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Extreme statistics in Raman fiber amplifiers: influence of pump depletion and dispersion

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Abstract: We experimentally and theoretically investigate the influence of pump depletion effects on extreme statistics observed in fiber Raman amplifiers. We also report on the impact of the dispersion of the fiber.

OCIS codes: (060.4370) Nonlinear optics, fibers; (060.2320) Fiber optics amplifiers.

1. Introduction

Following the recent description of rogue wave-like structures emerging from optical supercontinua generated in microstructured fibers [1], extreme statistics in nonlinear photonics has stimulated large interest in the community. It has indeed been outlined that the ultrashort rogue solitons initiated by modulation instability exhibit peak powers following a strongly non-Gaussian probability distribution. However, observation of such non-Gaussian behavior is not confined to processes involving ultra-broadband spectral expansion : similar heavy tailed probability distributions have also been reported at telecommunication wavelengths in fiber amplifiers based on partially incoherent pumping [2, 3]. In more detail, it has been shown that under negligible group velocity dispersion between the pump and the signal, the ultrafast fluctuations of the pump can be exponentially transferred on the signal, leading to strong reshaping of the gain properties [4].

We focus here our attention on Raman amplifiers [5] and we describe the influence of the dispersive properties of the fiber as well as the impact of the initial signal level. Experimental measurements highlight that both temporal and spectral properties are affected by these factors. The recorded evolutions can be reproduced by analytical and numerical modeling.

2. Experimental set-up

The experimental set-up we used is similar to the one reported in [2] and is sketched in Fig. 1a. The initial partially incoherent pump is delivered by a Raman laser [6] with an average power of 300 mW. The signal is a continuous wave at 1550 nm with an average power of 0.2 mW. The Raman amplifier under investigation is pumped in a co-propagating configuration and relies on the use of commercially available highly non-linear fibers (HNLF) with a typical length of 500 m, a non-linear coefficient $\gamma = 10 \text{ W}^{-1} \cdot \text{km}^{-1}$ and a dispersion β_2 in the range of $\pm 1 \text{ ps/nm/km}$. At the output of the device, the signal is characterized by means of a photodiode that reveals (Fig. 1b) the spontaneous emergence of spikes with amplitude exceeding more than 100 times the average power. Autocorrelation measurements provide additional information on the typical temporal duration of those extreme picosecond spikes. Moreover, the contrast of the autocorrelation (i.e. the ratio between the maximum of the autocorrelation and its minimum) is an indirect indication of the relative amplitude of the spikes. To complete the analysis of the amplified signal, we have also recorded the output optical spectrum. Note that spectral filtering of this expanded spectrum is a convenient way to isolate the rarest structures [7].

We first investigate the influence of the amplitude of the initial continuous seed. Records made for initial powers ranging from 0.2 mW to 8 mW reveal the strong impact of this factor: the autocorrelation is broadened when increasing power and the contrast decreases (Fig. 1c1). Regarding the spectral domain (Fig. 1c2), a narrowing of the output signal can be observed: due to the strong depletion effects occurring for high initial powers, the cross-phase modulation of the pump on the signal is weakened.

Thanks to several HNLFs, we have been able to explore various values of walk-off δ between the pump and the signal (Fig. 1d, values spanning from 0 ps to 75 ps). It appears from the autocorrelation measurements that the temporal width of the autocorrelation is not very sensitive for δ in the range 0-50 ps. Such a value has to be compared to the characteristic width of the pump fluctuations which is around 25 ps (blue curve, Fig. 1d1. Such interesting behavior has recently been used in [8]). For higher values of δ , the central peak of the autocorrelation broadens. The output spectrum is more sensitive and increasing walk-off values leads to a narrowing of the output spectrum. Let us note that no major difference has been noticed between using normally and anomalous dispersive HNLFs, confirming that the dynamics involved in the emergence of the spike is not linked to solitonic behavior.

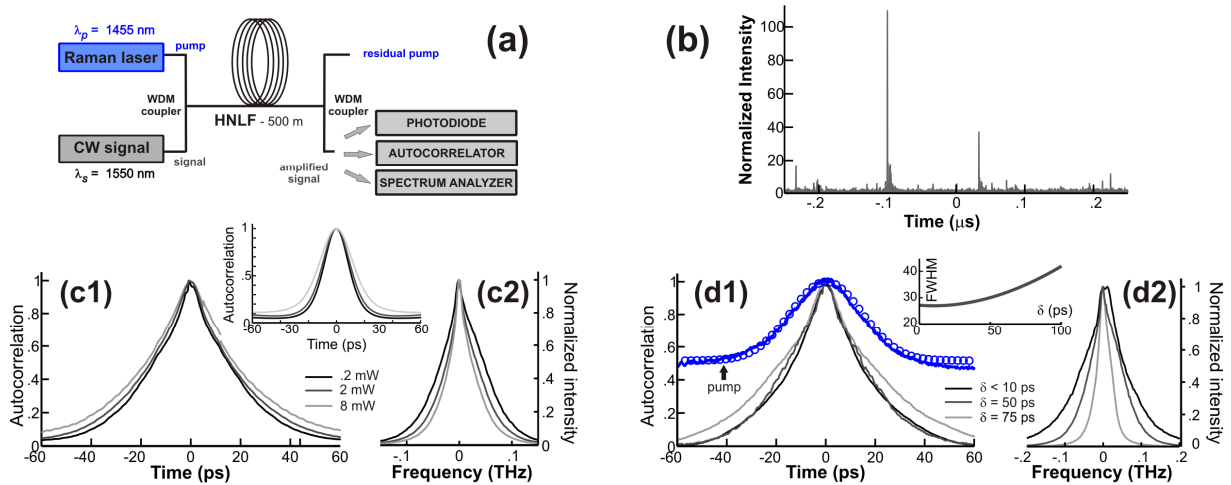


Fig. 1. (a) Experimental set-up. (b) Oscilloscope trace of the signal after amplification. (c) Influence of the initial signal average power : intensity autocorrelation (c1) and optical spectrum (c2). Inset : results from numerical simulations. (d) Influence of the walk-off parameter δ : autocorrelation (d1) and spectrum (d2). Inset : numerical result of the evolution of the autocorrelation width for various values of δ .

3. Theoretical modeling

In order to confirm the experimental temporal and spectral trends, we have modeled the evolution of the optical signal and pump fields in our Raman amplifiers by using a set of coupled non-linear Schrödinger equations [5] :

$$\begin{cases} \frac{\partial \psi_p}{\partial z} = -\frac{g_R}{2} |\psi_s|^2 \psi_p + 2 i \gamma |\psi_s|^2 \psi_p \\ \frac{\partial \psi_s}{\partial z} = \frac{g_R}{2} |\psi_p|^2 \psi_s + 2 i \gamma |\psi_p|^2 \psi_s + \delta \frac{\partial \psi_s}{\partial T} \end{cases}$$

We have carefully checked that second and third order dispersions and self-phase modulation were not crucial to explain the main features that have been experimentally observed. The partially incoherent nature of the pump is taken into account, the pump being modeled in the spectral domain by a Gaussian intensity field having a stochastic phase [6, 8]. Based on this model, we have been able to reproduce accurately the temporal and spectral properties of the amplified signal (see for example insets of Fig. 1c and 1d). Analytical predictions of the probability distribution function including depletion effects or walk-off effects have been derived and have confirmed the heavily tailed nature of statistics. Increasing depletion and walk-off both tend to lower the heavily tailed nature of the statistics.

4. Conclusion

In conclusion, we have experimentally and theoretically highlighted the influence of depletion effects as well as the impact of the walk off between the pump and signal. The temporal typical duration of the intense spike of light can therefore be tailored by adjusting these two parameters and it is possible to obtain structures having a longer duration than the initial fluctuations of the pump. All those points are crucial for a better understanding and control of the extreme structures that appear in fiber amplifiers pumped by a partially coherent source of light.

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