The potential and global outlook of integrated photonics for quantum technologies

Emanuele Pelucchi[1], Giorgos Fagas[1], Igor Aharonovich[2], Dirk Englund[3], Eden Figueroa[4,5], Qihuang Gong[6,7,8], Hübel Hannes[9], Jin Liu[10], Chao-Yang Lu[11], Nobuyuki Matsuda[12], Jian-Wei Pan[11], Florian Schreck[13,14], Fabio Sciarrino[15], Christine Silberhorn[16], Jianwei Wang[6,7,8] and Klaus D. Jöns[16]✉

Abstract | Integrated quantum photonics uses classical integrated photonic technologies and devices for quantum applications. As in classical photonics, chip-scale integration has become critical for scaling up and translating laboratory demonstrators to real-life technologies. Integrated quantum photonics efforts are centred around the development of quantum photonic integrated circuits, which can be monolithically, hybrid or heterogeneously integrated. In this Roadmap, we argue, through specific examples, for the value that integrated photonics brings to quantum technologies and discuss what applications may become possible in the future by overcoming the current roadblocks. We provide an overview of the research landscape and discuss the innovation and market potential. Our aim is to stimulate further research by outlining not only the scientific challenges of materials, devices and components associated with integrated photonics for quantum technologies but also those related to the development of the necessary manufacturing infrastructure and supply chains for delivering these technologies to the market.

The understanding provided by quantum mechanics revolutionized technology, leading to the development of semiconductors, transistors, lasers and, from there, to computers and the internet. These first-generation quantum technologies transformed society and advanced scientific understanding. The notion of non-local correlations (entanglement), which first seemed a flaw in quantum theory, has been experimentally tested with increasing sophistication and led to unexpected applications[1–5]. Quantum entanglement and quantum superposition[6] underlie the second generation of quantum technologies[7–9], which found applications in computation[10], simulation[11], communication[12], sensing and metrology[13–15] tasks.

Superconducting circuit-based and photon-based quantum computers have claimed computational advantage over today's conventional processors[16], albeit for specific tasks. Whereas many scalability, implementation and algorithmic challenges remain, quantum computing target applications include (a large family of) optimization problems, which could be used in designing targeted drugs more efficiently and for personalized medicine[17–19] or improving logistics[20] to protect natural resources and managing financial and personal risk[21]. Ultrasensitive quantum sensors could enable advanced medical imaging and high-precision navigation[22]. The quantum internet[23,24] theoretically promises information-secure communications, while democratizing access to cloud quantum computers.

In contrast to other platforms for realizing quantum technologies, quantum optics (that directly exploits the quantum properties of light, often at the level of individual light particles, the photons) offers a number of key advantages for several tasks, including information processing[25], computing[26] and communication[27]. Combined with the classical photonics tools and devices, quantum photonics has become an enabling technology to drive radical changes in all areas of quantum technology. As in classical photonics, chip-scale integration has become critical for scaling up and translating laboratory demonstrations to real-life technologies. The central goal of the emerging multidisciplinary field of integrated quantum photonics is to exploit the opportunities offered by quantum optics for practical developments in quantum communication, computation, simulations and sensing.

Although quantum technologies have attracted much attention, the potential of integrated quantum photonics[28] remains perhaps underappreciated. The development of integrated photonics for quantum

✉e-mail: klaus.joens@upb.de

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Key points

- Photonic quantum technologies have reached a number of important milestones in the last 20 years, culminating with the recent demonstrations of quantum advantage and space-to-ground quantum communication.
- Scalability remains a strong challenge across all platforms, but photonic quantum technologies can benefit from the parallel developments in classical photonic integration.
- More research is required as multiple challenges reside in the intrinsically hybrid nature of integrated photonic platforms, which require a variety of multiple materials, device design and integration strategies.
- The complex innovation cycle for integrated photonic quantum technologies requires investments, the resolution of specific technological challenges, the development of the necessary infrastructure and further structuring towards a mature ecosystem.
- There is an increasing demand for scientists and engineers with substantial knowledge of both quantum mechanics and its technological applications.

Silicon photonics
A materials platform for photonic integrated circuits. It uses silicon as the main optical medium and easily combines electronic and infrared optic elements.

Monolithic integration
The creation of multiple components on (the same) chip, as in complementary metal–oxide–semiconductor electronic integrated chips in silicon. The creation of all different functionalities is achieved by the same production platform and materials associated to it, with no external addition. Better understood as opposed to hybrid or heterogeneous integration.

technologies (IPQTs), especially quantum photonic integrated circuits (qPICs) (FIG. 1), will be essential to achieve robust technological breakthroughs. In this Roadmap, we outline the value that integrated photonics brings to quantum technologies and discuss future applications and their current roadblocks. Our aim is to stimulate further cross-disciplinary research by mapping out the uncharted territory, outlining the challenges of materials, devices and components associated with IPQTs and advocating for the need to develop the necessary infrastructure.

From classical to quantum PICs

The increasing volumes of information transmitted through optical fibres and the deployment of smart sensors in different industries motivated a growing effort towards the miniaturization of optical components and their large-scale integration, following, with a delay, what had already been achieved in the electronics industry.

Author addresses

[1]Tyndall National Institute, University College Cork, Cork, Ireland.
[2]ARC Centre of Excellence for Transformative Meta-Optical Systems (TMOS), Faculty of Science, University of Technology Sydney, Ultimo, New South Wales, Australia.
[3]Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA, USA.
[4]Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY, USA.
[5]Brookhaven National Laboratory, Upton, NY, USA.
[6]State Key Laboratory for Mesoscopic Physics, School of Physics, Peking University, Beijing, China.
[7]Frontiers Science Center for Nano-optoelectronics & Collaborative Innovation Center of Quantum Matter, Peking University, Beijing, China.
[8]Peking University Yangtze Delta Institute of Optoelectronics, Nantong, Jiangsu, China.
[9]AIT Austrian Institute of Technology GmbH, Vienna, Austria.
[10]State Key Laboratory of Optoelectronic Materials and Technologies, School of Physics, Sun Yat-sen University, Guangzhou, China.
[11]CAS Centre for Excellence and Synergetic Innovation Centre in Quantum Information and Quantum Physics, University of Science and Technology of China, Shanghai, China.
[12]Department of Communications Engineering, Graduate School of Engineering, Tohoku University, Sendai, Japan.
[13]Van der Waals-Zeeman Institute, Institute of Physics, University of Amsterdam, Amsterdam, Netherlands.
[14]QuSoft, Amsterdam, Netherlands.
[15]Dipartimento di Fisica, Sapienza Università di Roma, Rome, Italy.
[16]Institute for Photonic Quantum Systems, Center for Optoelectronics and Photonics Paderborn and Physics Department, Paderborn University, Paderborn, Germany.

Similar to their semiconductor electronics counterparts, photonic integrated circuits (PICs) rely on wafer-scale fabrication techniques to integrate many optical components and, often, complementary electronics, on a single substrate. The effort to develop a scalable manufacturing PIC platform has generated a number of solutions currently deployed in niche markets (such as data centre high-speed pluggable transceivers, specific integrated sensing/monitoring solutions for industrial automation or even the microelectromechanical systems (MEMS)-switching optics in optical projectors), whereas many other approaches are investigated for broader applications. These alternatives can be categorized by the material used for the photonic waveguide: silicon photonics, glasses, polymers, ferroelectrics, ceramics or III–V semiconductors (GaAs, InP) and III-nitrides (III-N).

Unlike integrated electronics, competing functionalities impede the realization of PICs from a single material system and platform (monolithic integration), resulting in several bespoke approaches for specific applications, with a proliferation of methods to integrate a variety of materials (III–Vs, 2D materials, point defects in specific materials, lithium niobate on insulator (LNOI) and so on), architectures (heterostructures, quantum dots, nanowires) and devices (lasers, modulators detectors, memories and so on) on the more common photonic platforms. The integration process of external components on top of the photonic waveguide chip itself presents huge challenges and can be broadly classified as hybrid, that is, the insertion in various ways of heterogeneous components to a specific chip platform[29], and heterogeneous, that is, the direct deposition (largely epitaxial) of various active materials on the chip wafers, and different from the native wafer composition[30]. Different sub-communities might use slightly different wording and definitions, as there is, unfortunately, no general consensus on the exact use of the terminology[31–35].

Integrated photonics plays a key role in the miniaturization, stabilization and scaling up of components for classical applications. Classical photonic integration platforms are expected to contribute to the development of quantum technologies, enabling more scalable, robust, compact and cheaper quantum devices. They will also impact quantum technologies that do not directly exploit the quantum properties of light, such as quantum computers based on atoms or ions[36], optical clocks[37] or gravimeters[38]. Such quantum devices require sophisticated control of laser beams to create or manipulate the quantum states. Quantum technologies based on cold atoms and trapped ions rely on laser beams to cool an atomic gas from room temperature to near absolute zero, and atomic clocks, for example, interrogate narrow linewidth transitions of these atoms to obtain an absolute frequency reference. In addition to that, ion trap quantum computers use sequences of laser pulses to implement gate operations between the qubits encoded in the ions. The type of atoms used in these devices dictates the wavelengths of the required laser beams and the operation protocol sets the requirements on the frequency and intensity control of the laser beams. Ultracold atom quantum simulators, using atoms trapped in optical

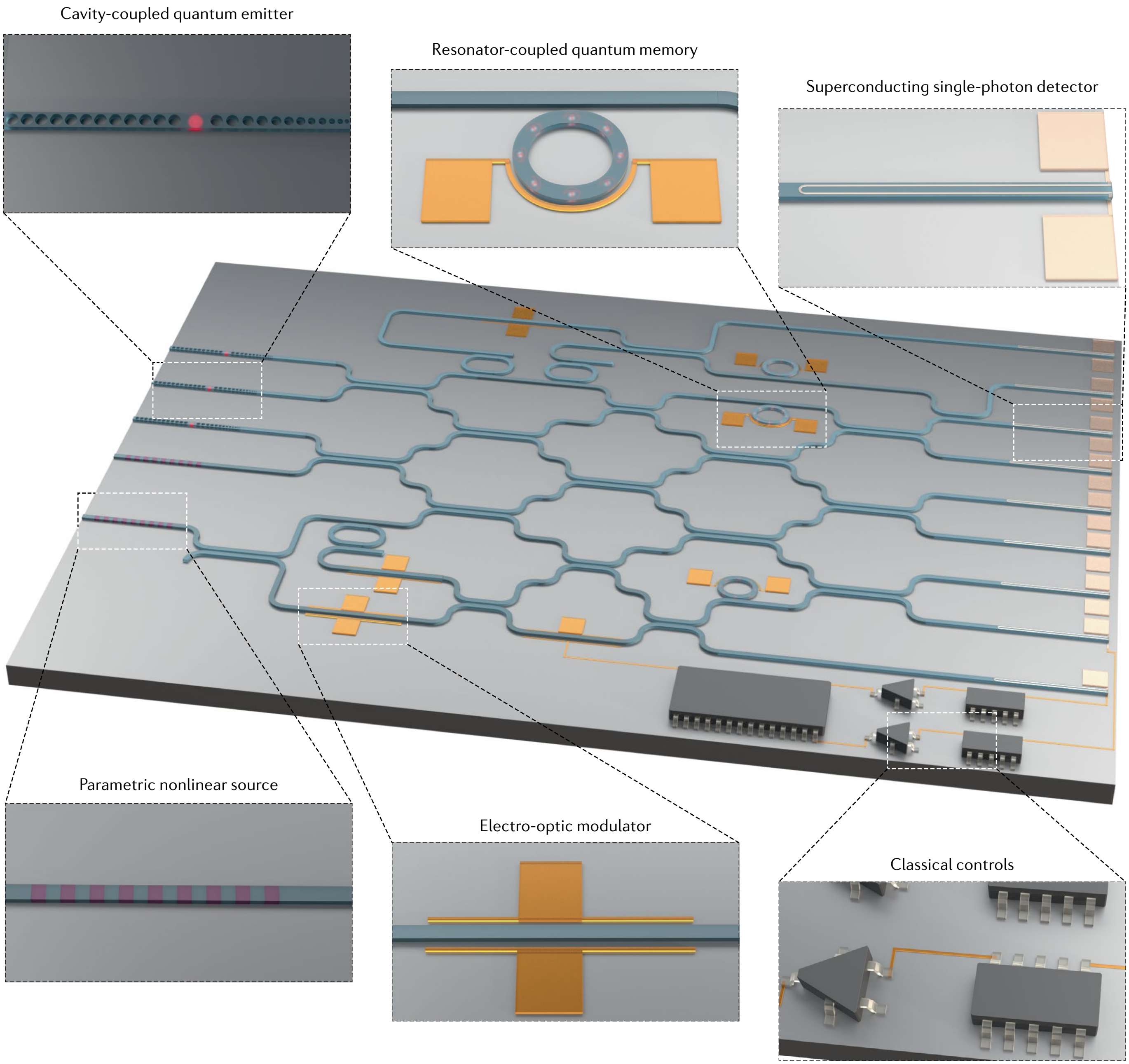


Fig. 1 | **qPIC architecture.** Quantum photonic integrated circuits (qPICs) are the devices realizing the various applications of integrated quantum photonics. They can be monolithically, hybrid or heterogeneously integrated and can harness the current progress of classical photonic integration platforms. qPIC architecture includes nonlinear optics (such as periodically poled structure) and quantum light sources (red dots/defects) in nanobeam cavities, quantum memories (optical resonators including ions/atoms), electro-optic modulators/switches and single-photon detectors (superconducting nanowires), classical controls (electronic components) and active and passive photonic elements. Some components are not represented in the figure due to space limitations, such as filter and classical pump sources.

lattices, have similar requirements in terms of the optical control systems. The challenge is to develop integrated photonics tailored to the specific needs of these quantum devices, which implies, but is not limited to, the fine tuning of the wavelengths/frequency, phase/polarization, power levels and intensity control of laser light, as well as integrated frequency[39] and microcombs[40].

The development of PICs for quantum devices can help overcome the fundamental bottleneck in achieving higher levels of technology readiness and commercialization. For example, integrated photonics has the potential to make trapped ion clocks orders of magnitude more compact and robust, and affordable enough to serve on mobile platforms, such as satellites, or for telecoms network synchronization, underground exploration and navigation. In quantum cryptography, the availability of cheap and small transmitter/receiver units would greatly facilitate an extensive roll-out.

Quantum repeater
A device capable of allowing transmission over long distances of quantum signals beyond the limits imposed by fibre losses (i.e. it allows repeating it over several network segments), without destroying the quantum superposition/features. Typical schemes share entanglement over several nodes and (often) necessitate quantum memories.

Coherent receivers
Receivers of an optical signal that are capable of recognizing both the intensity and the phase terms of the impinging light.

Feedforward operation
Feedforward is the process of monitoring a physical system and subsequently using the attained information to change the system, so as to control it towards a certain target state. For example, in quantum circuits, this implies taking a decision on how to modify a section of the circuit that will be active at a later stage after a specific previous outcome of another section of the circuit is known. Time constraints during operation are significant in this case.

Cluster states
Refers to a specific type of highly entangled state of multiple qubits. The design is such that, after a measurement on a single qubit component is performed, entanglement between the other components is preserved. Cluster states are especially useful in the context of the one-way quantum computer.

Quantum memory
A device capable (for a certain amount of time) of storing quantum information (or quantum state) and later release it on demand (it is, in short, the quantum-mechanical version of ordinary computer memory). They represent essential building blocks in quantum networks.

qPICs in quantum technologies

qPICs are expected to play an essential role in quantum technologies, as they provide several key features, including: scalable and fast reconfigurable architectures with small system footprint[41,42]; enhanced light–matter interaction when needed; a strongly required high stability of the optical elements[43]; a direct on-chip interfacing or co-integration with efficient single-photon detectors[44,45]; and complementary metal–oxide–semiconductor (CMOS) electronic readout and feedforward control[46]. We briefly outline below the impact of qPICs in different areas.

Quantum communication

Quantum communication can be classified into two families, largely overlapping in terms of leading photonic integration requirements (particularly for the fibre-based quantum communication systems): quantum cryptography (quantum key distribution, QKD)[47] and distributed quantum computation via a quantum internet[23,24]. In both cases, there are a number of recently funded international initiatives aiming at transitioning from individual and bulky tabletop apparatus to compact integrated systems. As these projects are still at an early development stage, the focus is on the much needed integrated optics[48] for creating on-chip platforms for quantum networks[49] and quantum repeater nodes[50], with integrated light sources (attenuated lasers, entangled, squeezed and single-photon sources), single-photon detectors, modulators, coherent receivers, routers, micro-optical elements and several other necessary components. Different types of quantum repeaters exist[51–55], requiring error correction, feedforward operation, cluster states or quantum memories to achieve arbitrary long-distance quantum communication. In general, challenges in quantum communications also include coupling external interfaces such as optical fibres or electrical controls and/or large-scale testing, integration of quantum memories and interfaces with classical telecommunications. Efficient photonic integration of frequency conversion will be important for entangling quantum nodes over long distances.

Typically, the efforts towards the exploration of suitable photonic waveguiding chips are concentrated on materials such as silicon (Si), silicon oxide (SiO_2), indium phosphide (InP) or Si–InP–polymer-hybrid PIC platforms and, recently, lithium niobate. There are, nevertheless, also approaches using nitrogen vacancies or silicon vacancies (NV/SiV) in diamond, rare-earth and silicon carbide (SiC) spin systems, as well as yttrium iron garnet/yttrium orthosilicate (YIG/YSO) platforms, mainly because of their promising quantum memory parameters. All platforms for quantum communications need to achieve a stronger integration of electronics and photonics to handle increased clock rates, low cost and portability, the relevant (classical) computational overhead of signal post-processing (for example, the post-selection of probabilistic measurement outcomes and quantum state analysis) and, ultimately, scalable deployment.

qPICs are expected to have an important impact on quantum communication through space links[56] and optical fibres, where integrated photonics offers advantages in terms of the physical footprint, weight, energy consumption, stability and manufacturability compared with existing proof-of-principle demonstrations.

Quantum computation and simulation

The fundamental requirements for any quantum computing technology[25,26,57–60] include the fine degree of control over the qubits and their nearly complete isolation from the environment. Among the different physical realizations of qubits, photons occupy a special place: they interact weakly with transparent optical media and little among themselves, which makes the information they encode robust against decoherence. Optical quantum computing can be classified into specific quantum computing models (for example, boson sampling)[61] and universal quantum computing models (for example, one-way or measurement-based)[62–65]. Depending on the way the quantum states of light are used to encode information, there are discrete variable and continuous variable[66] models, or their hybridization, providing different implementations of specific and universal quantum computation.

As an example of a specific quantum computation, boson sampling represents a fixed/specified sampling task that relates to the calculation of the expectation value of the permanent of a matrix (a function akin to the determinant)[61]. Its physical implementation is the following: n indistinguishable bosons (such as photons) are sent into a m-mode linear optical interferometer whose output distributions of bosons are recorded. These output distributions are hard to be sampled or simulated classically. A photonic system enables a natural and effective implementation of boson sampling. The first generation of boson sampling machines used a few photons[67–70], mainly in qPICs. Boson sampling with on-demand indistinguishable single-photon sources from quantum dots have been implemented to greatly boost the detected photon number[71–74]. Improved implementations (in both bulk optics and qPICs) of more scalable boson sampling followed. Examples include scattershot boson sampling[75,76], which can overcome the limitation posed by the probabilistic nature of parametric downconversion sources, and Gaussian boson sampling[77], which can dramatically enhance the sampling rate with the adoption of squeezed light sources. A milestone that demonstrates a quantum computational advantage was delivered by the Jiuzhang quantum computer based on Gaussian boson sampling[16]. Jiuzhang consists of 50 indistinguishable single-mode squeezed states, a 100-mode low-loss interferometer and 100 single-photon detectors, and, thus, allowed a sampling process of up to 76 detected photon-clicks (an overall Hilbert space of dimension 10^{30}), which got recently updated and extended to Jiuzhang 2.0 (REF.[78]).

Universal all-optical quantum computing is possible, as proved in the Knill–Laflamme–Milburn (KLM) scheme[79], which only requires indistinguishable single-photon sources, linear optical quantum circuits and single-photon detectors. Entangling operations rely on the quantum interference of photons and the successful detection of ancillary photons in the ancillary modes.

Dynamic range
The range of values that a certain apparatus/detector can achieve for a specific application.

The KLM scheme, however, suffers from heavy overhead requirements. A number of major functionalities have been demonstrated with tabletop optical components[80], and their translation to qPICs have been realized on several waveguide platforms, for example, KLM-type controlled NOT (also known as CNOT) gate and its heralding version[43,81], and compiled Shor's factorization[82]. These achievements were seen as important milestones.

The circuit implementation is pertinent for noisy intermediate-scale quantum applications, which do not require a large number of qubits. Moreover, stepping towards large-scale fault-tolerant quantum computing, both architectural and technological efforts have been dedicated to the one-way model by the fusion operation of large entangled cluster states. This approach is compatible with the nondeterministic nature of photons and particularly effective in conjunction with percolation strategies to realize fault-tolerant computing. Furthermore, it can be significantly improved by implementing resource state generation and fusion operation natively[83–85]. Experimental demonstrations include the creation of 18-qubit star graph states in bulk optics[86], four-photon star graph states and linear-and-box graph states in Si (REFS[87,88]) or SiO_2 chips[89] and programmable eight-qubit graph states in a Si chip[90].

Quantum simulation[11] is believed to be one of the most promising applications of quantum computers. In contrast to analogue quantum simulation approaches, the hardware requirements for universal photonic quantum simulators are nearly in line with that of universal quantum computers. Photonic quantum simulators[25,71,72,91] have been demonstrated in the lab and will benefit from the scaling perspective of integration. A qPIC enables a versatile noisy intermediate-scale quantum platform to execute specific quantum simulation tasks by implementing certain quantum simulation algorithms. For example, qPIC simulators[72] in Si and SiO_2 chips have been reported for the estimation of molecular eigenenergies by implementing quantum phase estimation[75,92,93] or variational quantum eigensolver[94,95] and for the simulation of spin dynamics in solid-state systems[96]. Photonic integration for quantum simulation has gone beyond demonstrators to establish qPIC platforms, see, for example, Si and SiO_2 devices for quantum walks[97–99] and boson sampling demonstrators. The on-chip generation and processing of squeezed states in the context of Gaussian boson sampling have enabled the calculation of molecular vibronic spectra on a Si chip (up to eight photons)[80] and a SiN chip (up to 18 photons)[100].

Integrated optics also promises to solve critical quantum control challenges in other quantum computing and simulation platforms. Co-integrating compact, phase-stable and high-quality PIC devices with natural and artificial atoms and trapped ions[101–104] can provide integrated, scalable and low-noise quantum controls of these atomic systems, for example, for laser initialization, laser cooling, qubit addressing and readout. Progress over the past few years includes experimental demonstrations of high-fidelity operations of trapped ions in PICs[105–107], controls of natural atoms in photonic crystals[108,109] and photon–spin interactions in waveguide devices[110,111].

Quantum sensing and metrology

Quantum sensing and metrology exploit quantum effects (such as entanglement and state squeezing) to optimize measurement precision. For example, low-power quantum radars[112,113] (proposed remote-sensing devices that may find applications for stealthy short-range target detection[114] or proximity sensing and environmental scanning in robotic applications) require extremely efficient detectors for electromagnetic field sensing. Such detectors are currently being developed using defects in diamonds[115,116], which have unprecedented sensitivity, while sufficient dynamic range and resolution can also be achieved[117]. Precise temperature sensors and other sensors for medical applications are also currently being developed. There is interest in new laboratory instrumentation (such as super-resolution imaging)[118]. A chip-based single-photon source has been used for high-precision quantum metrology using state squeezing[119].

Photonic integration can improve the performance and size, weight and power of such sensors through the use of compact quantum light sources, on-chip detection and signal routing. In particular, integrated single-photon detectors based on superconducting materials[44,120] offer unprecedented efficiencies at cryogenic temperatures. Such detectors can be combined with classical active circuit elements, such as modulators and MEMS tunable beam splitters to generate feedback loops, reconfigurable circuits, feedforward operations, as well as circuits for classical photonic applications, such as on-chip power stabilization and high-dynamic-range integrated power meters[121]. The adoption of PICs may ultimately deliver large-scale manufacturable, packaged and portable quantum sensors and clocks[122]. Efforts naturally and largely overlap with the quantum communication objectives for synchronization, equally in terms of active elements integration, coupling and routing.

Basic science

The development of quantum technologies relies on a better understanding of quantum effects and photonic integration can be an enabler for basic science discoveries[123–125], such as new physical effects, functionalities or devices. Examples include endowing and controlling new quantum effects in integrated optical and optomechanical cavities[126,127] (for example, quantum light from coupled quantum modes or advanced frequency comb quantum features), quantum coherence of macroscopic mechanical oscillators[128], quantum optical neural networks[129], new topological states with integrated photonic circuits[130] and their detection/characterization. The development and optimization of integrated quantum light detectors, together with additional building blocks, will be relevant for quantum reading[131], single and entangled photon LIDAR[132], optical clocks, quantum illumination[133], variational learning with photons[134] and quantum-enhanced optical super-resolution[135,136], addressing scalability and stability issues, including fast on-chip data analysis[137]. For most photonic quantum technologies, specifically designed and optimized quantum light sources are needed. A large scientific community is investigating different types of quantum light sources, from natural atoms to solid-state quantum emitters and nonlinear crystals, to cope with specific needs of individual applications.

Generally speaking, qPIC platforms may allow the fundamental understanding of new physics, such as topological and non-Hermitian physics, and allow the investigation of new physics, such as many-body phase transition and dynamics.

Challenges of IPQTs

Photonic devices and components

One of the challenges that photonic integration needs to overcome is that of matching the photonic integrated devices and/or components to the required quantum application. We provide below a non-exhaustive list of classical control devices and circuits that are currently being developed for integration, each at a different stage of maturity:

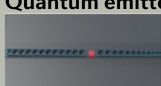
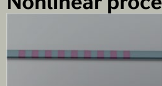
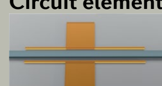
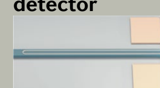
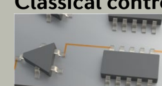
- On-chip laser sources and amplifiers at the specific wavelengths.
- On-chip frequency stabilization (such as sub-kHz, Hz lasers or frequency combs).
- On-chip frequency shifters.
- On-chip intensity control.
- On-chip frequency, phase and amplitude, mode control elements for trapped ions.
- On-chip MEMS and micro-optical elements fitted with high spec tolerances.
- On-chip low-loss, high-speed active photonic optical switches and passive signal routing.
- Ultra-low-loss optical waveguides and delays.
- On-chip low-noise (single-photon) detectors.
- On-chip polarization-preserving integrated waveguides at multiple wavelengths and integrated elements for polarization and wavelength handling and filtering.

Quantum photonics requires all classical building blocks mentioned above as well as:

- On-chip highly controllable and tunable, high-Q, low-mode-volume quantum cavities (such as ring resonators, photonic crystals).
- On-chip quantum memories in both their atomic or solid-state forms.
- On-chip stable quantum emitters based on nonlinear and high-order processes (such as heralded sources like spontaneous parametric downconversion sources), entanglement sources and squeezed light sources at various frequencies.
- On-chip quantum emitters based on quantum confinement.
- On-chip low-noise single-photon detectors and coherent receivers, such as homodyne detectors.
- On-chip efficient quantum frequency converters between visible and telecoms, optical and microwave.
- On-chip fast feedforward operations.

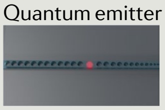
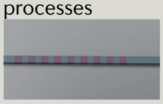
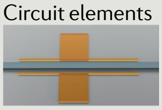
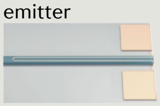
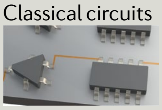
TABLE 1 summarizes the above list of devices in terms of the elementary building blocks, namely, quantum emitters, nonlinear processes (for conversion and quantum light sources), circuit elements, quantum memories, single-photon detectors and classical controls, that need to be integrated for quantum photonic applications. There are both many different device types

Table 1 | **Non-exhaustive list of devices as building blocks to realize integrated photonics for quantum technologies, their different types and platforms used to realize these building blocks**

Building blocks	Quantum emitter 	Nonlinear processes 	Circuit elements 	Quantum memory 	Single-photon detector 	Classical controls 
Types	Quantum dots Atomic-like defects Trapped ions Nanotubes	Frequency converters Parametric downconversion Four-wave mixing Squeezing	Mach–Zehnder Beam splitters MEMS Microcavities Circulators Phase shifters	EIT (Off-)Raman ORCA/FLAME AFC Spin (gradient) echo (Optical) phonons Delay lines	SPAD APD SNSPD TES	Laser light sources Electronic components Modulators Quantum cascade lasers
Platforms	III–V semiconductors Diamonds 2D materials SiC Rare-earth ions Radiation-induced defects (Si, etc.) Single molecules	Lithium niobate GaAs Si Silicon nitride Aluminium nitride Silica SOI	Polymer Lithium niobate III–V semiconductors Silicon, SOI, SiN Aluminium nitride Silica (laser written) Tantalum pentoxide Barium titanate	Atomic vapour Rare-earth ions Diamond SiC III–V semiconductors Silica Silicon	Si InGaAs NbN TiNbN WSi_2 $MoSi_2$ $NbSi_2$	Si III–V semiconductors Silicon nitride Transparent conducting oxides

AFC, atomic frequency comb; APD, avalanche photodiode; EIT, electromagnetically induced transparency; FLAME, fast ladder memory; MEMS, microelectromechanical system; ORCA, off-resonant cascaded absorption; SNSPD, superconducting nanowire single-photon detector; SPAD, single-photon avalanche diode; TES, transition-edge sensor.

Table 2 | **Examples of different quantum photonic use cases and their required integrated devices to realize scalability and real-life applications**

Devices	Quantum photonic use cases									
	Memory-based repeater	**Cluster-state repeater**	**One-way QC**	**Trapped-ion-based QC**	**QKD**	**Quantum imaging**	**Squeezed light sensing**	**Boson sampling**	**N00N-state sensing**	**QRNG**
Quantum emitter 	R	R	R	O	O	O	NA	R	O	O
Nonlinear processes 	O	R	R	O	O	R	R	R	O	O
Circuit elements 	R	R	R	R	R	R	R	R	R	R
Quantum memory 	R	O	R	NA	O	NA	NA	NA	NA	NA
Single-photon emitter 	R	R	R	O	R	R	R	R	R	R
Classical circuits 	R	R	R	R	R	R	R	R	R	R

N00N, a quantum state in the form $|N,0\rangle + |0,N\rangle$, where N is the number of particles; NA, not available; O, optional, the building blocks that are not mandatory but could substitute others or can be added; QC, quantum computer; QKD, quantum key distribution; QRNG, quantum random number generator; R, required.

and material platforms that can be used to realize these building blocks.

Integration into classical PIC platforms

Several applications requiring the integration of quantum photonic building blocks to ensure a scalable technology are showcased in TABLE 2. However, it is unlikely that there will be a 'one-size-fits-all' solution based on a single technological platform. Multiple applications will require bespoke integration.

There are several platforms currently under development that are investigated for specific quantum applications, in particular, with respect to their suitability for new hybrid approaches when compared with their classical counterparts (for example, the potential of cryogenic superconducting detectors will be fully exploited only when directly integrated on chip). Some prominent examples are:

- Silicon photonics and hybrid integration, which are, in themselves, a family of platforms (BOX 1).
- Silica-on-insulator/laser-written silica/various glasses can be eventually matched to other platforms to form complete systems. They are particularly effective for applications including boson sampling, quantum walks and quantum simulation (thanks to the 3D geometry).
- III–V platforms (InP and GaAs) provide monolithically integrated light sources (and detection, to some extent), as well as advanced cavities and quantum light sources (high-quality quantum dots) and high-speed modulation (electro-optical effect). These platforms provide high nonlinearities and adaptability to various wavelengths.
- Lithium niobate waveguide circuits (including LNOI), which offer avenues for reconfigurable waveguiding, strong nonlinear effects, electro-optical effect, hybrid integration with sources and detectors, implementation of periodically poled lithium niobate (PPLN) for on-chip frequency conversion and pair sources, and quantum memories based on erbium-doping (Er), low-loss photonic structures.
- Oxide single crystals and films (such as yttrium orthosilicate (YSO) or yttrium aluminium garnet (YAG)) doped with a variety of rare-earth ions (Eu, Yb, Er and others). In these platforms, exceptionally long coherence times can be reached, opening up perspectives for realizing quantum memories. Single-ion detection and manipulation has been demonstrated when the crystals or films are placed in photonic or fibre cavities and a great number of wavelengths can be addressed.

Hybrid integration
The insertion in various ways of heterogeneous components to a specific chip platform, for example, by gluing external components or by other methods, such as wafer bonding, transfer print and so on.

- Diamonds with native or implanted colour centres (NV, SiV, GeV and others) can implement photonic cavities, transferable membranes and mechanical resonators. This platform benefits from bright and stable photon emission associated with room-temperature operation and is an outstanding candidate for magnetic sensing, including spin qubits implementations.
- Other solid-state materials are not as mature as the platforms discussed above, but are currently being developed. They include wide-band-gap semiconductors with single-photon-emitting defects (SiC, III-N and others), rare-earth-doped crystals as qubits or quantum memories and, in general, 2D materials.
- Polymer platforms offer lower production costs and easier micromachining for optical interfaces. In combination with the hybrid integration of micro-optical components, these platforms are ideally suited for more complex systems that require a combination of heterogeneous optical materials.

Several devices at different levels of maturity and performance have been realized with all these material platforms. Demonstrations of all the elementary building blocks have been shown in silicon-derived platforms, such as silicon, silica, silicon carbide and silicon nitride, as well as aluminium nitride. Nevertheless, each platform has unique properties that can be used as summarized in TABLE 3 (in TABLE 4, the technological maturity is also indicated as a guideline to the reader). Another interesting aspect is whether quantum photonic integration can be achieved monolithically or will eventually rely on a heterogeneous/hybrid approach.

Box 1 | **Silicon photonics and hybrid integration**

Wafer-scale silicon-on-insulator technology, typically used for applications at telecoms wavelengths (especially quantum key distribution), when matched to hybrid-integration silicon photonics, allows for the inclusion of a number of different elements, such as:

- Quantum light sources, such as spontaneous four-wave mixing, which can be native in the technology or external
- III–V materials emitting in the infrared quantum light or simply used as excitation sources
- Silicon/germanium detectors or hybrid ones (such as superconducting nanowire single-photon detectors)
- Other nonlinear active elements (such as parametric oscillators other than spontaneous four-wave mixing, like generators and wavelength converters) and other crystals based on piezoelectric materials for frequency upconversion
- Optomechanical microelectromechanical systems structures
- Quantum memories

In a parallel development, the wafer-scale silicon nitride platform is witnessing growing interest, as it allows for higher energy photons and comes with the significant advantage of low losses (when specifically designed). It is also suitable for hybrid integration and microelectromechanical systems structures; it can be matched to III–V or 2D materials and allows for the addition of detectors for the near-infrared to visible for applications in that wavelength range. In general, there is growing interest in nanostructures as (III–V) quantum light sources to be integrated, together with plasmonics elements and nonlinear elements similar to the silicon-on-insulator platform.

Silicon photonics matched with polymer waveguiding offers advantages in terms of manufacturability and tasks such as waveguiding, coupling and 3D integration. Nonlinear optical polymers also allow for high electro-optic effects and parametric amplification[150,151], which is not possible in bulk silicon, given its centrosymmetric crystalline structure.

Potential roadblocks. All these platforms come with implementation challenges, some inherited directly from the classical domain applications and a number of others specific to qPICs. It is not within the scope of this Roadmap to give a comprehensive overview of all these issues, so we will restrict the discussion to some relevant general points.

The inability to reduce photon losses in the various platforms to the necessary very low levels required by quantum applications represents a serious challenge. This is normally exacerbated when multiple components need to be coupled together, as each coupling represents a potential source of losses. This issue is critical in fields such as quantum computing, where scalability will depend heavily on loss reduction. In general, the need for hybrid and multiple components integration (complexity) is conflicting with the structural simplicity that low-loss operations would require.

In general, none of the individual platforms seems to have the same level of performances across all domains. For example, despite its promise for quantum communication and some computation and simulations tasks, silicon photonics is largely limited in the choice of wavelength, restricting the type of sources that can be hybrid integrated or coupled to. For example, current best quantum dot sources of on-demand single and entangled photons[138,139] are largely emitting at higher energies than the silicon band gap and would require a SiN hybrid platform or a hybrid III–V one. This suggests that quantum information processing with truly on-demand sources is unlikely to be centred on pure silicon photonics. Similarly, NV centres sources require largely new bespoke solutions independent of the mainstream silicon photonics. Present research is scattered around ad hoc solutions, enhancing the risk of delaying the identification of a few common future platforms capable of serving most of the application requirements.

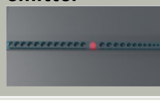
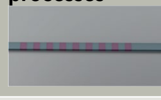
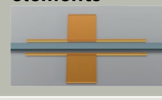
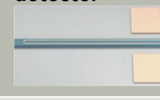
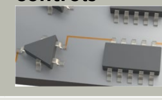
The challenge faced by the IPQT community is largely that of balancing the different needs and scale-up performances and to come up with clever solutions to bypass these roadblocks.

Global research and technology landscape

Despite the extensive research and development (R&D) in classical photonic integration, it is still at an early stage in terms of widespread applications and market penetration. A number of hybrid and heterogeneous integration platforms are being investigated, with a subset likely to materialize in the next few years as leading technologies for the deployment of data centres, 5G and the internet of things applications. IPQTs have emerged on top of these foreseeable short-term and medium-term developments and there is already a strong and dynamic ecosystem that can be harnessed to generate global supply chains of IPQTs and services.

Research areas benefitting from early investments and leveraging classical platforms will have the best chance to be exploited as the foundation of scalable and robust qPIC devices. However, there is the risk of dispersing the research effort into a set of competitive endeavours without strong support and coordination from national agencies. To avoid this risk and to

Table 3 | **Overview of several photonic integration platforms and which building blocks have been demonstrated on that particular platform either monolithically or in a heterogeneous or hybrid approach**

Platform	**Properties**	**Quantum emitter** 	**Nonlinear processes** 	**Circuit elements** 	**Quantum memory** 	**Single-photon detector** 	**Classical controls** 
Silicon	Transparent at telecoms CMOS standard Dense integration	M/H	M	M	M	M/H	H
Silica	Direct laser writing	H	H	M	M	H	H
Silicon nitride	CMOS compatible Large spectral window Low loss	H	M	M	H	H	H
Aluminium nitride	Electro-optic effect Piezoelectric effect	H	M	M	H	H	H
Silicon carbide	Long spin lifetime Large Kerr nonlinearity Transparent at telecoms CMOS compatible	M	M	M	M	H	H
Lithium niobate	Electro-optic effect Strong non-linearity	H	M	M	M	H	H
Diamond	Long spin lifetime High-quality emitters	M	M	M	M	H	H
III–V semi-conductors	Monolithic lasers High-quality emitters	M	M	M	M	M/H	H
Polymers	Large spectral window Substrate independent Mouldability Host for micro-optics	H	H	M	NA	H	H
Tantalum pentoxide	Transparent at telecoms Piezoelectric CMOS compatible	NA	M	M	NA	H	H

CMOS, complementary metal–oxide–semiconductor; H, heterogeneous or hybrid; M, monolithically; NA, not available.

potentially attain a sustainable competitive position in specific topics, a highly visible IPQT infrastructure and research base need 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. However, focusing on a too narrow number of photonic integration platforms at the current stage could be detrimental to the future of IPQTs. The field is still far from the maturity level where it is possible to identify winners and/or single suppliers of integration platforms.

Since many of the classical photonic integration platforms are, at the moment, spread over a number of bespoke solutions, an inclusive IPQT programme should emphasize collaborative efforts. This would allow the developed platforms to flourish and establish a widely exploitable multi-technological infrastructure. Many countries have been heavily investing in strong quantum technology research programmes amounting to several billion euros and it is encouraging to see that such efforts including IPQTs and qPICs are beginning to materialize worldwide.

Europe

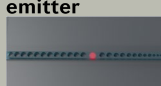
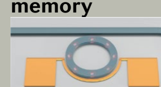
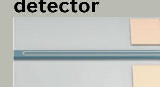
Europe has experience and expertise in photonic integration, which, along with a vibrant research and innovation ecosystem, could be harnessed to create global quantum supply chains for quantum technologies. In addition to several top-class facilities and world-leading groups in several European member states, there are major European research and technology organizations with dedicated cleanroom facilities supporting the research and development of photonic devices and components and their integration into systems. Within the Quantum Flagship, funded by the European Union, integrated quantum photonics has been recognized as a fundamental technology for the supply chain of quantum communications[140]. There are several initiatives to develop quantum random number generators (QRNGs) and components and modules for end-to-end qubit transmission. Within the Quantum Flagship quantum computing and simulation pillars, photonics is a key enabling technology, whereas photonic qubits have been identified as one of the platforms with intermediate technology maturity. The development of chip-integrated photonics also represents one of the key elements in the supply chain for quantum sensing and metrology. Furthermore, IPQTs and qPICs strongly feature in QuantERA, the European Research Area Network (ERA-NET) nationally co-funded programme in quantum technologies. Research focuses on the development of optimized materials, architectures and devices for integration into quantum photonic circuits.

European efforts are complemented by the UK National Quantum Technologies Programme, which has been running since 2013. This initiative led to the establishment of a Quantum Communications Hub and a Quantum Computing & Simulation Hub, both having work programmes on IPQTs and qPICs, including the setting up of a service focusing on the design, manufacturing, testing, packaging and rapid device prototyping of quantum photonic devices, as well as a dedicated programme on silicon quantum photonics.

Australia

Australia has been traditionally strong in photonics in both academic research and industry. The transition to quantum photonics has been boosted by the emergence of several start-ups in the field of spectroscopy, cybersecurity and quantum computing. Australia has several large centres of excellence that focus on photonics and quantum technologies, with significant investment from various government agencies. Within the field of quantum photonics, the research strengths lie in the development of solid-state qubits (based on diamond, hexagonal boron nitride and rare-earth systems), trapped ions, quantum optomechanics, atomic clocks (EQUS, TMOS and CQC2T)[141] and fabrication of integrated quantum photonic circuitry. The number of researchers in these areas is steadily growing, and Australia is well positioned

Table 4 | **Overview of several photonic integration platforms as in** TABLE 3**, categorized by their level of technological maturity**

Platform	Quantum emitter 	Nonlinear processes 	Circuit elements 	Quantum memory 	Single-photon detector 	Classical controls 
Silicon	E	D	D	E	D	D
Silica	E	P	D	E	P	P
Silicon nitride	P	D	D	E	P	D
Aluminium nitride	P	D	D	E	P	P
Silicon carbide	D	P	P	D	P	D
Lithium niobate	P	D	P	E	P	P
Diamond	D	P	P	D	P	E
III–V semiconductors	D	P	D	P	P	D
Polymers	E	E	P	NA	E	P
Tantalum pentoxide	NA	E	P	NA	P	P

D, development stage; E, early/explorative stage; NA, not available; P, proof-of-principle stage.

to bring these technologies to the market and train the new generation of scientists and engineers.

Asia

In Asia, China has been strongly supporting the development of photonic quantum technologies. There is significant knowledge base in the field of photon-based quantum computation and in the realization of thousand-kilometre space-to-ground QKD, both of which would benefit from chip-based photonic quantum technology.

Since 2015, the main funding agencies in China, such as the Chinese Academy of Sciences, the Natural Science Foundation of China and the Ministry of Science and Technology, as well as local agencies in Hefei, Shanghai, Jinan, Guangdong and Beijing, have provided more than 50 million Chinese Yuan to develop IPQTs, with more investment likely in the near future. The research programmes have covered a full range of PIC platforms, such as GaAs, Si, SiN, laser-writing glass, lithium niobate and diamond, targeting the practical implementations of photonic quantum computing, QKD and sensing tasks.

Singapore also has a strong quantum programme including quantum photonics. Singapore set up the Centre for Quantum Technologies almost 15 years ago and established a national Quantum Engineering Programme to fund focused research projects. The latter is now in its second cycle, with the aim to develop quantum science and technology into solutions for real-world applications. Research is supported across four pillars: communication and security, computing, sensors and foundry. This includes quantum control of light at the single-photon or few-photon level, waveguide-based and fibre-based platforms for ultra-scaled photonic integration, silicon quantum photonics, QRNGs and quantum cryptography.

Japan benefits from a strong background in integrated photonics technologies, which have been developed for commercial optical communications. Low-loss, large-scale PICs have contributed to pioneering research in IQPTs, such as the first application of an on-chip optical waveguide circuit to quantum technology (QKD)[142] and the realization of a universal linear optical qPIC[81]. Active research areas include quantum communication and networks, computing, sensing and optical clocks. For example, the Tokyo QKD Network[143] is a QKD test bed network in Tokyo continuously operated by the National Institute of Information and Communications Technology (NICT) under an industry–academia–government collaboration for long-term field tests, network experiments and application developments since 2010. The Japanese government regards optical and quantum technologies as a priority R&D area and formulated the Quantum Technology Innovation Strategy in 2020 (REF.[144]) as a new long-term national strategy, with a view to the industrialization and innovation of the technologies.

North America

In the USA, support from the government and academic and private sectors has been instrumental in the development and manufacturing of PIC technologies, with applications at the intersection of classical and quantum domains (such as shot-noise-limited coherent receivers) and to quantum information technologies, such as entangled photon sources. Among the most mature PIC architectures are ones based on silicon, germanium, silicon nitride, III–V compound semiconductors, lithium niobate and polymers. Near-term applications highlighted in recent US-based workshops and consensus reports[9,145–148] include quantum communication, quantum sensor networks, quantum computing and quantum simulators. For instance, the February 2020 Quantum Internet Blueprint workshop organized by the US Department of Energy (DOE) Office of Advanced Scientific Computing Research identified PICs for several priority research opportunities, including device scaling, miniaturization and integration of quantum network components such as quantum light sources, quantum memories with efficient optical interfaces, low-power switching and multiplexing, quantum frequency conversion and transduction and efficient single-photon detectors[148]. The targeted devices will need to satisfy stringent requirements for reliability and scalability and the ability to function across large temperature swings (from room temperature to liquid helium temperature). Moving forward will involve addressing challenges in PIC materials, manufacturing, device connectivity and standardization.

In Canada[149], the Quantum Photonic Sensing and Security programme was established for prototyping quantum systems to deliver measurement and communications solutions beyond classical photonics, in particular, in the fields of quantum encryption and security, environmental and health monitoring sensors. The Canadian Space Agency launched the Quantum Encryption and Science Satellite mission, with the aim of linking a satellite and a ground network to demonstrate QKD over large distances. In Mexico, there are growing efforts to participate in the development of qPICs, mainly supported by government agencies (Consejo Nacional de Ciencia y Tecnología (National Council of Science and Technology); CONACYT) and major academic institutions (Universidad Nacional Autónoma de México (National Autonomous University of Mexico); UNAM). Mexico is establishing an academic platform to train specialists and establish photonic-quantum-information-oriented companies in the next five years.

Innovation potential and market perspective

The innovation cycle for IPQTs is complex (FIG. 2), requiring investments, the resolution of specific technological challenges and further structuring towards a mature ecosystem.

Europe

In Europe, in addition to the many big companies that are already actively involved in quantum technologies (for example, Thales, Bosch, Atos, Telefonica, Teledyne, BAE Systems, BT), there is a large number of integrated and quantum photonics start-ups and small and medium-sized enterprises (SMEs) providing enabling technologies for IPQTs and qPICs. Examples include:

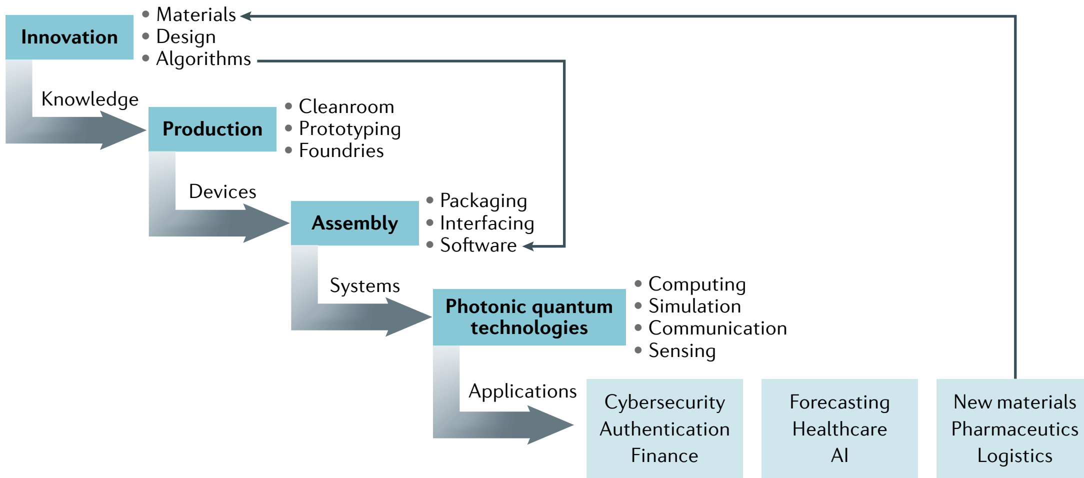


Fig. 2 | **The potential of the innovation cycle for photonic quantum technologies.** The development of photonic quantum technologies for everyday life not only requires new hardware, software and scalability through packaging but also a new production line to meet the standards, in particular, low losses, for fabrication. The innovation cycle will accelerate over the years as feedback from quantum simulation and computing applications will speed up the development of new materials, designs and algorithms. AI, artificial intelligence.

Toptica Photonics (tunable diode lasers for optical clocks and quantum sensors), Vixar/OSRAM (vertical-cavity surface-emitting lasers 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 and quantum simulation), QUANDELA (quantum light emitters), iPronics (integrated programmable photonic systems), 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), Single Quantum and MPD (single-photon detectors), SMART Photonics and LioniX (PICs), QZABRE and QNAMI (diamond magnetic sensors), Element6 (diamond platform with deliberate and controlled NV doping), KETS (InP QKD) and Qontrol (quantum control electronics). Several UK-based SMEs are contributing to quantum photonics, including: AegiQ (long-distance quantum-secure telecommunications), M-SQUARED (integrated photonic systems), nu-Quantum (single-photon components) and ORCA (quantum computing platform based on optical fibre).

Australia
Australia has a strong photonics-based industry, employing nearly 10,000 people in 465 companies. The development of IPQTs will complement and further drive this growing industry. Finisar grew from an Australian start-up to become a global manufacturer of optical communication components and subsystems and could well benefit from advances in quantum integrated circuitry. Similarly, innovations coming out of centres of excellence funded by the Australian Research Council, for example, the Centre for Transformative Meta-Optical Systems, can fuel the establishment and future growth of start-ups such as QuintessenceLabs (QRNG and QKD), Modular Photonics (multi-mode fibre networks and multiplexers) and Terra15 (sensors).

Asia
In China, there is a large number of companies and start-ups involved in the commercialization of quantum photonic and integrated photonic technologies. Technology giants such as Huawei, Baidu, Tencent and Alibaba have invested in quantum technologies. Other major players include: QuantumCTek (QKD), Qasky (QKD), PHOTEC (superconducting single-photon detectors), Chinainstru & Quantumtech (diamond NV sensors), IMECAS (silicon, SiN PICs), CUMEC (silicon, SiN PICs) and Liobate Technologies (LNOI PICs).

Singapore has a vibrant photonics ecosystem, as represented by the LUX Photonics Consortium, which comprises large multinationals and foundry services, indigenous large companies, small and medium enterprises and start-ups. There is a lot of activity in silicon photonics, with foundry services provided by CompoundTec and Advanced MicroFoundry. Quantum photonics start-ups exploiting emerging materials and new devices have been established alongside the Centre for Quantum Technologies. These include Atomionics (cold atom interferometry for quantum sensing for navigation and exploration) and SpeQtral (space-based QKD technologies).

In Japan, the R&D of photonic quantum technologies in industry has long been led by big companies such as NTT, NEC, Toshiba, Fujitsu, Hitachi and Mitsubishi Electric. Some of them have recently further expanded their activities and increased the investments in quantum technologies. Manufacturers and players in quantum photonics include NTT-AT (silicon PIC), NEL (silica PLC, PPLN), Oki Electric (PPLN), Shimadzu (periodically poled stoichiometric lithium tantalite), Hamamatsu Photonics (quantum cascade lasers and photon detectors), FMD (optomechanical components) and LQUOM (quantum communication

Heterogeneous integration
The direct deposition of various active materials (different from that of the chip, such as III–V semiconductors on silicon) on the chip wafers.

start-up), as well as the National Institute of Advanced Industrial Science and Technology (AIST) (silicon PIC, transition-edge sensors) and NICT (superconducting single-photon detectors).

North America

In North America, a rich and diverse ecosystem in integrated quantum photonics is emerging across the industrial, academic and government research sectors. There is substantial activity in the private sector, with start-up companies developing cutting-edge PIC technology for quantum computing, quantum communications and quantum sensing. Whereas quantum technology applications are still under development, research into quantum devices is already having a positive impact on the next generation of classical communication technologies, for example, in optical communications closer to channel capacities. Several Innovation Nodes I-Corps and National Science Foundation (NSF) I-Corps programmes have identified over 250 potential customers across both the short-term and the long-term markets for optical quantum technologies. Stakeholders and agencies pushing the development of photonic quantum technologies include the DOE Federally Funded R&D Centers (FFRDCs), the US Department of Defense, NASA and Raytheon, as well as second-stage beneficiaries from the industrial and commercial sectors (such as BAE Systems, Public Service Enterprise Group and Internet2). A US start-up that stands out is PsiQuantum, which has set out to develop a general-purpose photonic quantum computer.

Canada's quantum photonics research builds on an already strong innovation ecosystem supported by the Canadian Photonics Industry Consortium. There are 400 photonics companies employing more than 25,000 people in areas such as system integration, optical communications, image sensors and biophotonics. Newer start-ups include Xanadu, focused on general-purpose quantum computing based on squeezed light, Photonic Inc (photon spin interfaces in silicon, silicon-integrated photonics and quantum optics) and Quantropi (end-to-end solution for quantum-secure data communications).

Outlook

Integrated photonics is driving the scale-up of quantum devices and their commercialization. In different regions of the world, research hubs with strong expertise in photonic integration have been created over the past decade. These developments, together with a global community focus on IPQTs, is expected to contribute to boosting quantum communication, computing and simulation, sensing and metrology and quantum science in general. To this end, we believe that a concerted effort to bolster PICs is needed. It requires fostering key technologies, collaboration, addressing emerging markets and supporting a global infrastructure. This goes hand in hand with a strong support for the development of materials, devices and components associated with IPQTs with tailored research and innovation programmes around the world. The key performances of photonic circuits for quantum technology are driven by new and improved materials, advanced integration and packaging. Coordinated programmes are needed to invest in the development of components and supply chains for new photonic integration platforms and to build infrastructure for hybrid and heterogeneous integration to meet the challenges of IPQTs and cope with the demands of the global market.

PICs for quantum technology 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 globally shared infrastructure. Furthermore, we highlight the need for investment in education to train the next generation IPQT engineers. Regardless of the type of technology that will be used in commercial quantum devices, the underlying principles of quantum mechanics are the same. We predict an increasing demand for scientists and engineers with substantial knowledge of both quantum mechanics and its technological applications. Investing in educating the next generation will contribute to pushing the scientific and technological frontiers.

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