Extreme wave dynamics in ultrashort fiber lasers

Philippe Grelu[1,*], Caroline Lecaplain[1,2] , Jose M. Soto-Crespo[3]

[1]*Laboratoire ICB UMR 6303 CNRS – Université Bourgogne Franche-Comté, 9 av. Savary BP 47870, F-21000 Dijon, France*
[2]*EPFL - Ecole Polytechnique Federale de Lausanne, CH-1015 Lausanne, Switzerland*
[3]*Instituto de Optica, CSIC, Serrano 121, 28006 Madrid , Spain*
**philippe.grelu@u-bourgogne.fr*

Abstract *We review recent experiments that demonstrate the existence of optical wave transients of unusually high amplitude in fiber lasers operated in the vicinity of mode locking. These transients are analyzed in the context of optical rogue wave formation, with an important role played by the constraints of ultrafast measurements. From these investigations, a universal rogue wave mechanism is highlighted, which results from the evolution of a chaotic bunch of pulses or sub-pulses, subjected to numerous inelastic collisions, while traveling round the laser cavity.*

Optical rogue waves (RWs) are attracting considerable attention, as the possible tabletop counterpart of oceanic rogue waves [1]. While most of the investigations have considered so far the formation of RWs in conservative and integrable systems, there is a recent surge of interest to unveil these extreme wave events in active dissipative systems, such as in laser cavities [2]. Active dissipative systems include a sustained supply of energy, which, as the wind for deep-water rogue wave generation, can become decisive in the formation of waves of extreme amplitude. In addition, it is well known that nonlinearity and multi-dimensionality lead to the manifestation of chaotic dynamics for certain ranges of laser cavity parameters. Thus, laser systems combine several physical effects conducive to the formation of optical rogue waves.

Mode locked lasers, even though producing waves of extreme amplitude, cannot be considered as sources of optical rogue waves: when the train of ultrashort pulses is perfectly regular, the arrival of successive high-amplitude pulses can be anticipated. Similarly in hydrodynamics, tsunamis once formed can be traced over long distances and do not comply with the definition of a rogue wave, which should yield a high degree of unexpectedness. Thus, it seems logical to look for rogue waves among chaotic dynamics, and possibly, among chaotic ultrashort pulse dynamics. These chaotic dynamics can manifest in the vicinity of the robust and stable mode locked laser dynamics [3]. In the past few years, several dramatic chaotic dynamics associated with the propagation of transient ultrashort pulses in the laser cavity were identified: they comprise noise-like pulse emission [4], exploding dissipative solitons [5], and soliton rain [6]. Extreme fluctuations of the pulse energy in a Ti:Sapphire laser were also reported [7].

Since subdomains where RWs manifest should exist, numerical explorations were undertaken, based on lumped fiber laser ring cavity models [8,9]. Starting from single pulse mode-locked laser operation, complex dynamics can appear through bifurcations, which lead for instance to pulsating and chaotic dynamics [3]. Complexity is also exacerbated by the transition from single to multiple pulse dynamics, owing to the various scenarios of pulse-to-pulse interaction, from pulse bunching and soliton molecule formation, to pulsating and vibrating molecules, and to erratic and chaotic relative pulse motions. In the situation of erratic pulse motions inside the cavity, nonlinear pulse collisions will take place, at a rate that will be larger when the pulses are confined into a tight packet that propagates round the cavity. Numerical studies, addressing either propagation in the anomalous dispersion regime [8] or within normal cavity dispersion [9] predicted that extreme waves should indeed manifest, satisfying the three practical rogue wave criteria, namely (i) their unpredictable appearance and swift disappearance, (ii) their amplitude larger than twice the significant wave height (SWH) – the latter being the mean of the higher one third of the wave events, and (iii) their occurrence exceeding classical distributions. In the case of Ref. 8, the route taken to predict RWs went through multiple pulsing, which is favored in an anomalously dispersive laser cavity under intense pumping power, then pulse bunching, a widely represented multiple-pulse behavior, and finally, the destabilization of the pulse bunch that becomes highly chaotic.

However, the real-time characterization that is required to experimentally identify optical RWs among the ultrafast dynamics of chaotic pulses is extremely challenging. By using advanced real-time characterization, optical RWs could be singled out from complex ultrafast laser dynamics. In a first experiment, the laser operated in a chaotic multiple-pulse regime, in the vicinity of mode locking, and its output was analysed with a 45-GHz photodiode connected to a 20-GHz, 40-GSa/s real time oscilloscope

[10]. This allowed us to partially resolve the internal structure of 1-ns long chaotic pulse bunch, highlighting in a convincing way the nonlinear pulse collisions that create transient waves of extreme amplitude, which in turn were found to oblige the three main RW criteria. Naturally, the rate of RW detection in the experimental system was highly dependent on the detection bandwidth.

In a subsequent series of experiments, we investigated the statistical features of the so-called noise-like pulse dynamics [4], which can manifest in either anomalous or normal dispersion regime. This pulsed operation is understood as the destabilization of an energetic mode-locked pulse regime, and generally results in a compact bunch of 10-100 ps duration traveling round the laser cavity. Its internal structure is thus extremely difficult to resolve in real time. Hence, we used a recently developed technique of single-shot spectral characterization, the dispersive Fourier-transform technique [11,12]. Noise-like pulses are considerably stretched using a long dispersive line, so that the spectrum of each pulse becomes mapped into a temporal waveform that is long enough to be resolved by a photodiode connected to a fast real-time oscilloscope. This way, we could statistically analyze the succession of output optical spectra, to reveal the existence of what we dubbed as "spectral rogue waves", namely, spectral wave components whose extreme amplitude follow abnormal statistical distributions [13].

To conclude, the ultrafast fiber laser represents an efficient workbench to investigate extreme wave dynamics and optical rogue wave formation. However, it poses major challenges associated with the limitations of the real time characterization of the chaotic optical field. Recent advances highlighted a universal rogue wave mechanism, which results from the evolution of a chaotic bunch of pulses or sub-pulses, subjected to numerous inelastic collisions, while traveling round the laser cavity. We conjecture that spectral rogue waves found in compact noise-like pulse bunches have temporal rogue wave counterparts.

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