Quantum PIC Position Paper (Draft)

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Joint Focus Group from the Quantum Flagship and the Photonics21 ETP:

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Executive Summary

Modern era technology has been built on our understanding of quantum effects and continued advances in semiconductors, transistors, lasers, organic chemistry, magnetic resonance, etc. Despite quantum mechanics being more than one hundred years old, an increasing number of experiments have been devised to test the oddities of quantum mechanics. New discoveries are allowing us to embark on a second quantum technological revolution and exploit the laws of quantum mechanics to increase performance in computation, communication and sensing (incl. metrology). These engineering solutions are known collectively as Quantum Technologies. Quantum computers could offer exponentially faster computing over today's conventional processors to address optimization problems in drug design, risk management and logistics. Quantum internet holds the promise of super-secure communications, whilst quantum sensors will establish new medical diagnostic tools, provide resilient navigation systems, allow us to see through fog or smoke and underneath the ground, amongst numerous other things not possible at the moment. And, not to forget, quantum technologies will drive scientific discovery, from computing to sensing. These developments will secure Europe's technological future and societal progress.

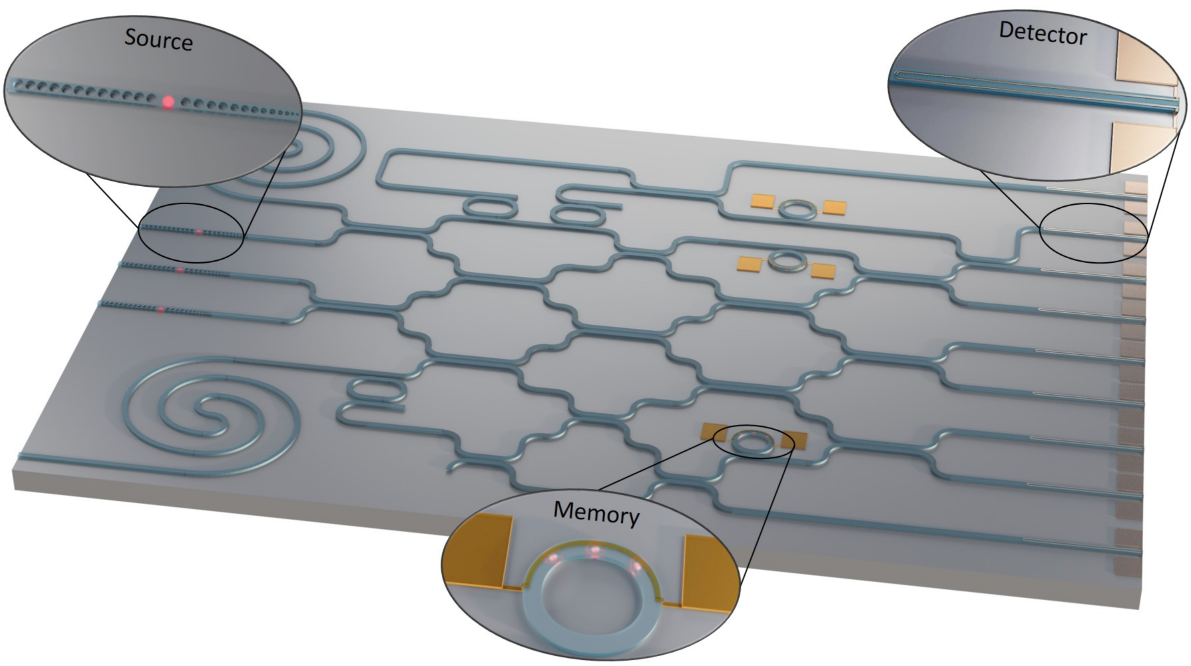

Figure 1: Quantum photonic integrated circuit, including non-linear optics (spirals) and quantum light sources (red dots) in nano-beam cavities, quantum memories (rings including ions), and superconducting detectors (strips), as well as active and passive photonic elements.

Quantum photonics, the applied science describing the generation, manipulation, and detection of single light particles, so called photons, plays an essential role in quantum technologies: either directly utilizing the quantum effects of photons, or indirectly as a carrier of energy or information that enable, probe and interact with quantum states. In effect, without quantum photonics, quantum technologies would be difficult to implement. Currently many systems use discrete photonics components, which are expensive, require time and expertise to set up, and lack the robustness required to deploy them in the real world.

These issues need to be overcome to make Quantum Technologies widely deployable and the way forward is through integration, moving from simple laboratory demonstrators to real life technologies.

The photonics community has already gained significant experience in photonics integrated systems developed and deployed in telecommunication, which has altered and revolutionized the telecommunication industry. Similar advancement could be achieved for quantum technology. Quantum photonic integrated circuits (QPICs), see Figure 1, can harness the current progress of “classical” photonic integration platforms (e.g. silicon-related photonics, InP, polymer or SiNx based hybrid PICs) while strongly impacting all pillars of quantum technologies (communication, computation, simulation, sensing & metrology), including facilitating breakthroughs in fundamental science advances.

QPICs are in many ways a disruptive key enabling technology similar to semiconductor integration. The latter has been essential for the miniaturization over the last 50 years of powerful electronic devices that have transformed our everyday life (computers, smartphones, internet of things etc.). The need for QPICs is evidenced in various EU funded quantum projects: for example, 12 out of 20 Quantum Flagship projects include photonic integration in their projects or have expressed interest in QPICs (see end of document).

However, similar to electronic chip integration, QPICs require the bespoke monolithic, hybrid or heterogeneous integration of several diverse devices on the same base platform to drive the miniaturization process and multiply quantum performance. This is a difficult task, requiring considerable collaboration across multiple centers of expertise in academia and industry. It also requires substantial investment that currently is too risky for industry to make. This presents an exceptional challenge ahead of us for quantum photonics and its application in quantum technologies.

The development of European QPICs will be essential in supporting the EU effort towards an effective quantum revolution sustaining innovation, robust European technological leadership, job creation and vigorous societal impact, joining the efforts of academia and industry. Nevertheless, the development of quantum photonic integration requires a coordinated effort on several fronts:

- Make QPICs a European priority as a disruptive enabling quantum platform
- Strongly support the development of materials, devices and components associated with quantum photonic integration with tailored programs
- Promote infrastructure for monolithic, hybrid, and heterogeneous integration challenges of QPICs
- Invest in a significant education effort in creating next generation quantum photonic engineers
- Enable collaboration across Quantum Technologies, QPIC and classical PIC communities

“Classical” photonic integrated circuits (PICs)

Photonic integrated circuits have several advantages over discrete photonic systems: small form factor, cost reduction, increased reliability and robustness and highly repeatable manufacturing. Current growth in datacentres and internet traffic, together with the perspective of a full deployment of 5G technologies and smart sensor deployment in automotive, MedTech and AgriTech, have spurred in the last decades a growing effort towards miniaturization of optical components and their large scale integration, following, with a delay of decades, what was achieved by the electronic industry. This effort has generated a number of integrated photonic circuit platforms currently deployed in niche markets. A much bigger number of various research platforms are currently investigated in view of their strong potential in wider applications. Among the various platforms, silicon-related photonics ones play a major role, as they benefit from developments of integrated circuits in the electronic industry and their high-volume capability. Other platforms could be categorised as “glasses of various nature” or “polymer based” technologies, or as III-V semiconductor ones. However, active materials (for light emitters, fast switches and quantum memories) are not available in a pure silicon platform and a number of disadvantages linked to the specific possible platforms (e.g. SiO_2, SiNx, Si, silicon-on-insulator etc.) are still hindering progress. This has spurred a branching of classical photonic integration technologies into several bespoke platforms for specific applications, with a proliferation of approaches to integrate a variety of materials (III-Vs, 2D materials, defects, lithium niobate on insulator etc.), devices (quantum dots, nanowires, modulators etc.) and components (detectors, memories). This integration on top of the photonic waveguide chip itself represents huge challenges and can be broadly classified as: (i) Hybrid, that is, the insertion of heterogeneous components to a specific chip platform in various ways; (ii) Heterogeneous, that is the direct nucleation of heterogeneous material on the chip wafers; and (iii) Composite assembly of devices that are produced on different platforms, fibre-pigtailed, and interconnected through an integrated photonic circuit that acts as a processing core. Similarly, the connected multi-chip-module concept, based on so-called chiplets, enables system fabrication using different platforms. Until the hybrid/heterogeneous and monolithic integration approaches reach sufficient maturity, this last approach is perhaps the most promising one to realize complete prototypes, as well as being cost-effective for small-medium production of devices for specific applications.

Why “quantum” photonic integrated circuits (QPICs)? Current implementations

Photonic platforms can leverage current advances in PICs and advance existing efforts in quantum photonic applications, while providing an opportunity to advance the development of quantum technologies. Indeed, many envisioned quantum photonics applications require photonic integration to move from simple laboratory demonstrators to real-world technologies. In particular, QPIC platforms will have a strong impact on:

Quantum Communication

The traditional optical communications sector is a heavy user of photonic integrated circuits. This will from an excellent basis, but the demands from quantum communication are much more stringent. Quantum communication, in which signals cannot be amplified to mitigate transmission losses, requires extra low-loss circuits and efficient light generation and detection units compared to traditional optical communication. Quantum communication can be presently classified over two main families, largely overlapping in terms of leading photonic integration requirements: quantum cryptography (quantum key distribution, QKD) and distributed cloud computing over a quantum internet. In both cases, there are a number of recent internationally funded projects (including through the Quantum Flagship) based on the transition from discrete and bulky tabletop devices to compact integrated systems. Since the projects are still in the early stages of development, the focus is on much-needed integrated optics to create on-chip platforms for terrestrial and free-space quantum networks and repeater nodes, with integrated quantum light sources, coherent receivers, routers, micro-optical elements, and various other necessary components. Challenges include the need for ultra-low loss integrated platforms (very important), coupling of external interfaces such as optical fibres or electrical contacts, sometimes at cryogenic temperatures, and/or large-scale testing, and integration of quantum memories. Efficient photonic integration of frequency conversion (ideally in a way that preserves polarization-based single-photon encodings) will be important for efficient entanglement of quantum nodes over long distances.

Typically, these efforts are concentrated on silicon-related photonic, InP-based or hybrid platforms, possibly also in spectral regions not used in conventional optical communications, and will develop towards stronger integration of electronics and photonics on single platforms to handle increased clock rates and the relevant (classical) computational overhead. Indeed, photonic integration is key in the development of the field as it would allow scalable deployment. As examples, in Fig 2 the realization of a QKD state generator using silicon integrated platform as well as the hybrid integration of transceivers for CV- and DV-QKD are shown. Important impact is expected in the field of secure space links and communications, as well as in quantum random number generators, where integrated photonics offers obvious advantages in terms of physical footprint, energy, stability, and manufacturability over their discrete counterparts.

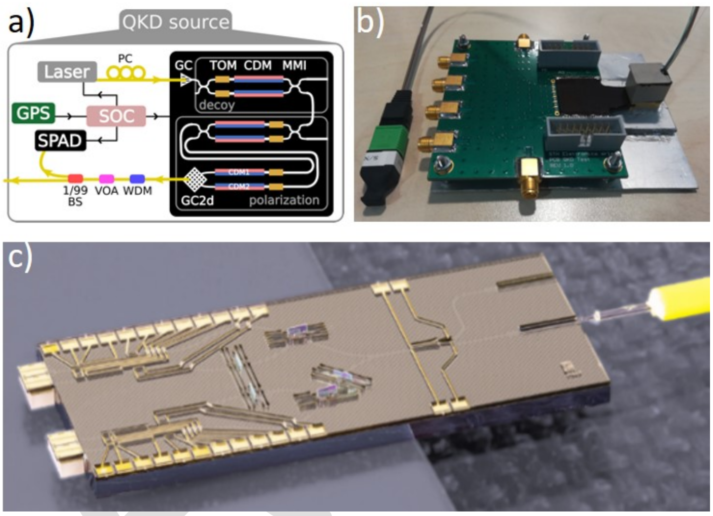

Figure 2: a) shows the scheme of the QKD state generator system and b) the integrated chip including connectors (from M. Avesani et al. arxiv 1907.10039, 2019). c) Photonic circuit with hybrid integration of transceivers for CV- and DV-QKD, including InP based single photon detectors (in courtesy of HHI).

<u>Quantum Computation</u>

Essential requirements for any type of quantum information processing (QIP) are a high degree of control over the information carriers and the decoupling of these carriers from their environment. Among the many physical realizations of qubits currently under investigation, photons have a special position: they interact only weakly with transparent media and little with each other, which makes the information they convey robust against decoherence. In addition, photons have many degrees of freedom that can be chosen for encoding quantum information, including the possibility of using continuous quantum variables.

However, in the context of circuit-based QIP, deterministic two qubit quantum gates require strong nonlinear interactions that are difficult to realize on the photonic platform. These challenges have not hindered a number of experimental demonstrations of quantum photonic functionalities using optical table-top components. Some of these functionalities have been successfully transferred to QPICs on various material platforms. These achievements were perceived by the scientific community as crucial milestones for the advancement of photonic quantum computing. It is worth noting that photonic integration for QIP has already gone beyond demonstrators to establish quantum circuit platforms, see for example glass platforms for boson sampling as shown in Fig 3.

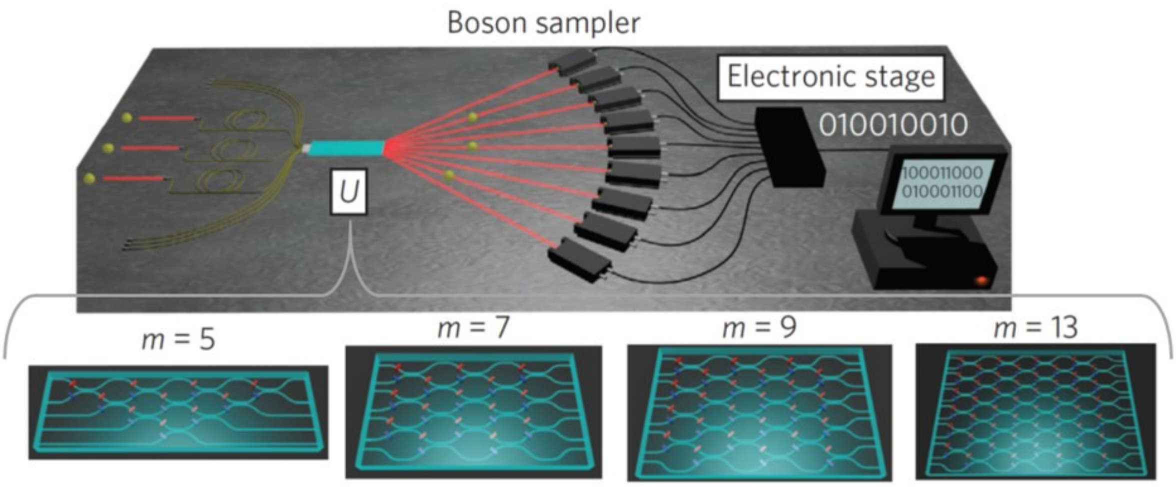

Figure 3: Boson Sampling experiment with integrated photonic circuits of different mode numbers (taken from Nature Photonics (2014): https://doi.org/10.1038/nphoton.2014.135)

Beside circuit-based QIP, specific architectures have been developed that are more suitable for a photonic path to quantum computing. 'One-way' or 'measurement-based' quantum computing with cluster states (both in discrete or continuous variables) fits nicely the implementation on a QPIC. Examples of quantum computing companies pursuing this approach are US-based PsiQuantum (www.psiquantum.com) and Canada-based Xanadu (www.xanadu.ai). Such approach has the potential to leap-frog other platforms on the path to a quantum computer with millions of qubits (https://arxiv.org/abs/2010.02905).

QPICs are essential for QIP as they provide many key features, including scalable and reconfigurable architectures (scalability being particularly important in the context of the strong redundancies required for error correction, similarly to other QIP technologies), small system footprint, enhanced light-matter interaction when needed, a very much required high stability of optical elements and a direct on chip interfacing with efficient detectors and CMOS electronics for performing a wide range of classical tasks. Integrated circuits can also be useful for other quantum computational platforms, as for example protocols with atomic traps, where the compact realization of (laser) excitation and detection is of paramount importance for scalability. Synergies with quantum communication are also relevant, as qubits distribution through quantum nodes will be a relevant resource in this context, again with photonic integration playing a major role for scalability.

Quantum Simulation

Photonic quantum simulators have already been achieved in a laboratory environment, and will benefit strongly from the scaling perspective of integrated quantum photonics. Based on linear optical reconfigurable circuits, using tunable Mach-Zehnder interferometers, simulations of vibrational quantum dynamics of molecules have been realized (see Fig. 4).

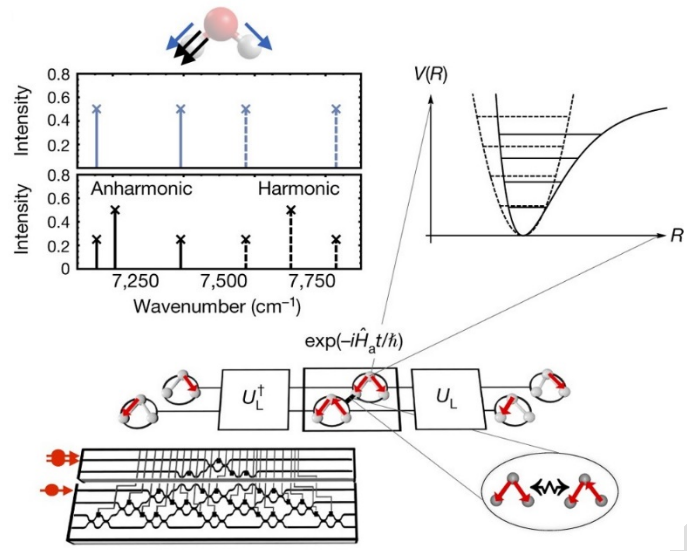

Figure 4: Quantum photonic integrated circuit with thermo-optic phase shifters (bottom) allows for simulating the vibrational quantum dynamics of molecules (taken from Nature (2018): https://doi.org/10.1038/s41586-018-0152-9)

Furthermore, quantum walk demonstrators and also boson sampling circuits have applications in quantum sensing. Scalability requires the integration of these components in large low-loss circuits, to minimize simulation errors based on photon losses. These efforts are also relevantly dedicated to "one way" quantum computing with cluster states. This approach could be particularly effective in conjunction with percolation theory strategies and would require scalability footprints aligned to what current integrated photonic circuits can indeed achieve. This is very pertinent for quantum simulation tasks, which are expected to impact a number of short-term research and development applications without the requirement of handling a significantly large number of qubits.

Atomic or ionic quantum simulators are presently witnessing strong developments, with quantum on-chip requirements to reduce footprint and increase dimensionality. Efforts largely overlap with the quantum communication and quantum computation objectives, equally in terms of active elements integration, coupling and routing.

Quantum Sensing & Metrology

Quantum sensing and metrology employ the fundamental laws of physics to optimize precision while exploiting quantum effects that have no classical analogues (such as entanglement and squeezing), aiming at increasing detection and resolution for a number of practical and innovative problems. For example, low-power quantum radars are interesting not only for stealthy short-range target detection but also for proximity sensing and environmental scanning (e.g. in robotic applications). The interest obviously is also strong in terms of new laboratory instrumentation (e.g. super-resolution) allowing exploring new material and device physics. Fig. 5 a) shows a proof-of-principle example for integrated quantum sensing using linear optical circuits for adaptive Bayesian multi-parameter estimation. The chip is connected with fibres to interface the circuit with light sources and detectors. To fully utilize the potential of on-chip quantum sensing all components are required to be integrated. Especially for source integration this typically demands heterogeneous or hybrid integration methods. A major building block to ensure the scalability of photonic quantum sensing involves efficient on-chip detectors, such as waveguide integrated superconducting single photon detectors (see Fig. 5b). Despite that these detectors fall into the quantum sensing and metrology domain they are crucial for nearly all applications of quantum photonic integrated circuits.

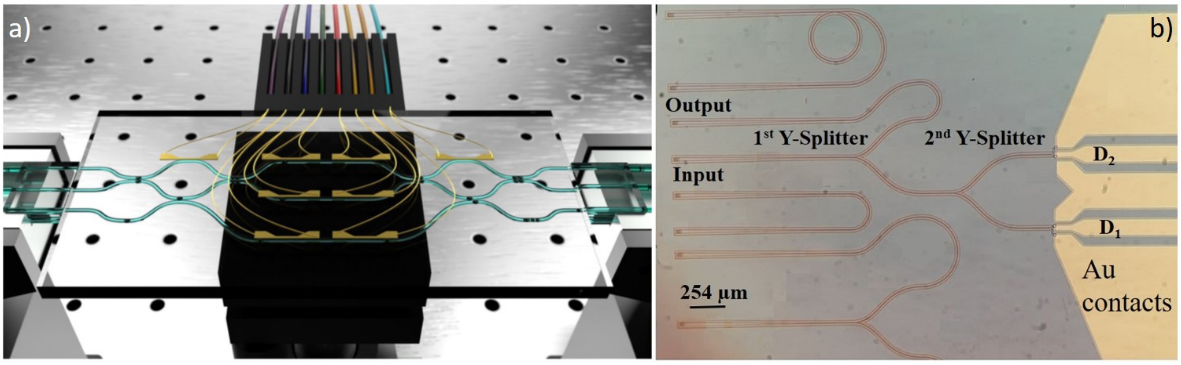

Figure 5: a) Schematic of a compact and versatile integrated photonic circuit for adaptive Bayesian multi-parameter estimation (taken from npj Quantum Information (2020) 6:92 ; https://doi.org/10.1038/s41534-020-00326-6). b) Optical microscope image of two (D1 and D2) Superconducting Nanowire Single Photon Detectors (SNSPDs) integrated on top of a silicon nitride PIC made of two 50:50 Y splitters and input/output ports realized with grating couplers. (Freely adapted from Gaggero et al, Optica 6, 823 (2019))

Another application for photonic integration is in sensor systems where light is used to control and probe quantum states, such as in sensors based on laser cooled atom systems. Those systems utilise several discrete components, connected through optical fibres.

Photonic integration clearly will be a major enabler, being in the field of compact quantum light sources, on chip detection and signal routing, taking up issues such as quantum reading, single and entangled photon LIDAR, quantum illumination, and quantum enhanced optical super-resolution, importantly addressing scalability and stability issues, including fast on-chip data analysis.

<u>Basic Science</u>

Underpinning the effort on quantum technologies there is obviously a strong effort on understanding and exploiting basic quantum effects. While this effort is pervading the research community, it is obvious that photonic integration is an important enabler for basic science discoveries. Examples include endowing and controlling novel quantum effects in semiconductor integrated optical cavities (e.g. quantum light from coupled quantum modes or advanced frequency combs quantum features), novel topological states with integrated photonic circuits and their detection/characterization, and quantum walk physics, as well as novel insights into interacting spin systems when matched to quantum simulation efforts.

The European Quantum Flagship

In the ramp-up phase of the Quantum Flagship 20 projects have been funded, working in all for pillars mentioned above. The majority of Quantum Flagship projects (12 out of 20) are working on versions of QPICs or intend to develop QPICs in future, as shown in the pie chart in Figure 6. A detailed table with the description of the projects and their link to QPICs is given at the end of the document. That table also includes a selection of QuantERA projects with connections to QPIC development and applications. The large fraction of projects benefiting from QPICs highlights the need for a European effort to develop an infrastructure for quantum photonic integrated circuits.

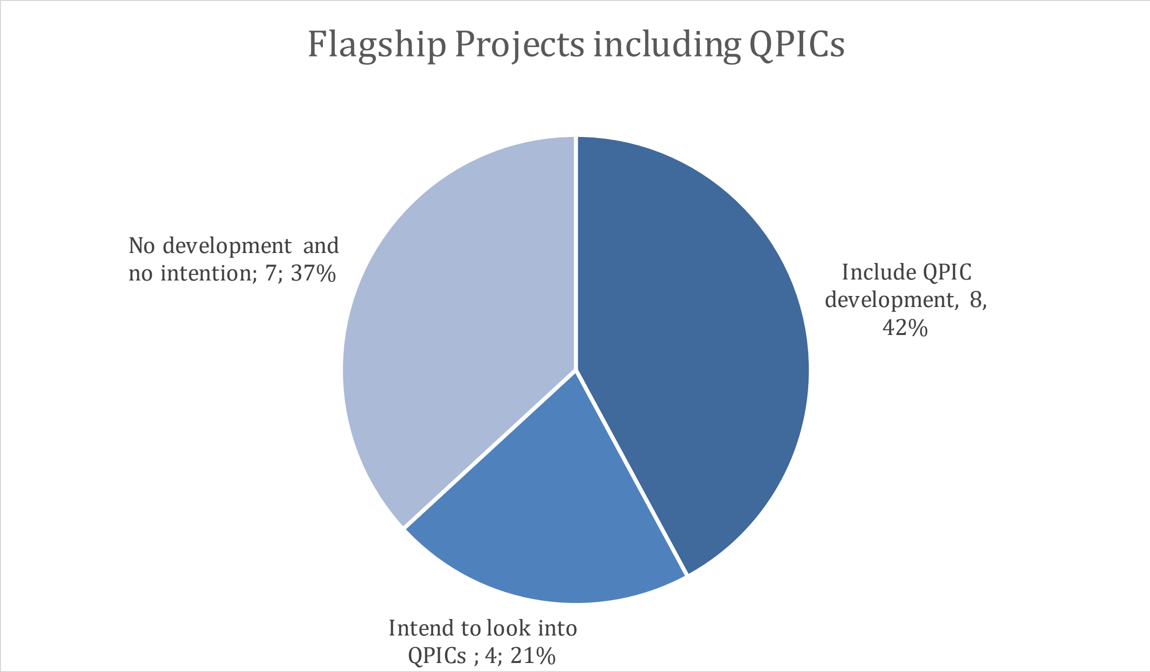

Figure 6: Pie diagram illustrating the need of quantum photonic integrated circuits within the Quantum Technology Flagship projects during the ramp up phase.

Quantum Photonics Challenges

Photonic quantum devices and components

Photonic integration has to be distinguished in a number of different maturity levels. We are still in the early instances of technological implementation of quantum PICs, and many challenges remain to be overcome. One of these is the development of dedicated photonic integrated devices and/or components tailored to the needs of the envisioned quantum applications. Below we consider a comprehensive (although possibly incomplete) list of devices currently being developed for integration, each at a different stage of maturity because the requirements for integrated quantum applications are very challenging:

- On chip quantum memories, both atomic and solid state based
- Stable on chip quantum light sources based on nonlinear and high order processes (heralded or not), and squeezed light sources at various frequencies
- On chip qubit generator with decoy-state functionality
- On chip quantum random number generator
- On chip quantum emitters based on low dimensional confinement
- On chip highly controllable and tuneable quantum cavities (e.g. ring resonators, photonic crystals)
- On chip low noise and coherent receivers
- Active photonic optical switches and on-chip signal routing with low loss and high speed
- On chip polarization preserving integrated waveguides at multiple wavelengths
- On chip MEMS and micro-optical elements fitted with high specification tolerances
- On chip low noise detectors tailored to different wavelengths regimes
- On chip and efficient quantum frequency converters
- On chip miniaturized photonic circuits for practical cryogenic application

Quantum photonics integration into PIC platforms

Quantum photonic integration has transitioned from pure fundamental research to application-driven activities. Several research groups and start-ups have started to develop QPICs on existing platforms. However, as with their classical counterpart, it is improbable that a "one for all" solution based on a single technological platform exists. Multiple applications require custom integration.

There are a number of platforms currently being developed and investigated for specific quantum application, particularly in terms of their suitability for novel hybrid and heterogeneous integration approaches compared to their classical counterparts (e.g., the potential of cryogenic detectors will only be fully utilized if they are integrated directly on-chip). Some prominent platform examples are:

- Silicon photonics and hybrid integration:
    - Wafer scale silicon-on-insulator (SOI) technologies, often for applications at telecom wavelengths; hybrid integration includes detectors, non-classical light sources, nonlinear active elements, quantum memories, and at the same time offers programmability as an additional asset.
    - Passive silicon-on-insulator (SOI) platform with hybrid integration of graphene and related materials for active functionalities as modulation and detection at telecom wavelengths (1.3µm – 1.65µm) and in the Mid-IR (2µm – 5µm) operations.
    - Silicon nitride wafer-scale platforms with hybrid integration of: III-V or 2D materials (e.g. graphene); detectors for applications in the near-infrared (~800 nm) to visible range; nanostructures as quantum light sources; nonlinear elements; plasmonics, etc.
    - Silicon-based platforms embodying epitaxial III-V semiconductor layers, thereby incorporating efficient light sources.
    - Silicon photonics as above, but paired with polymer waveguiding; polymers offer undeniable advantages in terms of manufacturability and tasks such as waveguiding, coupling, and for flexible and wearbale applications.
- Silica-on-insulator / laser-written silica / various glasses, possibly matched to other platforms to create complete systems; especially for applications such as boson sampling, quantum walks, and quantum simulations.
- III-V platforms (InP and GaAs); these readily provide active sources (and detection); advanced sources and cavities; and efficient, high bandwidth modulators. The capability to adapt to different wavelengths and low optical losses are key features.
- Lithium niobate waveguide circuits (including lithium niobate on insulator, LNOI), providing opportunities for reconfigurable waveguides, strong nonlinear effects, hybrid integration with non-classical light sources and detectors.
- Other substrates: these include diamonds and diamond defects as qubit centres/quantum light sources or as quantum environment probes, various 2D materials (early stages), silicon carbide (SiC) and nitrides (III-N).
- Assembly of different technology building blocks by 3D integration, on optical/electrical interposer, co-packaged or connected by passive waveguides or fibre routing systems
- Cryogenic grade photonic integration (all above cases) and packaging for complex quantum circuit operations

Market potential from a European perspective

QPICs are featuring as prominent quantum technologies as evidenced by the current activities. They can be employed in quantum communications, QIP, metrology and sensing and their applications. The telecom market alone is evaluated at over $300m in ten years on quantum optics chip level, which will drive a total market estimated to over a billion euros on quantum optics device level. The overall addressable market of quantum systems and services based on QPICs would be much larger given that the global market projections for quantum technologies range somewhere between $3,000 billion and $15,000 billion by 2030.

Europe has an extraordinary strength and knowledge in quantum photonic integration, along with a vibrant ecosystem that could be pulled together to define global quantum supply chains. While effort is presently scattered around a number of different platforms, there are several top-class facilities and world-leading groups with major academic contributions across several European member states. These are complemented by major European RTOs with dedicated cleanroom facilities supporting the research and development of quantum photonic devices and components and their integration into systems. Regarding industrial interest, there is a large number of quantum photonics start-ups and SMEs providing enabling technologies for QPICs, besides the many large European companies that are already actively involved in quantum technologies (e.g., Thales, Bosch, Atos, Telefonica, Teledyne, BAE Systems, BT). Examples include Toptica Photonics (tunable diode lasers for optical clocks & quantum sensors), Vixar/OSRAM (VCSELs for atomic sensors), OROLIA (space atomic clocks), FISBA (optical components and microsystems), AUREA (entangled photon sources and counters), LightOn (optical processing units for machine learning), QuiX (SiN QPICs for machine learning & quantum simulation), QUANDELA (quantum light emitters), LIGENTEC (SiN for QPICs), VLC Photonics (QPICs design), imasenic (single photon detector arrays), APE (single photon sources), VPIphotonics (design software for QKD), IDQ (QKD), QUARTIQ (optical single-ion clocks), SMART Photonics (PICs), and LioniX (PICs), NuQuantum (single photon detectors and sources), Orca Computing (photonic memory), KETs (quantum secure communication), QLM (quantum imager for gas detection), M Squared Lasers (atom interferometers, Quantum sensors, quantum computing) Q.ant (lasers for Quantum technologies, owned by Trumpf), Duality Quantum Photonics (QPICs), AegiQ (single photon source). The quantum photonic integrated circuit start-up PsiQuantum is largely a spin-off of European laboratories. They recently raised over €200m. Unfortunately, they moved to California, probably for better access to investor money.

A European vision for photonics integration infrastructure

While there is extensive research and development in classical photonic integration, and major deployment in specific applications such as telecom, it is only at its early stages in terms of wider applications and market penetration. A number of monolithic, hybrid, and hetero-integration platform are being investigated, with a subset very likely to materialize in the next few years as leading technologies for the deployment of future data centers, 5G and in particular for future 6G, in which the highest security will be a main requirement, and internet of things. Applications of quantum photonic integration have emerged on top of these foreseeable short and medium term developments. Those linked to quantum information and communication have the better chance to leverage 'classical' platforms and exploit them as the foundation of scalable and robust QIP devices. Nevertheless, quantum devices may have a specific requirement set that is not currently provided by 'classical' platforms, e.g. a combination of extremely low losses, photon indistinguishability, and photon polarization transparency. These specific features require a dedicated development that should be funded to push the current fabrication technologies to a more refined level and to improve the device packaging, which is typically the most critical step for device losses and reliability.

It should also be noted that QPICs based on CMOS-compatible silicon photonics have great potential in terms of mass-production of devices, but this technology has high entry costs and lacks versatility for rapid prototyping. This aspect should not be forgotten as it is very relevant both for the research community that is in need of a simple and reliable platform to test and validate new quantum protocols and for specific quantum applications (e.g. components for quantum satellite communications), where small numbers of highly-tailored devices are required.

There is a very strong and dynamic ecosystem that can be harnessed to position Europe in global supply chains of quantum photonics technologies and services. However, there is a risk to disperse effort into a collection of competitive endeavors in the absence of strong support, including coordination, at the European level. To avoid that risk and to sustain European leadership, a highly visible quantum photonic infrastructure and research base needs to be promoted. A community can be built around existing "classical" facilities by stimulating their parallel exploitation (or partial conversion) to activities in quantum technologies. It is nevertheless vital to underline that focusing on too narrow a set of photonic integration platforms at this stage could be detrimental to the future of European quantum photonic industry. The field is still far from maturity to identify "single" suppliers of integration platforms. Nevertheless, since many of the classical photonic integration platforms are already spread over a number of bespoke solutions, a European quantum photonic integration program should not support a random proliferation of alternatives but emphasize collaborative efforts. This would allow them to flourish and establish a widely exploitable multi-technological infrastructure open to European researchers.

Recommendations for actions

- Make QPICs a European priority as a disruptive enabling quantum platform
QPICS are essential for quantum technologies. They are required to achieve the functionality, compactness, robustness and cost required to enable wide adoption for quantum technologies. From the 20 Quantum Flagship projects, more than half have already expressed the need for collaborative photonic integration efforts. Europe has developed a strong lead in photonic integration over the past decades, but the gap is slowly closing. We need to foster our expertise in key technologies, address emerging markets, and build a strong infrastructure for Europe to maintain its leading role in quantum photonic integrated circuits and prioritize photonic integration as a key enabling technology.

- Strongly support the development of materials, devices and components associated with quantum photonic integration with tailored programs
Quantum performances of photonic circuits are driven by new and improved materials, advanced integration, and packaging, e.g. to meet the demands of operating at numerous wavelengths at high accuracy and stability. Without the development of new platforms, new on-chip devices and modules with better functionalities, Europe will not cope with the demands of the world market. Thus, Europe needs to invest in the development of components and supply chains for new photonic integration platforms and keep all knowledge within Europe so not to lose key technology to external partners.

  - Joint or coordinated Horizon Europe calls between both initiatives. The next possibility to establish such calls would be the work programme 2023-4. Both initiatives can benefit from each other: quantum technologies require new solutions and these solutions could bring benefit to other application areas. Collaboration will cross fertilize. Developing joint roadmaps where appropriate should be an objective.

- Promote infrastructure for monolithic, hybrid, heterogeneous, and composite integration challenges of QPICs
Quantum photonic integrated circuits are based on the integration of several key technologies on a single chip. Each technology is built around a common platform and requires different dedicated expertise, equipment, and facilities to be brought together under pan-European infrastructure. It is of crucial importance that Europe promotes a coordinated approach to maintain all technology required inside Europe and build synergy effects between key stakeholders.

  - Link-up existing PIC activities/projects/infrastructures with the Quantum Flagship and other EU-funded projects. Extend this aspect to regional developments
  - Safeguard European capacity to manufacture innovative quantum technology
  - Develop platform technologies and pilot lines for QPICs by building on existing centres and expertise
  - Ensure that IP generated in Europe leads to exploitation within Europe.

- Invest in a significant education effort to train next generation quantum photonic engineers
Integrated quantum photonic technologies will become reality in everyday life. Independent of the final technology used, the underlying principles of quantum mechanics are the same. An ever-growing demand is forecasted for scientists and engineers with substantial knowledge in both quantum photonics and its technological applications. The current talent

pool is insufficient to ensure future quantum-ICT innovation. Europe cannot afford to have the next wave of tech unicorns to be located outside Europe and experience the same brain drain as it happened with IT and software development. We need to provide the young generation with the education needed to become the next entrepreneurs in quantum photonic technologies and make their own start-up in Europe.

Flagship Project	QPICs	QPICS for	Project description
		Quantum Communication	
CiViQ	☑	receiver, transmitter QRNG components https://civiquantum.eu/	Development of quantum-enhanced physical layer security services that can be combined with modern cryptographic techniques, to enable unparalleled applications and services.
QIA	☑ (intention)	on-chip platforms of quantum network nodes, photonics integration with ion traps platforms, optical switches and ring resonators, frequency converters, optical memories https://quantum-internet.team/	Quantum Internet, end to end qubit transmission. Developing key hardware components: quantum processing nodes, repeaters. Integration into existing communications networks
QRANGE	☑	QRNG chips https://qrange.eu/	Developing of QRNG
UNIQORN	☑	InP chip for DV QKD transmitter InP chip for balanced receiver Polymer integration platform for heralded and entangled photon sources and squeezed light TIA development for CV QKD Room temperature Si-SPAD array https://quantum-uniqorn.eu/	Developing technologies for quantum communication applications aiming for mass-market deployment
		Quantum Simulation	
Qombs			Quantum simulator platform made of ultracold atoms performing simulations for engineering quantum cascade laser frequency combs.

PASQuanS	☑ (intention)	integrated fibre modulators and platforms for combining multiple elements: e.g. beam splitters, frequency converters, shutters https://pasquans.eu/	Development of Quantum Simulation Platforms
Quantum Sensing & Metrology			
iqClock	☑ (intention)	Rugged, miniaturised laser system for strontium optical clock https://www.iqclock.eu/	Development of ultra-precise and low-cost optical clocks
MetaboliQs			Development of a cardiac medical diagnostic imaging tool based on diamond quantum sensor technology
macQsimal	☑	Platform for integration with miniature atomic vapour cell with optics and electronics https://www.macqsimal.eu/	Development of miniaturised and integrated quantum-enabled sensors based on atomic vapour cells
ASTERIQS			Development of precise sensors made from diamonds to measure magnetic fields, electric field, temperature or pressure.
Quantum Computing Systems			
OpenSuperQ			Building a quantum computer with 100 qubits
AQTION	☑ (intention)	Platform for laser cooling of trapped atoms and ions https://www.aqtion.eu/	Development of a scalable quantum Computer
Basic Science			
2D-SIPC	☑	Photonics integrated chip for quantum networks https://2d-sipc.eu/	Exploration of new quantum devices based on 2D materials for quantum networks. The project focuses on integrated quantum photonics devices from 2D materials into integrated photonic chips.

S2QUIP	☑	Multiplexer for single photon sources https://www.s2quip.eu/	Development of an on-chip multiplexed entangled quantum light sources as a building block for quantum communication, photonic quantum simulations and sensing applications
SQUARE	☑	Multiple Platforms for integration of quantum photonics devices https://square.phi.kit.edu/	Development of new platforms for quantum computing, networking and communication
QMiCS			Building a quantum architecture to implement quantum communication protocols for distributed quantum computing. The project focuses on microwave technologies.
PhoG	☑	Integrated sources https://www.st-andrews.ac.uk/~phog/	Delivering compact, versatile, deterministic source of quantum light based on integrated waveguide networks with engineered loss, and to develop its applications in metrology and other quantum technology tasks.
PhoQuS			Development of platform for quantum simulation based on photonic quantum fluids
MicorQC			Building a scalable quantum computer based on microwave-controlled ion traps
Quantera Projects (projects including QPICS; incomplete)			
SQUARE	☑	Silicon photonics platform for integration of quantum photonics devices https://www.quantera.eu/	Development of silicon photonics platform for integrated quantum cryptography transmitters and receivers.
CUSPIDOR	☑	CMOS Compatible Single Photon Sources based on SiGe Quantum Dots http://www.cuspidor-quantera.eu/	CMOS-compatible photonic sources for quantum communication at telecommunication wavelengths, targeting integration with existing SOI-based quantum photonic circuits.
HiPhoP	☑	High dimensional quantum Photonic Platform	Single-photon sources based on semiconductor quantum dots coupled to

		http://www.quantumdot.eu/	highly reconfigurable 3D photonic glass chips
HYPER-U-P-S	☑ (intention)	Hyper-entanglement from ultra-bright photon pair sources http://hyper-u-p-s.opticsolomouc.org/	Quantum dot embedded in engineered photonic environment for the generation of highly indistinguishable and entangled photon pairs with near-unity extraction efficiency. Investigate performance in both free space and fibre based quantum networks.
ORQUID	☑ (intention)	Organic Quantum Integrated Devices http://orquid.lens.unifi.it	Use of single organic molecules as the interface between these photons, electrons, phonons three quanta so that they can work together as required. Make single molecules to interact with light in waveguides and cavities to generate and detect single photons for quantum photonics.
QuompleX	☑	Quantum Information Processing with Complex Media https://quomplex.wordpress.com/	Control the scattering process for multiple photons in complex media as multimode linear optical networks for generating, manipulating, and transporting complex quantum states of light.

Table 1: Summary of all Quantum Technology Flagship projects during the ramp-up phase of the European Quantum Flagship as well as a selection of QuantERA projects linked to QPICS. The interest in QPICS spans across all four pillars of the Flagship.

Near- and mid-term QPIC products as an enabler for applications in quantum technology

QPIC Technology, incl. relevant fabs in Europe	**Application and Requirements**	Wavelength, Bands	Current state/TRL and time to market
InP	QKD transmitters for CV and DV QKD	1310-1650 nm	TRL3, 2 years' time to market as assembly and packaging challenges are solved
InP-based monolithic photonic integration (SMART Photonics, Fraunhofer HHI)	Monolithic integration of passive waveguides with high-speed actives (lasers, modulators, photodetectors) → Main application in quantum communications (CV- & DV-QKD, QRNGs)	C band	TRL 4-5
InP-CMOS	Low noise balanced receiver (balanced PNs + TIA)	1310-1650 nm 100 MHz - 1 GHz bandwidth	TRL 4, time to market: 2-3 years
Hybrid integration with polymer materials	Quantum Communication protocols, entanglement-based applications, quantum repeaters (?), quantum memories, quantum sensors (?)	600-800 nm	TRL 3, time to market: 3 years for simpler systems, assembly and packaging needs to be addressed
Polymer-based hybrid photonic integration (PolyBoard, Fraunhofer HHI)	Hybrid integration of active elements (InP, GaAs, Si, …) with integrated waveguide platform and filtering elements Micro-optic integration of bulk crystals (ppLN, ppKTP, …) for generation of single and entangled photons → Main applications in quantum communications (CV- & DV-QKD, QRNGs) and quantum sensing (squeezed light, NV centers)	400 nm – 1650 nm	TRL 4-5

Silicon Photonics (SOI)	Sources for heralded photons and entangled photons, optical quantum simulators	Telecom range	TRL 3
SiN (University of Twente, QuiX, FBK Trento, Ligentec, EPFL, LioniX)	Reconfigurable integrated photonic circuits. Requirement: ultra-low insertion losses, scalability to larger circuit sizes.	400-2350nm	TRL 4; Start-up company (QuiX) is commercializing this circuits for quantum applications
Photonic Integration of N/V and SiC centers	Quantum sensors	Red visible spectrum	TRL 2-3
Si APDs and InGaAs APDs	All	500-1600 nm	Performance enhancement (QE and dark count rate)
Integration of superconducting detectors on chip.	All	500-1600 nm, MidIR and up to THz	TRL 3-4
Silicon Photonics (SOI)	QKD – ground and space: Complete QKD Alice module, laser, intensity modulator, polarization modulator, monitor and variable attenuator	1550 nm	In development
Femtosecond laser writing in glasses and crystals (IFN-CNR, University of Rostock, OptoScribe, Femtoprint)	Advantages: polarization transparency; 3D layouts; multi-material fabrication; rapid prototyping; perfect matching with optical fibres; low insertion losses. Application to: integrated sources by nonlinear phenomena; reconfigurable quantum photonic circuits; Quantum sensing. Requirement: ultra-low insertion losses, scalability to larger circuit sizes.	400-2000nm	TRL 4; Several commercial products being developed in other application fields, based on this technology.
Solid-state integrated quantum memories	Key components for quantum repeaters, on-demand single photon sources, quantum internet. Requirement for high coherence time and strong light-matter coupling.	600-1600nm	TRL 3
2D material integrated in waveguides	Fully integrated electrically gated single photon sources	600 – 900nm	TRL3