Observation of extreme temporal events in CW-pumped supercontinuum

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Abstract: We study experimentally and numerically the temporal features of supercontinuum generated with a continuous-wave ytterbium-doped fiber laser. We show that the temporal output of the supercontinuum is characterized by strong and brief power fluctuations, i.e. so-called optical rogue waves. We demonstrate numerically that these rare and strong events that appear and disappear from nowhere result from solitonic collisions.

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1. Introduction

Supercontinuum generation has attracted much attention [1] since the first demonstration in photonic crystal fibers (PCFs) using an extremely high power femtosecond oscillator [2]. It was soon followed by a number of impressive results in longer pulsed regime, quasi-continuous wave and even continuous wave (CW) pumping schemes [1]. Over the past decade, a large number of studies focused on the spectral properties of supercontinua, but the temporal properties were not so extensively studied, certainly because of the complexity to characterize them experimentally. Nevertheless, the coherence properties of supercontinua pumped with femtosecond lasers has been studied [3,4] because these characteristics are of primary interest for frequency comb generation. In the picosecond pumping regime, Solli et al. have recently reported important intensity fluctuations, corresponding to solitons located at the red edge of the spectrum [5]. By studying the statistical properties of these fluctuations experimentally and numerically, they observed an L-shaped profile indicating the presence of very rare events with a peak power well above the mean peak power of the output pulses. They called these rare events optical rogue waves (ORWs), by analogy with ocean freak waves, whose statistical properties of appearance exhibit the same L-shaped profile [5]. In the CW pumping regime however, only numerical studies were performed [6]. Temporal fluctuations with a very low degree of coherence were reported [6], but no experimental measurement has been performed to characterize the temporal properties of the output light.

The aim of this paper is to experimentally study the temporal properties of supercontinua in the CW pumping regime, and therefore to address the lack of information about this in the extensive literature concerning supercontinuum generation. We show experimentally and numerically that CW-pumped supercontinua also exhibit so-called ORWs, whose peak power is extremely much larger that the input average power of the CW laser. We stress that these extreme events differ from the ones observed with a pulsed pumping [5]. In our case we show that they result from temporal collision among a gas of solitons, whereas in the case of pulsed pumping they correspond to intense solitons that are ejected during the propagation from the pulsed temporal shape of the pump [5]. It is important to note that soliton collisions also arise in the picosecond (quasi-CW) regime [1]. As a consequence, the same interpretation of ORW formation should be possible in this pumping scheme.

2. Experiments

Efficient supercontinuum generation with a CW pump laser is achieved by pumping a fiber in a low anomalous dispersion region, i.e. just above the zero-dispersion wavelength. Due to modulation instability, solitonic pulses close to fundamental solitons are formed in the spectral region around the pump wavelength. These soliton-like pulses then experience Raman induced self-frequency shift, leading most of the time to a long-wavelength spectral broadening [7]. Depending on the dispersion properties of the fiber, the propagation of solitons can be accompanied by the generation of blue and/or red shifted dispersive waves [8] that can be trapped by solitons through cross-phase modulation [9–11].

The pump laser used in our experiments is a CW ytterbium-doped fiber laser delivering up to 20 W average power at the wavelength $\lambda_p$ of 1064 nm with a line width of 0.5 nm. The output of the fiber laser was collimated and launched into a 400 m long PCF with a zero-dispersion wavelength of 1062 nm and a nonlinear coefficient $\gamma$ of 10 $\text{W}^{-1}\text{km}^{-1}$. The output spectrum measured for a launched power of 10 W is displayed in Fig. 1(a). It spans from about 900 to 1300 nm, with an average output power of 2.2 W. It is now commonly accepted in the literature that for $\lambda > \lambda_p$, the spectrum is mainly composed of solitons (in fibers with a single zero-dispersion wavelength), and for $\lambda < \lambda_p$, it is mainly made of dispersive and trapped
dispersive waves [10,12,13]. In order to study the temporal properties of the most powerful pulses (i.e. the solitons located in the long-wavelength side of the supercontinuum), we used a setup similar to that used in pulsed pumping condition [14]. To this end, a long-pass spectral filter with a cut-off wavelength of 1200 nm was placed at the output of the fiber. The filtered light beam was then sent to a 12 GHz photodiode linked to a 2 GHz analogical oscilloscope with 10 GSamples/s. Figure 1(b) shows the temporal trace recorded on the oscilloscope and Fig. 1(c) is a close-up of this recording. It corresponds to a large number of experimental acquisitions represented end to end over a total temporal window of 0.35 ms. These experimental recordings show rare peaks, randomly distributed in time and whose intensity is clearly stronger (two to three times) that the surrounding peak mean amplitude. The probability density function (PDF) of this trace is represented in Fig. 1(d). In order to ensure that we account for pulses and not background noise in the statistical study, we only considered spikes with a power larger than a given threshold. This threshold value corresponds to red rectangles in Figs. 2(b), (c) and (d). Figure 1(d) shows that powerful and rare temporal events are generated and that they exhibit an L-shaped statistical curve. In logarithmic scale, the evolution of the PDF is quasi-linear, indicating a quasi-exponential behaviour in the linear scale (L-shape). The shape of our experimental PDF [Fig. 1(d)] does not depict a bell-shape profile which is characteristic of Akhmediev breathers [15,16].

![Fig. 1. (a) Experimental spectrum for a launched power of 10 W and a fiber length of 400 m. The vertical lines indicate the cut-off wavelength of the long-pass filter used. (b)-(c) Typical oscilloscope traces with long-pass filters. (d) Corresponding probability density function.](image)

In pulsed pumping schemes, these kind of rare events have been called ORWs [5] for their statistical similarities with the ocean rogue waves. Based on this criterion, one could also name our experimental extreme events ORWs. However, ORWs observed in Refs [5,14] are giant solitons that are ejected from the pump packet. We will show, in the following, that in the CW pumping scheme, these ORWs come from the collision of two propagating intense solitons. Thus the mechanism of ORW emergence, in our situation, is drastically different from the one of pulsed pumping even if the PDF feature remains similar.

As discussed previously, the most relevant criteria for characterizing the extreme events is the study of the PDF. In order to reproduce such a PDF and try to identify the mechanism responsible of the emergence of these ORW, we performed numerical simulations.

3. Numerical simulations

To get a deep insight on the formation of rare events in the temporal domain, we integrated the following generalized nonlinear Schrödinger equation which takes into account the third-order dispersion and Raman terms:

$$\frac{\partial E}{\partial z} = -\frac{1}{2}\beta_2 \frac{\partial^2 E}{\partial \tau^2} + \frac{\beta_3}{6} \frac{\partial^3 E}{\partial \tau^3} + i\gamma E(z, \tau) \int_{-\infty}^{\infty} R(\tau') |E(z, \tau - \tau')|^2 d\tau' - \frac{\alpha}{2} E$$  \hspace{1cm} (1)
where $E(z,t)$ is the electric field envelope of the pump in a retarded time frame $\tau = t - \beta_1 z$ moving at the group velocity $1/\beta_1$, $\gamma$ is the nonlinear coefficient at the pump wavelength, $\beta_2$ and $\beta_3$ are the second and third-order dispersion terms and $\alpha$ is the linear fiber attenuation at the pump wavelength. $R(\tau) = (1-f_R)\delta(\tau) + f_R h_R(\tau)$ is the nonlinear response of silica ($f_R = 0.18$ [17]). We checked that higher dispersion orders as well as higher nonlinear effects such as self-steepening have no noticeable impact on the results. The pump laser was taken as a plane wave, with additional white Gaussian noise corresponding to half photon per mode. We used 32768 points in a temporal window of 109 ps. This resolution corresponds to a good trade-off between time consuming and to the wrapping associated with the used split step Fourier method. It is important to note that the values of all fiber parameters (dispersion, attenuation, length and nonlinearity) as well as input pump characteristics have been chosen as close as in the experiments. All these values are listed in Fig. 2 caption. In order to account for the experimental long integration time imposed by the optical spectrum analyzer, an averaging procedure has been used numerically [6]. Figure 2(a) shows the numerical spectrum obtained by averaging 100 simulations corresponding to 100 different realizations of the initial input noise. The agreement between the experimental [Fig. 1(a)] and numerical [Fig. 2(a)] spectra is excellent. An example of simulated temporal output fiber intensity is displayed in Fig. 2(b) and the corresponding PDF is plotted in Fig. 2(c). The same qualitative features as in experiments are found. Rare and strong power temporal events are observed. The numerical PDF [Fig. 2(c)] depicts an L-shaped statistical profile in linear scale [Fig. 2(c)]. This numerical curve doesn't agree with the probability distribution obtained for the exact solutions of the nonlinear Schrödinger equation (NLSE) also called Akhmediev breathers [1516]. This is not surprising since in the Eq. (1) used here, Raman and third-order dispersion effects are added with respect to the NLSE studied in [1516]. Thus, the nature of the extreme waves presented here are different from the ones discussed in these Refs. The good qualitative agreement between experimental and numerical results on both spectral and temporal aspects allows us to investigate numerically the temporal formation of optical rogue waves, which is not accessible experimentally.

4. Discussion of extreme events formation

Let us focus our numerical analysis on a single-shot simulation corresponding to one initial noisy CW pump field. Figure 3 shows the spectral (a) and temporal (b) dynamics of the field propagation along the fiber. At the beginning of the fiber (approximately within the first 100 m), the modulation instability process converts the CW field into a train of solitonic pulses, with comparable but not identical peak powers due to noisy random initial conditions. The most powerful solitons [depicted by white circles in Fig. 3(a) and (b)] undergo the strongest Raman self-frequency shifts towards long wavelengths. In doing so, the dispersion that they experience increases and their group velocity decreases. Due to the discrepancies in group-velocities for solitons of different power levels, collisions occur between them. For instance,
in Fig. 3(b), a soliton collision occurs at each intersection between two soliton temporal trajectories. As explained in Refs [18–20], the most powerful soliton catches some energy from its less powerful neighbor during a collision. The amount of exchanged energy depends on the properties of the two initial solitons. A direct consequence of such a collision is a further enhancement of the Raman self-frequency shift of the strongest soliton [21]. This phenomenon is highlighted in Fig. 3(a), where two powerful solitons (represented by white dots) are decelerated (as discussed above) and red-shifted from the pump spectral region, between 200 and 300 m of propagation.

Figure 3(c) shows the peak power reached by the most powerful soliton as a function of the fiber length. This peak power increases until a length of about 250 m is reached. This corresponds to the formation of solitons through the modulation instability process. After this stage, the evolution of the maximum peak power presents very sharp and intense peaks from 250 to 400 m. A close-up of such an event is represented in the inset in Fig. 3(c). One can see that the peak power indeed rapidly increases and decreases in a very short fiber length of about 40 cm.

The temporal evolution of the spectrograms allows investigating the physical origin of the optical rogue wave appearing between 300 and 301 m within the fiber. Figure 4 displays the spectrogram evolution corresponding to the particular event highlighted in Fig. 3(c) in the vicinity of this fiber length. As in Fig. 3(a), white dots represent the most powerful soliton at each fiber length. Two solitons with a respective energy of 35 pJ and 28 pJ (respectively top and bottom red dots) are initially well separated in the time domain, for a fiber length of 299.925 m [Fig. 4(a)]. As discussed above, they travel at different group velocities because of their different spectral locations. Consequently, they become closer and closer in the time domain [Fig. 4(b)], until their collision occurs, for a fiber length of 300.6275 m [Fig. 4(c)]. After this collision, they again behave independently as can be seen from Figs. 4(d) and (e). It is important to note that their respective energy has changed during the collision (42 pJ and 24 pJ for top and bottom red dots respectively), as it has already been pointed out in Ref [20]. The most interesting aspect of this collision is the formation of a very isolated and temporally limited powerful spike with a peak power of 900 W, as can be seen in Fig. 4(f). This cluster spike is 3-4 times higher than the mean peak power and appears/disappears very quickly (in
less than 1 m, as seen in Figs. 4). This is the reason why, together with the PDF properties, we use the terminology of ORW for this extreme pulse. Thus, we evidence the mechanism of ORW formation as a collision between two already powerful solitons propagating at different velocities. Note that we checked that rare events in Fig. 2(b) have the same characteristic temporal shape than the one depicted in Fig. 4(f), i.e. resulting from soliton collisions. On the contrary, the other standard events have a classical pulse shape. This idea of soliton collision for rogue wave formation was already suggested in [15,22,23]. This collision is associated with a specific spectral signature in the form of a long tail located at the long-wavelength edge of the spectrum [right framed curve of Fig. 4(c)]. Spectrally filtering this tail could be a way to identify ORWs only from spectral measurements.

Even if particular care must be taken in trying to establish a comparison between optical rogue waves and their hydraulic counterparts, a very striking feature of the collision between solitons is the presence of the two satellites around the central peak [Fig. 4(c) and (f)], recalling the famous “three sisters” (three consecutive freak waves) often mentioned by seafarers [22]. This type of structure has not been reported in the pulsed regime because the most powerful soliton is rapidly ejected from the pulse and consequently, a limited number of collision occur [5,14].

5. Conclusion

We have reported for the first time to our knowledge a direct experimental temporal characterization of CW-pumped supercontinuum. In this context, we have observed the appearance of so-called optical rogue waves located at the long-wavelength edge of the spectrum. We show that these rare events do not correspond to Akhmediev breathers but are specific to supercontinuum generation including third-order dispersion and Raman effects. Numerical simulations were presented to provide a physical explanation of the formation of these rare temporal events that appear and disappear from nowhere. We indeed showed that they result from the collision of two powerful solitons located at the long-wavelength edge of the supercontinuum spectrum. This is very different from previous reports in pulsed regimes, in which ORWs are identified as powerful soliton ejected from the pump packet. Indeed, no rapid appearance and disappearance of extreme events was observed in this case. Finally, our numerical simulations highlight amazing similarities with freak waves in the ocean, such as their sudden appearance without any distinguishing mark, their disappearance without any trace or the presence of three consecutive high amplitude events (see e.g. Refs [22,24]).