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# Midinfrared optical rogue waves in soft glass photonic crystal fiber

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**Abstract:** We investigate numerically the formation of extreme events or rogue waves in soft glass tellurite fibers and demonstrate that optical loss drastically diminishes shot-to-shot fluctuations characteristic of picosecond pumped supercontinuum (SC). When loss is neglected these fluctuations include extreme events such as formation of highly energetic pulses located at the red end of the spectrum and we obtain right-skewed heavy-tailed distributions characteristic of extreme events statistics. On the other hand, when loss is included bandwidth fluctuations follow Gaussian-like statistical distributions. Our results thus implicitly show that rogue waves will not occur in any SC spectrum that is limited by loss, such as commercial silica fiber based SC sources.

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## 1. Introduction

Ever since it was first reported [1], SC generation has been widely investigated and demonstrated in several pump regimes, from continuous wave to ultrashort femtosecond [2]. Invariably, novel physics are uncovered and in particular an intriguing phenomenon in the form of statistically rare highly energetic pulses located at the red end of the spectra has been predicted numerically [3, 4] and observed experimentally [5] in optical fibers.

Such extreme events occur since pulses or solitons generated in a fiber can interact and transfer energy between each other during collisions. On average there will be a net energy transfer to the larger soliton and the mechanism can generate very high amplitude solitons [3, 6, 7]. This energy transfer and generation of strong nonlinear excitations, is in fact a generic nonlinear phenomenon well-known from biology [7–9], optical waveguide arrays [10], and discrete lattices [11].

The term optical "rogue wave" (RW) was coined [5] due to the high resemblance to the infamous so-called oceanic RWs. Moreover, these statistically rare events exhibited a shifting towards longer wavelengths and they distinctly appeared in the red end of the spectrum as large bandwidth fluctuations following right-skewed heavy-tailed statistics [5].

It should be noted, that in recent studies [12, 13] the authors pointed to the possibility of a RW occurring inside the SC spectrum, however in the following we limit the investigations to RWs as giant solitons located on the long wavelength side of the SC.

The above results were obtained in silica fibers at low powers, with spectra far from the loss edge, however here we investigate midinfrared (MIR) RW formation in soft glass fibers. Soft glasses, which among others include chalcogenide ( $n_2 \sim 0.8 \times 10^{-17} \text{ m}^2/\text{W}$ ) [14] and tellurite ( $n_2 \sim 0.6 \times 10^{-18} \text{ m}^2/\text{W}$ ) [15], exhibit much higher nonlinearities than silica ( $n_2 \sim 0.3 \times 10^{-19} \text{ m}^2/\text{W}$ ) [16], and thus offer a great reduction in the required fiber length or pump power. In addition soft glass fibers allow low loss guidance at much longer wavelengths, well into the MIR regime.

Hence we consider a 60 cm tellurite fiber with pitch ( $\Lambda=3 \mu\text{m}$ ), relative hole size ( $d/\Lambda=0.4$ ) and zero-dispersion wavelength (ZDW)  $\sim 1780 \text{ nm}$  [17] see Fig. 1(a), in which we show the measured loss and calculated dispersion. Now, since thulium mode-locked lasers exhibit a broad and high gain spectrum in the  $1.8$  to  $2.1 \mu\text{m}$  wavelength regime [18], we consider pumping at the thulium wavelength  $\lambda=1930 \text{ nm}$ , i.e., anomalous dispersion region to generate a large number of solitons as in the aforementioned studies in silica.

As seen in Fig. 1(a), this fiber entails substantial loss and we demonstrate that generation of RWs can be greatly reduced when the band edge of the generated SC approaches the loss edge at  $\sim 3 \mu\text{m}$ , similar to SC fluctuations limited by a photonic bandgap in a solid-core fiber [19]. We stress here however, that in a bandgap fiber the dispersion deviates to infinity as it approaches the edge of the gap. The rapid increase in dispersion alone will halt the solitons and this is exactly what stops them red-shifting in this case, before entering the actual regime of loss.

Therefore this has no resemblance whatsoever with the material loss edge of a conventional fiber, at which the dispersion is still finite and the solitons are still allowed to red-shift into the loss edge. Hence the dynamics is different in many ways, e.g., solitons/rogue waves approaching the loss edge will decay in power, whereas the rogue waves in a bandgap fiber will maintain their power, but spread out due to the increasing dispersion.

The broad absorption in the region  $2.5\text{-}5 \mu\text{m}$  is due to water in the glass, note however that this glass was melted in dry atmosphere and thus has already a considerably reduced water content compared with glasses melted in ambient atmosphere [17]. In addition, improvement of the glass melting procedure is expected to further reduce the water content, where complete removal of water would shift the loss edge to  $\sim 4 \mu\text{m}$ , at which confinement loss becomes significant. In comparison, the material IR edge loss is  $< 1 \text{ dB/m}$  for  $\lambda < 4.9 \mu\text{m}$  [20] which is negligible compared to confinement loss.

We consider pulse propagation both with and without including loss and demonstrate, for the first time to our knowledge, MIR RW formation, combining a tellurite fiber with a thulium pump. We base our simulations on the generalized nonlinear Schrödinger equation (GNLSE)

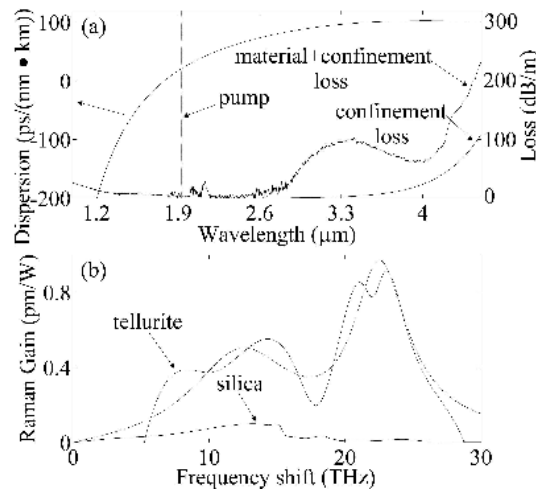


Fig. 1. (a) Optical loss for tellurite fiber with  $\Lambda=3 \mu\text{m}$  and  $d/\Lambda=0.4$ . Shown are the combined contribution from both material and confinement loss, as well as confinement loss alone. (b) Raman gain spectrum  $\hat{h}_R(\Omega)$  of tellurite with maximum peak at  $\Omega_R \sim 22.5 \text{ THz}$ . and silica with peak at  $\Omega_R \sim 13.2 \text{ THz}$ . The dashed curve shows the approximate Raman gain spectrum of tellurite.

[16] which we solve in the so-called interaction picture [21, 22], and we consider both higher order dispersion, loss, and stimulated Raman scattering, see [17] for details. In optical fibers the generation of RWs is assisted by the Raman effect [23], leading to an on-average energy transfer to the larger soliton, which is also the one red-shifting the fastest [24]. The fact that the Raman red shift increases with soliton power is exactly what enables spectral measurements of RWs [5].

We implement the Raman response function  $R(t) = (1 - f_R)\delta(t) + f_R h_R(t)$  in the GNLSE, where  $f_R=0.064$  and  $h_R(t)$  is derived from the measured Raman gain spectrum  $\tilde{h}_R(\Omega)$  [15], see Fig. 1(b). The tellurite Raman profile is markedly different from silica and the width (bandwidth) is substantially larger. Moreover, it consists of several peaks and thus the Raman profile  $h_R(t)$  should be approximated as a sum of decaying harmonic oscillators and we use two oscillators. The approximated gain profile is shown in Fig. 1(b) (dashed curve) which is more physical since it is non-zero for all  $\Omega>0$ , whereas the measured profile, due to filtering of the pump, drops off abruptly at  $\Omega\sim 5$  THz. The approximated Raman gain thus allows us to model small frequency shifts, which is important for narrowband pulses, e.g., ps pulses.

We pump at  $\lambda=1930$  nm, with a 5 ps pulse duration, and various peak powers. The nonlinear coefficient is  $\sim 0.14$  W<sup>-1</sup>m<sup>-1</sup> and noise is included by adding one random phase photon per mode in the frequency domain. To capture the statistics of the RWs, we perform 200 simulations for each peak power, i.e., 1000, 1500 and 2000 W and the resulting spectra are shown in Fig. 2. In all cases a SC is developed. However, the detrimental effect of loss is evident, giving rise to much narrower SC than in the corresponding lossless case. In particular, when pumping with a peak power of 1000 W, the SC is not formed at all when loss is included (therefore not shown in Fig. 2). Without loss the SC are very broad, and the ensemble of each peak power contains several MIR RWs at  $\sim 3.4$   $\mu\text{m}$ ,  $\sim 3.8$   $\mu\text{m}$ , and  $\sim 4.2$   $\mu\text{m}$  for peaks power of 1000, 1500 and 2000 W, respectively. From the inserts on the right it follows that shot-to-shot fluctuations can be substantial, which is manifested in noticeable bandwidth deviations from the most red-shifted RW, to the narrowest spectra.

When loss is included, the bandwidth fluctuations are much smaller. Moreover, the fluctuations decrease with peak power, since increasing the peak power, forces a larger fraction of the pulses to fully develop into the maximum allowed SC bandwidth, effectively limited by optical loss.

To investigate the statistics of each ensemble, we use a long-pass filter and select components above a particular wavelength, depending on the spectral extent of the ensemble median. In particular, cut-off wavelengths from top to bottom in Fig. 2 are 3.2  $\mu\text{m}$ , 3.6  $\mu\text{m}$ , 2.65  $\mu\text{m}$ , 4  $\mu\text{m}$ , and 2.7  $\mu\text{m}$ . Fourier transforming the remaining spectral components reveals a series of short pulses of varying peak powers, see Fig. 3.

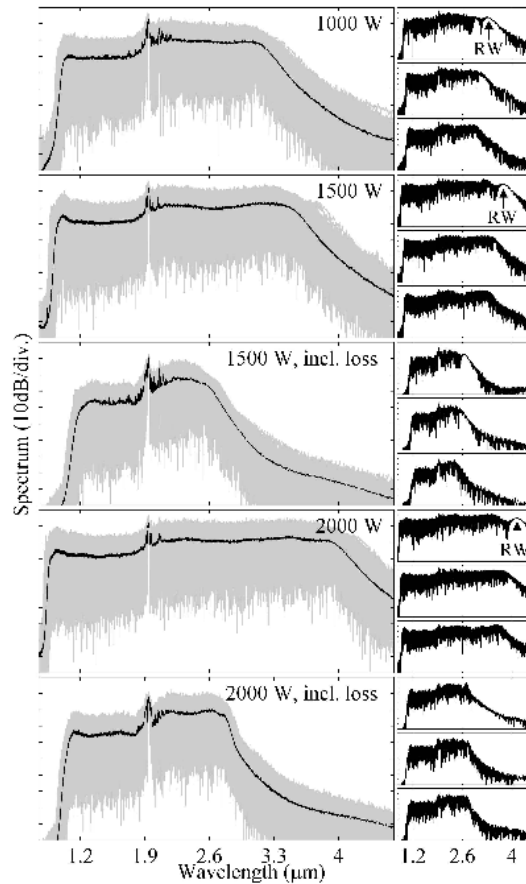


Fig. 2. Output spectra for various peak powers with and without including optical loss. In each ensemble the black lined spectrum depicts the ensemble median and the inserts on the right show (top, bottom) a RW and the narrowest spectrum and (middle) a spectrum close to the median.

As expected, when loss is neglected, peak powers of the pulses follow the characteristic heavy-tailed statistics. Conversely, when loss is included, the distributions become more Gaussian-like. Note that shifting the cut-off wavelengths within a certain range, does not alter the statistical distributions noticeably.

Next we adopt a general rule [25] to define a RW, and find that, in a purified tellurite fiber and for a broad range of peak powers, MIR RWs are formed on several occasions, see Fig. 3. In sharp contrast, with loss included, only a narrow range of peak powers allow formation of a RW.

In summary, RW formation will be significantly reduced if not eliminated in SC limited by optical loss. In combination with pushing the loss edge further in to the MIR, one can obtain a ps pumped MIR SC source with Gaussian-like bandwidth fluctuations.

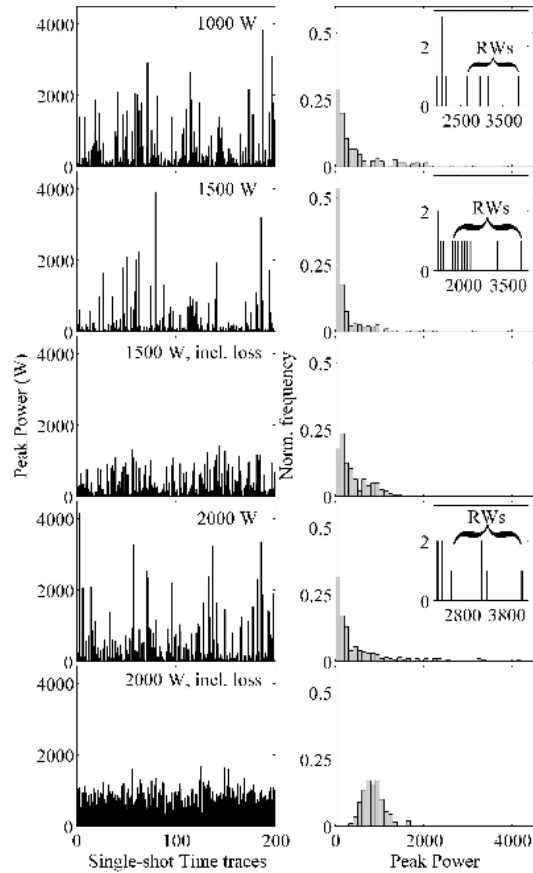


Fig. 3. (left column) Series of short pulses corresponding to the filtered components of the spectra. (right column) Statistical distributions of peak powers in the series of pulses. Inserts depict the RWs and their absolute frequency.

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