICs are a promising technology with great potential in several fields including telecom, sensing, and bio-photonics. In this work, we have reviewed the PON technology standards and evaluated the challenges and benefits of meeting its requirements with the prospective usage of PIC. Depending on the requirements, the type of materials, and components, a tailored approach has to be carefully specified. The different materials used in the available solutions for implementing PIC result in different behaviors, steps, processes, and capabilities. The main constraint of PIC is still the limited gain band of the active devices which are in its core. This may imply advanced processing and/or packaging

techniques to be able to cope with the existing standards, e.g., regrowth and hybrid packaging. After carefully choosing the standard to be followed and the packaging approach, its control complexity also has to be cautiously considered to guarantee that the solution is feasible and adapted. Specifically, for PON the most stringent requirements are the cost and robustness of the proposed solution. We have discussed several of the challenges to be considered when equating the introduction of PIC in the next-generation PONs, like productization, wideband wavelength range (O, C, and L-bands), laser control, and tunability mechanisms.

PON standards have different flavors that result in quite different requirements, especially regarding the wavelength ranges to be covered by the two traffic directions, i.e., the upstream and downstream. For instance, GPON and XGSPON have specifications of >200 nm spacing between upstream and downstream, while NGPON2 requires around 60 nm for the same parameter. Due to technological inherent limitations of some technologies, hybrid integration may be required, e.g., XGSPON and GPON. Smaller bands will ease this process and therefore potentiate monolithic PIC implementation, simplifying packaging and deployment, e.g., NGPON2.

PICs have typically two major interfaces, electrical and optical, each with different requirements, techniques, and available materials to be used. Packaging and technical considerations such as size, power, RF compliance, and sealing are relevant. In a nutshell, the manufacturability is anticipated to be one of the most critical steps for the technology to be successful, especially in PON.

In our vision, the use of PICs in PON and other subsystems is very close to being an effective reality with prospective advantages.

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