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The picosecond structure of ultra-fast rogue waves

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ABSTRACT

We investigated ultrafast rogue waves in fiber lasers and found three different patterns of rogue waves: single-peaks, twin-peaks, and triple-peaks. The statistics of the different patterns as a function of the pump power of the laser reveals that the probability for all rogue waves pattens increase close to the laser threshold. We developed a numerical model which prove that the ultrafast rogue waves patterns result from both the polarization mode dispersion in the fiber and the non-instantaneous nature of the saturable absorber. This discovery reveals that there are three different types of rogue waves in fiber lasers: slow, fast, and ultrafast, which relate to three different time-scales and are governed by three different sets of equations: the laser rate equations, the nonlinear Schrodinger equation, and the saturable absorber equations, accordingly. This discovery is highly important for analyzing rogue waves and other extreme events in fiber lasers and can lead to realizing types of rogue waves which were not possible so far such as triangular rogue waves.

Keywords: Extreme events, rogue waves, optical data processing, four-wave mixing

1. INTRODUCTION

Rogue waves which are also called freak waves are an example for extreme events with higher probability than expected by stochastic models.[1] Such waves appear in numerous fields, including hydrodynamics, atomic physics, optics, and lasers.

We investigated ultrafast rogue waves which are created in fiber lasers. We focused on their temporal structure and measured the rogue wave structure as a function of the laser power and state of polarization.

We also developed numerical models and extended them to include the non instantaneous response of the saturable absorber and the two components of the vector field. These models reveal that the underlying mechanism of ultrafast rogue waves is different then what was consider so far.

2. TIME LENS

In order to investigate the temporal structure of ultrafast rogue waves, we resorted to a time-lens with 500 fs resolution.[2–5] A time-lens is based on the temporal equivalent of an imaging lens in space. In spatial optics, a light propagates distance u from an object to a lens, and then an image is generated at a distance v from the lens. The equivalent temporal scheme of such a lens is a time-lens, where a signal is propagating in dispersive material a distance u until it reaches a highly nonlinear fiber where we impose on it a quadratic phase shift. Then, after propagating a distance v in more dispersive material, we obtain an image of the input signal. The image can be a magnified copy or a shrinkage copy according to the parameters of the time-lens and according to the dispersion values before and after the time-lens.

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3. GAIN MODULATIONS: SLOW ROGUE WAVES

Any fluctuation in a laser power is being compensated by a pump depletion leading to a negative feed-back, until the equilibrium is restored. This is due to the coupling between the power of the output light, and the value of the gain in the cavity. This can be understood by resorting to the laser rate equations as:[6]

$$\frac{\partial E(t)}{\partial t} = \frac{1}{\tau_c}\left(G(t) - \alpha\right)E(t) + i\omega E(t), \tag{1}$$

were $E(t)$ is the electric field in the cavity, τ_c is the cavity life-time, $G(t)$ is the gain as a function of time, α is the losses, and ω is the light frequency. The gain as a function of time follows:

$$\frac{\partial G(t)}{\partial t} = \frac{1}{\tau_f}\left(P - G(t) - |E(t)|^2 G(t)\right), \tag{2}$$

were τ_f is the fluorescence life-time, and P is the pump power of the laser. Evaluating these equations leads to a relaxation oscillations of the cavity due to any change in the pump power, as:

$$\omega_{ro} = \frac{1}{\sqrt{\tau_c^2 + \tau_f^2}}. \tag{3}$$

When modulating the pump power at frequencies which are close or larger than ω_{ro} a chaotic behavior can arise. From this chaotic intensity fluctuations, rare peaks with high intensity appears which are considered as rogue waves. However, these rogue waves have the time-scale of the relaxation oscillations of the laser which is at the order of milliseconds to microseconds.

4. SOLITONS COLLISIONS: FAST ROGUE WAVES

Solitons are a special light pulses in which the nonlinearity is compensating for the dispersion in the fiber. In such cases a soliton pulse can propagate in the cavity with out dispersion and preserve its shape. The equation describing the propagation of pulses in fiber which combines the nonlinear interaction and the dispersion of the light in the fiber is the nonlinear Schroedinger equation (NLSE):

$$i\frac{\partial u}{\partial z} + \frac{1}{2}\frac{\partial^2 u}{\partial t^2} + |u|^2 u = 0, \tag{4}$$

were u is the field envelope of the pulse traveling in the fiber. The solution for this equation is:[7]

$$u\left(z,t\right) = \Sigma_{k=1}^{N} u_k(z,t), \tag{5}$$

were $u_k(z,t)$ is the single soliton solution, namely:

$$u_k\left(z,t\right) = 2\nu_k sech\left(2\nu_k\left(t - \xi_k\right)\right) e^{i2\mu_k(t-\xi_k)+i\delta_k}, \tag{6}$$

were μ is the soliton amplitude, ξ is the soliton temporal delay, μ is the speed of the soliton, and δ is the phase of the soliton. When solving these equations with two solitons, we obtain that two soliton will interact with each other. A force between the two solitons will either pull them together or push them apart according to the relative phase between them. In addition, the interaction between the solitons can lead to power transfer from one soliton to another and to collisions between solitons, in which the solitons changes the speed due to the collision.

This complicated dynamics of many solitons interacting together, leads to rare events in which many soliton collide and generate a high peak. These high peaks are considered as rogue waves and their time-scales is the time-scale of the solitons.

5. ULTRA-FAST ROGUE WAVES

We tried modeling a fiber laser, but could not get the ultrafast rogue waves which were measured in the experiment. Therefore, we extended current models to include the polarization mode dispersion in the cavity and the non-instantaneous response of the saturable absorber. Only when including both phenomena, we numerically observed the same rogue waves as measured in the experiment.

Specifically, to simulate the laser, we extended the numerical model presented in.[8] The propagation of the vector field envelope was simulated in each element of the fiber laser and repeated over large number of round trips. The field envelope

$$\vec{\psi} = \{\psi_x, \psi_y\} \tag{7}$$

traveling in a dispersive nonlinear fiber is governed by the non-linear Schrdinger equation:

$$i\vec{\psi}_z + \frac{D}{2}\vec{\psi}_{tt} + |\vec{\psi}|^2\vec{\psi} = 0, \tag{8}$$

where D is the dispersion tensor of the fiber with different values for each component of the field due to PMD, z is the propagation distance, and t is time in a moving frame of reference with the group velocity.

The EDF is simulated by:

$$i\vec{\psi}_z + \frac{D_2}{2}\vec{\psi}_{tt} + \Gamma_2|\vec{\psi}|^2\vec{\psi} = \frac{ig_0}{1 + Q/Q_{sat}}\left(\vec{\psi} + \beta_2\vec{\psi}_{tt}\right), \tag{9}$$

where Q_{sat} represents the saturation energy, g_0 is the small signal gain, β_2 the spectral width of the gain, Γ_2 is the nonlinear coefficient, and the total energy Q is:

$$Q = \int_{-\infty}^{\infty} |\vec{\psi}|^2 dt. \tag{10}$$

The instantaneous saturable absorber is modeled by:

$$T(t) = T_0 + \Delta T\frac{I(t)^2}{I_{sat} + I(t)}, \tag{11}$$

where $I(t) = |\vec{\psi}|^2$, T_0 is the transmission for low intensity optical field, and I_{sat} is the saturation intensity. In order to include the response time of the saturable absorber, we imposed a low pass filter with a cut-off frequencies of 1 THz on $T(t)$.

The propagation in the fiber laser follows the principle states of polarization (PSP) in the cavity while the polarization controller couples between the two PSP according to:

$$\vec{\psi}_{out} = \begin{bmatrix} (1-\kappa)e^{i\varphi_1} & \kappa e^{i\varphi_2} \\ \kappa e^{-i\varphi_2} & (1-\kappa)e^{-i\varphi_1} \end{bmatrix} \vec{\psi}_{in}, \tag{12}$$

where κ is the amplitude coupling strength, φ_1 is the relative phase between the two states of polarization, and φ_2 is the cross phase.

The full results, as well as more details on the experiments and the numerical model are described in.[9]

6. CONCLUSIONS AND FUTURE PROSPECTS

We measured the statistics of ultrafast rogue waves in fiber lasers and found that the underlying mechanism is different than what was previously considered. We will continue to investigate extreme events in different schemes, such as phase locked fiber lasers,[6, 10–13] fiber lasers with unique states of polarization,[14, 15] and different types of fiber components[16–19] We hope to utilize our temporal imaging to focus light through dispersive material and to create rogue waves for high resolution imaging with nano-particles.[20–25]

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