White Paper on Integrated Photonics

authored by a Joint Focus Group of the

European Association on Smart Systems Integration (EPoSS)

and

Photonics21

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0. Executive Summary

Electronics and photonics are important topics for the European R&D&I landscape. Growing and emerging applications in markets like Connectivity, High Performance Computing, Agrifood and Natural Resources, Safety and Security, Industrial Sensing and Automation, Health and Wellbeing, Mobility and Space as well as Consumer Electronics profit from integrated photonic solutions that combine electronics, core photonics, passive optics and other technologies into miniaturized systems using different integration technologies.

Optical communications have been the backbone of the world's digitalization for several decades. The complex nature of transceiver PICs (Photonic Integrated Circuits) was, in the past, the main driver for technological advances in the whole Integrated Photonics value chain. However, emerging markets for Integrated Photonics may have completely different requirements and are not optimally served by integrated components, modules and systems originally coming from the optical communications area. Those applications include:

- High Performance Computing, with both in-system optical interconnects and optical solutions for new computing paradigms like neuromorphic and quantum computing.
- Agrifood and Natural Resources, with various types of sensors based on photonic technologies for detecting and measuring the level of potentially harmful molecules and substances.
- Safety and Security / Monitoring of Critical Infrastructure, monitoring the condition of civil infrastructure objects – bridges, viaducts, tunnels, railways and road constructions as well as critical infrastructure objects like pipelines, power plants and wind turbines.
- Industrial Sensing and Automation, with various kinds of miniaturized photonic sensors and imaging systems to measure the composition of numerous gases, liquids and solid materials, thicknesses of thin films, shapes and roughness of surfaces, as well as distances, speeds, accelerations, temperatures, pressures and many more quantities.
- Health and Wellbeing, with medical optical imaging (for instance, highly integrated and thus comparatively thin endoscopes), photonic biosensors and continuous monitoring of patients' health status, in order to detect diseases at a very early stage or to continuously monitor progression of illnesses outside a medical environment.
- Mobility and Space, with future mobility concepts that require advanced environmental sensing, in particular components for LiDAR systems. These are not only the basis for autonomous driving but are also an outstanding system for crash prevention.
- Consumer electronics, especially AR/VR/MR systems.

Europe has the potential to become a major player in the worldwide market of Integrated Photonics. The expert group has identified the following research, innovation and industrialization priorities for further strengthening Europe's position:

1. **Establish R&D ecosystems for joint development of electronic components and systems and photonics,** since photonics, electronics and related system design need to be interconnected in order to build industrially attractive solutions at an acceptable price point.
2. **Cost-efficient possibilities for prototyping including seamless access to services for SMEs.** There are EU based pure play PIC foundries with volume capability but the task of bringing the ecosystem to the required manufacturing readiness level across a range of technologies is far from complete.
3. **Ensure linking up of entire value chain**: This includes the all aspects like materials, design systems, front-end wafer fabrication, back-end test, assembly and packaging.
4. **Education activities** to have enough skilled persons for the photonics industry

Program and Funding recommendations are proposed to address those issues at a European level by joint R&D&I projects.

1. Need of the industry and society

> "We have entered a global race in which the mastery of technologies is central. It is largely thanks to disruptive technologies that Europe will be able to embark fully on its twin green and digital transition, while guaranteeing its resilience and autonomy."[1]
>
> *~Thierry Breton~*
> *European commissioner for Internal market*

Recent geopolitical tensions between the major powers, the unprecedented economic and social impact of the COVID-19 pandemic, as well as war between Russia and Ukraine have exposed critical vulnerabilities in Europe, with an immediate and pressing need to build more resilience and strategic autonomy in supply chains that are critical for stable economy and security in Europe.

With regard to Integrated Photonics, although Europe's position is under severe pressure from global competition from China and the US in particular, it still represents a strong economic opportunity, as well as a compelling case for bringing strategic production back to Europe. Integrated Photonics, being one of the key enabling technologies[2] of our time, is essential for ensuring competitiveness of European solution providers and downstream industries, by allowing them to innovate with new products and services. However, there is a good scientific, technical and economical foundation in Europe to build on that helps to bridge the gap to Europe's leadership and autonomy.

Among the many challenges faced by EU for the coming decade, technological, economic and security domains have a strong geopolitical component. Integrated Photonics has a role to play in each one of these. It is of strategic importance that Europe gains and subsequently retains its own production capability for Photonic Integrated Circuits (PICs hereafter), considering the strong technological footholds that are already available in many countries within its borders. Finally yet importantly, the need and the pressure to convert European R&D leadership to industrial leadership will not happen automatically but must be earned through targeted public and private investments, as well as coordinated policy action.

a. Security of supply

The use of semiconductors is critical for multiple economic sectors and societal functions in the Union and therefore, a resilient supply is essential for the functioning of the internal market. It is noteworthy that the EU Chips Act recognizes the need for accelerating investment in the field of semiconductor manufacturing technologies and chip design, **including PICs**. In terms of investments, it will undoubtedly be necessary to move up a gear due to the recent announcements by the US Commerce Department's Bureau of Industry and Security (BIS) on 7th October 2022 on new export controls affecting virtually all kinds of advanced chips and chip manufacturing equipment into China. In addition, import of electronic goods from China may be impossible in the future due to concerns regarding safety and security, especially for critical infrastructures.

It is crucial for the Chips Act that regulation and subsequent fund allocation results in creating a workable framework to ensure security of supply by attracting investments and **enhanced production capacities in semiconductor manufacturing including PICs**, as well as advanced packaging, test, and

[1] Excerpt from "The Geopolitics of Technology" by Thierry Breton, published on July 27, 2021

[2] Integrated Photonics is enabling for many other technologies and applications, like quantum communication, AI, sensors, and communication.

assembly via first-of-a-kind Integrated Production Facilities and Open EU Foundries (Pillar 2, "Security of supply").

b. Strategic Sovereignty of Europe

In 2017, French President Emmanuel Macron described sovereignty as *"our ability to exist in today's world to defend our values and interests"*[3]. The main EU policy driver regarding PICs relates to the geopolitical position that Europe envisions. The EU strives for technological sovereignty over its KETs and, in line with this, invests in R&D and in the industrial manufacturing function through, among other things, a targeted IPCEI[4] scheme and the European Chips Act.

Europe cannot be fully dependent on foreign providers, also bearing in mind that strategic sovereignty is not about market domination or autarky within Europe, but about creating critical mutual dependencies (or attaining critical indispensability in the global chains). PIC manufacturing can be a valuable asset for Europe, since many European countries possess a deep and valuable knowledge and innovation capacity in that domain.

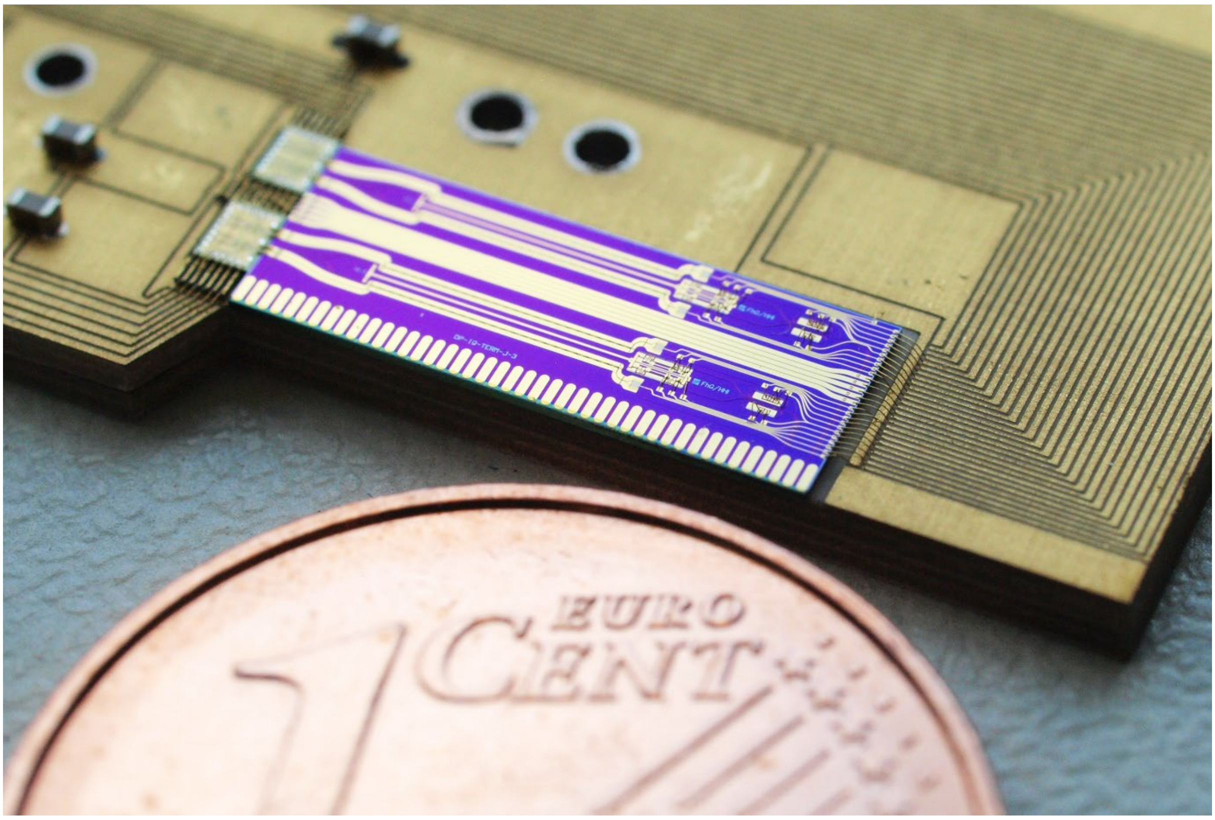

Figure 1: Dual Polarisation IQ Modulator for 512 Gbit/s transmission with 16QAM, and coin for scale. © Fraunhofer HHI

Technological sovereignty not only plays a role in Europe's economic competitiveness but also influences the extent to which the European "way of life" can continue to be lived, including democratic liberties and values, as well as strategic interests in security domain.

The EU must achieve an indispensable position in the global semiconductor value chain. To that end, the European Chips Act should strive towards expanding the European ecosystem for semiconductor

[3] Excerpt from *Speech by Commissioner Thierry Breton: Sovereignty, self-assurance and solidarity: Europe in today's geopolitics.* retrieved at https://ec.europa.eu/commission/presscorner/detail/en/SPEECH_22_5350

[4] IPCEI: Important Project of Common European Interest

technology, in particular by **focusing on leading edge and next generation technology by preparing the semiconductor industry for the ground-breaking potential of photonics, AI and Quantum technologies.**

This focus on leadership and manufacturing capability for next generation technology is the ultimate route to securing Europe's relevance in the global semiconductor ecosystem by increasing the capabilities and performance of European products and technologies that others rely on.

c. Green Deal:

PICs, as an enabling technology, are critical to the attainment of several European Commission (EC) priorities, two overarching priorities of which are the Digital Transformation, where sensors, cameras, lasers and communications technologies are vital, and the Green Deal, where the use of photonics will have a major impact. Optical links on the package and board level can not only be more energy efficient in the future where very high frequencies and data rates are required, but also save space and material compared to conventional copper connections.

Photonics is a vital green technology. In its study "Green Photonics"[5], SPECTARIS identifies a potential of three billion tonnes CO_2 reduction in 2030 through Photonics. From reduced energy consumption in data centers, reduced fertilizer use, reduced use of resources in manufacturing, and by enabling new production, testing, gas detection processes and technologies, PICs are catalysts towards a global sustainability.

d. Digital Society (including Security)

Concepts of sovereignty or strategic autonomy in KET for Europe become meaningless unless Europe has tangible capability to produce and to choose the technologies that are at the heart of many sectors of the economy and society. Mastery of tomorrow's technologies, including PICs, is fundamental for breakthrough of digital and green technologies that are becoming an essential driver of our resilience.

There is a critical role for PICs in ensuring that the European semiconductor ecosystem contributes to solutions for societal challenges, for example by enabling more sustainable semiconductor solutions with less energy consumption while contributing to climate goals. PICs and Integrated Photonics in general are also key for sovereignty in communication networks. While on system level there are European companies like Ericsson and Nokia, they are currently nearly 100% dependent on transceiver modules manufactured in China or the US. PICs are the key element of those transceivers. Further, PICs are key for quantum communication, including the possible implementation of a fundamentally secure internet. The latter is essential for trust in institutions (which is one of the UN Sustainable Development Goals). Digital society will collapse if it is not secure, and if it is not available at any time (uptime) and place. In addition, access by everyone is required, which drives the demand for low-cost solutions.

[5] https://www.spectaris.de/fileadmin/Content/Verband/Themenspecial/Study_GreenPhotonics_2020_eng.pdf

2. General trends in the research, innovation and industrialization area of Integrated Photonics

2.1. Key future markets and their requirements and functionalities:

2.1.1. **Connectivity**

Optical communications have been the backbone of the world digitalization for several decades. Thanks to the unparalleled capacity, energy efficiency and reach of optical fiber transmission, optical communication technology has been the cornerstone of all network segments for a long time now. First deployments in long distance transmission including submarine have been followed by use in metro-, core-, access- and datacenter-networks. In addition, mobile communication systems such as 5G and future 6G networks - despite being usually referred to as "wire-less"- are predominantly fibre-based. Furthermore, other wireless approaches are enabled by photonics, like microwave photonics and free-space-optical transmission. Cloud based applications, new fields such as high-performance computing and other ever more demanding applications are driving the exponentially growing demand for data transmission to higher data rates, while at the same time economic and ecological factors call for networks featuring even lower cost, smaller footprint and lower power consumption. The tele- and data-communication industry is thus constantly challenged to improve and adapt and will be even more so in the future.

Integrated Photonics has been a key enabler to respond to all these needs and will continue to do so with the challenges coming in the future. However, to further pursue the targets set out by customers, governments and society in general, more radical changes in the photonic integration landscape are required:

- Further scaling of data-rate beyond the upcoming 130 GBd (400/800 Gbit/s) generation, while at the same time minimizing power consumption, will require more efficient optical materials for functions such as the generation, modulation, detection and processing of light. Integration of new materials with established platforms such as silicon photonics and close integration with electronics, for instance through heterogeneous integration, will enable the manufacturing of next-generation network components at low cost.
- New packaging approaches and closer integration of functional blocks will be needed to accommodate higher bandwidths, smaller footprint, and denser operation of transceiver modules and application in harsh environments such as outdoors, space or at high temperatures, as seen in the industry's push towards co-packaged optics. As the main cost driver in optical modules, improved, simplified and automated assembly and packaging approaches of PICs, potentially modelled after the electronics industry's extensive experience, constitutes a significant step towards next-generation optical components. In particular, optical alignment of components is a time-consuming and highly customized process adding significant costs to the PIC value chain.
- Similarly, testing of PICs and electro-optical assemblies involves time-consuming and challenging technological approaches, as high analog bandwidths in conjunction with large number of RF, DC and precisely aligned optical connections are required. In particular, wafer-scale testing lacks standardized approaches that allow precise characterization of complex optical transceivers, thus again adding costs to end products. There is great potential for automated approaches leveraging European expertise in high value manufacturing and robotics.
- To fully utilize the optical bandwidth provided by optical fibers, additional technological advances will be needed. Expanding transmission windows beyond the commonly used transmission bands such as C-band for medium to long distance transmission and O-band for shorter distances will require PICs capable of operating at ultra-wide optical

bandwidths without sacrificing performance. Once again, new materials as extension to existing platforms will be needed to utilize new or even multiple fiber bands.

- Increased spectral efficiency of fiber links has in the past been achieved largely through improved modulation formats, often coupled with complex digital signal processing. However, as we are approaching the fundamental limits imposed by the bandwidth and noise (Shannon limit), as well as nonlinearity of optical fibers, we are faced with a diminishing return with the R&D efforts to push the performance of single links, even with a large number of wavelength channels. Spatial parallelization by using several fibers or multicore fibers, and therefore several transceivers, is thus imposing itself as an economically viable way to keep improving optical link capacity. New fiber technologies, e.g. with higher linearity, lower propagation delay and covering new wavelength regions, will also be exploited to push the boundaries of communication systems performance.
- Advances in optical systems will create new challenges for network automation and autonomy, which in turn will require cognitive networks powered by real-time network measurements, telemetry, artificial intelligence (AI) and machine learning (ML). PICs used in optical transponders can generate a huge amount of data to provide critical monitoring and sensing capabilities, thereby enabling improved network efficiency enablement and automation.

For a long time, optical communication has been the largest application of Integrated Photonics and is projected to remain so in the near future. The complex nature of transceiver PICs was in the past the main driver for technological advances in the whole PIC value chain, thus enabling the optical communication networks that we rely on today and also other applications, such as sensing, that make use of this technology. To keep up with future demand in bandwidth that our society heavily relies on today and will do so even more so in the future, further developments in the field of Integrated Photonics are needed to enable communication devices with higher efficiency and lower power consumption.

2.1.2. **High Performance Computing (HPC)**

HPC is essential in our daily lives. Good weather forecasts mitigate human risks and are vital for aviation, shipping, ground transportation, agriculture and many other fields; molecular models help in predicting the properties of future medicaments, while the ever-increasing power of AI supports us in many aspects of our lives. Furthermore, these developments play a critical role in addressing “digital autonomy”, “data- and compute security”, “pandemics” and “environmental disasters”[6]. In addressing the next global challenges of ‘sustainability’ and ‘Digital Continuum’, technology-oriented collaborations among the active stakeholders are pertinent, such reflected in the established “TransContinuum Initiative”)[7]. PIC technologies are already playing an important role on the path to Exascale network interconnect[8, 9].

To improve the sustainability of the infrastructures, especially in HPC, modular novel hardware design approaches are required, allowing for upgrades without the need to replace components that may remain. The end of Moore’s Law forces HPC designers to look for performance and energy efficiency by using specialized hardware, such as accelerators for gaining performance without changing the central parts of the system. Given their short latency advantage, PIC based connections are at the core of this approach to build more modular machines and enable the disaggregation of different functional

[6] ETP4HPC Strategic Research Agenda (October 2022)
[7]https://www.etp4hpc.eu/transcontinuum-initiative.html
[8] European Pilot for Exascale (EUPEX)
[9] HPCQS – High-Performance Computer - Quantum Simulator hybrid

blocks from the compute part. That would allow adaptation at the edge of the continuum to the new application needs by reconfiguration of the systems.

An increase of the density of computing power (measured in Flop/s per square meter floor space), require tightly integrating and cooling the most powerful computing elements, dictating also to reduce the length of cabling in the network. Today photonic solutions are already in use and continuously evolving in speed (now in the 400Gbps range) as the number of ports per switch (now in the 64-port range) also increases. It is estimated that today's data centers use between 10% and 40% of total power consumption just to move data. This percentage is expected to grow in the next few years due to the data-volume to be processed with the advent of exascale systems. When aiming at further increase of peak performance, HPC systems focus on PIC-based die-to-die interconnection technologies that can efficiently move data among computing resources, thanks to their ability to directly route light instead of electronic signals, which dramatically reduces latency and power consumption, improving the overall bandwidth at all levels of communication.

As die geometries shrink, data sets grow and data movement becomes a significant contributor to the system energy budget, the reduction of the distance between compute nodes, networking will increase efficiency of nodes. One trend many suppliers are embracing is chiplet architectures, with silicon ICs that are co-packaged and interconnected (2.5D, 3D) through an interposer. Interposers allow high bandwidth connections between chiplets, with low latency. Photonic interposers are under development in multiple research organisations and could further improve the bandwidth between chips. Integrating different dies (chiplets) in the same package allows cost reduction and facilitate diversity. Chiplets made from different technologies can be combined to optimise cost vs functionality. Lowering overall interconnect power consumption also drives the industry towards packaging the photonics close to the electronic interconnect, which is called "Optical co-packaging". This new way to build systems can be done with PICs.

HPC challenges of the coming years, due to the major increases in the amount of data to be processed are:

- To limit the length of data transfers such as by unifying memory access of processors and accelerators and integrating them physically near to each other, by using chiplets on photonic interposers, with associated programming models that can transparently take benefit of this heterogeneity of computing elements.
- Photonic Integrated Circuits entered datacenter links in the 2km reach several years ago but have yet to break through as a mainstream technology for intra-rack and intra-board distances. The value of a photonic interconnect is multi-fold, including low latency for a given distance (vs electrical connections), reduced loss and energy, and increased speed. A key challenge is the cost of implementing PIC solutions (including acquisition/ manufacturing costs, power per bit, reliability) to offer disaggregated systems.
- The convergence of HPC, datacentre and "cloudification" will open up numerous concerns, including data security. This will have consequences from the point of view of components specifications, such as increasing the communication/computing ratio, moving processing near data, more modularity and composability, diversification of accelerator techniques, and dealing with more diverse types of data. Here, flexibility in the system architecture can be achieved by multiple compositions of the same key elements (chiplets) on a common infrastructure of photonic interposer.

In addition, on a longer timescale, there are disruptive new HPC functionalities from PICs on the horizon. Implementation of unconventional, novel HPC architectures, such as neuromorphic computing and analog computing architectures will open up new computing paradigms. PIC-based neuromorphic accelerators, with their non-linear functions and bandwidth capabilities, will play a significant role for neural networks, with improved energy-efficiency compared to conventional ones. Analog computing making use of PICs are currently implemented only on small networks; their operational speed in the GHz range makes them unique for applications requiring extremely low latencies. Beyond this, Integrated Photonics enable new computing paradigms like quantum computing by optical/photonic co-processors or photonic qubit realization for instance by ion traps on a PIC. More information on benefits of Integrated Photonics for quantum technologies can be found in the joint Photonics21-Quantum Flagship paper on quantum PICs[10].

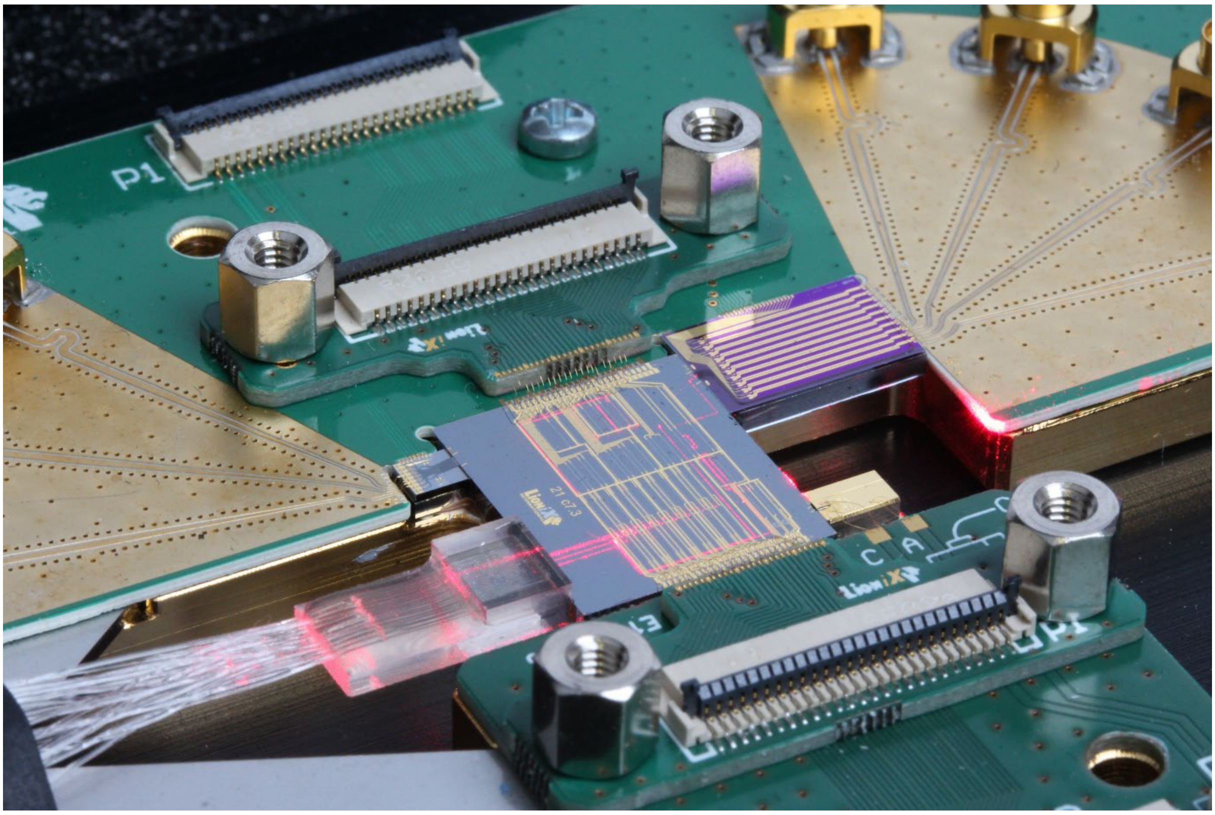

Figure 2: RF-Beamformer assembly featuring a large PIC with SiN waveguides, and butt-coupled integration of an InP modulator array (top right), InP gain chip (bottom right) and InP array of photodetectors (top-left). © LioniX International BV

2.1.3. **Agrifood and Natural Resources**

The contemporary world faces the challenges of climate change, pollution of the atmosphere and water, and soil degeneration. These materialize as serious threats, direct and indirect, to the European (and global) economy and to the security, health and social well-being of EU citizens. To mitigate these risks, a significant reduction of the emission of greenhouse gases and air/water contaminants, pesticides, and toxins of various kinds is a must. This ambitious goal requires not only developing an entirely new approach to the use of the natural resources of the planet but also changing our way of life. Implementing these imperatives will demand the development of new solutions in multiple domains, including energy production, manufacturing and mass production of goods, cultivation of

[10] https://www.photonics21.org/2022/position-paper-on-quantum-pics-available-for-download-now%21

plants and animal farming. This, in turn, will require mass-scale monitoring of the level of greenhouse gases directly enumerated in the Kyoto protocol (carbon dioxide, methane, nitrous oxide, chlorofluorocarbons, perfluorocarbons, and sulfur hexafluoride), other toxic and/or dangerous gases (ammonia, sulfur dioxide), liquids (benzene, toluene) and potentially harmful polymer substances in the form of micro- and nano-plastics. In general, various types of sensors based on photonic technologies have proved their applicability for detecting and measuring the level of dangerous molecules/substances with impressively high sensitivity and accuracy. The next vital step towards ubiquitous application is to minimize the size, weight, energy consumption and cost of the sensor. It is apparent that solutions based on **Integrated Photonics** can help to meet these challenges and thus counteract the environmental threats by providing efficient tools for mass-scale implementation of monitoring devices in industry, transportation systems, public institutions, and private houses. This requires continuous development and extensive use of currently existing photonic integration technologies, offered nowadays by European players on a commercial basis, as well as research on the platforms that have been up to date investigated only on the laboratory scale. Well-developed silicon-on-insulator, silicon nitride, and indium phosphide technologies offer a limited spectral range 400 nm – 3.7 µm, which needs to be complemented by entirely new solutions and platforms suitable for operation in the mid-infrared part of the spectrum (3-15 µm), where the strongest fingerprints of the majority of the dangerous substances are located. This will allow the development of new integrated sensors and/or sensing systems operating in the MIR fingerprint region.

The growing world population and its increasing impact on the environment require a higher efficiency and lower environmental impact in the agrifood sector. Precision agriculture aims to measure relevant growth parameters in real-time and uses this to control and optimize the production process. Important trends in precision agriculture are development of more autonomous processes, measurement of plant composition (water content, nutrients, chlorophyll, etc.) instead of appearance, measurement close to the plant, and further miniaturization of sensing devices. In food processing, process control is currently mainly based on physical parameters including time, temp, pressure and pH. Real-time process control based on compositional data which can be provided by photonic sensing is a huge opportunity. Photonics already plays a limited role in the agrifood sector, for instance in the use of LIDAR and hyperspectral imaging to monitor soil and water quality, fruit ripeness and defects, and near-Infrared spectroscopy for product composition, e.g. in milk. The high cost of current photonics solutions is however a significant hurdle and has tended to limit their use to niches of high value crops and processing.

To make further steps towards real-time actionable information in the agrifood domain, there is a need for small, robust sensors that are suitable for long-term use and have low operational costs. This is where Integrated Photonics-based sensor systems can play an important role in optimization of the agrifood sector. Integrated Photonics has the potential of high-volume, low-cost production of accurate sensors that have low power requirements and excellent robustness.

2.1.4. **Safety and Security / Monitoring of Critical Infrastructure**

The last decades observed the growing demand for fast and contactless detection of potential threats to people and critical infrastructure. Security and safety aspects have become specifically important in the turbulent global situation of the last few years. The Russian aggression on Ukraine, attacks on civil infrastructure, and acts of industrial sabotage add also an entirely new perspective to the challenges of critical infrastructure monitoring.

Integrated Photonics has proven potential in the field of monitoring the condition of civil infrastructure objects, providing miniaturized and energy-efficient interrogators of fiber-optic sensors of various kinds. Undoubtedly, one of the most prominent examples are interrogators of fiber Bragg gratings

(FBGs), which allow accurate measurement of strain and/or temperature of the monitored object at multiple locations. A significant number of those systems are dedicated to applications focused on structural health monitoring of different types of engineering objects – bridges, viaducts, tunnels, railways and road constructions, critical infrastructure objects (pipelines, power plants, wind turbines), as well as in automotive vehicles, trains, planes, etc. In principle, PICs could be used as interrogators to any of the sensing methods used, e.g. for distributed sensing (time or frequency domain reflectometry, Brillouin scattering-based methods). Further development of such PIC-based systems is required in order to increase the level of safety/security of infrastructure and vehicles, both with respect to natural threats such as severe weather, as well as to intentional hostile actions, e.g. terrorist acts. Furthermore, broadly implemented fiber-based sensor systems, interrogated by cost-optimized application-specific photonics integrated circuits (ASPICs), can be also used for surveillance and monitoring of trespassers, especially when (nuclear) power plants, pipelines or military objects are of concern.

Highly intensified traffic and significant concentration of people at airports, railway stations, in underground and public transport cause significant risk of sabotage based on explosive, chemical, or biological means. With this respect, Integrated Photonics may also provide tools for the efficient detection of explosive materials, toxic and flammable gases, drugs, and other prohibited chemicals, chemical & microbiological contaminations, identification of silent virus carriers, etc. This would require, however, leaving the niche of near-infrared and moving Integrated Photonics toward the mid-IR spectral range – the region of fingerprints, where the majority of such substances have their strongest unique spectral signatures.

2.1.5. **Industrial Sensing and Automation**

Digitalization and automation are general trends in the industry. Manual tasks are getting replaced with manufacturing robots, machine vision and artificial intelligence, which offer improvements in product quality, production capacity and work safety, while reducing manufacturing costs. All this requires new technology where Integrated Photonics is playing a key role. Primarily, it can be used to make various kinds of miniaturized sensors and imaging systems, which are discussed in more detail below. In addition, Integrated Photonics will surely contribute to industrial automation through optical communication solutions and potentially also through optical computing in the future. In some special cases, Integrated Photonics can also be used as part of the actual manufacturing tools, for example in laser processing.

Sensors are the most extensive application area for Integrated Photonics in the manufacturing industry. Industrial automation brings increasing needs to measure the composition of numerous gases, liquids and solid materials, thicknesses of thin films, shapes and roughness of surfaces, as well as distances, speeds, accelerations, temperatures, pressures and many more quantities. In many cases, small photonic chips and modules based on them can replace bulky conventional instruments that do not fit into manufacturing lines or simply cannot be afforded there.

Furthermore, automated manufacturing needs machine vision to guide the manufacturing and to ensure work safety in hybrid work that combines robots and humans. Integrated Photonics can provide miniaturized lidars and other imaging systems for 2D and 3D imaging. Integrated photonic systems for autonomous driving are not limited to the Mobility sector but can be applied to industrial shop floors and warehouses, where vehicles are enabled to deliver assembly parts without human guidance.

2.1.6. Health and Wellbeing

Many applications in the healthcare market benefit from Integrated Photonics. In medical optical imaging, highly integrated and thus comparatively thin endoscopes contribute to improved diagnostics and thus help to detect diseases such as cancer much earlier and more clearly. The necessary illumination can often be supplied externally via fiber bundles. The use of highly miniaturized components for beam delivery and light detection and their integration with passive optical elements such as lenses and mirrors allow more advanced imaging functionalities such as spectrally resolved imaging or even optical coherence tomography (OCT) functionalities. This approach can be extended to so-called *PillCams*, which are swallowed and ensure continuous image acquisition and transmission on their way through the digestive tract.

Integrated Photonics is also of benefit for photonic biosensors that can detect biomarkers with high sensitivity in blood plasma or other body fluids. The challenge is to engineer reusable compact sensor architectures that can compete with traditional diagnostic methods (ELISA[11], PCR[12]) and other sensing techniques, e.g. surface plasmon resonance (SPR), while retaining the advantages of photonic integration (sensitivity, multiplexing, and label- or reagent-free). While passive waveguide-sensor circuits can be developed for highly scalable mass production, co-integration with on-chip lasers, photodetectors, and microfluidics remains a challenge due to costly serial assembly processes involved. Future work needs to target the development of versatile, highly integrated, high performance (in terms of sensitivity, specificity, LOD) and reusable multiplex biosensors in an innovative concept that includes smart thermal management. While complex structures (e.g.

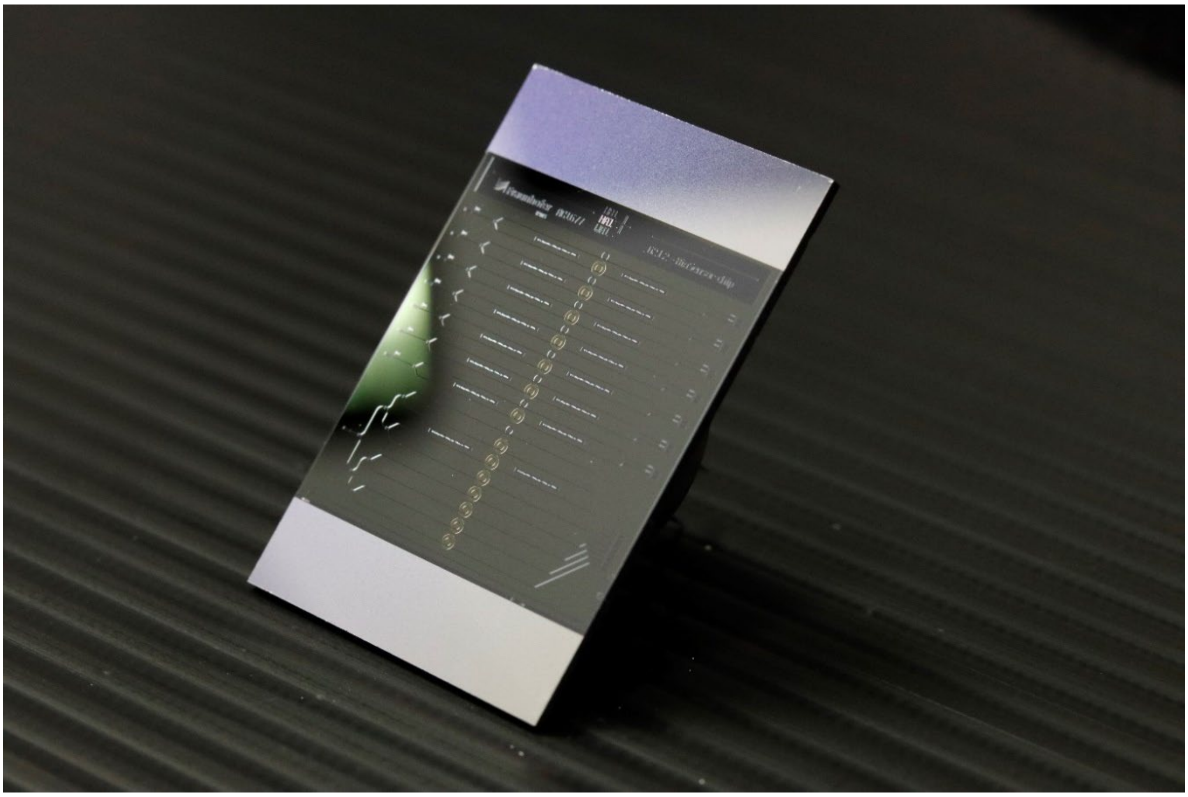

Figure 3: Silicon chip-integrated photonics as biosensors for optical detection of biomolecules © Fraunhofer IPMS

[11] ELISA: Enzyme-linked Immunosorbent Assay
[12] PCR: polymerase chain reaction

plasmonic metamaterials)[13] can achieve high sensitivities, the most easily integrable, highest mode-confining structures are based on micro-ring resonators (MRRs) and Mach-Zehnder interferometers (MZIs). PIC sensors are often developed on Si_3N_4-on-SiO_2 material platforms with the goal to use a low-loss nitride PIC technology. Integrated Photonics will lead to diagnostic tests for diseases based on the on-the-fly generation of complex "fingerprints" of many analytes and will accelerate the development of global digital medical diagnostics. For instance, neurodegenerative diseases such as Alzheimer's and Parkinson's may be diagnosed at a much earlier state than currently possible, although they have complex patterns of biomarkers and their detection is a major challenge for existing mass screening techniques.

The healthcare market will have to change in the coming years for a variety of reasons. In addition to acute patient care, the focus will increasingly be on continuous monitoring of patients' own health status, in order to detect diseases at a very early stage or to continuously monitor progression diseases outside a medical environment such as hospitals or inpatient care facilities. For medical laypersons, non-invasive diagnostics that do not require blood samples are of great advantage. In many cases, this can be technically solved optically by recording vital parameters through the skin. Long-term monitoring is only possible with the help of wearables, whose technical realization requires Integrated Photonics combined with energy-saving electronics. In this way, optical excitation, possibly spectrally resolved detection of the reflected light signal and local signal processing and evaluation can be realized in a small construction volume that meets the requirements of wearables. In consumer-oriented health sensing, the size and cost of integrated photonic solutions become much more critical. In general, tighter integration (i.e., either by 3D packaging or via more intelligence in driving and sensing electronics) and related R&D is needed to reach the price point for the entire solution. By using corresponding technologies in smartwatches, there is a smooth transition to applications in the field of consumer electronics.

2.1.7. Consumer Electronics

In the **consumer market**, there is a very significant trend towards displays and optical sensing for head-mounted devices. In form of AR glasses, they enrich the seen information about the real surroundings with digital information (like internet information, ambient sensors, GPS) that is specifically prepared for the user and thus make the real and digital world available to all of us in our everyday lives at the same time.

By easily being connected to other people, and by benefitting from the increase of safety and health through ambient sensors and information from the Internet, the user has a more comfortable and effortless as well as a safer life. This far-reaching positive impact on our lives must be seen in combination with the comparatively cheap products of the consumer industries and the probably huge, completely unsaturated market. In doing so, parallels can be drawn with earlier megatrends like “Smartphones", whose attractiveness was that access to Internet and software applications was made possible on a device that was affordable for large parts of the world’s population. Under the right conditions, the European industry base can benefit from head-mounted devices becoming the "next big thing".

In order to technically implement the described applications, elements like light sources (e.g. lasers and laser modules), optical elements for beam shaping and manipulation (like ultrathin curved waveguides, meta-lenses, tunable lenses and filters, next generation holograms, ultra-wide angle holograms), display technologies (like micro-LEDs, MEMS-mirrors, Phase Arrays) and sensors (e.g. for eye tracking) play a major role and are therefore part of the integration efforts. The technical

[13] N.L. Kazanski et al, Electronics 2021, 10, 973 and references therein.

specifications that are most sensitive in this field comprise lightweight, low power, scalability and cost efficiency. Beyond the individual components listed above, highly integrated solutions are required comprising all necessary photonic, optical and electrical elements. They must be lightweight and extremely power efficient, since consumer electronic devices are mostly battery powered. Given the potential enormous amount of devices with sometimes very limited lifetime, aspects of “Green ECS” come into play, e.g. recyclability of integrated photonic systems.

In order to tackle these challenges and to be able to benefit from the opportunities and advantages a safe market environment with an adequate legal framework for the use of lasers for companies is needed, so that technology and design boundaries can be clarified. This is necessary to allow a fast market entry, which is one of the most important success factors in consumer electronics (“2nd winner is 1st loser”).

Beyond this specific application in AR/VR/XR, Integrated Photonics is a crucial technology for mobile end devices like smartphones and tablets that all of us use every day multiple times. PICs are used in smart antennas for beam shaping, miniaturized projection systems with integrated infrared sensors enable biometric access to the device by face recognition, and high-resolution displays with integrated sensors provide an almost natural interaction with the device. These are just a few examples how mobile devices benefit from Integrated Photonics nowadays.

2.1.8. Mobility and space

If we want to assess the future relevance of photonics in mobility, we must take into account the significant change that our current mobility concepts will undergo in the future. Our plans and visions include greener, more climate-friendly, safer, and accessible mobility for everyone.

A combination of new business models and high technology that is yet to be developed will lead to an autonomous driving fleet in which vehicles are connected to one another, to other mobility participants and to ambient sensors. Mobility will be available to the whole society with different concepts of shared economy. It will satisfy significantly higher security standards than it is the case today.

In this future mobility concept, environmental sensing plays a central role, in particular components for LiDAR systems. They are not only the basis for autonomous driving but are also an outstanding system for crash prevention. Not only cars but also alternative mobility concepts, e.g. bikes and scooters, will benefit from these systems.

Technologies and their integration levels depend on the actual application. In the automotive context, range specifications are much higher due to the high velocities (typical technologies are Focal Plane Arrays (FPA), optical phased array (OPA), Micro Mirror deflection or coherent detection like FMCW) as for comparatively slow robots/vehicles in factories or households which are optimized for cost efficiency and short distances (technologies like time of flight (TOF), macro mirror deflection, flash-LIDAR).

Besides environmental sensing, cabin/passenger observation and user interaction (occupation sensing, eye tracking, integrated displays and controls, gesture sensors and air quality sensing) are core areas addressed best with photonic technologies (short range 3D sensing, smart textiles, optical fiber interrogators, integrated spectrometers).

All technological developments in this field need to be conducted under highest scrutiny to fulfil automotive safety requirements for autonomous and non-autonomous mobility options and robustness in harsh conditions. Especially the first point continuously needs clear legislation and standardization.

Despite the high technological maturity of current mobility concepts, there is considerable potential for further development and optimization. Numerous stringent emission norms and regulations mandated across the world have compelled OEMs to test their vehicles efficiently to ensure that they meet these norms. Modern vehicles such as electrified cars with e.g. battery electric powertrains require different types of test equipment, such as mobile-based equipment and others. The lack of R&D equipment for automotive testing would result in less innovative and efficient mobility solutions as well as significantly prolong the time-to-market.

Photonic Integrated Circuits also penetrate space applications. Here, main applications are laser communication terminals for inter-satellite communication, microwave photonics inside the satellite to eliminate bulky and heavy RF components, and intra-satellite high speed digital switching[14]. The global optical satellite communication market is estimated at $10B, with 23% growth rate[15].

2.1.9. Other applications

In addition, **other** applications and their associated components, technologies and technology combinations are likely to emerge in the future like optical inertial MEMS, quantum sensors or lasers with extended wavelength range just to name a few. These will greatly benefit from advances made in the current key applications named above.

Integrated Photonics is a critical enabler for second-generation **Quantum Technology** systems in computing, secure communications and sensors. PICs can provide the basis for the quantum effects themselves, or support other technical solutions with interconnect, readout, ion trapping, and interface to the outside world. A joint study was conducted recently by Photonics21 and the Quantum Flagship initiative of the EU, and a position paper outlining the present position and recommendations for future actions has been published.[16]

2.2. Technical trends

The **characteristics** of new and future integrated photonic components and their technologies are set by the individual application requirements. In addition to opening up new exciting functions through the integration of different technologies, an increased level of integration also makes it possible to reduce costs, weight, installation space and power. In order to keep not only the material costs but also the production costs low, a suitable scaling strategy has to be considered. This is important as the markets for these new products, some of which are still small, can potentially grow rapidly. Another aspect is a high focus on energy efficiency. This not only enables us to meet the requirements of the Green Deal, but also reduces installation space, weight, battery life in portable applications and costs.

The **technical challenges** initially lie in a suitable co-design strategy (including associated methods/tools) of the various technologies to be combined as well as in their common processability and hardware integration (compatibility). The high level of integration also requires a special focus on thermal management through thermally more robust components (e.g. laser with temperature-stable wavelength), optimized thermal design, and suitable cooling concepts. This aspect, as well as other requirements, will determine the design and technology of future packages of photonic components. A particular focus is on those cases in which photonics and electronics have to work together at high bandwidths (e.g. very high-capacity transceivers, interfaces to electronic switching circuits in communications and data systems, high pixel-count active sensors, 3D imaging and displays). Another technical challenge is the lack of standard solutions for hybrid integration. Additionally, we face a lack

[14] https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Space_Optoelectronics/Photonics
[15] https://www.reportlinker.com/p06323888/Optical-Satellite-Communication-Global-Market-Report.html
[16] https://www.photonics21.org/2022/position-paper-on-quantum-pics-available-for-download-now%21

of standards for development (e.g. qualification testing) or even legal framework conditions (e.g. for the regular use of smart glasses and similar applications).

2.2.1. Industry trends in heterogeneous integration

This section is structured as follows; first the current state of the industry in PIC fabrication is summarized. Then, four industrial trends are identified and, where applicable, development suggestions are provided.

In the current photonic integrated circuit (PIC) ecosystem, there is a large diversity of different materials and layer stacks, leading to an even larger variety of electronic and optical properties. Each PIC platform has benefits and drawbacks. The most commonly used and mature materials for PICs are Silicon, Silicon Nitride and Indium Phosphide, while others (e.g. germanium, thin film lithium niobate, barium titanate, other III/V and II/VI materials) are still evolving.

It is important to note, that none of the base materials used for PICs can provide a solution that fits all applications. This has led to the **first industry trend**: hybrid and heterogeneous photonic integration, i.e., merging different PIC technologies to compensate for missing functionality in individual cases. There are a variety of ways to combine PICs, such as die flip-chipping, wafer bonding, micro-transfer printing, edge coupling, and others. Amongst current examples, one that is particularly pronounced is the integration of III-V light sources with silicon photonics, which is missing from silicon technology on its own. The TRL of hybrid and bonding-based integration of III-V light sources has seen a clear improvement in recent years and some solutions are available commercially.

For sub-micron assembly, hitherto TO-can active alignment approaches have shown their capability for tens of millions of pieces per annum, at < 1 $ cost in fibre to the home (FTTH) applications. For the future evolution, however, with the additional challenges of parallelization, even smaller tolerances and on-wafer testability, new approaches should be found. Among these are micro transfer printing and hetero-epitaxial growth, which need to be developed to higher TRL. The micro-transfer printing may become a widespread approach to offer high-volume, high throughput, wafer-scale integration of electronic or photonic devices per chip. This method is a very agile and versatile back-end approach. The wafer-scale heterogeneous integration of novel materials, including III-V semiconductors and SiGe nanowire structures, with silicon-based PIC platforms has led to the development of new device concepts with exciting performance and functionality, together with potential for scalability and low production cost. The development of hetero-epitaxial growth and III-V regrowth on InP seeds[17][18] methods is an extremely exciting development. Most of these methods are however still in the research and development phase and only few are currently at actual (high-volume) manufacturing level. This means there is a clear and urgent need to develop a proper supply and value chain for heterogeneous integration.

With a world-wide increasing demand for photonic chips with more-and-more functionalities (i.e., building blocks) integrated together, a **second industry trend** is becoming visible; manufacturing PICs on increasingly larger diameter wafers. For silicon photonics, this trend is going towards 300 mm wafers for reasons of higher quality of manufacturing, particularly in lithography, but also for higher throughput. Already several industrial foundries offer 200 mm and 300 mm wafer processing options. For silicon nitride (SiN), the market does not seem to be large enough to process 300 mm wafers yet and the current market trend is towards processing 200 mm wafers. However, once the market demand is there, SiN processing can evolve to 300 mm manufacturing, similar to Si photonics. The notion of SiN gaining in market share can be traced back to two specific specifications of SiN compared

[17] https://www.mdpi.com/2076-3417/12/1/263
[18] Besancon et al. Appl. Sci. 2022, 12, 263

to other materials; first SiN has very low loss (both propagation loss and coupling loss) and secondly SiN has broadened the application spectrum of silicon photonic ICs into the visible wavelength spectrum, which is relevant, for example, in sensing applications. For InP, current availability is (depending on foundry) 75-100 mm, with a trend going towards 150 mm wafers. It presently seems unlikely that 300 mm InP wafers will become available in the near future. Here, InP-on-Si research is on the way, both using wafer bonding, e.g. by companies like SOITEC, and through hetero-epitaxy. It should be noted that for InP, which can yield ~30,000 lasers on a 75 mm wafer, it seems unlikely that 300 mm wafers will be economically needed in the foreseeable future, though the development of high-complexity circuits with large die sizes (e.g. for automotive LIDAR) could change that picture dramatically. Another approach could be hetero-epitaxy of GaAs on silicon, which with quantum dot technology can address the 1300nm wavelength region which is important for data communications.

All these photonic chips require electronic connections, either for read-out of the photodiodes or to drive the modulators, light sources and phase shifters. In some cases, where data rates and system complexity are low, present electronic solutions can be sufficient, however for high volume manufacturing of photonic chips with many building blocks, a more integrated approach is required, thereby facilitating high density connections and high speed (low parasitics). This shows a **third industry trend**; the need for electronic and photonic ICs with improved intimacy, both at design level and technology level. For integration with electronics, PIC platforms rely on (currently dominant) hybrid or (to a lesser extent) monolithic approaches. The hybrid integration relies on back-end of line (BEOL) integration of electronics and photonics through, e.g., wire bonds, micro-bumps or micro-transfer printing. The application requirements define the choice of electronic-photonic integration. Applications not impacted by parasitic capacitance and inductance of wire bonds or micro bumps continue to rely on hybrid integration approaches. On the other hand, the monolithic integration approaches rely on front-end of line (FEOL) integration of CMOS or BICMOS electronics and silicon photonics, either (a) by completely de-coupling the photonic processes from the transistor processes to allow the optimization of the photonic building blocks, or (b) by implementing photonic functions without making any change in the standard CMOS process flow. The reasoning here is twofold; first the footprint of a densely integrated photonic chip with many components and functions is multiple times larger than the electronic driving and/or readout chip. This means that in a monolithic approach, a large portion of the (expensive) electronic footprint will not be used. Secondly, for electronics a much smaller technology node is used than for photonics. This means that, adding (cheaper) photonics to an expensive electronic process will be many times more expensive than the hybrid approach for the same components and footprints.

A **fourth and final industry trend** is towards lower power consumption of photonic chips. Formerly, DC phase shifting that is performed via the use of heaters was a bottleneck particularly for large scale integrated PICs. Heaters are used, especially in passive technologies such as SiN, since they are easy to manufacture, the optical insertion loss is negligible, and they are very stable over time. However, heaters require significant drive power, meaning that for large systems they are not a scalable option. While active PIC technologies can provide low power and fast operation, there is generally a compromise in loss. There is accordingly an urgent need for more R&D towards the combination of low drive power, small footprint, low insertion loss, and high speed. More recently, large-scale integration of photonics in combination with electronics becomes a more important topic here. With higher density of components per area driven by applications like Quantum and Neuromorphic Computing combined with parallel increase in switching speed, the power consumption per bit has to significantly reduced.

2.3. Global business trends

A recent Market and Technology Report by Yole[19] points to a rapid evolution and spread of PIC technology. Core network and datacentre transmission speeds are already at 400Gbit/s and increasing rapidly, served mainly by InP PIC-based transceivers. In terms of mergers and investments, despite disruptions in the geopolitical arena as well as in overall trade and economic activity due to COVID-19, there are numerous significant and noteworthy developments not only globally, but also in Europe. Major systems integrators such as Ericsson and Nokia remain European-based, but many suppliers are global.

From overall European photonics industry point of view[20], the industry has grown from €76 billion in 2015 to €103 billion in 2019 with a growth rate of 7% per year and a share of 16% of the global market, maintaining its market share over the last 4 years and keeping its #2 global position. It is also noteworthy that the European photonics industry accounted for €103 billion in 2019, which makes the size of the photonics industry in Europe exceed the size of the microelectronics industry, which was worth €75 billion in 2019[21]. However, the situation with PIC production in Europe relative to global capabilities is less optimistic, which is well illustrated in by InP global production figures for 2020 relative to other global players (Figure 4).

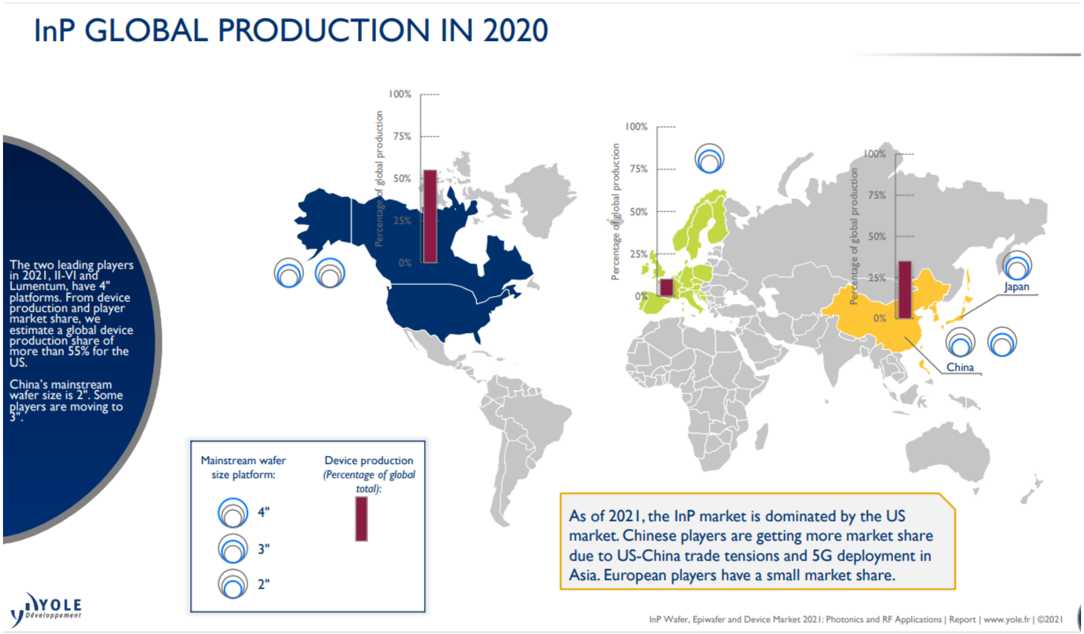

Figure 4: InP Global Production in 2020, from InP Wafer, Epiwafer and Device Market 2021 by Yole

Global trends in PIC supply chains are characterized by the ever-increasing investments by the leading global players, e.g. USA and China. Deteriorating US-China relations and the (still prevalent) impact of COVID-19 only further fuel domestic investments and strive towards self-sufficiency of these players.

The recent wave of stricter enforcement of the EU framework for the coordination of foreign direct investment screening in the European Union by the Member States could be seen as a response of

[19] *InP Wafer, Epiwafer and Device Market 2021: Photonics and RF Applications*, Yole Développement
[20] *Market Data and Industry Report 2020*, Photonics21 and Tematys, retrieved from: https://www.flipsnack.com/photonics21/photonics-market-data-and-industry-report-2020/full-view.html
[21] Ibid.

respective government bodies to current realities of technological leadership race, which also includes a race towards accessing IP in the PIC[22] domain.

In conclusion, a recent study by Roland Berger[23], also based on the analysis of trends and progress in other regions of the world, provides strong evidence and confirmation of the fact that PICs are critical for key industries in Europe. Therefore, taking a stake in production and assembly of PICs is important for security of supply in Europe, ensuring competitive advantage and prominence of the key industries, and thus ensuring economic power and stability of the Union[24]:

- Among the various applications of PICs, automotive, telecom, computing and healthcare are strategic sectors for EU economic prosperity and the functioning of society
- 20% of the global PIC market demand is expected to be from Europe, stressing the need for stake of Europe in the Integrated Photonics value chain
- In short term, lack of semiconductor manufacturing capability resulted in chip shortage leading to adverse effect on Europe's key industrial sector such as automotive
- In long term, the automotive sector faces shortage as semiconductor capacity outside Europe is not focused on the nodes which are required by the automotive OEMS
- Taking inspiration from *semicon*, Europe needs to have a stake in production and assembly of PICs to have both short term and long-term strategic advantage.

The connectivity infrastructure, which became the backbone of our society and economy with the recent multiple crises, will continue to be one of the key parts of the development of our societies and economies. As Europe is the home of two of the three largest telecom equipment vendors (Ericsson and Nokia), its position in the long term will be challenged with the rising concerns of its dependency to chips vendors from outside Europe (mainly Asia and USA). Concrete steps have been recently initiated to reinforce European strength in semiconductor business with the launch of the Chips Act and its ambitious goal to capture 20% of global chips market in 2030. Worth mentioning are the recent announcements of Intel to build an advanced silicon fab in the city of Magdeburg in Germany and ST Microelectronics associated with Global Foundries to advance FD-SOI ecosystem with a new 300mm facility in France. The situation in Photonic Integrated Circuits is more fragmented with many medium size companies present in the European ecosystem while several big players resulting from multiple fusions/acquisitions (Coherent, Broadcom, Cisco, Accelink, etc.) are based in USA and Asia, while some vertically-integrated photonic component manufacturers such as Lumentum and Coherent maintain volume wafer fabrication in the UK and Switzerland. A frank and unambiguous support to the photonics sector is therefore essential as it has a direct impact on European economies and citizens beyond digital infrastructures.

In the data center market, which is considered one of the main drivers of the photonics transceivers business, the main players are the web scale companies (Meta, Google, Microsoft, Amazon, etc.), who have started to implement their own equipment. Several innovations that have been recently initiated in the data center area, such as virtualization of network functions and cloud computing, and which have led to new businesses in this domain, are becoming mandatory with the advent of 5G. Firstly, the scale-up of capacity needed to respond to the growing data traffic requires critical innovations such as

[22] The EU's framework for the coordination of foreign direct investment (FDI) screening in the European Union (the EU) is set out in Regulation 2019/452 (as amended, the FDI Regulation), which was adopted in March 2019 and has been applied since October 2020. The FDI Regulation does not create an EU-level FDI screening mechanism, but sets out minimum requirements for EU Member States' FDI screening mechanisms and a mechanism for coordinating FDI reviews. The Commission strongly encourages Member States to implement FDI screening mechanisms, and 24 Member States have or are in the process of establishing one (as of June 2021, and compared to 11 before the FDI Regulation's adoption).
[23] *Towards Industrial PIC Set-up, Roland Berger 2022*, courtesy of PhotonDelta, the Netherlands
[24] Ibid.

Co-Packaged Optics, which has been identified as a major step to achieve >50 Tb/s connectivity, while lowering power consumption and increasing miniaturization. Meanwhile, the huge amount of data generated by new services, Internet of Things, digital industry, etc. needs massive computing capabilities with improved energy efficiency. While electronics accelerators are already a reality in modern processors bringing AI/ML to the heart of connectivity infrastructures, there are new initiatives to explore photonics-based processing or/and programmable photonics that can be unleashed with PICs.

3. SWOT analysis of Europe at research and industrial level

A SWOT analysis of Europe's position regarding research and commercialization of Integrated Photonics is summarized in the following table:

<u>Strengths</u>	<u>Weaknesses</u>
• High level of competence in research and manufacturing • Diverse industrial base, with many SMEs as well as larger companies covering wide range of application domains	• Lacking large (vertical) companies • Focus on components with lack of complete photonic-electronic solutions
<u>**Opportunities**</u>	<u>**Threats**</u>
• Bridge photonics community with the strong analog and RF design competence base in EU to create differentiating front-ends • Link to strong EU Comms history and to strong EU automotive OEM leadership	• There is a strong connection between health and semiconductor industry in the US (missing in EU) • Massive investments in competing countries, especially in Asia

This analysis is based on a more thorough investigation into different aspects of Integrated Photonics:

3.1. Access to manufacturing

<u>Strengths</u>	<u>Weaknesses</u>
• Existence of EU based pure-play foundries with volume capability ▪ Photonic integrated circuits ▪ Electronics/MEMS • Process Design Kits (PDK) • Full value chain in EU: Photonics, electronics, packaging • Long experience in (integrated) photonics R&D and manufacturing • Renowned institutes in EU • Large number of innovative SMEs with photonics ambition	• Limited standardization in process flows • Long lead-times lead to slow conversion of customers from prototype to product • Small number of design houses • Relative low volumes -> low number of wafers -> slower learning • Small number of large corporates active • Main driver is still communications, mainly dominated by US "big five"
<u>**Opportunities**</u>	<u>**Threats**</u>
• Strong collaboration between companies in the supply chain and pilot line projects: InPulse, PIXapp can become self-sustaining • Synergy by hybrid integration, use strong knowledge position in, e.g. transfer printing, full value chain in EU • Further standardization by using PDK • Wafer volume from datacom, lidar because of increased demand and increased chip size • Wafer volume -> improved datasets -> yield learnings	• Slow uptake: focus on electronics rather than photonics by big semiconductor players • Available talent • Long lead times in the supply chain / energy infrastructure

Summary and recommendations:

- Europe lacks volume manufacturing for PICs accessible to the wider marketplace; design houses emerging but still at small scale; PDKs limited or missing for emerging topics of Integrated Photonics
- Request for EC: we need momentum in Europe to establish a lively community and therefore (leverage) funding for infrastructure (Pillar 2 of Chips Act);
- For Pillar 1 it is requested to stimulate an ecosystem where the best technical solution regarding components and modules comes from European suppliers and therefore establish an industry where European system providers can source from European suppliers

3.2. Equipment for manufacturing:

Semiconductor manufacturing relies on an extraordinarily complex and global industry value chain. Whether for the manufacture of silicon chips or compound semiconductors such as III-Vs or their heterogeneous integration, it consists of multiple steps supported by a specialized ecosystem of materials, equipment and software design tools and core IP suppliers. Semiconductor manufacturing uses tens of different types of sophisticated wafer processing and testing tools, provided by specialist vendors for each step in the fabrication process. Highly advanced manufacturing equipment is developed by companies in the US, Japan and Europe, leveraging decades of global R&D efforts.

In semiconductor manufacturing equipment, US firms collectively account for more than 50% share of the global market in five of the major manufacturing process equipment categories (deposition tools, dry/wet etch and cleaning, doping equipment, process control, and testers). Likewise, Japan has over a 90% share of the photoresist processing market, vital equipment for the lithography process. On the other hand, ASML – a European company – has practically a 100% global market share in the EUV lithography machines essential to manufacture on advanced nodes below 7 nanometers. Also of vital importance is the leading position of European companies in III-V epitaxy including MOVPE (Aixtron) and MBE techniques.

Fabrication and integration process of ICs is considered to have two cascaded steps: -Front-end (wafer-based) fabrication -and Back-end, related to co-integration and co-packaging (after wafer dicing/cleaving) Manufacturing equipment, fabrication equipment and metrology equipment is relevant in both areas. Front-end challenges with novel materials relate to wafer handling challenges in relation to size (thickness, form factor, diameter), material mechanical and thermal properties that impact or limit front-end processing steps or (re-) define processing sequence. Similar impact on Back-end co-packaging and co-integration is apparent for chiplet assembly, (wire)bonding and hybrid integration of different materials such solder and overmould material, Printed Circuit Boards (PCB) and other novel components (such as optical fibers and fiber arrays) with specific material properties defines assembly and packaging sequence. Manufacturing equipment suppliers that address these novel manufacturing and metrology processes are: Ficontec, IMS, Salland Engineering, Ettenplan, Aixamtec.

Strengths	Weaknesses
• European leaders in critical manufacturing equipment including material growth (epitaxy), lithography, metrology, etc. • High-quality education • Key semiconductor manufacturing suppliers (Infineon, NXP, ST) of mature Silicon and derived IC technologies (SiGe, SOI, GaN) • Leading Research and Technology Organizations (CEA, FhG, IMEC,...) involved in semiconductor processes research and development	• No fully European big players in photonic/Opto-electronic chips/components manufacturing • Low presence of European industry in high volume / high end semiconductor markets (smart phones, PCs, etc.) • Increasing bottlenecks among machine manufacturers with lead times up to 24 months
Opportunities	**Threats**
• Digital infrastructures as foundation of society and economy • Unprecedented growth of photonics technologies expected in multiple areas (health, agri-food, digital, etc.) • The European Chips Act, that provides the strategy of decades for Europe, laying out ambitious plan to regain global leadership in semiconductors, aims to reach 20% global chip market share for Europe by 2030 • Europe has strong research in heterogeneous integration for many applications (high performance computing, photonics, RF). • Increasing attention to industrial and personal data security that requires trustworthiness of data storage and handling	• Geopolitical tensions, inflation and raw material disruptions have a negative impact on supply chains, semiconductors including photonic circuits, etc. • Massive state aid in China and the USA for new technologies (quantum, HPC, AI/ML, etc.) makes European competitiveness even more difficult • As for digital chips, Europe is lacking a full strategic value chain in photonic chips • Failure to attract and educate engineers within EU • Chips shortage revealed a fragile supply chain that is not resilient to global pandemic impacts

Summary and recommendations:

- There is a shortage in supply of manufacturing tools in critical tools, though European companies are very strong in some sectors (e.g. ASML, Aixtron).

3.3. Design / EDA

Europe has enormous expertise in design tools for photonic ICs. Recently, large-sized EDA vendors, which are most US-centric organizations, have also stepped into this arena, and started offering tools for photonic IC design. Many European SMEs offer best-in-class photonic IC design software, and in the current landscape, they have to compete with the large-size US entities. The European EPDA ecosystem is historically a very collaborative and close-knit community paving the way to offer interoperability among tools to deliver the best value for the designers. This collaborative nature of European EPDA vendors can put European companies into a leadership role in the standardization of compact models and circuit models. The lack of such standardization today makes it very difficult for foundries to provide sophisticated compact model libraries, and for designers to create IP at the circuit level. As such, it increases the development time for designers and the risk for companies to invest in circuit-level IP. Today, large EPDA vendors are not actively collaborating on standardization. It is a threat to both design houses (source of IP) and also for EU design software vendors.

Strengths	Weaknesses
• Significant presence of teams developing, selling and supporting state of the art PDA tools (majority of people in this space are in Europe). • A number of smaller, cooperating companies address the various aspects of the photonic design workflow (layout, circuit, application level). • Scientific leadership feeding our EPDA R&D through strong ties with industry leading institutes and universities (in EU and beyond). • Good access to European foundries supporting the various photonic technology platforms. Global operations of EU players are very strong compared to their small size.	• Lack of designers / small overall size of the commercial business in Europe. • Most design activity and associated revenue is outside Europe, increasing costs of doing business • Limited integration of photonic design processes with existing electronic design processes • Loose ecosystem in Europe – or lack of visibility thereof limits all kind of interest: ◦ Not enough local students (people that stay after their studies) ◦ Scale-up funding not available – creating a gap and forces companies into foreign ownership ◦ EU design houses turn to the US for easy solutions/partnerships

Opportunities	Threats
• Strengthen the EU ecosystem to gain competitive advantages for all players within the system. • M&A between European PDA players to create synergies, scale benefits and deal negotiation strengths with outside EU parties. • Promising growth of the European chip market represents growth opportunities for tool vendors. • Support of new technology trends (e.g. LNOI) and application areas (e.g. sensing, analytics, analog photonics) via swift adaptation of developed tools and processes. • IP protection, management and exploration to be better organized.	• Geopolitical evolutions and subsequent polarization will squeeze business out of Europe and into US and China. • Large non-EU EDA companies driving the narrative and winning the business. Investments of large US-based design companies threaten European-based offerings (and with this the independence of Europe). • Limited/delayed adaptation of tools and processes to support new technologies and application areas may cause Europe to miss out on related growth potentials to China and USA. • Competition on scarce software engineering resources will limit growth.

Recommendations:

- Stimulate the creation of truly integrated design software (electronic, photonic, including thermal effects) by interoperability between existing tools in both worlds
- Support the European EPDA community in making photonics PDK at par with electronics PDKS (such as by the addition of compact models)
- Enable the design software community in swift adaptation of their tools and processes for new technology trends (e.g. LNOI) and application areas (e.g. sensing, analytics, analog photonics)
- Since there is a close relationship between design tools and technology, new solutions for technology-independent design software are required

3.4. Assembly, co-integration, metrology and packaging

Packaging of integrated circuits (ICs) is considered an art and a science, aiming to protect and harness vulnerable photonics and electronics assemblies in a robust and controlled enclosure, often hermetically sealed, where the protective package can handle hazardous thermal, mechanical and chemical conditions, related to its application. The assembled package should comply to interface standards which are defined by its application domain, and compliant with applicable industry standards, such as for example defined by international automotive, medical or space standardization organizations. Provided these boundary conditions, the assembly process and assembly sequence will be identified by the variety of components and their material properties such as thermal conductance, material melting points, expansion coefficients and more. Complex integrated hybrid and heterogeneous assemblies can comprise printed circuits boards with (wire-bonded or flip-chip assembled) discrete components and multiple electronic ICs and photonics PICs that require numerous RF, DC and optical IO's with tight performance requirements. These modules should have sufficient shelf life and ensure performance without degradation over the required operational lifetime. Hence *advanced packaging* is considered a key technology to enable novel hybrid architectures where silicon electronics components are merged with photonic solutions on indium phosphide, silicon photonics, silicon nitride or lithium niobate platforms.

Strengths	**Weaknesses**
• Know-how and expertise of equipment manufacturers • RTOs	• Lack of tier-1, vertical operating product owners • Lack of co-design tools and experts
Opportunities	**Threats**
• Automation • Co-packaged optics & chiplet approach	• Dominance of outsourced manufacturing model employing suppliers in Asia • Lack of standardisation

4. Research, innovation and industrialization priorities

The expert group has identified the following research, innovation and industrialization priorities for further strengthening Europe's position in the worldwide market of Integrated Photonics:

1. **Establish R&D ecosystems for joint development of electronic component and systems and photonics:**
   Photonics, electronics and related system design need to be interconnected in order to build industrially attractive solutions at an acceptable price point. More R&D is required on novel co-design and manufacturing methods, connecting PICs and electronic integrated circuits by hybrid or heterogeneous techniques.

2. **Cost efficient possibilities for prototyping including seamless access to services for SMEs:**
   There are EU based pure play PIC foundries with volume capability but the task of bringing the ecosystem to the required manufacturing readiness level across a range of technologies is far from complete. A large investment is needed to have the current players fully focused on PICs and with manufacturing capability in volume. In addition, to go from a PIC to a product, integration of multiple technologies is often a key requirement, demanding a significant effort on heterogeneous and hybrid integration. Manufacturing is not yet a smooth and fully linked ecosystem.

3. **Ensure linking up of entire value chain**: This includes the all aspects like materials, design systems, front-end wafer fabrication, back-end test, assembly and packaging. Although capable design software is a necessary prerequisite, the data to feed it is a vital component for success. Further investment in the stabilization of the manufacturing technologies is required to get stable compact models which enable first time right results.

4. **Education activities** to ensure enough skilled persons for the photonics industry

5. Program and Funding recommendations

The analysis in this White Paper shows a high level of research and development activities for Integrated Photonic systems within the EU. However, volumes remain small, except for connectivity systems. To derive the necessary steps and support options for the European Commission, we will now briefly discuss:

1. in which way a production-ready product differs from a prototype and the steps that are normally carried out in product development; and
2. which gaps arise in the case of Integrated Photonics that currently complicate the development process, and what kind of help from the European Commission could facilitate a successful market entry of integrated photonic products.

1.) From Prototype to serial mass production

A prototype should prove the basic functionality of a potential product. Within the scope of series development, product specifications are refined and the product is typically optimized over several sample phases with regard to its key performance indicators (e.g. functionality, cost efficiency, installation space, energy consumption (during manufacturing and during application), robustness against failures, production with uniform quality and minimal waste).

This iterative product development process is typically carried out in close coordination with the customer or the higher-level system authority as the specification provider. Important steps in this process are:

- Product design and process development, including tolerance management and design for manufacturing. During this step, all relevant standards and legal requirements must be considered, in order to avoid unnecessary entrepreneurial risk
- Sample production
- Sample characterization (are the product specifications met?)
- Sample testing (including standardized tests such as AEC Q100, which is a well-known standard for stress test qualification for packaged integrated circuits used in automotive applications, or Telcordia GR-468 for reliability assessment in telecommunications)

Targets of product development process:

- Refinement of specification with customer
- Refinement of product understanding/ understanding of cause-effect relationships
- Assurance that product specifications are within tolerance over lifetime
- Optimization of manufacturing processes

All in all, the aim is to ensure that the right product is developed correctly.

The development process is complex and cost-intensive. However, releasing a product that has not been fully developed can lead to massive future costs and legal consequences for the company and even its employees. Even if this worst case does not occur, a product that has not been developed correctly will not be successful in the marketplace, but will give important pointers to competitors, who can then introduce an optimized product. In the current situation of the European ecosystem for Integrated Photonics, with technologies and products in quite early phases, we risk becoming a source of ideas for other regions, which in turn might earn a lot of money in the market.

2.) Current gaps on the road to volume production development and desired assistance from the European Commission:

a) A clear and legally robust environment based on agreed standards and legal requirements is urgently needed at the latest from the early development and design phase of a product in order to enable a fast track for innovative solutions e.g. for consumer products with long term use enabled by laser-driven sensors and displays.

    a. In this context, current standards are adapted and extended to the new technical requirements arising from the fields of applications with Integrated Photonics. It is important that the European Union supports this process right from the start and that international standardization is also harmonized with the legal requirements for Europe.

    b. An important part of the standardization work are studies to evaluate and understand the range and condition of use of photonic components interacting with tissues. A promotion of this work should be considered in future programs.

b) Due to the high research and development costs, high volumes are required in order to be able to produce the individual component at attractive costs. In this respect, it is clearly valuable for many applications to exploit a given technology as a common platform. In order to be able to optimally exploit our strengths on the long road between prototype and production-ready product, it is essential to think in terms of ecosystems across the entire value chain (materials, design of systems, front-end wafer fabrication, back-end, testing), from innovative research institutions to agile SMEs and LEs with their broad-based competencies and high market access. This close cooperation also promotes the standardization of integrated photonic related characterization and qualification testing which is crucial for cost-effective development.

    The EU would benefit here, for example, from funding through classic funding projects, in particular from projects to strengthen:

    - Platforms by bundling several applications of a technology
    - Ecosystems along the value chain of applications/application groups

c.) Especially for research institutions and SMEs, but even for the LEs, there is often a lack of venture capital in order to penetrate these new, globally competitive markets with the necessary strength and to be able to establish themselves in the medium and long term. The cost-drivers relating to prototyping and sample production, as well as characterization and qualification tests, should be given major consideration here. Here, we would like to see pilot lines for prototyping and sample preparation, that should use identical basic technologies like fabs for mass production, so that a transfer from prototyping in pilot lines to commercial manufacturing without technology adaptions can happen. linked seamlessly to volume manufacturing, as well common testing facilities available to all market participants (research Institutes, SMEs, LEs)

d.) Of course, in research as well as in product development, experts with a diverse knowledge are required (e.g. photonics, electronics, semiconductors, packaging). If Europe wants to enter the mass production of diverse products in this new field, there will be a high personnel demand that has not yet been covered. This division's growth is taking place in an already largely empty workforce market. Accordingly, targeted training initiatives are essential, across the complete range of skills. Alongside a continuing and growing demand for graduate and PhD-level scientists and engineers, we see a major need for people with appropriate craft skills to work as technicians and manufacturing practitioners. Furthermore, in a fast-developing sector such as ours, it is vital that education and training opportunities are flexible and dynamic, reflecting the needs of individuals as well as industry and society. Encouraging collaborations through funding programs between the industry, startups and universities for training the much-needed expert workforce might prove highly beneficial for sustaining the European competitive edge regardless of future policy revisions.

e.) Since manufacturing capacities are presently limited and product development in many application sectors is still in its infancy, an IPCEI especially for integrated photonic systems would be a particularly suitable tool, in order to eliminate our current weak spots and specifically strengthen the entire ecosystem (promotion of new manufacturing lines, development process from research up to product ramp-up, large-scale spill-over activities for the entire ecosystem and educational spill over activities).