Extreme value statistics in quasi-CW Raman fiber lasers

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Abstract: It is found that rare extreme events are generated in a Raman fiber laser. The mechanism of the extreme events generation is a turbulent-like four-wave mixing of numerous longitudinal generation modes.

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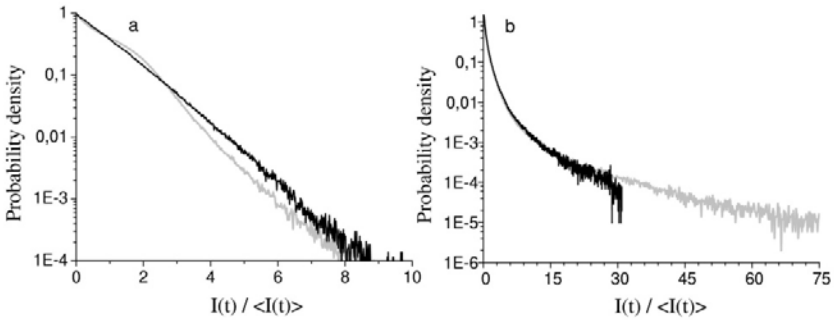
Extreme type statistics in nonlinear fiber optics has attracted a great attention since the experimental demonstration of optical rogue waves in supercontinuum (SC) generation [1]. In different systems there are different physical mechanisms attributed to the emergence of the rare intense events. The extreme events are defined by the interplay of the modulation instability, third-order dispersion and collisions of Raman-shifted solitons in SC sources [2, 4]. The formalism of Akhmediev breathers provides the sufficient advance in understanding of physics of rogue waves in optical system [5]. In Raman fiber amplifiers (RFAs) [3], the main mechanism is the exponential transfer of the intensity fluctuations from the pump wave to the signal via Raman response. Also it has been shown, that sporadic rogue waves events emerging from turbulent fluctuations as bursts of light during propagation of the optical wave along the long fiber could exist [6].

Here, we study the emergence of intense rare events in the laser generation on the example of the quasi-CW fiber laser on the example of the high-Q cavity RFL operating in the normal dispersion regime. The spectral, temporal and statistical properties of the generated radiation are described by the NLSE:

$$\frac{\partial A_s^\pm}{\partial z}+\left(\frac{1}{v_s}-\frac{1}{v_p}\right)\frac{\partial A_s^\pm}{\partial t}+\frac{i}{2}\beta_{2s}\frac{\partial^2 A_s^\pm}{\partial t^2}+\frac{\alpha_s}{2}A_s^\pm==i\gamma_s\left(\left|A_s^\pm\right|^2+2\left|A_p^\pm\right|^2\right)A_s^\pm+\frac{g_s}{2}\left(\left|A_p^\pm\right|^2+\left\langle\left|A_p\right|^2\right\rangle\right)A_s^\pm$$

We found that the statistical properties are sufficiently different for the intra-cavity and output spectrum, i.e. the statistical properties of the radiation generated at one pass and many cavity passes are different. The intensity PDF of the intra-cavity radiation is sufficiently non-exponentional revealing that correlations between different longitudinal modes do exist. It is found that the intensity PDF of the modes generated on the flat top at the spectrum center is exponential, Fig. 1a. Therefore, neighboring longitudinal modes at the central part of the spectrum are generated independently, i.e. they are uncorrelated. Contrary to the intuitive consideration that in the dispersive media closely spaced spectral components are more likely to be correlated than far away spaced components, exactly distant spectral components have to be correlated in the RFL. A physical reason of such far correlations is unclear. It seems that in some specific cases modes correlations could be enhanced, and, consequently, could sufficiently change spectral and statistical properties of the generated radiation.

Fig. 1 Intensity PDF of the modes filtered out from the (a) spectrum center and (b) spectral wing (filter is detuned by 1 nm from the



spectrum center). Filters spectral full widths are 0.1 nm (black) and 0.5 nm (gray).

Intensity PDF of spectral components at far spectral wings are sufficiently non-exponential revealing the existence of intense rare events having the probability higher than probability defined by the Gaussian distribution, Fig. 1b. The extreme rare events are more pronounced in the output radiation of the high-Q cavity RFL.

The temporal behavior of the total intra-cavity radiation is irregular with some rare events having the amplitude several times higher than the mean value, Fig.2a. The intensity evolution of the radiation within the narrow spectral region at the spectrum center is similar, Fig. 2b. Such intensity evolution is typical for stochastic signal which consists of many independently generated modes obeying the Gaussian distribution.

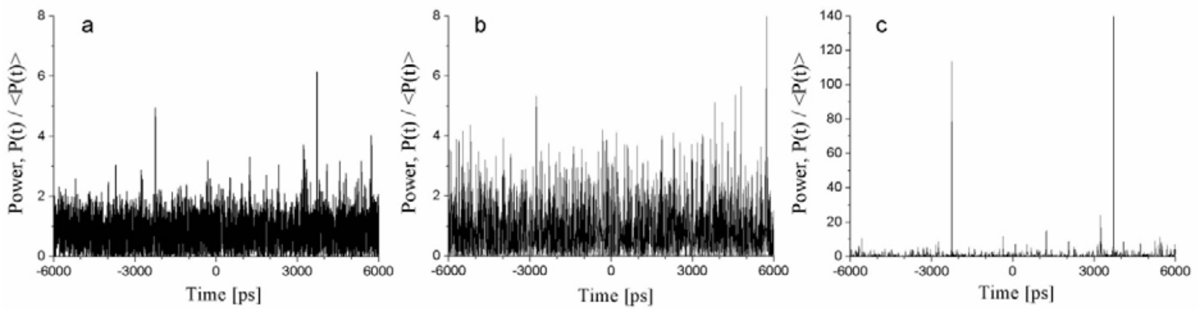


Fig.2 (a) The time dynamics of the total intra-cavity radiation as well as radiation generated within the 0.5 nm spectral width at the (b) spectrum center and (c) far spectral wing.

However, the output radiation comprises the events having the amplitude >100 times higher than the average output power in the given spectral region, Fig.2c. The typical temporal width of the extreme rare event at the laser output is ~10 ps. Recently, the results of our numerical calculations has been indirectly confirmed by experimental measurements of statistical properties of radiation using ultra-narrow spectral filters [7].

The extreme rare events are generated in RFL at far spectral wings thus being generated in one fiber pass only. The physical mechanism of rare events emergences in RFL is different from those observed in RFA. Indeed, the noise transfer from the pump wave to the generation wave has no influence on statistical properties of RFL. The rare events are generated in turbulent four-wave mixing interaction of numerous longitudinal modes and located at far spectral wings. The similar mechanism of extreme waves appearance during the laser generation could be important in other types of fiber lasers including random distributed feedback fiber lasers operating via Raman or Brillouin gain.

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