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MULTIMODE SOLITON CHANNELS IN SPACE DIVISION MULTIPLEXED TRANSMISSION SYSTEMS

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We experimentally and numerically demonstrate the inability for picosecond telecom pulses to form a single multimode soliton in a graded-index fiber. This property is useful in space-division multiplexed systems, to transmit independent soliton channels which do not merge into a single multimode soliton.

Keywords: Multimode fiber, space division multiplexing.

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1. Introduction. Optical solitons in multimode (MM) fibers have been predicted even before the discovery of their single-mode counterparts [1]. Only in the past few years, however, MM solitons have been experimentally investigated, both in parabolic graded-index fibers (GIF) [2–5] and in multimode step-index fibers (SIF) [6]. Both experimental results and numerical simulations have shown that multimode solitons in GIFs, composed by non-degenerate modes, are invariant to the input pulse duration, and form at a fixed energy, which depends on the input wavelength. Soliton pulsewidth $T_{FWHM} = 1.763 \cdot T_0$ and energy E_s are related to the fiber dispersion β_2, the mean modal velocity difference $\overline{\Delta\beta_1}$, and the effective beam waist w_e by the equations [5]

$$T_{FWHM} = \text{const} \cdot 1.763 \, \frac{|\beta_2(\lambda)|}{\overline{\Delta\beta_1}\,(\lambda)} \tag{1}$$

$$E_s = \frac{\lambda \, |\beta_2(\lambda)| \, w_e^2}{n_2 T_0}. \tag{2}$$

From Eqs. (1) and (2), it turns out that a multimode soliton forms into the GIF with initial pulsewidths between 100 fs and 200 fs, depending on the input wavelength.

2. Experiment/theory. Numerical simulations and experimental tests have been performed to investigate these properties. Simulations use a coupled-mode equations model derived from [7–10]; they include modal dispersion, four orders of chromatic dispersion, wavelength-dependent losses, random modal coupling, nonlinear Kerr and Raman terms.

Fig. 1a illustrates numerical simulations of a 60 fs or 300 fs optical pulse, with 42 μm input beam diameter, propagating at 1450 nm over 20 m or 1 km of GIF; at short distances, and for increasing input pulse energy E_{in}, an optical pulse forms during propagation with decreasing pulsewidth, scaling with $T_{FWHM} \propto 1/E_{in}$ as suggested by the theory of single-mode solitons. However, after 1 km of transmission, a single energy value of 1.0 nJ provides a soliton with minimum pulsewidth at the output. Fig. 1b is a similar case of 60 fs or 300 fs input pulse, with

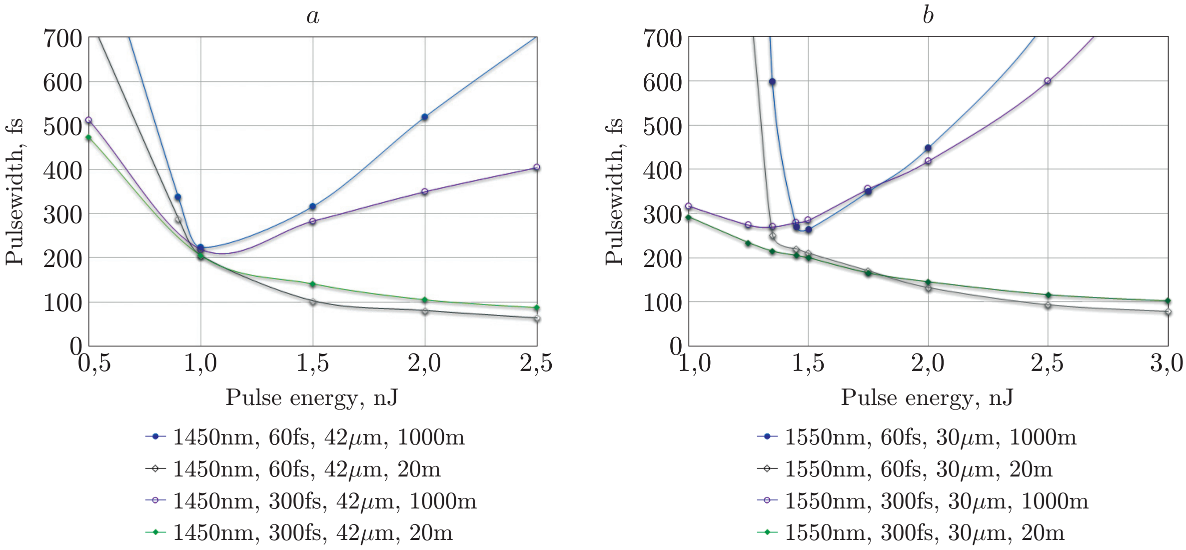

Fig. 1. *a*) Pulsewidth vs. input energy for a pulse propagating over 20 m or 1 km of GIF with input pulsewidth of 60 fs or 300 fs, at 1450 nm. *b*) Pulse propagating over 20 m or 1 km of GIF, input pulsewidth 60 fs or 300 fs, at 1550 nm

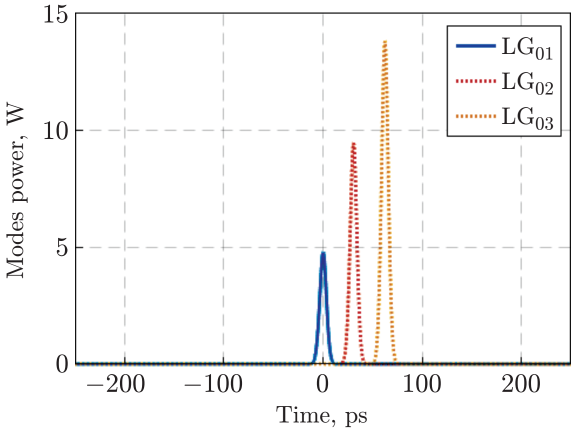

Fig. 2. Simulated mode power after 120 m of GIF, for a multimode 10 ps pulse, at 1550 nm, propagating at soliton energy

30 μm input diameter, propagating at 1550 nm over 20 m or 1 km of GIF. In this case, too both pulses generate the same soliton with minimum pulsewidth at the optimal energy of 1.5 nJ.

In both cases of short and long-distance transmission, the pulsewidth and the specific optimal energy of the multimode soliton appear to be independent of the input pulsewidth, and it is of the order of a few hundreds of femtoseconds at 1450 and 1550 nm. At long distances, the soliton pulsewidth increases because of the Raman-induced soliton self-frequency shift [11].

When picosecond pulses are propagated, typical of telecom applications, a multimode soliton including non-degenerate modes cannot form because of Eq. (1). In Fig. 2, a 10 ps pulse at 1550 nm composed by three non-degenerate modes LG_{01}, LG_{02}, LG_{03} is simulated. The modal energy is kept proportional to the respective mode effective area. When the energy into single modes is twice the value of Eq. (2), with w_e replaced by the modal waist, the three modes form single-mode solitons, which separate in time after 120 m of propagation.

An experimental confirmation of the pulse evolution illustrated in Fig. 2 has been provided

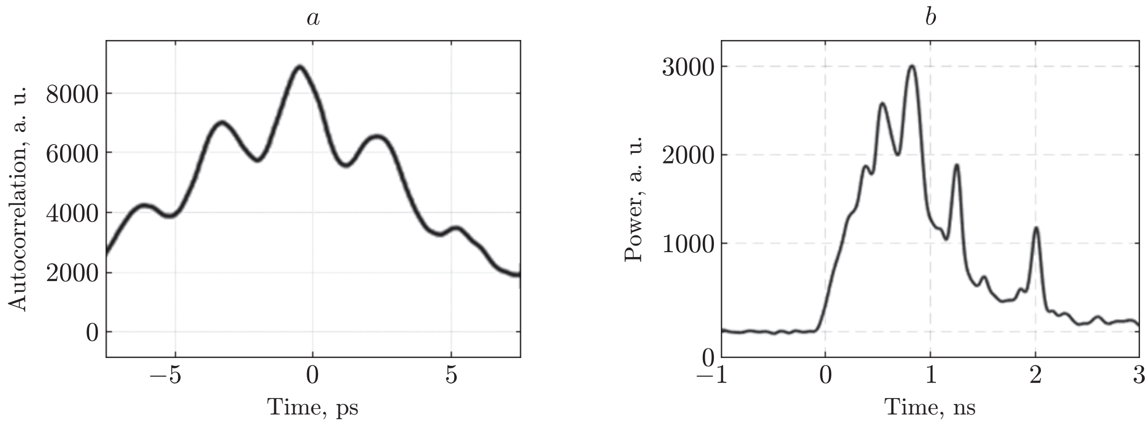

Fig. 3. *a*) Experimental autocorrelation trace after 6 m of GIF, for an input pulse of 8 ps, 1550 nm, at soliton energy. *b*) Experimental photodiode trace after 830 m

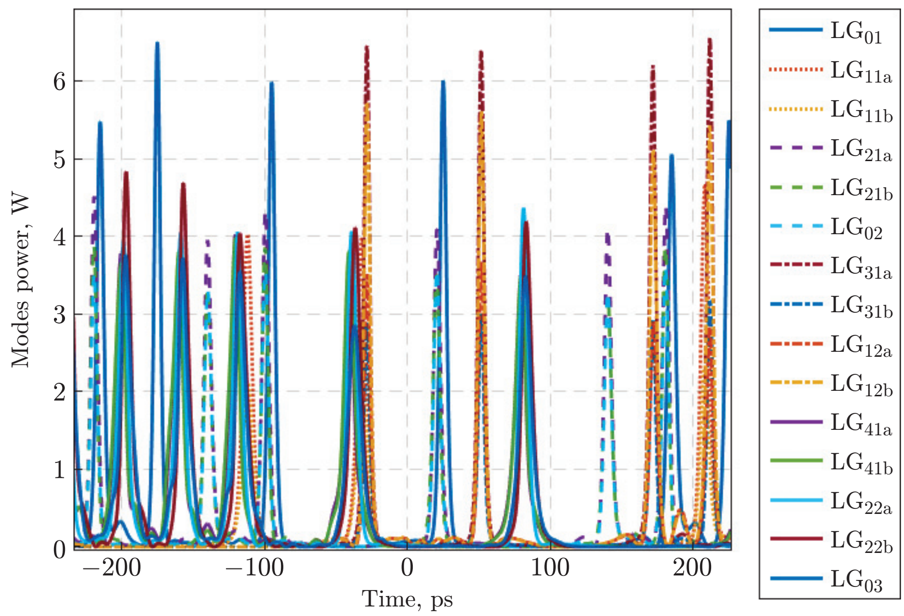

Fig. 4. Simulated transmission of 5 soliton channels over 5 km of GIF, consisting of 64 bit pulse trains, 10 ps pulsewidth, at 1550 nm

by propagating 8 ps pulses at 1550 nm wavelength and a repetition rate of 100 kHz, into 6 m or 830 m of OM4 GIF; the output pulse temporal shape was inspected by a fast photodiode (Alphalas UPD-35-IR2-D) and a real-time oscilloscope (Teledyne Lecroy WavePro 804HD) with 30 ps overall response time, and an intensity autocorrelator (APE pulseCheck 50) with femtosecond resolution. Input and output power were measured by means of a power meter with μW resolution. Pulse energy was varied in the range 0.5 nJ to 23 nJ, enough to provide soliton energy to the individual fiber modes. Fig. 3a shows the measured autocorrelation trace after 6 m of GIF at 5 nJ input energy; well-separated mode groups are visible in correspondence of all the tested pulse energies, indicating that a single multimode soliton does not form. At 830 m distance (Fig. 3b), mode groups are affected by sufficient modal delay to be detectable by the photodiode trace.

3. Conclusions. The capability of picosecond pulses to form solitons into individual mode groups can be advantageously used in space-division multiplexed systems (SDM), in order to transmit independent soliton channels which do not merge into a single multimode soliton.

The inability of picosecond pulses to form a single multimode soliton is the basis of soliton SDM, where individual channels are coupled into single modes or groups of degenerate modes; the pulse energy necessary to form soliton channels is generally larger by 2–3 times with respect to the single mode value, given by Eq. (2). Fig. 4 is a simulated example of soliton SDM transmission over 5 km of GRIN fiber. 15 modes LG01, LG11a, LG11b ... LG03 are launched in 10 ps optical pulse trains, composed by 64 bits, at 1550 nm. By properly distributing the power between modes, five groups of degenerate modes are transmitted over five different soliton channels. They propagate at different velocities, and experience elastic collisions with the other groups; even in the presence of random-mode coupling induced by GIF imperfections, which is included among degenerate modes in the simulation, solitons remain largely unaffected. At the receiver, mode-group demultiplexing outputs the sum of the modes of each group; the individual groups provide at the output undistorted soliton pulse trains.

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