Mode-selective frequency conversion in a three-mode fiber

Afshin Shamsshooli,[1] Cheng Guo,[1] Francesca Parmigiani,[2] Xiaoying Li,[3] and Michael Vasilyev[1*]

[1]*Department of Electrical Engineering, University of Texas at Arlington, Arlington, TX 76019, USA*
[2]*Microsoft Research, Cambridge, CB1 2FB, UK*
[3]*College of Precision Instruments and Opto-electronics Engineering, Key Laboratory of Opto-electronic Information Technical Science of Ministry of Education, Tianjin University, Tianjin, 300072, China*
[*]*E-mail: vasilyev@uta.edu*

Abstract: We present a scheme for spatial-mode-selective frequency conversion in a few-mode fiber and experimentally demonstrate upconversion of either of two signal modes from C-band to fundamental mode in S-band with crosstalk below –15.5 dB.

OCIS codes: (190.4410) Nonlinear optics, parametric processes; (190.4420) Nonlinear optics, transverse effects in; (060.4370) Nonlinear optics, fibers; (190.4380) Nonlinear optics, four-wave mixing.

Multiplexing and demultiplexing of spatial modes (e.g., those of multimode fibers and waveguides) is important for both classical and quantum communications, in which mode-division multiplexing is considered a promising way of increasing the channel capacity [1]. One of desired features of the mode demultiplexer is the dynamic reconfigurability of its mode basis. In classical transmission, such reconfiguration could reverse the mode mixing and relax the requirements on electronic processing of the received signals. In quantum key distribution, switching between mutually unbiased mode bases could increase the dimension of the Hilbert space used for encoding. In either case, low loss and low crosstalk of the demultiplexer are important. Recently, we have demonstrated such a demultiplexer in a two-mode $LiNbO_3$ waveguide [2, 3], where, by adjusting the spatial profile of a 1560-nm pump wave, we could selectively up-convert either mode TM_{00}, or mode TM_{01}, or any superposition of modes TM_{00} and TM_{01} of a 1540-nm signal to TM_{01} mode 775 nm, for both classical [2] and single-photon-level [3] signals. In this paper, we show that similar functionality (mode demultiplexing by mode-selective frequency conversion) can also be achieved in a $\chi^{(3)}$ nonlinear medium, such as a few-mode fiber (FMF), by a novel scheme based on inter-modal four-wave mixing (IM-FWM). Compared to $LiNbO_3$ platform, nonlinear FMFs can offer wider design options for mode- and dispersion-engineering and better mode match to the FMFs used in transmission links. IM-FWM in FMF has recently attracted attention for tunable wavelength conversion [4–6] and correlated photon-pair generation [7].

Our scheme of $\chi^{(3)}$-based mode-selective frequency conversion employs a combination of two IM-FWM processes illustrated in Fig. 1a. We use an elliptical-core FMF [5] 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, pumps 1 and 2 upconvert LP_{11a} signal to LP_{01} output mode. In process 2, pumps 3 and 4 upconvert LP_{01} signal to the same LP_{01} output mode. With all pumps 1, 2, 3, and 4 present, a selected superposition of signal LP_{01} and LP_{11a} modes is upconverted, whereas the orthogonal mode superposition is left unperturbed. Selection of the mode superposition is done by choosing relative powers of the 2 pairs of pump waves (i.e., relative weights of processes 1 and 2) and pump phase difference $\Delta\varphi = (\varphi_{p1} - \varphi_{p2}) - (\varphi_{p3} - \varphi_{p4})$. For each process, the phase-matching condition [8] 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}, and LP_{11b} curves are approximately parallel to the LP_{01} curve and horizontally shifted from it by ~24 nm ($\Delta\nu_1$ = 3 THz) and ~41 nm ($\Delta\nu_2$ = 5.1 THz), respectively. Thus, the phase matching is satisfied when the dashed lines in Fig. 1a are separated by 24 nm and 41 nm for processes 1 and 2, respectively. Energy conservation and phase matching put the following 4 constraints on the frequencies of the 6 involved waves: $\nu_{p1} - \nu_{p2} = \nu_{p3} - \nu_{p4} = \nu_{WC} - \nu_s = \Delta\nu_1$ and $\nu_s = \nu_{p3} + \Delta\nu_2 - \Delta\nu_1$, where ν_s (or ν_{p3}) and ν_{p1} (or ν_{p2}) can be chosen arbitrarily, and subscript "WC" stands for wavelength-converted output. In our experiment, we convert C-band signal at 1540 nm to S-band (1516.4 nm), using wavelengths 1552, 1576.4, 1556.9, and 1581.9 nm for pumps 1, 2, 3, and 4, respectively.

Our experimental setup is shown in Fig. 1c. The signal and pumps are carved into 10-ns-long flat-top pulses with a 10-MHz repetition rate by 3 intensity modulators and are amplified by telecom-grade C- and L-band erbium-doped fiber amplifiers (EDFAs). In process 1, signal and pump 2 are combined with a WDM coupler, converted to LP_{11a} mode via a phase plate PP1, combined with pump 1 in LP_{01} mode by a beam splitter, and coupled into the 1-km-long TMF by an objective. TMF output is collimated by a second objective. Part of the output is observed on an infrared camera, and the remaining part 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, pumps 3 and 4 are WDM multiplexed, converted to LP_{11b} mode via a phase plate PP2, combined with signal 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. Mode selectivity of each process is investigated by injecting the input signal into a wrong (undesirable) mode (LP_{01} in process 1, LP_{11a} in process 2).

Figure 2 shows the spectra at the LP_{01} output port of the TMF for processes (a) 1 and (b) 2. The conversion efficiencies (CEs) for the desired signal modes are –40.3 dB in process 1 and –38.7 dB in process 2, primarily limited by relatively low pump powers coupled into the TMF. The CEs for the undesirable signal modes are 15.5 dB and 20 dB lower than the corresponding desired-mode CEs. These numbers represent low amount of crosstalk from the undesirable input signal mode, which indicates good mode selectivity of our scheme. Average powers inside the TMF are 0 dBm for the signal in all cases and 16, 13, 15.5, and 13.8 dBm for pumps 1, 2, 3, and 4, respectively.

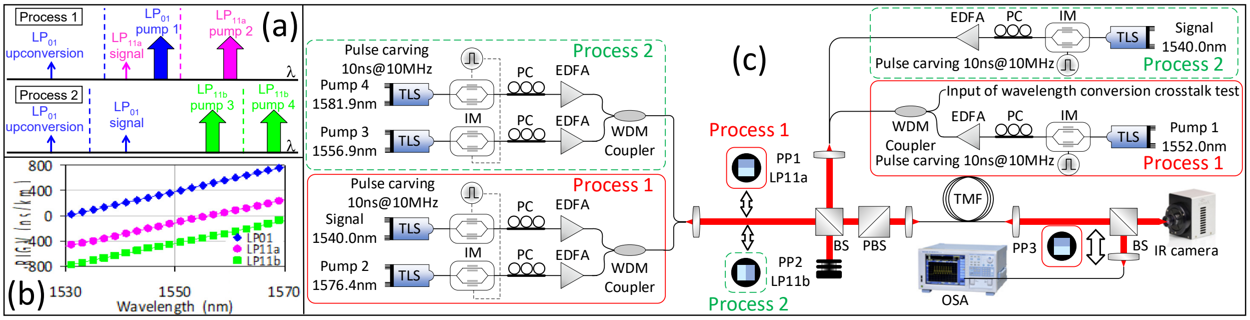

Fig.1. (a) Two parametric processes, whose combination enables mode-selective frequency upconversion in the TMF. (b) Measured relative inverse group velocity (RIGV) data for the modes of our TMF. (c) Experimental setup.

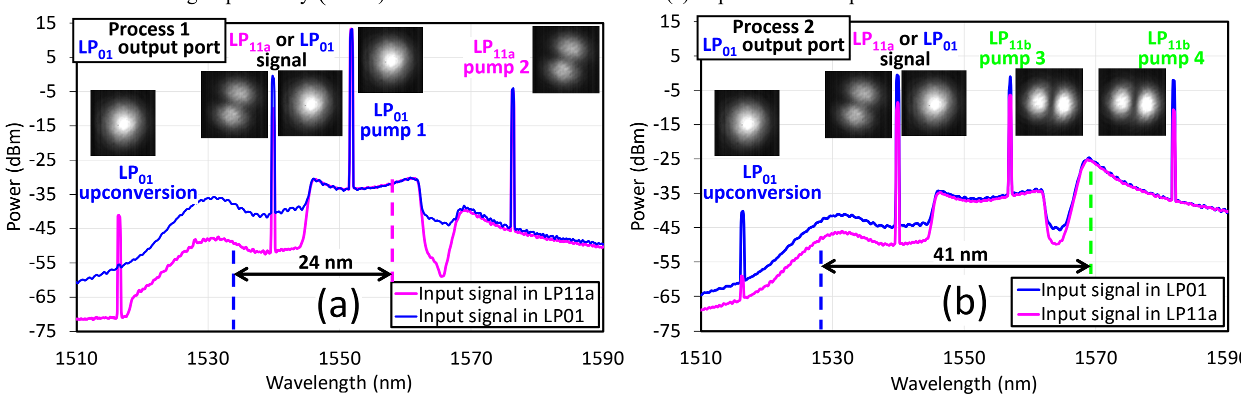

Fig. 2. Experimental results, measured at the LP_{01} “output port” of the TMF for processes (a) 1 and (b) 2. Each plot contains two spectra: one for signal input in the desired mode and the other – for signal input in the undesirable mode leading to crosstalk.

To summarize, we have experimentally demonstrated selective upconversion of either LP_{01} or LP_{11a} signal wave from C-band (1540 nm) to a single LP_{01} wave in S-band (1516.4 nm) with two pairs of pumps in different spatial mode configurations. The next step is to optimize the pump multiplexing scheme, both to minimize the losses and to reduce the fluctuations of pump phase difference $\Delta\varphi$. This would enable upconversion of any superposition of the signal LP_{01} and LP_{11a} modes, and would also increase the CE. For further CE increase, one could employ high-power EDFAs and, possibly, a customized highly-nonlinear FMF with a smaller core size. Extension of the mode-selective frequency conversion into single-photon regime would, in addition, require strong suppression of the amplified spontaneous emission of the pump beams at signal and upconverted frequencies, as well as very narrow bandpass filtering of the output to minimize contribution of Raman noise [3].

This work has been supported in part by the NSF grants ECCS-1937860 and ECCS-1842680.

References

[1] D. J. Richardson, J. M. Fini, and L. E. Nelson, “Space-division multiplexing in optical fibres,” Nature Photon. **7**, 354 (2013).

[2] Y. B. Kwon, M. Giribabu, L. Li, S. C. Samudrala, C. Langrock, M. Fejer, and M. Vasilyev, “Experimental demonstration of spatial-mode-selective frequency up-conversion in a multimode $\chi^{(2)}$ waveguide,” *CLEO 2016*, San Jose, CA, paper STh3P.4.

[3] Y. B. Kwon, M. Giribabu, L. Li, C. Langrock, M. Fejer, and M. Vasilyev, “Single-photon-level spatial-mode-selective frequency up-conversion in a multimode $\chi^{(2)}$ waveguide,” *CLEO 2017*, San Jose, CA, paper FF2E.1.

[4] O. F. Anjum , M. Guasoni, P. Horak , Y. Jung , P. Petropoulos , D. J. Richardson, and F. Parmigiani, “Polarization-Insensitive Four-Wave-Mixing-Based Wavelength Conversion in Few-Mode Optical Fibers,” J. Lightwave Technol. **36**, 3678 (2018).

[5] F. Parmigiani, P. Horak, Y. Jung, L. Grüner-Nielsen, T. Geisler, P. Petropoulos, and D. Richardson, “All-optical mode and wavelength converter based on parametric processes in a three-mode fiber,” Opt. Express **25**, 33602 (2017).

[6] O. F. Anjum , M. Guasoni, P. Horak , Y. Jung, M. Suzuki, T. Hasegawa, K. Bottrill, D. J. Richardson, F. Parmigiani, and P. Petropoulos, “Selective wavelength conversion in a few-mode fiber,” Opt. Express **27**, 24072 (2019).

[7] K. Rottwitt *et al*, “Photon-pair sources based on intermodal four-wave mixing in few-mode fibers,” Fibers **6**, 32 (2018).

[8] R.-J. Essiambre *et al*, “Experimental investigation of inter-modal four-wave mixing in few-mode fibers,” IEEE PTL **25**, 539 (2013).