Ultrabroadband Dispersive Radiation by Spatiotemporal Oscillation of Multimode Waves

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Abstract: We study supercontinuum in graded-index multimode fibers. Spatiotemporal oscillations of solitons produce radiation spanning from the mid-IR to ultraviolet. Applications to ultrafast fiber sources and connections to spatiotemporal modulation and conical wave instability are discussed.

OCIS codes: (190.0190) Nonlinear optics; (190.5530) Pulse propagation and temporal solitons; (060.4370) Nonlinear optics, fibers.

The spatiotemporal nonlinear dynamics of ultrafast pulses in multimode optical fiber (MMF) is an exciting environment for nonlinear optics. Besides the instrinsic scientific interest of the rich and diverse physics, research is motivated by the powerful degrees of freedom multimode fibers provide for applications for laser light sources, telecommunications, imaging, and computing. Here we study the emission of dispersive radiation by the spacetime oscillations of multimode solitons in graded-index (GRIN) fiber. This process, unique to multimode fiber, generates coherent ultrashort pulses over a remarkable spectral range. GRIN supercontinuum could therefore be the basis of tunable amplifiers or oscillators producing coherent electromagnetic pulses spanning from the ultraviolet to the infrared - a cost-efficient and robust source that would be useful for many applications.

We recently reported observations of remarkably broadband supercontinuum generated by ultrashort pulses in the anomalous dispersion regime of a graded-index multimode fiber [1]. Particularly unexpected was the generation of a series of visible spectral sidebands. These were made even more curious by simulations, conducted using the generalized multimode nonlinear Schrödinger equation (GMMNLSE) [2], which implied a set of similar sidebands were generated well into the infrared - a nominally-opaque portion of the fiber's transmission spectrum.

The origin of these sidebands can be understood by analogy with the Kelly sidebands commonly observed in soliton fiber lasers [3]. In a soliton fiber laser, as the soliton traverses the cavity, it experiences loss due to output coupling and lossy elements in the cavity. This loss is then compensated in the gain fiber. In each stage, the soliton adjusts its duration to maintain the balance of nonlinear and dispersive phase that defines it. This adjustment is accomplished in part by the radiation of dispersive waves. This radiation is emitted periodically as the soliton circulates, so certain frequencies of radiation are resonantly enhanced as they repeatedly re-encounter the radiating soliton.

In multimode fibers, pulses in different modes travel at different speeds (modal dispersion). Kerr nonlinearity facilitates interactions between the pulses, however. These may cause a spontaneous equalization of pulse velocities, leading to a spatiotemporal synchronization. In some cases, this forms a multimode soliton, which can propagate for a long length of fiber without change to its temporal profile. Similar to single-mode fiber, stable solitons correspond to temporally-invariant, bell-shaped pulses. Multimode solitons, however, contain multiple spatial modes. Their spatial evolution is therefore not necessarily invariant, but periodic due to the interference of the fields in different modes. For multimode solitons with a radially-symmetric spatial shape, this evolution is a periodic shrinking and growing of the beam. The average intensity of the soliton therefore oscillates, similar to a soliton in a fiber laser. Unlike in the laser, where gain and loss perturb the soliton as outside influences, in the case of MMF the intensity oscillations are intrinsic to the spatially-multimode wave propagation.

Figure 1a shows the evolution of the spectrum of an ultrashort pulse (400-fs, 164-nJ, 1550-nm) launched into a graded-index multimode fiber. Details of the experiments and simulations are given in Refs. 1 and 3. Dramatic spectral broadening is observed, including at several distinct sidebands in the visible and infrared portions of the spectrum. The growth of these dispersive wave sidebands is remarkable. The simulation realistically models infrared loss in the fiber, with loss that increases exponentially with decreasing frequency. At the first red-shifted dispersive wave, at 72
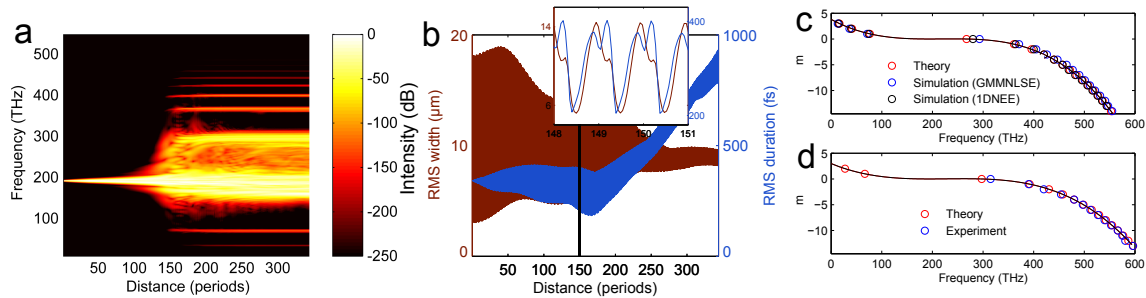
Fig. 1. a: Space-time evolution of the beam width and pulse duration. Oscillations in space lead to in-phase oscillations in time. b: the spectral evolution of the field shows the growth of dispersive waves due spatiotemporal oscillation, in both the visible and IR spectral regions. c: Comparison of the sideband positions predicted by theory, simulation using the GMMNLSE, and a 1D NEE with longitudinally-varying nonlinearity. d: Comparison of theory and experimental sideband positions.

THz (4200 nm), the loss is 10^5 dB/km. This loss is easily overcome by the spectacular gain the dispersive waves experience. The dispersive waves entire growth occurs in only a few centimeters, during which they each experience a gain of roughly 6×10^6 dB/km.
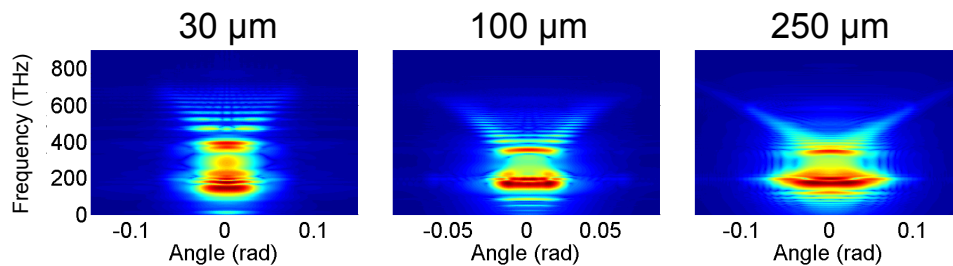

Fig. 2. Spatially-resolved spectra for supercontinuum pumped by 1550-nm ultrashort pulses in GRIN MMFs of the indicated core radius.

Kodama *et. al* derived the sideband positions in the presence of third-order dispersion [4] for solitons experiencing periodic amplitude modulation. Both simulation and experiment show excellent agreement with this model (Fig 1c, d). Using a 1D nonlinear envelope equation with a longitudinally-varying nonlinearity, we investigate the effect of third-harmonic generation and sub-carrier frequency effects on the sidebands. These effects lead to more efficient sideband generation, whose positions also agree with theory (Fig. 1c). Despite its accuracy, this model nonetheless neglects the fundamentally spatiotemporal nature of the dispersive waves. Simulations using a spacetime GNLSE (Fig. 2) show the spatially-resolved supercontinua generated in GRIN multimode fibers with increasing core radius. As the core size increases, we observe a transition to the hyperbolic shape that is commonly observed in filamentation studies [5].

References

1. L.G. Wright, D.N. Christodoulides and F.W. Wise, "Controllable spatiotemporal nonlinear effects in multimode fibres," Nat. Photon. **9**, 306 (2015)
2. F. Poletti and P. Horak, "Description of ultrashort pulse propagation in multimode optical fibers," J. Opt. Soc. Am. B **25**, 1645 (2008).
3. L.G. Wright, S. Wabnitz, D.N. Christodoulides and F.W. Wise, "Ultrabroadband dispersive radiation by spatiotemporal oscillation of multimode waves," Phys. Rev. Lett. **115**, 223902 (2015)
4. Y. Kodama, M. Romagnoli, S. Wabnitz, and M. Midrio, "Role of third-order dispersion on soliton instabilities and interactions in optical fibers," Opt. Lett. **19**, 165 (1994)
5. A. Couairon and A. Mysyrowicz, "Femtosecond filamentation in transparent media," Physics Reports **441**, 47 (2007).