Ultrabroadband Dispersive Radiation by Spatiotemporal Oscillation of Multimode Waves

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Abstract: We show that spatiotemporal oscillations of multimode solitons in graded-index fibers generate dispersive radiation spanning the mid-IR to UV. We discuss routes to compact sources of coherent ultrashort pulses across the electromagnetic spectrum.

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Multimode fibers (MMFs) are rich environments for nonlinear optical pulse propagation. In the past decades, single-mode fibers (SMF) have been the basis for experiments on many important concepts in nonlinear dynamics. The study of modulation instability, solitons, and their behaviour under perturbations, has led both to major scientific results as well as advances in ultrafast fiber light sources. This study facilitated understanding of SMF-based supercontinuum, and more recently has given rise to many studies on extreme waves in optics. In SMF, the transverse spatial degrees of freedom of the guided optical wave are fully restricted. In contrast, in MMFs the wave has three-dimensional freedom, and this freedom spans from zero to infinite with the size of the waveguide.

In MMFs with anomalous dispersion, a family of spatiotemporal solitary waves, called multimode solitons, exist. We recently observed that pulses launched into graded-index MMF would spontaneously reshape in spacetime to form a non-dispersing wavepacket. This wave, termed a multimode soliton, exhibits many qualitative similarities with the temporal solitons of SMF, but is distributed into multiple spatial modes. As a result, multimode solitons exhibit spatiotemporal dynamics, including spatiotemporal fission, compression and Raman self-frequency shifting. These aspects of multimode soliton propagation are much more complex than their single mode counterparts, but their physical origin is similar. The same is true of resonant dispersive radiation [1,2].

When MM solitary waves propagate through GRIN fiber, their periodic spatial evolution gives rise to a synchronized temporal evolution through the emission of resonant dispersive radiation. As with other aspects of MM solitons, physical insight can be gained by analogy with perturbed solitons in SMF. In a SMF laser cavity, a circulating soliton experiences gain and loss. When it is attenuated, its intensity drops and its duration expands until the linear dispersive phase matches the rate of nonlinear phase. When it is amplified, the soliton compresses to accomplish the same goal. For each adjustment, the soliton sheds a small amount of dispersive radiation. This radiation is broadband, but particular frequencies will reencounter the soliton periodically (once every N round trips). At these resonant frequencies, so-called Kelly sidebands emerge. In a GRIN fiber, a coherent modal superposition evolves periodically in space. As a result, the intensity of a MM soliton in GRIN fiber oscillates, leading to temporal oscillations. Dispersive radiation which reencounters the soliton is resonantly enhanced (Fig. 1a-b). For both simulation (Fig. 1c) and experiments (Fig. 1d), the spectral positions of the sidebands are accurately predicted by theory developed for SMF Kelly sidebands [4].

The sidebands extend throughout and beyond the transparent bandwidth of fused silica. Beyond roughly 1.7 μm, the loss of fused silica increases exponentially, and so it is usually considered opaque beyond roughly 2 μm. Even though this is included in our simulations (the loss is 10^5 dB/km at the first red-shifted sideband, ≈ 4 μm), dispersive waves extending as far as 75 μm are predicted. The dispersive waves are coherent, ultrashort pulses, and so despite the relatively small efficiency ($<1\%$ in our simulations), they are potentially attractive for applications. In particular, spatial degrees of freedom may be useful for extending frequency combs deeper into the infrared and ultraviolet. Similar effects may be expected in multimode cavities, for example formed by a pair of curved mirrors. For air-filled cavities, mJ-level pump pulses may yield μJ-level ultrashort pulses simultaneously in the ultraviolet, mid-IR and beyond.

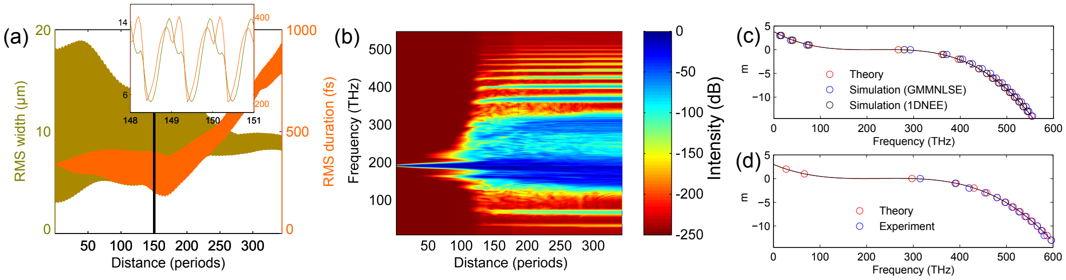

Fig. 1. (a) Evolution the beam width and pulse duration through a GRIN MMF. Oscillations in time are caused by oscillations in space. (b) Red and blue-shifted dispersive waves are radiated at harmonics of the spatiotemporal oscillation. (c) Sideband predictions from theory versus results with a GMMNLSE model [3] and a 1D nonlinear envelope equation where the nonlinearity varies longitudinally to mimic the GRIN spatial dynamics. (d) Theory and experimental sidebands.

As the fiber dimensions are increased, the spatiotemporal aspects of dispersive wave emission become richer. The propagation of intense ultrashort pulses in various bulk media has been an important area of study in the past decades [5]. Filamentation occurs for powers above the critical power for self-focusing. Fig. 2a shows the spatiotemporal spectrum of supercontinuum in a GRIN MMF. Although the power is below the critical power, the field has a similar shape as would be expected for free-space filamentation. In particular, the emission in the normal-dispersion regime has a conical shape. However, when the initial condition is changed (Fig. 2b), the spatial properties of the dispersive waves change (although their phase-matching is unchanged). In addition, the red-shifted dispersive waves do not have the same conical shape, because the waveguide approaches single-mode guidance for long wavelengths.

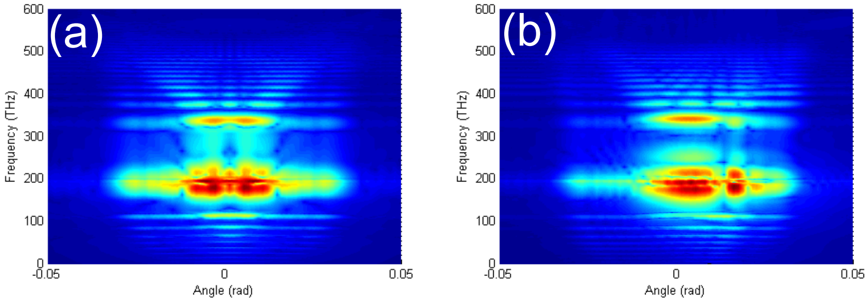

Fig. 2. (a) Simulated spatiotemporal spectrum of a pulse propagating in GRIN MMF, for a centered Gaussian excitation. (b) Same, but with the beam initially displaced.

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