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Experimental signatures of extreme optical fluctuations in lumped Raman fiber amplifiers

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ABSTRACT

In this work, we experimentally investigate several temporal and spectral methods to highlight extreme fluctuations which can develop during the Raman amplification of an ultrashort pulse train. Forward and backward pumping schemes are compared to dual pass configurations.

1. Introduction

The study of extreme statistics in nonlinear fiber optics is a topic that has recently stimulated much attention. Following the pioneering work of Solli and coworkers [1] that have reported the observation of statistics analogous to hydrodynamic rogue waves in the formation of optical supercontinuum, most of the initial works have focused on the passive propagation of picosecond pulses in photonic crystal fibers [2]. Those different studies carried out in the anomalous dispersion regime have highlighted the specific role played by modulation instability, Akhmediev breathers [3,4] as well as Raman frequency shifted solitons that are also affected by third-order dispersion and resulting pulse-to-pulse interactions [5,6]. However, observation of statistics that strongly deviate from a Gaussian distribution is absolutely not restricted to supercontinuum generation and can also be observed in telecommunication applications in the context of transmissions [7–9], Raman fiber lasers [10,11] as well as discrete amplification [12,13]. More precisely, in this latest field, it has been shown that under certain conditions, statistical distribution of an amplified signal can be strongly reshaped during the amplification process. Examples of this deleterious degradation have been discussed for parametric amplifiers [12,14–16] and for Raman amplifiers [13,17–19]: in both cases, a quasi-instantaneous gain and a low walk-off between the signal and a partially coherent pump lead to a dramatic transfer of fluctuations from the pump to the signal in a co-propagating configuration. In a previous work, we have numerically and analytically described the evolution of a continuous signal in a co-propagating amplifier in the presence of a low walk-off and pump depletion [18]. We have also shown that an adequate frequency shifted optical bandpass filter can isolate the most extreme structures [17].

In this contribution, we focus our attention on experimental results outlining the drastic consequences of the transfer of intensity fluctuations from the pump to a pulsed signal in a lumped Raman amplifier. Indeed, due to their scarcity and their high amplitude, characterization of the impact of extreme statistics remains a tricky task. Contrary to widespread quantitative techniques such as the measurement of the optical noise signal ratio (OSNR) or the relative intensity noise (RIN) [20], we have chosen to present here a set of alternative qualitative methods that show the emergence of extreme fluctuations in a 10 GHz pulse stream. More precisely, this paper will successively present statistical records using photodiodes, optical auto-/cross-correlations, RF spectrum and optical spectrum. Forward and backward pumping schemes will be compared to dual-pass configurations.

2. Experimental setup

Our experimental setup is sketched in Fig. 1a. An actively mode-locked erbium-doped fiber laser delivers a train of 2.9 ps pulses at a repetition rate of 10 GHz and with an initial average power of 10 mW (corresponding to a peak power of ~300 mW) at a wavelength of 1550 nm. Let us note that our previous works [13,17] or [21] involved much lower repetition rates as the signal source was a MHz passively mode-locked fiber laser. The pump is delivered by a Raman continuous wave fiber laser centered at 1455 nm with an average power up to 2 W. An essential point is that this pump is a partially incoherent wave (~20 GHz of spectral

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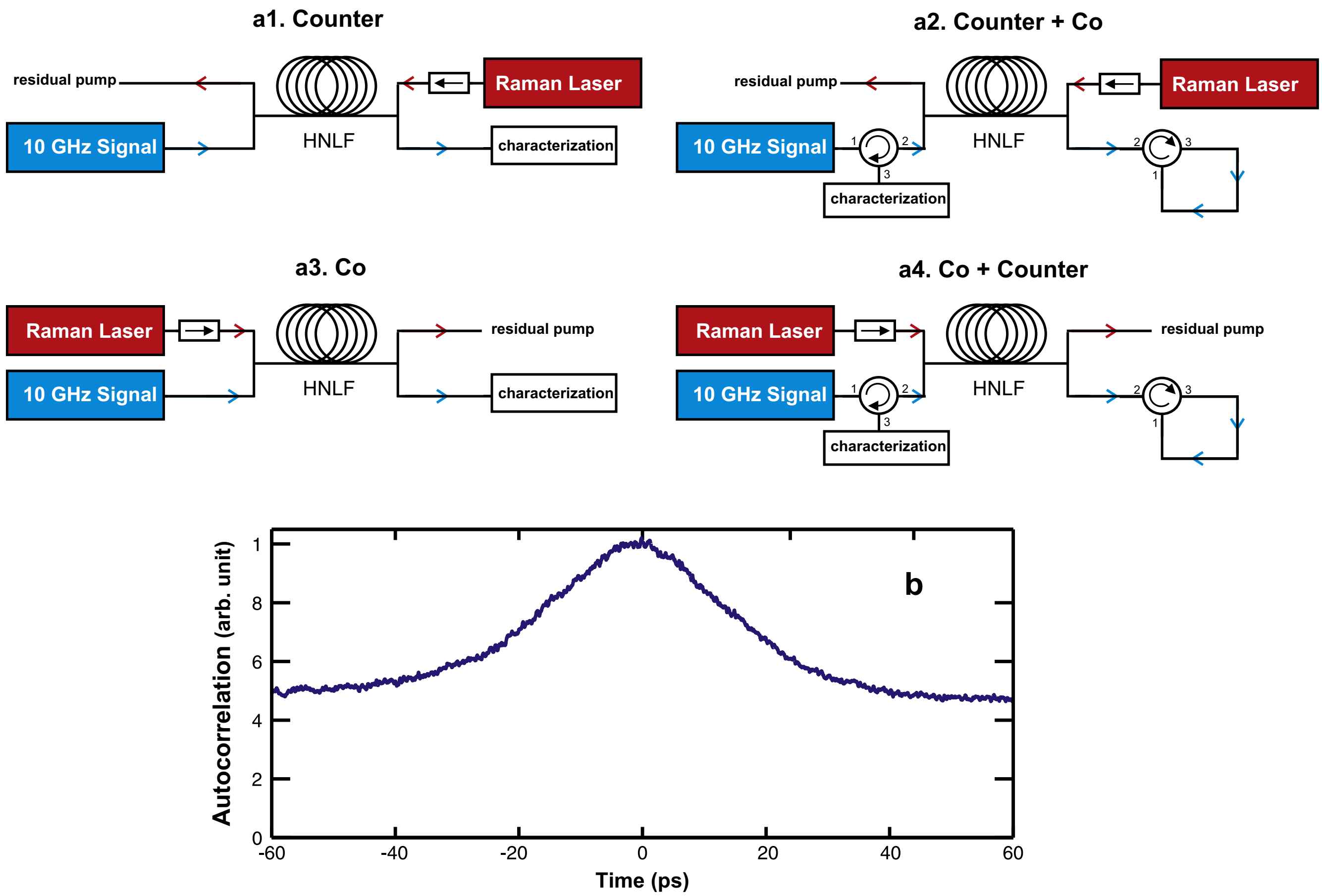

Fig. 1. (a1–a4) Various experimental setups under investigation. (b) Intensity autocorrelation of the pump.

width) that exhibits high contrast, fast intensity fluctuations [21]. Indeed, its intensity autocorrelation signal (plotted in Fig. 1b) presents a characteristic contrast of one half [13,22] with a temporal width of 25 ps. This temporal duration is a characteristic time of the shortest pump fluctuations and is much larger than the picosecond signal to be amplified while being shorter than the temporal separation between two successive pulses.

The amplification is performed in a 1-km long highly nonlinear fiber (HNLF). The low normal dispersion (0.7 ps km^{-1} nm^{-1}) enables us to avoid solitonic or modulation instability effects. The high nonlinearity (10 W^{-1} km^{-1}) leads to a high Raman gain coefficient whereas linear losses and third-order dispersion are limited (0.70 dB km^{-1} and 0.01 ps nm^{-2} km^{-1} respectively at 1550 nm). We have compared several pumping schemes: backward pumping (Fig. 1a1), forward pumping (Fig. 1a3) and two bi-directional pumping (Fig. 1a2 and a4) relying on the use of optical circulators. Moreover, several pump powers ranging from 500 to 1500 mW have been tested, leading to integrated gains from 5 to 15 dB in single pass configurations and gains from 10 to 22 dB in dual-pass configurations.

Several characterizations of the optical properties of the amplified signal have been carried out. In the temporal domain, we have recorded the output pulse train and its associated statistics thanks to a high speed digital sampling oscilloscope (Tektronix TDS CSA 8200) combined with a photodiode having a 30 GHz bandwidth. We have complemented our study by using an optical intensity autocorrelator (Femtochrome, FR-103HS) to investigate pulse-to-pulse fluctuations. Radio frequency spectra as well as optical spectra were also recorded and further insights on the spectral stability were gained by mapping the spectral evolution into the temporal domain.

3. Oscilloscope observations and statistical records

The most intuitive and straightforward way to explore and evaluate signal variation at the output of the Raman amplifier is the direct observation on a high-speed oscilloscope. Indeed, the eye-diagram enables us to visualize the variations of the signal level in the various experimental configurations. Given the finite bandwidth of the electronics under use (typically 30 GHz, much below the optical bandwidth of our pulses), we do not resolve the details of the temporal intensity profile of the picosecond pulses. Therefore, we do not monitor rigorously the peak power of the pulses, but rather the fluctuations of their energy. As a first approximation and given the fact that the amplified pulses do not exhibit any pulse splitting in our normally dispersive fiber, we can however consider that those energy fluctuations are directly proportional to peak power variations [23].

The choice of the pumping configuration has a strong impact on the amplifier performance as can be readily noticed in Fig. 2. When the signal and the pump counter-propagate in the fiber, the output pulse train exhibits a low level of fluctuations (Fig. 2b) and maintains a quality comparable to the initial mode-locked signal (Fig. 2a) even for high pump levels (Fig. 2b2 and b3). On the contrary, in a co-propagating scheme, the stability of the output pulse train is drastically affected (Fig. 2c). Moreover, the pump level impacts directly on the signal degradation: higher the pump power is, higher the fluctuations are (Fig. 2c1 and c2). However, for the highest values of the pump power (Fig. 2c3), fluctuations seem to decrease. Similar conclusions can be drawn in bi-directional configurations (Fig. 2d).