# High Energy Raman Soliton Dynamics in Multimode GRIN Fibers

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*We experimentally observed the fission of high energy femtosecond pulses in a GRIN standard fiber, leading to complex soliton dynamics with huge Raman frequency shifts.*
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Nonlinear pulse propagation in multimode (MM) optical fibers is a subject of renewed research interest, due to their potential for optical communications and fiber lasers [1–4]. Yet, complex pulse propagation effects in MM fibers remain far from being completely understood. Here, we consider the high-energy regime of femtosecond pulse propagation in a standard graded-index (GRIN) MM fibers. Intrapulse Raman scattering leads to the fission of the initial pulse into many MM solitons, which undergo Raman soliton self-frequency shift (SSFS). The impact on SSFS of self-imaging in GRIN MM fibers has been recently investigated by a simple singlemode model, involving a spatially varying effective mode area [5]. Here we reveal a new pulse propagation regime: the initial pulse fission undergoes a decay into several fundamental MM solitons with different wavelengths and amplitudes, but with constant time duration. Our experimental setup to study the generation and fission of high-energy MM solitons consists of an ultra-short Yb-based laser system equipped by a hybrid optical parametric amplifier (OPA). 61 fs pulses with a wavelength of 1550 nm are generated with a repetition rate variable from 25 to 100 kHz. The laser beam is attenuated by variable ND filters, and coupled with a 30 cm long multimode standard 50/125 GRIN fiber with relative index difference $\Delta = 0.0102$ and chromatic dispersion $\beta_2 = -22$ ps$^2$/km by a 75 mm lens producing a 45μm beam waist at the fiber input. A micro-lens focuses the output near field in an optical spectrum analyzer (OSA) and a spectrometer, with wavelength range 600-1700 nm and 1100-4000 nm, respectively. Output spectra have been recorded at different input peak powers (from a few Watts up to 5 MW).
Fig. 1 shows the recorded normalized spectra as a function of the total output energy. The fission of the input pulse due higher-order effects leads to several red-shifted pulses. These can be easily fitted with a sech$^2$ shape, indicating soliton formation with energies ranging up to 100 nJ, depending on the input pulse energy. The corresponding SSFS shows a non-monotonic behaviour, as a function of the pulse energy: one observes that the most Raman-shifted soliton wavelength increases up to 2.24 μm for a total output energy of about 100μJ; at higher energies the SSFS halts, and it appears to oscillate around a fixed value. This effect has also been investigated by varying some of the set-up parameters. For example, the focal length of the input lens, as well as the fiber length, which was decreased down to 19 mm and 3 cm: SSFS suppression was always observed. Our observations (not presented here) reveal that this SSFS saturation behaviour is due power clamping at the output of the GRIN MMF. This is due to a rapid increase of nonlinear fiber losses, owing to higher-harmonic generation and fluorescence emission in the first centimeters of the fiber [4].

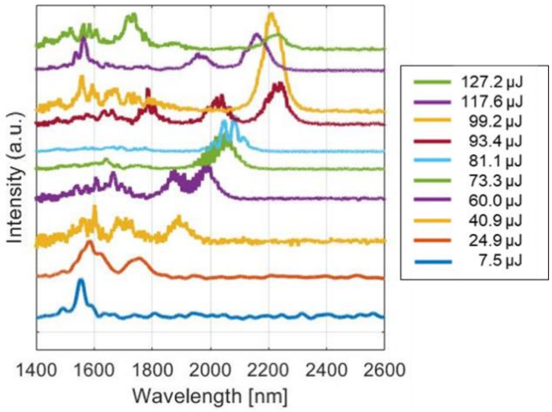

Fig. 1 Normalized output spectra at different output energies.

In summary, we unvealed a new regime of high-energy MM soliton generation by Raman-induced fission, which leads to stable, >100 nJ soliton pulse emission in the mid-infrared. This work was supported by the European Research Council (grant No. 740355), and by the Russian Ministry of Science and Education, (grant No. 14.Y26.31.0017).

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