Generation of spatio-temporal extreme events in noise-like pulses NPE mode-locked fibre laser

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Abstract: We experimentally study spatio-temporal generation of extreme events in the radiation of NPE mode-locked fibre laser generating noise-like pulses. We show that new pulses starts from high-intensity spatio-temporal structure which consist of mainly 3 subsequent pulses which are both separated over fast and slow evolution time. Statistical analysis of the noise-like pulse evolution over round-trips shows that the pulse width and intensity varies with a period of around 85 round-trips which does not change from pulse to pulse. The intensity probability density function has a heavy tail originated only from events of pulse formation.

OCIS codes: (190.4370) Nonlinear optics, fibers; (140.3510) Lasers, fiber.

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1. Introduction

Fibre lasers mode-locked by nonlinear polarization evolution (NPE) are well known in physics and applications by a robust design and high performance output. NPE-mode-locked fibre lasers are characterized by a great variability of possible lasing regimes even in the case of single-pulse operation (one pulse travelling in the cavity) [1]. In many cases, NPE-mode-locked lasers are designed to operate in a regime of noise-like pulses. First studies of the phenomena go back to 90s [2, 3] . Since then it has been demonstrated that lasers generating noise-like pulses possess a very rich and complex dynamics [4-14]. Recent studies suggests that mechanisms of coherence's loss in noise-like pulses mode-locked laser include interplay of modulation instability, parametric instability, cascaded four-wave mixing [15]. A possibility to control in experiments pump power and polarization controller settings, offers new opportunities to tailor and control lasing. In particular, the output performances of the laser could be optimized during laser's operation by using an evolutionary algorithm that prescribes a set of cavity parameters entailing specific self-starting mode locking [16]. Further, self-mode-locking of noise-like pulses was shown in [17]. The noise-like pulses can be used for pumping supercontinuum sources [18, 19], for applications in ultra-high resolution optical coherence tomography [20].

While in the temporal domain noise-like pulses might have a complex structure, distinct and steady-state regimes revealed in the spatio-temporal domain. Indeed, recently it has been experimentally shown that generation regimes of passively mode-locked fibre lasers could be distinguished on the basis of their spatio-temporal properties rather than temporal properties alone [21]. Similar approaches are used to study generation of passive cavity solitons [22, 23], writing and erasing of topological solitons [24], interaction of multiple vectorial dissipative solitons in a vertical-cavity surface-emitting laser, [25], studies of rain of solitons in passively mode-locked fibre laser [26], soliton explosion in passively mode-locked fibre laser [27, 28], generation of coherent structures in quasi-CW lasers [29-31]. Recent experimental studies of spatio-temporal dynamics of noise-like pulses include observation of various stable and unstable regimes [32], and Q-switched like soliton bunches [33].

Spatio-temporal mapping allows one to observe small scale structures within the radiation forming noise-like pulses. For example, the so-called spiny solitons can randomly populate the top of the noise-like pulse, as it has been shown through numerical modelling in [34]. It has been shown that dissipative rogue waves can be generated via bunching of structures within a noise-like pulse [35-37]. Other types of optical rogue waves have been recently identified as aperiodically generated spatio-temporal structures: dark three-sister rogue waves [38] and waves emerging from interaction of three pulses having different group velocities [39, 40] . Also it has been experimentally shown via spatio-temporal analysis that rogue waves could be in a mode-locked fibre laser operation in multiple-soliton state in which hundreds of solitons occupied the whole laser cavity.

In the present paper, we experimentally study spatio-temporal generation of extreme events in the radiation of NPE mode-locked laser generating noise-like pulses. We show that the formation of new pulses starts from the spatio-temporal extreme event having similar structure from pulse to pulse. Rogue wave consists of mainly 3 subsequent pulses which are both separated over fast and slow evolution time. Statistical analysis show that once the noise-like pulse is formed, it does not have events with extreme intensity. All extreme events in the radiation are located in areas of new pulses formation.

2. Experimental setup and basic laser properties

We study a nonlinear polarization evolution (NPE) mode-locked laser made of the Er-doped active fibre (Er-DC) placed in the ring cavity together with a 1 km long normal-dispersion (ND) fibre (D = - 44ps/nm/km), polarization beam splitter (PBS) and polarization controllers (PC1 and PC2), Fig. 1. In such a long cavity, the stochastization processes are important. An isolator (I) ensure a unidirectional propagation. The laser is pumped by a laser diode (LD) through wavelength-division multiplexer. The radiation is characterized by photodiode (PD) connected to the oscilloscope (DSO). Typical average output power was about 20 mW. The laser operates well above the generation threshold.

The generation spectrum of the laser is shown in Fig. 2(a). There are two peaks generated on the top of the gain profile. Note that the number of the peaks, their position depend strongly on the settings of the polarization controllers and the pump power of the laser diode. It is known that such laser design allows generation in various temporal regimes [6]. We operate the laser in the regime of noise-like pulses. The laser generates a train of pulses, Fig. 2(b). As we are interested in less stable generation to initiate processes of pulses formation and break up, we have not optimized the parameters of the cavity, the pump power or polarization controllers settings. Each pulse has a complex temporal structure being a noise-like pulse in its nature, Fig. 2(c). The structure of the pulse is changed from pulse to pulse.

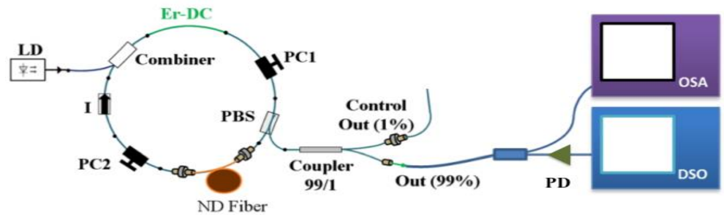

Fig. 1. A scheme of the NPE mode-locked fibre laser delivering noise-like pulses.

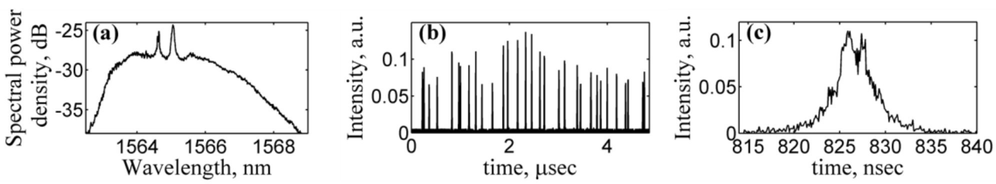

Fig. 2. (a) Generation spectrum and (b) typical time dynamics in the regime of the noise-like pulses. (c) Temporal structure of the noise-like pulse.

3. Generation of spatio-temporal extreme events

The much more insight can be gained from analysis of the spatio-temporal intensity dynamics of the laser. We have recorded extremely long time traces, I(t), up to 10 000 of consecutive cavity passes. To get a spatio-temporal dynamics from initial time trace, we calculate intensity autocorrelation function of the time trace and find exact cavity round-trip time by locating its second peak. On the next step, we slice the initial intensity dynamics, I(t), into the segments length of each is equal to a cavity round-trip time. Consecutive round-trip intensity dynamics then stacked upon each other to form a two-dimensional intensity spatio-temporal dynamics, I(t,z), where z is a propagation coordinate measured in terms of number of round-trips or in terms of equivalent propagation length.

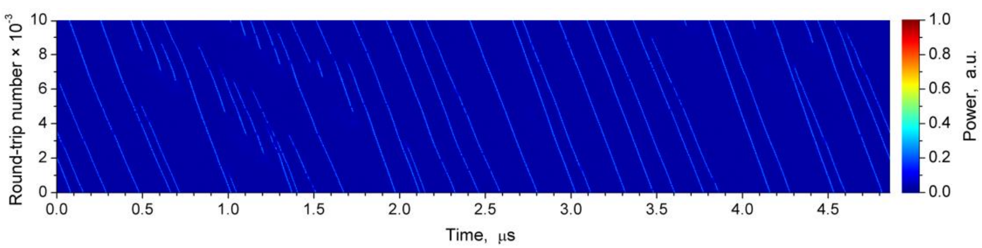

Fig. 3. Intensity spatio-temporal dynamics of mode-locked laser delivering noise-like pulses.

The resulted intensity spatio-temporal dynamic is shown on Fig. 3. The full cavity round-trip is shown over OX axis. The spatio-temporal dynamics is plotted with a round-trip time of 4.8 μs. The pulses have some residual velocity in this reference frame, what results in tilted propagation in spatio-temporal dynamics. Since sampling rate of the oscilloscope is not multiple of inverse laser cavity round-trip time, the frame of reference used differs slightly from co-moving reference frame where pulses are immobile. The intensity spatio-temporal dynamics reveals chain-like events of pulses appearance and break-up.

The high resolution over time and round-trips allows us to study the formation of the pulses in details. In Fig. 4(a) we show the spatio-temporal region where the new noise-like pulses are started. Interestingly, every pulse starts its generation from a rogue spatio-temporal structure.

The structure in most cases has a form of 3 distinct peaks of high intensity, Fig. 4(b)-(c). Peaks are separated both over the time and over the round-trips. Typical separation over time is about 2 ns. The simple time dynamics plotted at different round-trips, see curves below each panel on Fig. 4, does not allow to get a full picture of the structure of rogue event, as it does not represent the extent of the structure over the slow evolution coordinate, i.e. over round-trips. The each sub-peak in spatio-temporal rogue event lasts for ~5 round-trips, see intensity evolution shown on Fig. 4(c) at fixed time coordinate.

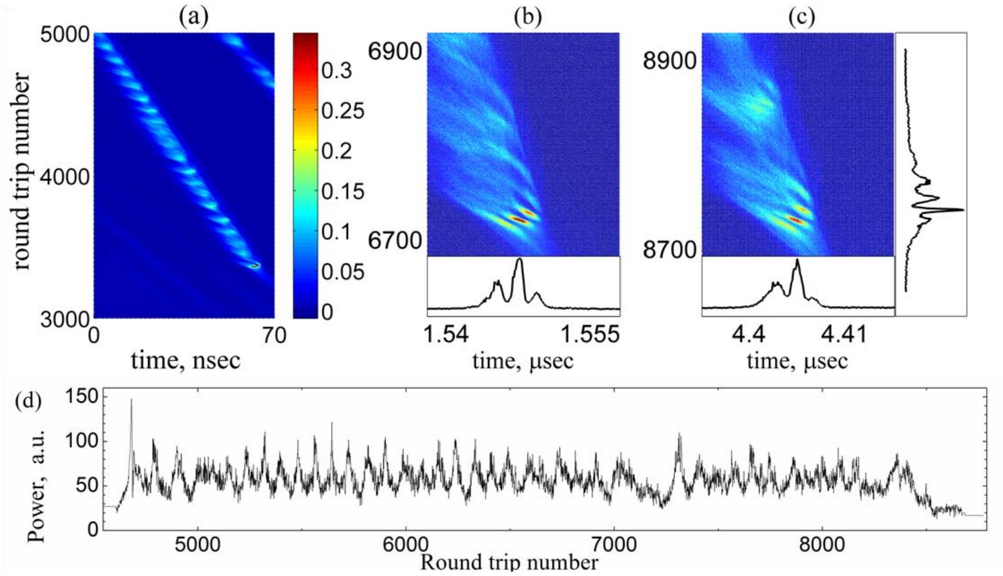

Fig. 4. (a) Evolution of a noise-like pulse. (b)-(c) The formation of the two new noise-like pulses from spatio-temporal extreme event. Time traces I(t) shown at the bottom of (b) and (c) are plotted at 6722th and 8731th round-trip, respectively. The slow intensity dynamics over round-trips, I(z), is plotted on right at fixed time coordinate. (d) Dynamics of the noise-like pulse in the local co-moving reference frame.

Plotting the dynamics over round-trips at fixed time coordinate, Fig. 4(c), does not allow one to study the evolution of the pulse's properties over a large number of roundtrips, as pulse's envelope propagates with non-zero speed in the co-moving reference frame, despite the fact that most of the radiation is immobile in this frame. To get inside of the long-term dynamics, we move into local co-moving reference frame. In other words, we calculate how the intensity depends on the round-trip number over a tilted line shown in Fig. 4(a), $I(t_0+z/v, z)$, where v is a speed of co-moving reference frame. The resulted slow intensity dynamics shown on Fig. 4(d) makes clear long-term structure of the pulse, including the periodic oscillations of the pulse intensity over round-trips.

4. Properties of noise-like pulses

Further we study average properties of the noise-like pulses in the cavity. To do this, we extract each stationary pulse (i.e. which does not appear and breaks up during the observation), and plot how the intensity depends on the round-trip number, $I(t_0+z/v, z)$. In this way we track instantaneous changes in the pulses' speed which could be a result of inter-pulse interaction, pulse wavelength fluctuations or other processes and is reproduced in the spatio-temporal dynamics as propagation over curved paths rather than over straight-lines which correspond to the propagation of the structures with fixed speed. The instantaneous intensity of noise-like pulses fluctuates strongly not only over time coordinate, but also over the slow evolution coordinate (round-trips), Fig. 5(a) (grey curve). Despite the strong fluctuations, periodic evolution of the intensity is clearly visible.

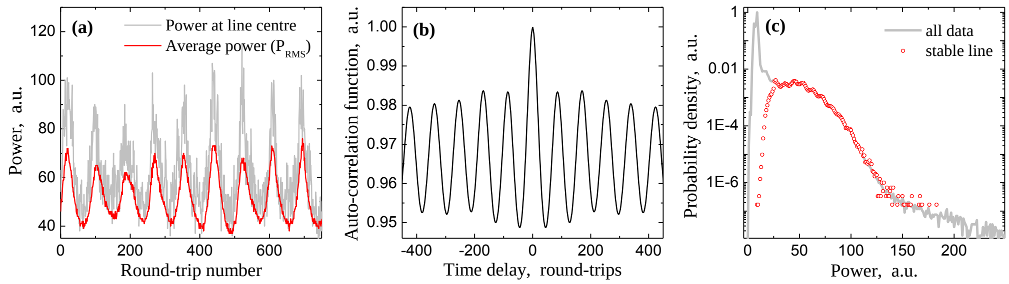

Fig. 5. Slow dynamics of a stable pulse: (a) instantaneous intensity dynamics (grey curve) and dynamics averaged over the pulse (red curve); (b) auto-correlation function of rms intensity; (c) probability density function of single stable pulse (red circles) and the whole registered data (grey curve), including all pulses and background.

To get access to average noise-like pulse characteristics, we perform averaging over the pulse width (i.e. over fast time coordinate), and calculate the rms intensity over the pulse, $P_{RMS}(z)=\int P^2(z,T)dT \big/ \int P(z,T)dT, \quad T{=}t{+}z/v$, see red line on Fig. 5(a). Both instantaneous and averaged intensity dynamics have a form of pulsations what means that both peak intensity and energy are varied quasi-periodically with slow time. From average evolution of the pulse intensity, one can define the period of inter-pulse oscillations via autocorrelation analysis, $g(\tau)=\int P_{RMS}(z+\tau)P_{RMS}(z)dz$, Fig. 5(b), which equals to 85 round-trips. We picked up every pulse in the cavity, repeated the analysis and found that ACF period is the same for all pulses in the cavity. This means the noise-like pulse periodicity properties are defined by the cavity itself, rather than local properties of the pulse (like instantaneous intensity and pulse width). Despite pulses are noise-like both over temporal and round-trip coordinates, the system demonstrates quite good stability in average properties.

Finally, we calculate intensity probability density function (pdf) directly from the recorded time trace, Fig. 5(c). The intensity pdf reveals a high probability to find low intensity events as well as a presence of events with high intensity. More information one can get by using a slow evolution dynamics similar to shown on Fig. 5(a), grey curve. We analyze a set of such temporal dynamics across the pulse width. The resulted pdf is shown on Fig. 5(c), red curve. After normalization, the intensity pdf over the pulse completely coincides with a central part of pdf of whole registered data pool, Fig.5(c), with no low-intensity (background) nor high-intensity (extreme events) tails. In particular, this means, that every pulse in the cavity has the same statistical properties. As we used in our analysis only stationary pulses, the extreme events are not present in the intensity pdf of the pulse. This observation agrees with early shown fact that rogue events are attributed to the noise-like pulse formation events.

6. Conclusion

To conclude we report on the experimental study of NPE mode-locked fibre laser delivering noise-like pulses. We observed the formation of new noise-like in real-time measurements of spatio-temporal dynamics, and found that every new noise-like pulse starts its generation from extreme spatio-temporal event of 2 of 3 sub-sequent intense pulses separated both over time and round-trips. We provide a statistical analysis of properties of noise-like pulses and found that pulses breathe with a period of 85 round-trips. The probability density function of the intensity over the pulse does not contain extreme events if the area of pulse formation is excluded, so all extreme events in the total laser radiation occur where new pulses are formed.

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