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TOPICAL REVIEW — Solid-state quantum information processing

Quantum photonic network on chip*

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We provide an overview of quantum photonic network on chip. We begin from the discussion of the pros and cons of several material platforms for engineering quantum photonic chips. Then we introduce and analyze the basic building blocks and functional units of quantum photonic integrated circuits. In the main part of this review, we focus on the generation and manipulation of quantum states of light on chip and are particularly interested in some applications of advanced integrated circuits with different functionalities for quantum information processing, including quantum communication, quantum computing, and quantum simulation. We emphasize that developing fully integrated quantum photonic chip which contains sources of quantum light, integrate circuits, modulators, quantum storage, and detectors are promising approaches for future quantum photonic technologies. Recent achievements in the large scale photonic chips for linear optical computing are also included. Finally, we illustrate the challenges toward high performance quantum information processing devices and conclude with promising perspectives in this field.

Keywords: quantum photonic chip, entanglement production and manipulation, quantum communication, quantum computing

PACS: 42.50.Ex, 42.82.–m, 03.67.Hk, 03.67.Lx **DOI:** 10.1088/1674-1056/27/5/054207

1. Introduction

Quantum information science is a rapidly developing field of interdisciplinary research at the nexus of quantum mechanics and information theory. It plays a significant role in many subdisciplines of physics, information technology and engineering. Qubits and entanglement are at the heart of various quantum information processing (QIP) protocols, underlying the potentiality and challenge for different quantum systems. Many physical realizations of qubits are currently studied, including superconducting circuits,[1–4] trapped ions,[5–7] cold atoms,[8–10] nuclear magnetic resonance,[11–14] semiconductor quantum dots,[15,16] solid-state color centers,[17–19] and photons.[20,21] Photons occupy a special place in this spectrum: they interact very weakly with optical media and not at all among themselves, which insures the information robust against decoherence. Due to their fast propagation speed, photons become natural candidates for transmitting quantum information and distributing quantum correlations in quantum networks.[22] Additionally, photons possess many degrees of freedom, including spatial path, polarization, frequency, time bins, and angular momentum, which can be chosen for the encoding of quantum information. Photons also possess continuous variables, such as the quantized field quadratures, which can be used in special classes of information protocols.[23,24] Hybrid approaches involving both continuous and discrete variables also exist.[25,26] Quantum information encoded in these degrees of freedom can be manipulated and transferred from one degree of freedom to another with conventional optical tools.[27]

In the past few years, a surprise progress has been made both in theoretical and experimental fields of quantum optics.[28–31] However, complex quantum optical schemes realized in bulk optics suffer from severe drawbacks. On the one hand, it is a difficult task to build advanced interferometric structures using bulk-optical components, since the stability and optical phase accuracy are hard to satisfy the requirements of quantum mechanics. On the other hand, it is difficult to build a large scale setup. An overwhelming approach to beat these limitations is to adopt on-chip integrated photonic devices which offer many advantages compared to bulk optics. A straightforward advantage of quantum photonic chip (QPC) is the scalability, which is a natural character for all the electronic and optical chips. A practical QIP includes at least thousands of logic gates, which was not achievable by bulk optics but can be realized by photonic integrated circuits. For example, complementary metal–oxide–semiconductor (CMOS) technology based QPC can reach the scale of 10^{15}–10^{17} qubits $\times$ time steps for Shor's algorithm to factorize numbers beyond classical ability, wherein the required resource is estimated by

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Campbell *et al.* in an improved magic-state type protocol.[32] The second advantage is the stability. The phase can be stably and precisely controlled on the QPC which is not possible for bulk optics. Controlling phase is not always necessary for classical photonic chips, however, for quantum chips, the phase controlling is always required and plays a key role in QIP. From this point, the QIP relies on the chip version much more heavily than the classical information processing. Thirdly, the QPC can be reconfigured. By the thermal-optic effect, electro-optic effect, etc., the phase of each unit in the QPC can be adjusted so the chip can be reconfigured, resulting in a universality for the chip which can be competent for a large range of QIP. Another advantage is that the chip can accommodate more quantum components like quantum memories and quantum detectors on the same platform which is called a fully integrated QPC. The last but not least, the mass manufacture of quantum chip will reduce the cost drastically, which is always the key point to be considered for a practically used quantum technology. Therefore, QPC opens the door for more complex quantum optical systems and has become one of the most active fields of research today.

The materials platform and fabrication technology of QPC can be inspired by the classical counterpart. The core components necessary for the quantum architecture are already under investigation and optimization by classical photonics engineers. In conventional photonic integrated circuits, light is guided in waveguides consisting of a core and a slightly lower refractive index cladding which are usually fabricated by different methods in different materials.[33–35] A typical photonic quantum circuit takes several optical paths or modes and mixes them together forming a linear optical network (LON), which in general consists of nested interferometers. Quantum integrated circuit has become central to the technological progress by providing methods to miniaturize and fabricate vital components, such as quantum light sources, linear optical elements, quantum memories, and highly efficient single-photon detectors. Over the past several years, QPC has proven to be a highly promising experimental platform, it allows for the realizations of all aspects of QIP applications, ranging from quantum communication, quantum computation, to quantum simulation,[36–39] each of which puts specific constraints on the underlying physical technology. In this review, we will introduce several different material platforms for the realization of various QPCs and focus on the applications of QIP realized in quantum photonic network (QPN). Our goal here is to provide a comprehensive view of the major tasks accomplished so far and those to be addressed next.

2. Integrated platforms for QPNs

We will first review the prevailing material platforms used for QPCs. Integrated optical materials capable of producing and manipulating entangled photons are highly desired, and these will become pivotal ingredients for fully integrated quantum technologies. Here we put particular emphasis on silicon photonic integration platforms, nonlinear optical dielectric materials, and III–V compound semiconductors.

Silicon photonic integration platforms, which include silicon (Si), silicon nitride (SiN), and silicon carbide (SiC), as well as silicon-on-insulator (SOI) and silica-on-silicon (SOS), provide popular solutions as they have several appealing characteristics. Si features strong $\chi^{(3)}$ nonlinearity, which in combination with tight mode confinement enables compact single photon source and on-chip path entanglement, as well as strong thermo-optical effect which can be used to modulate the phase of photon. Carrier depletion in Si waveguide can also lead to highly scalable optical modulation in a faster but lossy way.[40] SiN can be made into ultra low loss waveguides due to its low absorption from visible to infrared wavelengths,[41] it has also been demonstrated for efficient photon generation in the nanowire structure ring resonators.[42] SiC shows exceptional properties such as wide bandgap, high thermal conductivity, low thermal expansion, and good chemical inertness, which make it an ideal candidate for some quantum applications.[43] The SOI platform offers two major advantages over other materials: compatibility with the CMOS industry, and well developed fabrication techniques for Si electronics and photonics.[44] However, these favorable characteristics come at the expense of poor mode matching with optical fibers. SOS material is a natural choice for the development of quantum integrated circuit since it exhibits high coupling efficiency with optical fibers, and low propagation losses, and it is transparent at wavelength of photon generation and detection.[45] This platform is well adapted for complex linear networks, but it cannot support nonlinear and electro-optic effects.

Nonlinear optical dielectric materials, such as lithium niobate ($LiNbO_3$ or LN), lithium tantalate (LT), and potassium titanyl phosphate (KTP), form an attractive candidate integration platform. For instance, the LN crystal (usually called the "silicon of photonics") presents strong effective second order nonlinearities, large piezoelectric coefficient, outstanding electro-optic and acousto-optic properties, and capability for ferroelectric poling.[46] Moreover, mature and reliable waveguide fabrication techniques using either the proton exchange or the Ti-indiffusion method make them ideal for parametric down-conversion, frequency conversion, and electro-optics modulation processes.[33] The LN modulators based on electro-optic effect have been demonstrated for fast path and polarization control of single photons.[47] Generation and manipulation of qubits in such materials can harness the strong second order nonlinearity which can be specifically tailored by exploiting quasi-phase-matching (QPM) with poling structure

on a single bulk crystal platform.[48–52] When the bulk crystal is fabricated into the waveguide structure, the photon flux will be considerably enhanced. Combining with the current development of quantum memories in the LN waveguide,[53] the LN becomes a promising material for integrated quantum devices. Towards a complex integration, a few examples have recently been reported, reviews can be found in Refs. [54] and [55].

III–V compound semiconductors, including gallium arsenide (GaAs), gallium nitride (GaN), and indium phosphide (InP), are widely used platforms in optoelectronics as their direct bandgap allows laser emission, and many of them exhibit the electro-optic effect which allows fast on-chip switching.[56–58] The III–V materials have a high refractive index and usually present a strong second order nonlinearity which allows compact and efficient frequency conversion processes, but they show larger linear losses compared to the Si-based waveguides. GaAs is the most developed III–V photonic platform for quantum applications, it allows high density integration, strong light confinement in waveguides, and fast electro-optic switching.[59] InP is one of the few semiconductors that can provide both active and passive optical devices.[60–64] InP epitaxial layers can be designed to provide lasers that emit light in telecommunication wavelength windows, they can also be used to fabricate optical waveguides that are transparent in these wavelengths. Others materials such as AlGaAs can be used to propagate and manipulate photons with improved transmission window compared to GaAs,[65,66] while InGaAs can be used for detection.[67–69] However, the same as the Si-based platform, mode matching with the optical fibers and propagation losses are issues which limit the complexity of the circuit from III–V compound semiconductors materials.

From the above descriptions, we can see that no single integration platform can gather all the desired characteristics for an advanced application, and it remains an open question which material is best suited for the integration of larger quantum circuits, especially when a fully integrated chip is considered. In addition to the above integration platforms, other important materials including semiconductor quantum dots[70] and diamond-on-insulator[71] have emerged as competitive platforms for realizing highly functional integrated circuits. Orieux *et al.* and Bogdanov *et al.* provided an overview on several material platforms and offer comprehensive discussions on the degree of integration in individual and composite platform approaches.[72,73]

3. Functional elements for QPCs

The most important elements for QPCs include nonclassical light sources that can generate single photons or photon pairs via nonlinear interactions, linear optical devices such as beam splitters (BSs), polarization beam splitters (PBSs), phase shifters (PSs), interferometers, and filters, quantum memories that can store quantum states, and single photon detectors that can register the single photons precisely. We exploit the waveguide technology to discuss the design of different functional blocks to build up QPN. In the following, we will discuss in detail the implementation of these basic components.

3.1. Non-classical light sources

The first key element of the integrated optical circuits is a source of nonclassical states of light. Single-photon states can be generated either in a deterministic manner using single-photon emitters[74] or probabilistically by heralding the generation of the desired state in one of the correlated photon pair with the detection of the second member.[75,76] It is also necessary to generate two- or multi-photon entangled states, which constitute the most important resource in QIP.[77,78] Currently, the best on-chip sources of photon pairs make use of the second-order and third-order nonlinear processes, in particular, spontaneous parametric down-conversion (SPDC) and spontaneous four-wave mixing (SFWM), respectively. SPDC is possible in a periodically poled nonlinear crystal as well as in the III–V compound materials, while SFWM usually takes place in the Si-based platform.

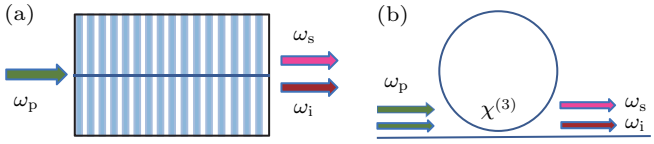


Fig. 1. (color online) (a) A pair of signal–idler photon pair with frequencies ω_s and ω_i is generated via SPDC from PPLN waveguide pumped by ω_p. (b) Two photons at frequencies ω_p are absorbed and a pair of photons at frequencies ω_s and ω_i are generated via SFWM.

In a SPDC process, a pump laser is sent through a nonlinear crystal with large second order susceptibility $\chi^{(2)}$, the pump photon ω_p has a small probability of being annihilated while creating a pair of down-converted photons ω_s and ω_i, obeying energy and momentum conservation. As for most cases of waveguide structure in the optical dielectric materials, QPM is exploited in a periodically inverted medium as shown in Fig. 1(a). Conservation of momentum requires a matching of the wave vector of the pump photon and the down-converted photons according to $k_p = k_s + k_i + 2\pi/\Lambda$, where Λ is the inversion period of the modulation area and k_j $(j = p, s, i)$ are the wave vectors in the waveguides. Indistinguishable pairs of photons generated via SPDC have been an invaluable tool in quantum optics experiments.

Entangled photon pairs can also be produced in Si via SFWM.[79,80] In a SFWM process, two pump photons at frequency ω_p are absorbed and a pair of energy- and momentum-conserving photons at frequencies ω_s and ω_i are generated as

shown in Fig. 1(b), satisfying $2\omega_p = \omega_s + \omega_i$ and $2k_p = k_s + k_i$. Si waveguides and Si micro-ring resonators with a SOI structure, which enjoy the high refractive index contrast between the core of Si and the silica cladding, can achieve high generation rate of photon pairs in small size.[81–87] Silverstone *et al.* developed a quantum circuit that integrated two photon-pair sources via SFWM in an interferometer with a reconfigurable PS, and demonstrated a high visibility quantum interference in the SOI device.[88]

3.2. Linear optical devices

Linear optical elements are pivotal components in the manipulation of classical and quantum states of light. In QPCs, BS also known as directional coupler (DC), can be realized by designing a device comprised a coupling region consisting of two closely adjacent waveguides as shown in Fig. 2(a), the evanescent fields from the waveguides overlap, and the light is able to couple from one guide to the adjacent one. The amount of light coupling from one waveguide into the other (the coupling ratio is $1-\eta$, where η is the BS reflectivity) can be tuned. An arbitrary split ratio can be achieved by tuning the separation of the waveguides and the length of the coupling region. The DC is now usually designed as its equivalence, namely, the multi-mode interferometer (MMI). Meantime, the wavelength multiplexing and PBS can be designed similarly with the DC as shown in Fig. 2(b).[89]

For DCs composed of Si wire waveguides, Fukuda *et al.* demonstrated a PBS with dimensions of 7 μm×16 μm that exhibited an polarization extinction ratio of 15 dB for a single coupler.[90] By engineering the dielectric permittivity locally at the sub-wavelength scale, it is possible to manipulate the flow of light inside the Si to realize on-chip polarization splitters, power splitters, mode converters, and wavelength filters.[91] Based on complex nanophotonic structures on compact Si platform, Shen *et al.* designed and fabricated an integrated nanophotonics PBS with a footprint of 2.4 μm×2.4 μm, which is the smallest PBS ever demonstrated.[92] Piggott *et al.* designed a wavelength-division multiplexer (WDM) that splits 1300 nm and 1550 nm light from an input waveguide into two output waveguides, making this the smallest dielectric wavelength splitter.[93] On-chip PBS devices can be realized by designing a zero-gap coupler,[94] i.e., there is no gap between the waveguides in the central coupling section, two waveguides are merged to a single one with doubled width. For transitions, V-shaped straight waveguides in the branching regions are connect to the input and output waveguides. The branching angle and the length of the central coupling region can be designed using the local normal mode method.[95]

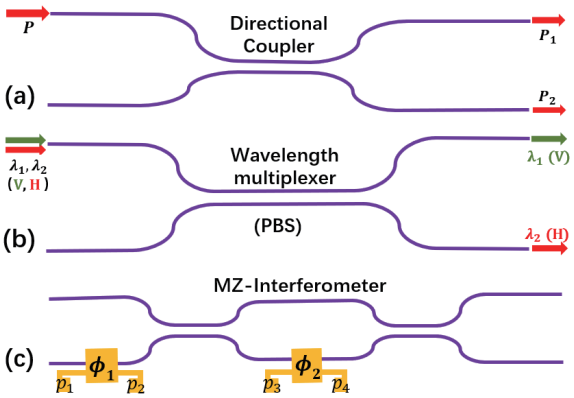


Fig. 2. (color online) (a) Directional coupler, (b) wavelength multiplexer or PBS, and (c) MZI with variable PSs.

Another important component for quantum technologies is phase-controlled Mach–Zehnder interferometer (MZI), which is consisted of two DCs and two PSs as shown in Fig. 2(c). The PS in the middle of MZI controls the relative phase between superposition states before the two modes are recombined at the second DC. The MZI then acts as a high-quality DC with precisely controlled splitting ratio. For the decomposition of a unitary operation, the MZI with two PSs is the basic element. In the case of Si, the simplest method to control the phase is via the thermo-optical effect. By using resistive elements deposited on the surface of the device, the temperature of the waveguide structure beneath the resistor can be locally raised. The local heating causes the refractive index to change slightly, thus inducing an optical phase difference which can be adjusted across a full range from 0 to 2π between the two different waveguides.[96–98] For optical dielectric materials such as LN and LT, an outstanding feature is their capability of electro-optic modulation that enables on-chip manipulation of optical phase via external control voltages, which features in fast speed and ultra-low loss. These electro-optic properties have been widely used to develop various versions of PSs.[99]

3.3. Quantum memories

Quantum memories are important building blocks for QIP applications, which can be used to store quantum states for a tunable amount of time. Possible applications include the scalable multi-photon states for quantum computing, quantum relay in far space quantum communication, etc. The most important criteria for evaluating the performance of quantum memories including fidelity, efficiency, storage time, wavelength, and bandwidth.[100] Many quantum storage protocols have been investigated during the past years,[101,102] including solid-state atomic ensembles in rare-earth-ion doped crystals, semiconductor quantum dots, NV centers in diamond, single trapped atoms, cold atomic gases, etc. Optical waveguide in rare-earth-doped crystal becomes one of the most promising

systems and has been widely investigated for implementation of quantum memories, because it can provide the possibility of chip-scale integration. Important progresses associated with a variety of possible devices have been made.[103–106] Staudt *et al.* investigated the Ti : Er : $LiNbO_3$ waveguide devices operated with stimulated photon echo, and measured the visibility for interfering echoes close to 100%, which demonstrated the possibility of storing the amplitude and phase of two subsequent coherent pulses.[107] They also demonstrated a high degree coherent storage of the relative phase between pulses in two independent quantum memories, each placed in an arm of a fiber-optic interferometer at 4 K.[108] Saglamyurek *et al.* showed the coherent storage of time-bin entangled photons with Ti : Tm : $LiNbO_3$ waveguide cooled to 3 K, and obtained an entanglement fidelity higher than 95%.[53] $LiNbO_3$ waveguides have also been doped with praseodymium, neodymium, and other rare-earth ions, which could extend the properties of host crystal and allow an integrated approach to different storage wavelengths.[109] The realization of quantum devices based on ion-doped waveguides provide a foundation for the development of future quantum memories.

3.4. Single photon detectors

Single photon detectors (SPDs) are extremely sensitive devices capable of registering individual photons that are absorbed and converted to discriminable signals. The performance of SPDs can be characterized in terms of their spectral range, dead time, dark count rate, detection efficiency, timing jitter, and ability to resolve photon numbers.[110] To achieve high efficiency, fully integrated SPDs are highly desirable because interfacing with off-chip detectors will lead to unavoidable coupling losses. Superconducting nanowire single photon detectors (SNSPDs) represent the most promising photon counting technology, and offer single photon sensitivity from visible to mid-infrared wavelengths, short recovery time, low dark counts, and timing jitter.[111] SNSPDs can be implemented in integrated photonic circuit by sputtering an ultrathin niobium nitride film on top of waveguides and subsequent patterning into narrow wires.[112,113] They can also be integrated with Si-based quantum photonic circuits, where the detector elements are ultrathin superconducting nanowires placed on top of optical waveguides.[114] Najafi *et al.* reported their demonstration of scalable waveguide integrated SNSPDs which are consisted of 10 integrated detectors connected in parallel on a same photonic chip with average system detection efficiency beyond 10% and high device yield.[115] Multi-wire structures can also be configured to work as photon-number resolving (PNR) detectors.[116,117] Many other technologies relevant to PNR detectors and avalanche photodetectors have made enormous progress in recent years,[118–121] however, the development of these integrated detectors still faces a number of challenges.

4. On-chip QPNs for the generation and manipulation of quantum states

In the previous sections, the integrated platforms and the key building blocks for QPNs have been introduced, the functional components discussed above can be used to construct more complex integrated circuits. To demonstrate the practicality of combinations of these components, we will describe some important achievements obtained with the aforementioned elements. The first important applications are on-chip generation and manipulation of quantum states. Since 2013, the QPCs for quantum applications start to contain the quantum sources not just the linear network, which increases the complexity of the chip.[122,123] Our group and the group from Bristol University reported the on-chip generation and manipulation of path-entangled states from LN and SOI, respectively.

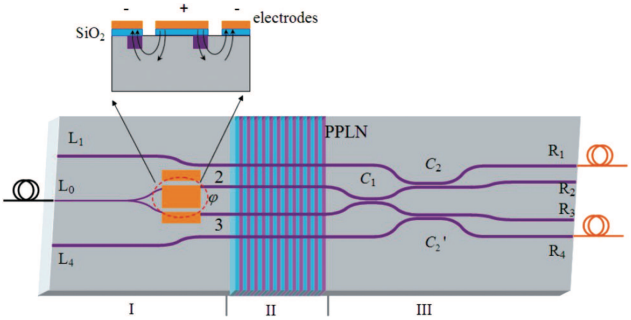


Fig. 3. (color online) The LN photonic chip with dimensions of 50 mm×5 mm×0.5 mm. The widths of the single mode waveguides are 2 μm for the pump (section I) and 6 μm for the entangled photons (sections II and III). The PPLN section is 10 mm long with a poled period of 15.32 μm. The interaction length of C_1 (C_2) is 650 μm (1300 μm) at a gap of 4 μm between the coupled waveguides. The electrodes are 8.35 mm long with a separation of 6 μm. Reproduced from Ref. [123].

We take the LN chip as the example. It consists of three sections, and comprises six different optical functions made of proton exchanged waveguides as shown in Fig. 3. In section I, a 780 nm pump is coupled into waveguide L_0 and equally distributed by a Y-branch single mode BS, then the electrodes above each path are used to control the phase between the two paths. Transition tapers are adopted to connect the 780 nm Y branch with the 1560 nm single mode waveguides. Section II is the PPLN region, in which degenerate photon pairs at 1560 nm are produced indistinguishably from either one of the two PPLN waveguides, yielding a path entangled state $(|2,0\rangle + e^{i\Delta\varphi}|0,2\rangle)/\sqrt{2}$. Section III is designed to engineer entanglement. Quantum interference is realized by a 50/50 coupler (C_1). By varying the phase difference via the bias voltage U applied in section I, we observe a continuous evolution from the two-photon separated state $|1,1\rangle$ to the bunched two-photon N00N state. The entangled pairs are separated from

the pump by on-chip wavelength filters (C_2 and C_2'), the entangled photons at 1560 nm are transfered to waveguides R_1 and R_4, whereas the pump at 780 nm remains in R_2 and R_3. The characterization of the emitted two-photon states has been performed with a Hong–Ou–Mandel interferometer, and the deterministically separated identical photon pair is characterized by 92.9% visibility of HOM interference.

In 2017, a group from University of Paderborn designed a fully on-chip polarization entangled source at degenerate wavelengths in the telecom regime.[124] Based on Ti-diffused PPLN waveguides, orthogonally polarized photon pairs via type II SPDC are generated in two different channels. Then the pairs are split on an integrated zero-gap PBS, resulting in the desired polarization entangled state.

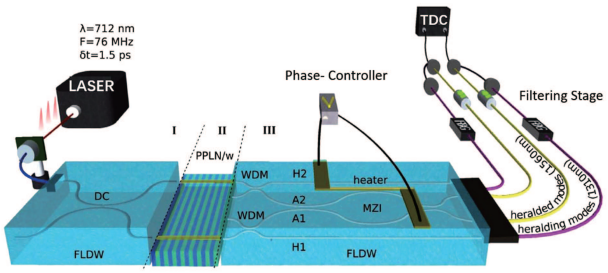


Fig. 4. (color online) Integrated tunable N00N state generator. DC: 50/50 coupler, FLDW: femtosecond-laser-direct-written, WDM: wavelength-division multiplexers, filtering stage: fiber Bragg gratings (FBG) filters, detection system: APD, TDC: time-to-digital converter. Reproduced from Ref. [125].

The number of photons on chip needs to scale up, which is an essential prerequisite for quantum computing or simulation. Photons up to 4 have been demonstrated in LN chip[125] and SOI chip,[126] respectively. In 2016, Vergyris *et al.* demonstrated an on-chip generation of configurable heralded two-photon states by taking a hybrid strategy which combine two different fabrication techniques, i.e., PPLN waveguides for efficient photon pair generation and femtosecond-laser-direct-written (FLDW) waveguides on glass for photon manipulation. As shown in Fig. 4, a ps-laser at 712 nm is coupled to a DC in block I to simultaneously pump two PPLN waveguides in block II in which pairs of photons at 1310/1560 nm will be produced by SPDC. Each pair is then coupled to block III and deterministically separated via integrated WDMs. The two 1310 nm photons in the outer modes H1 and H2 herald the complementary 1560 nm photons routed towards a MZI. Then the heralded two-photon states ranging from product states to entangled states can be produced, with fidelities of 99.5% and 95.0%, respectively. Four photons on silicon QPC were demonstrated by Faruque *et al.* with an on-chip MZI of two photons which were generated from two silicon waveguide rings, respectively and heralded by the other two photons.

5. On-chip QPNs for quantum communications

Quantum communication is an important branch of quantum information science, it requires the transfer of quantum states from one place to another which allows the distribution of entanglement over an appropriate distance. Quantum nodes are used for the storage and processing of quantum information, while quantum channels are required to transmit quantum information. Quantum networks consisted of quantum nodes and channels require interfaces that enable qubits transfer between some useful wavelengths, while preserving quantum coherence and entanglement. Tanzilli *et al.* demonstrated qubits transfer between photons at different wavelengths, and verified that entanglement remains unaffected even though one of the two entangled photons is submitted to a wavelength up-conversion process.[127] There are many protocols and applications pertaining to quantum communications, including quantum key distribution (QKD), quantum teleportation, quantum secret sharing, and so on. By far, the most advanced applications of quantum communication are QKD and quantum teleportation.[128–130] In this section, we will review recent integration efforts completed by QPCs in these two fields.

5.1. On-chip QPNs for QKD

Since the first proposal of a QKD protocol in 1984, tremendous progress has been made in free-space over the past decades.[131–134] QKD offers an interesting alternative to create and distribute a random key among two parties who share an initial secret, and it is now the first quantum information application to reach the level of a mature commercial technology. The development of integrated photonic platforms will be crucial for moving on from the current bulky, costly systems to compact and miniaturized devices that can be mass manufactured at low cost and it could enable the wide adoption of handhold quantum devices for secure communications. Despite its importance, however, the development of chip-scale integrated QKD systems is still at the beginning stage.

Early steps in integrated direction considered a client–server scenario,[135] where the client Alice holds a device with integrated elements while the server Bob incorporates resources that are difficult to integrate. Vest *et al.* designed a new integrated optics architecture for Alice with an effective size of 25 mm×2 mm×1 mm and demonstrated a short range free space QKD by using polarization encoding.[136] The above systems provided a proof-of-principle characterization of partially integrated QKD systems, however fully integrated systems are necessary for a wide range of applications. Sibson *et al.* designed a QKD system of higher integration with a low error rate in a recent experiment.[137] In this system, Alice's module is integrated on InP, it involves a tunable telecom laser source, and both active and passive elements such as

electro-optic phase modulators and MZI enabling the reconfigurable implementation of the transmitter functionalities of different QKD protocols as shown in Fig. 5(a). Bob's module on the other hand is integrated on SiO_xN_y and includes passive elements enabling the receiver functionalities of these protocols, with the exception of the detection stage as shown in Fig. 5(b). By utilizing the reconfigurability of the devices, three prominent QKD protocols, BB84, coherent one way, and differential phase shift were implemented. Therefore, the feasibility of using fully integrated devices within QKD systems was demonstrated. Wang *et al.* demonstrated high fidelity entanglement distribution and manipulation between two separate fiber connected Si photonic chips.[138] Path-entangled states are generated on one chip, and distributed to another chip encoded in polarization degrees of freedom, via a two-dimensional grating coupler on each chip. This path-to-polarization conversion allows entangled states to be coherently distributed, which can be certified by a Bell test violation.

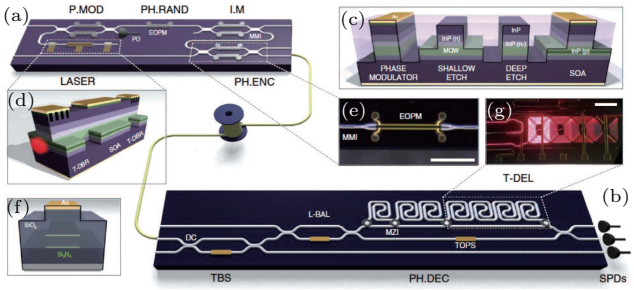


Fig. 5. (color online) Integrated photonic devices for QKD. (a) Alice's module is integrated on InP, (b) Bob's module is integrated on SiO_xN_y chip. (c) and (f) The waveguide cross-section based on InP and SiO_xN_y platform, respectively. (d) Wavelength tunable laser made of two tunable distributed Bragg reflectors (T-DBR) and a semiconductor optical amplifier (SOA). (e) Electro-optic phase modulators (EOPM). (g) Microscopic image of the receiver's delay lines. Reproduced from Ref. [137].

5.2. On-chip QPNs for quantum teleportation

Quantum teleportation is a fascinating process that allows one to transfer a quantum state using the resource of quantum entanglement as a channel.[139] Metcalf *et al.* reported a fully integrated implementation of quantum teleportation in which all key parts of the circuit, entangled state preparation, bell-state measurement, and quantum state tomography are performed on a reconfigurable photonic chip.[140] In the integrated SOS chip, waveguides and DCs are written by an ultraviolet laser and are used to construct multiple single-photon and two-photon interferometers. In addition, four thermo-optical PSs are used to manipulate and measure the single-qubit quantum states. The authors use four photonic qubits generated from two SPDC sources with traditional bulk optical components. Qubits Q1, Q2, and Q3 are sent to the QPC as shown in Fig. 6. The quantum state of photon Q1, which is prepared using a MZI with two PSs θ_1 and ϕ_1, will be teleported to photon Q3. A Bell state encoded on photons Q2 and Q3 will serve as the quantum channel implemented by the controlled-phase gate CZ2. Controlled-phase gate CZ1 performs the required Bell state measurement on Q1 and Q2 at Alice's side. To analyze the output state of the quantum teleportation protocol, Bob uses another MZI with two PSs ϕ_2 and θ_2 to perform quantum state tomography of the qubit Q3. The experimental demonstration of quantum teleportation on an integrated photonic chip opens the way to more complex implementations in future integrated systems.

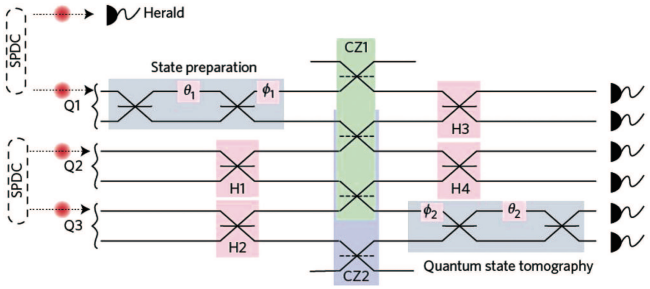


Fig. 6. (color online) SOS chip architecture for quantum teleportation. The chip is based on dual-rail encoding and contains several integrated BSs with reflectivities $1/2$ or $1/3$ and thermo-optics PSs. Reproduced from Ref. [140].

Quantum teleportation is not restricted to qubits, but can also involve multiple degrees of freedom and higher-dimensional quantum systems.[141,142] It can also be extended to continuous variable (CV) systems.[143] Masada *et al.* presented an integrated photonic implementation for CV entanglement generation and characterization of EPR beams using off-chip homodyne detectors in a SOS chip.[144] When combined with integrated squeezing and non-Gaussian operations, these results will open the way to universal QIP with light.

6. On-chip QPNs for quantum computation

Quantum computer is a system of many qubits whose evolution can be controlled and measured, while quantum computation is a unitary transformation that acts on this many-qubits state. The power of quantum computers resides on the fundamental rules of quantum mechanics, such as the quantum superposition principle and entanglement. Large-scale and reliable computation based on quantum physics would have a significant impact on the way that information is processed, encoded, and transmitted. Quantum computers promise to greatly increase the efficiency of solving certain computational problems, such as factoring large integers, searching for a marked item in unstructured database, and quantum simulation.[145]

6.1. On-chip QPNs for universal quantum computing with quantum gates

Linear optics with photon counting is a prominent candidate for implementing quantum computation. An efficient

quantum computer by linear optics can be constructed using only single photon sources, passive linear optics elements, and photo-detectors.[146–148] Universal logic gates for quantum computation can be implemented by a set of single qubit rotations and arbitrary entangling two-qubit gate, such as controlled-NOT (CNOT) gate. Single-qubit gates in integrated circuit can be implemented via DCs and PSs. Arranging several DC elements allows fabrication of two-qubit and multi-qubit logic gates which are essential in QIP.

On the basis of the theoretical scheme presented in Ref. [149] and experimental demonstration of the path encoded CNOT gate in bulk optics,[150–154] in 2008, Politi *et al.* demonstrated high fidelity integrated implementation of CNOT gate, which is essentially direct writing the waveguides onto a SOS chip.[155] The chip is composed of two $1/2$ reflectivity couplers and three $1/3$ couplers as shown in Fig. 7(a). It has six input and output modes, two of which are auxiliary at both ends denoted by V_A and V_B, the waveguides denoted by C_0 and C_1, T_0 and T_1 encode the states 0 and 1 for the control and target qubits, respectively. The control qubit keeps unchanged when passing through the device, and the target qubit flips its state conditional on the control qubit being in the 1 state. Then they only need to pay attention to two-photon coincidences at the outputs of the device, not all of the possible two-photon coincidences are valuable results, there should be precisely one photon in the control qubit waveguides and one photon in the target qubit waveguides. Therefore, the success of the gate is heralded by detection of a photon in both the control and target outputs, which happens with probability $1/9$.

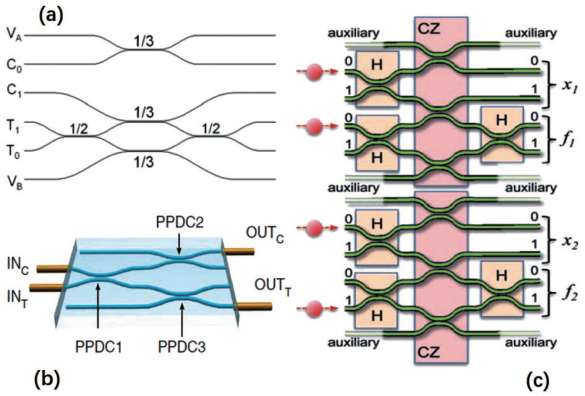


Fig. 7. (color online) (a) Integrated implementation of path encoded CNOT gate (reproduced from Ref. [155]). (b) Polarization encoded CNOT gate on a glass chip (reproduced from Ref. [156]). (c) Integrated circuit of Shor's quantum factoring algorithm (reproduced from Ref. [160]).

In 2011, Crespi *et al.* demonstrated the integrated photonic CNOT gate for polarization encoded qubits, which are consisted of three partially polarizing directional couplers (PPDCs) on a glass chip fabricated by ultrafast laser writing technique as shown in Fig. 7(b).[156] The target and control qubits interfere at PPDC1 in which the transmissivities for horizontal and vertical polarization are $T_H^{(1)} = 0$, $T_V^{(1)} = 2/3$, respectively. Then the contributions of the polarization qubits are balanced at PPDC2 and PPDC3, each with the transmissivities $T_H^{(2,3)} = 1/3$ and $T_V^{(2,3)} = 1$. The CNOT operation succeeds with probability $1/9$. The results open new perspectives for handling hybrid quantum states based on different degrees of freedom of light, such as path, polarization, and orbital angular momentum. This would greatly improve the computing capability of a quantum device. Other schemes for realizing on-chip quantum logic gates can be found in literature of Refs. [157] and [158]. Those logical gates resemble small to medium scale interferometers are either designed to perform a particular task or can be reconfigured for a variety of tasks.

Shor's quantum factoring algorithm harnesses the quantum mechanical properties of superposition and entanglement to factorize a product of two large prime numbers exponentially faster than any known classical method.[159] The full Shor's algorithm is designed to factorize arbitrary given input, whereas the compiled version is designed to find the prime factors of a specific input. Politi *et al.* described a compiled version of Shor's quantum factoring algorithm to factorize 15 on a SOS chip.[160] The integrated waveguide circuit consists of six Hadamard gates each implemented by a $1/2$ reflectivity coupler, and two controlled π-phase gates each implemented by three $1/3$ couplers as shown in Fig. 7(c). The circuit requires four photonic qubits which are injected into the waveguide chip using a polarization maintaining fiber, and detected with SPAPDs at the end face. They performed the initialization by giving an input state $|\Psi\rangle_{in} = |0\rangle_{x_1}|0\rangle_{x_2}|0\rangle_{f_1}|1\rangle_{f_2}$, and measured the output state of qubits x_2, x_1, and x_0 which can lead to finding the order for the algorithm. The measured results have a fidelity of 99.1% with the ideal probability distribution. This demonstration of a small scale compiled Shor's algorithm on a chip shows promise for large-scale quantum computing in integrated waveguides.

Quantum phase estimation is fundamental for many quantum algorithms, including Shor's factorization algorithm and HHL algorithm.[161] Recently, based on Si QPC, adaptive Bayesian approach to quantum phase estimation was implemented by quantum logic gates and then used for simulating molecular energies.[162] By combining variational methods and phase estimation, the efficient calculation of Hamiltonian spectra was also demonstrated on a QPC, which underlines that QPC can find many applications from physics to chemistry.[163]

6.2. On-chip QPNs for quantum walk and boson sampling

Quantum walk (QW), the quantum mechanical counterpart of classical random walk,[164,165] is an advanced tool for building quantum algorithms, and it has been proven feasible

to realize a universal model of quantum computation.[166,167] The remarkable feature of QW is that it spreads quadratically faster than random walk and allows the exponentially speed-up of search algorithms.[168,169] It is essential to note that two different models of QWs are widely studied: discrete-time QW (DTQW) in which the walker evolves in discrete steps governed by a random event,[170,171] and continuous-time QW (CTQW) in which the walker is described by time independent Hamiltonians.[172]

QW can be implemented via a constant splitting of photons into several possible sites. A single photon coupled into a 50 : 50 DC will emerge from either port with exactly the same probability. Employing this simple DC device as a building block is the best way to simulate a DTQW, the role of the coin is played by the DC itself since it routes the photon to occupy two different spatial modes simultaneously.[173] To demonstrate the principle of DTQW based on 50 : 50 couplers, Gräfe *et al.* considered a system composed of 31 splitting stages fed by two different input states: a single photon coupled into one of the input ports, and a single photon being in a coherent superposition state.[174] Another interesting scenario arises when randomizing the waveguide parameters or the phases of every DC, i.e., it allows one to study decoherence and dephasing effects in DTQW. Crespi *et al.* experimentally studied the localization properties of a pair of non-interacting particles obeying bosonic (fermionic) statistics by simulating a one-dimensional (1D) DTQW of a two-photon polarization entangled state in a disordered medium.[175] Their integrated waveguide circuits shown in Fig. 8(a) were fabricated by femtosecond laser writing in glass. The discrete m-axis and n-axis denote the different sites and the time steps of the QW, respectively. Different colors indicate different PSs and violet waveguides represent the accessible paths for photons injected from inputs A and B. The controlled PSs are achieved by deforming one of the S-bent waveguides at the output of each coupler, thus the network is capable of implementing an eight-step DTQW with static disorder, as well as a six-step DTQW with dynamic disorder.

In DTQW, the walker hops between lattice sites in discrete time steps, while in CTQW, the probability amplitude of the particle leaks continuously to neighboring sites which can be realized via optical waveguide lattice.[176] In 2010, Peruzzo *et al.* demonstrated QWs of two identical photons in an array of 21 continuously evanescently coupled waveguides in a single SiO_xN_y chip (Fig. 8(b)).[177] The propagation constant and coupling constant between adjacent waveguides are designed to be uniform. Using such a chip, they were able to test classical random walks using single photons and QWs using entangled photon pairs generated from type-I SPDC. Entangled photon pairs are injected into two of the three polarization maintaining fibers which are coupled to the waveguide chip. At the output of the chip, an array of multimode fibers guide the photons to single photon counting modules used to post-select all possible two-photon coincidences between different outputs of the array. In 2014, Poulios *et al.* experimentally implemented QWs of correlated photons in a 2D network of laser written waveguides in a swiss cross geometry.[178] They demonstrated high-visibility quantum interference on the fully 3D integrated waveguide device with unique features that cannot be observed in planar arrangements. CTQW in QPCs provides useful models for various physical phenomena and concepts, such as Bloch oscillations,[179,180] perfect quantum states transfer,[181,182] and other interesting effects.[183–185]

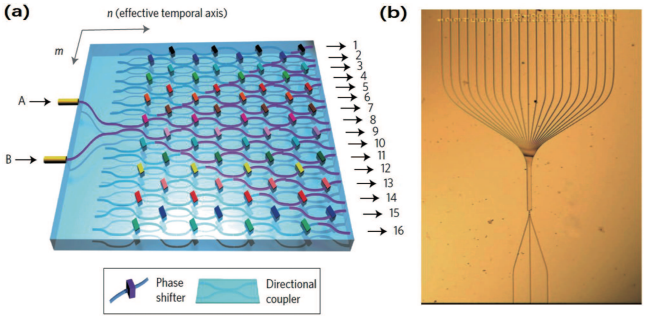


Fig. 8. (color online) (a) Integrated circuit for DTQW (reproduced from Ref. [175]). (b) CTQW in a SiO_xN_y chip consists of an array of 21 waveguides (reproduced from Ref. [177]).

Although quantum computers can solve certain problems faster than classical computers, and both theoretical and experimental progresses are paving the way for possible implementations, it is still a long way off to realize a fully functioning quantum computer. One of the most exciting applications pertains to the intermediate model of quantum computing, boson sampling,[186] sampling from the probability output distribution of n identical bosons scattered by an interferometer with m modes ($m > n$). This is a demanding task, which rapidly becomes impractical to calculate with a classical computer as the numbers of m and n increase. Fortunately, it is possible to perform the sampling efficiently in the optical domain by sending photons through a LON with unitary transformation U and measuring the photons distribution at the output ports. The predicted probability amplitude of output is proportional to the permanent of $n \times n$ submatrices of experimentally determined U.

In 2013, four groups independently came up with different schemes for experimental implementation almost simultaneously. Broom *et al.* performed boson sampling experiments using an optical network with input and output modes $m = 6$ and input photons $n = 2$ or 3, they experimentally verified that n-photon scattering amplitudes are given by the permanent of submatrices derived from a unitary of six-mode integrated optical circuit.[187] Spring *et al.* constructed a quantum boson-sampling machine in a 6×6 SOS waveguide chip as shown in

Fig. 9(a) to sample the output distribution resulting from the nonclassical interference of photons.[188] They also found that the measured probabilities of given output has a good agreement with predictions. Tillmann *et al.* designed an integrated optical circuit consisted of five spatial modes coupled by eight BSs and eleven PSs (Fig. 9(b)), which was written inside high-purity fused silica using laser writing technique, and observed three-photon interference that leads to the boson sampling output distribution.[189] Crespi *et al.* reported on the experimental implementation of the boson sampling problem by studying three-photon interference in a randomly chosen, five-mode integrated photonic chip, which was also realized by a laser writing technique in a glass substrate as shown in Fig. 9(c).[190] All groups used up to three photons as non-interacting bosons and obtained the similar results, verifying that boson sampling in a photonic circuit can efficiently been carried out as an intermediate model of quantum computation.

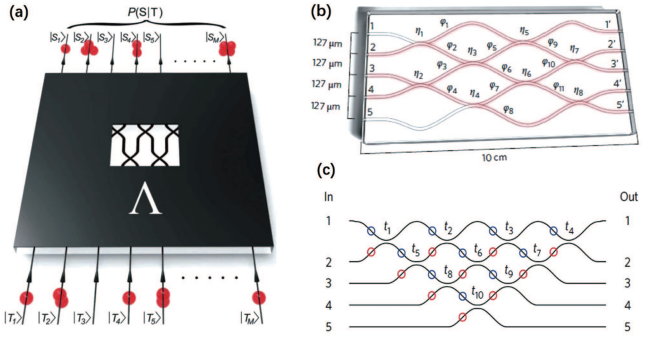


Fig. 9. (color online) (a) Model of quantum boson sampling machine.[188] (b) The circuit consists of five input and output modes (1 to 5), eight DCs (η_1 to η_8), and eleven PSs (φ_1 to φ_{11}).[189] (c) Implementation of the 5×5 modes integrated photonics network in Ref. [190].

In 2017, Wang *et al.* implemented up to five photons boson sampling experiments, and demonstrated that these multi-photon boson sampling machines have reached a computational complexity that can compete with early classical computers.[191] Boson sampling is the only known way to make permanents show up as amplitudes, which is an important function for computer science. It is necessary to mention that a boson sampling device does not need any nonlinearities or entangled particles, it requires only indistinguishable bosons, low decoherence linear evolution.

6.3. On-chip QPNs for quantum simulation

Quantum simulation was first proposed by Richard Feynman in 1982.[192] He considered one controllable quantum system that can be used to imitate other quantum systems, and is therefore able to tackle problems that are intractable on classical computers. Quantum simulators would not only provide new results that cannot be classically simulated, but also allow us to test various models.[193] QPCs supply a good platform for controlling the quantum system in a feasible and reconfigurable way, therefore they can be adopted as good candidates for realizing various quantum simulators.

Wang *et al.* experimental demonstrated the quantum Hamiltonian learning (QHL)[194] with a digital quantum simulator on a programmable silicon QPC, which learns the electron spin dynamics of a negatively charged nitrogen-vacancy center in bulk diamond.[195] They further demonstrated an interactive QHL protocol that allows one to characterize and verify single-qubit gates using other trusted gates on the same device. Their device integrates entangled photon sources, projective measurements, and quantum logical operations onto a single chip as shown in Fig. 10. A 10 mW continuous-wavelength pump laser at near 1550 nm is coupled into the chip through optical fibers. Black lines denote the Si nano-photonic waveguides, and gold wires represent the thermo-optical PSs and their transmission lines. A pair of non-degenerate signal (red) and idler (blue) photons are generated via SFWM in the spiral waveguide sources. These photons are split equally via MMI BSs,[196] producing a path-encoded maximally entangled state. The idler photon undergoes a unitary operation $\hat{U}$ or $\hat{V}$ conditional on the state of the signal photon. Performing measurements $\hat{M}$ on the signal photon enables the estimation of the likelihood function for the QHL implementations. Photons are detected off-chip by fiber-coupled SNSPD. With the developments of quantum integrated devices, the QHL protocol can be scaled up to learn more complex Hamiltonians.

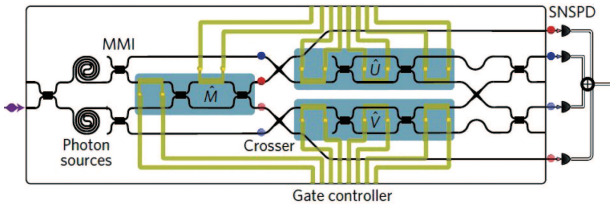


Fig. 10. (color online) The silicon quantum photonic simulator (reproduced from Ref. [195]).

On-chip quantum simulations also include the simulations of the quantum transport, the bosonic and fermionic statistics, Anderson localization, etc.[197–201] In general, quantum simulation is typically less demanding than quantum computation, it does not require either explicit quantum gates, error correction, or high accuracy, and it can be exploited to address particular problems without the request of universality. Even though there is still a lot of work to do, quantum simulation remains a very promising field of research with many potential applications.

6.4. Large scale QPN chips

Integrated quantum technologies enable the fabrication of complicated LONs with unprecedented levels. An arbitrarily reconfigurable LON can be described by an $N \times N$ unitary operator, which can be implemented as a two-mode MZI.[202] A

specific array of two-mode operations is mathematically sufficient to implement any unitary operator. So it is possible to construct a single device with sufficient versatility to implement any possible operation up to the specified number of modes. Carolan *et al.* demonstrated a single reprogrammable optical circuit that is sufficient to implement all possible linear optical protocols up to the size of that circuit.[203] The six-mode universal device is consisted of a cascade of 15 MZIs with 30 thermo-optic PSs, which is electrically and optically interfaced for arbitrary setting of all PSs via classical control and processing system, as shown in Fig. 11. The measurement results are gotten out with a 12-single-photon detector system with the input of up to six photons. The versatility of this universal linear optical processor is demonstrated for several quantum information protocols, including heralded quantum logic and entangling gates, boson sampling experiments, and six-dimensional complex Hadamard operations.

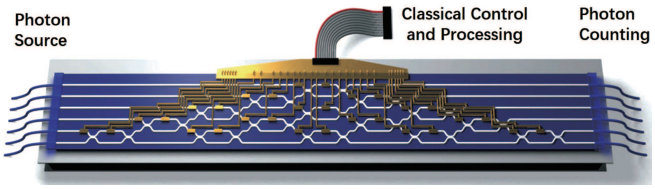


Fig. 11. (color online) A fully reconfigurable processor made with planar silica waveguides consisted of a cascade of 15 MZIs, controlled with 30 thermo-optic PSs (reproduced from Ref. [203]).

In 2017, Shen *et al.* designed a programmable nanophotonic processor featuring a cascaded array of 56 programmable MZIs in a Si photonic integrated circuit, to demonstrate that a fully optical neural network could offer an enhancement in computational speed and power efficiency.[204] Harris *et al.* used a more complex programmable processor to explore the quantum transport problems with static and dynamic disorder.[205] The processor is composed of 88 MZIs, 26 input modes, 26 output modes, and 176 PSs. In 2018, Wang *et al.* demonstrated a unique large scale QPC able to generate, control, and analyze high-dimensional entanglement. The device integrates 16 SFWM photon-pair sources, 93 thermo-optical PSs, 122 MMIs, 256 waveguide-crossers, and 64 optical grating couplers on a single chip.[206] These large scale integrated device can be rapidly reprogrammed to implement many linear optical protocols,[207] paving the way for applications of fundamental science and quantum technologies.

7. Conclusion and perspectives

In this review, we have provided an overview of several platforms and some basic components needed for integrated optical circuits. We also discussed the applications of advanced integrated circuits with different functionalities in QIP. High fidelity integrated implementation of the key components of photonic circuits, as well as the realization of quantum communication and quantum computing devices is extremely promising. Research on integrated quantum photonics marks the first step in moving from discrete optical components to integrated circuits capable of implementing different functions. It provides not only a solid strategy for miniaturizing, scaling, and high performance QIP technologies, but also paves the way for future quantum technologies and pushes the piratical applications of QIP.

Although considerable progress has been achieved, this field is still in its early stage which naturally confronts with many challenges. The main challenges for the next generation of quantum photonic devices focus on increasing the component density, adding functionality, and integrating both active and passive quantum elements onto a single device. By comparing among several different platforms, we found Si and $LiNbO_3$ not only exhibit a particularly high degree of integration, but also have mature techniques of waveguides fabrication. Based on these platforms, on-chip QPNs consisting of four or more different types of devices have been demonstrated. However, there is no single integration platform which can gather all the desired characteristics for a specific application. It is natural to think about that the next generation of QIP systems and devices will adopt hybrid integration technologies with the goal of bringing together the best elements of each platform.[208,209] Femtosecond laser direct writing waveguide technologies, which can be applied to a wide range of material systems, enable the rapid fabrication of complex 3D integrated networks,[210] and it allows for quantum circuits that are impossible to implement in bulk optics or 2D waveguide circuits. It is envisioned that integrated quantum photonic approaches will not only dramatically enhance the complexity and capacity of information processing, but also enable novel functionalities that are otherwise inaccessible in conventional experiments. Because of the great promise it holds for demonstrating the true disruptive potential of QIP in large-scale systems, the field of integrated QIP is a subject of extremely active and innovative research worldwide. Beyond any doubt, the resulting developments in the next years will change the landscape of our future communication and computation capacities and practices.

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