Integrated generation of high-dimensional entangled photon states and their coherent control

C. Reimer,[1] M. Kues,[1,2] P. Roztocki,[1] L. Romero Cortés,[1] S. Sciara,[1,3] B. Wetzel,[1,4] Y. Zhang,[1] A. Cino,[3] S. T. Chu,[5] B. E. Little,[6] D. J. Moss,[7] L. Caspani,[8] J. Azaña,[1] and R. Morandotti[1,9,10]

[1]INRS-EMT, 1650 Boulevard Lionel-Boulet, Varennes, Québec, J3X 1S2, Canada.
[2]School of Engineering, University of Glasgow, Rankine Building, Oakfield Avenue, Glasgow G12 8LT, UK.
[3]University of Palermo, Department of Energy, Information Engineering and Mathematical Models, Palermo, Italy.
[4]School of Mathematical and Physical Sciences, University of Sussex, Falmer, Brighton BN1 9RH, UK.
[5]Department of Physics and Material Science, City University of Hong Kong, Tat Chee Avenue, Hong Kong, China.
[6]State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Precision Mechanics, CAS, Xi'an, China.
[7]Centre for Micro Photonics, Swinburne University of Technology, Hawthorn, VIC, 3122 Australia.
[8]Institute of Photonics, Department of Physics, University of Strathclyde, Glasgow G4 0NW, UK.
[9]Institute of Fundamental and Frontier Sciences, University of Electronic Science and Technology of China, Chengdu 610054, China.
[10]National Research University of Information Technologies, Mechanics and Optics, St. Petersburg, Russia.
Corresponding authors: michael.kues@emt.inrs.ca; morandotti@emt.inrs.ca

Abstract: Exploiting a frequency-domain approach, we demonstrate the generation of high-dimensional entangled quantum states with a Hilbert-space dimensionality larger than 100 from an on-chip nonlinear microcavity, and introduce a coherent control platform using standard telecommunications components.

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The realization of high-dimensional states (D-level quantum systems, i.e. qu$D$its, with $D > 2$) and their control are essential towards solving questions in fundamental physics, and are at the heart of quantum information science [1]. Integrated photonics has recently become a leading platform for the compact, cost-efficient, and stable generation and processing of non-classical optical states [2], including the generation of entangled two-photon states making use of the polarization, spatial, or temporal degrees of freedom. However, with these current methods, ways of accessing and manipulating high-dimensional states without drastically increasing quantum circuit complexity have remained elusive (i.e. path-entanglement schemes require D coherently-excited identical sources and a complex concatenation of beam splitters [3], while time-bin entanglement requires complicated stabilized multi-arm interferometers [4]). Thus, to date, integrated entangled quantum sources have been limited to qubits ($D = 2$).

Here, we demonstrate the on-chip generation of entangled qu$D$it states, where the photons are created in a coherent superposition of multiple frequency modes using spontaneous four-wave mixing within an integrated microcavity [5,6], forming a frequency-bin entangled state. We confirm the realization of a quantum system with at least one hundred dimensions, formed by two entangled qu$D$its with $D = 10$ [7]. Furthermore, using off-the-shelf telecommunications components, we introduce a coherent manipulation platform to control frequency-bin entangled states, capable of performing deterministic high-dimensional gate operations [7].

The experimental setup is shown in Fig. 1. A mode-locked laser is spectrally filtered and used to excite an integrated microring resonator. Photon pairs are generated, covering multiple resonances due to the broad phase-matching condition. For the coherent manipulation, we exploit two programmable spectral phase filters in combination with electro-optical phase modulation. The first programmable filter is used to impose an arbitrary phase and amplitude mask on the frequency components of the quantum state. The phase modulation is then used to deterministically shift and mix different frequency components. The second programmable filter is finally used to select different frequency components after the mixing, and route them to single photon detectors for coincidence detection.

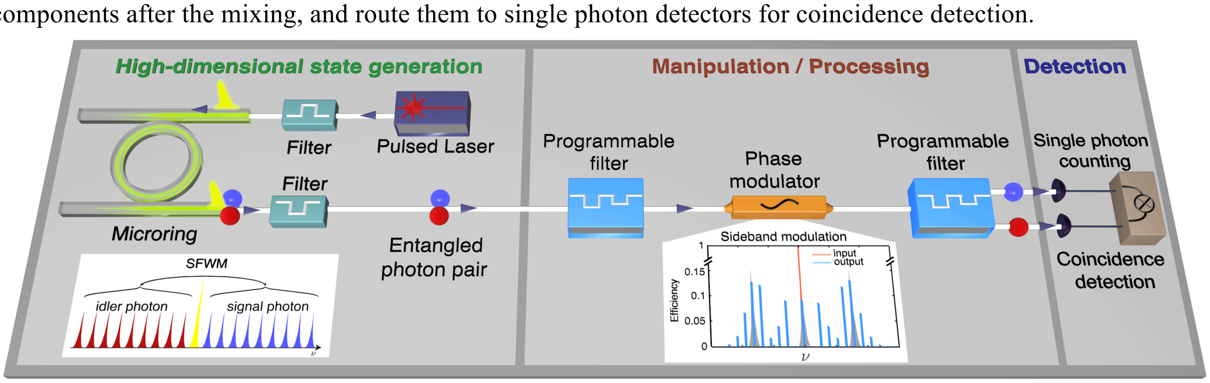

Fig. 1: Experimental setup for the generation and coherent control of high-dimensional frequency-bin entangled quantum states [7].

This coherent control scheme can be used to implement arbitrary phase gates, as well as to perform deterministic high-dimensional projection measurements. We validate this platform by measuring violations of a high-dimensional Bell inequality and performing quantum state tomography, see Fig. 2 for the particular example of $D = 4$. In particular, we characterize the quantum interference for $D = 2$, 3, and 4, where we measure raw visibilities of 83.7%, 86.6%, and 86.4% (without background subtraction), all violating their respective high-dimensional Bell inequalities [8]. We then performed quantum state tomography to experimentally extract the state density matrices also for $D = 2$, 3, and 4, confirming that the experimental quantum states are very close to the ideal maximally entangled states with measured fidelities of 88.5%, 80.9%, and 76.6% for $D = 2$, 3, and 4, respectively.

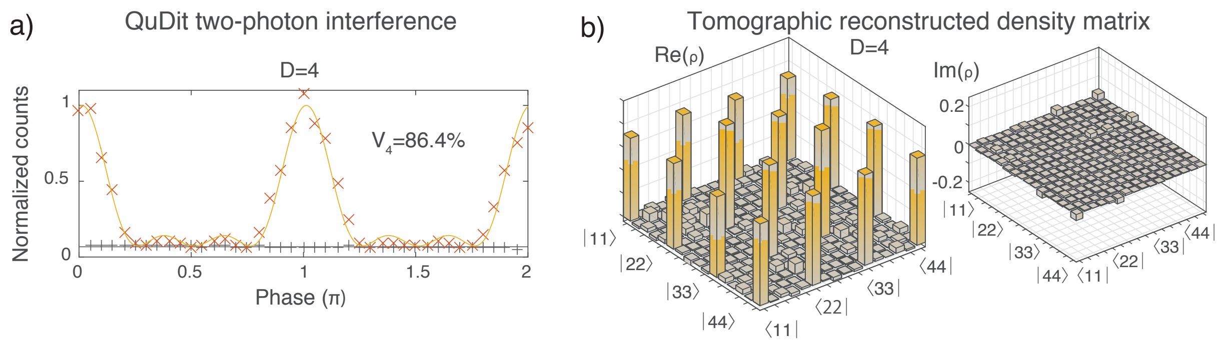

Fig. 2: For a high-dimensional frequency-bin entangled state with D=4 we measured a) two-photon quantum interference with a visibility of V_4=86.4% violating the high-dimensional Bell inequality, and we reconstructed b) its density matrix via a tomography measurement with a measured fidelity of 76.6% [7].

Finally, we perform measurements to determine the dimensionality and purity of the high-dimensional entangled state. First, we measure the frequency distribution of the quantum state and extract its joint spectral intensity. This is then used to determine the lower bound for the state dimensionality by means of a Schmidt mode decomposition [9]. We confirm that for ten selected spectral mode pairs, the quantum state has a minimum Schmidt number of 9.4. We then measure the second-order coherence function using a Hanbury Brown and Twiss setup, and confirm that the photons are generated in a superposition of highly pure frequency modes. The second-order coherence measurement is then used to measure the effective dimensionality of the state [10], which was determined to be 10.45 ± 0.53 for ten selected frequency mode pairs. Since the minimum and effective dimensionality agree well with each other, we conclude that the quantum state has a Schmidt number of 10 and Hilbert space dimensionality of 100, which is formed by two entangled quDits with $D = 10$.

Our results represent the first realization of high-dimensional entangled qu*D*it states on a photonic chip. Furthermore, the quantum states are generated and manipulated within a single spatial mode and can be transmitted over long propagation distances, underlining their usability for high-dimensional quantum key distribution applications. Our results indicate that microcavity-based high-dimensional frequency-bin entangled states and their spectral-domain manipulation can open up new venues for reaching the processing capabilities required for meaningful quantum information science in a powerful and practical platform.

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