Silicon quantum photonic device for multidimensional controlled unitaries

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Abstract: We present a fully reconfigurable silicon quantum photonic device capable of performing controlled four-dimensional unitary operations with 0.84 ± 0.02 fidelity. We report its characterisation by process tomography and deploy it to successfully perform a quantum model learning protocol.

Qudits are quantum states with dimension higher than traditional qubits and offer certain advantages for quantum information processing [1]. With their intrinsically higher information capacity, qudits have been used to obtain larger violation of local-realistic theories thus playing an important role in both quantum communication and quantum computing [2–4].

A fundamental prerequisite to enable qudits as carriers of quantum information in such applications is the demonstration of high-fidelity, arbitrary operations upon qudits. We do so introducing a silicon quantum photonic device capable of performing arbitrary unitary operations on a four-dimensional qudit (i.e. ququart) controlled by a qubit encoded in an ancillary register. We study the device performance by carrying out a selection of tomographic state reconstructions and find an average state fidelity of 0.95 ± 0.02. We demonstrate the first integrated quantum process tomography results for four dimensions and report an average process fidelity of 0.84 ± 0.02 from a range of processes uniformly sampled from the Hilbert space.

These results confirm the consistent performance of silicon quantum photonic technology under extensive testing involving the deployment of qudits and prove its readiness for practical applications.

References

[1] Erhard, Manuel, et al. "Twisted photons: new quantum perspectives in high dimensions." Light: Science & Applications 7.3 (2018): 17146-17146.

[2] Santagati, Raffaele, et al. "Localization-based two-photon wave-function information encoding." Optics express 27.15 (2019): 20787-20799.

[3] Bechmann-Pasquinucci, H., and Wolfgang Tittel. "Quantum cryptography using larger alphabets." Physical Review A 61.6 (2000): 062308

[4] Kaszlikowski, Dagomir, et al. "Violations of local realism by two entangled N-dimensional systems are stronger than for two qubits." Physical Review Letters 85.21 (2000): 4418.

[5] Clements, William R., et al. "Optimal design for universal multiport interferometers." Optica 3.12 (2016): 1460-1465.

[6] Durt, Thomas. "About Weyl and Wigner tomography in finite-dimensional Hilbert spaces." Open Systems & Information Dynamics 13.4 (2006): 403-413.

[7] Gilchrist, Alexei, Nathan K. Langford, and Michael A. Nielsen. "Distance measures to compare real and ideal quantum processes." Physical Review A 71.6 (2005): 062310.

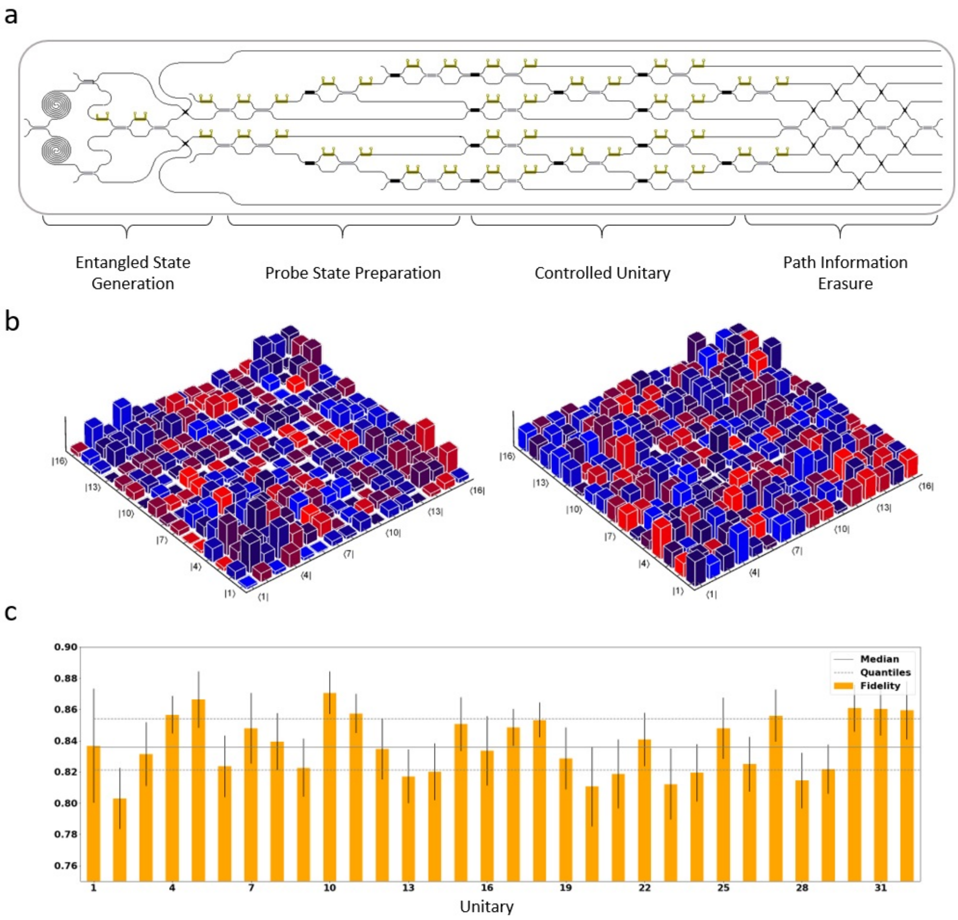

Fig. 1. **a)** Schematics of the silicon photonic device highlighting the four stages of computations implemented in the corresponding quantum circuit. Two integrated spiral waveguide photon sources generate a path-entangled pair of photons. Variable beam splitters in the form of Mach-Zender interferometers (MZIs) entangle the two photons where one serves as the control qubit and the other encodes the ququart. Next, a compact scheme [5] is adopted for dialing 4D unitary operations on the ququart. Finally, post-selection and path-erasure ensure control and target qubit are in required superposition. **b)** 3D reconstructed complex process matrices which completely and uniquely describe the unitary maps implemented on the photonic device. Each process reconstruction requires 300 projective measurements and 15 state tomographic reconstructions under the Weyl-Wigner quantum tomography strategy [6]. **c)** Synoptic view of 32 Haar random unitary processes sampled from the Hilbert space shows an average process fidelity of 0.84 ± 0.02. Bar chart reports on the vertical axis the process fidelity measurements [7] defined as $F_p = Tr(\chi_{tgt}\chi)$ where χ_{tgt} is the process matrix for the operation targeted whereas χ is the reconstructed process matrix defined in **b)**.