High-dimensional entanglement in large-scale Silicon quantum photonics

S. Paesani[1], J. Wang[1,2], Y. Ding[3], R. Santagati[1], P. Skrzypczyk[4], A. Salavrakos[5], J. Tura[6], R. Augusiak[7], L. Mančinska[8], D. Bacco[3], D. Bonneau[1], J. Silverstone[1], Q. Gong[2], A. Acín[5,9], K. Rottwitt[3], L. Oxenløwe[3], J. O'Brien[1], A. Laing[1], M. Thompson[1]

[1]*QETLabs, University of Bristol, BS8 1FD, Bristol, United Kingdom;* [2]*State Key Laboratory for Mesoscopic Physics, Peking University, Beijing 100871, China;* [3]*SPOC, Technical University of Denmark, Kgs. Lyngby, DK-2800, Denmark;* [4]*H. H. Wills Physics Laboratory, University of Bristol, BS8 1TL, Bristol, United Kingdom;* [5]*ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Barcelona, Spain;* [6]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany;* [7]*Polish Academy of Sciences, Aleja Lotników 32/46, 02-668 Warsaw, Poland;* [8]*QMATH, University of Copenhagen, Universitetsparken 5, 2100 Copenhagen Ø, Denmark;* [9]*ICREA - Institució Catalana de Recerca i Estudis Avançats, Pg. Lluís Companys 23 Barcelona, 08010, Spain.*

Photons represent a promising platform for multidimensional quantum technologies, offering various degrees of freedom for encoding and processing qudits (e.g., orbital angular momentum, time-bin and frequency [1,2]). We report the experimental implementation of a novel approach for the generation and processing of high-dimensional entangled systems based on large-scale integrated quantum photonics [3]. The experiment is performed using a Silicon quantum photonic chip able to create, control and analyze on-chip high-dimensional entanglement up to dimensions 15×15 (see Fig. 1A and inset). The photonic chip integrates more than 500 optical elements, including 16 photon-pair sources based on χ_3 non-linearities, 93 phase-shifters and 122 beam-splitters. Bipartite path-encoded high-dimensional systems with an arbitrary degree of entanglement are obtained by the coherent excitation of an array of identical integrated photon-pair sources, and integrated circuits allow high fidelity arbitrary measurements on-chip. In Fig. 1B the tomographies of the generated maximally-entangled states are reported for various local dimensions, and an example for $d = 12$ is shown in Fig.1C presenting a fidelity of 81%. The quality of the generated high-dimensional entanglement and the universality of the photonic processor are further exploited to experimentally implement a wide range of multidimensional applications, such as violation of high-dimensional Bell inequalities [4], self-testing of high-dimensional states, randomness generation and dimensional witnessing.

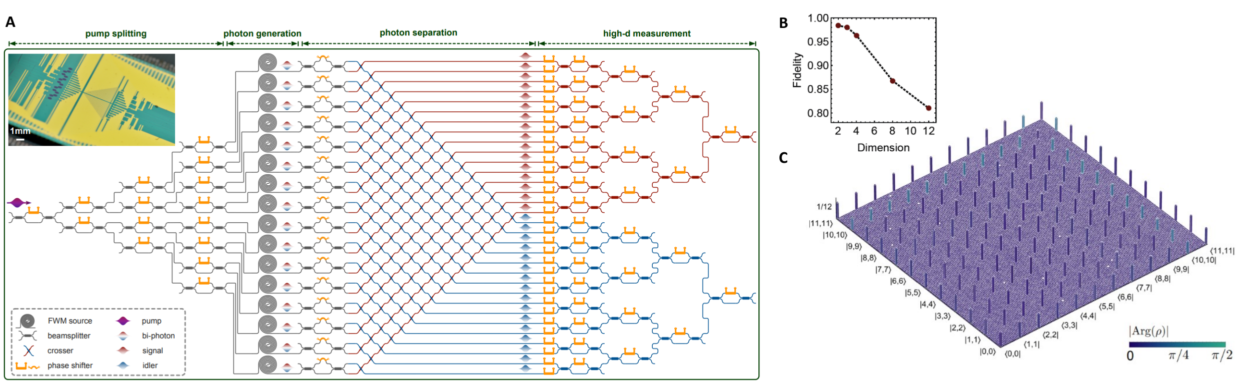

Figure 1: **A**. Diagram of the integrated circuit. A photon pair is generated in superposition across 16 photon-pair sources, producing a multidimensional bipartite entangled state. Using triangular structures of MZIs, we perform arbitrary local projective measurements on the entangled qudits. **B**. Fidelities for reconstructed density matrices of bipartite entangled states for different local dimensions. **C** State tomography in dimension 12.

References

[1] A. Mair, A. Vaziri, G. Weihs, A. Zeilinger, Nature 412, 313316 (2001).
[2] M. Kues *et al.*, Nature 546, 622–626 (2017).
[3] J. Wang *et al.*, Science 360, 285–291 (2018).
[4] A. Salavrakos *et al.*, Phys. Rev. Lett. 119, 040402 (2017).