Cascaded Intermodal Four-Wave Mixing in a Few-Mode Fiber

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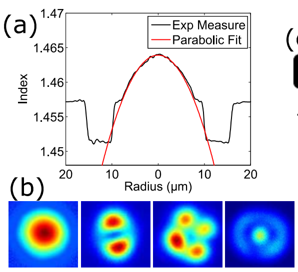
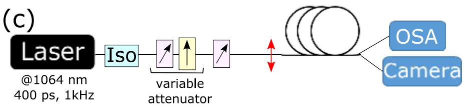
During the last few years, intensive works on multimode fibers allowed for the observation of a series of complex and novel nonlinear spatiotemporal phenomena such as: multimode solitons, geometric parametric instability, supercontinuum generation, and self-induced beam cleaning [1-4]. Among these phenomena, inter-modal four-wave mixing (IMFWM) demonstrated larger frequency shifts in comparison with single-mode fibers. In this work, we studied IMFWM in a few-mode graded-index fiber (GRIN-FMF) pumped in the normal dispersion regime at 1064 nm. We report parametric sidebands detuned by hundreds of THz from the pump.

In our experiments, we used a 1-m-long piece of GRIN-FMF that exhibits a central parabolic index shape (Fig. 1(a)) and supports four groups of modes (LP_{01}, LP_{12}, LP_{11} and LP_{02}) at 1064 nm (Fig. 1(b)). A scheme of our experimental setup is presented in Fig. 1(c). Figure 1(d) shows a set of spectra recorded while increasing the pump peak power from 44 kW to 80 kW (the pump beam was mainly guided in the LP_{01} mode). We first observed the generation of a narrowband far-detuned sideband located at 625.2 nm (198 THz from the pump) due to the intermodal phase matching. When increasing the pump power to 50 kW, the conversion efficiency into this sideband increased, we observed new far-detuned spectral peaks at 555.2 nm, 512.6 nm, 800.1 nm and 1355.1 nm. For pump powers above 59 kW, six additional spectral peaks ranging between 400 and 500 nm appeared. Also, a broad continuum of 200 nm bandwidth developed around the pump.

Spectral and spatial measurements combined with analytical analysis based on ref. [5] allowed us to determine that the pump energy at 1064 nm is essentially transferred to the first and second anti-Stokes (625.2 nm and 555.2 nm) due to IMFWM. The 625.2 nm component then acts as a secondary pump and generates all the observed anti-Stokes peaks below 532 nm and their corresponding Stokes. The positions of the visible parametric sidebands predicted by the analytical approach for the secondary pump are listed in Fig. 1(e). They are found in very good agreement with the experimental ones.





(e)

Order	-1	1	2	3	4	5	6	
Experiments	800.1	512.6	473.3	452	433.6	421.5	405.6	nm
Calculations	800.2	513.0	477.5	453.4	435.0	419.9	407.2	nm
Simulations	818	514	477	452	434	416	-	nm

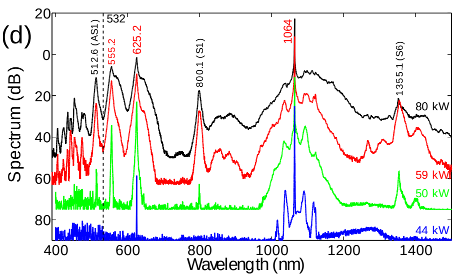


Fig. 1 (a) Refractive index profile of the FMF fiber. (b) Spatial group of modes experimentally identified at 1064 nm. (c) Experimental setup (ISO: isolator; OSA: optical spectrum analyser). (d) Output spectra recorded for different pump peak powers (e) Experimental versus analytical and simulated parametric wavelengths for a secondary pump at 625 nm.

To confirm our physical interpretation, we numerically solved the (3+1)D nonlinear Schrödinger equation [4]. For a pump at 1064 nm, we obtained idler wavelengths at 633 nm and 540 nm, which is in agreement with the experimental observations (625.2 nm and 555.2 nm). We also performed a separate numerical simulation with a pump wavelength set at 633 nm, and noticed a remarkable agreement with both the analytic calculations, and the experimental observations (Fig. 1(e)). Hence, we validated the secondary pump mechanism.

In conclusion, we identified a new cascaded inter-modal FWM mechanism, inducing the generation of a series of spectral sidebands ranging from 405 nm up to 1355 nm, the largest frequency range observed to date in a FMF.

References

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