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Large-scale Integration of Multidimensional Quantum Photonics Circuits on Silicon

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Abstract: We report the first large-scale silicon-photonics quantum circuit, integrating more than 500 photonic components, able to generate, manipulate and measure multidimensional entanglement fully on-chip with unprecedented precision, controllability and universality.

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1. Introduction

Multidimensional quantum systems exhibit distinct quantum properties and offer improvements in key applications, such as increasing capacity in quantum communication [1], strengthening quantum correlations [2], and enriching quantum simulation and computing schemes [3]. Photons represent a promising platform able to naturally encode and process qudits in various degrees of freedom, e.g., orbital angular momentum, temporal bin and frequency [4,5]. However, these approaches present limitations in terms of controllability, precision, universality and a full integration of elements, which represent bottlenecks for further developments of multidimensional quantum photonic technologies.

We report a large-scale integrated quantum photonics circuit in the silicon-on-insulator platform able to create, control and analyze on-chip multidimensional entanglement up to dimensions 15×15. Path-encoded qudits are obtained, where each photon exist over d spatial modes simultaneously, and entanglement is produced by an excitation of an array of d identical integrated photon-pair sources. Our chip enables the generation of multidimensional entangled states with an arbitrary degree of entanglement, and arbitrary multidimensional measurements with very high fidelity, verified by quantum state tomographies, Bell violations and other quantum protocols.

2. Results

Silicon quantum photonics offers intrinsic stability, high precision and dense integration [6]. We manufactured a large-scale silicon quantum photonic circuit for multidimensional entanglement (Figure 1A and inset). A multidimensional entangled state $|\Psi\rangle = \sum_{k=0}^{d-1} c_k |k\rangle |k\rangle$ is produced by a coherent excitation of an array of d identical photon-pair sources, where c_k can be arbitrarily chosen by controlling the pump distribution through a network of MZIs before the sources, and $|k\rangle$ $(k = 0, \ldots, d-1)$ represents the logical state having a photon in its k-th optical mode. A network of asymmetric MZIs and crossers is used to separate the photons, and a triangular network of MZIs and phase-shifters is used to perform arbitrary local projective measurements on the qudits. The high indistinguishability of photon sources and high fidelity of qudit projectors enable the high-quality generation, control and analysis of multidimensional entanglement. We used quantum compressed sensing techniques to reconstruct bipartite entangled states. Figure 1B shows the reconstructed density matrix for a 12-dimensional entangled state having a high fidelity of 81%, showing a significant improvement of the quality for multidimensional entanglement.

Multidimensional entanglement can be verified by the violation of generalized Bell inequalities $\tilde{I}_d \leq C_d$, where $\tilde{I}_d$ is a function of the joint probabilities, and C_d is the classical bound for LHV models. We study a Bell-type inequalities,

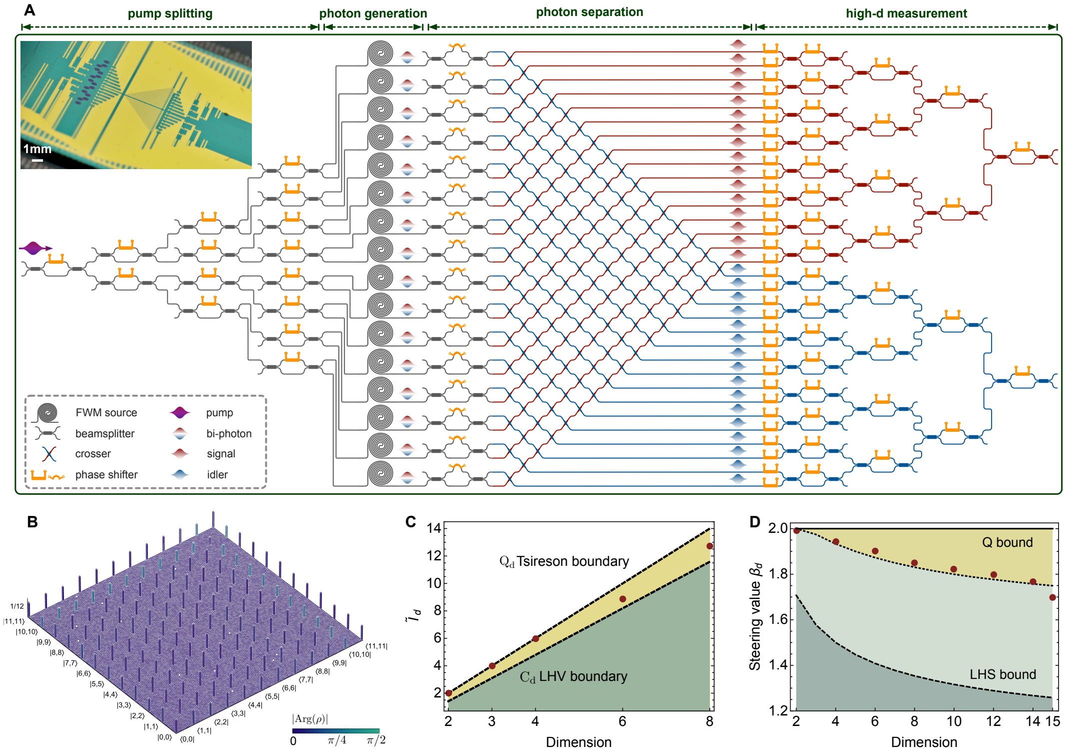

Fig. 1. **A**. Diagram for the integrated multidimensional quantum device. It integrates 16 spontaneous four-wave mixing photon-pair sources, 93 phase-shifters, 122 beamsplitters, 256 crossers and 64 grating couplers. A photon pair is generated in superposition across 16 optical modes, producing a multidimensional bipartite entangled state. The photons are separated by a network of asymmetric MZIs and crossers. Using a network of MZIs, we perform arbitrary local projective measurements on the entangled qudits. **B**. Reconstructed density matrix for a d-dimensional entangled state with a local dimension of 12. **C**. Bell violations, and **D**. EPR steering violations on d-dimensional entangled states. Red points are measured Bell values $\tilde{I}_d$ and steering values β_d, respectively.

that is tailored to obtain a maximal violation for maximally entangled qudit states [7]. The maximum value of $\tilde{I}_d$ obtainable with quantum states is given by Q_d, namely the Tsirelson bound. Figure 1C shows the measured Bell values for dimensions 2 to 8. In all cases the classical bound is violated. In particular in dimensions 2 to 4 a strong violation is observed, closely approaching the Q_d bound. Moreover, we obtained strong violations of the EPR steering inequalities for the 2 to 15-dimensional states, verifying the presence of d-dimensional entanglement up to 15 in the one-sided device-independent scenario, see Fig. 1D. The high precision and controllability of our technology enable the experimental demonstration of unexplored applications, such as quantum randomness expansion and self-testing on multidimensional states.

In summary, we have demonstrated the first large-scale silicon-photonic quantum circuit comprising more than 500 elements, and enabling high-quality multidimensional entanglement up to dimensions 15 × 15.

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