Spatiotemporal Nonlinear Interactions in Multimode Fibers

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Abstract *We observe experimentally a novel spatiotemporal dynamics of multimode fibers allowing for a new type of parametric instability and an original phenomenon of light self-organisation. Our experiments agree well with theoretical predictions and numerical simulations based on the Gross-Pitaevskii equation.*

Introduction

In contrast to single mode fibers (SMFs), multimode fibers (MMFs) provide the exciting possibility to introduce the spatial dimension and to explore the intrinsic coupling between spectral and spatial degrees of freedom in beam propagation. Such a complex dynamics may provide a new way for light control, enabling the development of breakthrough technologies to overcome the capacity and energy crunch of SMF systems. In this context, MMFs and in particular graded-index multimode fibers (GRIN MMFs) have recently attracted a great deal of attention for both fundamental and applied research. These fibers can permit to develop space-division-multiplexing systems for telecommunications [1], and ultra-broadband tuneable high-power light sources of high spatial beam quality for military and health-care applications. Only recently the group of F. Wise reported the experimental observation of multi-octave supercontinuum including intense combs of visible light and dispersive waves generated through femtosecond multimode soliton formation in the anomalous dispersion regime of GRIN MMFs [2-5].

In our work we operate in the normal dispersion regime and pump the GRIN MMFs with long sub-nanosecond pump pulses. In this propagation regime, we avoid the long pulse break-up that the modulation instability process would otherwise induce in the anomalous dispersion regime. We show the first experimental demonstration of a novel form of parametric instability, self-induced by nonlinear space-time coupling in GRIN MMFs operating in the highly multimode regime [6]. This original type of frequency conversion allows for generating a series of very intense and spatially coherent sidebands with exceptionally large frequency shifts, ranging from the visible to the near infrared spectral domain. We also discuss the influence on the spatiotemporal dynamics of the technological discrepancies in the parabolic profile of refractive index of the GRIN MMFs.

Experimental setup

We used a few meter-long, standard commercially available GRIN MMF pumped by an amplified Nd:YAG microchip laser, delivering 900 ps pulses at 1064 nm with 30 kHz repetition rate. We excited a large number of guided modes (~200) by focusing on the input face of the fiber a Gaussian pump beam with a diameter close to the value of the fiber core diameter. To analyze the Kerr-induced spectral and spatial beam reshaping occurring in the GRIN fiber, we used a VIS-near IR optical spectrum analyzer, and CCD camera with 10nm-wide bandpass interference color optical filters. Thanks to the long duration of pump pulses and the low modal dispersion of the GRIN MMF, a large number of initially excited modes could keep their temporal overlap for several tens of meters, thus allowing for strong nonlinear interactions over the entire length of the fiber under study.

Results and discussion

Figure 1 illustrates a typical example of output experimental spectrum generated by an input pump pulse with peak power $P_{P\text{-}P}$ = 50kW in a 6m-long GRIN MMF. Figure 1 shows the generation of a sequence of bright peaks, with a frequency shift from the pump as large as 123.5 THz for the first pair of sidebands. We thus observed that a narrowband near-IR laser can be directly converted into an extremely wide spectral range from the visible to near-infrared

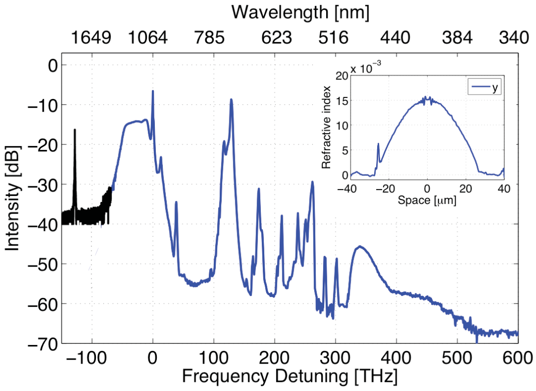

Fig. 1: Experimental spectrum obtained at the output of a 6m-long GRIN MMF with input peak power $P_{P\text{-}P}$=50kW; Inset: refractive index profile versus *y*-axis.

wavelengths. Such an interesting comb of sidebands with a frequency shift from the pump proportional to the square root of their respective integer order is generated by a space-time coupling mechanism. In fact, our new type of parametric instability is dynamically phase-matched by the longitudinal refractive index grating induced, via the Kerr nonlinearity, by the natural periodic self-imaging of multimode waves in GRIN MMFs. This type of spatiotemporal instability was not observed when we initially excited the fundamental mode of the fiber only.

The spatial beam shape of pump and Stokes waves is shown in Fig.2. Surprisingly, we notice that an initially multimode field (speckled pattern) evolves at high powers into a bell-shaped beam at all wavelengths. This nonlinear beam resembles to the quasi-fundamental mode of the fiber, and is very robust against mechanical perturbations. Note that, this counterintuitive effect of self-organization of multimode light is very different from the

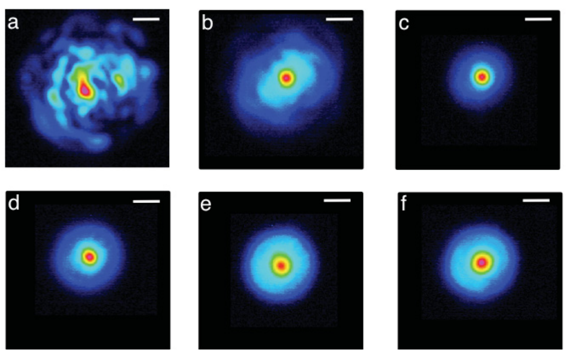

Fig. 2: Experimental 2D output spatial profiles of the pump at 1064 nm with $P_{P\text{-}P}$=0.06 kW (a) and $P_{P\text{-}P}$=50 kW (b), and at the anti-Stokes sidebands at 750 nm (c), 650 nm (d), 600 nm (e) and 550 nm (f) at $P_{P\text{-}P}$=50 kW; Results obtained in the 6m-long GRIN MMF; Scale bar =10 μm.

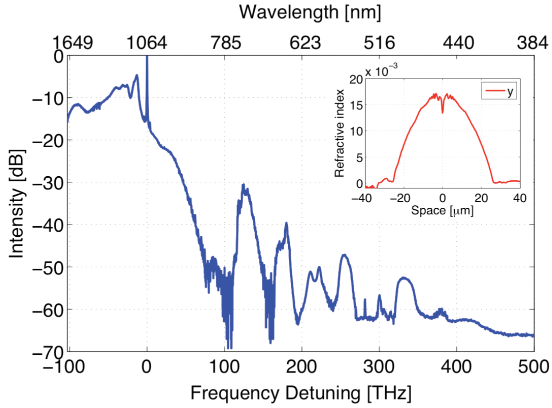

Fig. 3: Experimental spectrum obtained at the output of a 10m-long GRIN MMF with input peak power $P_{P\text{-}P}$=40kW; Inset: refractive index profile versus *y*-axis.

phenomena of Raman and Brillouin beam clean-up, that have been previously studied in the literature [7,8].

We also investigated the influence of the parabolic refractive index profile of the GRIN MMF. Figure 3 presents an example of the output experimental spectrum obtained for an input peak power $P_{P\text{-}P}$ = 40kW injected in a 10m-long GRIN MMFs with an index profile having a characteristic “dip” in the fiber center (see the inset of Fig.3), in contrast with the well-defined index profile of the fiber involved in previously discussed results (see inset of Fig.1). We observed that such a seemingly minor imperfection drastically reduces the conversion efficiency of the spatiotemporal instability process: the first order sideband peak pair appears with around 30dBs of lower intensity.

Moreover, as presented in Fig.4, in spite of the highly multimode input excitation at the pump wavelength, in the present case we

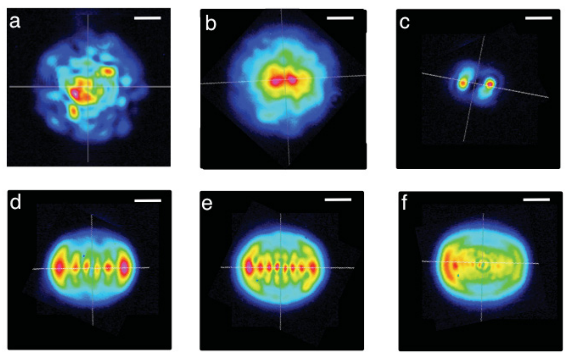

Fig. 4: Experimental 2D output spatial profiles of the pump at 1064 nm with $P_{P\text{-}P}$=0.06 kW (a) and $P_{P\text{-}P}$=40 kW (b), and at the anti-Stokes sidebands at 750 nm (c), 650 nm (d), 600 nm (e) and 550 nm (f) at $P_{P\text{-}P}$=40 kW; Results obtained in the 10m-long GRIN MMF; Scale bar =10 μm.

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observed that the generated sidebands were carried by higher-order modes with even parity symmetry. The higher the order of the peak, the higher was the order of the associated spatial mode. In this case the spatiotemporal dynamics can be understood as being determined by the phase-matching conditions of the intermodal four-wave mixing, which permits to calculate the wavelengths and modal compositions of the observed parametric spectral lines [9].

Our experimental results agree very well with theoretical predictions [10] and our numerical simulations performed by directly solving the generalized (3+1)D nonlinear Schrödinger equation (3DNLSE), also known as the Gross-Pitaevskii equation:

$$\frac{\partial A}{\partial z} - i\frac{1}{2k_0}\nabla_\perp^2 A + i\frac{\kappa''}{2}\frac{\partial^2 A}{\partial t^2} + i\frac{k_0\Delta}{\rho^2}r^2 A = i\gamma|A|^2 A \quad (1)$$

where A(x,y,t) is the complex field envelope, *t* is time, *x* and *y* are the transverse beam coordinates, *z* is the beam propagation coordinate, γ is the fiber nonlinear coefficient, $r^2 = x^2 + y^2$, ρ is the fiber core radius, k_0 is the wave vector, κ'' is the group velocity dispersion at the pump wavelength.

Conclusions

We reported on a new methodology to shape intense optical pulses in both their spectral and spatial domains. We demonstrated the first experimental observation of spatiotemporal parametric instability, self-induced by the collective oscillations of multimode waves, and providing a large frequency shift of around 123.5THz for the first-order sidebands. We noticed that the conversion efficiency of this parametric effect considerably decreases when the parabolic refractive index profile has a “dip” in the centre owing to the technological process of fiber fabrication. Moreover, we showed that, by exploiting the Kerr effect, it is possible to significantly increase the spatial coherence of an initially low quality (multimode) beam [11].

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