Accelerating nonlinear interactions in tapered multimode fibers

M. A. Eftekhar[1*], Z. Sanjabi-Eznaveh[1], J. E. Antonio-Lopez[1], H. E Lopez Aviles[1], S. Benis[1], M. Kolesik[2], A. Schülzgen[1], F. W. Wise[3], R. Amezcua Correa[1], and D. N. Christodoulides[1]
[1]*CREOL, College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816-2700, USA*
[2]*The College of Optical Sciences, The University of Arizona, Tucson, AZ 85721, USA*
[3]*School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853, USA*
[*]*Corresponding author: m.a.eftekhar@knights.ucf.edu*

Abstract: We theoretically and experimentally demonstrate that the processes of multimode soliton fission and dispersive wave generation in parabolic-index multimode fibers, are substantially altered when the rate of intermodal nonlinear interactions is progressively increased during propagation.

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Since the late seventies, nonlinear fiber optics has grown into a full-fledged field leading to a host of applications. These range from supercontinuum generation and fiber-based parametric oscillators, to pulse compression and soliton generation, to mention a few. In this regard, single-mode fibers have established themselves as the most convenient platform. This is particularly true with the use of microstructured fibers, where the optical intensity can be confined to areas as small as a few micrometers, thus boosting nonlinear effects. In addition, since field propagation only occurs in a single mode, the computational complexity is considerably reduced since nonlinear dynamics can be accurately modeled using nonlinear Schrödinger-type equations [1]. However, recent progress in realizing high-power lasers as well as advancements in computational power and numerical schemes have laid the ground for a renaissance of multimode optical fiber (MMF) technologies [2]. The presence of hundreds and even thousands of modes, interacting with each other both linearly and nonlinearly, make MMFs exceedingly complex. Moreover, the variety of nonlinear processes in these settings is much richer, thus opening up new prospects for observing novel optical phenomena. Examples of these effects include multimode solitons (MMS), spatial self-beam cleaning, and geometric parametric instabilities [2–5]. Parabolic-index MMFs are ideal testbeds for conducting nonlinear studies because they minimize the walk-off among modes, hence extending the effective intermodal interaction length. Such an index-profile, analogous to a harmonic potential in quantum mechanics, has an equidistant set of eigenvalues, resulting in a self-imaging behavior of the propagating spatiotemporal field. When a parabolic-index multimode fiber is excited in the anomalous dispersion regime, this recursive behavior leads to a broadband phase matching of the optical multimode solitons and a sequence of Cherenkov radiation lines [6].

Here, we demonstrate for the first time, the manner in which MM-solitons and dispersive wave (DW) behavior can alter itself when the intermodal collision rate speeds up along propagation. In a parabolic MMF, the spacing between eigenvalues is given from the relation $\delta = a^{-1}\sqrt{2\Delta}$. By properly engineering the waveguide radius or index-difference, the intermodal oscillations can be accelerated or decelerated. In our study, by gradually reducing a fiber's core radius, these oscillation are sped up along the propagation direction. The schematic of such a system is depicted

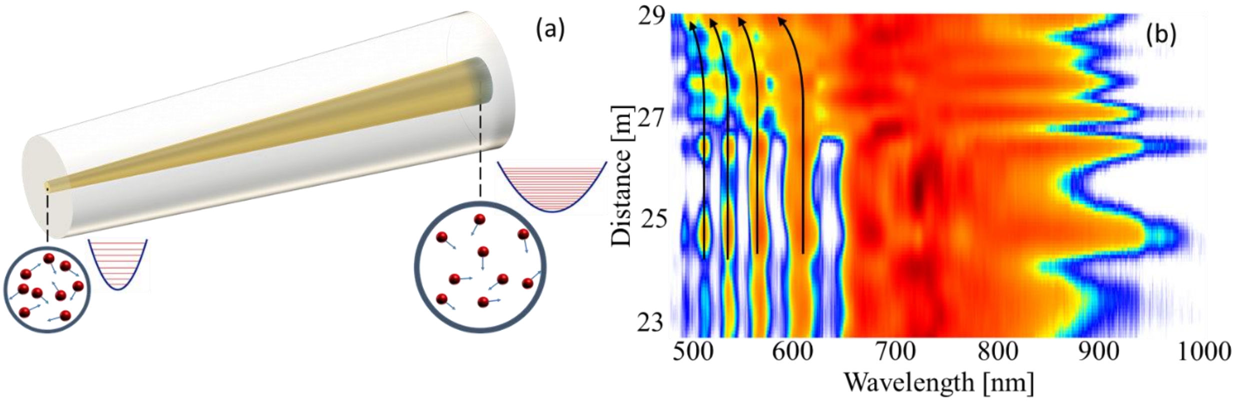

Fig. 1 (a) A typical multimode fiber gradually tapered in the propagation direction. As the core diameter decreases the spacing between consequent eigenvalues increases which results in accelerated intermodal oscillations.(b) Visible portion of the spectrum shows the DW-comb blue-shifting behavior under the tapering condition where the interaction rate among constituent modes of MM-solitons accelerates.

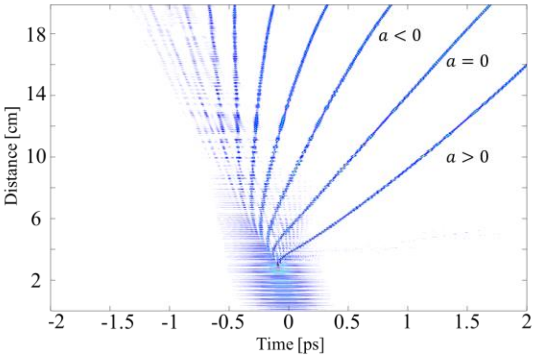

Fig. 2 Temporal evolution of MM-solitons in a tapered MMF with the radius varying from 40 μm to 20 μm over 20 cm.

in Fig. 1(a). To experimentally investigate this effect, we launch 100-fs pulses at 1550 nm from a mode-locked Ti:Sapphire laser system into a 29-m long tapered graded-index MMF. The fiber is composed of 25 m uniform section with a 50 μm core diameter followed by a 4-m taper, narrowing down to 10 μm. Through consecutive cut-backs, the spectrum evolution for fixed input conditions is recorded (Fig. 1(b)). As depicted in this figure, the spectrum consists of a broadband DW-comb which remains invariant through the uniform section. As the solitons enter the tapered region, they experience an acceleration of oscillations. These accelerating oscillations lead to the growth of a new series of DWs, drifting towards shorter wavelengths. The temporal behavior of the ensued multimode solitons can be analyzed using gUPPE simulations. The emerging temporal picture is depicted in Fig. 2. Interestingly, each of the generated solitons exhibit a radically different behavior with respect to each other. The first emitted soliton starts to accelerate following a short period of deceleration. This is a clear indication of blue-shifting solitons. The second soliton travels with a constant velocity while subsequent solitons are all captured in their deceleration phase. Although blue-shifting solitons are by nature uncommon, the spectrum observed in our experiment reveals in fact these characteristic signatures. Figure 3 shows the spectrum evolution along the taper in the infrared window at consecutive propagation distances. Before the tapering starts, most of the energy resides on the long-wavelength edge of the spectrum (2000 nm), because of intrapulse Raman scattering. After going through the tapering section, the spectral energy now moves instead towards shorter wavelengths (Fig.3). As a result, in the later stages, the energy is uniformly distributed across the NIR window.

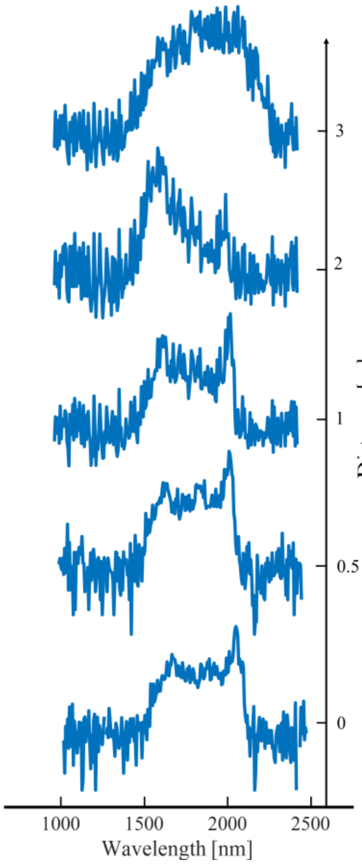

Fig. 3 The IR portion of the spectrum measured experimentally along a tapered MMF. The first frame shows the region just before the taper where the energy is mostly piled up on the long wavelength edge. Later and along the taper, the energy is transferred to shorter wavelengths.

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