Spatial Beam Evolution in Nonlinear Multimode Fibers

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Abstract: We discuss some recent results illustrating the role of input wave-front shaping, propagation dynamics and output beam diagnostics in order to observe spatial beam cleaning in nonlinear multimode fibers and amplifiers.

The nonlinear dynamics of laser beams in multimode fibers is particularly rich [1], and promising for several areas of applications. The light pattern at the output of a graded-index (GRIN) fiber is influenced by the stress and bending cumulated along the fiber, and it evolves as the input power increases, owing to the Kerr effect. These processes contribute to modify the power fraction carried by each of the modes, with respect to the distribution initially imposed at the input coupling stage. In some cases, the output power distribution of the guided modes can be predicted by the Rayleigh-Jeans distribution. This situation arises when the system reaches equilibrium, and it is known that disorder can accelerate this process [2]. However, several types of input conditions can drastically delay reaching this final state, and favor the robust selection of a specific low-order guided mode. Those special input conditions can be identified by combining an input wavefront shaping with an iterative method [3]. Spatial beam self-cleaning has been reported in both the normal and in the anomalous dispersion regimes, e.g., at 1.064µm and 1.5µm, thus opening the way for possible applications in laser manufacturing and life science [4]. In addition, the spatial self-cleaning process can generate coherent beams, which opens up new perspectives for the generation of high powers based on coherent beam combining methods [5].

The study of space-time complexity also requires specific tools of beam diagnostics, that are well suited for a multimode fiber. Cameras are often presenting time-average intensity images; however, several techniques are known today for obtaining a spatio-temporal portrait of laser beams. Whenever laser pulses are long enough to permit direct detection, it is possible to obtain a complete 3D map by cumulating the output data over several consecutive pulses, and scanning the output pattern with a single mode fiber [6].

New perspectives in the topical area of nonlinear multimode fibers are certainly stimulated by material science [7], and novel fiber lasers. The availability of active multimode fibers is one of the key points develop new powerful lasers, in particular spatiotemporal mode locking and self-similar multimode lasers, to cite only a few recent advances [8,9]. It is important to stress that the dynamics of the propagation of coherent beams in an active multimode fiber is not a straightforward extension of the case well-known for single mode fibers. The large area available in multimode fibers is associated with complex multimodal propagation effects, e.g., including the presence of periodically spaced maxima of intensity in the case of GRIN fibers. We have numerically and experimentally explored the nonlinear beam evolution in several types of Yb-doped fibers and tapers [10,11] for a wide range of different input signal powers, with or without a diode pump.

Figure 1 presents an example of experimental and numerical results of spatial beam self-cleaning in Yb-doped fibers, as well as some sample cases of numerical simulations. In details, panel (a) shows the near-field at the output of a segment of Yb-doped fiber, when using an input microchip laser with a repetition rate of 500 Hz, pulse duration of 500 ps at 1064 nm in a lossy configuration (unpumped fiber). The Yb fiber of fig 1(a) has a large core diameter of 100 µm and a core-cladding refractive index difference of 0.017, with a parabolic index distribution. The guiding cladding has a squared shape with 400 µm of side, for a total fiber length of 3.4 m. Although more than 75% of the laser power is lost (the fiber is not pumped), it is still possible to observe beam cleaning at the fiber output when we increase the input power above 34 kW, in spite of the large size of the fiber. Beam cleaning is also possible when optical gain is activated by pumping the fiber with a diode, as reported in Refs. [10,11].

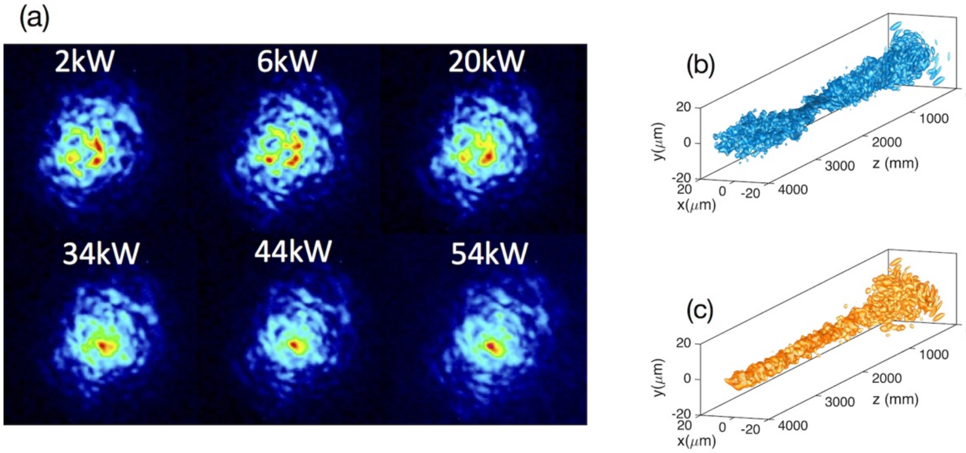

Fig 1. (a) Example of experimental results of beam cleaning in an Yb-doped fiber in absence of pumping; (b) numerical simulations of nonlinear beam evolution in an Yb-doped fiber in absence of diode pumping, and (c) in presence of a 20W forward pumping

It is also possible, under some approximations, to numerically simulate nonlinear beam propagation in presence of gain. Numerical simulations include the effects of diffraction, waveguide contribution, nonlinearity and Yb amplification. Spatial disorder, which is associated with the generation of speckles, can be simulated by considering local deformations of the fiber refractive index profile. In panel (b) of fig.1 we show examples of numerical simulations of beam propagation an Yb-doped fiber with a core diameter of 52 µm and numerical aperture of 0.19, in the absence of diode pumping. The input power (3kW) is not enough for obtaining beam cleaning after just a few tens of centimeters. For longer lengths, fiber absorption hampers any further nonlinear interactions. Whereas fig.1(c) shows that beam self-cleaning can be recovered by adding gain via a diode pump at 979 nm: nonlinear interactions are enhanced by distributed amplification. Although these simulations come with a series of approximations (e.g., uniform cladding pumping, steady-state regime or absence of temporal dynamics), they can capture some of the key features of nonlinear beam reshaping in active fibers in the presence of nonlinearity and disorder.

In conclusion, in this presentation we overview recent advances of nonlinear beam shaping and spatial beam cleaning in multimode fibers, including the control of the input phase front, the use of new detection systems, and nonlinear multimode propagation effects in active fibers.

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