Transverse-Mode-Entangled Photon-Pair Generation in Optical Fiber

D.-B. Kim[1,2], X.-Y. Hu[1,2], S. Li[1,2], J. Carpenter[3], A. B. U'Ren[4], K. Garay-Palmett[5], V. O. Lorenz[1,2]

[1] *Department of Physics, University of Illinois Urbana-Champaign, Urbana, Illinois 61801, USA.*
[2] *Illinois Quantum Information Science & Technology Center (IQUIST), University of Illinois Urbana-Champaign, Urbana, Illinois 61801, USA.*
[3] *School of Information Technology and Electrical Engineering, The University of Queensland, Brisbane, QLD 4072, Australia.*
[4] *Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Apartado Postal 70-543, 04510 DF, México.*
[5] *Departamento de Óptica, Centro de Investigación Científica y de Educación Superior de Ensenada, Ensenada, México.*
dbkim3@illinois.edu,kgaray@cicese.edu.mx,vlorenz@illinois.edu

Abstract: We present our experimental results on generating photon pairs entangled in a transverse-mode Bell state in few-mode optical fiber by controlling the transverse mode of the pump to selectively excite spontaneous four-wave mixing processes.

Photon-pair sources exploiting the high-dimensional nature of transverse spatial modes have been studied in free space [1], waveguides [2], and optical fibers [3], towards expanding quantum information processing capabilities beyond the typical qubit-based protocols. Optical fiber has the advantage of direct generation of entangled photon pairs via spontaneous four-wave mixing (SFWM) in modes that can be seamlessly interfaced with existing optical fiber technology, but there has been little progress in generating and verifying transverse-mode entanglement in optical fiber. Here, we incorporate a mode multiplexing technique developed to increase classical communication capacity [4] to demonstrate photon-pair generation in a transverse-mode Bell state in few-mode optical fiber. This technique has the potential to be extended to highly multimode states without multi-input multi-output processing through the use of a single dynamic spatial light modulator (SLM) [4]. The source [3, 5–7] also can enable hybrid entanglement [5], corresponding to inseparability between the transverse and frequency degrees of freedom, and allows flexibility in engineering the quantum state by adjusting pump bandwidth, fiber length, and fiber birefringence.

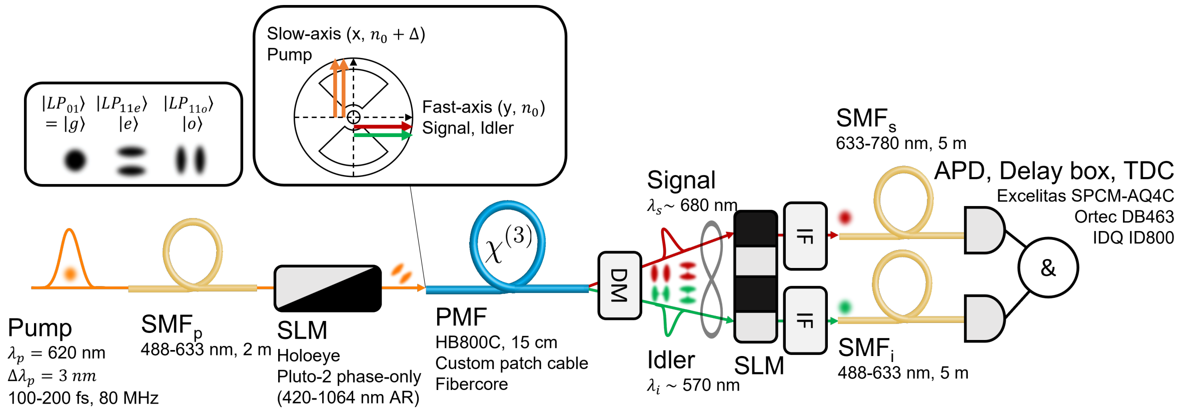

Fig. 1. Simplified experimental setup. SMF: single-mode optical fiber, SLM: spatial light modulator, PMF: polarization-maintaining optical fiber, DM: dichroic mirror, IF: interference spectral filter, APD: avalanche photodiode, TDC: time-to-digital converter. Polarization optics are omitted for simplicity.

To show entanglement of the excited modes in a two-dimensional transverse mode Bell state, we use an SLM to control the pump transverse-spatial mode and thus the modes in which the photon pairs are emitted. For photon-pair generation and control (see simplified setup shown Fig. 1), a reflective SLM is placed in the Fourier plane before a few-mode polarization-maintaining optical fiber to control the transverse modes of two pump photons, and thus to selectively excite two out of fifteen SFWM processes that create signal and idler photon pairs in a particular frequency-transverse-mode entangled state. The available modes were determined via simulations building off our previous work [3]. By setting the pump modes to be $|T_{p1}\rangle = |T_{p2}\rangle = (|e\rangle + |o\rangle)/\sqrt{2}$ and applying spectral filtering to block intermodal SFWM processes corresponding to a pump mode $|eo\rangle$, we select two frequency-indistinguishable SFWM processes comprising a maximally entangled transverse-mode Bell state between the photons, $|T_sT_i\rangle \otimes |\omega_s\omega_i\rangle = (|ee\rangle + |oo\rangle)/\sqrt{2} \otimes |\omega_s\omega_i\rangle$, where $T_{p1,p2}$, T_s, and T_i are the transverse modes of the pump, signal and idler, respectively; ω_s (ω_i) is the frequency of the signal (idler) photon; and we have used the following shorthand notation for linearly polarized (LP) modes: $|e\rangle = |LP_{11e}\rangle, |o\rangle = |LP_{11o}\rangle$, where e (o) corresponds to even (odd) parity with respect to the polarization-maintaining fiber's slow axis.

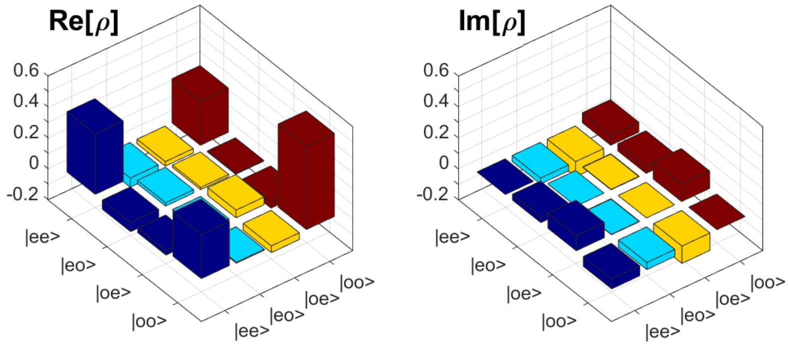

Fig. 2. Real (left) and imaginary (right) parts of the experimentally reconstructed density matrix ρ of a transverse-mode entangled state via quantum state tomography, with axes labeled with the signal and idler transverse mode states, $|T_sT_i\rangle$.

To verify the entanglement of our target state, quantum state tomography was conducted with measurement basis states of $\{|e\rangle, |o\rangle, (|e\rangle + |o\rangle)/\sqrt{2}, (|e\rangle - |o\rangle)/\sqrt{2}\}^{\otimes}2$, which corresponds to a total of 16 coincidence projective measurements. We use another SLM to project the transverse modes of the signal and idler photons into the mode of SMFs only when they coincide with the measurement mode. The SMFs are connected to APDs for coincidence measurements. Using the experimentally obtained density matrix, shown in Fig. 2, a Bell state purity of $tr[\rho^2] = 0.68$ and a tangle of 0.35 were calculated. This being our very first result showing transverse mode entanglement in optical fiber, there are clear roads to improvement: removal of chirp from the pump, more precise control of pump transverse modes, more accurate spectral filtering, and longer acquisition time should lead to values that exhibit better resemblance with the target transverse mode Bell state in the near future.

In summary, we present preliminary results on generation and verification of transverse-mode-entangled photon pairs in optical fiber, where creation was controlled via pump transverse mode and states were measured via transverse mode quantum state tomography.

This work is supported by NSF award Nos. 1806572, 1640968 and 1839177.

References

1. M. Hiekkamäki and R. Fickler, "High-dimensional two-photon interference effects in spatial modes," Phys. Rev. Lett. **126**, 123601 (2021).
2. L.-T. Feng, M. Zhang, X. Xiong, Y. Chen, H. Wu, M. Li, G.-P. Guo, G.-C. Guo, D.-X. Dai, and X.-F. Ren, "On-chip transverse-mode entangled photon pair source," npj Quantum Inf. **5**, 1–7 (2019).
3. K. Garay-Palmett, D. Cruz-Delgado, F. Dominguez-Serna, E. Ortiz-Ricardo, J. Monroy-Ruz, H. Cruz-Ramirez, R. Ramirez-Alarcon, and A. U'Ren, "Photon-pair generation by intermodal spontaneous four-wave mixing in birefringent, weakly guiding optical fibers," Phys. Rev. A **93**, 033810 (2016).
4. J. Carpenter, B. C. Thomsen, and T. D. Wilkinson, "Degenerate mode-group division multiplexing," J. Light. Technol. **30**, 3946–3952 (2012).
5. D. Cruz-Delgado, R. Ramirez-Alarcon, E. Ortiz-Ricardo, J. Monroy-Ruz, F. Dominguez-Serna, H. Cruz-Ramirez, K. Garay-Palmett, and A. U'Ren, "Fiber-based photon-pair source capable of hybrid entanglement in frequency and transverse mode, controllably scalable to higher dimensions," Sci. reports **6**, 1–9 (2016).
6. D.-B. Kim, B. Fang, O. Wang, X. Hu, Y. Zhang, X. Chen, K. Garay-Palmett, A. U'Ren, and V. Lorenz, "Towards frequency-transverse-mode hybrid-entangled photon-pair generation in optical fiber," in *CLEO: QELS_Fundamental Science,* (Optical Society of America, 2020), pp. FTu3C–6.
7. D. Kim, X. Hu, Y. Zhang, X. Chen, K. Garay-Palmett, A. U'Ren, and V. Lorenz, "Stimulated-emission-based characterization of optical fiber photon-pair source in frequency and transverse mode," in *Frontiers in Optics,* (Optical Society of America, 2020), pp. JM6B–22.