Emerging applications of wavelength conversion

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***Abstract*—We discuss three emerging applications of wavelength conversion: 1) hybrid amplification outside of EDFA band, based on a combination of two wavelength converters and an EDFA, 2) spatial-mode-selective wavelength conversion, and 3) generation of spatial-mode-entangled photon pairs.**

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

Wavelength converters, apart from merely converting a signal from one wavelength band to another, can be used for many important functions in nonlinear-optical signal processing [1–3]. In the recent years, the list of these functions has been extended by three emerging applications, which will be discussed here: 1) hybrid amplification outside of EDFA band, based on a combination of two wavelength converters and an EDFA [4, 5], 2) spatial-mode-selective wavelength conversion [6–11], and 3) generation of spatial-mode-entangled photon pairs [12–15].

The signal amplification outside of EDFA C- and L-bands can, in principle, be provided by fiber Raman and optical parametric amplifiers (OPAs), but they are significantly less power-efficient than EDFAs and their high-gain regimes suffer from double Rayleigh backscattering noise (in Raman) [16] as well as stimulated Brillouin scattering (SBS) and pump-to-signal relative intensity noise (RIN) transfer (in OPA). Thus, instead of employing a fiber OPA as a stand-alone high-gain amplifier, it makes sense to use it near or slightly above 0-dB conversion efficiency merely as a wavelength converter between the wavelength band of interest (e.g., S-band) and either C- or L-band, in combination with a nearly-ideal high-gain amplifier such as an EDFA: first fiber OPA converts S-band to C- or L-band, where main gain is provided by the energy-efficient EDFA, and then second OPA converts the signal back to S-band. This avoids high-gain fiber OPA issues and improves the pump efficiency over a stand-alone OPA solution. After developing optical-spectrum-based OPA noise-figure characterization technique [4, 5], instead of relying on detected photocurrent noise measurements [17–20], we have proven this hybrid amplification approach capable of achieving the total noise figure comparable to that of an EDFA (4–6 dB) [4, 5].

The need to grow the transmission link capacity of both classical and quantum communications has generated a lot of interest in space-division multiplexing (SDM) utilizing few-mode fibers (FMFs). One key enabler of such SDM communications is a dynamically reconfigurable multiplexer / demultiplexer of spatial modes. In classical transmission, such reconfigurability could reverse the mode mixing and relax the requirements on electronic processing of the received signals. In quantum key distribution, this dynamic reconfigurability enables measurements alternating between mutually unbiased mode bases, which could increase the dimension of the Hilbert space used for encoding. In either case, low loss and low crosstalk of the demultiplexer are important. We have demonstrated such a demultiplexer in a two-mode $LiNbO_3$ waveguide [6, 7], 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 [6] and single-photon-level [7] signals. More recently, we have developed a scheme of similar functionality (mode demultiplexing by mode-selective frequency conversion) in a $\chi^{(3)}$ nonlinear medium (FMF), which is based on a combination of two inter-modal four-wave mixing (IM-FWM) processes [8]. Compared to $LiNbO_3$ platform, nonlinear FMFs [21] can offer wider design options for mode- and dispersion-engineering and better mode match to the FMFs used in transmission links. Our results have shown good crosstalk performance (mode selectivity) for each of the two IM-FWM processes [8, 9] and demonstrated their combined ability to selectively convert any mode superposition in either (LP_{01}, LP_{11a}) [9, 10] or orbital-angular-momentum-compatible (LP_{11a}, LP_{11b}) [11] two-mode signal space.

Taking full advantage of SDM links for quantum communications requires the use of photon pairs entangled in spatial mode space compatible with the transmission-line FMFs. Recently, we have proposed a scheme for generating spatially-entangled photons directly in the FMF [12], which relies on a combination of two IM-FWM processes. Under proper conditions, the spatial mode of the signal or idler photon alone will be uncertain, but, once one of these photons is measured to be in one mode, the other will be found in the orthogonal mode. Using classical-level input signals, we have observed high signal-idler mode selectivity for these two individual processes in both (LP_{01}, LP_{11a}) [12, 13] and orbital-angular-momentum-compatible (LP_{11a}, LP_{11b}) [14] two-mode signal spaces, and demonstrated that, when combined, these two processes couple the input two-mode seed signal to an orthogonal two-mode idler for various signal-mode superpositions [13, 15].

In the talk, we will describe the operating principles of all three emerging schemes, present our recent results for each, and discuss future directions.

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REFERENCES

[1] M. Vasilyev, Y. Su, and C. J. McKinstrie, “Introduction to the special issue on nonlinear-optical signal processing,” IEEE J. Sel. Top. Quant. Electron., vol. 14, no. 3, pp. 527–528, May–Jun. 2008.

[2] P. G. Patki, P. Guan, L. Li, T. I. Lakoba, L. K. Oxenløwe, M. Vasilyev, and M. Galili, “Recent Progress on Optical Regeneration of Wavelength-Division-Multiplexed Data,” *IEEE J. Sel. Top. Quant. Electron.*, vol. 27, no. 2, 7700812, Mar.–Apr. 2021.

[3] L. Li, P. G. Patki, Y. B. Kwon, V. Stelmakh, B. D. Campbell, M. Annamalai, T. I. Lakoba, and M. Vasilyev, “All-optical regenerator of multi-channel signals,” *Nature Comm.*, vol. 8, 884, Oct. 2017.

[4] A. Shamsshooli, C. Guo, M. Vasilyev, Y. Akasaka, and T. Ikeuchi, “Noise figure of a 3-stage hybrid amplifier using parametric wavelength converters and EDFA,” in *Proc. IEEE Photon. Conf.*, Sep. 28 – Oct. 1, 2020, paper WE3.4., doi: 10.1109/IPC47351.2020.9252276.

[5] C. Guo, A. Shamsshooli, Y. Akasaka, T. Ikeuchi, and M. Vasilyev, “Noise figure study for a 3-stage hybrid amplifier using parametric wavelength converters and EDFA,” to appear in *IEEE Photon. Technol. Lett.*, vol. 33.

[6] 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,” in *Proc. CLEO conference*, San Jose, CA, June 5–10, 2016, paper STh3P.4.

[7] 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,” in *Proc. CLEO conference*, San Jose, CA, May 14–19, 2017, paper FF2E.1.

[8] A. Shamsshooli, C. Guo, F. Parmigiani, X. Li, and M. Vasilyev, “Mode-selective frequency conversion in a three-mode fiber,” in *Proc. CLEO conference*, San Jose, CA, May 10–15, 2020, paper SM3P.3.

[9] A. Shamsshooli, C. Guo, F. Parmigiani, X. Li, and M. Vasilyev, “Reconfigurable Spatial-Mode-Selective Frequency Conversion in a Three-Mode Fiber,” *IEEE Photon. Technol. Lett.*, vol. 33, published online April 26, 2021, doi: 10.1109/LPT.2021.3075688.

[10] A. Shamsshooli, C. Guo, F. Parmigiani, X. Li, and M. Vasilyev, “Reconfigurable mode-selective frequency conversion in a three-mode fiber,” in *Proc. IEEE Photon. Conf.*, Sep. 28 – Oct. 1, 2020, paper ThF1.2, doi: 10.1109/IPC47351.2020.9252379.

[11] A. Shamsshooli, C. Guo, F. Parmigiani, X. Li, and M. Vasilyev, “Toward OAM-selective frequency conversion in a three-mode fiber,” to be presented at *CLEO 2021 conference*, San Jose, CA, May 11–13, 2021, paper SM1F.5.

[12] A. Shamsshooli, C. Guo, F. Parmigiani, X. Li, and M. Vasilyev, “Toward Generation of Spatially-Entangled Photon Pairs in a Few-Mode Fiber,” in *Proc. CLEO conference*, San Jose, CA, May 10–15, 2020, paper JTh2A.27.

[13] A. Shamsshooli, C. Guo, F. Parmigiani, X. Li, and M. Vasilyev, “Progress Toward Spatially-Entangled Photon-Pair Generation in a Few-Mode Fiber,” submitted to *IEEE Photon. Technol. Lett.*

[14] A. Shamsshooli, C. Guo, F. Parmigiani, X. Li, and M. Vasilyev, “Toward Generation of Orbital-Angular-Momentum-Entangled Photon Pairs in a Few-Mode Fiber,” in *Proc. Frontiers in Optics / Laser Science Conference*, September 14–17, 2020, paper FM1D.2, doi: 10.1364/FIO.2020.FM1D.2.

[15] A. Shamsshooli, C. Guo, F. Parmigiani, X. Li, and M. Vasilyev, “Progress Toward Generation of Spatially-Entangled Photon Pairs in a Few-Mode Fiber,” in *Proc. IEEE Photon. Conf.*, Sep. 28 – Oct. 1, 2020, paper MI2.2, doi: 10.1109/IPC47351.2020.9252314.

[16] M. Vasilyev and S. Radic, “Optical Amplifiers,” in *Springer Handbook of Optical Networks*, eds. B. Mukherjee, I. Tomkos, M. Tornatore, P. Winzer, and Y. Zhao, New York, NY, USA; Springer, 2020, ch. 3, pp. 51–81.

[17] G. M. D’Ariano, M. Vasilyev, and P. Kumar, “Self-homodyne tomography of a twin-beam state,” *Phys. Rev. A*, vol. 58, no. 1, pp. 636–648, Jul. 1998.

[18] M. Vasilyev, S.-K. Choi, P. Kumar, and G. M. D’Ariano, “Investigation of the photon statistics of parametric fluorescence in a traveling-wave parametric amplifier by means of self-homodyne tomography,” *Opt. Lett.*, vol. 23, no. 17, pp. 1393–1395, Sep. 1998.

[19] M. Vasilyev, S.-K. Choi, P. Kumar, and G. M. D’Ariano, “Tomographic measurement of joint photon statistics of the twin-beam quantum state,” *Phys. Rev. Lett.*, vol. 84, no. 11, pp. 2354–2357, Mar. 2000.

[20] P. Voss, M. Vasilyev, D. Levandovsky, T.-G. Noh, and P. Kumar, “Photon statistics of single-mode zeros and ones from an erbium-doped fiber amplifier measured by means of homodyne tomography,” *IEEE Photon. Technol. Lett.*, vol. 12, no. 10, pp. 1340–1342, Oct. 2000; erratum: *IEEE Photon. Technol. Lett.*, vol. 12, no. 12, pp. 1713–1713, Dec. 2000.

[21] L. Cui, X. Liu, C. Guo, Z. Zhang, N. Zhao, M. Vasilyev, and X. Li, “Measurement of effective nonlinear coefficients in few-mode fibers,” *Opt. Lett.*, vol. 44, no. 23, pp. 5768–5771, Dec. 2019.