

Towards Frequency–Transverse-Mode Hybrid-Entangled Photon-Pair Generation in Optical Fiber

D.-B. Kim¹, B. Fang², O. Wang³, X. Hu¹, Y. Zhang¹, X. Chen¹, K. Garay-Palmett⁴,
A. B. U'Ren⁵, V. O. Lorenz¹

¹*Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*

²*The Center for Dynamics and Control of Materials: An NSF MRSEC, The University of Texas at Austin, Texas 78712, USA*

³*Department of Applied Physics and Applied Mathematics, Columbia University, New York, New York 10027, USA*

⁴*Departamento de Óptica, Centro de Investigación Científica y de Educación Superior de Ensenada, Ensenada, México*

⁵*Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Apartado Postal 70-543, 04510 DF, México*

dbkim3@illinois.edu

Abstract: We present stimulated-emission-based characterization of transverse photon-pair modes in birefringent fiber, towards an optical fiber source of photon-pairs hybrid-entangled in frequency and transverse spatial mode. © 2020 The Author(s)

1. Introduction

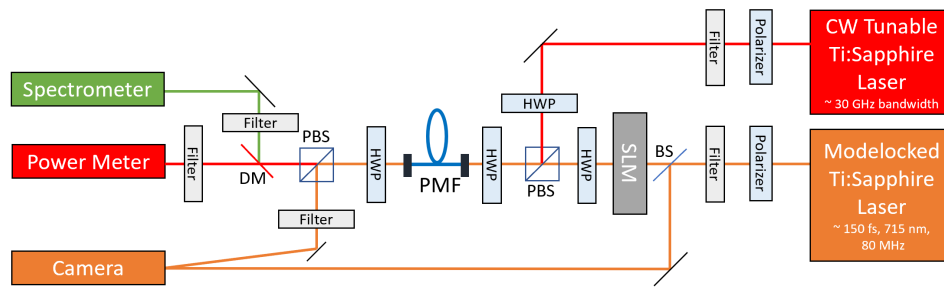
Spontaneous four-wave mixing (SFWM) is a commonly used interaction to generate heralded single photons for use in quantum protocols. In SFWM, photon-pairs are created via the annihilation of two pump photons and creation of signal and idler photons in a medium with $\chi^{(3)}$ nonlinear susceptibility, such as optical fiber. The transverse confinement present in optical fiber leads to transverse pump, signal and idler modes that are discrete, like polarization, but unlike polarization, the number of modes is unlimited. Thus, the transverse degree of freedom in optical fiber is an important resource for quantum information protocols. Recently it was shown [2, 3] that by employing optical fibers in which multiple transverse modes are supported, photon-pairs can be generated in controllable hybrid-entangled states in the spatial and spectral degrees of freedom.

Encoding in transverse mode is typically difficult as it requires splitting photons based on transverse mode. In an optical fiber source, however, dispersion can result in distinct correlations between transverse mode and frequency. This allows for spectral filtering to separate transverse modes. This strategy was explored recently in [2, 3], where it was shown that the optical fiber can support distinct combinations of the transverse modes of the two pump photons and signal and idler photons. Each combination corresponds to distinct signal and idler spectral peaks, appearing symmetrically around the pump. In the current work we present preliminary results towards the experimental characterization and control of high-order spectral-spatial entanglement and creation of a reliable theory of SFWM in the presence of multiple transverse modes in birefringent fibers.

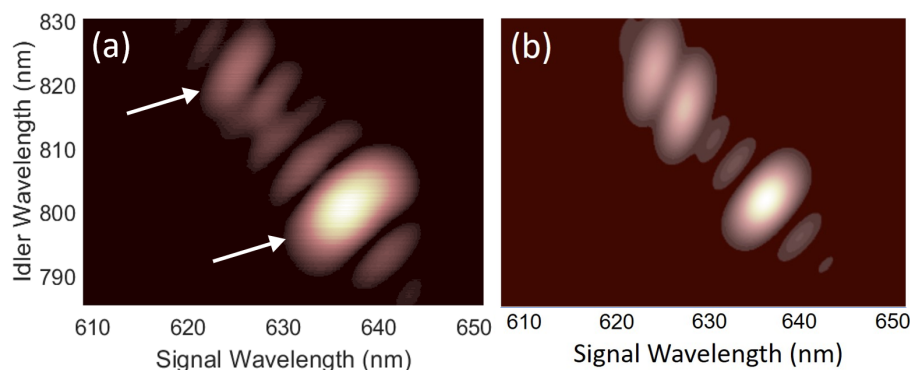
2. Methods and Results

To generate photon-pairs we employ the SFWM interaction in polarization-maintaining fiber (PMF), in which two pump photons at angular frequency ω_p travelling along the fast axis of the fiber are annihilated and two side-band photons are created along the slow axis at angular frequencies ω_s and ω_i , denoted as signal and idler, respectively. We measure the joint spectral density of a few-mode PMF using stimulated emission tomography with the experimental setup shown in Fig. 1. Data is taken with 715 nm pump beam and idler seeding beam for a 1.4 cm long HB800C fiber (Fibercore Ltd). The measured joint spectral density is shown in Fig. 2 (a) and exhibits two clearly defined transverse modes; only two modes appear because the cut-off wavelength of the fiber is 680-780 nm and thus the fiber is few-mode only for the signal wavelength. The strong peak corresponds to the linearly polarized (LP) spatial modes (pump, signal, idler) = (LP₀₁, LP₀₁, LP₀₁) while the weaker peak corresponds to (LP₀₁, LP₁₁, LP₀₁).

As a next step towards control over the excited modes, we use a fiber that is few-mode for the pump as well as the signal and idler and a spatial light modulator to control the pump transverse-spectral mode and thus the modes in which the photon-pairs are emitted. We employ an off-axis holography setup [4] (see Fig. 1) to extract the phase and amplitude information of the pump beam. To control the mode, a reflective phase-only spatial light



modulator (SLM) is placed in the Fourier plane before the fiber to modify the phase of the coupled Gaussian beam, thus producing desired spatial modes at the input of the fiber (see Fig. 1, where the SLM is shown as transmissive for simplicity). We use transfer matrix methods [5] and algorithms shared by J. Carpenter to precisely control the spatial modes. We first measure the transfer matrix of the fiber in the LP mode basis and then invert the matrix to determine the phase mask for the SLM to obtain the desired output mode. We are currently in the process of optimizing the algorithm. The stimulated emission technique will allow us to precisely explore the multi-dimensional space with high efficiency and resolution. We will then increase the number of available modes by using highly multimode fiber, to demonstrate larger alphabets (more supported modes) and potentially transverse-mode Bell states.



3. Conclusion and Outlook

We have presented measurements of the joint spectral intensity of multiple transverse modes in optical fiber and an experimental setup towards generating signal-idler hybrid entangled states in spatial mode and frequency. As a next step we will control the pump modes in few-mode and multimode fiber to demonstrate hybrid entanglement. This work is supported by NSF award Nos. 1806572, 1640968 and 1839177.

References

1. L. A. Rozema, C. Wang, D. H. Mahler, A. Hayat, A. M. Steinberg, J. E. Sipe, and M. Liscidini, *Optica* **2**, 430 (2015).
2. D. Cruz-Delgado, J. Monroy-Ruz, A. M. Barragan, E. Ortiz-Ricardo, H. Cruz-Ramirez, R. Ramirez-Alarcon, K. Garay-Palmett, and A. B. U'Ren, *Opt. Lett.* **39**, 3583 (2014).
3. D. Cruz-Delgado, R. Ramirez-Alarcon, E. Ortiz-Ricardo, J. Monroy-Ruz, F. Dominguez-Serna, H. Cruz-Ramirez, K. Garay-Palmett, A. B. U'Ren, *Sci. Rep.* **6**, 27377 (2016).
4. E. CuChe, P. Marquet, and C. Depeursinge, *Applied Optics* **39**, 23 (2000).
5. J. Carpenter, B. C. Thomsen, T. Wilkinson, *J. Lightwave Technol.* **34**, 24 (2012).