Multidimensional laser beam shaping with multimode optical fibers

M. Zitelli[1], F. Mangini[2], M. Ferraro[1], and S. Wabnitz[1,3]

[1]*Dipartimento di Ingegneria dell'Informazione, Elettronica e Telecomunicazioni, Sapienza Università di Roma, Roma 00184, Italy*

[2]*Dipartimento di Ingegneria dell'Informazione, Università di Brescia, Brescia 25123, Italy*

[3]*Novosibirsk State University, 1 Pirogova str., Novosibirsk 630090, Russia*

E-mail: stefan.wabnitz@uniroma1.it

Multimode fibers (MMFs) have the capacity to carry high-energy beams, which is important for up-scaling the power of fiber laser sources. Among different types of MMFs, graded-index (GRIN) fibers are capable of supporting the propagation of multi-component or multimode solitons [1-3]. These nondispersive nonlinear wave-packets are particularly interesting for mode-locked fiber laser sources of ultrashort pulses [4].

In this presentation, we present our recently discovered properties of femtosecond MMF solitons, whose complex spatiotemporal dynamics makes them very different from their well-known singlemode counterparts. In singlemode fibers, a soliton forms when chromatic dispersion pulse broadening is compensated for by self-phase modulation. This means that a singlemode soliton can have an arbitrary temporal duration, provided that its peak power is properly adjusted. In contrast, forming a MMF soliton also requires the compensation of modal dispersion. This leads to the property that MMF solitons composed of non-degenerate modes with axial symmetry have both a fixed temporal duration and energy at each wavelength, independently of the input pulse duration: we call these spatiotemporal objects "walk-off solitons" [5].

In addition, our numerical and experimental studies of spatiotemporal femtosecond soliton propagation over up to 1 km spans of GRIN fibers reveal that initial multimode soliton pulses naturally and irreversibly evolve into a single-mode soliton [6]. This is carried by the fundamental mode of the fiber, which acts as a dynamical attractor of the multimode system for up to the record value (for multimode fibers) of 5600 chromatic dispersion distances. This evidence invalidates the use of variational approaches, which intrinsically require that the initial ansatz, involving the multimode composition of a soliton, is indefinitely maintained upon propagation, so that no modal energy redistribution occurs.

The simulation shown in Fig.1a shows that, after approximately 120 m of propagation, the fundamental mode acquires the energy carried by higher-order modes. In the subsequent 880 m of propagation, a substantially monomodal soliton propagates, which experiences a continuous wavelength red-shift, owing to Raman self-induced scattering. As the soliton wavelength increases above 1700 nm, it loses its energy because of linear loss, leading to a slow temporal broadening (bottom-right inset of Fig. 1a).

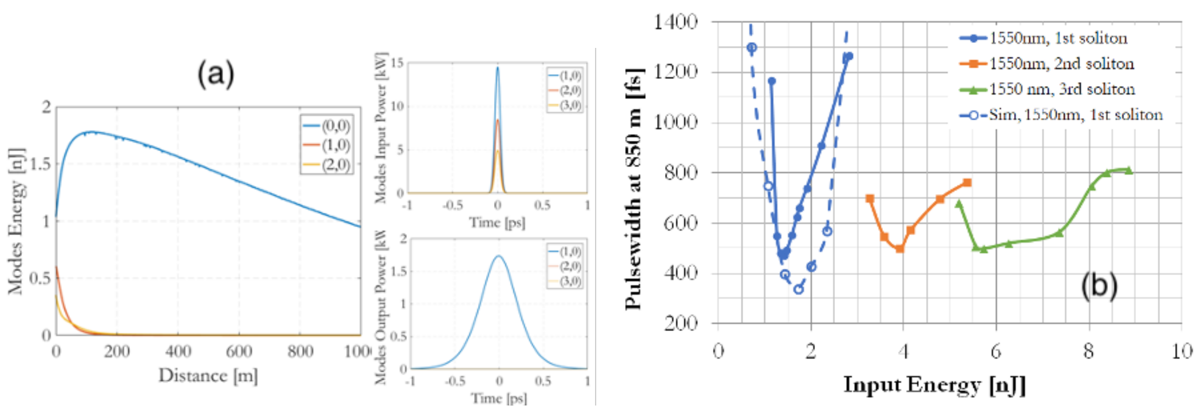

Fig. 1 Numerical propagation of three axial modes over 1 km of GRIN fiber (a); Experimental vs. simulated soliton temporal duration at 1550 nm, after 850 m of GRIN fiber (b).

We experimentally investigated walk-off soliton generation in a GRIN fiber, by injecting femtosecond pulses with 67 fs temporal duration at 1550 nm, Gaussian beam shape (M^2=1.3) and 1/e^2 input diameter of approximately 30 µm. Fig. 1b shows the dependence on input pulse energy of the measured output soliton temporal duration, after 850 m of GRIN fiber. Different Raman solitons are described by separate curves. As can be seen from the blue solid curve (first Raman soliton) in Fig.1b, there is an optimal input energy of 1.75-2.25 nJ, leading to minimum pulse width (i.e., 450 fs after 850 m). For larger input energies, the fission of the input higher-order soliton into fundamental walk-off solitons leads to a second and then a third Raman pulse.

The process of high-energy soliton fission in a GRIN fiber was analyzed in details in Ref.[7], again by comparing experimental observations and simulations. We always observed that solitons produced by the fission have a nearly constant Raman wavelength shift, and the same pulse width over a wide range of soliton energies.

The propagation of GRIN fiber solitons is closely linked with the effect of beam self-imaging. This effect is of interest for many applications, such as implementing a fast saturable absorber mechanism in fiber lasers via multimode interference. We could experimentally directly visualize the longitudinal evolution of beam self-imaging by means of femtosecond laser pulse propagation in both the anomalous and the normal dispersion regime of GRIN fibers [8]. Light scattering out of the fiber core via visible photo-luminescence emission permits us to directly measure the self-imaging period and the beam dynamics.

The generation of up-conversion luminescence is produced by the multiphoton absorption of femtosecond infrared pulses. We directly estimated the average number of photons involved in the up-conversion process, by varying the wavelength of the pump source [9]. This has permitted us to highlight the role of nonbridging oxygen hole centers and oxygen-deficient center defects, and directly compare the intensity of side-scattered luminescence with numerical simulations of pulse propagation.

In a last series of experiments, we proposed and demonstrated a new approach for generating multicolor spiral-shaped beams [10]. It makes use of standard silica fibers, combined with a tilted input laser beam. The resulting breaking of the axial symmetry of propagation inside the fiber leads to the propagation of helical beams. The associated output far-field has a spiral shape, independently of the input laser power value. When using high-power femtosecond laser pulses, a visible supercontinuum spiral emission can be generated. With appropriate control of the input laser coupling conditions, the colors of the spiral spatially self-organize in a rainbow distribution. Our method is independent of the laser source wavelength and polarization. Therefore, standard optical fibers may be used for generating spiral beams in many applications, ranging from communications to optical tweezers and quantum optics.

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