Title	The potential and global outlook of integrated photonics for quantum technologies
Authors	Pelucchi, Emanuele;Fagas, Giorgos;Aharonovich, Igor;Englund, Dirk;Figueroa, Eden;Gong, Qihuang;Hannes, Hubel;Liu, Jin;Lu, Chao-Yang;Matsuda, Nobuyuki;Pan, Jian-Wei;Schreck, Florian;Sciarrino, Fabio;Silberhorn, Christine;Wang, Jianwei;Jons, Klaus D.
Publication date	2021-12-23
Original Citation	Pelucchi, E., Fagas, G., Aharonovich, I., Englund, D., Figueroa, E., Gong, Q. H., Hannes, H., Liu, J., Lu, C. Y., Matsuda, N., Pan, J. W., Schreck, F., Sciarrino, F., Silberhorn, C., Wang, J. W. and Jons, KD (2021) 'The potential and global outlook of integrated photonics for quantum technologies', Nature Reviews Physics, doi: 10.1038/s42254-021-00398-z
Type of publication	Article (peer-reviewed)
Link to publisher's version	https://www.nature.com/articles/s42254-021-00398-z - 10.1038/s42254-021-00398-z

The potential and global outlook of integrated photonics for quantum technologies

Emanuele Pelucchi

Tyndall National Institute, University College Cork, Lee Maltings, Dyke Parade, Cork T12R5CP, Ireland

Giorgos Fagas

Tyndall National Institute, University College Cork, Lee Maltings, Dyke Parade, Cork T12R5CP, Ireland

Igor Aharonovich

ARC Centre of Excellence for Transformative Meta-Optical Systems (TMOS), faculty of Science, University of Technology Sydney, Ultimo, New South Wales 2007, Australia

Dirk Englund

Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

Eden Figueroa

1. Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794, USA; 2. Brookhaven National Laboratory, Upton, NY, 11973, USA

Qihuang Gong

1. State Key Laboratory for Mesoscopic Physics, School of Physics, Peking University, Beijing, 100871, China; 2. Frontiers Science Center for Nano-optoelectronics & Collaborative Innovation Center of Quantum Matter, Peking University, Beijing, 100871, China; 3. Peking University Yangtze Delta Institute of Optoelectronics, Nantong 226010, Jiangsu, China.

Hübel Hannes

AIT Austrian Institute of Technology GmbH, Giefinggasse 4, 1210 Vienna, Austria

Jin Liu

State Key Laboratory of Optoelectronic Materials and Technologies, School of Physics, Sun Yat-sen University, Guangzhou 510275, China.

Chao-Yang Lu

CAS Centre for Excellence and Synergetic Innovation Centre in Quantum Information and Quantum Physics, University of Science and Technology of China, Shanghai 201315, China

Nobuyuki Matsuda

Department of Communications Engineering, Graduate School of Engineering, Tohoku University, Sendai, Japan.

Jian-Wei Pan

CAS Centre for Excellence and Synergetic Innovation Centre in Quantum Information and Quantum Physics, University of Science and Technology of China, Shanghai 201315, China

Florian Schreck

1. Van der Waals-Zeeman Institute, Institute of Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, the Netherlands; 2. QuSoft, Science Park 123, 1098 XG Amsterdam, the Netherlands

Fabio Sciarrino

Dipartimento di Fisica, Sapienza Università di Roma, Italy

Christine Silberhorn

Paderborn University, Institute for Photonic Quantum Systems, Center for Optoelectronics and Photonics Paderborn, and Physics Department, Warburger Straße 100, 33098 Paderborn, Germany

Jianwei Wang

1. State Key Laboratory for Mesoscopic Physics, School of Physics, Peking University, Beijing, 100871, China; 2. Frontiers Science Center for Nano-optoelectronics & Collaborative Innovation Center of Quantum Matter, Peking University, Beijing, 100871, China; 3. Peking University Yangtze Delta Institute of Optoelectronics, Nantong 226010, Jiangsu, China.

Klaus D. Jöns

Paderborn University, Institute for Photonic Quantum Systems, Center for Optoelectronics and Photonics Paderborn, and Physics Department, Warburger Straße 100, 33098 Paderborn, Germany

email: klaus.joens@upb.de

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.

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-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.

Website summary

Photonics is one of the key platforms for emerging quantum technologies but its full potential can only be harnessed by exploiting miniaturization via on-chip integration. This Roadmap charts new directions and discusses the challenges associated with the hybrid integration of a variety of materials, devices, and components.

[H1] Introduction

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 nonlocal correlations (entanglement) which first seemed a flaw in quantum theory, has been experimentally tested with increasing sophistication and led to unexpected applications.[1,2,3,4,5]. Quantum entanglement and quantum superposition[6] underlie the second-generation of quantum technologies[7,8,9] which found applications in computation[10], simulation[11], communication[12], sensing and metrology[13,14,15] 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[17,18,19] 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 under-appreciated. The development of integrated photonics for quantum technologies (IPQT), especially quantum photonic integrated circuits (qPICs) (Figure 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 IPQT and advocating for the need to develop the necessary infrastructure.

[H1] 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. 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 center 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) ones.

Unlike integrated electronics, competing functionalities impede the realization of PICs from a single material system and platform (monolithic integration) resulting into 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 (LN) 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.

Integrated photonics play 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[31], optical clocks[32] or gravimeters[33]. 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 set the requirements on the frequency and intensity control of the laser beams. Ultracold atom quantum simulators, using atoms trapped in optical 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[34] and microcombs[35].

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 telecom 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.

[H1] 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[36,37]; enhanced light-matter interaction when needed; a strongly required high stability of the optical elements[38]; a direct on-chip interfacing or co-integration with efficient single photon detectors[39,40]; and CMOS electronic readout and feedforward control[41]. We briefly outline below the impact of qPICs in different areas.

[H2] Quantum communication

Quantum communication can be classified into two families, largely overlapping in terms of leading photonic integration requirements (particularly for the fiber-based quantum communication systems): quantum cryptography (quantum key distribution, QKD)[42] 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 table-top apparatus to compact integrated systems. As these projects are still at an early development stage, the focus is on the much needed integrated optics[43,44] for creating on-chip platforms for quantum networks[45] and quantum repeater nodes[46], 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[47,48,49,50,51], 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 fibers 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- 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 in quantum communication through space links[52] and optical fibers, where integrated photonics offers advantages in terms of the physical footprint, weight, energy consumption, stability and manufacturability compared to existing proof-of-principle demonstrations.

[H2] Quantum computation and simulation

The fundamental requirements for any quantum computing technology[25, 26, 53,54,55,56] include the fine degree of control over the qubits and their nearly-complete isolation from the environment. Among the different physical realisations 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)[57] and universal quantum computing models (for example one-way or measurement-based)[58,59,60,61]. Depending on the way the quantum states of light are used to encode information, there are discrete variable and continuous variable[62] models, or their hybridisation, providing different implementations of specific and universal quantum computation.

As an example of a specific quantum computation, boson sampling represents a specific sampling task that relates to the calculation of the expectation value of the permanent of a matrix[57] (a function akin to the determinant). 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[63,64,65,66], 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[67,68,69,70] Improved implementations (in both bulk optics and qPICs) of more scalable boson sampling followed. Examples include scattershot boson sampling[71,72] that can overcome the limitation posed by the probabilistic nature of parametric down-conversion sources, and Gaussian boson sampling[73] that 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 up to 76 detected photon-clicks (an overall Hilbert space of dimension 10^{30}), which is the largest reported photonic quantum system to date.

Universal all-optical quantum computing is possible as proved in the Knill-Laflamme-Milburn (KLM) scheme[74], 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. The KLM scheme, however, suffers from heavy overhead requirements. A number of major functionalities have been demonstrated with tabletop optical components[75], and their translation to qPICs have been realised on several waveguide platforms, for example, KLM-type Control-NOT (CNOT) gate and its heralding version[38,76], and compiled Shor's factorisation[77]. These achievements were seen as important milestones.

The circuit implementation is pertinent for noisy intermediate-scale quantum (NISQ) 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[78,79,80]. Experimental demonstrations include the creation of 18-qubit star-graph states in bulk-optics[81], 4-photon star-graph states and linear-and-box graph states in Si (Refs[82,83]) or SiO_2 chips[84], and programmable 8-qubit graph states in a Si chip[85].

Quantum simulation[11] is believed to be one of the most promising applications of quantum computers. In contrast to analog quantum simulation approaches, the hardware requirements for universal photonic quantum simulators are nearly in line with that of universal quantum computers. Photonic quantum simulators[25,67,68,86] have been demonstrated in the lab, and will benefit from the scaling perspective of integration. qPIC enables a versatile NISQ platform to execute specific quantum simulation tasks by implementing certain quantum simulation algorithms. For example, qPIC simulators[68] in Si and SiO_2 chips have been reported for the estimation of molecular eigenenergies by implementing quantum phase estimation[71,87,88] or variational quantum eigensolver[89,90], and for the simulation of spin dynamics in solid-state systems[91]. Photonic integration for quantum simulation has gone beyond demonstrators to establish qPIC platforms, see for example Si and SiO_2 devices for quantum walks[92, 93,94] 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[75] (up to 8 photons) and a SiN chip (up to 18 photons)[95].

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[96,97,98,99], 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[100,101,102], controls of natural atoms in photonic crystals[103,104], and photon-spin interactions in waveguide devices.[105, 106].

[H2] 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[107,108](proposed remote-sensing devices which may find applications for stealthy short-range target detection[109] or proximity sensing and environmental scanning in robotic applications) require extremely efficient detectors for electro-magnetic field sensing. Such detectors are currently being developed using defects in diamonds[110,111] which have unprecedented sensitivity, while sufficient dynamic range and resolution can also be achieved[112]. 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)[113]. A chip-based single photon source has been used for high-precision quantum metrology using state squeezing.[114]

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[115,39] offer unprecedented efficiencies at cryogenic temperatures. Such detectors can be combined with classical active circuit elements such as modulators and Micro-electromechanical systems (MEMS) tunable beam splitters to generate feedback loops, reconfigurable circuits, feed-forward operations as well as circuits for classical photonic applications such as on-chip power stabilization and high dynamic range integrated power meters[116]. The adoption of PICs may ultimately deliver large-scale manufacturable, packaged and portable quantum sensors and clocks[117]. Efforts naturally and largely overlap with the quantum communication objectives for synchronization, equally in terms of active elements integration, coupling, and routing.

[H2] 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[118,119,120] such as new physical effects, functionalities or devices. Examples include endowing and controlling new quantum effects in integrated optical and optomechanical cavities[121,122](for example quantum light from coupled quantum modes or advanced frequency comb quantum features), quantum coherence of macroscopic mechanical oscillators[123], quantum optical neural networks[124], new topological states with integrated photonic circuits[125] and their detection/characterization. The development and optimization of integrated quantum light detectors together with additional building blocks will be relevant for quantum reading[126], single and entangled photon LIDAR[127], optical clocks, quantum illumination[128], variational learning with photons[129], and quantum enhanced optical super-resolution[130,131,] , addressing scalability and stability issues, including fast on-chip data analysis[132]. 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 non-linear 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.

[H1] Challenges of IPQT

[H2] 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 maturity stage:

- 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 and

- On-chip highly-controllable and tunable, high-Q, low mode volume quantum cavities (such as ring resonators, photonic crystals)
- On-chip quantum memories both in their atomic or solid-state form
- On-chip stable quantum emitters based on nonlinear and high order processes (such as heralded sources like spontaneous parametric down-conversion (SPDC) 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 telecom, 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, non-linear 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 and material platforms that can be used to realise these building blocks.

[H2] 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 to 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 (see 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 highnonlinearities 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.
- 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 under 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 micro-machining 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 realised 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 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.

[H3] Potential roadblocks. All these platforms come with implementation challenges, some inherited directly from the classical domain applications, and a number of others qPICs-specific. 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[133,134] are largely emitting at higher energies than the silicon bandgap 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 come up with clever solutions to bypass these roadblocks.

[H1] 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 hetero-integration platforms are being investigated, with a subset likely to materialize in the next few years as leading technologies for the deployment of data centers, 5G and the internet of things applications. IPQTs have emerged on top of these foreseeable short- and medium- term developments and there is already a strong and dynamic ecosystem that can be harnessed to generate global supply chains of IPQT technologies 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 endeavors without strong support and coordination from national agencies. To avoid this risk and to 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 IPQT. 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 photonic program 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 programs amounting to several billion euros and it is encouraging to see that such efforts including IPQTs and qPICs are beginning to materialise worldwide.

[H2] 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 Organisations 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.[135] 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 key elements in the supply chain for quantum sensing and metrology. Furthermore, IPQT and qPICs strongly feature in

QuantERA, the European Research Area Network (ERA-NET) nationally co-funded program in quantum technologies. Research focuses on the development of optimised materials, architectures and devices for integration into quantum photonic circuits.

European efforts are complemented by the UK National Quantum Technologies Program, 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 programs on IPQT 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 program on silicon quantum photonics.

[H2] 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 startups in the field of spectroscopy, cybersecurity and quantum computing. Australia has several large centers 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[136,137] and fabrication of integrated quantum photonic circuitry. The number of researchers in these areas is steadily growing and Australia is well positioned to bring these technologies to the market and train the new generation of scientists and engineers.

[H2] 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 realisation 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 supported more than 50M Chinese Yuan to develop IPQT with more investment likely in the near future. The research programs have covered a full range of planar lightwave circuit (PLC) platforms such as GaAs, Si, SiN, laser-writing glass, LN, and diamond, targeting the practical implementations of photonic quantum computing, QKD and sensing tasks.

Singapore also has a strong quantum program including quantum photonics. Singapore set up the Centre for Quantum Technologies almost 15 years ago and established a national Quantum Engineering Program 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- or few- photon level, waveguide- 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 IQPT, such as the first application of an on-chip optical waveguide circuit to quantum technology (QKD)[138] and the realization of a universal linear-optical qPIC[76]. Active research areas include quantum communication and network, computing, sensing, and optical clocks. For example, the Tokyo QKD Network[139] a QKD testbed network in Tokyo continuously operated by 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 Quantum Technology Innovation Strategy in 2020[140] as a new long-term national strategy with a view to the industrialization and innovation of the technologies.

[H2] North America

In the United States, support from the government, 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[9,141,142,143,144] 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[144]. 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[145] the Quantum Photonic Sensing and Security program was established for prototyping quantum systems to deliver measurement and communications solutions beyond classical photonics, in particular in the field 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 (CONACYT) and major academic institutions (UNAM). Mexico is establishing an academic platform to train specialists and establish photonic quantum information oriented companies in the next five years.

[H1] Innovation potential and market perspective

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

[H2] 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 enterprise (SMEs) providing enabling technologies for IPQT and qPICs. Examples include: Toptica Photonics (tunable diode lasers for optical clocks & 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 nitrogen-vacancy doping), KETS (InP QKD), 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), ORCA (quantum computing platform based on optical fibre).

[H2] Australia

Australia has a strong photonics-based industry, employing nearly 10,000 people in 465 companies. The development of IPQT 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 Australia Research Council-funded centres of excellence, 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) and Modular Photonics (multi-mode fibre networks and multiplexers), Terra15 (sensors).

[H2] Asia

In China there is a large number of companies and start-ups involved in the commercialisation 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), cnphotec (superconducting single-photon detectors), Chinainstru& Quantumtech (diamond NV sensors), IMECAS (silicon, SiN PLCs), CUMEC (silicon, SiN PLCs), and Liobate Technologies (LNOI PLCs).

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 the industry has long been led by big companies such as NTT, NTT Electronics, Toshiba, Fujitsu, Hitachi, Mitsubishi Electric. Some of them have recently further expanded 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 (periodically poled lithium niobate), Shimadzu (periodically poled stoichiometric lithium tantalite)[146], Hamamatsu Photonics (quantum cascade lasers and photon detectors), FMD (optomechanical components), LQUOM (quantum communication start-up) as well as National Institute of Advanced Industrial Science and Technology (AIST) (silicon PIC, transition-edge sensors) and NICT (superconducting single-photon detectors).

[H2] 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 startup 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 programs have identified over 250 potential customers across both the short-term and 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), 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 startup 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 startups 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).

[H1] 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 IPQT 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 IPQT with tailored research and innovation programs around the world. The key performances of photonic circuits for quantum technology are driven by new and improved materials, advanced integration, and packaging. Coordinated programs 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 IPQT, 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 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.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation program under Grant Agreement No. 820423 (S2QUIP), No. 860579 (MoSaiQ), No. 820404 (iqClock), No. 820474 (UNIQORN) and No. 899814 (Qurope). This research was supported by Science Foundation Ireland under Grant Nos. 15/IA/2864, 12/RC/2276_P2. G.F. acknowledges support by the European Union funded ASCENT+ programme (Grant agreement ID: 871130). Fl.S. thanks the Netherlands Organisation for Scientific Research (NWO) for grant No. NWA.QUANTUMNANO.2019.002, Quantum Inertial Navigation. I.A. acknowledges the Australian Research Council (CE200100010) and the Asian Office of Aerospace Research and Development (FA2386-20-1-4014) for the financial support. Q. G. and J.W. acknowledge the National Key R&D Program of China (No. 2019YFA0308702, 2018YFB2200403), the Natural Science Foundation of China (No. 61975001, 11527901), Beijing Natural Science Foundation (Z190005), and Key R&D Program of Guangdong Province (2018B030329001). Fa.S. acknowledges support by the ERC Advanced Grant QU-BOSS (QUantum advantage via non-linear BOSon Sampling, grant agreement No. 884676). N.M. is grateful for support from JST CREST JPMJCR2004, MEXT Q-LEAP JPMXS0118067581, and JSPS KAKENHI 20H02648.

Author contributions

E.P., G.F., and K.D.J. conceived the perspective article. E.P., G.F., and K.D.J. drafted the initial manuscript, with contribution from J.W., Fa.S., C.S., and D.E. All authors have read, discussed, and contributed to the writing, reviewing, and editing of the manuscript before submission. K.D.J. coordinated and managed the project.

Competing interests

The authors declare no competing interests.

Peer review information

Nature Reviews Physics thanks Juan Arrazola, Di Liang and the other anonymous reviewers for their contribution to the peer review of this work.

Publisher's note

Box 1: Silicon photonics and hybrid integration

Wafer-scale silicon-on-insulator (SOI) technology, typically used for applications at telecom 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 (SFWM), 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 other parametric oscillators than SFWM like generators and wavelength converters) and crystals based on piezoelectric materials for frequency upconversion, optomechanical micro-electromechanical systems (MEMS) 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 MEMS 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 wave guiding, coupling, and 3D integration. Nonlinear optical polymers also allow for high electro-optic effects and parametric amplification[147,148], which is not possible in bulk silicon given its centrosymmetric crystalline structure.

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. MEMS Micro-electromechanical system, EIT Electromagnetically induced transparency, ORCA Off-resonant cascaded absorption, FLAME Fast ladder memory, AFC Atomic frequency comb, SPAD Single-photon avalanche diode, APD Avalanche photodiode, SNSPD Superconducting nanowire single photon detector, TES Transition-edge sensor.

Building blocks	**Quantum emitter**	**Non-linear processes**	**Circuit elements**	**Quantum memory**	**Single photon detector**	**Classical controls**
Types	• Quantum dots • Atomic-like defects • Trapped ions • Nanotubes	• Frequency converters • Parametric down-conversion • Four-wave mixing	• Mach-Zehnder • Beam splitters • MEMS • Micro-cavities • 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

		Squeezing				
Platforms	III/V semiconductors Diamonds 2D materials SiC Rare earth ions Radiation induced defects (Si, etc) Single molecules	Lithium niobate GaAs Si Silicon nitride Aluminum nitride Silica SOI	Polymer Lithium niobate III/V semiconductors Silicon, SOI, SiN Aluminum nitride Silica (laser written) Tantalum pentoxide Barium titanate	Atomic vapour Rare-earth ions Diamond SiC III/V semiconductor Silica Silicon	Si InGaAs NbN TiNbN WSi_2 $MoSi_2$ $NbSi_2$	Si III/V semiconductors Silicon nitride transparent conducting oxides

Table 2: Examples of different quantum photonic use cases and their required integrated devices to realize scalability and real-life applications. R stands for required, O (optional) are building blocks which are not mandatory but could substitute others or can be added; NA stands for not available.

Devices	**Quantum photonic use cases**									
	Memory-based repeater	**Cluster-state repeater**	**One-way QC**	**Trapped ion-based QC**	**QKD**	**Quantum imaging**	**Squeeze-light sensing**	**Boson sampling**	**N00N-state sensing**	**QNRG**
Quantum emitter	R	R	R	O	O	O	NA	R	O	O
Non-linear 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

Table 3: Overview of several photonic integration platforms and which building blocks have been demonstrated on that particular platform either monolithically (M) or in a heterogeneous or hybrid approach (H). NA stands for not available.

Platform	Properties	Quantum emitter	Non-linear processes	Circuit elements	Quantum memory	Single photon detector	Classical controls
Silicon	• Transparent at telecom • 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	• Electrooptic effect • Piezoelectric effect	H	M	M	H	H	H
Silicon carbide	• Long spin lifetime • Large Kerr nonlinearity • Transparent at telecom • CMOS compatible	M	M	M	M	H	H
Lithium niobate	• Electrooptic 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 semiconductors	• 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 telecom - Piezo electric - CMOS compatible	**NA**	**M**	**M**	**NA**	**H**	**H**

Table 4 Overview of several photonic integration platforms as in Table 3, categorized by their level of technological maturity. E stands for Early/Explorative stage, P for Proof-of-Principle stage, D for Development stage and NA for not available)

Platform	**Quantum emitter**	**Non-linear 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**

Figure 1: Quantum photonic integrated circuit (qPIC) architecture. qPICs are the devices realising 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 non-linear optics (such as periodically poled structure) and quantum light sources (red dots/defects) in nano-beam 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.

Figure 2: The potential of the innovation cycle for photonic quantum technologies. The development of photonic quantum technologies for everyday' s 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 since feedback from quantum simulation and computing applications will speed up the development of new materials, designs, and algorithms.

GLOSSARY

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.

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

Monolithic integration: The creation of multiple components on (the same) chip, as in CMOS 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.

Quantum repeater: a device capable of allowing transmission over long distances of a quantum signals beyond the limits imposed by fiber 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.

Quantum memory: a device capable (for a certain amount of time) to store 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.

Feedforward operation: Feed-forward is the process of monitoring a physical system and subsequently use the attained information to change the system so as to control it toward a certain target state. For example, in quantum circuits this implies taking a decision on how to modify a section of the circuit which 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: the term refers to 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.

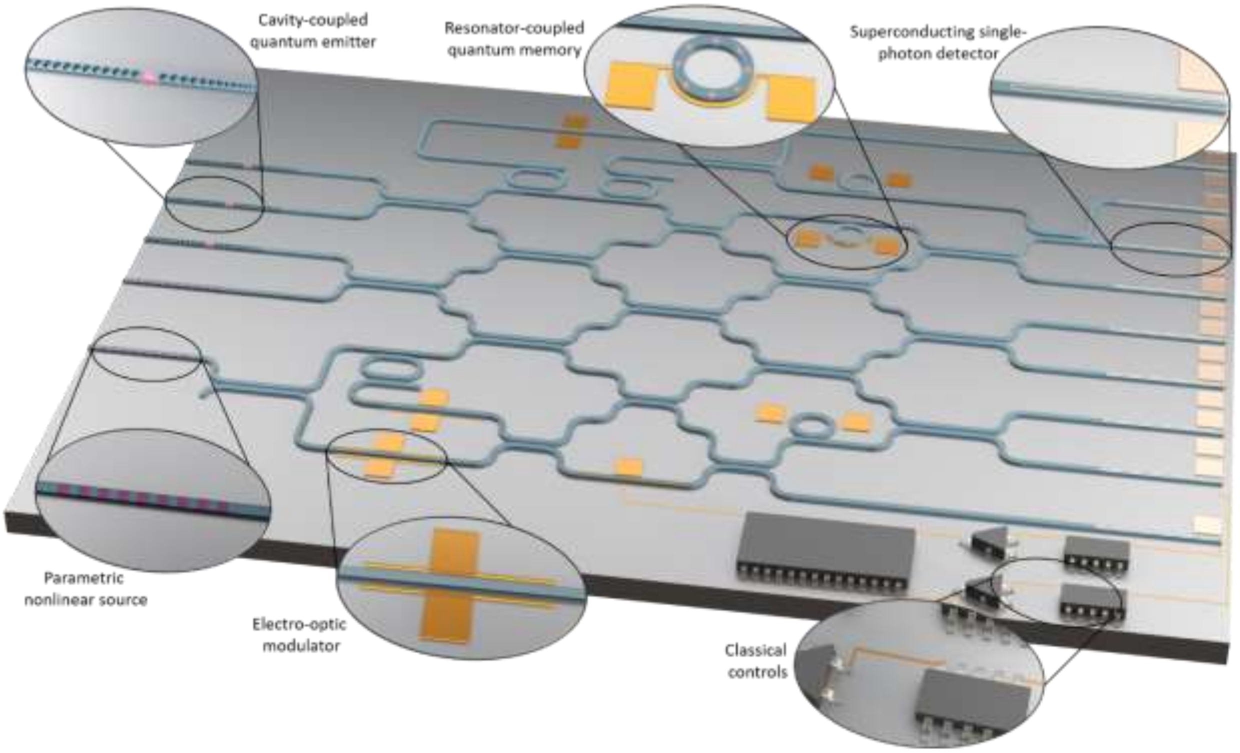
One way (quantum computing): specific methodology to perform a quantum computation where a multi-entangled state is prepared, and subsequent qubit measurements project the original state into the solution of the computation outcome. As a result, the original multi-entangled state is “consumed” by the process.

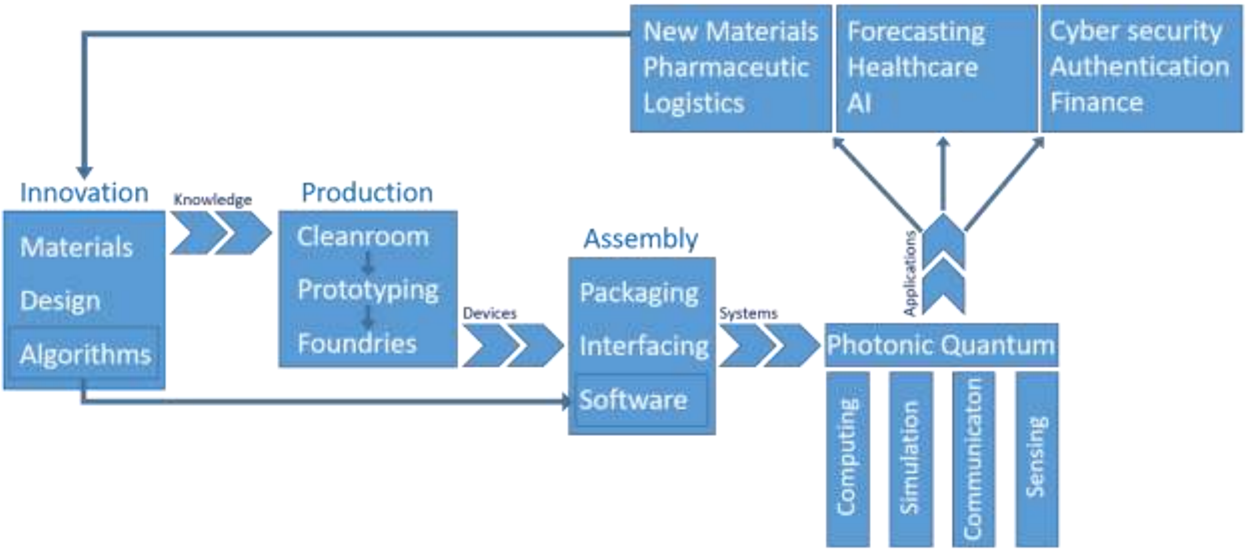
Dynamic range: the range of values that a certain apparatus/detector can achieve for a specific application

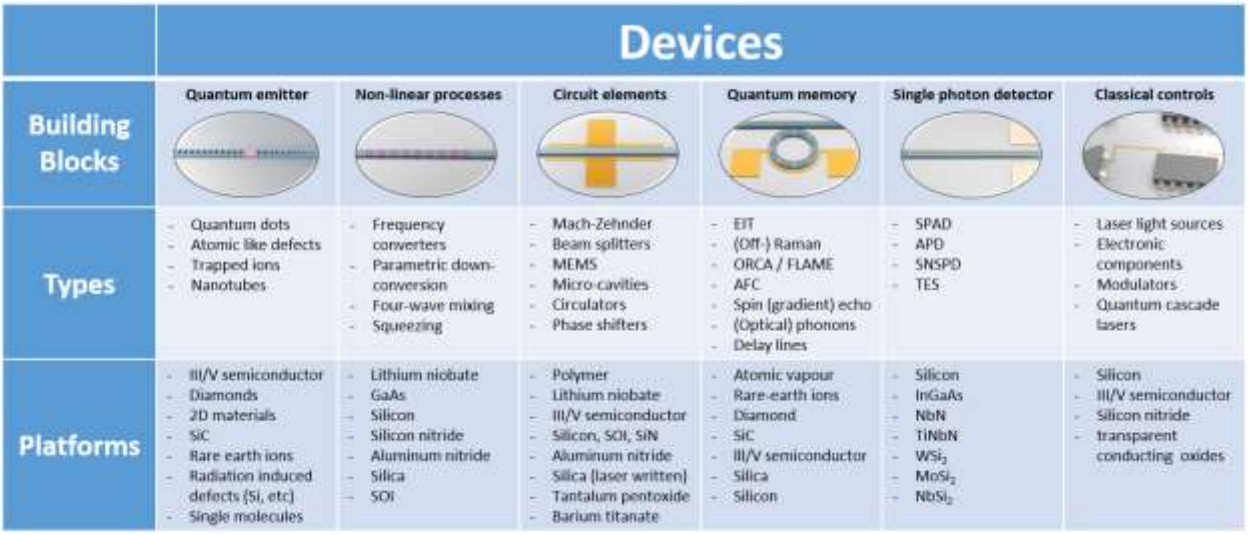
N00N: a quantum state in the form $|N,0\rangle + |0,N\rangle$ where N is the number of particles.

Coherent receiver: receiver of an optical signal which is capable of recognizing both the intensity and phase terms of the impinging light.

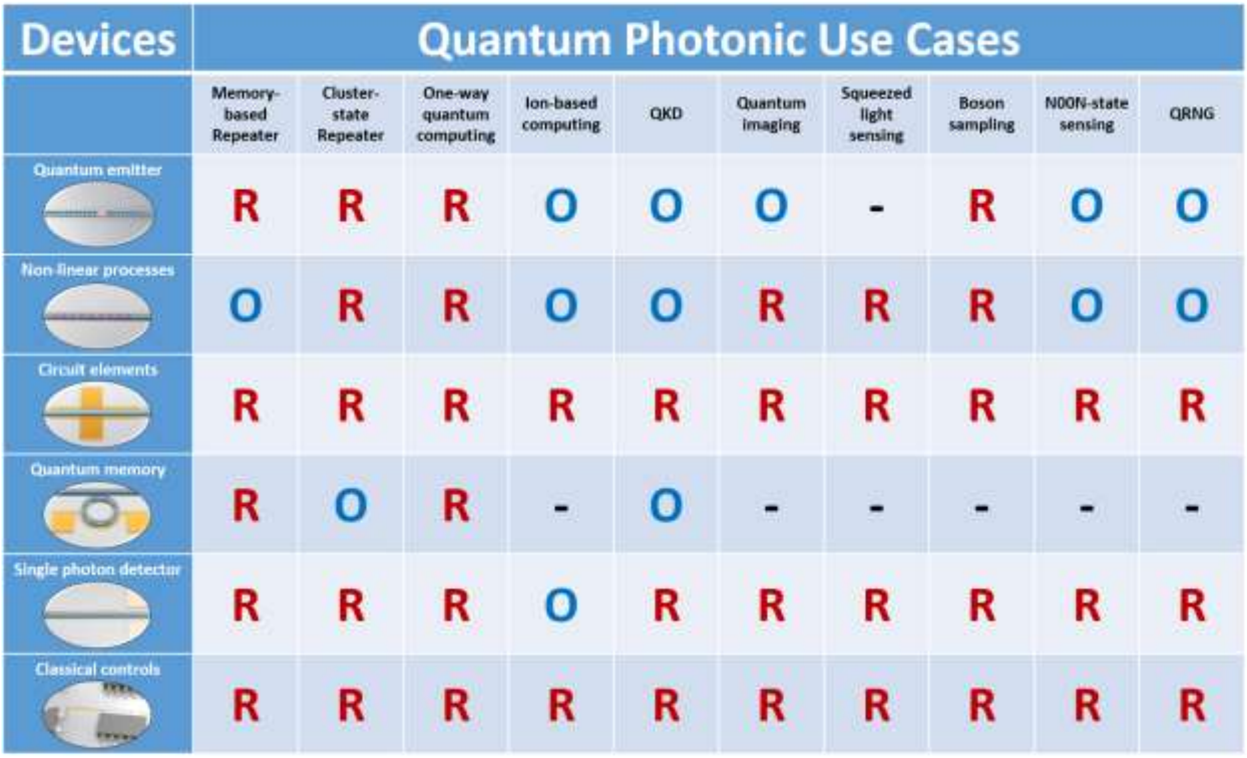
Silicon photonics: A material platform for photonic integrated circuits. It uses silicon as the main optical medium and easily combines electronic and infrared optic elements.


Cavity-coupled quantum emitter
Resonator-coupled quantum memory
Superconducting single-photon detector
Parametric nonlinear source
Electro-optic modulator
Classical controls


New Materials
Pharmaceutic
Logistics
Forecasting
Healthcare
AI
Cyber security
Authentication
Finance
Innovation
Materials
Design
Algorithms
Knowledge
Production
Cleanroom
Prototyping
Foundries
Devices
Assembly
Packaging
Interfacing
Software
Systems
Applications
Photonic Quantum
Computing
Simulation
Communicaton
Sensing

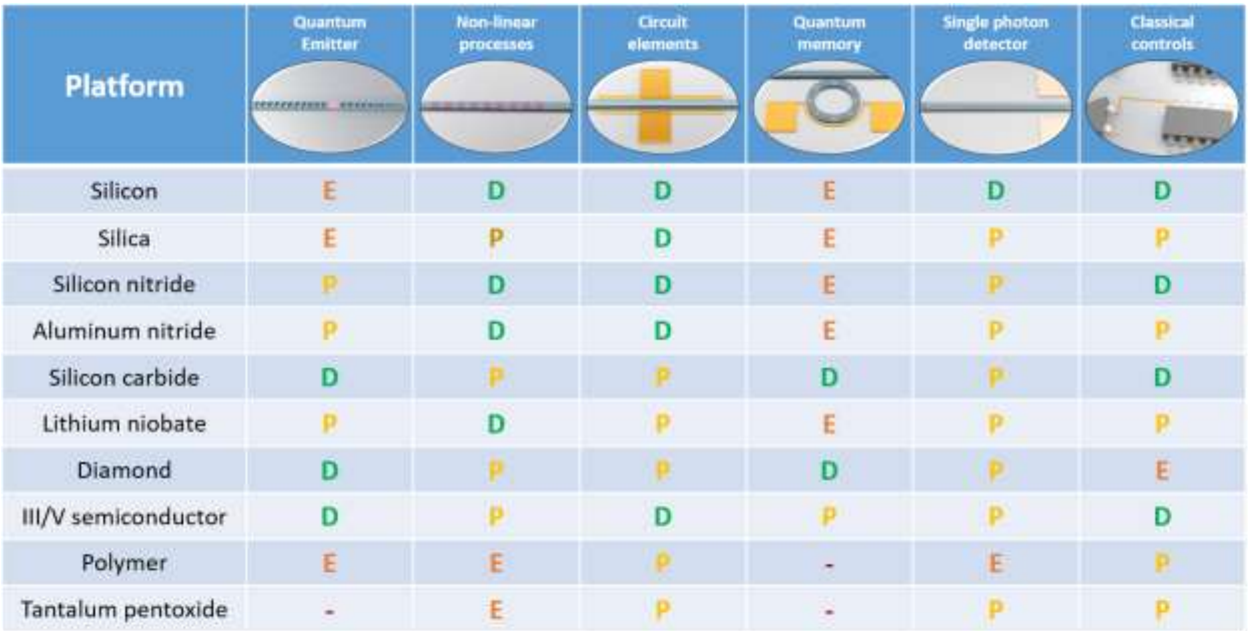


	Devices					
Building Blocks	Quantum emitter	Non-linear processes	Circuit elements	Quantum memory	Single photon detector	Classical controls
Types	- Quantum dots - Atomic like defects - Trapped ions - Nanotubes	- Frequency converters - Parametric down-conversion - Four-wave mixing - Squeezing	- Mach-Zehnder - Beam splitters - MEMS - Micro-cavities - 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 semiconductor - Diamonds - 2D materials - SiC - Rare earth ions - Radiation induced defects (Si, etc) - Single molecules	- Lithium niobate - GaAs - Silicon - Silicon nitride - Aluminum nitride - Silica - SOI	- Polymer - Lithium niobate - III/V semiconductor - Silicon, SOI, SiN - Aluminum nitride - Silica (laser written) - Tantalum pentoxide - Barium titanate	- Atomic vapour - Rare-earth ions - Diamond - SiC - III/V semiconductor - Silica - Silicon	- Silicon - InGaAs - NbN - TiNbN - WSi_2 - $MoSi_2$ - $NbSi_2$	- Silicon - III/V semiconductor - Silicon nitride - transparent conducting oxides



Devices	Quantum Photonic Use Cases									
	Memory-based Repeater	Cluster-state Repeater	One-way quantum computing	Ion-based computing	QKD	Quantum imaging	Squeezed light sensing	Boson sampling	N00N-state sensing	QRNG
Quantum emitter	R	R	R	O	O	O	-	R	O	O
Non-linear 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	-	O	-	-	-	-	-
Single photon detector	R	R	R	O	R	R	R	R	R	R
Classical controls	R	R	R	R	R	R	R	R	R	R

Platform	Properties	Quantum Emitter	Non-linear processes	Circuit elements	Quantum memory	Single photon detector	Classical controls
Silicon	- Transparent at telecom - 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
Aluminum nitride	- Electrooptic effect - Piezoelectric effect	H	M	M	H	H	H
Silicon carbide	- Long spin lifetime - Large Kerr nonlinearity - Transparent at telecom - CMOS compatible	M	M	M	M	H	H
Lithium niobate	- Electrooptic 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 semiconductor	- Monolithic lasers - High quality emitters	M	M	M	M	M/H	H
Polymer	- Large spectral window - Substrate independent - Mouldability - Host for micro-optics	H	H	M	-	H	H
Tantalum pentoxide	- Transparent at telecom - Piezo electric - CMOS compatible	-	M	M	-	H	H



Platform	Quantum Emitter	Non-linear 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
Aluminum 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 semiconductor	D	P	D	P	P	D
Polymer	E	E	P	-	E	P
Tantalum pentoxide	-	E	P	-	P	P

References

---

[1] Georgescu, Iulia. "How the Bell tests changed quantum physics." Nature Reviews Physics (2021): 1-3; DOI: 10.1038/s42254-021-00365-8

[2] Scarani, Valerio. “*Quantum physics: a first encounter: interference, entanglement, and reality*”. Oxford University Press, 2006

[3] Glauber, Roy J. "*Nobel Lecture: One hundred years of light quanta*." Reviews of modern physics 78.4 (2006): 1267; DOI 10.1103/RevModPhys.78.1267

[4] Scully, Marian O., Berthold-Georg Englert, and Herbert Walther. *"Quantum optical tests of complementarity*." Nature 351.6322 (1991): 111-116; DOI: 10.1038/351111a0

[5] Aspect, Alain. "Closing the door on Einstein and Bohr’s quantum debate." Physics 8 (2015): 123;

[6] Pan, J. W. et al. *“Multiphoton entanglement and interferometry*”. Rev. Mod. Phys. 84, 777–838 (2012).

[7] J. P. Dowling and G. J. Milburn, “*Quantum technology: the second quantum revolution*” Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences 361(1809), 1655-1674, (2003). DOI:10.1098/rsta.2003.1227

[8] I. H. Deutsch, “ *Harnessing the Power of the Second Quantum Revolution*” (2020), arXiv:2010.10283 [quant-ph]

[9] S. Lloyd and D. Englund, “*Future Directions of Quantum Information Processing*,” Final Report for Workshop Funded by the Basic Research Office, Office of the Assistant Secretary of Defense for Research & Engineering. (2017), https://basicresearch.defense.gov/Portals/61/Documents/future-directions/Future_Directions_Quantum.pdf?ver=2017-09-20-003031-450

[10] A. Steane, “*Quantum computing*” Reports on Progress in Physics, 61(2), 117, (1998). DOI: 10.1088/0034-4885/61/2/002

[11] I. M. Georgescu, S. Ashhab, and Franco Nori, “*Quantum Simulation*” Rev. Mod. Phys. 86, 153 (2014). DOI: 10.1103/RevModPhys.86.153

[12] N. Gisin and R. Thew, “*Quantum communication*” Nature Photonics 1, 165–171 (2007). DOI:10.1038/nphoton.2007.22

[13] C. L. Degen, F. Reinhard, and P. Cappellaro, “*Quantum sensing*” Rev. Mod. Phys. 89, 035002 (2017). DOI: 10.1103/RevModPhys.89.035002

[14] V. Giovannetti, S. Lloyd, L. Maccone, “*Advances in quantum metrology*” Nat. Photon. 5, 222 (2011). DOI: 10.1038/nphoton.2011.35

[15] E. Polino, M. Valeri, N. Spagnolo, and F. Sciarrino, “*Photonic quantum metrology*”, AVS Quantum Sci. 2, 024703 (2020); DOI 10.1116/5.0007577

[16] Zhong, Han-Sen, Hui Wang, Yu-Hao Deng, Ming-Cheng Chen, Li-Chao Peng, Yi-Han Luo, Jian Qin et al. "*Quantum computational advantage using photons*." Science 370, (2020): 1460-1463. DOI: 10.1126/science.abe8770

[17] Y. Cao, J. Romero and A. Aspuru-Guzik, "*Potential of quantum computing for drug discovery,*" in IBM Journal of Research and Development, vol. 62, pp. 6:1-6:20, 1 (2018), DOI: 10.1147/JRD.2018.2888987

[18] Batra, Kushal, Kimberley M. Zorn, Daniel H. Foil, Eni Minerali, Victor O. Gawriljuk, Thomas R. Lane, and Sean Ekins. "*Quantum Machine Learning for Drug Discovery*." (2020). chemrxiv.org/articles/preprint/Quantum_Machine_Learning_for_Drug_Discovery/12781232/1

[19] Li, Junde, Mahabubul Alam, Congzhou M. Sha, Jian Wang, Nikolay V. Dokholyan, and Swaroop Ghosh. "*Drug Discovery Approaches using Quantum Machine Learning.*" arXiv preprint arXiv:2104.00746 (2021).

[20] Vikstål, Pontus, et al. "*Applying the Quantum Approximate Optimization Algorithm to the Tail-Assignment Problem.*" Physical Review Applied 14.3 (2020): 034009.DOI: 10.1103/PhysRevApplied.14.034009

---

[21] Egger, D. J., Gambella, C., Marecek, J., McFaddin, S., Mevissen, M., Raymond, R., ... & Yndurain, E. "*Quantum computing for Finance: state of the art and future prospects".* IEEE Transactions on Quantum Engineering. 1, 3101724 (2020); DOI: 10.1109/TQE.2020.3030314

[22] Bongs, Kai, et al. "Taking atom interferometric quantum sensors from the laboratory to real-world applications." Nature Reviews Physics 1.12 (2019): 731-739; DOI: 10.1038/s42254-019-0117-4

[23] Kimble, H. Jeff. "The quantum internet." *Nature* 453.7198 (2008): 1023-1030.DOI : 10.1038/nature07127

[24] Wehner, Stephanie, David Elkouss, and Ronald Hanson. "Quantum internet: A vision for the road ahead." *Science* 362.6412 (2018). DOI: 10.1126/science.aam9288

[25] Flamini, Fulvio, Nicolo Spagnolo, and Fabio Sciarrino. "Photonic quantum information processing: a review." *Reports on Progress in Physics* 82.1 (2018): 016001. DOI: 10.1126/science.aam9288

[26] O'Brien, Jeremy L. "Optical quantum computing." *Science* 318.5856 (2007): 1567-1570.DOI: 10.1126/science.1142892

[27] J. L. O'Brien, A. Furusawa and J. Vučković, "*Photonic quantum technologies*" Nature Photonics 3, 687-695 (2009). DOI: 10.1038/nphoton.2009.229

[28] J. Wang, F. Sciarrino, A. Laing, & M. G. Thompson, "*Integrated photonic quantum technologies*" Nature Photonics 14, 273–284 (2020). DOI: 10.1038/s41566-019-0532-1

[29] See for example Bower, C. A., E. Menard, and P. E. Garrou. "*Transfer printing: An approach for massively parallel assembly of microscale devices.*" 2008 58th Electronic Components and Technology Conference. IEEE, 2008.DOI: 10.1109/ECTC.2008.4550113; Corbett, Brian, et al. "*Transfer print techniques for heterogeneous integration of photonic components.*" Progress in Quantum Electronics 52 (2017): 1-17. DOI: 10.1016/j.pquantelec.2017.01.001; Alexe, Marin, and Ulrich Gösele, eds. "*Wafer bonding: applications and technology.*" Vol. 75. Springer Science & Business Media, 2013; Lasky, J. B. "*Wafer bonding for silicon-on-insulator technologies*." Applied Physics Letters 48.1 (1986): 78-80. DOI: 10.1063/1.96768

[30] See for example Gutierrez-Aitken, Augusto, et al. "*Advanced heterogeneous integration of InP HBT and CMOS Si technologies*." 2010 IEEE Compound Semiconductor Integrated Circuit Symposium (CSICS). IEEE, 2010; DOI: 10.1109/CSICS.2010.5619667; Alcotte, R., et al. "*Epitaxial growth of antiphase boundary free GaAs layer on 300 mm Si (001) substrate by metalorganic chemical vapour deposition with high mobility.*" Apl Materials 4.4 (2016): 046101.DOI: 10.1063/1.4945586; Wang, Zhechao, et al. "*Room-temperature InP distributed feedback laser array directly grown on silicon.*" Nature Photonics 9.12 (2015): 837-842.DOI: 10.1038/nphoton.2015.199

[31] J. I. Cirac, & P. Zoller, "*Quantum computations with cold trapped ions*" Phys. Rev. Lett. 74, 4091 (1995). DOI: 10.1103/PhysRevLett.74.4091

[32] P. Kómár, E. M. Kessler, M. Bishof, L. Jiang, A. S. Sørensen, J. Ye & M. D. Lukin "*A quantum network of clocks*" Nature Physics 10, 582–587(2014). DOI; 10.1038/nphys3000

[33] A., Sven, M. Gebbe, M. Gersemann, H. Ahlers, H. Müntinga, E. Giese, N. Gaaloul et al. "*Atom-chip fountain gravimeter*" Physical review letters 117, 203003 (2016). DOI: 10.1103/PhysRevLett.117.203003

[34] B. Stern, X. Ji, Y. Okawachi, A. L. Gaeta & M. *Lipson "Battery-operated integrated frequency comb generator"* Nature 562, 401–405(2018)

[35] Junqiu Liu et al., *"Photonic microwave generation in the X- and K-band using integrated soliton microcombs*" Nature Photonics 14, 486–491(2020)

[36] Wim Bogaerts et al., *"Programmable photonic circuits"* Nature 586, 207–216(2020). DOI: 10.1038/s41586-020-2764-0

[37] J. Wang et al. "*Multidimensional quantum entanglement with large-scale integrated optics*". Science 360, 285-291 (2018). DOI: 10.1126/science.aar7053

[38] A. Politi, et.al., "*Silica-on-silicon waveguide quantum circuits*". Science320, 646–649 (2008). DOI: 10.1126/science.1155441

[39] Pernice, W. H. P. et al. "*High-speed and high-efficiency travelling wave single-photon detectors embedded in nanophotonic circuits*". Nat. Commun. 3, 1325 (2012). DOI: 10.1038/ncomms2307

[40] Najafi, F., Mower, J., Harris, N. et al. "*On-chip detection of non-classical light by scalable integration of single-photon detectors*" Nat Commun 6, 5873 (2015). DOI. 10.1038/ncomms6873

[41] Jeroen PG van Dijk, Edoardo Charbon, and Fabio Sebastiano. "*The electronic interface for quantum processors.*" Microprocessors and Microsystems 66, 90-101 (2019);DOI 10.1016/j.micpro.2019.02.004

[42] HK. Lo, M. Curty, & K. Tamaki, "*Secure quantum key distribution*" Nature Photonics 8, 595–604 (2014). DOI: 10.1038/nphoton.2014.149

internet: A vision for the road ahead" Science 362 (6412) (2018). DOI: 10.1126/science.aam9288

val", Science 357, 1392-1395. DOI: 10.1126/science.aan5959; DOI:

---

[44] Noel H. Wan, et.al, “*Large-scale integration of artificial atoms in hybrid photonic circuits*”. Nature 583, 226–231 (2020); DOI: 0.1038/s41586-020-2441-3

[45] I. Cirac, P. Zoller, H. J. Kimble, and H. Mabuchi,” *Quantum state transfer and entanglement distribution among distant nodes in a quantum network*” Phys. Rev. Lett. 78, 3221 (1997). DOI: 10.1126/science.aam9288

[46] H.-J. Briegel, W. Dür, J. I. Cirac, and P. Zoller, “*Quantum Repeaters: The Role of Imperfect Local Operations in Quantum Communication*” Phys. Rev. Lett. 81, 5932 (1998). DOI: 10.1103/PhysRevLett.81.5932

[47] Muralidharan, Sreraman, Jungsang Kim, Norbert Lütkenhaus, Mikhail D. Lukin, and Liang Jiang. "*Ultrafast and fault-tolerant quantum communication across long distances.*" Physical Review Letters 112, (2014): 250501.DOI: 10.1103/PhysRevLett.112.250501

[48] Glaudell, Andrew N., Edo Waks, and Jacob M. Taylor. "*Serialized quantum error correction protocol for high-bandwidth quantum repeaters*." New Journal of Physics 18, no. 9 (2016): 093008. DOI 10.1088/1367-2630/18/9/093008

[49] Fowler, Austin G., David S. Wang, Charles D. Hill, Thaddeus D. Ladd, Rodney Van Meter, and Lloyd CL Hollenberg. "S*urface code quantum communication.*" Physical Review Letters 104, (2010): 180503. DOI 10.1103/PhysRevLett.104.180503.

[50] Azuma, Koji, Kiyoshi Tamaki, and Hoi-Kwong Lo. "*All-photonic quantum repeaters.*" Nature communications 6, (2015): 1-7. DOI:10.1038/ncomms7787

[51] Borregaard, Johannes, Hannes Pichler, Tim Schröder, Mikhail D. Lukin, Peter Lodahl, and Anders S. Sørensen. "O*ne-way quantum repeater based on near-deterministic photon-emitter interfaces*." Physical Review X 10, (2020): 021071. DOI 10.1103/PhysRevX.10.021071

[52] Chen, Yu-Ao, et al. "An integrated space-to-ground quantum communication network over 4,600 kilometres." Nature 589.7841 (2021): 214-219. DOI: 10.1038/s41586-020-03093-8

[53] T. D. Ladd, et.al., “*Quantum computers*”. Nature 464, 45–53 (2010). DOI: 10.1038/nature08812

[54] C. Monroe, “*Quantum information processing with atoms and photons*” Nature 416, 238–246 (2002). DOI: 10.1038/416238a

[55] Ming Gong, et.al, “*Quantum walks on a programmable two-dimensional 62-qubit superconducting processor”.* Science 372, 948-952 (2021). DOI: 10.1126/science.abg7812

[56] F. Arute, et.al, “*Quantum supremacy using a programmable superconducting processor*”. Nature 574, 505–510 (2019). DOI: 10.1038/s41586-019-1666-5

[57] S. Aaronson & A. Arkhipov “*The computational complexity of linear optics*”. In Proc. Forty-third Annual ACM Symposium on Theory of Computing 333–342 (Association for Computing Machinery, 2011). DOI: 10.1145/1993636.1993682

[58] R. Raussendorf & H. J. Briegel “*A one-way quantum computer*”. Phys. Rev. Lett. 86, 5188–5191 (2001). DOi: 10.1103/PhysRevLett.86.5188

[59] M. A. Nielsen. “*Optical quantum computation using cluster states*”. Phys. Rev. Lett. 93, 040503 (2004). DOI: 10.1103/PhysRevLett.93.040503. DOI 10.1103/PhysRevLett.93.040503

[60] Walther, P., Resch, K., Rudolph, T. et al. “*Experimental one-way quantum computing*”, Nature 434, 169–176 (2005). DOI: 10.1038/nature03347

[61] Saggio, V., Asenbeck, B.E., Hamann, A. et al. “*Experimental quantum speed-up in reinforcement learning agents*.” Nature 591, 229–233 (2021). DOI:10.1038/s41586-021-03242-7

[62] N. C. Menicucci, S. T. Flammia, and O. Pfister, “*One-Way Quantum Computing in the Optical Frequency Comb*” Phys. Rev. Lett. 101, 130501 (2008). DOI: 10.1103/PhysRevLett.101.130501

[63] Spring, Justin B., et al., "*Boson sampling on a photonic chip*" Science 339, 798-801 (2013): DOI: 10.1126/science.1231692

[64] M. A. Broome et al., “*Photonic boson sampling in a tunable circuit*,” Science, 339, 794 –798 (2013).DOI: 10.1126/science.1231440

[65] M. Tillmann et al., “*Experimental boson sampling*,” Nat. Photonics 7, 540 –544 (2013); DOI: 10.1038/nphoton.2013.102

[66] A. Crespi et al., “*Integrated multimode interferometers with arbitrary designs for photonic boson sampling*,” Nat. Photonics, 7 545 –549 (2013). DOI: 10.1038/nphoton.2013.112

[67]A. Aspuru-Guzik and P. Walther, “*Photonic quantum simulators*” Nat. Phys. 8, 285–291 (2012). DOI: 10.1038/nphys2253

[68] Nicholas C. Harris et al., *“Quantum transport simulations in a programmable nanophotonic processor”* Nature Photonics 11, 447–452 (2017): DOI: 10.1038/nphoton.2017.95

[69] Wang, Hui, et al. "High-efficiency multiphoton boson sampling." *Nature Photonics* 11.6 (2017): 361-365.DOI: 10.1038/nphoton.2017.63

---

[70] H. Wang (2019). “Boson sampling with 20 input photons and a 60-mode interferometer in a 10^{14}-dimensional hilbert space". *Physical review letters*, *123*(25), 250503. (2019). DOI; 10.1103/PhysRevLett.123.250503

[71] Lund, Austin P., et al. "Boson sampling from a Gaussian state." *Physical review letters* 113.10 (2014): 100502.

DOI: 10.1103/PhysRevLett.113.100502

[72] Bentivegna, M. et al. “*Experimental scattershot boson sampling*”. Sci. Adv. 1, e1400255 (2015). DOI; 10.1126/sciadv.1400255

[73] Craig S. et.al, “*Gaussian Boson Sampling*”. Phys. Rev. Lett. 119, 170501 2017. DOI 10.1103/PhysRevLett.119.170501

[74] E. Knill, R. Laflamme & G. J. Milburn “*A scheme for efficient quantum computation with linear optics*”. Nature 409, 46–52 (2000). DOI 10.1038/35051009

[75] S. Paesani et al., *“Generation and sampling of quantum states of light in a silicon chip”* Nature Physics 15, 925–929 (2019) ; DOI: 10.1038/s41567-019-0567-8

[76] J. Carolan, et al. “*Universal linear optics*”. Science 349, 711–716 (2015). DOI: 10.1126/science.aab3642

[77] A. Politi, J. C. F. Matthews & J. L. O’Brien. *“Shor’s quantum factoring algorithm on a photonic chip”*. Science325, 1221 (2009). DOI: 10.1126/science.1173731

[78] T. Rudolph, “*Why I am optimistic about the silicon-photonic route to quantum computing*” APL Photon. 2, 030901 (2017). DOI: 10.1063/1.4976737

[79] Daniel E. Browne and Terry Rudolph. “*Resource-efficient linear optical quantum computation*”. Physical Review Letters, 95(1):010501, 2005. DOI: 10.1103/PhysRevLett.95.010501

[80] Mihir Pant, Don Towsley, Dirk Englund, and Saikat Guha. “*Percolation thresholds for photonic quantum computing*”. Nat. Commun., 10(1):1–11, 2019. DOI 10.1038/s41467-019-08948-x

[81] Xi-Lin Wang et.al., “*18-Qubit Entanglement with Six Photons’ Three Degrees of Freedom*”. Phys. Rev. Lett. 120, 260502 (2018). DOI: 10.1103/PhysRevLett.120.260502

[82] J. C. Adcock, et.al., “*Programmable four-photon graph states on a silicon chip*”. Nat. Commun. 10, 3528 (2019). DOI 10.1038/s41467-019-11489-y

[83] Daniel Llewellyn, et.al., “*Chip-to-chip quantum teleportation and multi-photon entanglement in silicon*”. Nature Physics 16, 148–153 (2020). DOI: 10.1038/s41567-019-0727-x

[84] Ciampini, M. A. et al. “*Path-polarization hyperentangled and cluster states of photons on a chip*”. Light Sci. Appl. 5, e16064 (2016). DOI: 10.1038/lsa.2016.64

[85] Caterina Vigliar, et.al., *“Error protected qubits in a silicon photonic chip.”* arXiv:2009.08339 [quant-ph] 2021.

[86] Slussarenko, Sergei, and Geoff J. Pryde. "Photonic quantum information processing: A concise review." Applied Physics Reviews 6.4 (2019): 041303. DOI: 10.1063/1.5115814

[87] S. Paesani, A. A. Gentile, R. Santagati, J. Wang, N. Wiebe, D. P. Tew, J. L. O’Brien, and M. G. Thompson, *“Experimental Bayesian Quantum Phase Estimation on a Silicon Photonic Chip”* Phys. Rev. Lett. 118, 100503 (2017);DOI:10.1103/PhysRevLett.118.100503

[88] R. Santagati et al., *“Witnessing eigenstates for quantum simulation of Hamiltonian spectra”* Science Advances 26, 4, 1, eaap9646 (2018) DOI: 10.1126/sciadv.aap964

[89] A. Peruzzo et al., *“A variational eigenvalue solver on a photonic quantum processor”* Nature Communications 5, 4213 (2014); DOI:10.1038/ncomms5213

[90] Cerezo, Marco, et al. "Variational quantum algorithms." Nature Reviews Physics (2021): 1-20. DOI 10.1038/s42254-021-00348-9

[91] J. Wang et al., *“Experimental quantum Hamiltonian learning”* Nature Physics 13, 551–555(2017); DOI: 10.1038/nphys4074

[92] Lahini, Yoav, Assaf Avidan, Francesca Pozzi, Marc Sorel, Roberto Morandotti, Demetrios N. Christodoulides, and Yaron Silberberg. "*Anderson localization and nonlinearity in one-dimensional disordered photonic lattices.*" Physical Review Letters 100, (2008): 013906. DOI: 10.1103/PhysRevLett.100.013906

[93] A. Crespi, R. Osellame, R. Ramponi, V. Giovannetti, R. Fazio, L. Sansoni, F. De Nicola, F. Sciarrino, P. Mataloni, “*Anderson localization of entangled photons in an integrated quantum walk*”, Nature Photonics 7, 322–328 (2013): DOI: 10.1038/nphoton.2013.26

[94] M. Gräfe, R. Heilmann, M. Lebugle, D. Guzman-Silva, A. Perez-Leija and A. Szameit “*Integrated photonic quantum walks*” Journal of Optics, Volume 18, (10) 103002 (2016). DOI: 10.1088/2040-8978/18/10/103002/meta

---

[95] J. M. Arrazola, et.al., “*Quantum circuits with many photons on a programmable nanophotonic chip.”* Nature 591, 54–60 (2021). DOI: 10.1038/s41586-021-03202-1

[96] Manuel Endres, Hannes Bernien, Alexander Keesling, et al. “*Atom-by-atom assembly of defect-free one-dimensional cold atom arrays*”, Science 354, 1024-1027 (2016); DOI: 10.1126/science.aah3752

[97] A. Omran, H. Levine, A. Keesling, G. Semeghini, et al., “*Generation and manipulation of Schrödinger cat states in Rydberg atom arrays*” Science 365, 570-574 (2019); DOI: 10.1126/science.aax9743

[98] C. Figgatt, A. Ostrander, N. M. Linke, K. A Landsman, D. Zhu, D. Maslov, C. Monroe, “*Parallel Entangling Operations on a Universal Ion Trap Quantum Computer*” Nature 567, 61 (2019). DOI: 10.1103/RevModPhys.79.135

[99] Choi, Taeyoung, Shantanu Debnath, T. A. Manning, Caroline Figgatt, Z-X. Gong, L-M. Duan, and Christopher Monroe. "*Optimal quantum control of multimode couplings between trapped ion qubits for scalable entanglement.*" Physical Review Letters 112, 190502 (2014); DOI 10.1103/PhysRevLett.112.190502

[100] K. K. Mehta et al. *“Integrated optical addressing of an ion qubit*”. Nat. Nanotechnol. 11, 1066–1070 (2016).DOI: 10.1038/nnano.2016.139

[101] K. K. Mehta, et.al, “*Integrated optical multi-ion quantum logic*”. Nature 586, 533–537 (2020). DOI: 10.1038/s41586-020-2823-6

[102] R. J. Niffenegger, et.al, “*Integrated multi-wavelength control of an ion qubit*.” Nature 586, 538–542 (2020). DOI: 10.1038/s41586-020-2811-x

[103] D. E. Chang, J. S. Douglas, A. González-Tudela, C.-L. Hung, and H. J. Kimble. “*Quantum matter built from nanoscopic lattices of atoms and photons*”. Rev. Mod. Phys. 90, 031002 (2018).DOI: 10.1103/RevModPhys.90.031002

[104] T. G. Tiecke, et.al, “*Nanophotonic quantum phase switch with a single atom*”. Nature 508, 241–244 (2014). DOI: 10.1038/nature13188

[105] David D. Awschalom et.al, “*Quantum Spintronics: Engineering and Manipulating Atom-Like Spins in Semiconductors*”. Science 339 1174-1179 (2013). DOI: 10.1126/science.1231364

[106] W. B. Gao, A. Imamoglu, H. Bernien & R. Hanson. “*Coherent manipulation, measurement and entanglement of individual solid-state spins using optical fields*”. Nature Photonics 9, 363–373 (2015). DOI: 10.1038/nphoton.2015.58

[107] S. Barzanjeh, S. Guha, C. Weedbrook, D. Vitali, J. H. Shapiro, and S. Pirandola, “*Microwave Quantum Illumination*”, Phys. Rev. Lett. 114, 080503(2015). DOI: 10.1103/PhysRevLett.114.080503

[108] D. Luong, S. Rajan and B. Balaji, "*Entanglement-Based Quantum Radar: From Myth to Reality*" IEEE Aerospace and Electronic Systems Magazine 35 (4), 22-35, (2020). DOI:10.1109/MAES.2020.2970261

[109] M. Lanzagorta "*Amplification of radar and lidar signatures using quantum sensors*" Proc. SPIE 8734, Active and Passive Signatures IV, 87340C (2013). DOI:10.1117/12.2017016

[110] V. M. Acosta, E. Bauch, M. P. Ledbetter, C. Santori, K.-M. C. Fu, P. E. Barclay, R. G. Beausoleil, H. Linget, J. F. Roch, F. Treussart, S. Chemerisov, W. Gawlik, and D. Budker, “*Diamonds with a high density of nitrogen-vacancy centers for magnetometry applications*” Phys. Rev. B 80, 115202 (2009)

[111] T. Wolf, P. Neumann, K. Nakamura, H. Sumiya, T. Ohshima, J. Isoya, and J. Wrachtrup, “*Subpicotesla Diamond Magnetometry*” Phys. Rev. X 5, 041001 (2015). DOI; 10.1103/PhysRevX.5.041001

[112] M.H. Abobeih, J. Randall, C.E. Bradley, *et al.* “*Atomic-scale imaging of a 27-nuclear-spin cluster using a quantum sensor*” *Nature* **576,** 411–415 (2019). DOI: 10.1038/s41586-019-1834-7

[113] S. D. Huver, C. F. Wildfeuer, and J. P. Dowling, “*Entangled Fock states for robust quantum optical metrology, imaging, and sensing*” Phys. Rev. A 78, 063828 (2008). DOI: 10.1103/PhysRevA.78.063828

[114] H. Wang et al., “*Observation of Intensity Squeezing in Resonance Fluorescence from a Solid-State Device*” Phys. Rev. Lett. 125, 153601 (2020) https://doi.org/10.1103/PhysRevLett.125.153601

[115] Ferrari, Simone, Carsten Schuck, and Wolfram Pernice. "*Waveguide-integrated superconducting nanowire single-photon detectors.*" Nanophotonics 7, (2018): 1725-1758. DOI 10.1515/nanoph-2018-0059

[116] Gyger, Samuel, Julien Zichi, Lucas Schweickert, Ali W. Elshaari, Stephan Steinhauer, Saimon F. Covre da Silva, Armando Rastelli, Val Zwiller, Klaus D. Jöns, and Carlos Errando-Herranz. "*Reconfigurable photonics with on-chip single-photon detectors.*" Nature communications 12, (2021): 1-8. DOI: 10.1038/s41467-021-21624-3

[117] Newman, Zachary L., et al. "Architecture for the photonic integration of an optical atomic clock." Optica 6.5 (2019): 680-685. DOI: 10.1364/OPTICA.6.000680

[118] Shadbolt, Peter, et al. "Testing foundations of quantum mechanics with photons." Nature Physics 10.4 (2014): 278-286. DOI: 10.1038/nphys2931

---

[119] Peruzzo, Alberto, et al. "A quantum delayed-choice experiment." *Science* 338.6107 (2012): 634-637. DOI: 10.1126/science.1226719

[120] Chen, Xiaojiong, et al. "A generalized multipath delayed-choice experiment on a large-scale quantum nanophotonic chip." *Nature communications* 12.1 (2021): 1-10. DOI: 10.1038/s41467-021-22887-6

[121] M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt *"Cavity optomechanics"* Rev. Mod. Phys. 86, 1391 (2014)

[122] Gaeta, Alexander L., Michal Lipson, and Tobias J. Kippenberg. "Photonic-chip-based frequency combs." *nature photonics* 13.3 (2019): 158-169. DOI: 0.1038/s41566-019-0358-x

[123] Verhagen, Ewold, et al. "Quantum-coherent coupling of a mechanical oscillator to an optical cavity mode." *Nature* 482.7383 (2012): 63-67. DOI 10.1038/nature1078

[124] G. R. Steinbrecher, J. P. Olson, D. Englund & J. Carolan, *"Quantum optical neural networks"* npj Quantum Information 5, 60 (2019)

[125] Wu, Y., Li, C., Hu, X., Ao, Y., Zhao, Y., Gong, Q., "*Applications of Topological Photonics in Integrated Photonic Devices*" Advanced Optical Materials 2017, 5, 1700357. DOI: 10.1002/adom.201700357

[126] S. Pirandola, "*Quantum Reading of a Classical Digital Memory*" Phys. Rev. Lett. 106, 090504 (2011). DOI; 10.1103/PhysRevLett.106.090504

[127] Liu, Han, et al. "*Enhancing LIDAR performance metrics using continuous-wave photon-pair sources*" Optica Vol. 6, (10), 1349-1355 (2019). DOI: 10.1364/OPTICA.6.001349

[128] Si-Hui Tan, B. I. E., V. Giovannetti, S.Guha, S. Lloyd, L. Maccone, S. Pirandola, and J. H. Shapiro, "*Quantum Illumination with Gaussian States*" Phys. Rev. Lett. 101, 253601 2008. DOI: 10.1103/PhysRevLett.101.253601

[129] Carolan, J., Mohseni, M., Olson, J.P. et al. "*Variational quantum unsampling on a quantum photonic processor*". Nat. Phys. 16, 322–327 (2020). DOI: 10.1038/s41567-019-0747-6

[130] Y. Israel, R. Tenne, D. Oron, et al., *" Quantum correlation enhanced super-resolution localization microscopy enabled by a fibre bundle camera"* Nat Commun 8, 14786 (2017). DOI: 10.1038/ncomms14786

[131] Matthias Fink *et al.*, "*Entanglement-enhanced optical gyroscope*" *New J. Phys.* **21** 053010 (2019). DOI:10.1088/1367-2630/ab1bb2

[132] J. Haas, Julian, et al. "*Chem/bio sensing with non-classical light and integrated photonics*" Analyst 143, 593-605 (2018). DOI: 10.1039/C7AN01011G

[133] Schimpf, C., Reindl, M., Basso Basset, F., Jöns, K. D., Trotta, R., & Rastelli, A. "*Quantum dots as potential sources of strongly entangled photons: Perspectives and challenges for applications in quantum networks*". Applied Physics Letters, *118*(10), 100502. (2021).DOI: 10.1063/5.0038729

[134] Chung, T., Juska, G., Moroni, S. *et al.* "*Selective carrier injection into patterned arrays of pyramidal quantum dots for entangled photon light-emitting diodes.*" Nature Photonics **10,** 782–787 (2016). DOI: 10.1038/nphoton.2016.203

[135] Strategic Research Agenda of the Quantum Flagship https://ec.europa.eu/newsroom/dae/document.cfm?doc_id=65402

[136] Roberson, T. M., and Andrew G. White. "Charting the Australian quantum landscape." *Quantum Science and Technology* 4.2 (2019): 020505. DOI 10.1088/2058-9565/ab02b4/meta

[137] See for example https://equs.org/; https://tmos.org.au/;https://www.cqc2t.org/

[138] T. Honjo, K. Inoue and H. Takahashi, "Differential-phase-shift quantum key distribution experiment with a planar light-wave circuit Mach-Zehnder interferometer," Opt. Lett. 29, 2797-2799, (2004). DOI: 10.1364/OL.29.002797

[139] Sasaki, Masahide, et al. "Field test of quantum key distribution in the Tokyo QKD Network." *Optics express* 19.11 (2011): 10387-10409. DOI: 10.1364/OE.19.010387

[140] https://www.mext.go.jp/en/content/20210315-mxt_kouhou02-000013440-13.pdf

[141] Awschalom, David, et al. "Development of quantum interconnects (quics) for next-generation information technologies." *PRX Quantum* 2.1 (2021): 017002.DOI: 10.1103/PRXQuantum.2.017002

[142] Monroe, Christopher, Michael G. Raymer, and Jacob Taylor. "The us national quantum initiative: From act to action." *Science* 364.6439 (2019): 440-442. DOI: 10.1126/science.aax0578

[143] Alexeev, Yuri, et al. "Quantum computer systems for scientific discovery." *PRX Quantum* 2.1 (2021): 017001.DOI: 10.1103/PRXQuantum.2.017001

[144] K. Kleese van Dam, From Long-Distance Entanglement to Building a Nationwide Quantum Internet: Report of the DOE Quantum Internet Blueprint Workshop, Brookhaven National Lab.(BNL), Upton, NY (United States), 2020. https://www.osti.gov/biblio/1638794

[145] Sussman, B., Corkum, P., Blais, A., Cory, D. and Damascelli, A., 2019. "*Quantum Canada*." Quantum Science and Technology, 4(2), p.020503. DOI: 10.1088/2058-9565/ab029d

---

[146] Yutaka IDO, et al., “Development of Microchip Laser / Periodically Poled Stoichiometric LiTaO3 (PPSLT) for the Light Source of MALDI”, The Review of Laser Engineering, 2009, Volume 37, Issue 4, Pages 290-295,   DOI /10.2184/lsj.37.290,

[147] Baehr-Jones, Tom W., and Michael J. Hochberg. "Polymer silicon hybrid systems: A platform for practical nonlinear optics." *The Journal of Physical Chemistry C* 112.21 (2008): 8085-8090.DOI: 10.1021/jp7118444

[148] Zhang, Ziyang, et al. "Hybrid photonic integration on a polymer platform." *Photonics*. Vol. 2. No. 3. Multidisciplinary Digital Publishing Institute, 2015. DOI: **10.3390/photonics2031005**