# Toward Generation of Spatially-Entangled Photon Pairs in a Few-Mode Fiber

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**Abstract:** We describe a novel scheme for spatial-mode-entangled photon-pair generation in a few-mode fiber. We experimentally verify the underlying inter-modal parametric processes with two-mode classical signal input and demonstrate high mode purity of the generated idler.
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Entangled states are essential for quantum communication, computing, and information processing. Entanglement in multiple degrees of freedom (hyperentanglement), e.g., in polarization, frequency, time-bin, and spatial modes has a potential for carrying larger amounts of quantum information. While polarization, frequency, and time-bin entanglement generation has already been implemented in integrated form compatible with low-loss transport over optical fiber, the spatial entanglement still relies on bulk-crystal-based setups. Spatially- or orbital-angular-momentum- (OAM) entangled photons have been generated in crystal platforms and transported over hollow-core photonic crystal fiber [1], a few-mode fiber (FMF) [2], and vortex fiber [3]. As a possible alternative to crystal platform, FMF is gaining traction for nonlinear devices based on inter-modal four-wave mixing (IM-FWM), owing to FMF's wide options for mode- and dispersion-engineering, and excellent mode match to the FMFs used in low-loss transmission links. Correlated photon pairs have recently been generated in FMFs by IM-FWM [4, 5], but no attempts of spatial-mode entanglement have been made yet. In this paper, we discuss a novel scheme for generation of spatial-mode-entangled photon pairs directly in the FMF and report first steps toward its experimental realization, confirming the spatial-mode properties of the underlying IM-FWM processes with classical seed signals.

Our spatial-mode entanglement scheme employs a combination of two IM-FWM processes of Fig. 1a. We use an elliptical-core FMF [6] that supports three non-degenerate modes: $LP_{01}$, $LP_{11a}$, and $LP_{11b}$, to be referred to as three-mode fiber (TMF) below. In IM-FWM process 1, with the help of pumps 1 and 2 a signal photon is created in mode $LP_{01}$ at frequency $\nu_s$, while idler photon is created in mode $LP_{11a}$ at frequency $\nu_i$. In process 2, their roles interchange: in the presence of pumps 3 and 4, signal photon at frequency $\nu_s$ is created in mode $LP_{11a}$, whereas the idler photon at frequency $\nu_i$ is created in mode $LP_{01}$. With all four pumps present, processes 1 and 2 take place simultaneously. Their probabilities can be equalized by adjusting relative powers of the two pump pairs, which results in generation of the maximally-entangled state $|LP_{01}\rangle_s|LP_{11a}\rangle_i + e^{i\varphi}|LP_{11a}\rangle_s|LP_{01}\rangle_i$, where phase $\varphi$ can be changed by varying the pump phase difference $\Delta\varphi = (\varphi_{p1} + \varphi_{p2}) - (\varphi_{p3} + \varphi_{p4})$. For each of the two processes in Fig. 1a, the phase-matching condition [7] requires equal group velocities at the average frequencies of the two waves present in each spatial mode. These average frequencies, converted to wavelengths, are shown by dashed lines in Fig. 1a. Figure 1b shows measured relative inverse group velocities (RIGV) $1/v_g$ of $LP_{01}$, $LP_{11a}$, and $LP_{11b}$ modes of our TMF. The $LP_{11a}$ curve is approximately parallel to the $LP_{01}$ curve and horizontally shifted from it by ~25 nm ($\Delta\nu_1$ = 3 THz), i.e., the phase matching is satisfied when the dashed lines in Fig. 1a are separated by 25 nm. Energy conservation and momentum conservation (phase matching) impose 4 constraints on the frequencies of the 6 involved waves: $\nu_{p1(p3)} = \nu_{i(s)} + \Delta\nu_1$ and $\nu_{p2(p4)} = \nu_{s(i)} - \Delta\nu_1$, hence any two frequencies that are not separated by $\Delta\nu_1$ can be arbitrarily chosen. In our experiment, we choose signal to be at 1562.3 nm and idler to be at 1564.6 nm, which results in pumps 1, 2, 3, and 4 placed at 1540.1, 1587.5, 1538.3, and 1589.3, respectively.

Our experimental setup is shown in Fig. 1c. The test signal and pumps are carved into 10-ns-long flat-top pulses with a 10-MHz repetition rate by intensity modulators and are amplified by telecom-grade C- and L-band erbium-doped fiber amplifiers (EDFAs). In process 1, signal and pump 1 are combined with an arrayed waveguide grating (AWG) multiplexer, collimated into a free-space $LP_{01}$ mode, and combined by a beam splitter with pump 2 that has been converted to $LP_{11a}$ mode by a phase plate PP1. The three waves are then coupled into a 1-km-long TMF by an objective. The TMF output is collimated by a second objective. Part of the output is observed on an infrared camera, and the remainder is coupled into a single-mode fiber (SMF) connected to the optical spectrum analyzer (OSA), which in this case measures the $LP_{01}$ "output port" of the TMF. By inserting phase plate PP3 prior to SMF coupling, we can also measure $LP_{11a}$ "output port" of the TMF. In process 2, signal and pump 4 are combined by a WDM coupler, converted to $LP_{11a}$ mode via a phase plate PP2, combined with pump 3 in $LP_{01}$ mode by a beam splitter, and coupled into the TMF similarly to process 1. To maximize IM-FWM, we co-polarize all three input waves in each process via polarization controllers (PCs) and polarization beam splitter (PBS).

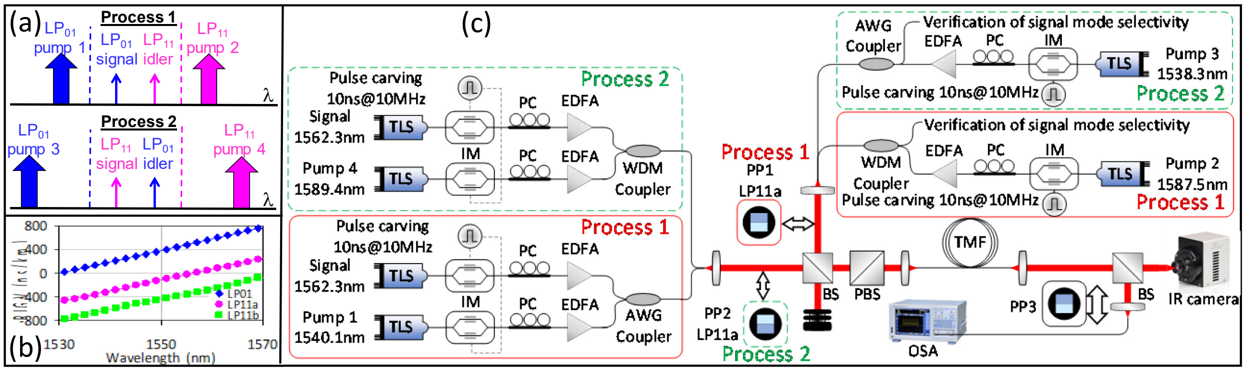


Fig.1. (a) Two parametric processes, whose combination enables generation of spatial-mode-entangled signal-idler photon pairs in the TMF. (b) Measured relative inverse group velocity (RIGV) data for the modes of our TMF. (c) Experimental setup.

We characterize idler-mode impurity by comparing idlers in $LP_{01}$ and $LP_{11a}$ output ports of the TMF. The depth of suppression of undesirable parametric interactions, i.e., mode selectivity of the parametric amplification processes 1 and 2, is quantified by comparing the idler generated by the desired process to that generated by an undesirable process, observed when the input signal is injected into a wrong mode: $LP_{11a}$ for process 1, $LP_{01}$ for process 2. In the former case, this injection is done by combining signal and pump 2 via WDM coupler prior to their conversion to $LP_{11a}$ mode. In the latter case, it is done by combining signal and pump 3 by AWG before the beam splitter.

Figure 2 shows the spectra at the $LP_{01}$ (blue traces) and $LP_{11a}$ (magenta traces) output ports of the TMF for processes (a) 1 and (b) 2. One can easily see a significant change in the idler power between the two traces, indicating high spatial-mode purity of the idler (23.1 and 17.5 dB for processes 1 and 2, respectively). Average powers inside the TMF are 0 dBm for the signal in all cases and 13, 10.5, 13, and 10.5 dBm for pumps 1, 2, 3, and 4, respectively. Easily-measurable signal-to-idler conversion efficiency is CE $= g - 1 = \langle n \rangle$, where $g$ is the phase-insensitive parametric gain, and $\langle n \rangle$ is the average number of generated parametric photons per mode, also representing the probability of a single pair generation for our case of CE << 1. In Fig. 2, CEs are equal to –45.2 and –46.2 dB for processes 1 and 2, respectively. The CEs of the undesirable processes, measured by injecting the signal into the wrong mode, are suppressed by 28 and 38 dB, compared to processes 1 and 2, respectively.

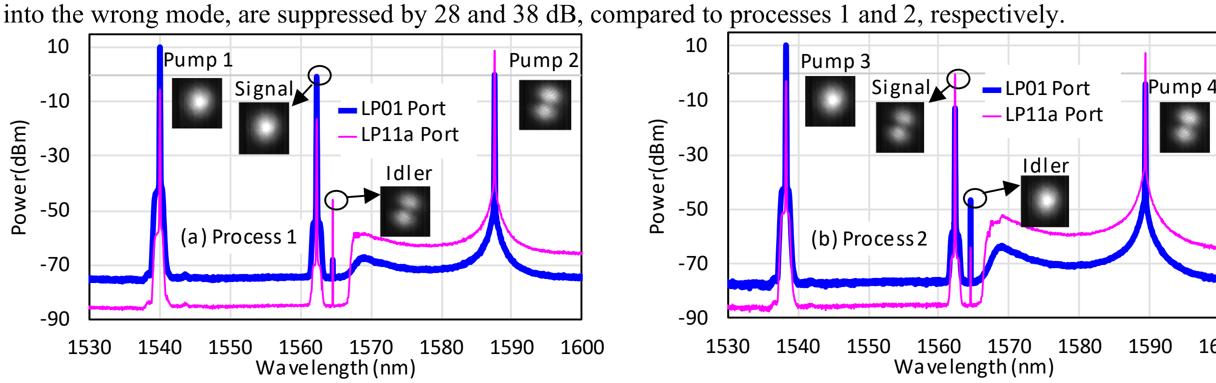


Fig. 2. Optical spectra measured at the $LP_{01}$ (blue traces) and $LP_{11a}$ (magenta traces) output ports of the TMF for processes (a) 1 (signal in $LP_{01}$ mode) and (b) 2 (signal in $LP_{11a}$ mode).

To summarize, we have experimentally demonstrated low-gain parametric amplifier in TMF, which couples $LP_{01}$ signal to $LP_{11a}$ idler and $LP_{11a}$ signal to $LP_{01}$ idler with high mode selectivity. In the spontaneous regime, the combination of these two processes would generate spatial-mode-entangled signal-idler photon pairs. The next step is to optimize the pump multiplexing scheme, both to minimize the losses and to reduce the fluctuations of pump phase difference $\Delta\varphi$. Spontaneous regime would, in addition, require strong suppression of the amplified spontaneous emission of the pump beams at signal and idler frequencies, as well as narrow bandpass filtering of the output to minimize contribution of Raman noise [8]. A straightforward modification of our scheme could engage modes $LP_{11a}$ and $LP_{11b}$ instead of $LP_{01}$ and $LP_{11a}$, which may lead to generation of OAM-entangled pairs.

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**References**

[1] W. Löffler *et al*, PRL **106**, 240505 (2011).
[2] Y. Kang *et al*, PRL **109**, 020502 (2012).
[3] D. Cozzolino *etal*, Adv Phot **1**, 046005 (2019).
[4] K. Rottwitt *et al*, Fibers **6**, 32 (2018).
[5] C. Guo *et al*, Opt Lett **44**, 235 (2019).
[6] F. Parmigiani *et al*, OE **25**, 33602 (2017).
[7] R.-J. Essiambre *et al*, PTL **25**, 539 (2013).
[8] Y. B. Kwon *et al*, *CLEO 2017*, FF2E.1.