# Giant Dispersive Wave Generation Induced by Soliton Collisions

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**Abstract:** We report on a novel effect in which soliton collisions can lead to the generation of dispersive wave with extreme peak power and enhanced spectral shift in a photonic crystal fiber with two zero-dispersion wavelengths.

**OCIS codes:** (060.5530) Pulse propagation and temporal solitons; (060.5295) Photonic crystal fibers; (320.6629) Supercontinuum generation

## 1. Introduction

The increasing availability of photonic crystal fibers (PCF) with novel dispersion profiles is driving continued research to identify nonlinear propagation effects previously unobservable in standard fibers [1]. In this paper, we report on a novel mechanism that occurs during noise-driven long pulse supercontinuum (SC) generation in a PCF with a concave dispersion profile and two zero dispersion wavelengths (ZDW). Specifically, we show that spontaneous soliton collisions occurring during the SC generation process can lead to the generation of very large-amplitude dispersive waves in the long wavelength normal dispersion regime. These collision-induced dispersive waves have an order-of-magnitude higher peak power than the dispersive waves generated in standard fibers from single soliton excitation [2]. The process of soliton spectral repulsion during the collisions is identified as a key mechanism underlying the extra bandwidth generated. From a fundamental viewpoint, these giant dispersive waves are of interest because they occur very rarely, exhibiting characteristics of extreme-value "rogue" statistics. Moreover, these results are of applied interest in ongoing efforts to generate broadband supercontinuum spectra with extended wings.

## 2. Numerical Model

We simulate 4 ps FWHM hyperbolic secant pulses at 900 nm propagating in commercially available PCF with two ZDWs (NKT Photonics NL-PM-750). The generalized nonlinear Schrödinger equation is solved numerically using standard techniques including noise, the full dispersion profile, Raman scattering etc [3]. The dispersion profile of the PCF is illustrated in Fig. 1 with the short- and long-wavelength ZDWs at 790 nm and 1264 nm, respectively. An ensemble of 1000 simulations in the presence of different noise seeds was simulated to investigate the stochastic properties of pulse propagation.

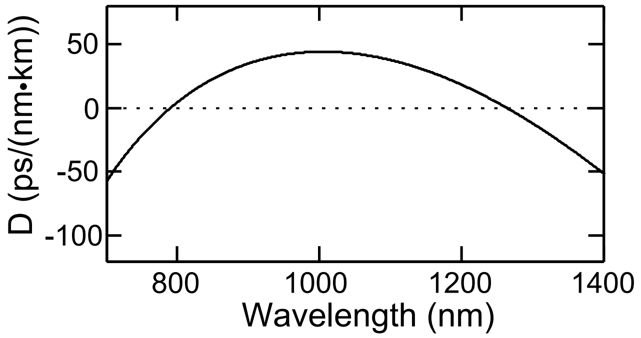

Fig. 1. Dispersion profile of the fiber used in simulations (NKT Photonics NL-PM-750).

## 3. Results

With long pulse excitation, the broadband SC spectrum develops from an initial stage of noise-induced modulation instability (MI), which is then followed by the emergence of solitons across the pulse profile. Because of the Raman soliton self-frequency shift, the solitons shift to longer wavelengths, but as they approach the long wavelength ZDW at 1264 nm, they shed energy in form of a resonant dispersive wave [4]. However, because the MI is seeded from noise, the precise way in which this occurs varies significantly from shot-to-shot in the ensemble. To show this explicitly, Fig. 2 (a) shows an output spectrum typical of what could be called “median” results obtained from the ensemble. The propagation distance here was 1.7 m. The dispersive wave emitted by the most red-shifted soliton in this case is centered at around 1500 nm. However, for a small number of events in the ensemble, we find that the SC spectrum extends significantly further towards longer wavelengths beyond 1500 nm, and an “extreme” event of this type is shown in Fig. 2 (b). The dispersive wave here was generated around 1540 nm. An important difference between these median and extreme cases is manifested in the temporal profile: specifically, we find that the peak power of the temporal intensity of the “extreme” dispersive wave exceeds by more than an order of magnitude that of the median case. These results are shown in Figs. 2 (c-d).

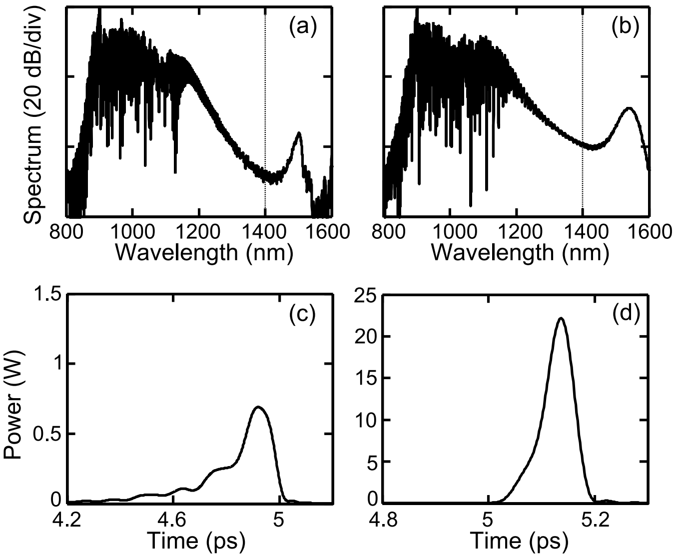

Fig. 2. Top: (a) median event with dispersive wave at 1500 nm and (b) extreme event where the SC spectrum extends further in the infrared with a dispersive wave at 1540 nm. Bottom: temporal profiles of the dispersive waves for (c) median and (d) extreme events.

We have carried out a detailed statistical analysis of the results from the ensemble to determine the distribution of these rare giant dispersive wave events in more detail. Figure 4 shows a histogram of the probability distribution of filtered dispersive wave peak power, where we filter using a cutoff wavelength at 1500 nm. This choice of filter wavelength allows us to conveniently capture the long wavelength high amplitude dispersive waves.

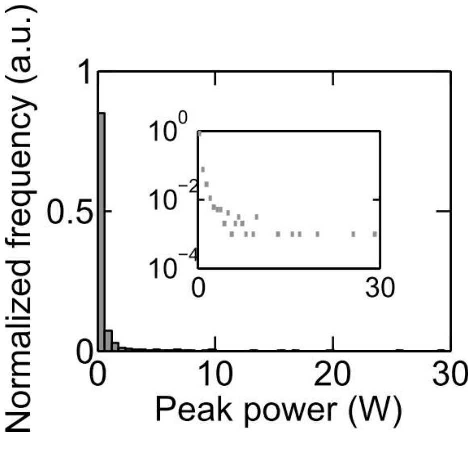

Fig. 3. Dispersive wave peak power histogram when filtering above 1500 nm. Inset, histogram using logarithmic y-axis.

## 4. Discussion

Quantifying the statistics of the ensemble via the histogram in Fig. 3 allows us to clearly see that the giant dispersive wave generation exhibits a long-tailed “L-shape” which is characteristic of extreme value or rogue wave events [4]. To understand the underlying physics of these giant dispersive waves, we examine the evolution of the pulse temporal and spectral envelopes as a function of propagation distance. To this end, Figure 4 shows the time-wavelength representation of the pulse at 10 cm intervals around the distance of 1.7 m at which the extreme dispersive wave is generated. From these results, we can identify that the dispersive wave component is generated when two of the emerging solitons with different wavelengths collide. The spectrogram in Fig. 4(b) shows that during the collision the spectra of the individual solitons repel each other and are extended in opposite spectral directions; it is this soliton spectral repulsion and extension that results in the overall spectrum extending well into the long-wavelength normal dispersion regime. This local spectral broadening combined with a large local temporal intensity at the time of the collision leads to the generation of a giant dispersive wave. It should be emphasized that no dispersive wave is emitted by the two individual solitons before or after the collision.

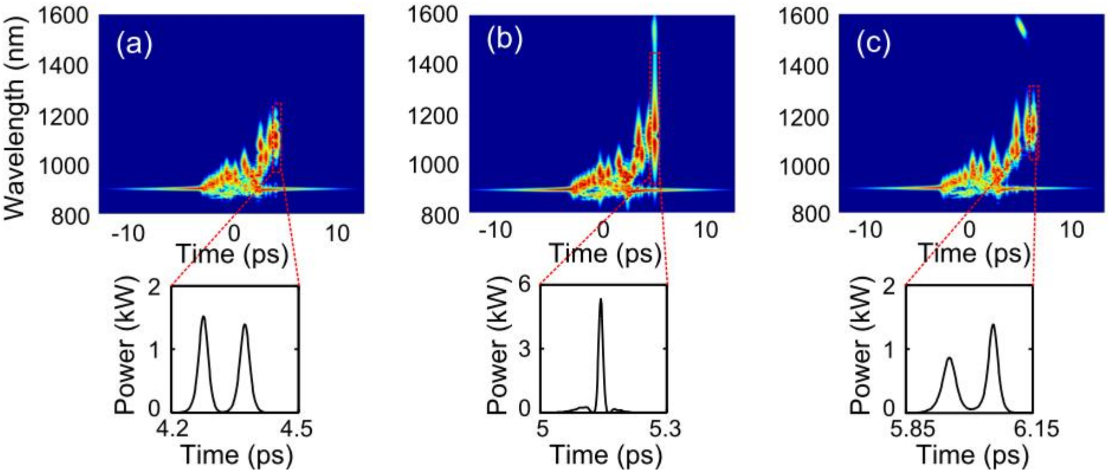

Fig.4. Spectrograms and zoomed time traces at propagation distances of (a) 1.6 m, (b) 1.7 m and (c) 1.8 m illustrating the two-soliton collision process and associated large-amplitude dispersive wave generation with extreme redshift.

## 4. Conclusions

We have used numerical simulations to demonstrate a novel extreme-value phenomenon associated with SC generation in a PCF with two ZDWs. Collisions of solitons with different wavelengths were shown to generate dispersive waves with extreme spectral position and peak power. Soliton spectral repulsion is the underlying mechanism for the additional bandwidth generation and to our knowledge, this is the first time this has been explicitly identified as a spectral broadening mechanism in supercontinuum generation. Although these results have been studied in the context of the fundamental properties of supercontinuum generation, there may be important links with collision mechanisms in wavelength-division multiplexing soliton systems [5,6].

## 5. References

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