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Optical rogue waves and soliton turbulence in nonlinear fibre optics

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Abstract

We examine optical rogue wave generation in nonlinear fibre propagation in terms of soliton turbulence. We show that higher-order dispersion is sufficient to generate localized rogue soliton structures, and Raman scattering effects are not required.

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There is currently intense research into extreme value fluctuations (optical rogue waves) in long pulse fibre supercontinuum (SC) generation [1]. This interest is motivated by the possibility to obtain important insights into related hydrodynamic instabilities, as well as by potential applications in generating stable SC [2]. Optical rogue waves are generated under conditions where SC broadening develops from initial spontaneous modulation instability. Following the appearance of a noise-driven temporal modulation on the input pulse, a large number of distinct solitons emerge, a small number of which undergo extreme Raman frequency shifts to longer wavelengths. Although this suggests that Raman scattering plays a central role in their formation through inelastic energy exchange [3], here we revisit the dynamics of optical rogue wave formation in terms of the well-known soliton turbulence description in which solitons play the role of statistical attractors in any non-integrable nonlinear Schrödinger equation (NLSE) model [4]. Specifically, we show that Raman scattering is unnecessary for intense rogue pulses to emerge from SC generation, and third-order dispersion on its own is sufficient to stimulate a single large rogue soliton in the long distance limit. An additional novel result is that the rogue soliton undergoes a continuous frequency shift to longer wavelengths with propagation as a result of interaction with the turbulent background, even in the absence of Raman scattering.

Our simulations use the fibre nonlinear Schrödinger equation (NLSE) with only third order dispersion and no Raman response. Nonlinearity $\gamma = 0.011$ W^{-1}m^{-1} and dispersion coefficients $\beta_2 = -0.41$ ps^2 km^{-1} and $\beta_3 = 0.069$ ps^3 km^{-1}. SC generation is modelled under long-pulse conditions by numerically solving the NLSE with a 500 W peak power 10 ps pulse input at 1064 nm, and with periodic boundary conditions. Our results show that the initial modulation instability of the input pulse leads to pulse breakup and decay into multiple solitons which then are subject to multiple collisions and interactions [4]. Fig. 1(a) and (b) show the calculated field spectrograms at selected distances where we clearly see the emergence of one distinct soliton pulse in the time-frequency domain. This soliton emerges from a low amplitude broadband turbulent background, and gains energy from the background with propagation as shown in Fig. 1 (c). Significantly, even though no Raman scattering is involved, we still observe a steady frequency shift to longer wavelengths as shown in Fig. 1(d). For comparison, however, we note that the appearance of an isolated rogue soliton in the presence of Raman scattering occurs at propagation distances approximately 10-20 times shorter.

In an optical context, these results are significant in that they show that rogue wave fluctuations in SC generation can occur under conditions where Raman effects are negligible. In the context of SC generation dynamics, this is a new observation, and suggests that frequency-shifting processes in SC generation may contain intrinsic contributions from non-Raman processes. In a wider context, these results also suggest that extreme-value processes may be universal in all systems governed by perturbed NLSE propagation dynamics.
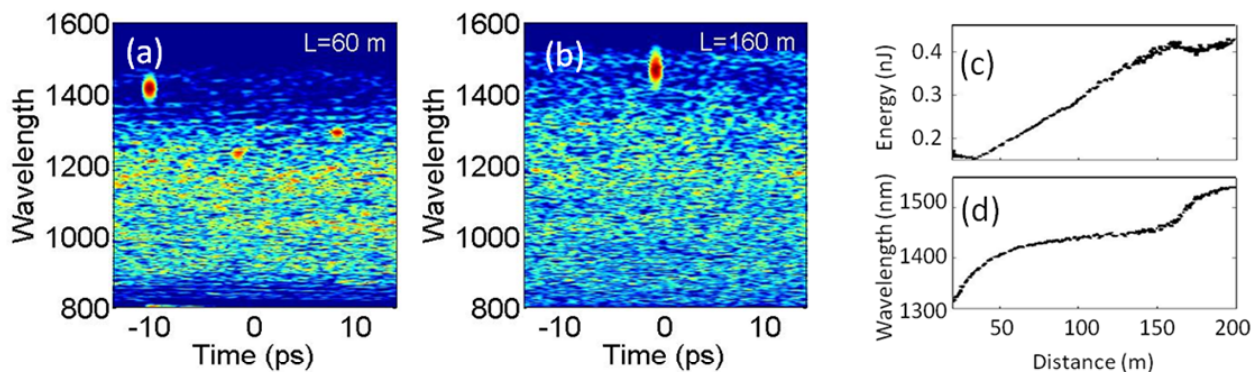

Fig. 1 (a) and (b) spectrogram evolution of SC field at selected distances shown. (c) and (d) Evolution of the energy and the wavelength of the highest intensity soliton as a function of distance.

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