Quantum PIC Position Paper

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

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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 over one hundred years old, an increasing number of experiments have been devised to test its oddities. Recent discoveries have sparked a second quantum technological revolution, which allows us to exploit the laws of quantum mechanics to increase performance in computation, communication, sensing and 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 communication promises highly secure telecommunications, whilst quantum sensors will establish new medical diagnostic tools, provide resilient navigation systems, allow us to see through fog 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.

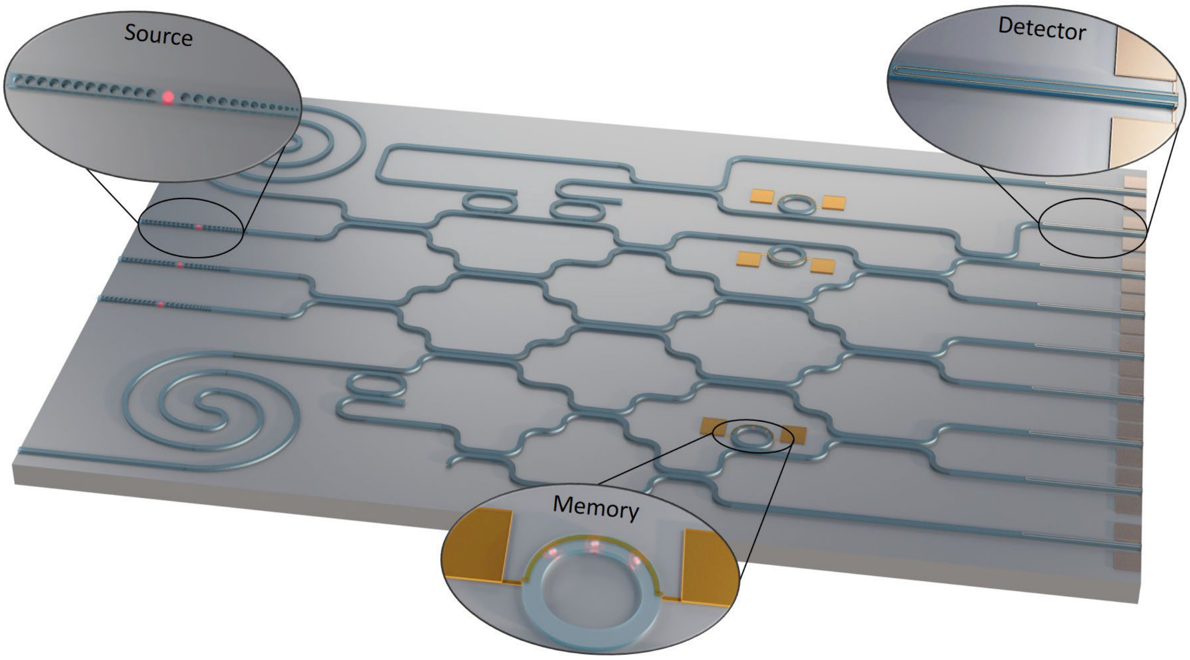

Figure 1: Quantum photonic integrated circuit, including non-linear optics (spirals) and quantum light sources (red dots) in nano-beam cavities, quantum memories (rings including ions), and superconducting detectors (strips), as well as active and passive photonic elements (taken from Nat Rev Phys (2021): https://doi.org/10.1038/s42254-021-00398-z)

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. Without quantum photonics and photonics, quantum technologies would be difficult to implement. Currently, many systems use discrete photonic 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 integrated photonic systems developed and deployed in telecommunication, which have 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 while strongly impacting all pillars of quantum technologies (communication, computation, simulation, sensing & metrology), and foster breakthroughs in fundamental science.

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.).

QPICs require the integration of several diverse device functions on the same base platform to drive the miniaturization process and multiply quantum performance. This is a difficult task, requiring collaboration across multiple centers of expertise in academia and industry. It also requires substantial investment that currently is too risky for industry to make. These exceptional challenges for quantum photonics and its applications need to be overcome to place Europe in a leading position in quantum technologies. The need for QPICs is evidenced in various EU funded quantum projects: for example, 12 out of 20 Quantum Flagship projects include photonic integration or have expressed interest in QPICs (see Appendix A).

We recommend a coordinated effort on the following fronts:

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

The development of European QPICs will be essential in supporting the EU effort towards an effective quantum revolution: accelerating European innovation, enforcing robust European technological leadership, creating jobs and producing significant societal impacts by joining the efforts of academia and industry.

“Classical” photonic integrated circuits (PICs)

Photonic Integrated Circuits (PICs) are photonic systems fabricated on planar substrates, often using tools and techniques that are familiar in the semiconductor industry. Photonic integrated circuits have several advantages over discrete photonic systems: small form factor, cost reduction, increased reliability and robustness and highly repeatable and scalable manufacturing. They are widely deployed in optical telecommunications. Current growth in datacentres and internet traffic, together with the deployment of 5G systems and smart sensor deployment in the automotive, MedTech and AgriTech sectors, have spurred a growing effort towards miniaturization of optical components and their large-scale integration. These efforts echo the achievements of the electronic industry, which started down this track several decades earlier, and have resulted in several integrated photonic circuit platforms currently deployed in specific markets. Many more research platforms are currently being investigated, given their strong potential in specific applications.

Unlike electronic integrated circuits, which are mostly fabricated on silicon wafers, photonic integration is presently conducted on a range of material platforms having different strengths. PICs typically incorporate many active and passive component functions such as sources, detectors, modulators, waveguides, couplers and nonlinear functions. Furthermore, the breadth of the light spectrum used in a variety of applications ranging from ultraviolet to mid-infrared is difficult to cover with a single platform technology.

Silicon-based photonic platforms play a major role, as they benefit from developments of integrated circuits in the electronic industry and their high-volume capability, with manufacturing on large wafers. III-V semiconductors will also be of major importance, due to their high functionality, including efficient light generation. III-V semiconductor PICs are widely used in telecommunications. Furthermore, we note the value of glasses and polymers, due to their transparent properties, and ferroelectric materials for their efficient acousto-optic, electro-optic and piezoelectric interactions.

Active materials (for light emitters, fast switches and quantum memories) are not available in a pure silicon platform, and solutions are found in hybrid, heterogeneous or compound routes. 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-V semiconductors, 2D materials, lithium niobate on insulator, etc.), device structures (quantum dots, nanowires, etc.) and components (e.g. detectors, modulators, memories, transceivers).

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

Photonic platforms can leverage developments in PICs and advance efforts in quantum photonic applications, providing an opportunity to accelerate the development of quantum technologies. Indeed, many envisioned quantum photonics applications require photonic integration to move from simple laboratory demonstrators to real-world technologies, demonstrated in realistic application scenarios in co-existence with classical solutions. In particular, QPIC platforms will have a strong impact on:

Quantum Communication

The classical optical communications sector has been a heavy user of photonic integrated circuits for many years. This will form an excellent basis, though the demands from quantum communication are much more stringent. For example, quantum communication, in which signals cannot be amplified to mitigate transmission losses, requires extremely low-loss circuits and efficient light generation and detection units compared to traditional optical communication.

Quantum communication can be presently classified into two main families, that are largely overlapping in terms of leading photonic integration requirements: quantum cryptography and authentication (e.g. 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, large-scale testing, and integrating quantum memories. Efficient photonic integration of frequency conversion (ideally in a way that preserves polarization-based single-photon encoding) will be necessary for entanglement of quantum nodes over long distances. Quantum repeaters are a particular challenge, since they are required to maintain photon entanglement. Different proposals exist for the implementation of quantum repeaters, all at an early maturity stage: photon pair sources (e.g. parametric down-conversion sources), multi-mode memories, linear optical interferometers, photon number resolving detectors and frequency converters are all examples of enabling photonic devices.

Furthermore, the programmability and management of the technological solutions will also be relevant for enabling dynamic quantum networks. This improves their adaptability and smooth integration in current infrastructures while satisfying the requirements of transmission of quantum signals over optical networks in coexistence with conventional signals. This is an essential requirement that enables wide deployment of the technology. Therefore, this issue needs to be considered early in the development and design of QPICs.

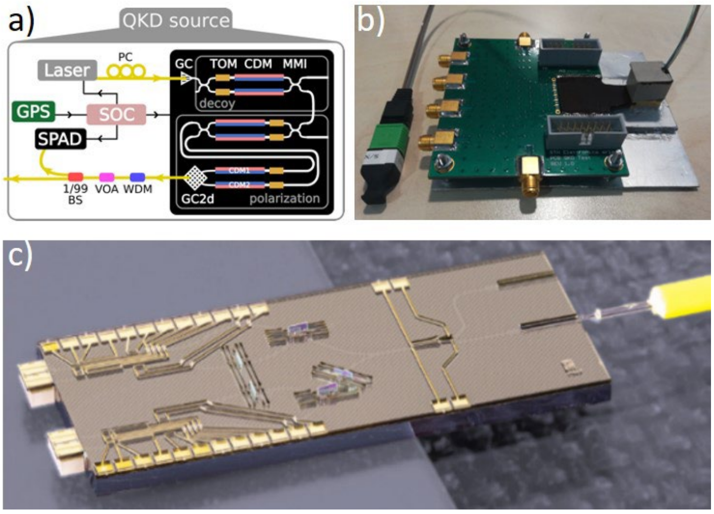

Figure 2: a) shows the scheme of the QKD state generator system and b) the integrated chip including connectors (taken from Quantum Physics (2019): https://doi.org/10.48550/arXiv.1907.10039) . c) Photonic circuit with hybrid integration of transceivers for CV- and DV-QKD, including InP based single photon detectors (courtesy of HHI)

Typically, QPIC efforts for quantum communication are concentrated on silicon-related, InP-based or hybrid platforms, possibly in spectral regions not used in conventional optical communications. Development is underway towards greater integration of electronics and photonics on single platforms, for example, to handle increased clock rates and the relevant (classical) computational overhead. Indeed, photonic integration is vital in the development of quantum communication, as it allows scalable deployment. Figure 2 shows the realization of a QKD state generator on a silicon integrated platform, as well as the hybrid integration of transceivers for continuous variable and discrete variable (CV- and DV-) QKD. Significant impact is expected in the field of secure space links and communications, as well as in quantum random number generators, where integrated photonics offers apparent advantages in terms of physical footprint, energy, stability, and manufacturability over their discrete counterparts. Equally, traditional fibre-based networks (e.g. passive optical networks or even metro optical networks) can benefit from quantum communications, provided that both classical and quantum techniques can share a common deployed infrastructure.

Quantum Computation

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, since 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 or measurement-based nonlinearities 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.

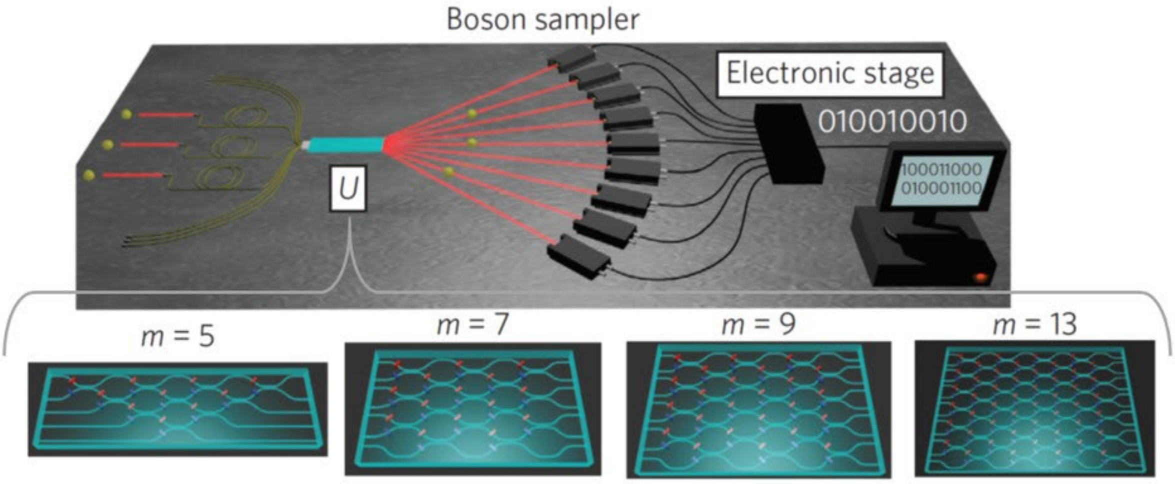

Figure 3: Boson Sampling experiment with integrated photonic circuits of different mode numbers (taken from Nature Photonics (2014): https://doi.org/10.1038/nphoton.2014.135)

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, Canada-based Xanadu and the European based QuiX, which has commercialised a PIC-based 12-mode quantum photonic processor. Such an approach has the potential to leap-frog other platforms on the path to a quantum computer with millions of qubits.

QPICs are essential for QIP as they provide many key features, including scalable and reconfigurable architectures, small system footprint, enhanced light-matter interaction when needed, high stability of optical elements and direct, on-chip interfacing with efficient detectors and CMOS electronics for performing a wide range of classical tasks. Particularly crucial are scalability and reconfigurability, which are needed to provide error correction redundancies, similarly to other QIP technologies. It also allows control and management solutions that can ease real-world implementation and integration within subsystems, systems and networks.

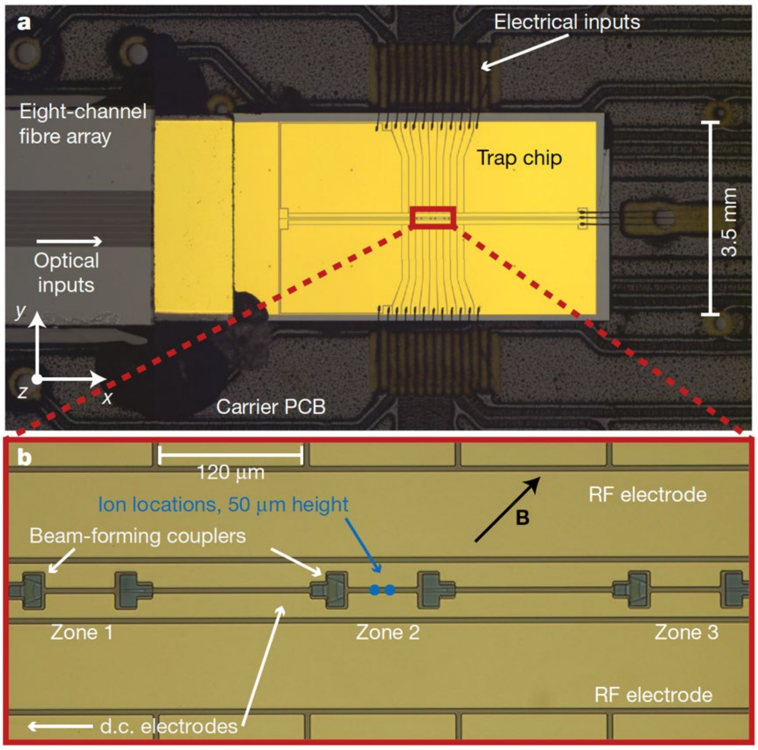

Fig. 4: Optical micrograph of an assembled ion trap device with an eight-channel fibre array attached. b, Higher-magnification view near the trap zones (taken from Nature (2020) https://doi.org/10.1038/s41586-020-2823-6)

Photonic integrated circuits can also benefit other quantum computational platforms. For example, in protocols with atomic or ion traps (Figure 4), the compact realization of laser excitation and light detection is paramount for scalability. Another promising quantum computing platform is based on spin qubits in silicon, where qubits can communicate through photons, which represents a unique opportunity for direct integration with silicon photonics. Superconducting quantum computers can also benefit from QPIC development. The major challenge there lies in making fast optical transceivers that operate at cryogenic temperature with very low energy dissipation. Working at cryogenic temperatures is a requirement for several QPIC applications. Synergies with quantum communication exists, particularly with the quantum internet, since distribution of qubits through quantum nodes will be a requirement 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. 5).

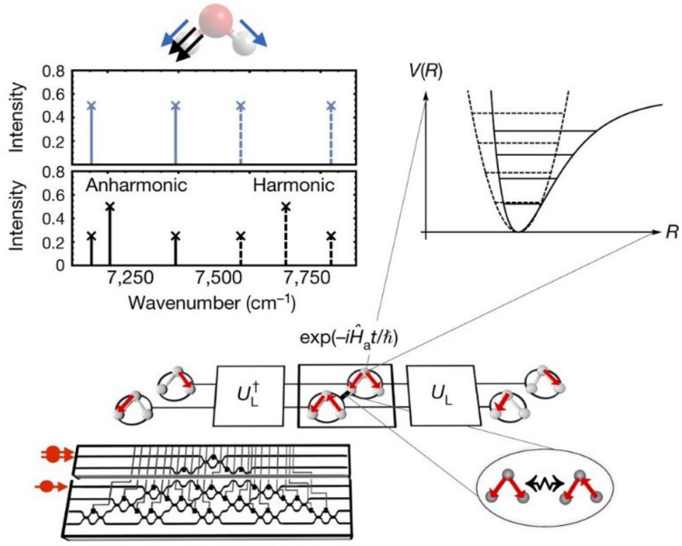

Figure 5: Quantum photonic integrated circuit with thermo-optic phase shifters (bottom) allows for simulating the vibrational quantum dynamics of molecules (taken from Nature (2018): https://doi.org/10.1038/s41586-018-0152-9)

Scalability requires integrating these components in large low-loss circuits to minimize simulation errors based on photon losses. These efforts are also applied 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 that are aligned to what integrated photonic circuits can 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 major developments, with quantum on-chip requirements to reduce footprint and increase dimensionality. These usually require light for control and probing purposes outside the standard optical telecommunication band and therefore different photonic platforms. Efforts largely overlap with the quantum communication and quantum computation objectives, especially in terms of integration of active elements, 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 many 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). There is also a significant interest in new laboratory instrumentation (e.g. super-resolution) enabling the study of new material and device physics.

Photonic integration will be a significant enabler in the fields of compact quantum light sources, on-chip, single-photon detection and signal routing. They solve problems from diverse areas such as quantum reading, single and entangled photon LIDAR, quantum illumination, and quantum-enhanced optical super-resolution, addressing scalability and stability issues, including fast on-chip data analysis. Fig. 6 a) shows an optical circuit connected through fibre optics to light sources and detectors used for quantum sensing. Many quantum sensor systems require low-noise solutions and would particularly benefit from integrating all components on a chip. Figure 6 b) shows a QPIC with a single-photon detector.

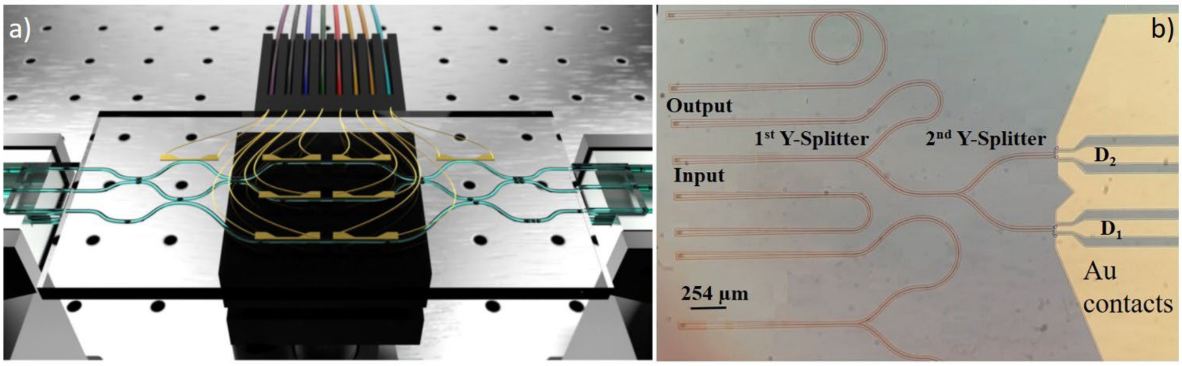

Figure 6: a) Schematic of a compact and versatile integrated photonic circuit for adaptive Bayesian multi-parameter estimation (taken from npj Quantum Information (2020): https://doi.org/10.1038/s41534-020-00326-6). b) Optical microscope image of two (D1 and D2) Superconducting Nanowire Single Photon 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 Optica (2019): https://doi.org/10.1364/OPTICA.6.000823)

Other applications for photonic integration are sensor systems where light is used to control and probe quantum states, such as in sensors based on laser-cooled atom systems or diamonds used for gravity, acceleration and magnetic sensing. Those currently utilise several discrete components connected through optical fibres and would benefit from integration to reduce size and cost and improve robustness. Applications in bio-sensing, medical diagnostics, pharmaceutical drug testing and genomics could significantly benefit from photonic integration of quantum sensors with micro-fluidic platforms.

Basic Science

Underpinning the research into quantum technologies is a strong effort to understand and exploit basic quantum effects. While this effort is pervading the research community, it is evident that photonic integration is an important enabler for fundamental 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), novel topological states with integrated photonic circuits and their detection/characterization, quantum walk physics, and 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, 19 projects have been funded[1], working in all four of the pillars mentioned above. A survey of the Quantum Flagship projects concluded that most projects (12 out of 19) are working on versions of QPICs or intend to develop QPICs in future, as shown in the pie chart in Figure 7. A detailed table with the description of the projects and their link to QPICs is provided in Appendix A. That table also includes a selection of QuantERA projects with connections to QPIC development and application, highlighting that a significant fraction of projects benefits from QPICs, signifying the need for a European effort to develop an infrastructure for quantum photonic integrated circuits.

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[1] Out of the 21 funded projects 19 started with the beginning of the ramp-up phase on 1 October 2018. The two projects NEASQC and QLSI started on 1 September 2020 and are not included in the survey.

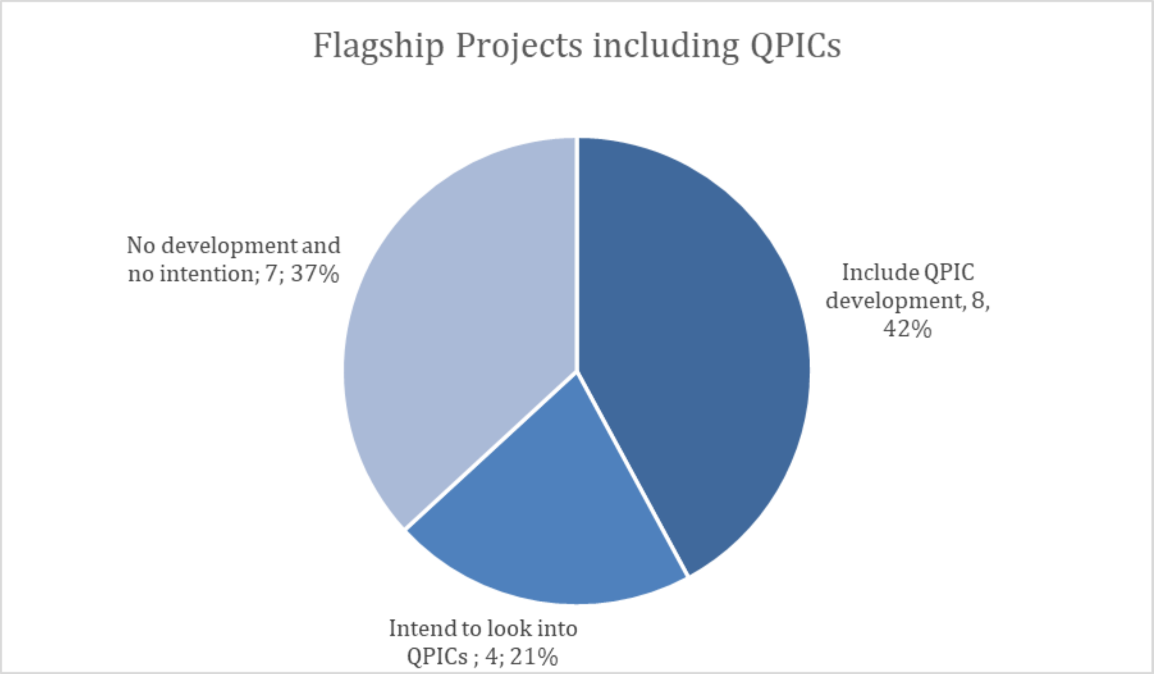

Figure 7: Pie diagram illustrating the need of quantum photonic integrated circuits within the Quantum Technology Flagship projects during the ramp-up phase.

Quantum Photonics Challenges

Photonic quantum devices and components

Photonic integration presently spans a range of maturity levels, from large-scale deployment of complex PICs in classical telecommunications systems, to highly experimental platforms addressing specific application needs. We are still in the early days of the technological implementation of quantum PICs, and many challenges remain to be overcome, including the development of dedicated photonic integrated devices and/or components tailored to the needs of the envisioned quantum applications. Below we consider a lengthy but surely 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:

Components:

- On-chip quantum light sources (e.g. based on nonlinear and high order processes, squeezed light and quantum emitters such as quantum dots, colour centres, defects, and 2D materials)
- Active and reconfigurable photonic circuit elements (attenuators, switches, and modulators based on electro-optic, thermo-optic or MEMS and micro-optical elements)
- On-chip quantum memories (e.g. atomic and solid state based)
- Passive photonic integrated circuit elements (e.g. polarisation preserving, ultra-low-loss optical waveguides, couplers, cavities, splitters)
- Integrated detectors for various wavelength ranges (room temperature or cryogenic, low noise, high efficiency, high timing resolution, small dead time)
- Packaging (e.g. 100s of fibres with cryogenic compatibility, high optical isolation)

Devices:

- On-chip photonic and electrical control and read-out units (on-chip lasers, power stabilization, feed-forward electronics, with possible cryogenic compatibility)

- Large-scale integrated optical photonic processors including on chip quantum random number generator
- On chip and efficient quantum frequency converters
- On chip quantum sensing of biological fluids (hybrid chips with microfluidics)
- On chip low noise and coherent receivers and qubit generators with decoy state functionality
- Integrated cluster state generation, fusion, manipulation and readout units.

Quantum photonic integration into PIC platforms

Quantum photonic integration has transitioned from fundamental research to application-driven activities. Several research groups and start-ups have begun 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 will require custom integration.

There are a number of platforms currently being developed and investigated for specific quantum applications, 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 listed below:

- **Silicon photonics and associated hybrid integration** is in itself a family of platforms, including silicon-on-insulator (SOI) and silicon nitride.
    - **Silicon-on-insulator** technology has mainly been developed for telecom wavelengths and has been applied to QKD. When matched to hybrid/heterogenous integration, silicon photonics can incorporate a number of different elements, such as active III-V materials emitting in the infrared as quantum light or simply as excitation sources, silicon/germanium or hybrid detectors (e.g. SNSPDs), and other nonlinear and active elements/materials for various needs including quantum memories.
    - Wafer scale **silicon nitride platforms** are witnessing a growing interest, as they are not limited to the infrared region and allow for higher energy photons (for example they allow a broad transparent window for ion-based computing) and come with the significant advantage of low losses (when specifically designed). They are also suitable for hybrid integration (and MEMS structures). Pairing these platforms with polymer waveguiding offer additional advantages in terms of manufacturability (also true for what follows below).
- **III-V platforms (InP and (Al)GaAs**) readily provide efficient active sources (and detection); deterministic high-fidelity sources of single and multiple photons based on cavities and waveguides; efficient, high bandwidth modulators, as well as various passive functions. These platforms can offer high-functionality monolithic circuits operating in various different wavelength ranges, with efficient active devices and low optical losses.
- **Silica-on-insulator / laser-written silica / various glasses** can be matched to other platforms to create complete systems, especially for applications such as boson sampling, quantum walks, and quantum simulations, not excluding advanced microfluidics for sensing designs.
- **Lithium niobate** waveguide circuits (including lithium niobate on insulator, LNOI), can provide fast and efficient electro-optic control of light on chip (e.g. modulation) and wavelength conversion (e.g. parametric down conversion, second harmonic generation) in a wavelength range from 350nm to 5.5 µm, as well as hybrid integration with non-classical light sources and detectors.

- **Other substrates** (and their possible integration with previous platforms) include diamond and diamond defects as qubit centres/quantum light sources or as quantum environment probes, various 2D materials (early stages), silicon carbide (SiC), nitrides (III-N), tantalum pentoxide (Ta_2O_5), barium titanate ($BaTiO_3$), and others.

For some applications, cryogenic versions of the above photonic and electronic integration platforms will be required, together with appropriate packaging and assembly schemes, in order to facilitate complex quantum circuit operations.

We should highlight here the need to develop high performance packaging and assembly technologies specifically for quantum applications, where coupling losses are critical, and cryogenic operation may be a requirement. In turn, this also means the development of suitable read-out and control electronics as well as their packaging. Packaging and assembly developments are as important as the QPIC developments themselves, no matter which integration method is chosen.

Market potential from a European perspective

QPICs are featuring as prominent quantum technologies as evidenced by the current activities. They are needed in quantum computing and simulation, quantum communications, QIP, metrology and sensing and their applications. If they are not developed in Europe, they will certainly be developed elsewhere, with Europe falling behind in this area and ultimately in the field of quantum technologies as a whole.

Major initiatives in quantum technologies have been established around the globe. Public funding worldwide is estimated at over €18bn[2], including the initial funding of €1bn (over 10 years) of the European Flagship on Quantum Technologies (European investment increased significantly since then though the exact amount remains unclear) and other multibillion investments released through the quantum science and engineering programmes of the UK, Germany and France. Soaring public funds find their match in VC investments to start-ups and significant resource allocation to quantum technology programmes in global technology giants across the full value chain, from technology enablers and the hardware stack to quantum software and applications in communications, computing, and sensing. These investments are triggered by progress in the field and reflect the significant market size for quantum technologies. Market estimates range from US$2.9bn in 2030 (Yole Development)[3] to the more aggressive forecast of $31.57bn by 2026 (Research & Markets)[4], typical for emerging technologies. The telecom market alone, specifically for quantum cryptography and timing applications, accounts for approximately one third of the total market, or possibly more, and provides a large near-term addressable market of quantum systems and services based on QPICs. Quantum computing, leading in terms of market size, also presents a great opportunity for QPICs as demonstrated by recent progress of scalable photonic computation.

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. 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

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[2] https://onlinelibrary.wiley.com/doi/10.1002/phvs.202000044

[3] https://www.i-micronews.com/products/quantum-technologies-2021/

[4] https://www.researchandmarkets.com/reports/5317365/quantum-technology-market-by-computing

components and their integration into systems, as well as shared deployment infrastructures and close-to-market testbeds. These efforts cover a number of major platforms.

Regarding industrial interest, we see a large number of quantum photonics start-ups and SMEs providing enabling technologies for QPICs, as well as the many large European companies that are already actively involved in quantum technologies (e.g. Atos, BAE Systems, Bosch, BT, Teledyne, Telefonica, Thales). Examples of smaller companies presently engaged in this field (and this is surely not an exhaustive list) include AegiQ (single photon sources), APE (single photon sources), AUREA (entangled photon sources and counters), CSEM (LNOI for QPICs), Duality Quantum Photonics (QPICs), FISBA (optical components and microsystems), IDQ (QKD), imasenic (single photon detector arrays), KETS (quantum secure communication), LIGENTEC (silicon nitride for QPICs), LightOn (optical processing units for machine learning), LioniX (silicon nitride PICs and hybrid assemblies), M Squared Lasers (atom interferometers, quantum sensors, quantum computing), NuQuantum (single photon detectors and sources), Orca Computing (quantum computation and photonic memory), OROLIA (space atomic clocks), Q.ant (lasers for Quantum technologies, owned by Trumpf), QLM (quantum imaging for gas detection), QUANDELA (quantum light emitters), QUARTIQ (optical single-ion clocks), QuiX (silicon nitride QPICs for machine learning & quantum computation), SMART Photonics (PICs), Sparrow Quantum (deterministic single-photon chip technology), Toptica Photonics (tunable diode lasers for optical clocks & quantum sensors), Vixar/OSRAM (VCSELs for atomic sensors), VLC Photonics (QPICs design), and VPIphotonics (design software for QKD). The quantum photonic integrated circuit start-up PsiQuantum, which recently raised over €200M, is largely a spin-off of European laboratories, though now based in the USA. Fortunately, several European startups are now also working in this area.

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 regarding wider applications and market penetration. Several monolithic, hybrid, and hetero-integration platforms are presently being investigated, and there is likely to be consolidation in the next few years as the technologies develop. They will be leading technologies for the deployment of future data centres, 5G and the coming 6G and the internet of things in which the highest security will be the primary requirement.

Applications of quantum photonic integration have emerged on top of the foreseeable short- and medium-term developments. Those linked to quantum information and communication have a better chance to leverage 'classical' platforms and exploit them as the foundation of scalable and robust QIP devices. This entails developing quantum nodes, subsystems and systems for real-world implementation and the improvement of the maturity and readiness level, thus reducing the time-to-market of quantum technologies in future quantum communication networks. Nevertheless, the envisioned quantum devices are likely to have specific requirements that are not currently provided by 'classical' platforms, e.g. a combination of extremely low losses, photon indistinguishability, and photon polarization transparency. These specific features require dedicated developments that need investment to push the current fabrication technologies to a more mature level and to improve the device packaging and integration, which is typically one of the most critical steps for device losses and reliability. This development is risky and is accordingly unlikely to be funded by private or corporate sources. It would significantly benefit from European funding, pulling pan-European efforts, expertise and resources together, which is likely to be more successful than single national funding.

Europe has a very strong and dynamic ecosystem that can be harnessed to position Europe in the global supply chains of quantum photonics technologies and services. However, there is a risk of effort being dispersed 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 to leverage from their experience, investment and manufacturing capability and, where required, augment them with new facilities that deliver unmet functionalities and specific performance enhancement, drawing in new players. This would be a more efficient use of European investment, allow existing suppliers to grow, and establish a widely exploitable multi-technological infrastructure open to European researchers much faster than starting afresh.

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 that are needed to enable wide adoption for quantum technologies. From the 19 Quantum Flagship projects that started at the beginning of the ramp-up phase, more than half have already expressed the need for collaborative photonic integration efforts. Europe has developed a strong position in photonic integration over the past decades, but the rest of the world is not standing still. 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 performance of photonic circuits is driven by new and improved materials, advanced integration, and packaging. Without the development of new platforms, new on-chip devices and modules with better functionality, accuracy and stability, Europe will not cope with the demands of the world market. Thus, Europe needs to invest in developing components and supply chains for new photonic integration platforms and ensure that it maintains a globally leading position in these key technologies.

    - We recommend joint or coordinated Horizon Europe calls between the Quantum Flagship and Photonics Partnership, the next opportunity for which will be in the Horizon Europe work programme for 2023/24. Both initiatives can benefit from each other: quantum technologies require new solutions which could also benefit other application areas. The collaboration will cross-fertilize. On a related note, we also recommend joint road-mapping activities in key areas.

- Promote infrastructures for QPICs
  Quantum photonic integrated circuits are based on several key technologies, each requiring dedicated expertise, equipment, and facilities to be brought together. Europe must promote a coordinated approach to ensure complete coverage of these strategic technological capabilities within Europe and to build synergies 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 appropriately on existing centres and expertise
    - Ensure availability of supporting technologies such as packaging, testing and system integration
    - Take measures to ensure effective innovation and market introduction, so that IP generated in Europe leads to exploitation within Europe.

- Invest in a significant education effort to train next generation quantum photonic engineers
  As integrated quantum photonic technologies become a reality in everyday life, there will be an ever-growing demand for scientists and engineers with substantial knowledge of quantum photonics, photonic integration and its technological applications. The current talent pool is insufficient to ensure future quantum innovation. Europe cannot afford to have the next wave of tech unicorns located outside Europe. 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-ups in Europe.

Appendix 1: Quantum PIC Technology in Quantum Flagship and QuantERA Projects

	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, quantum dot entanglement sources, 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			
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
Qombs			Quantum simulator platform made of ultracold atoms performing simulations for engineering quantum cascade laser frequency combs.
Quantum Sensing & Metrology			
ASTERIQS			Development of precise sensors made from diamonds to measure magnetic fields, electric field, temperature or pressure.
iqClock	☑ (intention)	Rugged, miniaturised laser system for strontium optical clock https://www.iqclock.eu/	Development of ultra-precise and low-cost optical clocks
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
MetaboliQs			Development of a cardiac medical diagnostic imaging tool based on diamond quantum sensor technology
Quantum Computing Systems			
AQTION	☑ (intention)	Platform for laser cooling of trapped atoms and ions https://www.aqtion.eu/	Development of a scalable quantum Computer
OpenSuperQ			Building a quantum computer with 100 qubits

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.
MicroQC			Building a scalable quantum computer based on microwave-controlled ion traps
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
QMiCS			Building a quantum architecture to implement quantum communication protocols for distributed quantum computing. The project focuses on microwave technologies.
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

Quantera Projects (projects including QPICS; incomplete)			
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 http://www.quantumdot.eu/	Single-photon sources based on semiconductor quantum dots coupled to 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.
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.

uTP4Q	☑	A versatile quantum photonic IC platform through micro-transfer printing (Website not yet available)	Build a flexible platform for QPICs through micro-transfer printing of quantum dot sources, modulators and detectors on common SiN-platform.

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