Demonstration of SiN-photonic Controlled-NOT Gate using Path-entangled Qubit Pairs from a Si-photonic Quantum Splitter

Jong-Moo Lee(1)*, Wook-Jae Lee(1), Min-su Kim(1), Sungwan Cho(1), Gabriele Navickaite(2), Juan Fernandez(3), and Jung Jin Ju(1)

(1) Electronics and Telecommunications Research Institute, Daejeon 34129, Korea
(1)*jongmool@etri.re.kr
(2) LIGENTEC SA, Lausanne, Switzerland
(3) VLC Photonics S.L., Camino de Vera s/n - 46021 Valencia, Spain

Abstract We fabricate a silicon-nitride photonic integrated circuit (PIC) to demonstrate a controlled-NOT quantum-logic gate and a silicon PIC generating path-entangled qubit pairs by splitting degenerate photon pairs. We measure 81% fidelity of CNOT using the fully packaged PICs.

Introduction

Recent progress of quantum computing with the possibility of quantum supremacy [1] inspires the photonic-integrated-circuit (PIC) technology to expand its application to quantum information technology (QIT) [2-5]. Photons are attractive in QIT because they do not interact with the environment and can be transferred through the fiber-optic networks. There have been many efforts using photons on demonstrating quantum logic operations [2-4] and quantum repeaters [5-7] which are essential for the quantum computing and networks.

Silicon PICs are very useful in QIT with the merit of the high-density integration and the high nonlinearity to generate photon pairs by the spontaneous four-wave mixing (SWFM) [8,9]. Silicon-nitride (SIN) PICs are attractive in QIT with the merit in low optical loss (0.1dB/cm, 1.5dB/facet), low thermo-optic coefficient ($dn/dT=\sim10^{-5}/K$), and the negligible polarization dependence [10,11]. Quantum interference through a SiN PIC has been demonstrated using single-photon qubits from a bulk laser system [10] and the possibility of the controlled-NOT (CNOT) gate using a SiN PIC has been estimated by classical measurements of transmission spectrum through the SiN PIC without using single-photon qubits in the reference [11].

Here, we demonstrate the quantum logic operation of the CNOT gate through a SiN PIC, by using the path-entangled qubit pairs from a Si PIC.

Experiments

Figure 1 shows the schematic drawing and photos of the experimental setup to generate the

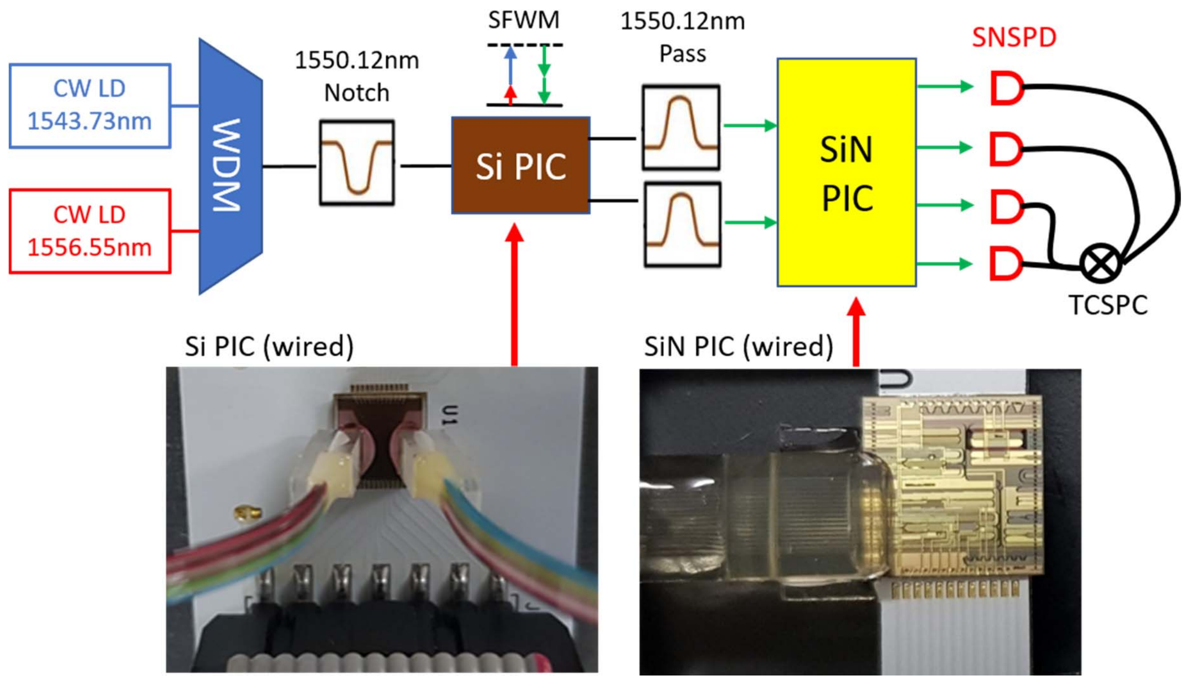

Fig. 1: Schematic drawing and photos for the experimental setup of qubit-pair generation and CNOT operation.

path-entangled qubit pairs and measure the CNOT gate operation. The Si PIC and SiN PIC are optically wired for the connection of photonic signals and electrically wired to adjust the optical phase of the PICs as in Fig. 1. Noise filtering is important in measuring quantum effect as in our previous results in reference [9] and we include a notch filter and bandpass filters as in Fig. 1.

Identical photon pairs are generated through the Si waveguide by degenerate SFWM and the identical pairs are split through the quantum splitter as in Fig. 2, by the similar way to the reference [8]. The split state of qubit pairs is used as the input to the SiN CNOT gate after the noise filtering through the bandpass filters. The photons after the logic operation through the CNOT gate are detected by superconducting-nanowire single-photon detectors (SNSPD). The detected single-photon signals are processed to the quantum correlation results using the time-correlated single-photon counting (TCSPC) technique.

Figure 3 shows the schematic drawing and photos of SiN CNOT gate fabricated in this experiment. The CNOT gate is operated by linear-optic quantum interference based on Hong-Ou-Mandel (HOM) effect [11]. We use the path-entangled photon qubits from the Si PIC as the input to the CNOT gate and measure the out photons from the output ports depending on the input states.

Measured Results

Figure 4 shows the measured correlation counts of the path-entangled photon pairs from the Si PIC. The results in Fig. 4 clearly show the degenerate photon pairs split into path-entangle qubit pairs.

Figure 5 shows the measured second-order correlation $g^{(2)}(0)$ of the heralded single-photon qubit from the Si PIC. The path-entangle photon shows the single-photon property with $g^{(2)}(0)$ less

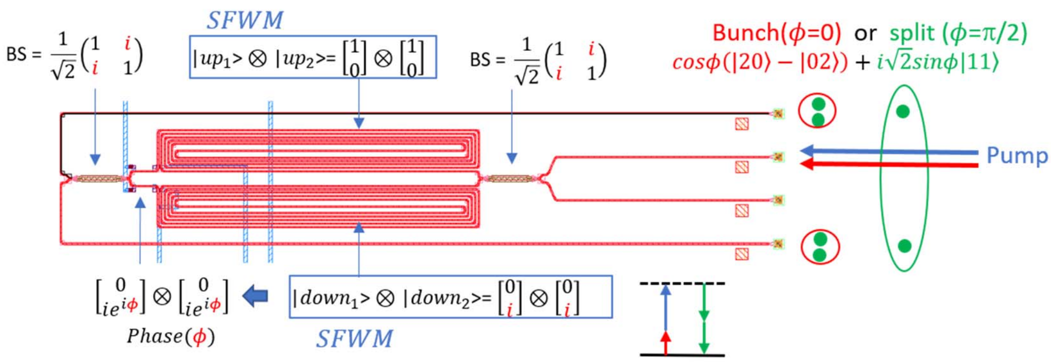

Fig. 2: Schematic drawing of the quantum splitter to generate and split photon pairs into the path-entangled qubits

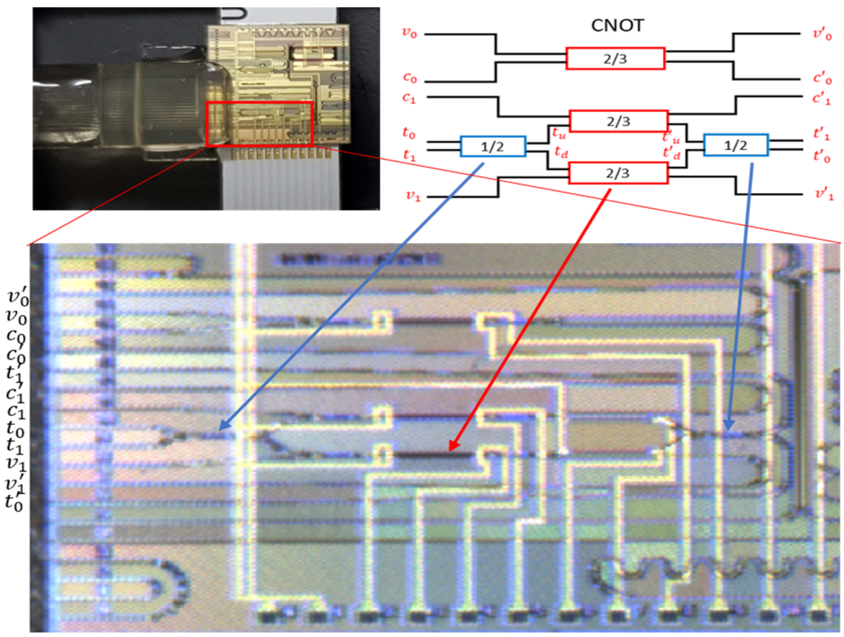

Fig. 3: Schematic drawing and photos of SiN CNOT gate.

than 0.05 in Fig. 5.

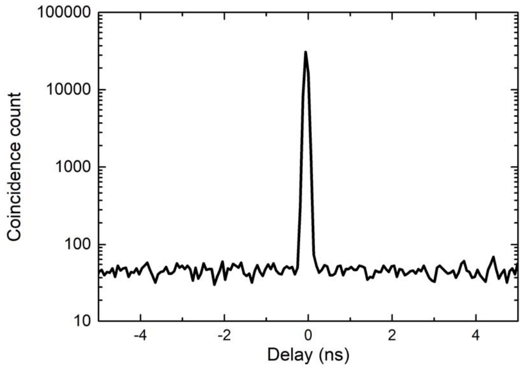

Fig. 4: Measured correlation counts of the path-entangled photon pairs from the Si PIC.

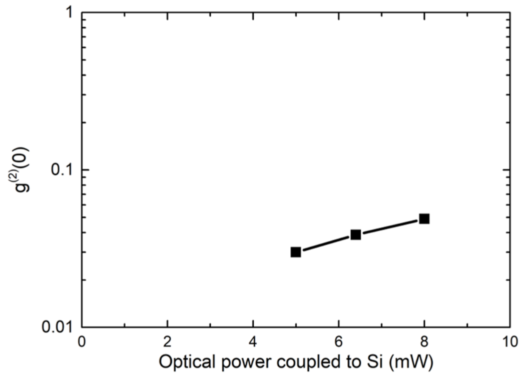

Fig. 5: Measured second-order correlation $g^{(2)}(0)$ of the heralded single-photon qubit from the Si PIC.

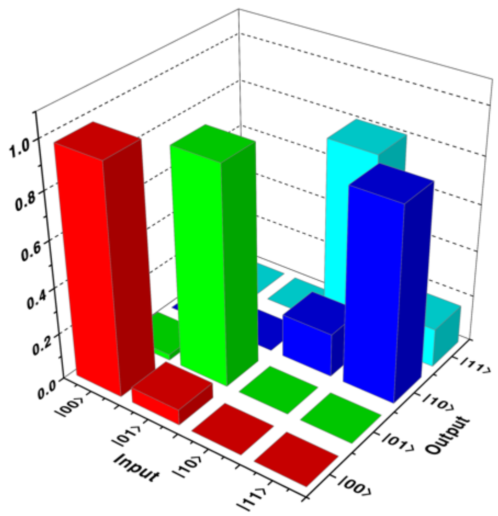

Fig. 6: Measured output qubit states through the SiN CNOT gate depending on the input path-qubit states.

Figure 6 shows the measured output qubit states through the SiN CNOT gate depending on the input entangled-path qubit states. The results in Fig. 5 clearly show the 2-qubit state changes to |11> from |10> input and to |10> from |11> input. The fidelity of the signal is about 81% in Fig. 5, and we expect it can be improved by reducing multi-photon noises from the input photon qubits. These changes of the quantum states are due to the quantum interference between the single-photon qubits and the CNOT operation can be useful in the future application of photons to QIT such as quantum computing and quantum repeaters.

Conclusions

We demonstrated a SiN PIC operating as the quantum-logic CNOT gate with the fidelity of 81%, by using the quantum-entangled qubit pairs from a Si PIC as the input qubits to the SiN PIC. This result shows the bright possibility of the combination of Si and SiN PICs for the quantum information process.

Acknowledgements

We fabricated the Si PIC including the photon-pair source at IMEC through Europractice, and the SiN PIC including the CNOT gate at Ligentec through VLC Photonics. The authors acknowledge the financial support of this research by IITP (20170000740011001) and NRF (2020M3E4A1078453) funded by the Korean government (MSIT).

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