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NONLINEAR OPTICS IN MULTIMODE FIBERS

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Abstract

We overview the emerging field of nonlinear optics in multimode optical fibers, which enable new methods for the ultrafast light-activated control of temporal, spatial and spectral degrees of freedom of intense pulsed light beams.

1 Introduction

Although nonlinear optical effects in multimode optical fibers (MMFs), such as 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 in the past few years. In this presentation, we overview a series of recent experiments that have demonstrated new effects such as: the propagation of multimode optical solitons (MMSs), geometric parametric instabilities, and spatial beam self-cleaning.

2 Multimode fiber solitons

Optical solitons are well known to propagate in the anomalous group-velocity dispersion regime of nonlinear singlemode fibers, representing a balance between chromatic dispersion and self-phase modulation. Optical solitons play a key role in understanding purely one-dimensional pulse temporal dynamics in a variety of applications ranging from communications, supercontinuum generation (SCG), or mode-locked lasers.

On the other hand, MMSs provide the natural platform to understand the spatiotemporal dynamics of pulses in nonlinear MMFs. A MMS is a soliton with multiple components, self-consistently held together by fiber nonlinearity, which maintains its shape unchanged upon propagation. In the absence of nonlinearity, modal dispersion leads to temporal broadening of a multimode optical pulse. As pointed out by Hasegawa [1], because of self and cross-phase modulation, in the anomalous dispersion regime a pulse in a given mode of the MMF experiences a force of attraction towards the center of mass of the total pulse intensity, which ultimately may bind all modes together to form a single self-trapped entity: the MMS.

The first experimental study of soliton propagation in MMFs dates back to 1988, when Grudinin et al. [2] have shown that femtosecond Raman solitons, generated in the anomalous dispersion regime of a graded-index (GRIN) MMF pumped by highly multimode pulses from a Q-switched and mode-locked Nd:YAG laser, emerge with a clean beam size, close to that of the fundamental mode of the fiber. It was observed that Raman solitons in a MMF have energy about 6 times larger than that of a singlemode fiber soliton with the same pulse duration.

Soliton propagation in MMS was left uninvestigated, largely because of the success of singlemode fiber based optical communications and devices in the 1990s, until the experiments by Renninger and Wise in 2013 [3]. Their experiments and simulations demonstrated the stable trapping, in the temporal domain, of the pulse energy in the first three modes of a GRIN MMF. Because of cross-phase modulation, higher-order modes (HOMs) exhibited 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.

A subsequent experiment studied the more general case where a much larger proportion of the MMS energy gets coupled into different HOMs at the input of a GRIN fiber, so that MMS comprising up to 8-13 modes are formed, with an overall beam size up to $\simeq 3$ times the fundamental mode size. In this situation, a complex interplay of soliton fission and Raman scattering occurs [4].

For relatively large input pulse energies, so that multiple MMSs are generated, the initial pulse gets temporally compressed at first, and subsequently undergoes Raman-induced fission into multiple MMS and dispersive waves [4]. As the pulse energy grows larger, an initial beam mostly composed by HOMs is progressively cleaned into a bell-shaped beam composed by LOMs.

Later Zhu et al. [5] studied the intermediate (between quasi-singlemode and highly multimode) case of MMS dynamics in a few-mode GRIN fiber, that supports propagation of LP_{01} and LP_{11} mode groups only (for a total of three spatial eigenmodes). This type of fiber is of interest for optical communication links using spatial-division-multiplexing [6].

Another fundamental mechanism, which is known to play a key role in SCG in singlemode fibers, is the process of dispersive wave (DW) emission from MMSs, which can be interpreted in analogy with Cherenkov radiation in electrodynamics. Wright et al. injected femtosecond pulses in the anomalous dispersion regime of a GRIN MMF, and revealed the formation of broad multi-octave SC spectra, which are characterized by the presence of an ultra-wideband series of unequally spaced sharp spectral peaks extending from the visible into the mid-infrared regions [7].

A subsequent study [8] clarified that the mechanism underlying the formation of these sideband series is the generation of DWs, resonantly phase-matched by the spatio-temporal intensity oscillations, due to self-imaging, of MMSs along the fiber.

3 Frequency conversion

MMFs can be exploited for phase-matched nonlinear mixing with large frequency shifts, by using the dispersion of the guide modes to compensate for bulk dispersion [9]. This intermodal four-wave mixing (IFWM) was recently exploited by Bendahmane et al. for telecom signal amplification and new frequency generation in a GRIN MMF, pumped in the normal dispersion regime [10].

A different type of parametric amplification process is intermodal modulational instability (IMI), which occurs in the normal dispersion regime of a few-mode GRIN MMF. IMI gain curves can be tuned by nonlinearity: the peak gain modulation frequency scales as the square root of the pump power [11].

As first predicted by Longhi, the periodic self-imaging of a beam in MMFs leads, via the Kerr effect, to a long-period grating which, regardless of the sign of fiber dispersion, introduces a parametric instability and generates ultrashort optical pulses [12]. This type of geometric parametric instability (GPI) was observed by Krupa et al. in 2016: a series of visible sidebands were generated with large frequency detuning (123.5 THz) from a 1064 nm pump [13].

Remarkably, the sideband peaks were carried by a well-defined and stable bell-shaped spatial profile. The position of GPI sidebands can be precisely engineered through appropriate fiber design, by varying the MMF core size, and concatenating different fibers [14]. A systematic analysis of GPI in nonlinear GRIN MMFs including dispersion to all orders shows that the sideband widths and positions may also be controlled by the pump power level [15].

A cascaded process of IFWM and GPI was recently experimentally demonstrated by Dupiol et al. with a 1064 nm pump, leading to far-detuned parametric frequency conversion in a few mode GRIN fiber, with parametric gain spanning from the visible (405 nm) up to the near-infrared (1355 nm) [16]. Recently, Krupa et al. have demonstrated that both spatial and spectral control of GPI sidebands can be also achieved by tailoring the fiber refractive index profile. Namely, the presence of a dip into the refractive index profile of a GRIN MMF permits to change the spatial content of spectral sidebands from the fundamental into HOMs [17].

By pumping GRIN fibers with sub-ns pulses in the normal dispersion regime, based on the interplay of GPI and Raman scattering, efficient and flat SCG extending into the visible spectral range has been reported by different groups [18, 19]. The generated spectra span more than two octaves, from below 450 nm up to beyond 2500 nm, and exhibit a high-quality, bell-shaped beam.These results may lead to a new class of high brightness and power, compact multi-octave SC sources. Eftekhar et al. further demonstrated that the spatial input profile of the pump beam can be used for a versatile tailoring the spectral content of SCG in GRIN fibers, when pumped at 1550 nm [20].

The spectral and spatial properties of second harmonic (SH) generation in an optically poled GRIN fiber were recently studied by Ceoldo et al. [21]. In contrast with poled singlemode fibers, the infrared pump generated a series of sharp sidebands around its SH, owing to the self-imaging induced χ^2 grating. The interaction between the fundamental and its SH leads to their mutual spatial cleaning from disordered speckles into bell-shaped beams [21]. Highly efficient ($\simeq 6.5\%$) and nearly instantaneous SH generation was also observed in germanium-doped GRIN silica MMFs [22].

A wavefront shaping approach has recently been introduced by Tzang et al. to control, by a spatial light modulator at the fibre input coupled with real-time spectral feedback and genetic algorithm optimization, the efficiency of stimulated Raman scattering cascade and IFWM in a MMF [23].

4 Spatial beam shaping

As well known, because of random linear mode coupling, multimode optical fibers spread a light pulse among many transverse modes. This leads to the loss of beam quality, and the emergence of a speckled output spatial beams.Recent experiments have unexpectedly demonstrated that GRIN MMFs can be used as ultrafast all-optical tools for the transverse beam manipulation of high-power laser pulses. The Kerr effect is the driving mechanism that overcomes speckle distortions, and leads to a spatially clean output beam, robust against fibre bending. Initial observations of this spatial beam self-cleaning effect involved relatively long, sub-ns pulses [24, 25]. The Kerr cleaning process was demonstrated to be effective even with femtosecond pulses in the normal dispersion regime of a GRIN MMF [26]. 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 [27].

For the use of multimode active fibers in amplifiers and lasers, it is important to investigate the possibility of Kerr self-cleaning in active, doped MMFs. Guenard et al. obtained relatively low input power threshold self-cleaning using a double-clad ytterbium doped multimode fiber (YMMF) with non-parabolic refractive index profile [28]. They have also studied a coupled-cavity laser configuration, where a passively Q-switched Nd:YAG microchip laser is combined with an extended cavity including the doped MMF [29]. For appropriate coupling levels with the extended cavity, beam self-cleaning was induced in the external cavity MMF, leading to a quasi-single mode laser output, and two-fold temporal pulse compression. Spatial self-cleaning was accompanied by far-detuned nonlinear frequency conversion.

In recent experiments, Niang et al. demonstrated spatial beam self-cleaning and supercontinuum generation (between 520 and 2600 nm) in a tapered Ytterbium-doped MMF with parabolic core refractive index and doping profiles [30]. By taper cut-back, longitudinal switching of different self-cleaned modes was also observed.

For many applications, including multi-photon imaging, it is necessary to focus and 3D scan the output pulsed beam from a MMF across a sample. As a first step to achieve flexible nonlinear focusing from a MMF, by adjusting the input injection conditions, Deliancourt et al. demonstrated Kerr beam self-cleaning in a GRIN MMF, leading to different output beam profiles, from a bell shape, and close to the LP_{11} mode [31].

Subsequent experiments including optimized adaptive wave-shaping, have achieved Kerr beam self-cleaning of many low-order modes in a GRIN MMF. The optimized self-cleaning of five different LP modes was obtained, with a power threshold growing larger with the mode order [32].

The process of spatial beam compression typical of self-cleaning can be accompanied by a simultaneous temporal compression in GRIN MMFs. In a quasi-continuous wave excitation regime, the nonlinear mode coupling process depends on instantaneous power, which permits to explore the entire range of the complex nonlinear spatiotemporal reshaping dynamics with a single optical pulse [33].

Experiments carried out in the anomalous dispersion regime of a GRIN MMF and using highly chirped optical pulses in the telecom band, demonstrated up to tenfold reduction of the threshold peak power for self-cleaning into the fundamental mode of the fiber, with remarkable stability upon further increases of the pulse peak power [34]. Highly efficient self-selection of the LP_{11} mode was also observed .

The Kerr beam cleaning into the fundamental mode of the GRIN MMF can be theoretically explained as the result of the long-term evolution of a random nonlinear wave. The optical wave exhibits a thermalization process, characterized by an irreversible evolution toward an equilibrium state. This thermalization of the optical field was described by Aschieri et al. as an effect of classical wave condensation [35].

By using a truncated model limited to the three lowest radially symmetric modes, Podivilov et al. have shown that Kerr beam self-cleaning results from a parametric mode mixing instability. In the full multimode case, FWM generates a large number of nonlinearly interacting modes with randomized phases, or an optical turbulent state. This model permits to connect self-cleaning to 2D hydrodynamic turbulence and wave condensation [36].

By using a specially designed multimode air–silica microstructure optical fiber, Dupiol et al. studied the competition between Kerr beam self-cleaning and Raman beam cleanup. It was observed that, unlike standard GRIN MMFs, Stokes Raman beam generation and cleanup lead to depletion and degradation of beam quality for the pump. Yet, the generation of a multimode supercontinuum ranging from 500 nm up to 1800 nm was reported [37].

5 Conclusion

Multimode nonlinear optics is a promising and flexible new platform for developing a whole new class of optical signal processing devices, and for the up-scaling of the energy of coherent fiber laser sources.

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