TRANSMITTING MONOMODAL SOLITONS INTO MULTIMODAL FIBERS

Mario Zitelli,[1,*] Mario Ferraro,[1] Fabio Mangini,[2] and Stefan Wabnitz[1]

[1] Department of Information Engineering, Electronics and Telecommunications (DIET), Sapienza University of Rome, Via Eudossiana 18, 00184 Rome, Italy
[2] Department of Information Engineering (DII), Univ. of Brescia, Via Branze 38, 25123 Brescia, Italy

Abstract: Experimental evidence of spatiotemporal femtosecond soliton propagation over long spans of parabolic graded-index (GRIN) fibers, supported by numerical simulations, reveals that initial multimode soliton pulses naturally and irreversibly evolve into a singlemode soliton.
MOTS-CLEF: Fibres multimodes et phénomènes modaux; Effets non linéaires en optique guidée (Club JNOG)

1. INTRODUCTION

Multimode fibers (MMFs) have recently attracted considerable interest, motivated by their potential for increasing the transmission capacity of long-distance optical links via the technique of mode-division-multiplexing (MDM), which exploits the multiple transverse modes of the fiber as information carriers, and by their increased tolerance to high signal powers. Multimode graded-index optical fibers (GRIN MMFs) are commonly considered capable of supporting spatiotemporal solitons over long distances [1]. Theoretical treatments of spatiotemporal soliton propagation in MMFs mostly rely on the variational approach (VA) [2], based on the assumption that the initial beam shape is maintained unchanged upon propagation. When neglecting the temporal dimension, the variational method permits to include the Kerr effect in the description of periodic spatial self-imaging (SSI), which occurs in GRIN MMFs [3].
In this work we present the experimental evidence, supported by numerical simulations, that an initially excited multimode femtosecond soliton, composed by a few low-order transverse modes, irreversibly decays into a singlemode soliton, owing to the energy transfer of higher-order modes into the fundamental mode of the MMF, induced by inter-modal four-wave mixing (IM-FWM) and stimulated Raman scattering (SRS). Once formed, the singlemode soliton propagates stably over the tested fiber lengths of up to 1 km, which corresponds to the record transmission distance in a MMF of 4600 modal dispersion distances, and 5600 chromatic dispersion lengths. This effect is of particular importance for technological applications, since it reveals that nonlinearity can counteract the effects of modal dispersion and random mode coupling, and enables the stable transport of high spatial quality beams over long distances by means of large area MMFs. As a side aspect, our results invalidate theoretical predictions based on the VA, since the beam shape substantially evolves along the fiber, in such a way that the initial beam profile is not maintained.

2. NUMERICAL SIMULATIONS

A numerical model, suitable for studying the propagation of multimodal pulses over long spans of GRIN fiber, is based on the coupled-mode equations. This requires a preliminary knowledge of the power distribution among the fiber modes at fiber input. The model couples the fields of propagating

modes via Kerr and Raman nonlinearity, through four-wave mixing (FWM) terms of the type $Q_{plmn}A_lA_mA_n^*$, being Q_{plmn} the coupling coefficients proportional to the overlap integrals of the transverse modal field distributions. The lack of symmetry between coupling coefficients is responsible for a slow, but irreversible transfer of energy from higher-order modes towards the fundamental, when pulses carried by different modes are temporally and spatially overlapping. This energy transfer is boosted by SRS, whereby the fundamental mode shifts its wavelength with respect to higher-order modes.
Fig. 1 shows the simulated energy (left) and wavelength (right) evolution of the propagating modes (1,0) or LP_{01}, (2,0) or LP_{02}, (3,0) or LP_{03}, when coupling at the fiber input a Gaussian pulse with 67 fs pulsewidth, 1550 nm wavelength, 30 µm diameter, for the optimal peak power of 28 kW, which is suitable for spatiotemporal soliton generation.

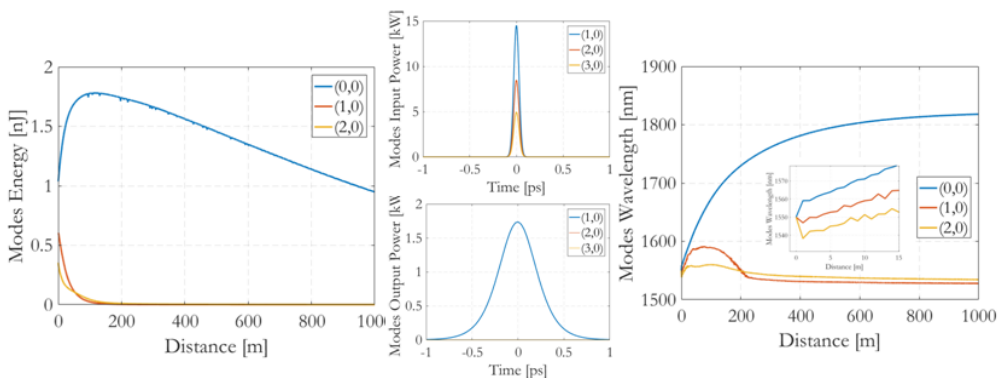

Fig. 1. Numerical simulation of 3 axial modes propagating over 1 km of GRIN fiber.

The top-center inset shows the temporal profile of the input power in the 3 modes. During propagation over the first 10 meters of fiber, nonlinearity forces the carrier wavelengths of the 3 modes to split, so that pulses in each fiber mode experience different chromatic dispersions, in order to compensate for modal dispersion-induced walk-off. As a result, a spatiotemporal soliton is formed: the 3 modes remain mutually trapped, and propagate with the same speed. However, as a result of its nonlinear coupling with higher-order axial modes, after approximately 120 m of propagation the fundamental mode acts as an attractor. Namely the fundamental mode absorbs nearly completely the energy carried by the other two modes. The remaining energy in higher-order modes is carried by low-power dispersive waves, with a wavelength close to input value of 1550 nm. In the subsequent 880 m of propagation, a substantially monomodal soliton propagates, experiencing a progressive wavelength increase caused by Raman soliton self-frequency shift (SSFS). As the soliton wavelength grows above 1700 nm, it starts losing its power by linear attenuation, and it adiabatically broadens in time, in order to preserve the monomodal solitonic condition (bottom-center inset).

3. EXPERIMENTAL EVIDENCE

The simulation of Fig. 1 has shown that, for sufficiently short input pulses, a spatiotemporal soliton is formed after a few dispersion lengths, and the temporally trapped modes experience an irreversible transfer of energy towards the fundamental mode. After hundreds of dispersion/nonlinearity lengths, a singlemode soliton is formed, and it propagates in a stable manner.
In order to experimentally confirm the generation of monomodal solitons over long spans of GRIN multimodal fiber, a test-bed was prepared by using femtosecond pulses propagating over 120 m of fiber; the distance was chosen based on the results of Fig.1, indicating that a monomodal soliton is formed at that distance. Input pulses at 1550 nm had 67 fs pulsewidth; the laser beam was focused on

the fiber input with $1/e^2$ input diameter of approximately 30 μm rate, with Gaussian beam shape (M^2=1.3). The used fiber is a span of commercial parabolic GRIN fiber, with core radius r_c=25 μm, cladding radius 62.5μm, cladding index n_{clad}=1.444, relative index difference Δ=0.0103. At the fiber output, spectral and temporal profiles, as well as the beam near-field were collected.

Fig. 2 shows an example of measured autocorrelation traces (top row), beam near-field (central row), and spectra (bottom row) after 120 m of fiber transmission, for input pulse peak powers corresponding to: a) 22 kW (pre-soliton regime), b) 29 kW (soliton regime), c) 37 kW (soliton regime with Raman SSFS), d) 109 kW (multiple soliton generation), respectively. The experimental data confirm the generation of a pulse with minimum duration at the solitonic power (25-30 kW input peak power). The output spectra show sech-shaped lobes, suffering SSFS up to the wavelength of linear absorption, near 2100 nm. As can be seen, the output beam reaches its minimum waist at the same input power value that leads to a minimum output pulsewidth. Specifically, the beam waist reduces down to 8.5 μm, close to the 7.7 μm theoretical value for the fundamental mode beam in a GRIN fiber, confirming that a substantially fundamental mode has survived at the solitonic power; the minimum pulsewidth was 250 fs at 120 m. For higher input peak powers (110 kW and 190 kW), a second and then a third soliton are observed at the fiber output: each of them experiences a beam waist reduction. The two or three solitons are generated from a common fission process after a few meters of propagation; the first soliton eventually experiences Raman self-frequency shift up to 2100 nm and it is absorbed; the second and third solitons shift at higher powers, so that they can be eventually observed at the output.

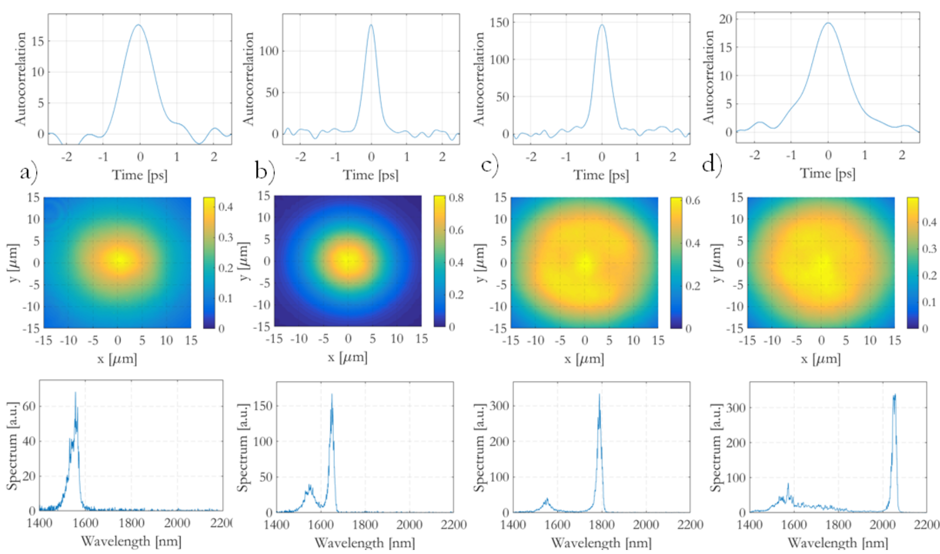

Fig. 2. Measured autocorrelation traces spectra (top row), beam near-field (central row), and spectra (bottom row) after 120 m of fiber transmission, for input pulse peak powers corresponding to: a) 22 kW pre-soliton regime, b) 29 kW soliton regime, c) 37 kW soliton regime with Raman shift, d) 109 kW multiple soliton generation.

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REFERENCES

[1] B. Crosignani and P. D. Porto, "Soliton propagation in multimode optical fibers," Opt. Lett. 6, 329–330 (1981).

[2] S.-S. Yu, C.-H. Chien, Y. Lai, and J. Wang, "Spatio-temporal solitary pulses in graded-index materials with Kerr nonlinearity," Opt. Commun. **119**, 167–170 (1995).

[3] M. Karlsson, D. Anderson, and M. Desaix, "Dynamics of self-focusing and self-phase modulation in a parabolic index optical fiber," Opt. Lett. 17, 22–24 (1992).