Rogue-wave-like characteristics in femtosecond supercontinuum generation

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M. Erkintalo,[1] G. Genty,[1,*] and J. M. Dudley[2]

[1]*Tampere University of Technology, Optics Laboratory, FI-33101 Tampere, Finland*
[2]*Université de Franche-Comté, Institut FEMTO-ST, 25030 Besançon, France*
Corresponding author: goery.genty@tut.fi

We experimentally study the characteristics of optical rogue waves in supercontinuum generation in the femtosecond regime. Specifically, the intensity histograms obtained from spectrally filtering the supercontinuum exhibit the L-shaped characteristics typical of extreme-value phenomena on both the long-wavelength and short-wavelength edges of the spectrum owing to cross-phase modulation and soliton-dispersive wave coupling. Furthermore, the form of the histogram on the long-wavelength edge varies from L-shaped to quasi-Gaussian as wavelengths closer to the pump are included in the filtered measurements. Our observations are in agreement with numerical simulations.

Recent research into optical fiber supercontinuum (SC) generation has identified the SC noise and stability properties as subjects of particular interest [1]. Although SC amplitude and phase stability are naturally key factors in assessing potential applications, there has been significant recent attention paid to experiments by Solli *et al.*, who have shown that the shot-to-shot statistics of the broadband SC spectra are associated with the excitation of a small number of statistically rare "rogue" soliton events associated with an enhanced redshift and temporal intensity [2]. Because these experiments were carried in a regime where the spectral broadening was seeded by modulation instability (MI), there has been wide interest in drawing analogies with mechanisms potentially underlying the formation of oceanic rogue waves and the way in which large-amplitude nonlinear waves can appear from low-amplitude perturbations [3]. Within an optics context, these results have also rapidly initiated a number of studies into techniques for supercontinuum stabilization and control [4–6] and have significantly extended previous studies into the parameter dependence of the supercontinuum noise properties as a function of wavelength [7].

The initial work on optical rogue waves was performed in the context of SC generated in the picosecond regime, where the spectral broadening was seeded by the spontaneous growth of MI sideband components [2]. In this Letter, however, we report experimental results that show that the characteristic features of the rogue-wave statistics in SC generation can also be observed using input pulses in the femtosecond regime, where MI effects are less apparent and where clear signatures of soliton-related dynamics such as soliton-dispersive wave coupling are observed. We show that the statistical distribution of the time series corresponding to the long-wavelength edge of the SC spectrum exhibits the L-shape signature of rogue events. Furthermore, we study how the statistical distribution of the time-series amplitude changes as a function of filtered spectral position and bandwidth, showing that the histogram evolves toward a quasi-Gaussian distribution for shorter wave-

length cutoffs. Finally, by directly measuring the statistical properties of the filtered short-wavelength edge of the SC, we show that cross-phase modulation coupling leads to similar L-shaped statistical distributions for the Raman-shifted solitons on the long-wavelength side and dispersive waves in the normal dispersion region.

Our experiments used a Ti:sapphire laser producing 200 fs pulses at a repetition rate of 80 MHz with 15 kW peak power to pump a 6-m-long photonic crystal fiber (PCF) with zero dispersion at 1040 nm and nonlinear coefficient $\gamma = 11 \, \mathrm{W^{-1} \, km^{-1}}$. The pump wavelength is located at 1028 nm, which lies slightly in the normal dispersion regime. Under these pump conditions, the generated SC would be expected to exhibit sensitivity to input pulse noise but without the dominant effect of spontaneous MI sideband growth in the initial evolution dynamics [1]. To investigate the statistical properties of the SC we use an edge-pass filter to select part of the long- or short-wavelength spectral structure. To measure pulse intensity statistics, we use a direct detection technique with a 1 GHz bandwidth InGaAs (for the long-wavelength edge) or a silicon photodidode (for the short-wavelength edge) and a 10 Gsample/s oscilloscope. Time series of 1 ms can be readily recorded corresponding to 80,000 shot-to-shot energy measurements and, because the timing jitter of the oscilloscope is much less than the width of the detected pulses, reliable statistics can be acquired [8].

Figure 1 (left) shows the SC spectrum generated at the output of the fiber, which spans 650 nm from 750 – 1400 nm at −20 dB bandwidth. The absence of distinct soliton spectral structure on the long-wavelength edge is indicative of strong shot-to-shot variations in the SC spectrum [1], and this is confirmed directly in Fig. 1 (right) by the recorded histogram of the photodiode signal amplitude. Here we used a filter with 1400 nm cutoff wavelength that selects the −20 dB long wavelength edge of the SC spectrum. In this way, only the femtosecond Raman solitons in the spectra that are redshifted beyond the
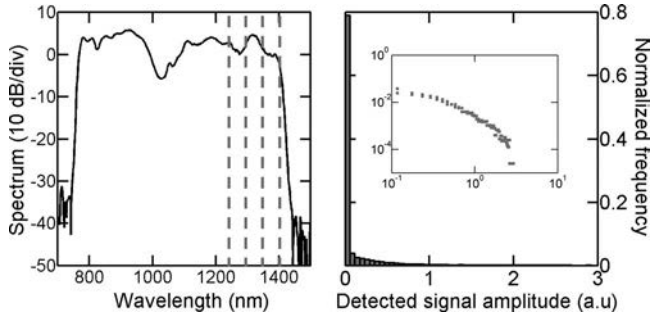
Fig. 1. (left) Measured spectrum and (right) corresponding histogram of the time series when filtering above 1400 nm. The gray dotted lines mark the position of the filter cutoff wavelength. Inset, histogram in log–log scale.

cutoff wavelength will be completely captured. Significantly, although we employ excitation conditions using femtosecond pulses in the normal dispersion regime, the histogram also exhibits the characteristic L shape of an extreme-value process similar to the generation of optical rogue waves observed in the long-pulse regime. Using long-pass filters with shorter cutoff wavelengths, we could observe a change in the statistical distribution from L shape to quasi-Gaussian, as illustrated in Fig. 2. The change in the statistical distribution results from the larger filtered bandwidth, which captures more fully a wider intensity range of redshifted solitons and not only the rogue events that undergo the most extreme frequency shifts.

At this point, we emphasize that the wavelength dependence of the statistics occurs because of the particular nonlinear dynamics associated with the energy transfer on the long-wavelength region of the SC and not as a result of any selection-bias artifact associated with the spectral filtering. Specifically, we have carefully checked, both experimentally and through numerical simulations, that if one uses the same filtering technique to examine the spectral wings under different physical conditions (e.g., shorter fiber lengths, or with shorter duration pulses of 50–150 fs, where modulation instability is not present) it is possible to obtain statistics that do not reflect any extreme-value behavior, irrespective of the position of the filter.

We have also investigated the statistical distribution of time series corresponding to the blue edge of the SC spectrum. To match the −20 dB level on the blue edge to our available filters, the input power was decreased, yielding the spectrum shown as an inset
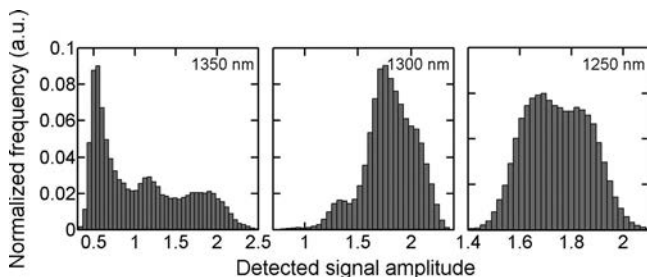
in Fig. 3. Using a short-pass filter with a cutoff wavelength at 800 nm, an L-shape histogram similar to that of the long-wavelength edge was recorded as plotted in Fig. 3. Filtering the red part of the SC spectrum at 1350 nm under these conditions yielded a similar L-shape variation. Although the captured time series when filtering the blue SC edge do not correspond to rogue waves in the sense defined in [2] but to dispersive waves propagating in the normal dispersion regime, the statistical behavior clearly reveals a strong coupling between the red and blue wings of the SC spectrum. Indeed, solitons on the long-wavelength side of the SC interact through cross-phase modulation with the dispersive waves in the normal dispersion region, which can lead to trapping phenomena, where the spectral location of the dispersive waves are correlated to the spectral position of the solitons [9,10]. In other words, rogue events corresponding to solitons with longer wavelengths induce larger dispersive-wave blueshifts, and thus the blue dispersive waves follow similar statistical properties as the redshifted solitons. Indeed, tuning the cutoff wavelength of the short-pass filter toward the pump at 900 nm was found to yield a change of the histogram from L shape to quasi-Gaussian, as with the long-wavelength edge.

Our experimental observations are in good agreement with numerical simulations performed using the generalized nonlinear Schrödinger equation, which has been successfully used in many previous studies of SC generation modeling. The input parameters correspond to those of Fig. 3. In our simulations, noise is included in the frequency domain through a one-photon-per-mode background and via a term that describes thermally driven spontaneous Raman scattering [1]. To simulate the histograms, multiple simulations were carried out in the presence of different random noise seeds. The simulated SC spectrum averaged over 700 individual simulations, and the corresponding calculated histograms for filters with cutoff wavelengths at 1350 nm and 800 nm plotted in Fig. 4 are qualitatively in good agreement with the experiments. Specifically, the histograms for time series corresponding to blue- and red-edge filtering each exhibit a L-shape distribution. To further illustrate the coupling between the blue- and red-edge statistics the simulated spectrogram of a spectrum
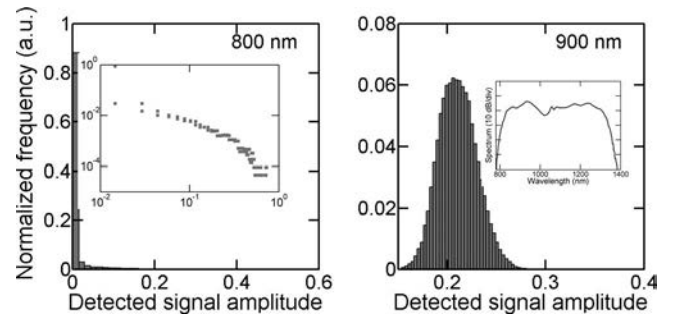

Fig. 3. Histogram of photodiode signal amplitude illustrating the blue edge fluctuations in the SC spectrum. The corresponding SC and the histogram in log–log scale are shown as insets. Spectral filtering at (left) 800 and (right) 900 nm.

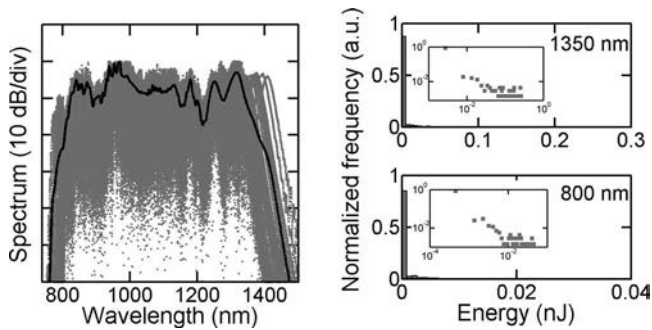Fig. 2. Histogram of the time series when performing spectral filtering above 1350, 1300, and 1250 nm.

Fig. 4. Left, individual results from simulation ensemble (gray; for clarity only 50 individual shots are plotted) with calculated mean (solid). Right, energy histogram for filter cutoff wavelengths at 1350 and 800 nm. Insets, histograms in log–log scale.

for a median and extreme "rogue" event are shown in Fig. 5. A significant difference between these results is clearly observed on the red-wavelength side, where the most energetic soliton has shifted much farther for a rogue event. The dispersive wave on the blue-wavelength side trapped by this soliton through cross-phase modulation is correspondingly shifted to a shorter wavelength compared with the median event case. The statistical distribution of the short-wavelength edge of the SC is therefore correlated to that of the long-wavelength edge. It is also interesting to note that the number of solitons is identical in both cases and that the location of the two most red-shifted solitons is the main difference.

There are several major conclusions from this work. We have experimentally shown that optical rogue waves can be observed with high-power femtosecond pulses and normal-dispersion pumping re-
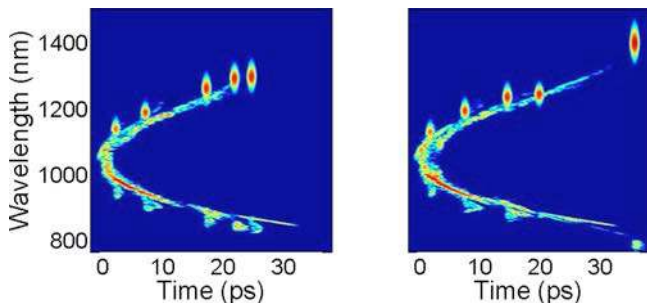
gime, confirming the presence of non-Gaussian rogue wave statistics in SC generation under conditions other than those using long-pulse excitation. In fact, additional simulations indicate that rogue waves are a general feature of SC generated in a low-coherence regime. Furthermore, we have shown that the statistical distribution evolves from an L shape toward a quasi-Gaussian when filters with shorter cutoff wavelength and larger spectral bandwidth are used to isolate the rogue events. More detailed studies of the wavelength dependence of the SC statistical properties will be expected to yield improved insight into the mechanisms by which input pulse noise is transferred onto the output SC to yield extreme-value characteristics. We have also demonstrated that the short-wavelength edge of the continuum follows similar statistics owing to cross-phase modulation coupling between the redshifting solitons and blue dispersive waves, a result that may have important consequences for practical applications seeking to exploit short-wavelength components of SC spectra.

Fig. 5. (Color online) Simulated spectrogram for a (left) median and (right) rogue event.

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