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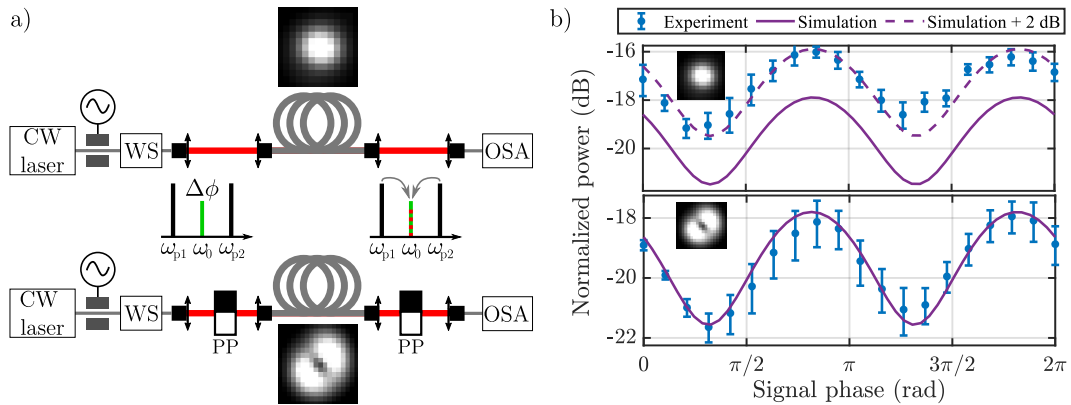
# Intra-Modal Phase-Sensitive Four-Wave Mixing in a Few-Mode Fiber

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Phase-sensitive parametric processes based on four-wave mixing (FWM) in third-order nonlinear media are attractive for the demonstration of numerous functionalities including low-noise amplification, high-sensitivity detection and signal phase quantization with applications to e.g. communication and sensing [1]. Until now, such processes have been demonstrated exclusively in single-mode optical fibers and waveguides. Meanwhile, the exploitation of the spatial (transverse) dimension of waveguides is also being explored for such applications, for instance in order to provide a new multiplexing degree of freedom in telecommunications [2]. One open question is whether the use of phase-sensitive processes can be made compatible with optical fibers and waveguides supporting multiple spatial modes. Some (inter-modal) phase-sensitive processes have been numerically investigated in few-mode fibers (FMFs) [3]. However, to the best of our knowledge, no experimental demonstration of phase-sensitive processes in FMFs has been reported so far. In this work, we demonstrate experimentally intra-modal phase-sensitive FWM, separately in two modes (LP<sub>01</sub> and LP<sub>11</sub>), in a 2-km long step-index FMF [4] supporting 4 LP-modes at 1550 nm.

The experimental setup is represented in Fig. 1(a). Intra-modal degenerate phase-sensitive processes are demonstrated in either the LP<sub>01</sub> or the LP<sub>11</sub> mode by injecting two continuous-wave (CW) pumps and a CW signal into the chosen mode of the FMF. The three waves are generated from a sinusoidally (20 GHz) phase-modulated (PM) CW laser to ensure that the signal frequency  $\omega_0$  is halfway between the frequencies of the pumps ( $\omega_{p1}$  and  $\omega_{p2}$ ) and that all interacting waves are phase coherent. For the LP<sub>11</sub> demonstration, a  $0|\pi$  phase plate (PP) is used to shape the beam phase distribution. An amplitude and phase programmable filter (WS) is used to vary the input signal phase  $\Delta\phi$ . Due to intra-modal FWM, an idler is generated in the same mode at a frequency equal to that of the signal, resulting in interferences at the signal/idler frequency  $\omega_0$ . The power at  $\omega_0$  is measured as a function of the input signal phase for both LP<sub>01</sub> and LP<sub>11</sub> modes (Fig. 1(b)). As expected, both experimental curves have  $\pi$ -periodic sinusoidal variations. The experimental results are in good agreement with numerical simulations of nonlinear propagation in FMFs obtained by solving the multimode nonlinear Schrödinger equation [5] for LP<sub>11</sub>. For LP<sub>01</sub>, the experimental results are shifted by 2 dB compared to the simulation results, as a result of stimulated Brillouin scattering, which is not taken into account in the model.



**Fig. 1** a) Experimental setup for LP<sub>01</sub> (top) and LP<sub>11</sub> (bottom) modes. b) Normalized signal/idler power at  $\omega_0$  as a function of input signal phase in LP<sub>01</sub> (top) and LP<sub>11</sub> (bottom) modes when a total input power of 22 dBm (equally distributed on both pump waves) is injected into the FMF. Dots: experimental results. Curves: simulated data. OSA: optical spectrum analyzer.

In conclusion, intra-modal signal/idler-degenerate phase-sensitive FWM has been demonstrated successfully for the first time in the LP<sub>01</sub> and LP<sub>11</sub> modes of an FMF supporting 4 modes at 1550 nm.

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