Quantum State Tomography of an On-chip Polarization-Spatial Qubit SWAP Gate

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Abstract: We experimentally demonstrate a chip-scale polarization to spatial-momentum qubit SWAP gate. High fidelity of the SWAP gate operation is confirmed by quantum state tomography, with average gate fidelity up to 97.30%.

Introduction

Recent developments in quantum computing bring us closer towards quantum supremacy [1]. In order to build a practical quantum computer, deterministic high-fidelity one-qubit and two-qubits logic gates are essential [2]. Specifically, SWAP gate is of special value as it can coherently transfer the value of two qubits encoded in different degrees of freedom (DOFs) without measuring or perturbing them. Thus, SWAP gate can serve as an ideal interface to convert coding from one DOF to another.

Experimental Results

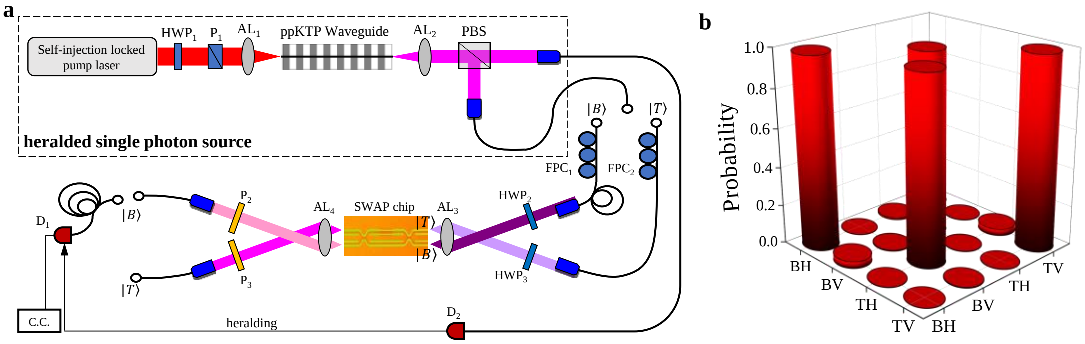

Figure 1| **a,** Experiment setup for truth table measurement. HWP: half wave plate; P: polarizer; AL: aspheric lens; PBS: polarization beam splitter; FPC: fiber polarization controller; C.C.: coincidence counting. **b,** Measured truth table for different given input polarization states, with average gate fidelity of 97.41%, without background subtraction.

In this abstract, we demonstrate a single photon SWAP gate on a silicon-on-oxide chip, served as an interface between polarization and spatial mode qubits. The SWAP operation is first examined by truth table measurements, and the experimental setup is illustrated in Figure 1a. A heralded single photon source is used to carry the input polarization qubit, generated by type-II spontaneous parametric down-conversion (SPDC) from a ppKTP waveguide with center wavelength around 1556 nm. A 2-in-2-out free-space coupling system accesses the $|T\rangle$ and $|B\rangle$ channels of the SWAP chip at both input and output facets. For the truth table measurements, a half-wave plate (HWP$_2$ or HWP$_3$) rotates the input polarization states and output states are projected by a pair of polarizers (P$_2$ and P$_3$). We perform the measurements on single-photon qubits with heralded single photons. The signal photons are used to carry input polarization qubits and sent to $|T\rangle$ and $|B\rangle$ channels with different polarization states, while the idler photons are directly detected by a superconducting nanowire single photon detector (SNSPD). After the SWAP operation, signal photons are detected by another SNSPD after polarization projection measurement by P$_2$ and P$_3$. Figure 1b shows the measured truth table for different input polarization states from $|T\rangle$ and $|B\rangle$ channels, and we achieved an average fidelity of 97.41% without subtracting accidental counts.

Next, we perform quantum state tomography on our SWAP gate. First, we prepare an input set of six polarization states ρ_{pol} (H, V, D, A, L, R) by HWP and QWP, and measure the corresponding output spatial momentum states ρ_{sm} (0, 1, +, -, i, -i; top output of MZI as 0, bottom output of MZI as 1). The experimental setup for quantum state tomography is illustrated in Figure 2a. The six output spatial momentum states after the SWAP operation are projected on a customized fiber Mach-Zehnder interferometer (MZI) to perform the quantum state tomography, with the coincidence counts are collected from the two output ports of MZI. Figure 2b and 2c shows the quantum state tomography results for $|T\rangle$ and $|B\rangle$ channel input, respectively. The state fidelity is defined as: $F = (Tr(\sqrt{\sqrt{\rho_{pol}}\rho_{sm}\sqrt{\rho_{pol}}}))^2$, which describes the overlap between the input polarization states and measured output spatial momentum states. Based on the tomography measurements, we achieve an averaged fidelity of 97.24 ± 0.29% for the six spatial momentum-encoded states, with the $|T\rangle$ channel input, and an averaged fidelity of 97.36 ± 0.32% with the $|B\rangle$ channel input. The high fidelity from quantum state tomography measurements is in support of the excellent performance of our SWAP gate.

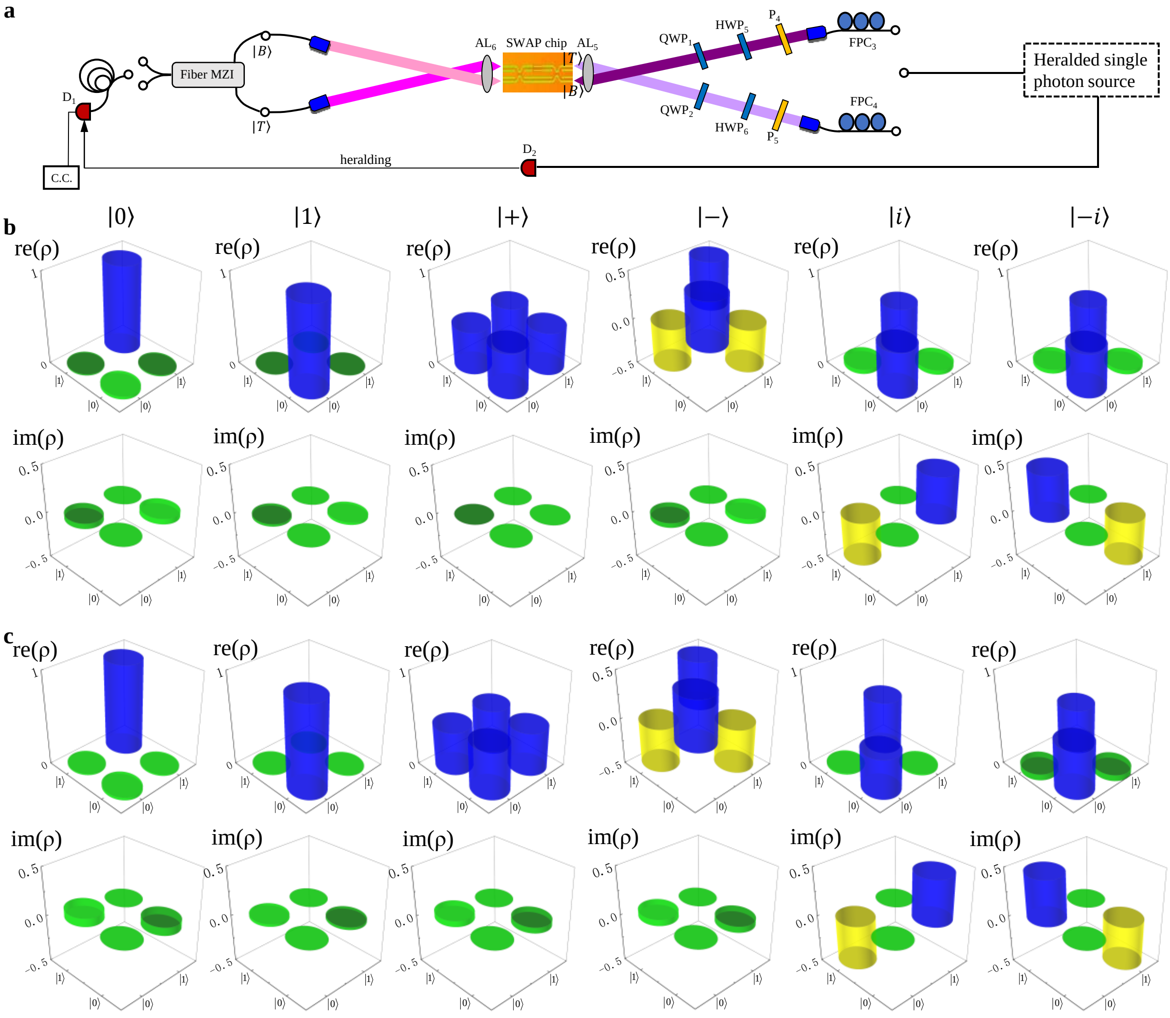

Figure 2| a, Experimental configuration of the quantum state tomography measurement for SWAP operation. **b,** Reconstructed density matrix ρ_{sm} of measured path-encoded states $|0\rangle$, $|1\rangle$, $|+\rangle$, $|-\rangle$, $|+i\rangle$ and $|-i\rangle$ for $|T\rangle$ channel input states. The state fidelities between ideal ρ_{pol} and measured ρ_{sm} are calculated to be 97.21%, 97.56%, 96.72%, 97.30%, 97.46%, and 97.21% respectively, for an averaged fidelity of 97.24 ± 0.29%. **c,** Reconstructed density matrix ρ_{sm} of measured path-encoded states for $|B\rangle$ channel input states, with state fidelities of 97.88%, 97.28%, 96.96%, 97.34%, 97.55% and 97.18% respectively, for an averaged fidelity of 97.36 ± 0.32%.

Conclusion

We demonstrated a chip-scale single-photon polarization to spatial-momentum SWAP gate. The SWAP gate operation is examined by quantum state tomography with high fidelity of 97.30%. Our deterministic and coherent quantum interface is very promising for practical linear optical quantum computing [3].

References

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