Spatial-Mode-Selective Frequency Conversion

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Abstract: We discuss wavelength conversion of a selected signal spatial mode, which preserves its quantum state and does not disturb other signal spatial modes. We present the results for a lithium niobate waveguide and a few-mode-fiber.

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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 recent years, the interest in growing the transmission link capacity of both classical and quantum communications by space-division multiplexing (SDM) in few-mode fibers (FMFs) has brought attention to the spatial-mode properties of wavelength converters. Under proper phase-matching in a multimode waveguide or fiber, spatial-mode-selective wavelength conversion can be achieved with high efficiency (close to 100%) and low crosstalk (< –20 dB). For SDM application with classical signals, where each spatial mode represents a separate signal channel, the selective conversion of a spatial mode without disrupting other signal modes can be used for reconfigurable spatial-mode de-multiplexing. This classical de-multiplexing capability can be also extended to the quantum regime, where the quantum state of the signal is preserved during frequency conversion, owing to the unitary nature of the wavelength conversion process. Such a converter can, for example, be used for alternating projective measurements in mutually unbiased bases in spatial domain, increasing the dimensionality of quantum encoding.

In this talk, we will review our results on spatial-mode-selective frequency conversion in both second-order (periodically-poled lithium niobate, or PPLN, waveguide) and third-order (FMF) nonlinear media.

First, we have demonstrated such a demultiplexer based on sum-frequency generation (SFG) in a two-mode PPLN waveguide [4, 5], 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 [4] and single-photon-level [5] signals. The same process in reverse can be used for generation of quantum states entangled in spatial domain: annihilation of a 775 nm pump photon creates a signal photon at 1540 nm and an idler photon at 1560 nm, whose individual spatial states in (TM_{00}, TM_{01}) basis are completely uncertain. However, if one of these photons is found to be in a particular superposition of TM_{00}, TM_{01} modes, then the other will be in the orthogonal superposition.

More recently, we have developed a scheme of similar functionality (mode demultiplexing by mode-selective frequency conversion) in a third-order nonlinear medium (FMF), which is based on a combination of two inter-modal four-wave mixing (IM-FWM) processes [6]. Compared to PPLN platform, nonlinear FMFs [7] 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 [6, 8] and demonstrated their combined ability to selectively convert any mode superposition in either (LP_{01}, LP_{11a}) [8, 9] or orbital-angular-momentum-compatible (LP_{11a}, LP_{11b}) [10] 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. Such pairs can be generated directly in the FMF, but, in contrast to PPLN, this requires a different set of two IM_FWM processes, as we have shown for both (LP_{01}, LP_{11a}) [11, 12] and orbital-angular-momentum-compatible (LP_{11a}, LP_{11b}) [13] two-mode signal spaces. Using classical-level input signals, we have observed high signal-idler mode selectivity for these two individual processes, 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 [12, 14].

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