Integrated Quantum Photonics on Silicon Platform

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Abstract: We present our recent study on silicon integrated quantum photonics, from single photon sources to applications of quantum communication, generation and manipulation of high-dimensional quantum entanglement states, and sampling of quantum state of light. © 2020 The Author(s)

OCIS codes: 270.5585, 130.0130

1. Introduction

Quantum mechanics has enabled an information-technological revolution. In particular, quantum cryptography provides ultimate secure communication [1], quantum computing offers the possibility of computational supremacy over classical computers in solving certain problems [2], quantum simulators can effectively simulate the vibrational quantum dynamics of molecules [3], and quantum metrology is able to realize high-resolution and highly sensitive measurements of physical parameters [4]. Quantum information can be naturally carried by atoms, electrons, superconducting Josephson junctions, and photons, which all can be embed in large-scale integrated devices. Thanks to the excellent coherence, weak interaction with the environment, and low-loss transmission over optical fibers, flying photons are ideal quantum state carriers for applications in quantum communications, quantum networks, and distributed quantum information processing, where silicon photonics offers an excellent platform for those quantum photonics technologies. Owing to the distinct advantages of complementary metal-oxide-semiconductor (CMOS) compatible fabrication, high refractive index and high nonlinearity of silicon, very large-scale silicon quantum photonic circuit can be realized. Here, we present our recent work on integrated quantum photonics, from single photon sources to applications in quantum communication, high-dimensional (HiD) quantum entanglement, and generation and sampling of quantum states of light, all based on silicon photonics.

2. Single photon sources on silicon

Single photon source is a fundamental resource for quantum photonic technologies. An ideal single photon source (SPSs) should emit single photons deterministically with high purity and distinguishability for all sources. So far, SPSs are mainly based on two systems, the first of which are solid-state systems including quantum dot, defects, etc., which are capable of emitting single photons deterministically. Another is based on spontaneously nonlinear systems, e.g. spontaneous parametric down-conversion (SPDC) and spontaneous four-wave mixing (SFWM), which emit photons probabilistically, and near-deterministic sources can be achieved by multiplexing technology, provided high herald efficiency is achieved. So far each system has their distinct advantages and challenges. SFWM in spiral nanowires [5] or silicon microring resonators [6] have been widely investigated for quantum photonics on silicon,

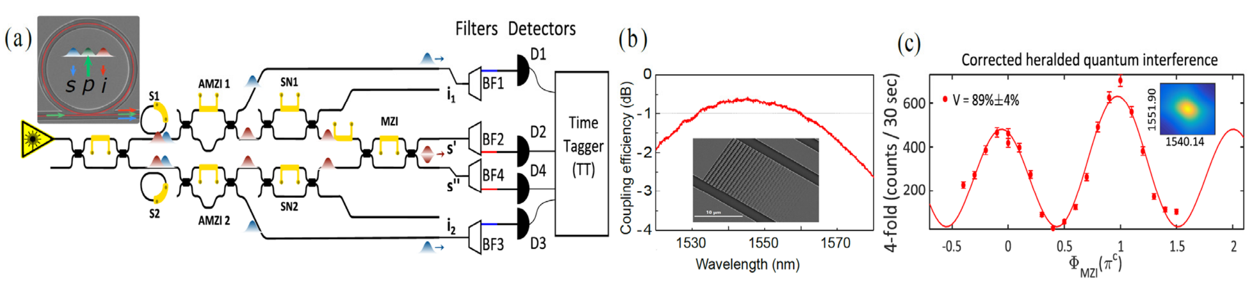

Figure 1. (a) Experimental setup and the equivalent circuit diagram of photonic chip, where two highly indistinguishable ring-resonator photon-pair sources S1 and S2 generate signal-idler photons pairs by SFWM, AMZI filters separate signal and idler photons, and switching networks (SN) steer signal photons and a final MZI for heralded quantum interference, and 4-fold coincidence events is recorded using a time-tagger. (b) High efficiency apodized fiber-to-chip grating coupler with less than 1 dB coupling loss. (c) The corrected heralded quantum interference between heralded signal photons exhibiting 89%±4% interference. The inset shows the Joint Spectral Intensity (JSI) with 91% purity indicating high indistinguishability (visibility) of our sources.

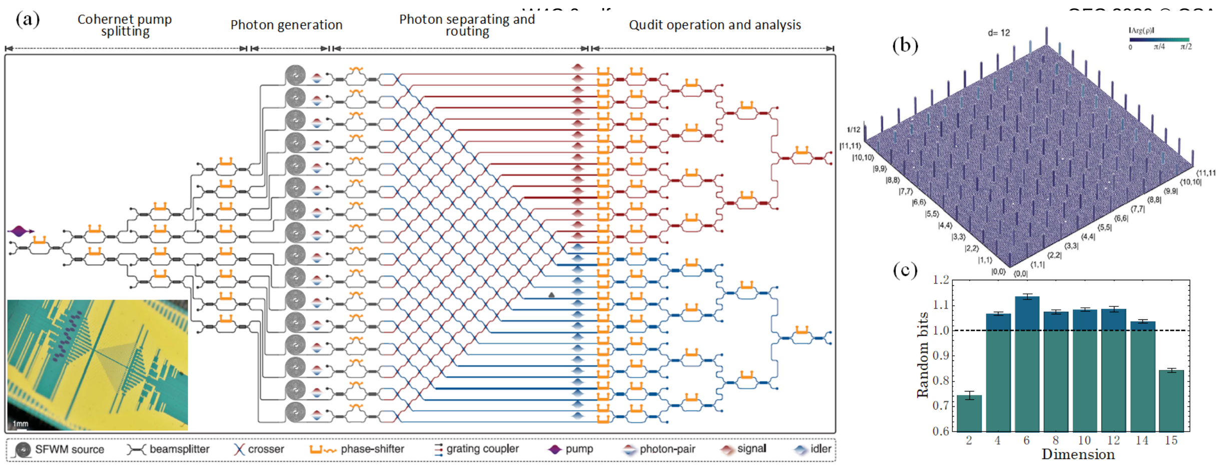

Figure 2. (a) Schematic on-chip generation and manipulation of HiD quantum entanglement state. The inset shows the fabricated silicon quantum chip, and (b) experimental quantum state tomography of generated 12-dimensional quantum state, indicating a fidelity of 81%. (c) Randomness per round certified in a one-sided DI scenario by d-dimensional steering correlations.

thanks to the excellent indistinguishability by coherent pumping, and compatibility with silicon photonics. Silicon mirroring resonators are preferred choice due to their property of filter-free high spectral purity, which is a requirement for multiphoton quantum technologies. One of the challenges, which exists in all other silicon photonics technologies, is how to efficiently couple photons out from the silicon chip for single photon detection. We provide silicon photonics platform with aluminum (Al) mirror, which is able to realize efficient coupling between standard single mode fiber (SMF) and silicon chip with coupling loss lower than 1 dB [7], as shown in Fig. 1(c). We realized bright silicon microring resonator sources with 91% spectral purity and high-rate of 4-fold coincidence events, as shown in Fig. 1, significantly important for multiphoton quantum technologies, as discussed below.

3. High-dimensional quantum entanglement

Quantum entanglement is a core quantum mechanism that is distinct from the classical world, and is one of the most important resources for quantum photonic technologies [8]. In particular, when compared with two-dimensional (qubit) entanglement states, quantum entangled states in high-dimensional Hilbert space provide higher information efficiency and better noise resilience for quantum communication, higher efficiency and flexibility for quantum computing, and richer resources for quantum simulation of physical systems. The advantage of excellent indistinguishability by coherent pumping makes silicon photonics a promising platform for quantum entanglement generation. As shown in Fig. 2, we demonstrate a large scale silicon quantum photonic chip, which consists of coherent pumping, photon generation, photon separating and routing, and qudit operation and analysis, able to generate and manipulate quantum entanglement in path in an up to 15 dimension Hilbert space [9]. Quantum state tomography (QST) confirms the high fidelity of the generated high dimensional quantum state. One of the promising applications is for randomness expansions. As compared to qubit entanglement, more than one random bit is obtained with high-dimensional quantum entanglement states, as shown in Fig. 2(c).

4. Quantum Communication

Quantum communication provides a new means of transmitting secure information. So far, point-to-point quantum key distribution (QKD) has been widely developed, but the distance of quantum communication link is significantly restricted. In order to extend the communication reach, future quantum communication will be based on quantum

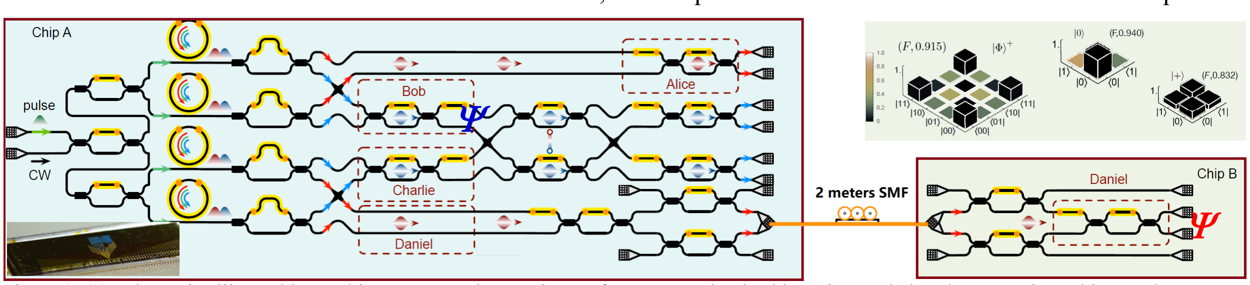

Figure 3. (a) Schematic silicon chip-to-chip quantum teleportation. A femto-second pulsed laser is coupled to the transmitter chip A, where single-photon pairs are generated in the microring resonators, and maximally entangled Bell state $|\Phi\rangle^{+}$ between Charlie and Daniel and arbitrary single qubit states $|\Psi\rangle$ at Bob are produced. The single qubit states $|\Psi\rangle$ is teleported to receiver chip B by performing Bell measurement between Bob and Charlie. Quantum states are transferred and teleported between the two chips by path to polarization conversion using 2D grating couplers. Reconstructed density matrices for Bell state $|\Phi\rangle^{+}$ and teleported single qubit states $|0\rangle$ and $|+\rangle$ are also reported.

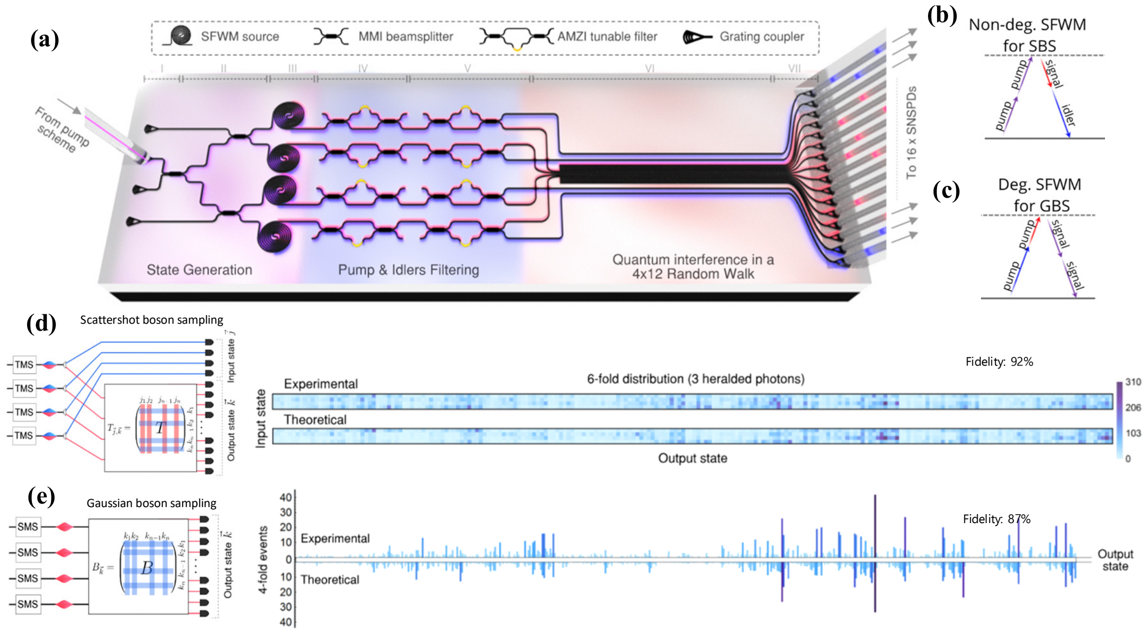

Figure 4. (a) The schematic of boson sampling using silicon chip, which integrates spiral photon sources, 12 continuously coupled waveguides, a network of MMIs, and grating couplers. AMZIs separate the idler (blue) and signal (red) photons. Schematic of scattershot boson sampling (d) and Gaussian boson sampling (e) using non-degenerated SFWM (b) and degenerated SFWM (c), corresponding experimental results show 92% and 87% fidelities respectively.

communication networks [10], where teleportation of photonic quantum states is at the heart of this technology. In quantum teleportation, an unknown quantum state can be transmitted to the destination by locally collapsing the state and remotely reconstructing. And quantum communication network is based on the long-range distribution of multi-photon entangled states and the teleportation of qubit states [11]. Quantum teleportation of photonic qubit has been demonstrated on-chip. For future quantum communication network, quantum teleportation between individual nodes (by quantum transceiver chips) will be an indispensable and important step. With the bright silicon microring photon-pair sources with high purity and distinguishability as introduced above, we for the first time have demonstrated silicon chip-to-chip quantum teleportation linked by standard SMF with high fidelity [12], as detailed in Fig. 3.

5. Boson Sampling

Boson sampling is a specific quantum computing task that solves the output probability statistics when bosons, e.g. photons, are injected and interfered in a linear interferometer. It has been theoretically proved an efficiency advantage over known classical algorithms by conventional computers [13]. Though boson sampling does not enable university quantum computing, it introduces new applications in QKD [14], quantum simulation of molecular quantum dynamics [15] and other applications. In order to implement boson sampling in a scale that surpass conventional computers, it requires the integration of all necessary components, e.g. photon sources, interferometers, and high-fidelity operation in a single chip, and CMOS compatible silicon photonics offers an ideal platform. We have demonstrated a silicon photonic quantum chip, which is able to generate and process quantum states of light on-chip with up to 8 photons [16], as presented in Fig. 4(a). Both scattershot (see Fig. 4(d)) and Gaussian boson sampling (see Fig. 4(e)) protocols are demonstrated with high fidelity in the same silicon chip, paving the way towards future efficient quantum simulators.

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