Quantum Entanglement and Teleportation Based on Silicon Photonics

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ABSTRACT
Quantum entanglement and teleportation are the key resources building the backbone of quantum technologies, such quantum communications, quantum networks, and quantum computations. The quantum communication networks are based on long-range distribution of entangled photons and teleportation of photon qubit states. The resource efficient measurement-based quantum computing models relies on cluster entangled states and the teleportation of logical operations between qubit sites. Silicon photonics provides a versatile platform for quantum information processing on chip, thanks to the CMOS-compatible fabrication process, ability to integrate thousands of components, and precise manipulation of quantum states on a single chip. Here we show our recent work on quantum entanglement and quantum teleportation technology based our advanced silicon photonics platform, a significant step towards future quantum network and optical quantum computing.
Keywords: quantum entanglement, quantum teleportation, quantum communication, quantum computing, silicon photonics, quantum photonics.

1. INTRODUCTION

Quantum information technologies have opened a new era of technological revolution. Quantum communication is able to realize secure communication between many users guaranteed by quantum physics [1], quantum computing could solve particular computational problems much more efficient than classical computers [2], and quantum simulation is able to efficiently simulate particular complex quantum systems [3]. The quantum information could be effectively carried on a few candidates, such as electrons, Josephson junctions, trapped-ions, and photons. In such quantum technological competition, there is no winner yet since each one has its own advantages and disadvantages. Quantum photonics technologies based on flying photons are particularly interesting because photons naturally have weak interaction with environment making photonic quantum state stable with high fidelity. Moreover, it can propagate through optical fiber with very low-loss, making it promising for long distance quantum communication.

Quantum entanglement and teleportation are the basic backbone behind the quantum technologies [4-6]. Quantum entanglement and teleportation of photonic qubits are extremely important for quantum photonic technologies, for instance, quantum communication networks [7] are based on long-distance distribution of multi-photon entangled state and teleportation of qubit photonic states [8]. In quantum computing, quantum teleportation is able to efficiently improve the success probability in the Knill–Laflamme–Milburn (KLM) optical quantum computing scheme [4]. A more resource efficient optical quantum computing scheme reported recently, i.e. measurement-based quantum computing [5] is fully based on cluster entangled states and teleportation of logical operators between qubit sites.

Recently years, integrated quantum photonics provides important means for implementing quantum photonics technologies [9], thanks to the powerful controllability and able to integrate multiple functionalities on a single chip. In particular, silicon photonics has attracted tremendous attention for quantum photonics technology [6, 10, 11]. The main motivation driving behind is the potential to integrate thousands of optical components on a single chip with the CMOS compatible fabrication process. Future quantum photonic and electric hybrid device is not a dream, and thousands of quantum photonic devices could be fabricated simultaneously with the mass production.

Here, we report our recent results of quantum photonic entanglement and teleportation technologies based on our advanced low-loss silicon photonics platform. We demonstrate reconfigurable silicon quantum photonic chip, and exhibit the first silicon chip to chip quantum teleportation and on-chip quantum entanglement swapping with high fidelity, which are important towards future quantum photonic network and optical quantum computing.

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2. SILICON MICRORING BASED HERALDED SINGLE PHOTON PAIR SOURCE

Single photon pairs could be effectively generated in silicon material by spontaneous four wave mixing (SFWM) process [12, 13]. Such heralded single-photon sources (HSPSs) have to meet some criteria to be scalable. Multiphoton quantum photonics technologies require HSPSs with high indistinguishability, spectral purity and heralding efficiency. Typically, cm-long Si-waveguides are used to produce photon-pairs [13]. The weakness of Si-waveguide source is that the photon pairs produced from waveguide sources are highly entangled in frequency [14], as shown in the left inset of Fig. 1(e). Improving spectral purity of the photons requires narrowband filters, which causes a significant reduction of photons, as indicated in Fig. 1(e), as well as heralding efficiency. Moreover, photons are actually generated everywhere throughout the quantum circuit, which induces background noise in quantum operations and hinders quantum error corrections. Thus it is important for a quantum photonic circuit architecture to be able to noiselessly interface the nonlinear photon sources and linear-optic circuits. Recently, microring resonator sources have been reported [15, 16]. As exhibited in Fig. 1(a), pump light is aligned to a resonance wavelength of the microring resonator, signal-idler pair can be generated at the corresponding resonance wavelengths, which can be separated with an asymmetric MZI afterwards, and filtered out by an arrayed waveguide grating (AWG) filters. The microring resonator source can greatly improve the signal-to-noise ratio by locally enhancing the SFWM, thus removing background noises, as shown in Fig. 1(b). It offers high brightness, high spectral purity and heralding efficiency without any spectral filtering. By controlling the pump light power and coupling with aluminium mirror assisted high efficiency fiber-to-chip grating coupler (coupling loss ~1 dB) [17], we achieve high photon number purity and coincidence to accidental ratio (CAR) with high brightness of tens of kHz pair generation rate, as shown in Fig. 1(c) and 1(d).

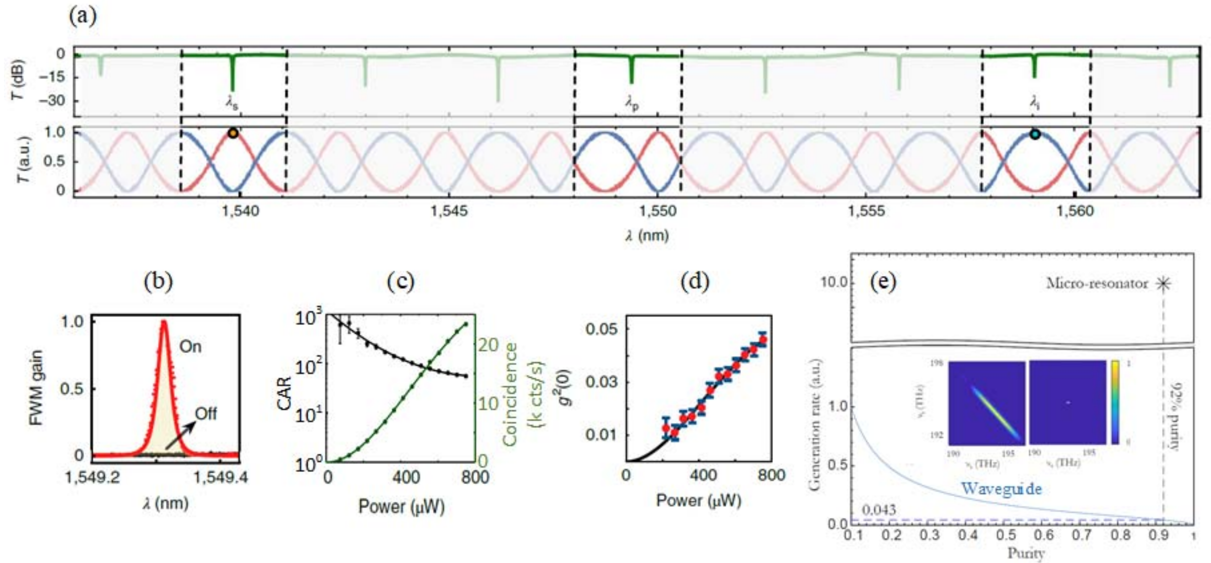

Figure 1. Photon pair generation in a fabricated microring resonator. (a) The measured transmission spectra for an MRR (top) and asymmetric MZI (bottom), with free spectral ranges FSR of 400 GHz and 320 GHz, respectively. (b) FWM enhancement in the MRR on-resonance. Background noise in the whole device is efficiently suppressed (off resonance). (c) Measured raw brightness and CAR as a function of input power. (d) Tests of photon number purity by measuring the heralded $g^{(2)}(0)$. (e) The trade-off between total generation rate of the photon-pairs and the spectral purity due to spectral filtering. Achieving 92% purity decimates the generation rate of the waveguide HSPSs. The unfiltered spectral purity and the generation rate of the MRR is significantly better as an HSPS. The insets indicate the JSA of a waveguide HSPS without filtering (Purity ≈ 12%) and with filtering (Purity ≈ 92%) respectively.

3. SILICON CHIP BASED QUANTUM TELEPORTATION AND SWAPPING

With the high quality silicon microring HSPS, we design programmable quantum photonic circuits able to realize generation, Bell projection or fusion operation, and measurement of quantum state on a single chip. As shown in Fig. 2(a), pump light is split to four beams input to four identical microring resonator HSPSs. After the waveguide crossers ($\hat{\mathbf{R}}$), two entangled states of $|\Phi\rangle^{+}_{1,2}$ and $|\Phi\rangle^{+}_{3,4}$ are generated. Blue photon 2 and 3 at Bob and Charlie respectively are manipulated able to prepare an arbitrary qubit states. A linear-optic quantum circuit ($\hat{\mathbf{O}}$) in the red dash line box is programmed to work as a bosonic Bell projector $\hat{\mathbf{O}}_{\text{Bell}}$ or fusion operator $\hat{\mathbf{O}}_{\text{Fusion}}$ on the two blue photons. The four photons are separated by asymmetric Mach–Zehnder interferometers (MZIs) and routed via waveguide crossers. An array of MZIs and phase-shifters enable the preparation ($\hat{\mathbf{P}}$) and projective measurement ($\hat{\mathbf{M}}$) of multi-qubit states. Yellow parts indicate electronically controllable thermal-optic phase-shifters.

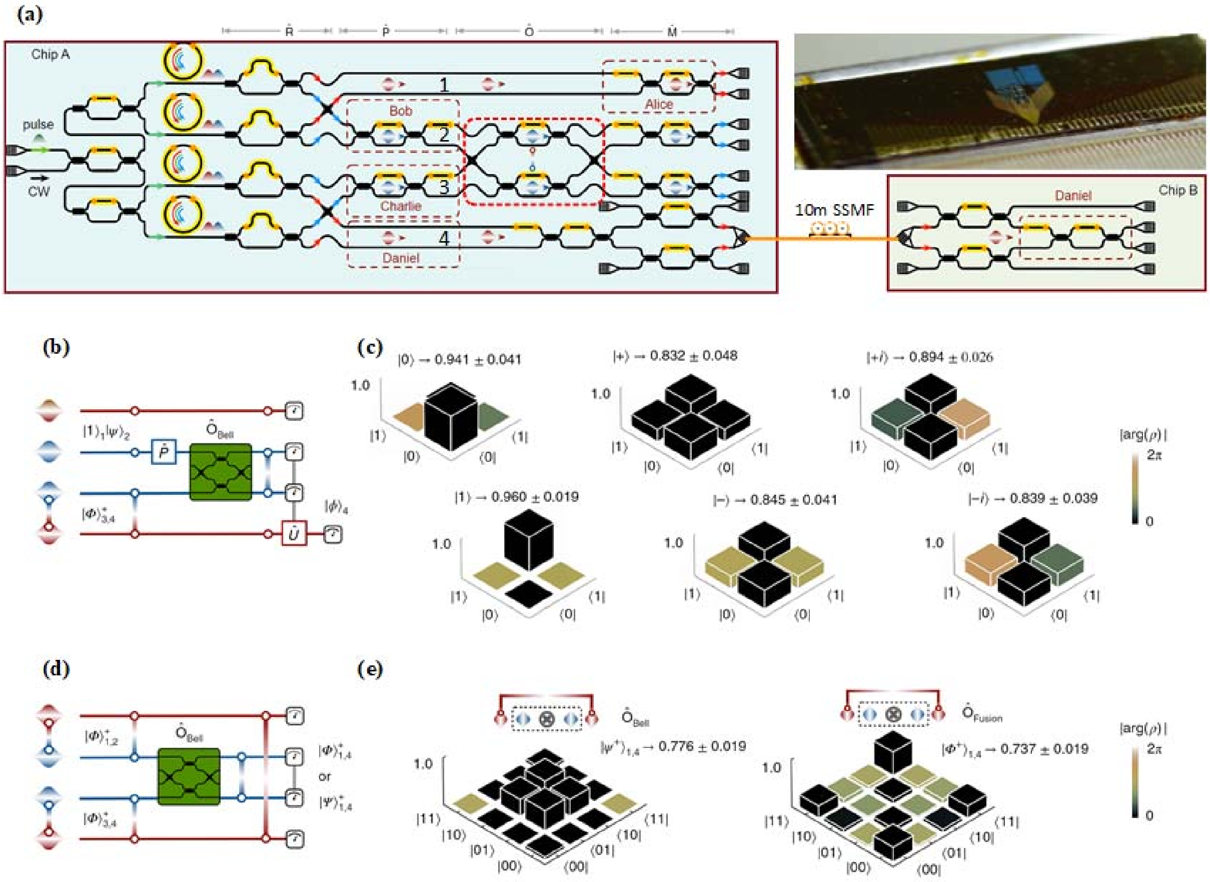

Figure 2. Schematic silicon chip-to-chip quantum teleportation and silicon on-chip quantum entanglement swapping. The inset shows the fabricated silicon chip. (b) Quantum circuit diagram for the teleportation of arbitrary single-qubit states from $|\Psi\rangle_2$ to $|\Phi\rangle_{4'}$, by performing Bell measurement of qubits 2, 3; (c) Experimental results for the chip-to-chip single-qubit teleportation. A full set of six states $\{|0\rangle, |1\rangle, |+\rangle, |-\rangle, |+i\rangle, |-i\rangle\}$ are teleported from the transmitter to the receiver, respectively, corresponding to a mean fidelity of 0.885±0.037. (d) Quantum circuit diagram of entanglement swapping of two-qubit entangled states from two Bell pairs $\{|\Phi\rangle^+_{12}, |\Phi\rangle^+_{34}\}$ to $|\Phi\rangle^+_{14}$ or $|\Psi\rangle^+_{14}$. (e) Experimental results for two-qubit entanglement swapping. Performing $\hat{\mathbf{O}}_{Bell}$ ($\hat{\mathbf{O}}_{fusion}$) on $|\Phi\rangle^+_{12}$ and $|\Phi\rangle^+_{34}$ results in swapped entanglement $|\Phi\rangle^+_{14}$ ($|\Psi\rangle^+_{14}$) between photons that have not interacted.

In the quantum teleportation, an unknown quantum state $|\Psi\rangle$ can be transmitted to the destination by locally collapsing the state and remotely reconstructing it in the destination [18]. This requires access to Bell states and Bell measurements. As shown in Fig. 1(a), we first prepare an arbitrary single-qubit state $|\Psi\rangle_2$ in photon 2 (‘B’) at Bob via a unitary $\hat{\mathbf{P}}$, and a Bell entangled state $|\Phi\rangle^+_{34}$ between photon 3 (‘C’) at Charlie and photon 4 (‘D’) at Daniel in transmitter chip A. Qubit 4 is then distributed to the receiver chip B through a 10 m-long standard single mode optical fibre (SSMF). Here we used the path-polarization conversion technique [19] by two-dimensional grating couplers, so that coherent teleportation between two chips is preserved. Photon 1 (‘A’) at Alice is used as a trigger. We then configure the linear-optic quantum circuit ($\hat{\mathbf{O}}$) to bosonic Bell projector $\hat{\mathbf{O}}_{Bell}$, which is then performed between Bob and Charlie, and the state is projected into the $|\Psi\rangle^+_{23}$ basis. In this process, the quantum state $|\Psi\rangle_2$ at Bob is teleported to Daniel with a local rotation $\hat{\boldsymbol{\sigma}}_x$. In our experiment, we prepare six different $|\Psi\rangle_2$ states at Bob and reconstruct at Daniel, where we obtain quantum state $|\Phi\rangle_4$. Full quantum state tomography (QST) is implemented at Daniel in order to reconstruct density matrices for the received six $|\Phi\rangle_4$ states. The QST of the recovered teleported states $|\Phi\rangle_4$ on the receiver are reported in Fig. 2(c), showing high fidelity for all six $|\Phi\rangle_4$ states with an average fidelities of F =0.885±0.037.

In the quantum entanglement swapping protocol, i.e. teleportation of entanglement, the sets of entanglement of photons {A, B} and photons {C, D}, can be swapped [18]. In this case, collapsing entanglement of photons {B, C} onto a Bell state will result in the entanglement of the other two photons {A, D}. It is an interesting and unique phenomenon because photons {A, D} have never interacted with one another before. Figure 2(d) shows the quantum circuit for entanglement swapping, where two Bell pairs $|\Phi\rangle^+_{12} \otimes |\Phi\rangle^+_{34}$ are prepared in the microring resonator array. When $\hat{\mathbf{O}}_{Bell}$ is performed on qubits 2 and 3, qubits 1 and 4 are projected into the entangled state $|\Psi\rangle^+_{14}$, and when $\hat{\mathbf{O}}_{fusion}$ is performed on qubit 2 and 3 and measurement is carried out in the $\boldsymbol{\sigma}_x$ $\boldsymbol{\sigma}_x$ basis, entangled state $|\Phi\rangle^{+}_{14}$ is obtained. We perform QST on qubits 1 and 4 and reconstruct $|\Psi\rangle^{+}_{14}$ and $|\Phi\rangle^{+}_{14}$ each from nine global measurement settings. Figure 2(e) reports the measured density matrix ρ, with fidelities of 0.776 ± 0.018 and 0.737 ± 0.019 for reconstructed $|\Psi\rangle^{+}_{14}$ and $|\Phi\rangle^{+}_{14}$, respectively, demonstrating successful on-chip entanglement swapping of photonic states.

4. CONCLUSIONS

We have demonstrated high quality silicon microring resonator based heralded single photon source, based on which we designed and fabricated low-loss quantum photonic chips, where we realized entangled state generation, Bell projection or fusion operation, and projective measurement on the same chip. We successfully demonstrated important quantum protocols, including the first silicon chip to chip quantum teleportation of single qubit, and on-chip quantum entanglement swapping, which will be significant step towards future quantum communication network and quantum photonic computing.

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