Highly pure 4-qubit states fully integrated in a programmable silicon-photonic chip

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Abstract: We demonstrate 98% Hong-Ou-Mandel (HOM) visibility, 82% Greenberger–Horne–Zeilinger (GHZ) fidelity, and Bell's inequality violations by 4-photon coincident measurements using a silicon-photonic chip including photon-pair sources, filters, and linear-optic gates.

Multipartite entanglement of photons in a photonic integrated chip is an attractive resource for quantum computation and communication networks [1–3]. Here, we prepare and manipulate 4-photon qubits in a silicon-photonic integrated circuit (SiPIC) controlled by a computer program. We measure 4 photons from 4 sources at a time by 4-photon coincidence.

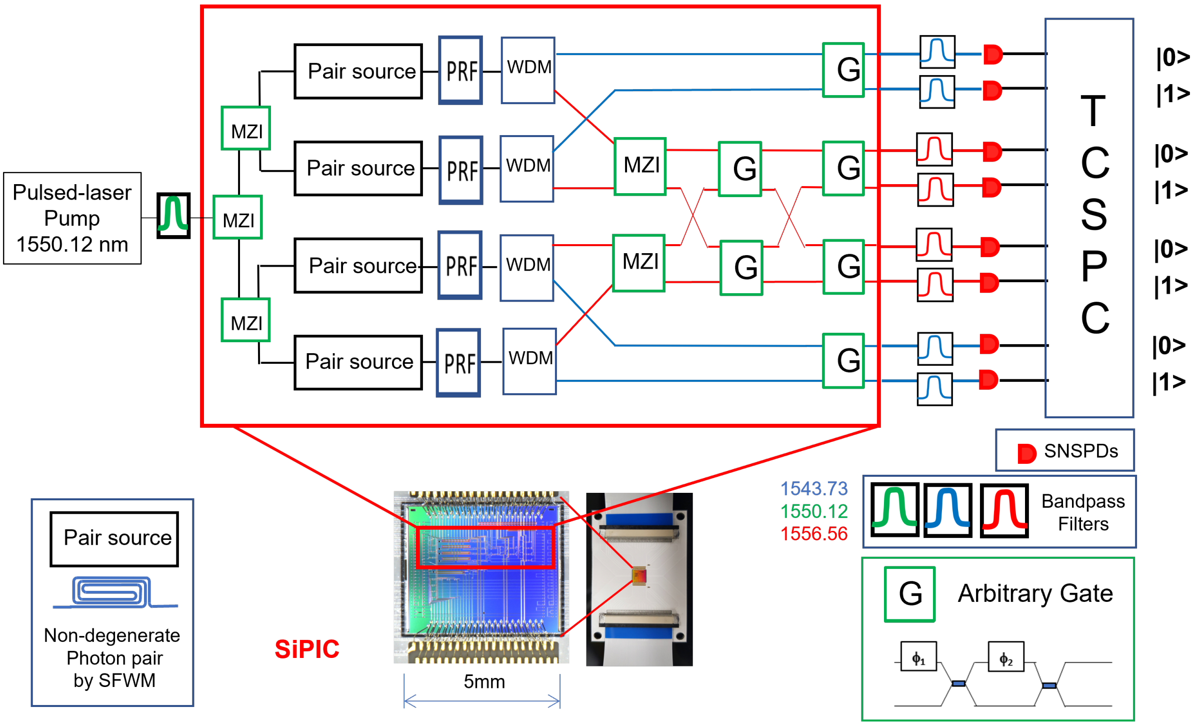


Fig. 1. Experimental setup to measure the quantum states of 4-photon qubits prepared by the programmable SiPIC.

The photon pairs are generated by non-degenerate spontaneous four-wave mixing (SFWM) process through 4 spirals in the SiPIC. We include pump-rejection filters (PRF), wavelength-division-multiplexing filters (WDM), and arbitrary gates (Gate), in addition to the photon-pair sources in the SiPIC as in Fig. 1. PRF and WDM are made of asymmetric Mach-Zehnder interferometers (MZI), while variable switches and Gates consist of symmetric MZI. This experiment is with the same chip used in our previous report of 99% HOM visibility. The previous report was by 2-photon coincidence measurements with a photon pair generated by degenerate SFWM through rings or spirals selectively by tuning the rings in the SiPIC. HOM visibility with a degenerate photon pair is not equivalent to the purity of the quantum state but HOM visibility with two separable photons individually heralded by 4-photon coincidence can be equivalent to the purity of the quantum state. The details of the structure of the SiPIC are shown in the reference [4]. We control the phase of the MZIs and Gates to give variations to the 4-photon qubit states in Fig. 1. The last 4 Gates in the SiPIC are also used for an on-chip tomography of the 4 qubits. In this report, we show experimental results on HOM interference, GHZ state, and Bell's inequality violations for the 4-photon qubit states prepared and analyzed by adjusting the phase of the MZIs and Gates in the SiPIC.

Figure 2 shows HOM interference measured by 4-photon coincidence for the average pumping powers 0.1 mW and 0.4 mW per spiral, respectively. The measured HOM visibility is 98% for the 0.1 mW pumping power, while 80% for the 0.4 mW because of degradation in the coincidence to accidental ratio (CAR) at the high pumping power. The 98% HOM visibility means the purity of the photon qubit can reach 98% because the two heralded photons used in the HOM interference are separable photons differently from the non-fully-separable pair used in our previous report [4]. The HOM visibility of 98% is the best result ever reported, as we know, by 4-photon coincident measurements in a SiPIC.

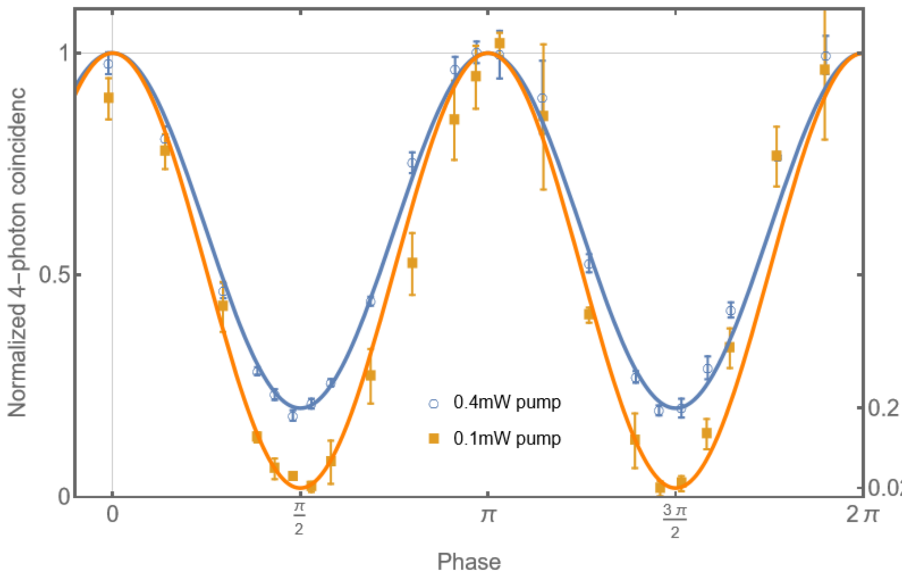


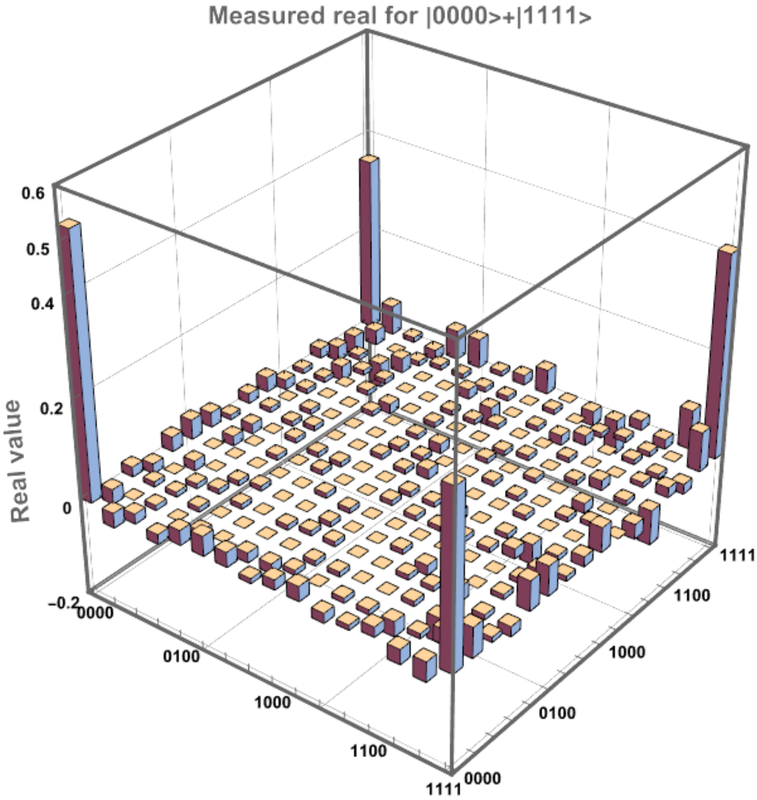
Fig. 2. HOM interference measured by 4-photon coincidence for the average pumping powers 0.1 mW and 0.4 mW per spiral, respectively. The measured visibility is 98% for the 0.1 mW pumping.

The density matrix of a 4-qubit state is a 16x16 matrix and the 256 complex components of the matrix can be reconstructed from real values obtained by 255 sets of Pauli measurements [2, 5]. Figure 3 shows the real and imaginary components of the density matrix reconstructed from the Pauli measurements of the programmable SiPIC. The fidelity of the measured density matrix $\rho_{measured}$ can be calculated by trace of the matrix product of $\rho_{measured}$ and ρ_{pure}, that is, $Fidelity = Tr(\rho_{pure}\rho_{measured})$ [6]. The fidelity of the measured density matrix is estimated as 82% to $(|0000\rangle + |1111\rangle)$ GHZ state, without any compensation for the measured data. The full tomography result of the 4-photon GHZ state with the fidelity of 82% in a SiPIC is the best result reported, in our knowledge.

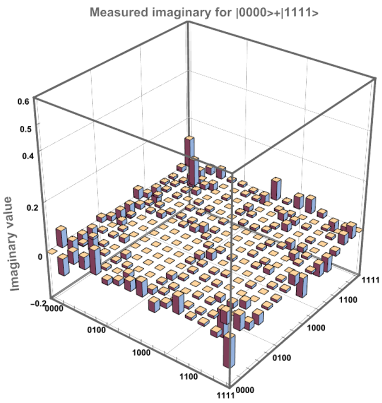
Table 1. Entanglement certificates

	Value	Condition
MABK	$3.91 \pm 0.26\ (7.42\sigma)$	>2
Witness	-0.15 ± 0.02	<0

Violation of Bell's inequality is an interesting test distinguishing quantum physics from classical physics. Bell's inequality is known to be used as an entanglement certification and there have been reports on Bell's inequality test with a multipartite system such as a 4-qubit GHZ state instead of a 2-qubit state [7, 8]. Here, we apply Mermin–Ardehali–Belinskii–Klyshko (MABK) inequalities [8] to our tomography data of the 4-qubit GHZ state for the first time, in our knowledge, for qubits in a SiPIC. The Bell's inequality test result by MABK shows a definite violation with the experimental value of 3.91 which is larger than the classically predicted maximum value of 2, as shown in table 1. We also estimated a witness to check the genuine entanglement of the GHZ state. An observable W is called an entanglement witness if $Tr(W\rho) < 0$ and it is estimated as a negative value of -0.15



(a) Real



(b) Imaginary

Fig. 3. Real and imaginary components of the density matrix reconstructed from tomography results of the programmable photonic circuits in SiPIC. The fidelity of the measured density matrix is 82% to $(|0000\rangle + |1111\rangle)$ GHZ state.

in this experiment. The violation of Bell's inequality and the negative witness in table 1 guarantee the quantum entanglement of the GHZ state in this experiment.

In summary, we demonstrated 98% HOM visibility, 82% GHZ fidelity, and the violation of Bell's inequality with 4-photon qubits in a SiPIC. These results show the promising future of silicon-photonic qubits for quantum computation and networks.

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