Spatiotemporal Dynamics in Multimode Nonlinear Optical Fibers

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Abstract

We overview experiments associated with nonlinear beam propagation in multimode optical fibers. We show that complex spatio-temporal phenomena permit to control the nonlinear beam reshaping across its spatial, temporal and spectral dimensions.

1. Introduction

Although nonlinear optical effects in multimode optical fibers (MMFs), such as the modal-phase matching of four-wave mixing (FWM), have been known since a long time, the manipulation of the temporal and spectral properties of ultrashort pulses combined with the degrees of freedom provided by fiber multimodality is a research field which has only emerged over recent years.

2. Spatiotemporal beam control

In this talk, we review a set of recent experiments associated with the nonlinear propagation of multimode optical pulses. It has been observed that the effect of periodic intensity oscillations associated with self-imaging in graded-index (GRIN) MMFs leads, via the Kerr effect, to a longitudinal grating that may scatter far-detuned optical sidebands over multiple octaves. Moreover, self-imaging also leads to nonlinear mode coupling that, in combination with random linear mode coupling, surprisingly favors the stable emergence of low-order transverse spatial modes at the MMF output, a process that has been named beam self-cleaning.

2.1. Multimode solitons and dispersive wave generation

Multimode solitons (MMSs) are the most natural object within the spatiotemporal dynamics of optical pulses in nonlinear MMFs. In the anomalous dispersion regime, any pulse modal component sees a force of attraction towards the center of mass of the multimode pulse, which may bind all modes together into a single self-trapped entity: the MMS [1].

Early experimental studies of soliton propagation in MMFs by Grudinin et al. [2] showed that femtosecond Raman solitons are produced in GRIN MMFs with a clean beam size, close to that of the fundamental mode of the fiber.

More recent experiments by Renninger and Wise [3] demonstrated that, because of cross-phase modulation, higher-order modes (HOMs) exhibit a nonlinearity-induced blue shifting in the spectral domain, so that they slow down, and propagate with the same group velocity along with the fundamental mode.

Dispersive wave (DW) emission from MMSs, which can be interpreted in analogy with Cherenkov radiation in electrodynamics, leads to ultra-wideband series of unequally spaced sharp spectral peaks extending from the visible into the mid-infrared regions [4]. The mechanism of DW sideband series generation is the resonant phase-matching with MMS, owing to their spatio-temporal intensity oscillations, or self-imaging [5] .

2.2. Geometric Parametric Instabiilities

The periodic self-imaging of a beam in MMFs also leads to a geometric parametric instability (GPI) [6]: a series of visible sidebands were generated with large frequency detuning (123.5 THz) from a 1064 nm pump [7]. GPI permits to convert a near-infrared multimode laser directly into the visible and mid-infrared range. Remarkably, both pump and sideband peaks were carried by a well-defined and stable bell-shaped spatial profile. The position of GPI sidebands can be engineered by fiber design, e.g., varying the MMF core size, or concatenating different fibers [8]. The sideband widths and positions may also be slightly controlled by the pump power level [9].

2.3. Supercontinuum Generation

By pumping GRIN fibers with sub-ns pulses in the normal dispersion regime, efficient high-brightness supercontinuum generation extending into the visible spectral range was reported [10, 11]. The generated spectra span more than two octaves, from below 450 nm up to 2500 nm, and exhibit a high-quality, bell-shaped beams.

2.4. Spatial beam self-cleaning

Because of random linear mode coupling, multimode optical fibers spread a light pulse among its many transverse modes, leading to a severe loss of beam quality and speckled output transverse patterns. Recent experiments have demonstrated that the Kerr effect may overcome speckle distortions, and lead to spatially clean output beams, which are robust against fibre bending. Initial observations of this spatial beam self-cleaning effect involved long, subns pulses [12, 13], and where later extended to the case of femtosecond pulses, propagating in the normal dispersion regime of a GRIN MMF [14]. The polarization dynamics of Kerr beam self-cleaning was recently investigated by Krupa et al., showing that spatial beam cleaning is accompanied by significant nonlinear polarization rotation of the beam, along with an increase of the degree of linear polarization [15].

3. Conclusions

Multimode nonlinear optics is a promising and flexible new platform for developing a whole new class of optical signal processing devices. These are very promising for the upscaling of the energy of coherent fiber laser sources.

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