Spatio-Temporal Beam Mapping for Studying Nonlinear Dynamics in Graded Index Multimode Fiber

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Abstract: We experimentally demonstrate high-resolution mapping of the spatio-temporal dynamics of the beam cleaning process in graded index multimode fibers. This high-resolution characterization reveals the time-dependent nature of the beam self-cleaning process.

Thanks to their reduced modal dispersion, graded index multimode fibers (GIMFs) permit long interaction distances between guided modes, allowing for the emergence of new nonlinear dynamics. Among these effects, we may mention multimodal solitons, spectral sideband generation via geometric parametric instability (GPI), Kerr self-cleaning, Raman beam cleaning, and supercontinuum generation [1-6]. The Kerr beam self-cleaning process has been experimentally reported by Krupa *et al.* by launching into GIMFs sub-nanosecond pulses propagating in the normal dispersion regime [6]. This early study showed that, at high powers, the Kerr effect in GIMFs transfers into a single mode, close to the fundamental, a large part of the energy that was initially coupled into a large number of transverse modes. Up to now, the Kerr beam self-cleaning process has been only experimentally studied with slow cameras that integrate the beam energy over a large temporal window of a few hundreds of microseconds that is longer than the period of the pulse train. However, since the Kerr effect is almost instantaneous, we anticipate that the transverse energy redistribution should be determined by the instantaneous value of the pulse power that varies over a picosecond time scale. In particular, we expect that the output beam will exhibit a transition from a multimodal distribution at the pulse edges, toward a quasi-singlemode content at the pulse center (by assuming a quasi-Gaussian unimodal energy distribution in time, for example). Unfortunately, any slow speed camera will time-integrate the superposition of all those different beam states, and will not allow for an accurate characterization of the processes at stake in the beam self-cleaning phenomenon. In this communication, we present a new detection device that captures the spatial distribution of the output laser beam over 50 frames per pulse (i.e., a temporal resolution of 30 ps, for a pulse duration of 1.5 ns at $1/e^2$). We used this system to reveal, for the first time to our knowledge, the time-dependent nature of the beam self-cleaning process.

Our experimental bench is based on a microchip laser delivering 1.5 ns ($1/e^2$) pulses at a rate of 27 kHz, centered at 1064 nm. The 44 µm diameter Gaussian beam (@$1/e^2$) with a linear polarization state is injected into a GIMF. This fiber has a length of 6 m, a core radius of 25 µm, a core to cladding index difference of 0.015, and a numerical aperture of 0.2. Near field imaging, taken with a CCD camera, shows that for an input peak power of 500 W we obtain a speckled multimode beam at the fiber output. The Kerr beam self-cleaning process appears as the power reaches 2.5 kW, with a large part of the output beam energy remaining confined into the fundamental mode. From these preliminary results, we performed a spatiotemporal mapping. This consists of collecting, via a single mode optical fiber, the energy contained in each pixel of the enlarged image of the beam, and measuring its temporal profile via a 25 GHz bandwidth InGaAs photodiode linked to a 20 GHz Oscilloscope (Lecroy 820zi). The use of a fast oscilloscope allows for a good dynamic range, and a temporal resolution below 30 ps. In this way, we obtained a 3D matrix that permits us to reconstruct, for each point in time, the intensity profile of the output beam. The scanning stage is composed of a motorized 3-axis stage. It is important to note that a second silicon photodiode measures the input signal beam and acts as a trigger.

In a first step, we plotted the evolution, versus the input peak power, of the beam temporal profile obtained by performing an integration over all pixels of the output beam image (see fig. 1 (a)). The reconstructed pulse shape remains constant up to 10 kW, where Raman scattering (SRS) arises, causing a depletion at the center of the signal pulse. On the one hand, the observed behavior demonstrates the negligible impact that fiber dispersion and group velocity difference between modes have on the output pulsed profile during the self-cleaning process. On the other hand, an integration restricted to the beam area defined by the fundamental mode highlights the mechanism of the spatial self-cleaning, which is based on the energy exchange between transverse modes. Indeed, in that situation a cyclic evolution of the pulse peak power is observed, revealing the periodic nature of the energy exchange between the fundamental and other higher-order modes (see inset figure 1 (a)) [7].

In a second step, and from the same set of data, we plotted the output beam pattern computed at different points in time, i.e., for different positions inside the pulse profile (with 30 ps resolution). In the linear regime, the same specular transverse intensity distribution is obtained at each position across the entire pulse profile (see fig. 1 (b)). By increasing the input peak power, only the top of the pulse starts to self-clean, whereas the pulse wings exhibit almost the same speckles as obtained in linear conditions (see fig. 1 (c)). Finally, for very high peak powers, the Raman process comes into play, until it significantly depletes the central portion of the pulse. The remaining pulse at 1064 nm remains mostly self-cleaned, and it always shows a bell-shaped spatial profile. Only the low energy pulse wings remain with a speckled output spatial intensity pattern.

It is also important to note that, by combining our temporal analysis with a multiband filter, we could record the spatio-temporal evolution of both the signal beam and of the second Raman Stokes beam. In that configuration, we could show that the 1280 nm 2nd Stokes wavelength is cleaned by the combined action of Kerr and Raman cleanup processes. The temporal shape and position of that cleaned wavelength is then clearly visible on fig.1 (d).

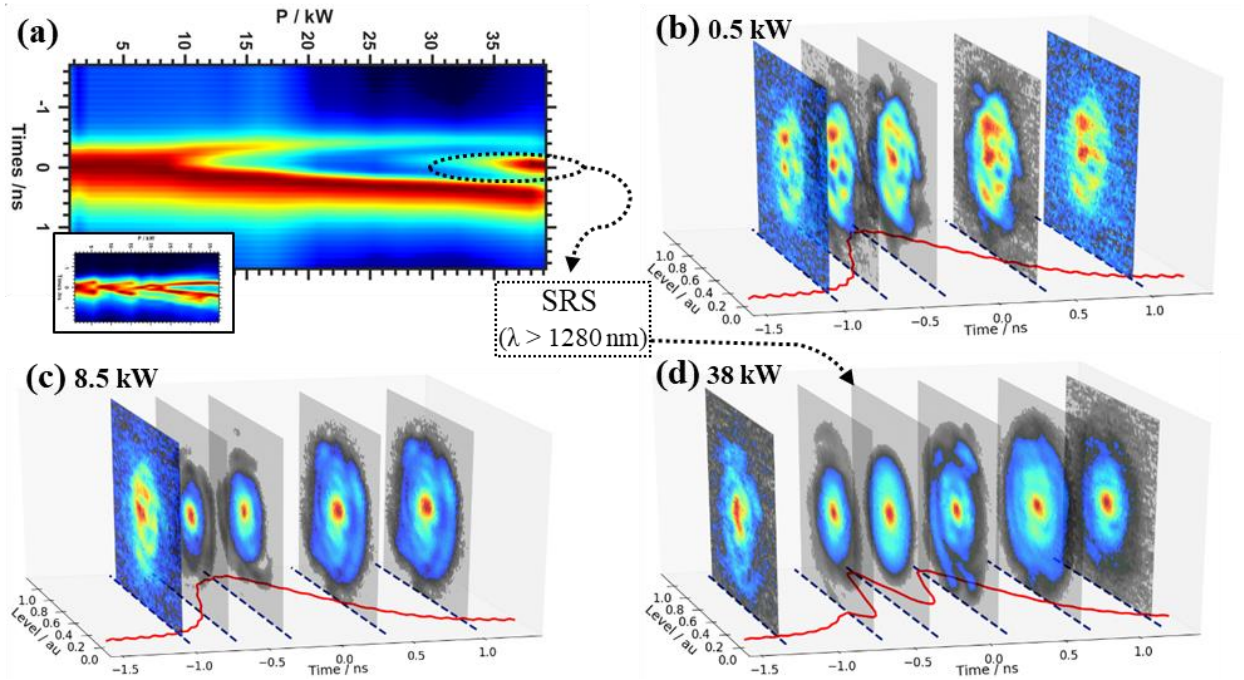

Fig. 1: (a) Evolution of the temporal profile of the pump pulse at 1064 nm (integrated over all pixels constituting the output image) versus peak power. Inset: Evolution of the temporal profile of the pump pulse at 1064 nm versus peak power when light is collected at the beam center by a standard singlemode fiber. (b-d) Temporal profile of the pump wave (red line) after propagation in a 50/125 6m long GIMF with local reconstruction of the output beam profile for (b) 0.5 kW, (c) 8.5 kW and (d) 36 kW.

In conclusion, we carried out a set of high-resolution (30 ps) spatio-temporal mapping of a beam after propagation through a GIMF by using a new experimental procedure, involving a fast oscilloscope and a motorized stage. We have experimentally shown that Kerr beam self-cleaning is a complex spatiotemporal process, based on a cyclic energy exchange between transverse modes. Different spatial energy distributions and cleaning efficiencies may be observed for different points in time across the pulse profile. A spatial selection of the energy constituting the output beam profile may also introduce significant pulse reshaping. We may envisage several applications of the observed temporal pulse reshaping, such as a fast saturable absorber.

[1] A. Picozzi, G. Millot, and S. Wabnitz, “Nonlinear virtues of multimode fibre,” Nat. Photonics 9, 289–291 (2015).
[2] W. H. Renninger and F. W. Wise, “Optical solitons in graded-index multimode fibres,” Nat. Commun. 4, 1719 (2012).
[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] K. Krupa, *et al*, “Observation of geometric parametric instability induced by the periodic spatial self-imaging of multimode waves,” Phys. Rev. Lett. 116, 183901 (2016)
[5] Terry, Nathan B., Alley, Thomas G., et Russel, Timothy H., ”An explanation of SRS beam cleanup in graded-index fibers and the absence of SRS beam cleanup in step-index fibers,” Optics express, 2007, 15, 17509-17519 (2007).
[6] Katarzyna Krupa, *et al*, "Spatial beam self-cleaning in multimode fiber," Nat. Photon. 11, p. 237 (2017).
[7] Katarzyna Krupa, Alessandro Tonello, Vincent Couderc, Alain Barthélémy, Guy Millot, Daniele Modotto, and Stefan Wabnitz; “Spatiotemporal light beam compression from complex nonlinear mode mixing,” Phys. Rev. A, 97, (2018).