Direct Measurement of Temporal Rogue Waves Generated by Spontaneous Modulation Instability

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Abstract: We measure in real time the intensity profiles of the localized structures emerging from spontaneous modulation instability in an optical fiber. The experimental results are in excellent agreement with previous numerical studies confirming that solitons on finite background provide a natural framework to explain the generation of rogue waves.

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The possible analogy between the emergence of statistically rare extreme waves at the surface of the oceans and the propagation of light in an optical fiber has attracted significant attention, with the possibility for the first time to acquire a large amount of data and reliable statistics, and study in real time the dynamics that can lead to the emergence of rogue waves [1]. One possible rogue wave generation mechanism is the nonlinear localization dynamics experienced by a noisy CW field due to modulation instability (MI). Whilst the dynamics of a noisy MI field have been investigated indirectly in the spectral domain using dispersive Fourier transform [2], there is no experimental study of MI in the time domain, and this, so far, has prevented a direct comparison between numerical studies and experiments. Here, we respond to this need and, using a temporal magnification system [3], we report for the first time on the measurement in real time of the intensity profile of a chaotic field spontaneously developing from noise due to MI. We show that the peak intensity of the localized structures present in the chaotic field follows the long-tailed statistics of rogue waves. We also directly compare the temporal profile of the localized structures with known analytical solutions of the NLSE, confirming that solitons on a finite background (SFBs) or breathers indeed constitute a natural basis with which to naturally interpret the development of a spontaneous MI field. Finally, we can conclude that the most intense localized structures arise from the collisions of SFBs.

The nonlinear propagation of a light field in optical fibers is described by the nonlinear Schrödinger equation (NLSE)

$$i\frac{\partial A}{\partial z}-\frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2}-\gamma\left|A\right|^2 A=0 \qquad (1).$$

Here $A(z,T)$ is the evolving field, β_2 is the fiber dispersion and γ represents the nonlinear Kerr coefficient. If β_2 is negative (anomalous dispersion), the system is modulationally unstable and any small perturbation to the CW stable state is amplified exponentially due to the nonlinearity. Analytical solutions of Eq. 1 with peculiar spatio-temporal localization characteristics exist in the form of SFBs or breathers. These localization dynamics have made SFBs ideal prototypes of rogue waves, and they have been recently observed in a series of controlled optical fiber experiments using coherently seeded perturbations [1]. However, it is also well-known that MI can be triggered from noise present on top of the CW field e.g. from intensity or phase noise, or even from quantum fluctuations. Because of the broadband incoherent nature of the noise in this case, the dynamics are dramatically different from the seeded case with the development of a chaotic field with emerging highly localized structures with random characteristics. This stochastic regime is of particular significance because

Figure 1 shows an example of a numerical simulation corresponding to our experimental parameters demonstrating the development of a 700 mW noisy CW field into a series of irregular localized pulses at selected distances of a standard telecom fiber. We can clearly see the generation of a chaotic pulse train with 100% contrast after about 7 km of propagation when sufficient energy has been transferred from the CW pump to the noise sidebands through nonlinear amplification. The temporal intensity profile varies with further propagation. The typical duration of the individual pulses is approximately 1 ps with peak values which can vary significantly with respect to the average background CW power. It is these the emergence of these localized structures which has never been measured in the time domain. Here we do so using the experimental setup also shown in Fig. 1. Using a time lens system (PicoLuz UTM-1500) with 76 magnification and 300 fs resolution, we can stretch the fluctuations of the chaotic MI field to timescales that can be measured with our real-time 30 GHz detection system.

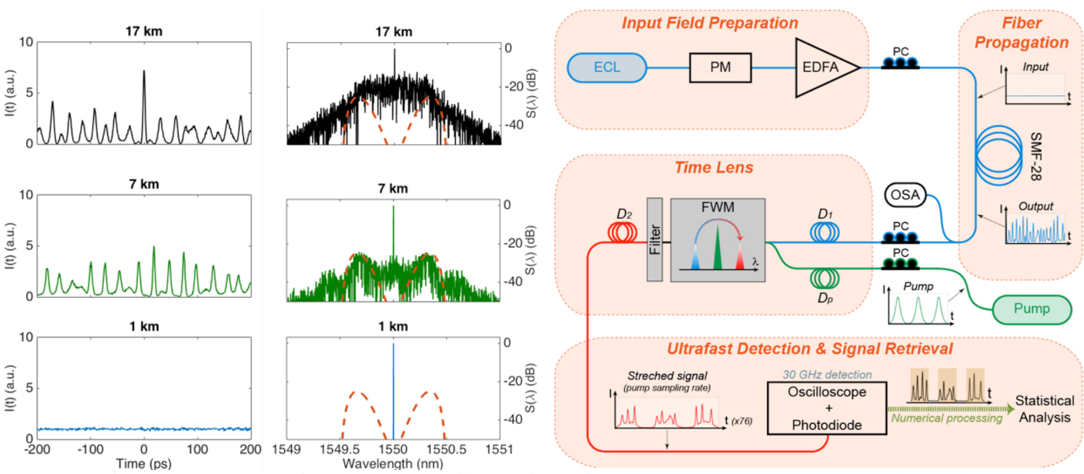

Figure 1: *Evolution of a 700 mW CW laser field in a SMF-28 fiber. Left panels show temporal evolution and middle panels the spectral evolution at selected distances. The red lines in the spectra indicate the MI gain. The right panel shows the experimental setup used to capture the MI field in real time. A phase modulator (PM) was used to suppress Brillouin scattering in the fiber and ensures operations in the pure MI regime.*

Figure 2 compares the experimental results with the stochastic simulations at 12 km and 17 km distances where the chaotic pulses have emerged. All powers are normalized to average power at the given distance to have comparable results. Excellent qualitative agreement is observed both in terms of intensity variations (see Fig. 2a-b) and peak intensity (Fig. 2c-d), confirming the presence of rogue waves above a (normalized) threshold intensity of 9 (using the standard two times of the significant wave height criterion [1]). Comparison of experimentally observed intensity profiles with analytical breather solutions of Eq. 1 in Fig. 2e-f further confirm that the latter are a natural basis to interpret the structure of a chaotic MI field and that the most intense structures arises from the collision of two SFBs.

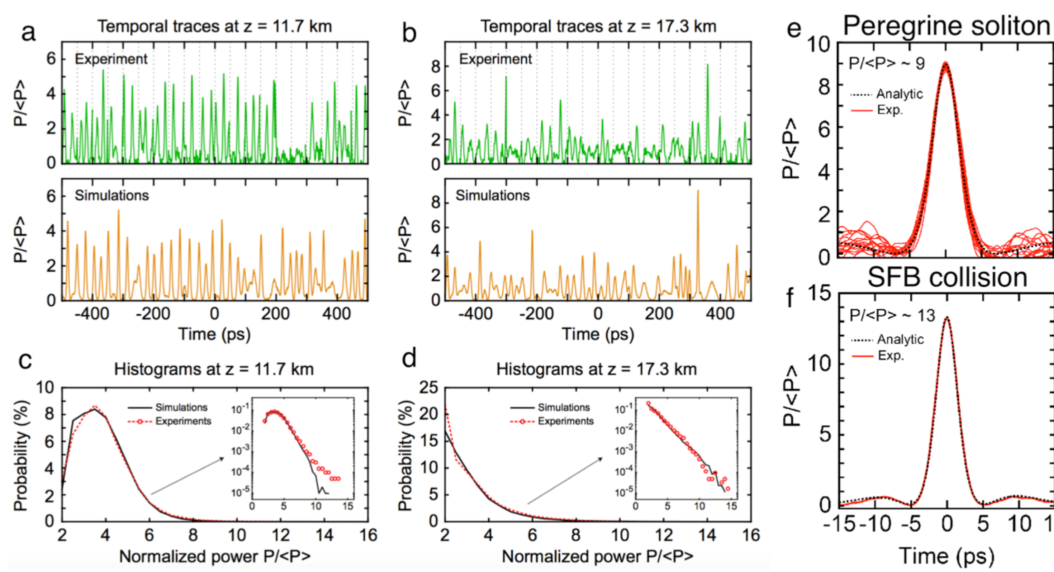

Figure 2*: Comparison between experimental and numerical results. a) and b) show examples of the chaotic pulse train at two distances. c) and d) show the histogram of the peak intensity over 100,000 events, insets show the results on a semi-logarithmic scale. e) and f) illustrate experimentally measured intensity profiles compared with analytical solutions of Eq. 1.*

References

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