An Integrated Quantum Light Source of Frequency Degenerate Polarization Entangled Bell States

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Abstract: An integrated quantum light source of telecom band polarization entangled Bell state generation is proposed and demonstrated on a SOI chip. Its output state can be switched between two frequency-degenerate Bell states.

1. Introduction

Polarization entangled Bell states, as the maximally entangled quantum states of two-qubit quantum system [1], could be measured and discriminated by linear optics. They are frequently used in quantum communication, such as quantum dense coding [1], quantum teleportation [2], etc. On-chip generation of these states will simplify realizations of these applications and make them more practical. In previous works of polarization entangled photon-pair generation using spontaneous four wave mixing (SFWM) in silicon waveguides, a mono-color pump light is employed and the signal and idler photons are subsequently frequency non-degenerate. Therefore, the generated states could not be discriminated by Bell state measurement (BSM) based on linear optics. In this work, we propose a silicon photonic quantum circuit design of integrated quantum light sources to generate frequency-degenerate polarization entangled Bell states, and demonstrate it on a SOI chip. Its output state can be switched between two Bell states by thermal-optic phase control, which are discriminated by the simplified BSM.

2. Circuit design and experiment setup

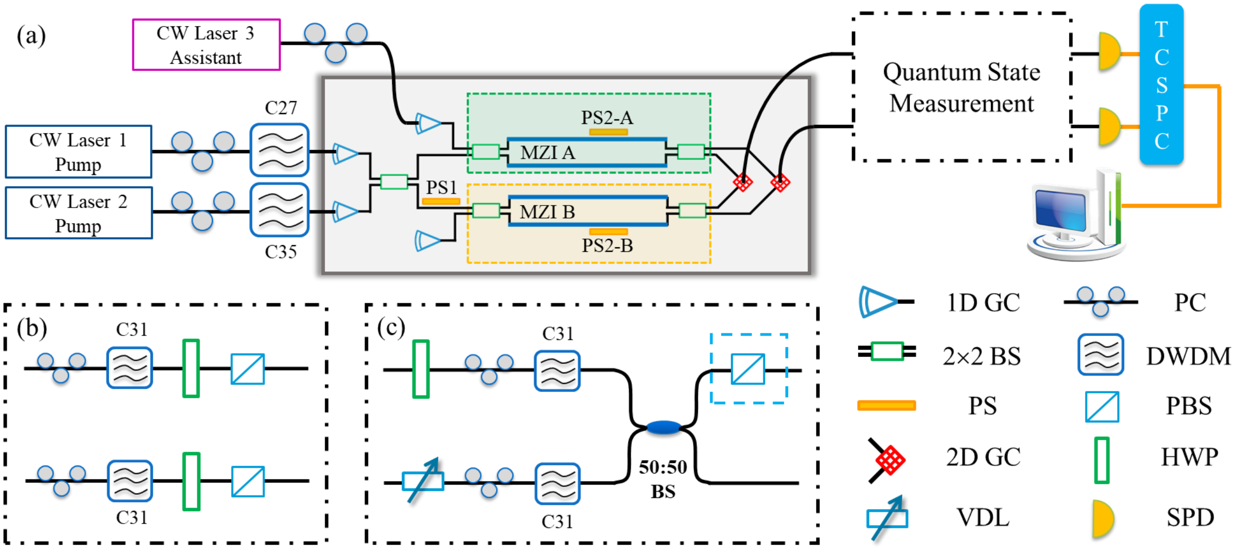

Fig. 1. (a) The sketch of the circuit and the experiment setup. The grey rectangle in the center represents the chip. The green/orange dashed rectangles show the Mach-Zehnder interferometer structures MZI A/B, respectively. The waveguides as SFWM media are shown as deep-blue bold straight lines in the MZIs. (b) The measurement setup for two-photon interference fringes under two non-orthogonal bases. (c) The simplified Bell state measurement setup. CW: continuous-wave. 1D GC: 1-dimensional grating coupler; BS: beam splitter, the splitting ratio of all splitters in this setup is 50:50; PS: phase shifter; 2D GC: 2-dimensional grating coupler; PC: polarization controller; DWDM: optical filter made of dense wavelength division multiplexing devices; HWP: half wave plate; PBS: polarization beam splitter; VDL: variable delay line; SPD: single photon detector. TCSPC: time correlated single photon counting circuit.

Fig. 1(a) shows the sketch of the circuit and the experiment setup. Two continuous-wave pump lights with different wavelengths are injected into the circuit. An on-chip beam splitter is used to combine the two pump lights and equally divide them into two Mach-Zehnder interferometer structures (MZI A/B, shown in Fig. 1(a)). In each MZI, frequency degenerate photon pairs are generated in the two arms made of silicon waveguides via non-degenerate SFWM process.

Quantum interference occurs between the generated biphoton states at the output beam splitter of each MZI. The output state is the superposition of bunch state and anti-bunch state. By adjusting the thermal-optic phase shifters (PS2-A/B shown in Fig. 1(a)), only anti-bunch state is left. Under this condition, the quantum state at the four outputs of two MZIs is path-entangled [3]. Then the path-polarization conversion is realized with the help of 2D grating couplers. The polarization entangled Bell states are achieved. Additionally, another thermal phase shifter (PS1 shown in Fig. 1(a)) is used to adjust the phases of pump lights in MZI B. With this phase shifter, the output can be switched between the two polarization entangled Bell states $|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|HV\rangle \pm |VH\rangle)$. The photon pairs are coupled into fiber, going through the quantum state measurements and finally detected by two single photon detectors. The results are recorded by the TCSPC. Two quantum state measurements are taken, including the measurement of two-photon interference fringes under two non-orthogonal polarization bases and the simplified BSM. The measurement setups are shown in Fig. 1(b) and 1(c), respectively, in which frequency-degenerate photon pairs are selected by optical filters.

3. Measurement results

Measurement results of two-photon interference fringes under two non-orthogonal polarization bases are shown in Fig. 2(a), with the raw fringe visibilities of 90.7% and 72.2%, respectively. The relative phase difference between the two fringes is 24.9°. The 2.4° error relative to the expected 22.5° comes from the manual operation on the half wave plates (HWP). The single side count rates of idler photons do not vary with the angle of HWP2 when the angle of HWP_1 is set at 0° and 22.5°, indicating its independence with two-photon interference fringes. These results prove the generation of polarization entangled states.

The simplified BSM results are shown in Fig. 2(b). By applying two specific voltages on the phase shifter PS1, the Bell states $|\Psi^{\pm}\rangle$ are achieved. The raw coincidence counts with respect to the time delay is measured, with the visibility of 85.8%. These results prove that the source can output two frequency degenerate Bell states $|\Psi^{+}\rangle$ and $|\Psi^{-}\rangle$, which can be controlled by the thermal-optic phase shifters. The two generated states can be discriminated by BSM, showing its potential on quantum encoding.

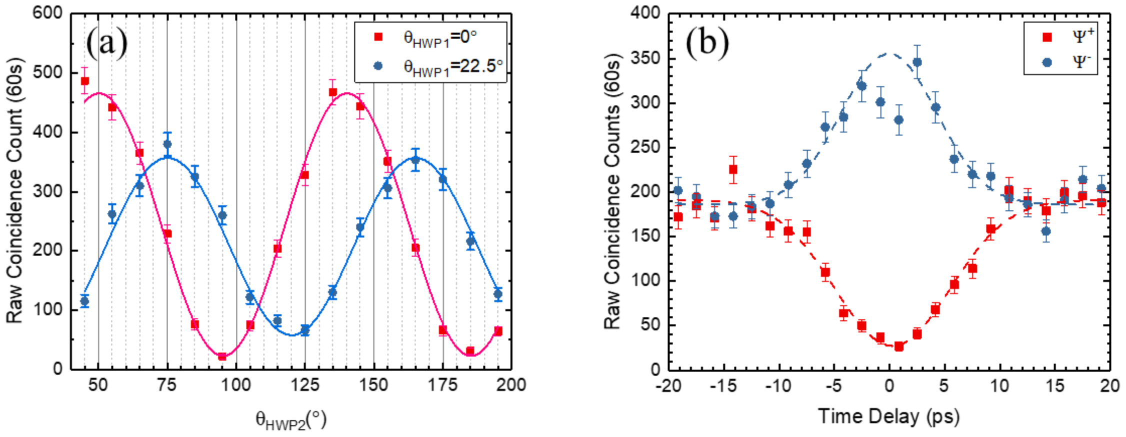

Fig. 2. (a) The two-photon interference fringes of raw coincidence counts under two non-orthogonal polarization bases. (b) Results of the simplified BSM: the raw coincidence counts with respect to the time delay when the quantum state is $|\Psi^{+}\rangle$ and $|\Psi^{-}\rangle$, respectively.

Acknowledgments

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