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Statistical characterization of the internal structure of noiselike pulses using a nonlinear optical loop mirror

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ABSTRACT

In this work we study statistically the internal structure of noiselike pulses generated by a passively mode-locked fiber laser. For this purpose, we use a technique that allows estimating the distribution of the amplitudes of the sub-pulses in the bunch. The technique takes advantage of the fast response of the optical Kerr effect in a fiber nonlinear optical loop mirror (NOLM). It requires the measurement of the energy transfer characteristic of the pulses through the NOLM, and the numerical resolution of a system of nonlinear algebraic equations. The results yield a strongly asymmetric distribution, with a high-amplitude tail that is compatible with the existence of extreme-intensity sub-pulses in the bunch. Following the recent discovery of pulse-energy rogue waves and spectral rogue waves in the noiselike pulse regime, we propose a new way to look for extreme events in this particular mode of operation of mode-locked fiber lasers, and confirm that rogue wave generation is a key ingredient in the complex dynamics of these unconventional pulses.

1. Introduction

Considering the ever-growing number of applications involving short and ultrashort optical pulses (sensing, micromachining, medicine etc.), their characterization is essential. However measuring and characterizing precisely optical signals that are much shorter than the response time of the fastest optoelectronic devices remains a challenging task. The optical autocorrelation technique [1] is able to estimate the duration of ultrashort pulses, by taking advantage of the ultrafast response of a nonlinear process (typically, second harmonic generation) in an interferometric scheme. For more precise characterization, several techniques have emerged that allow retrieving the complete pulse profile (amplitude and phase of the electric field), one noticeable example being Frequency Resolved Optical Gating (FROG) [2]. However, the need for careful beam alignment and for sophisticated algorithms may limit the applicability of such techniques, especially when complex waveforms are considered.

On the other hand, when very complex waveforms containing a fine inner structure or signals made up of a large number of elements are under study, characterization using a statistical approach is useful [3]. However, when the size of the inner details lies below the response time of optoelectronic devices, alternative characterization techniques have to be developed. One example of such a complex, densely packed signal is the "sea of solitons" produced when a wide, ∼ns pulse propagating down a nonlinear and dispersive fiber eventually breaks up into a large number of solitons with different amplitudes [4]. Studying this problem, in particular characterizing the amplitude distribution of the formed solitons is very relevant in practice, especially considering that the formation of the sea of solitons constitutes the first stage of supercontinuum generation under ns pumping [5]. Developing an experimental method to estimate the statistics of a sea of solitons would thus be helpful to understand the physics of supercontinuum generation, in particular in the ns regime where numerical calculations tend to be prohibitively long.

Such a method would also be very beneficial for the study of another type of extremely complex objects, the so-called noiselike pulses (NLPs) [6–22]. Although they are produced by passively mode-locked fiber lasers, NLPs differ radically from solitons. They are often described as compact (∼ns-long) wavepackets containing from thousands to millions of sub-ps sub-pulses with randomly varying amplitudes. These complex waveforms are now gaining wide recognition in diverse applications including supercontinuum generation [23–25], nonlinear frequency conversion [26,27], sensing, imaging [28] and micromachining [29]. In spite of this, the physics underlying the formation and evolution of NLPs is still debated. One particularly interesting aspect of the current

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research on NLPs is their connection with extreme events known as optical rogue waves [30–32]. Rogue waves are rare events of giant amplitude. Although the concept originates from oceanography, its optical counterpart was since discovered and studied first in a conservative context [30,33], and then in dissipative systems such as fiber lasers [34–38], in particular in the mode locking regime. To qualify formally as rogue wave, an event should 1) be unpredictable and ephemeral in nature; 2) have an amplitude higher than twice the significant wave height (SWH, or average amplitude of the highest third of all events); finally, although rare, 3) these events should be far more frequent than a classical (e.g., Gaussian or Rayleigh) statistics would predict (typically producing a pronounced L-shaped statistical distribution).

Recently, a few theoretical and numerical studies highlighted the connection between rogue waves and NLPs [39,40], and several works reported the experimental observation of extreme events in the NLP regime of passively mode-locked fiber lasers [41,42]. Considering the strong shot-to-shot fluctuations of NLPs, a simple approach consists in looking for extreme occurrences of the energy of the bunch. In [41], the energy of NLPs periodically emitted by a passively mode-locked fiber ring laser was first characterized. Both normal and anomalous dispersion regimes were considered. Extreme events fulfilling the above criteria were recorded, although only in the anomalous dispersion regime of the laser. Considering however that the NLPs are subject to a chaotic dynamics of their fine inner structure, it seems reasonable to consider that extreme events occur primarily at a local scale (very intense ultrashort spikes); such a view is also confirmed by numerical simulations [39,40]. Due to their local nature, such events would not necessarily be associated with an extreme alteration in the energy of the whole bunch. This means that extreme fluctuations of the internal structure of the NLP may take place even in absence of pulse-energy rogue waves. Hence rogue wave characterization through NLP energy monitoring seems too restrictive, as at least part of the local extreme events remains unnoticed. Unfortunately, direct detection of ps or sub-ps spikes is not possible, as they lie beyond the reach of even the fastest electronics [38]. On the other hand, interesting results were obtained by applying the dispersive Fourier transform technique [43], which allowed single-shot measurement of the optical spectrum of NLPs [41,42]. In [41], the statistics of the maximal spectral intensity of the pulses was characterized using this tool, and analysis of the recorded data revealed the presence of extreme events (called spectral rogue waves). Contrary to the case of bunch energy characterization, extreme events are now observed in both dispersion regimes. Using the same technique, rogue waves in the normal dispersion regime were also evidenced in [42], in the Raman-shifted part of the spectrum of the NLPs. These results confirm that extreme events can arise within the fine structure of the NLP, even when the total energy of the bunch does not exhibit such extreme variations. Unfortunately, relating these spectral rogue waves to the existence in the time domain of extremely intense spikes is not a trivial task. Therefore, it would be highly beneficial to have at hand a technique able to resolve the internal structure of NLPs beyond the limits of optoelectronic schemes, making it possible to evidence extreme fluctuations down to ultrashort time scales, thereby giving access to fundamental manifestations of the rogue wave phenomenon in that kind of pulses.

In this paper, we propose and apply a method to study statistically the sub-pulses in NLPs generated by a passively mode-locked fiber laser, in particular with the purpose of bringing to light the existence of extreme fluctuations in the internal structure of these bunches that can be interpreted as optical rogue waves. We use a fiber nonlinear optical loop mirror (NOLM) [44] to determine indirectly the statistical distribution of the amplitudes of the sub-pulses composing the NLPs, from pulse energy measurements. The ultrafast ($\sim$fs) response time of the optical Kerr effect in silica fiber allows extracting information on the sub-pulses in the bunch, in spite of the limitations imposed by fiber dispersion. The estimated statistics is compatible with the existence of extremely intense spikes within the bunch.

2. Choice of the setup and general principle of the method

The nonlinear transmission of a NOLM is a sinusoidal function of input power. Most schemes rely on a power imbalance between the beams that counter-propagate in the loop, which is obtained typically through the use of an asymmetric coupler [44], or by inserting an attenuator (or amplifier) asymmetrically in the loop [45]. In general, the loop is made of non-polarization-maintaining fiber and includes polarization controllers, which allow adjusting the phase bias of the transmission characteristic. However, this empirical method only yields imprecise and hardly reproducible tuning of the transmission, which usually drifts slowly with time due to the environmentally sensitive residual birefringence of the fiber loop, thus requiring frequent readjustments. Stable transmission can be achieved if the NOLM is made of polarization-maintaining fiber, however the possibility to adjust the bias through polarization controllers is lost in this case. Therefore, such schemes would be highly impractical for the implementation of the technique proposed here, which assumes that the NOLM transmission function is well defined, its bias is precisely tuned and remains constant over time.

Fortunately, better performance can be expected from a polarization-imbalanced architecture [46]. In this scheme, a 50/50 coupler is used, so that the counter-propagating powers are equal, although polarization symmetry is broken through the use of a quarter-wave retarder (QWR) in the loop. NOLM switching is then obtained thanks to the polarization dependence of the Kerr effect [47]. Because the device operation strongly depends on polarization, light polarization is strictly controlled, at the NOLM input and within the loop. In order to control polarization in the loop, twist is applied to the fiber: twist introduces optical activity and overcomes environmentally sensitive residual birefringence, which ensures that light ellipticity is maintained during propagation [48]. Therefore, the environmental sensitivity of the device is strongly reduced and readjustments are less critical. The nonlinear transmission characteristic is also precisely defined (in the continuous-wave limit) in function of the NOLM parameters, input polarization state and QWR angle [49]. Besides, polarization control offers an easy way to adjust precisely the NOLM transmission characteristic. In particular, changing the QWR angle allows tuning the phase bias of the transmission; however this also alters the contrast of the transmission function [49]. In this work, we will ensure that a high contrast (ideally infinite, i.e., zero minimal transmission) is obtained, as it will improve the precision of the method. For this purpose, we select at the NOLM output the polarization component that is orthogonal to the input polarization: in this case, adjusting the QWR angle only modifies the phase bias of the transmission, whereas maximal contrast is maintained [50]. For example, assuming circular (say, right) input polarization, and selecting the orthogonal (circular left) polarization component at the NOLM output (using a QWR and polarizer), the NOLM power transmission is given by [50]

$$T = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{1}{4}\left[1 - \cos\left(\pi\frac{P_{\text{in}}}{P_{\pi}} + \Delta\phi\right)\right], \quad (1)$$

where P_{in}, P_{out} and P_{π} are the NOLM input, output and switching powers, respectively ($P_{\pi}=6\pi/(\gamma L)$ where γ is the nonlinear coefficient for linear polarization and L is the loop length), and the