REVIEWS

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Chip-based quantum communications

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Abstract: Quantum communications aim to share encryption keys between the transmitters and receivers governed by the laws of quantum mechanics. Integrated quantum photonics offers significant advantages of dense integration, high stability and scalability, which enables a vital platform for the implementation of quantum information processing and quantum communications. This article reviews recent experimental progress and advances in the development of integrated quantum photonic devices and systems for quantum communications and quantum networks.

Key words: quantum communications; quantum networks; integrated quantum photonics

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1. Introduction

The security of quantum communication (e.g., quantum key distribution; QKD) is enabled by the fundamental principles of quantum mechanics[1, 2]. Quantum key distribution allows users to share unconditionally secured keys, even if an eavesdropper can take control of the communication channel.

The first QKD protocol was proposed by Bennett and Brassard in 1984[3], which is referred to as the BB84 protocol. This adopts four polarization states of a single photon to encode random keys. The strict security proof was then completed by Shor, Preskill *et al.*[4]. The first entanglement-based protocol was the E91 protocol, which was proposed by Ekert in 1991[5]. Generally speaking, the implementations of QKD protocol can be divided into two categories: preparation-measurement QKD protocols, such as the BB84, in which one party generates random keys in quantum states of light, and sends to the receiver where the keys are decoded[6]; and entanglement-based QKD protocols, such as the E91 protocol, in which Alice prepares entangled states and shares one party of the states with Bob, and measurement generates random keys[6].

The state-of-the-art photonic quantum technologies have allowed the experimental realizations of thousands of kilometers ground-to-satellite QKDs[7], promising the realization of global-scale quantum communication networks. Meanwhile, integrated photonic devices, which have already been widely implemented in fiber-optic telecommunications, can be expected to also play an important role in QKD and quantum communications. In particular, they can deliver chip-based quantum photonic transceivers with low cost, miniatured footprint, high reliability and portability, which are key to the implementation of practical quantum cryptography. In this review, we discuss recent progress of chip-based preparation-measurement QKDs and entanglement-based QKDs in silicon (Si), indium phosphide (InP) and silicon nitride (Si_xN_y) devices, as well as recent demonstrations of integrated quantum memories, which promise the improvement of the transmission distance of quantum communications in optical fibers. In this review, we focus on telecom-band integrated photonic devices for quantum communications which are compatible with today's optical fiber telecommunications infrastructures.

2. Integrated QKD transceivers

The preparation-measurement quantum key distribution (PM-QKD) represents a major class of quantum communication protocols, such as differential phase shift (DPS) and coherent one way (COW) protocols. This type of protocol separates the communication system into two parts which are transmitter and receiver. The first realization of PM-QKD is mainly implemented with bulk-optic devices, for example from the seminal QKD experiments[8] to the ground-to-satellite QKD network[9], and those bulk-optic QKD transceivers have been widely commercialized. Integrated optics promise the new generation of integrated QKD transceivers that are more reliable, compact, cheaper, and portable.

In 2004, a pioneering work by researchers in NTT reported the first integrated QKD devices in silica waveguide lightwave circuits, which demonstrated the encoding and decoding of quantum keys in integrated Mach-Zehnder interferometers[10]. This work has achieved a kHz secured key rate and 5.0% quantum bit-error rate (QBER) in a 20 km-length optical

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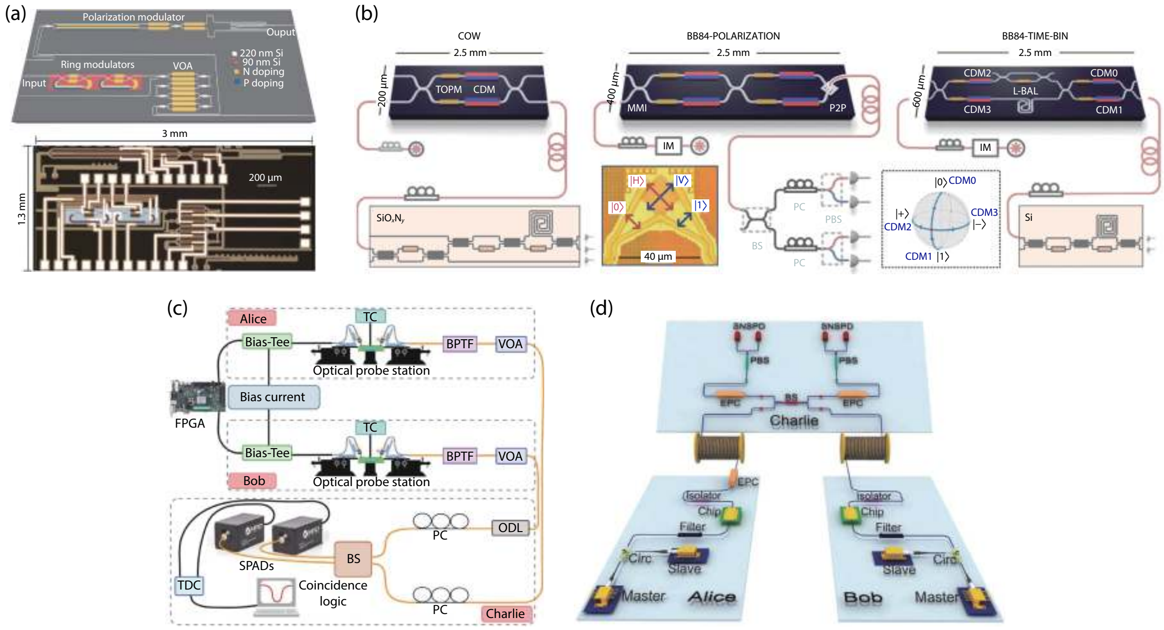

Fig. 1. (Color online) Integrated silicon photonic QKD transmitters. (a) Polarization-encoding PM-QKD transmitter, consisting of ring modulators, VOAs, and polarization modulators[12]. (b) Three implementations of high-speed QKD[11]. (c) HOM interference between WCPs generated by III–V on silicon waveguide integrated lasers[22]. (d) Polarization-encoding MDI-QKD with integrated silicon photonics[24].

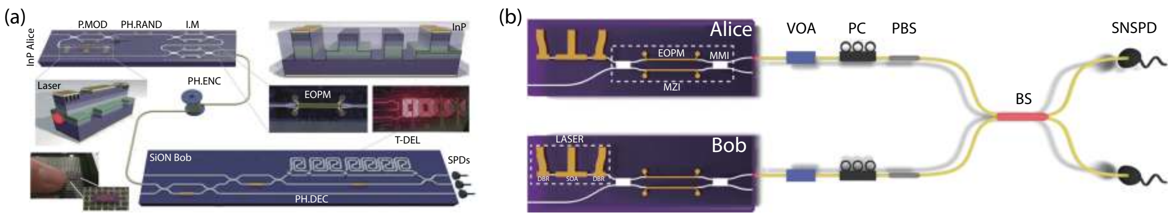

Fig. 2. (Color online) Integrated InP photonic QKD transmitters. (a) A chip-to-chip QKD system between a 2 × 6 mm^2 InP transmitter and a 2 × 32 mm^2 SiO_xN_y receiver[16]. (b) An implementation of MDI-QKD using two 6 × 2 mm^2 InP transmitter chips in which two weak coherent states are on-chip generated independently[25].

fiber. Importantly, it demonstrated the stable interferometric realization of QKD transceivers in integrated optics. Recently, silicon photonics have emerged as a leading quantum photonic platform with the benefits of miniaturization, cost-effective device manufacture, and compatibility with classical silicon photonic interconnection and microelectronics[11].

Several works have shown that silicon photonics are capable of implementing quantum communication tasks. For example, in Fig. 1(a) it shows a polarization-encoding QKD transmitter in a silicon chip[12].

The QKD transmitter integrates ring modulators for light pulse generation, a variable optical attenuator (VOA) weakening power down to single-photon level, and a polarization modulator for the preparation of two orthogonal polarization bases. In 2017, researchers in Bristol reported a QKD transceiver that allows high-fidelity and high-speed quantum operations of single photon states, and also reaches estimated asymptotic secret key rates of up to 916 kbps and QBER as low as 1.01% in a 20 km fiber[11].

Quantum key information was carried in the polarization of single photons, which was implemented by two-dimensional grating coupler. Furthermore, recent demonstrations of chip-enabled metropolitan QKD system[13] and full daylight QKD[14] imply their practical applications. The challenge of silicon-based QKD transmitter is the difficulties of integrating laser sources and fast low-loss quantum state operators. A hybrid integration of III–V semiconductor laser and silicon photonic devices could provide a solution for weak light generation. Weak pulses down to single photons can be generated by externally modulating the laser light using carrier-injection or carrier-depletion modulators. In order to prepare all of QKD bases with nanosecond speed and high fidelity, the transmitters may require a combination of carrier-depletion modulators (fast speed) and thermo-optic phase modulators (large dynamics).

The III–V compound semiconductors such as InP enable light emissions and high-speed modulations of photons, thanks to their direct bandgap property[15]. The integrated InP platform can therefore deliver integrated QKD transmitters, in which lasers, attenuators, fast electro-optic modulators, photodiodes, stable interferometers, and other passive devices can be integrated in a single InP chip[16]. This represents a monolithically integrated version of QKD transmitters. Fig. 2(a) shows the first chip-based PM-QKD system between an InP QKD transmitter and a silicon oxynitride (SiO_xN_y) receiver[16]. It demonstrated three types of major PM-QKD protocols, including BB84, COW and DPS, and reached a high clock rate up to 1.7 GHz and a low QBER of 0.88%. In the experi-

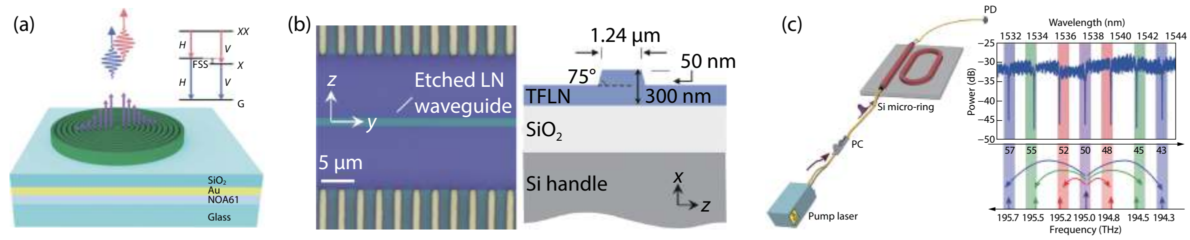

Fig. 3. (Color online) On-chip entangled photon sources. (a) Generation of entangled photons from a single quantum dot embedding in photonic nanostructures[34]. (b) Generation of entangled photons in a thin-film waveguide using the SPDC process[35]. (c) Generation of entangled photons in a silicon photonic microring resonator using SFWM process[46].

ment, the SiO_xN_y receiver chip was adopted to minimize the loss of time-bin qubits when on-chip decoding the quantum keys using long waveguide delay lines.

Despite the unconditional security in ideal QKD models, possible security-threatening attacks have appeared in real-world physical implementations. In particular, due to the complexity of detection systems and the inconsistency between theory and experiments, many attacks are aimed at detectors[17–19]. In 2012, Lo *et al.* proposed measurement-device-independent quantum key distribution (MDI-QKD)[20] which can remove all detector side channel attacks and greatly improve the security in the real-world applications. The MDI-QKD relies on the Bell-state measurement, which can be implemented by performing the Hong-Ou-Mandel (HOM) interference of two weak coherent states of photons[21]. When two indistinguishable pulsed photons meet at a balanced beam splitter (BS), HOM interference happens and it results in photon bunching after the BS. Recently, as shown in Fig. 1(c), two independent quantum transmitters that hybridly integrate III–V lasers on silicon waveguides were used to implement the HOM interference, and a visibility of 46% between two weak-coherent pulses was demonstrated[22]. Note that the maximum achievable HOM visibility is 50% in such an experiment[23]. Full silicon chip-based MDI-QKD systems using polarization encoding have been reported, see Fig. 1(d), which include two transmitter chips and one server chip[24]. Weak coherent states were injected from external lasers. Furthermore, the HOM interference and MDI-QKD between two InP transmitter chips have been demonstrated, as shown in Fig 2(b). This allows the measurement of HOM interference with a visibility of 46.5 ± 0.8% between two weak coherent states on-chip generated from two independent InP transmitters[25]. The full MDI-QKD protocol has been implemented with two InP transmitters with integrated lasers[26]. These demonstrations promise the realization of a fully integrated MDI-QKD network in the near future.

3. Integrated photonics for entanglement-based quantum communications

Entanglement plays a key role in quantum cryptography[5] and quantum internet[27]. For example, the E91 QKD protocol assumes that two legitimate users, say Alice and Bob, share the entangled state beforehand. Any eavesdropper's disruptive behavior of the system weakens the entanglement so that it can be detected by Bell inequality tests[28]. The E91 protocol relies fewer assumptions of the system, while the success of key sharing depends on the violation of Bell inequalities. That forms the key idea of device-independent quantum key distributions (DI-QKD)[29–32]. In general, entanglement is of great importance in the architecture of quantum communication networks and quantum network[27]. In the past few decades, significant progress of the generation and distribution of entangled photons have been made, such as the demonstration of satellite-based entanglement distribution between two locations separated by 1203 km on Earth[33]. We here discuss the recent development of integrated quantum photonic devices and systems for entanglement-based quantum communications.

On-chip parametric sources and artificial atomic sources able to generate entangled-photon pairs have been reported in a range of material platforms. Artificial atomic structures such as quantum dots, defects, and dopants represent excellent quantum systems, which have allowed the generation of single photons, entangled photons, and spin-photon entanglement. Engineering the interactions of solid-state atoms and photons in nanostructures can significantly improve the entanglement quality. For example, entangled photon pair source with high brightness and indistinguishability was realized by embedding quantum dots in photonic nanostructures[34], see Fig. 3(a). Most solid-state sources work at the visible wavelength, and this requires wavelength up-conversion to the telecom band for low-loss transmission in optical fiber. We thus focus on the parametric sources below.

Tight confinement of light in optical waveguides or structures enables enhancement of nonlinear optical effects (e.g., second-order and third-order nonliear effects), which allow the efficient generation of entangled photon-pairs via the spontaneous parametric down conversion (SPDC) or spontaneous four-wave mixing (SFWM) process, respectively. Typical on-chip parametric sources on the lithium niobate (LN), gallium arsenide (GaAs), Si and Si_xN_y materials have been reported. Fig. 3(b) shows a thin-film periodically poled lithium niobate (PPLN) waveguide, which is able to generate energy-time entanglement at telecom wavelength with high brightness and coincidences-to-accidentals value[35]. Polarization-entangled photon pairs could also be generated by engineering the LN waveguide[36]. Energy-time entangled photon-pairs at telecom wavelength have been generated in GaAs ridge waveguides using type-II SPDC[37]. The phase matching condition is critical in these SPDC sources, in which birefringent, dispersion, or modal conditions need to be deliciated engineered. In Si and Si_xN_y platforms, the phase matching condition for standard SFWM can be naturally matched. They have delivered entangled photons encoded in path[38], polarization[39], time-bin[40] and transverse mode[41] in waveguides[42, 43], micro-ring resonators[44–46], or multimode structur-

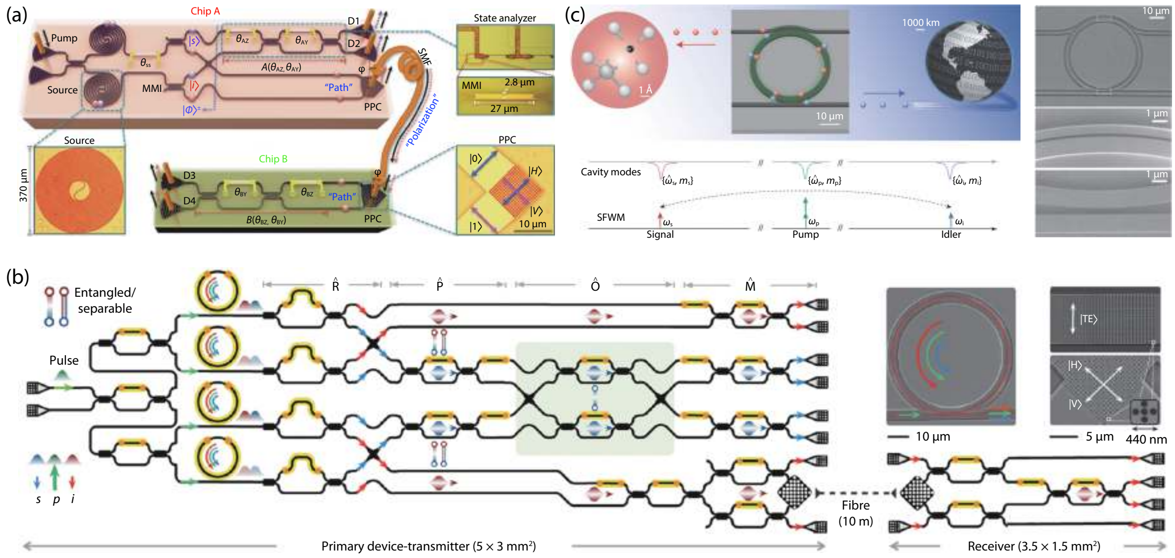

Fig. 4. (Color online) Chip-based entanglement distribution and quantum teleportation. (a) Silicon photonic circuit diagram for a chip-to-chip entanglement distribution experiment[49], and (b) for a chip-to-chip quantum teleportation experiment[52], (c) scheme of a visible-telecom entanglement experiment in the silicon nitride system[53].

es[47]. The micro-ring resonator configurations allow the generation of bright and pure photon-pairs. Together with the energy conservation condition, the production of multiple entangled photons is enabled in micro-ring resonators[46, 48, 49], as shown in Fig. 3(c), which could find applications in the wavelength-multiplexed quantum communication systems.

The implementation of on-chip entanglement-based quantum communication protocols has become possible thanks to the capabilities of on-chip generations and manipulations of entangled photon pairs in different degrees-of-freedoms of photons[27]. For example, these include the manipulation of path-encoding entangled states in Mach-Zehnder interferometers[38], polarization-encoding entangled states by engineering birefringent structures[39], and time-bin entangled states in Franson interferometers[40].

Recent technological progress of integrated quantum photonic devices has allowed the implementation of quantum-communication protocols beyond a single chip, which is key to future quantum networks[27, 50]. The first chip-to-chip entanglement distribution was reported in 2016[51], with all key components integrated monolithically on silicon chips, see Fig. 4(a). On-chip entangled Bell states were generated and one qubit was distributed to another silicon chip by converting on-chip path-encoding states and in-fiber polarization states via the two-dimensional grating couplers. The distribution of entanglement was verified by performing a Bell-type inequality of two distributed qubits measured on two separated chips. Quantum teleportation is the core part in quantum communication networks[52, 53]. The first on-chip teleportation was reported in 2014[54]. Then, as Fig. 4(b) shows, the first chip-to-chip teleportation of arbitrary single-qubit state between two silicon chips was demonstrated using the path-polarization conversion technique. The teleported states were reconstructed with a mean value of 90% fidelity. Moreover, cross-band entangled photon pairs between the visible-telecom wavelength were generated on a silicon nitride chip with a micro-ring resonator and further distributed over a 20 km fiber, see Fig. 4(c)[55]. High photon number purity and brightness were achieved with low pump consumption of hundreds of microwatts. Importantly, it provides an entangling link between the visible-band photon that can interface with quantum memories and the telecom-band photon that features low-loss transmission in optical fiber.

4. Recent development of on-chip quantum memories

Long distance distributions of entanglement and large-scale implementations of quantum network rely on quantum memories and quantum relays[27]. For example, quantum memories in quantum nodes can generate entanglement between distant parties and therefore extend the communication distance. This requires the memories to be able to coherently and efficiently interface the flying qubit and static qubit, and the nodes able to perform local Bell state measurements (BSM). The ideal quantum memory is a device that can store quantum information of photonic flying qubits, preserve it for a while with high fidelity, and then retrieve information on demand. In this section, we review recent experimental developments of integrated quantum memory in the rare-earth ions system. This system works in the telecom band, thus it is compatible with fiber-based long-distance quantum communications systems.

Note that other systems, such as vacancy centers in diamond, have proved to be great potential platforms[56–59]. For example, in the nitrogen vacancy (NV) center, the electron spin qubit can interact with photon flying qubit, and nuclear spin allows local BSM operations[60]. Spin-photon entanglement has been experimentally demonstrated in the NV center system[61], and in quantum dot system[62]. In general, these systems only work at the visible wavelength. Excellent reviews of this topic can be found in Refs. [63, 64].

To store the flying qubit state in the static qubit, an ideal method is to employ an absorbing matter that can absorb the photon with high probability and re-emit an identical photon some time later. In this way, the information carried by the photon is preserved in the matter in a fully control-

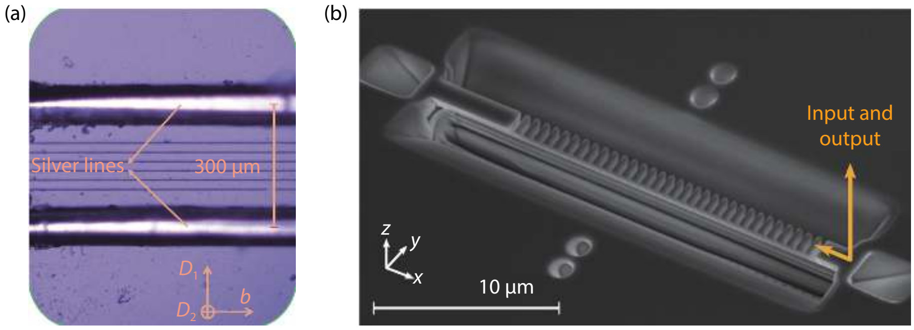

Fig. 5. (Color online) Integrated quantum memories in the ERIC system. (a) An optical microscope image of five quantum memories in laser-written optical waveguides[75]. (b) A scanning electron microscope image of a quantum memory integrated in a photonic crystal nanocavity[78].

lable way. The rare-earth ions doped crystal (REIC) is one of the most promising solid-state quantum memory systems, featuring a broad inhomogeneous absorption spectrum up to GHz and a long coherence time up to millisecond at cryogenic temperatures[65]. A typical system includes an ensemble of identical rare-earth ions in a host crystal. Using the doping technique, ions are fitted inside the crystal lattice structure serving as a solid-state host, which shifts the energy level of the ion's electron states inhomogeneously. Therefore, the total absorption bandwidth of the REIC system is greatly enlarged, while each ion still possesses a long lifetime. A crucial feature of the ion ensemble is known as collective excitation[66]. When a single photon flying in z direction meets N ions in the crystal at time $t = 0$. After the absorption of the photon, the ion ensemble undergoes a collective excitation and its state evolves as

$$|\psi\rangle = \frac{1}{\sqrt{N}}\sum_{j=1}^{N} \mathrm{e}^{i2\pi\delta_j t}\mathrm{e}^{ikz_j}\,|g_1\cdots e_j\cdots g_N\rangle, \quad (1)$$

where δ_j is the detuning of the j-th ion due to inhomogeneous broadening, k is the wavevector of photon, z_j is the position of the j-th ion along the z axis, and $|g\rangle$ ($|e\rangle$) denotes the ground(excited) state of a single ion. The key idea is that re-emission occurs only when the time-dependent phase factor $\mathrm{e}^{i2\pi\delta_j t}$ of all terms returns to unit. Utilizing this as a starting point, many protocols have been proposed and experimentally realized, e.g., AFC[66, 67], CRIB[68] and ROSE[69] protocols.

Significant effort has been put into the experimental realizations of REIC quantum memory, both in bulk materials[70–74] and integrated optical waveguides[75–79]. To obtain a high storing efficiency, a large optical depth of the material is required. Optical waveguides or photonic crystal nanocavities that can be fabricated directly in the REIC material therefore result in strong confinement of light field and enhanced photon-spin interactions. On-chip quantum memories have been demonstrated in optical waveguides[77] and in photonic crystal cavities[80], as shown in Fig. 5. In Fig. 5(a), five waveguide-based quantum memories (dark narrow lines) were fabricated using the femtosecond laser-writing technique. The silver electrodes were used to provide the electric field on the ion ensemble. It has been shown that the spectrum of the waveguide is broader than that of the bulk material, but the coherence lifetime remains unchanged[76]. The storage fidelity of a mean value of 99% has been demonstrated with inputs of weak coherent pulses. Fig. 5(b) shows an quantum memory in a REIC photonic crystal nanocavity, which was fabricated by focused-ion-beam milling[80]. The space between slots was modified quadratically in the center to form the cavity. The coherence lifetime of the cavity was measured to be 149 ± 4 μs[80]. A storage time of 10 μs for coherent light and a 2 μs multimode storage were demonstrated[80].

In general, the REIC quantum memory offers nearly optimal fidelity and on-demand storage time. However, the efficiency of most reported experiments is below 30%, and the efficiency of the forward collecting scheme in to-date experiments is up bounded by 54.1%[67]. The realization of more practical quantum memories thus requires further improvements of efficiency in future experiments, as well as more efficient protocols.

5. Discussion and conclusion

The development of chip-based QKD devices and systems is still in its infancy, which mainly focuses on the proof-of-principle demonstrations of standard QKD protocols. One significant effort is to monolithically integrate key quantum optical components in a semiconductor chip for the purpose of key distribution and information sharing between integrated photonic chips. The relative high excess loss of integrated photonics makes it challenging to realize fully device-independent QKD systems.

The state-of-the-art bulk-optics QKD systems enable satellite-relayed global-scale quantum communication networks[7, 9]. Typically, the satellite QKD systems work in the visible wavelength window, which is challenging for the integrated photonics implementations because more deliciated nanofabrication technologies are required in the short wavelength region and also because most of optoelectronic devices such as laser, modulator and detectors are designed and developed for the telecommunication region. Nevertheless, the integrated solution is unlikely to be fully comparable to the satellite-QKD system that carries a large telescope, APT and an adaptive optics system. That being said, integrated QKD technologies could lead to a much more cost-effective and high-yield applications in fiber-based and short-distance free-space systems (e.g., drone-relayed mobile QKD[81]). In particular, its comparability with fiber telecommunication infrastructure could benefit and ultimately deliver a cointegration of quantum transceivers for secured key sharing, as well as classical transceivers for telecommunication data sharing; note that demonstrations of quantum-classical fiber-optical system (no integration of QKD components) have been reported[82–84].

Integrated quantum photonics has become an important platform for the development of quantum information processing and quantum communication. Many leading candidates have emerged, such as indium phosphide, silicon, silicon nitride and lithium niobate. In the future, it can be expected to deliver chip-based QKD transmitters and receivers with miniature size, low cost, high stability and flexible portability. Broadly speaking, large-scale integrations and reliable operations of integrated quantum photonic devices and circuits will ultimately benefit the formation of powerful quantum information processing nodes for the future quantum internet.

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References

[1] Gisin N, Thew R. Quantum communication. Nat Photonics, 2007, 1, 165

[2] Wootters W K, Zurek W H. A single quantum cannot be cloned. Nature, 1982, 299, 802

[3] Bennett C H, Brassard G. Quantum cryptography: Public key distribution and coin tossing. Theor Comput Sci, 2014, 560, 7

[4] Shor P W, Preskill J. Simple proof of security of the BB84 quantum key distribution protocol. Phys Rev Lett, 2000, 85, 441

[5] Ekert. Quantum cryptography based on Bell's theorem. Phys Rev Lett, 1991, 67, 661

[6] Curty M, Lewenstein M, Lütkenhaus N. Entanglement as a precondition for secure quantum key distribution. Phys Rev Lett, 2004, 92, 217903

[7] Liao S K, Cai W Q, Liu W Y, et al. Satellite-to-ground quantum key distribution. Nature, 2017, 549, 43

[8] Bennett C H, Bessette F, Brassard G, et al. Experimental quantum cryptography. J Cryptol, 1992, 5, 3

[9] Chen Y A, Zhang Q, Chen T Y, et al. An integrated space-to-ground quantum communication network over 4, 600 kilometres. Nature, 2021, 589, 214

[10] Honjo T, Inoue K, Takahashi H. Differential-phase-shift quantum key distribution experiment with a planar light-wave circuit Mach-Zehnder interferometer. Opt Lett, 2004, 29, 2797

[11] Sibson P, Kennard J E, Stanisic S, et al. Integrated silicon photonics for high-speed quantum key distribution. Optica, 2017, 4, 172

[12] Ma C X, Sacher W D, Tang Z Y, et al. Silicon photonic transmitter for polarization-encoded quantum key distribution. Optica, 2016, 3, 1274

[13] Bunandar D, Lentine A, Lee C, et al. Metropolitan quantum key distribution with silicon photonics. Phys Rev X, 2018, 8, 021009

[14] Avesani M, Calderaro L, Schiavon M, et al. Full daylight quantum-key-distribution at 1550 nm enabled by integrated silicon photonics. npj Quantum Inf, 2021, 7, 93

[15] Orieux A, Diamanti E. Recent advances on integrated quantum communications. J Opt, 2016, 18, 083002

[16] Sibson P, Erven C, Godfrey M, et al. Chip-based quantum key distribution. Nat Commun, 2017, 8, 1

[17] Lydersen L, Wiechers C, Wittmann C, et al. Hacking commercial quantum cryptography systems by tailored bright illumination. Nat Photonics, 2010, 4, 686

[18] Zhao Y, Fung C H F, Qi B, et al. Quantum hacking: Experimental demonstration of time-shift attack against practical quantum-key-distribution systems. Phys Rev A, 2008, 78, 042333

[19] Makarov V, Anisimov A, Skaar J. Effects of detector efficiency mismatch on security of quantum cryptosystems. Phys Rev A, 2006, 74, 022313

[20] Lo H K, Curty M, Qi B. Measurement-device-independent quantum key distribution. Phys Rev Lett, 2012, 108, 130503

[21] Hong C K, Ou Z Y, Mandel L. Measurement of subpicosecond time intervals between two photons by interference. Phys Rev Lett, 1987, 59, 2044

[22] Agnesi C, da Lio B, Cozzolino D, et al. Hong–Ou–Mandel interference between independent III –V on silicon waveguide integrated lasers. Opt Lett, 2019, 44, 271

[23] Rarity J G, Tapster P R, Loudon R. Non-classical interference between independent sources. J Opt B, 2005, 7, S171

[24] Wei K J, Li W, Tan H, et al. High-speed measurement-device-independent quantum key distribution with integrated silicon photonics. Phys Rev X, 2020, 10, 031030

[25] Semenenko H, Sibson P, Thompson M G, et al. Interference between independent photonic integrated devices for quantum key distribution. Opt Lett, 2019, 44, 275

[26] Semenenko H, Sibson P, Hart A, et al. Chip-based measurement-device-independent quantum key distribution. Optica, 2020, 7, 238

[27] Wehner S, Elkouss D, Hanson R. Quantum Internet: A vision for the road ahead. Science, 2018, 362, eaam9288

[28] Clauser J F, Horne M A, Shimony A, et al. Proposed experiment to test local hidden-variable theories. Phys Rev Lett, 1969, 23, 880

[29] Acín A, Massar S, Pironio S. Efficient quantum key distribution secure against no-signalling eavesdroppers. New J Phys, 2006, 8, 126

[30] Acín A, Brunner N, Gisin N, et al. Device-independent security of quantum cryptography against collective attacks. Phys Rev Lett, 2007, 98, 230501

[31] McKague M. Device independent quantum key distribution secure against coherent attacks with memoryless measurement devices. New J Phys, 2009, 11, 103037

[32] Vazirani U, Vidick T. Fully device-independent quantum key distribution. Phys Rev Lett, 2014, 113, 140501

[33] Yin J, Cao Y, Li Y H, et al. Satellite-based entanglement distribution over 1200 kilometers. Science, 2017, 356, 1140

[34] Liu J, Su R B, Wei Y M, et al. A solid-state source of strongly entangled photon pairs with high brightness and indistinguishability. Nat Nanotechnol, 2019, 14, 586

[35] Zhao J, Ma C X, Rüsing M, et al. High quality entangled photon pair generation in periodically poled thin-film lithium niobate waveguides. Phys Rev Lett, 2020, 124, 163603

[36] Duan J C, Zhang J N, Zhu Y J, et al. Generation of narrowband counterpropagating polarization-entangled photon pairs based on thin-film lithium niobate on insulator. J Opt Soc Am B, 2020, 37, 2139

[37] Autebert C, Bruno N, Martin A, et al. Integrated AlGaAs source of highly indistinguishable and energy-time entangled photons. Optica, 2016, 3, 143

[38] Wang J W, Paesani S, Ding Y H, et al. Multidimensional quantum entanglement with large-scale integrated optics. Science, 2018, 360, 285

[39] Corrielli G, Crespi A, Geremia R, et al. Rotated waveplates in integrated waveguide optics. Nat Commun, 2014, 5, 4249

[40] Zhang X, Bell B A, Mahendra A, et al. Integrated silicon nitride time-bin entanglement circuits. Opt Lett, 2018, 43, 3469

[41] Li C L, Liu D J, Dai D X. Multimode silicon photonics. Nanophotonics, 2018, 8, 227

[42] Feng L T, Zhang M, Xiong X, et al. On-chip transverse-mode entangled photon pair source. npj Quantum Inf, 2019, 5, 2

[43] Silverstone J W, Bonneau D, Ohira K, et al. On-chip quantum inter-

ference between silicon photon-pair sources. Nat Photonics, 2014, 8, 104
[44] Silverstone J W, Santagati R, Bonneau D, et al. Qubit entanglement between ring-resonator photon-pair sources on a silicon chip. Nat Commun, 2015, 6, 7948
[45] Grassani D, Azzini S, Liscidini M, et al. Micrometer-scale integrated silicon source of time-energy entangled photons. Optica, 2015, 2, 88
[46] Mazeas F, Traetta M, Bentivegna M, et al. High-quality photonic entanglement for wavelength-multiplexed quantum communication based on a silicon chip. Opt Express, 2016, 24, 28731
[47] Paesani S, Borghi M, Signorini S, et al. Near-ideal spontaneous photon sources in silicon quantum photonics. Nat Commun, 2020, 11, 2505
[48] Suo J, Dong S, Zhang W, et al. Generation of hyper-entanglement on polarization and energy-time based on a silicon micro-ring cavity. Opt Express, 2015, 23, 3985
[49] Wang F X, Wang W Q, Niu R, et al. Quantum key distribution with on-chip dissipative kerr soliton. Laser Photonics Rev, 2020, 14, 1900190
[50] Wang J W, Sciarrino F, Laing A, et al. Integrated photonic quantum technologies. Nat Photonics, 2020, 14(5), 273
[51] Wang J W, Bonneau D, Villa M, et al. Chip-to-chip quantum photonic interconnect by path-polarization interconversion. Optica, 2016, 3, 407
[52] Ren J G, Xu P, Yong H L, et al. Ground-to-satellite quantum teleportation. Nature, 2017, 549, 70
[53] Gottesman D, Chuang I L. Demonstrating the viability of universal quantum computation using teleportation and single-qubit operations. Nature, 1999, 402, 390
[54] Metcalf B J, Spring J B, Humphreys P C, et al. Quantum teleportation on a photonic chip. Nat Photonics, 2014, 8, 770
[55] Lu X Y, Li Q, Westly D A, et al. Chip-integrated visible–telecom entangled photon pair source for quantum communication. Nat Phys, 2019, 15, 373
[56] Dutt M V G, Childress L, Jiang L, et al. Quantum register based on individual electronic and nuclear spin qubits in diamond. Science, 2007, 316, 1312
[57] Gaebel T, Domhan M, Popa I, et al. Room-temperature coherent coupling of single spins in diamond. Nat Phys, 2006, 2, 408
[58] Hanson R, Mendoza F M, Epstein R J, et al. Polarization and readout of coupled single spins in diamond. Phys Rev Lett, 2006, 97, 087601
[59] Epstein R J, Mendoza F M, Kato Y K, et al. Anisotropic interactions of a single spin and dark-spin spectroscopy in diamond. Nat Phys, 2005, 1, 94
[60] Maurer P C, Kucsko G, Latta C, et al. Room-temperature quantum bit memory exceeding one second. Science, 2012, 336, 1283
[61] Togan E, Chu Y, Trifonov A S, et al. Quantum entanglement between an optical photon and a solid-state spin qubit. Nature, 2010, 466, 730
[62] He Y, He Y M, Wei Y J, et al. Quantum state transfer from a single photon to a distant quantum-dot electron spin. Phys Rev Lett, 2017, 119, 060501
[63] Rozpędek F, Yehia R, Goodenough K, et al. Near-term quantum-repeater experiments with nitrogen-vacancy centers: Overcoming the limitations of direct transmission. Phys Rev A, 2019, 99, 052330
[64] Lodahl P, Mahmoodian S, Stobbe S. Interfacing single photons and single quantum dots with photonic nanostructures. Rev Mod Phys, 2015, 87, 347
[65] Thiel C W, Böttger T, Cone R L. Rare-earth-doped materials for applications in quantum information storage and signal processing. J Lumin, 2011, 131, 353
[66] Lauritzen B, Minář J, de Riedmatten H, et al. Approaches for a quantum memory at telecommunication wavelengths. Phys Rev A, 2011, 83, 012318
[67] Afzelius M, Simon C, de Riedmatten H, et al. Multimode quantum memory based on atomic frequency combs. Phys Rev A, 2009, 79, 052329
[68] Sangouard N, Simon C, Afzelius M, et al. Analysis of a quantum memory for photons based on controlled reversible inhomogeneous broadening. Phys Rev A, 2007, 75, 032327
[69] Damon V, Bonarota M, Louchet-Chauvet A, et al. Revival of silenced echo and quantum memory for light. New J Phys, 2011, 13, 093031
[70] Jobez P, Timoney N, Laplane C, et al. Towards highly multimode optical quantum memory for quantum repeaters. Phys Rev A, 2016, 93, 032327
[71] Sabooni M, Beaudoin F, Walther A, et al. Storage and recall of weak coherent optical pulses with an efficiency of 25%. Phys Rev Lett, 2010, 105, 060501
[72] Yang T S, Zhou Z Q, Hua Y L, et al. Multiplexed storage and real-time manipulation based on a multiple degree-of-freedom quantum memory. Nat Commun, 2018, 9, 1
[73] Davidson J H, Lefebvre P, Zhang J, et al. Improved light-matter interaction for storage of quantum states of light in a thulium-doped crystal cavity. Phys Rev A, 2020, 101, 042333
[74] Amari A, Walther A, Sabooni M, et al. Towards an efficient atomic frequency comb quantum memory. J Lumin, 2010, 130, 1579
[75] Askarani M F, Puigibert M L G, Lutz T, et al. Storage and reemission of heralded telecommunication-wavelength photons using a crystal waveguide. Phys Rev Appl, 2019, 11, 054056
[76] Liu C, Zhou Z Q, Zhu T X, et al. Reliable coherent optical memory based on a laser-written waveguide. Optica, 2020, 7, 192
[77] Liu C, Zhu T X, Su M X, et al. On-demand quantum storage of photonic qubits in an on-chip waveguide. Phys Rev Lett, 2020, 125, 260504
[78] Saglamyurek E, Sinclair N, Jin J, et al. Broadband waveguide quantum memory for entangled photons. Nature, 2011, 469, 512
[79] Bennett C H, Wiesner S J. Communication via one- and two-particle operators on Einstein-Podolsky-Rosen states. Phys Rev Lett, 1992, 69, 2881
[80] Craiciu I, Lei M, Rochman J, et al. Nanophotonic quantum storage at telecommunication wavelength. Phys Rev Appl, 2019, 12, 024062
[81] Liu H Y, Tian X H, Gu C S, et al. Drone-based entanglement distribution towards mobile quantum networks. Natl Sci Rev, 2020, 7, 921
[82] Wang B X, Mao Y Q, Shen L, et al. Long-distance transmission of quantum key distribution coexisting with classical optical communication over a weakly-coupled few-mode fiber. Opt Express, 2020, 28, 12558
[83] Mao Y Q, Wang B X, Zhao C X, et al. Integrating quantum key distribution with classical communications in backbone fiber network. Opt Express, 2018, 26, 6010
[84] Cai C, Sun Y M, Zhang Y R, et al. Experimental wavelength-space division multiplexing of quantum key distribution with classical optical communication over multicore fiber. Opt Express, 2019, 27, 5125

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