Reconfigurable mode-selective frequency conversion in a three-mode fiber

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***Abstract*—We present a scheme for spatial-mode-selective frequency conversion in a few-mode fiber and experimentally demonstrate upconversion of arbitrary superpositions of two signal modes from C-band to the fundamental mode in S-band with conversion efficiencies within 1 dB range of one another.**

***Keywords*—Nonlinear optics in fibers, inter-modal four-wave mixing, wavelength conversion, quantum communication.**

I. INTRODUCTION

Mode-division multiplexing promises increase in channel capacity of both classical and quantum communications [1], hereby bringing attention to multiplexers and demultiplexers of spatial modes. 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. Not long ago, 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 upconvert either mode TM_{00}, or mode TM_{01}, or any superposition of these two modes of a 1540-nm signal to TM_{01} mode at 775 nm, for both classical [2] and single-photon-level [3] signals. More recently, we have proposed a scheme of similar functionality (mode demultiplexing by mode-selective frequency conversion) in a $\chi^{(3)}$ nonlinear medium, such as a few-mode fiber (FMF), based on a combination of two inter-modal four-wave mixing (IM-FWM) processes [4]. 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 [5–7] and correlated photon-pair generation [8]. Our preliminary results [4] have shown good crosstalk performance (mode selectivity) for each of the two IM-FWM processes individually. In this paper, we implement both of these two processes simultaneously and demonstrate their combined ability to handle any mode superposition in the two-mode signal space.

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 [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, 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 4 pumps 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 [9] 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 are 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 1542.9 nm to S-band (1519.5 nm), using wavelengths 1554.4, 1578.7, 1560.4, and 1585.1 nm for pumps 1, 2, 3, and 4, respectively.

II. EXPERIMENT

Figure 1c shows our experimental setup. All pumps and the signal are carved into 10-ns-long flat-top pulses with 10-MHz repetition rate by 3 intensity modulators. The pumps are then amplified by telecom-grade C- and L-band erbium-doped fiber amplifiers (EDFAs). Pump 2 is converted to LP_{11a} mode by a phase plate PP1, combined with pump 1 in free space by beam splitter BS1, and combined with pumps 3 and 4, which have been converted to LP_{11b} mode by a phase plate PP2, by free-space beam splitter BS2. All the pumps are combined with the signal by a dichroic beam splitter and coupled into the 1-km-long TMF by an objective. The TMF output is split between an infrared camera and 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 PP4 prior to SMF coupling, we can also measure LP_{11a} "output port" of the TMF. We can gradually vary the signal spatial mode from LP_{01} to LP_{11a} by vertically moving the phase plate PP3 (when it is centered on the beam, it generates LP_{11a} mode; when it is far off the center, it leaves the mode in LP_{01}; in the intermediate positions it generates various two-mode superpositions). To maximize IM-FWM, we co-polarize all three input waves in each process. Mode selectivity of each individual process is quantified by comparing conversion efficiency (CE) for the "desired" signal mode (LP_{11a} in process 1, LP_{01} in process 2) to the CE for the "undesirable" signal mode (LP_{01} in process 1, LP_{11a} in process 2). The gray and blue traces in Fig. 2a show the ratio of these two efficiencies (crosstalk) for process 2 to be about 20 dB. Crosstalk for process 1 is similarly good (not shown in Fig. 2a).

Figure 2a also shows the LP_{01} output port spectrum for simultaneous processes 1 and 2 (4 pumps present). Average powers inside the TMF are 0 dBm for the signal and 17.5, 2, 9.5, and 7.5 dBm for pumps 1, 2, 3, and 4, respectively. At these powers the CEs for processes 1 and 2 are nearly equal. If we had stable phase $\Delta\varphi = (\varphi_{p1} - \varphi_{p2}) - (\varphi_{p3} - \varphi_{p4})$, we would have been able to select for upconversion a superposition of LP_{01} and LP_{11a} modes with a specific relative phase. However, such stabilization (based on optical comb) has not been implemented in our setup yet, and our $\Delta\varphi$ fluctuates randomly on 0.1–1 μs scale. This means that we can observe mode-independent signal upconversion to LP_{01}, as both LP_{01} and LP_{11a} components of any signal superposition are independently upconverted to LP_{01} and added incoherently. This is illustrated in Fig. 2b, which shows nearly the same CEs (within 1 dB range from one another) measured for various signal superpositions with weight of LP_{11a} component ranging from 0 to 100%.

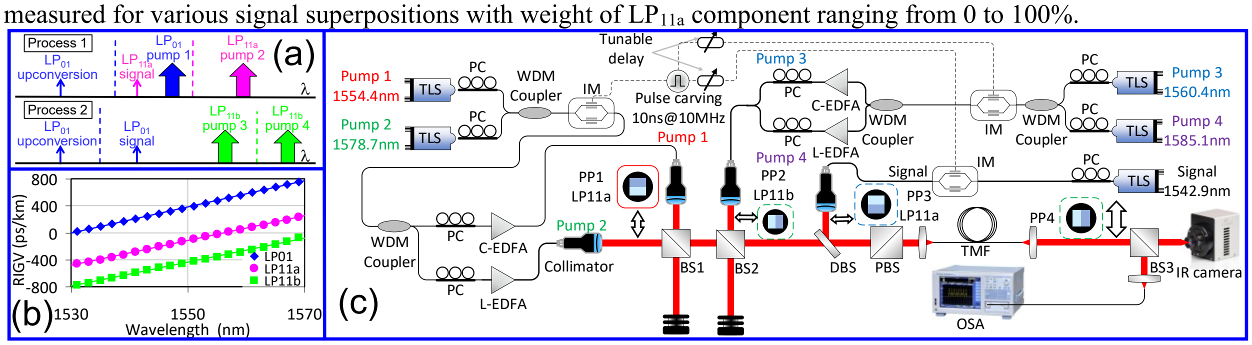

Fig.1. (a) Two parametric processes, whose combination enables mode-selective frequency upconversion in the TMF. (b) Measured relative inverse group velocity (RIGV) data for the modes of our TMF. (c) Experimental setup.

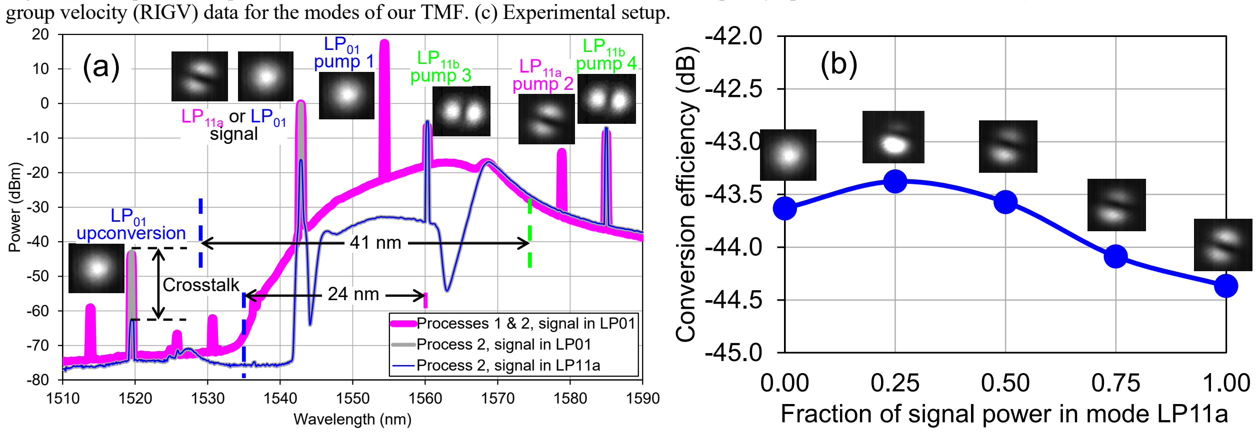

Fig. 2. (a) Spectra at LP_{01} port for process 2 alone (gray, blue) and processes 1, 2 combined (purple). (b) CE for various signal mode superpositions.

III. Discussion and Conclusions

We have simultaneously implemented two IM-FWM processes necessary for mode-selective frequency conversion. We have shown that, in the absence of pump phase stabilization, this scheme produces mode-independent signal frequency conversion. To increase CEs, one could employ high-power EDFAs and, possibly, a customized highly-nonlinear FMF with a reduced core size.

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