Spatio-temporal generation regimes in quasi-CW Raman fiber lasers

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Abstract: We present experimental measurements of intensity spatio-temporal dynamics in quasi-CW Raman fiber laser. Depending on the power, the laser operates in different spatio-temporal regimes varying from partial mode-locking near the generation threshold to almost stochastic radiation and a generation of short-lived pulses at high power. The transitions between the generation regimes are evident in intensity spatio-temporal dynamics. Two-dimensional auto-correlation functions provide an additional insight into temporal and spatial properties of the observed regimes.

OCIS codes: (140.3510) Lasers, fiber; (140.3550) Lasers, Raman.

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1. Introduction

Raman fiber laser (RFL) is a great platform for demonstration of nonlinear physics. High gain and up to several kilometer long cavity create perfect conditions for nonlinear effects to develop. Even the slightest variation of the parameters can lead to a qualitative change in generation regime of the laser. It is known that RFLs have stochastic time dynamics being CW on millisecond time scale and quasi-CW on sub-ns time scale. The quasi-CW properties of radiation are defined by the co-existence of a big number of longitudinal modes having fluctuating phases and amplitudes [1]. The modes interact through the four-wave mixing. These processes could be described in the limit of Gaussian statistics within the model of optical wave turbulence [2]. In general, approaches of the optical wave turbulence found broad implications in optics recently [3] being capable to describe the emergence of optical rogue waves, supercontinuum generation [4], random fiber lasers [5]. Recently, intermittency and rogue waves in integrable turbulence has been observed using optical fiber as a test system [6–8]. Turbulent-like generation in fiber lasers could be also modeled within the Ginzburg-Landau equation [9].

The real statistical properties of radiation of quasi-CW RFLs could differ from Gaussian statistics [1]. Residual mode correlations result in deviations of statistics from Gaussian and appearance of optical rogue waves in the generation of quasi-CW lasers [10–12]. This makes the intensity dynamics not completely stochastic.

Residual mode correlations could also lead to partial mode-locking in RFLs. In [13] the pulsed laser is demonstrated. The laser reported to be very hard to adjust and unstable. Another work [14] reported a partially mode-locked RFL generating noise-like pulses of 2.5 ns width which are filled by an irregular bunches of shorter pulses. Intermode beating harmonically mode-locked RFLs generating tens of nanoseconds long noise-like pulses reported in [15, 16]. Properties of such partially mode-locked regimes are usually hard to assess in temporal measurements.

Recently it has been experimentally shown that generation regimes of passively mode-locked fiber lasers could be distinguished on the basis of their spatio-temporal properties rather than temporal properties alone [17]. Indeed, the laser radiation is trapped in the laser cavity making round-trips there. So any given temporal pattern $I(t)$ will be periodically out-coupled from the cavity. Each snapshot of this intensity pattern registered periodically at the laser output corresponds to the same pattern which has evolved in the cavity for different number of round-trips. In this way, the intensity spatio-temporal dynamics, $I(t,z)$ could be measured, see details [17]. The same concept was used to experimentally study various systems including observation of long-range interaction of solitons [18], specific dynamics in passively mode-locked lasers [19–22]. In quasi-CW RFLs the existence of laminar and turbulent generation regimes was observed in spatio-temporal domain [23].

However, the question whether there is only one distinct turbulent regime or a range of different regimes could exist has not been previously addressed neither experimentally nor numerically. In this paper we observe different types of spatio-temporal dynamics in the quasi-CW RFL. The regimes are varied from partial mode-locking to almost stochastic generation of different spatio-temporal patterns to emergence of short-lived pulses on the stochastic background.

2. Experimental setup and data acquisition

The laser was formed of 1 km of fiber with normal group velocity dispersion $D = -44\frac{ps}{nm \cdot km}$ and two highly reflective fiber Bragg gratings (FBG) with spectral width of 1 nm, Fig. 1. The pump radiation at 1450 nm from another RFL was coupled into the laser cavity through a WDM coupler. The setup lases at 1550 nm owning to the Raman gain. The output intensity dynamics were registered from the 1% rejection port of 99/1 coupler by 50 GHz DC photo-detector and 6 GHz digital sampling oscilloscope.

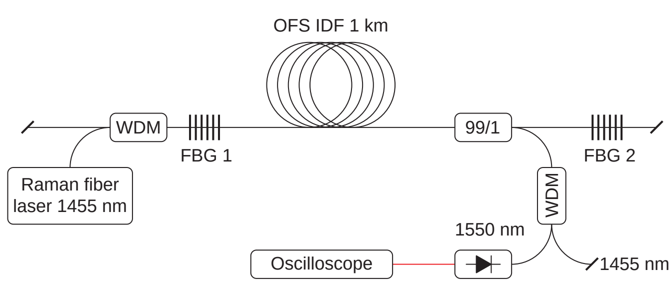

Fig. 1. Experimental Setup.

We experimentally measured very long time traces $I(t)$ of length up to 128 million points which corresponds to 3.2 ms in time, i.e. more than 320 round-trips. We characterized the dynamics in spatio-temporal domain way rather than in solely temporal domain following the approach of [17]. Briefly, to measure the intensity spatio-temporal dynamics, $I(t,z)$, we do autocorrelation of the initial time trace, $I(t)$, to find the exact cavity round-trip time. The time trace $I(t)$ is then split into time traces of equal length (of round-trip time), which are consecutively plotted one over another. Each layer corresponds to the same temporal pattern observed on the next round-trip. In this way, the intensity spatio-temporal dynamics is measured.

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3. Results and discussion

The intensity dynamics of the quasi-CW RFL depends on the pump power, Fig. 2. At all pump power levels the time dynamics looks irregular, only near the generation threshold slight periodic modulation of the intensity could be seen, Fig. 2(a). From such intensity dynamics alone, it is impossible to distinguish the difference in generation regimes of the laser if any exists. The measured intensity probability density functions (PDF) could provide additional information about the details of the generation regime, see insets at Fig. 2. Intensity PDF gradually develops the exponential high intensity tail while pump power increases and becomes broader revealing the generation of more intense events. The combination of intensity PDF measurements and intensity dynamics measurements, $I(t)$, still do not allow clearly reveal difference in the generation regimes over power. Note that in our case the limited electrical bandwidth of the measurement setup could influence quantitatively the observed time dynamics and statistical properties, but does not affect the measurements in qualitative way [24].

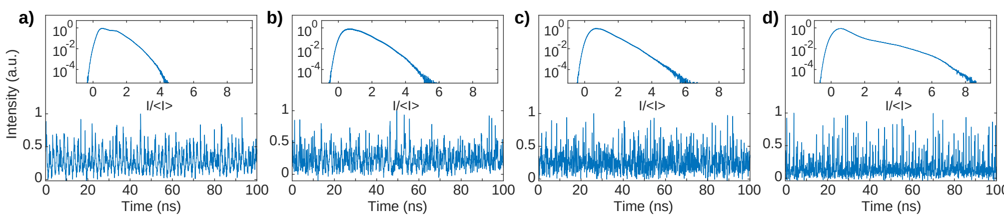

Fig. 2. Temporal dynamics and probability density functions for different pump powers. All traces presented show stochastic nature of the output radiation, with the mean level of the signal being the only visually discriminable parameter, but not clear enough to determine the operational regime of the laser. **a)** 1.5 W of pump power, **b)** 2.0 W, **c)** 3.0 W, and **d)** 3.25 W.

The situation is completely different if the laser dynamics is analyzed in spatio-temporal domain, Fig. 3. A clear distinction and similarity between generation regimes is observed. Partial modulation at low powers forms a distinct spatio-temporal pattern, Fig. 3(a), which could be thought as operation in partially mode-locked regime. Indeed, the stable over large evolution time (hundreds of round-trips) modulation of the intensity can be clearly seen with the well defined frequency despite the pulses itself are of noise-like structure. The mechanism responsible for this particular modulation frequency is not entirely clear, but it could be possible that this regime could be potentially developed into a proper high-quality mode-locking if the cavity is designed in a specific way or additional appropriate saturable absorption mechanism is introduced into the cavity. Note that lasers operating in similar temporal regime of partial mode-locking are previously reported in the literature [13–16,25], however the spatio-temporal dynamics have not been analyzed.

At higher power, the spatio-temporal dynamics changes drastically, Fig. 3(b). In this case there is no periodicity in temporal dynamics. Despite the stochastic time dynamics $I(t)$, some localized bright structures are clearly visible in the spatio-temporal domain. Further increase of the pump power leads to the change of spatio-temporal pattern and to the narrowing of bright structures both over temporal and evolution coordinates, Fig. 3(c). Note that observed regimes are principally different from previously observed turbulent dynamics [23]. In particular, dark and gray solitons are not generated.

At highest available pump power of 3.25 W, another completely unexpected spatio-temporal regime is observed, Fig. 3(d). The radiation is filled with some short-lived intense pulses which change the overall intensity statistics, see Fig. 2(d). Such pulses are non-stationary and short

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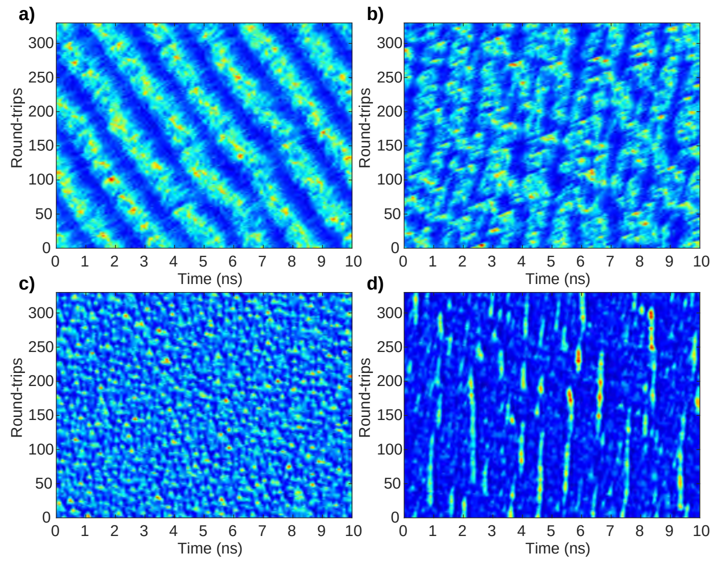

Fig. 3. Spatio-temporal dynamics at different pump power levels. **a)** Partial mode-locking at 1.5 W. **b)** and **c)** Turbulent generation with of different spatio-temporal properties, at 2.0 W and 3.0 W respectively. **d)** Emergence of short-lived pulses at 3.25 W.

lived, but they are quite-stable if compared to the round-trip time. We assume that the gain in the laser cavity with total normal dispersion becomes high enough to develop short high intensity pulses into parabolic structures similar to systems reported in [26–29]. The detailed mechanism of the formation of such pulses should be further studied.

Measurements of the intensity spatio-temporal dynamics allow to perform more advanced analysis of the generation properties. For example, additional information about the generation regime can be extracted from the two-dimensional auto-correlation analysis, $G_I(\tau,\xi) = \langle I(t,z)I(t+\tau,z+\xi)\rangle$, Fig. 4. The conventional one-dimensional intensity autocorrelation function (ACF), $G_I(\tau) = \langle I(t,z)I(t+\tau,z)\rangle$, is actually a cross-section of two-dimensional autocorrelation function $G_I(\tau,\xi)$ at fixed evolution coordinate z, see graphs on the top of panels on Fig. 4. One can also calculate the one-dimensional ACF function over evolution coordinate by fixing the fast time t in the way $G_I(\xi) = \langle I(t,z)I(t,z+\xi)\rangle$ to reveal periodicity properties and typical life-time of the structures, see graphs on the left of panels on Fig. 4.

Near the generation threshold, the two dimensional ACF is stripe-like revealing well established periodicity in partially mode-locking regime, Fig. 4(a). The ACF period corresponds to the modulation frequency in time domain. The average width of the noise-like pulse could be well measured from 2D ACF: pulses are of 0.85 ns width which is a half of the period of the envelope. Note the red round dot at zero delay, which corresponds to the short sub-structure with very short lifetime. The width of the zero-delay peak ($\sim$100 ps) indicate the duration of the fast irregular sub-pulses structure. For turbulent regimes no obvious periodicity over evolution coordinate can be observed Figs. 4(b)–4(c). The width of the central peak over evolution coordinate provides an average lifetime of the structures which decreases while pump power increases. The temporal width of a typical structure, $\sim$300 ps at 2.0 W, Fig. 4(b), is surprisingly larger than in the partially mode-locked regime despite the fact that the generation power is higher. So the stochastic filling could be of different nature in these two regimes. At further pump power increase, the typical width of the stochastic structure becomes smaller, down to 150 ps at 3.0 W, Fig. 4(c), as one could expect as nonlinearity becomes stronger. Note that there

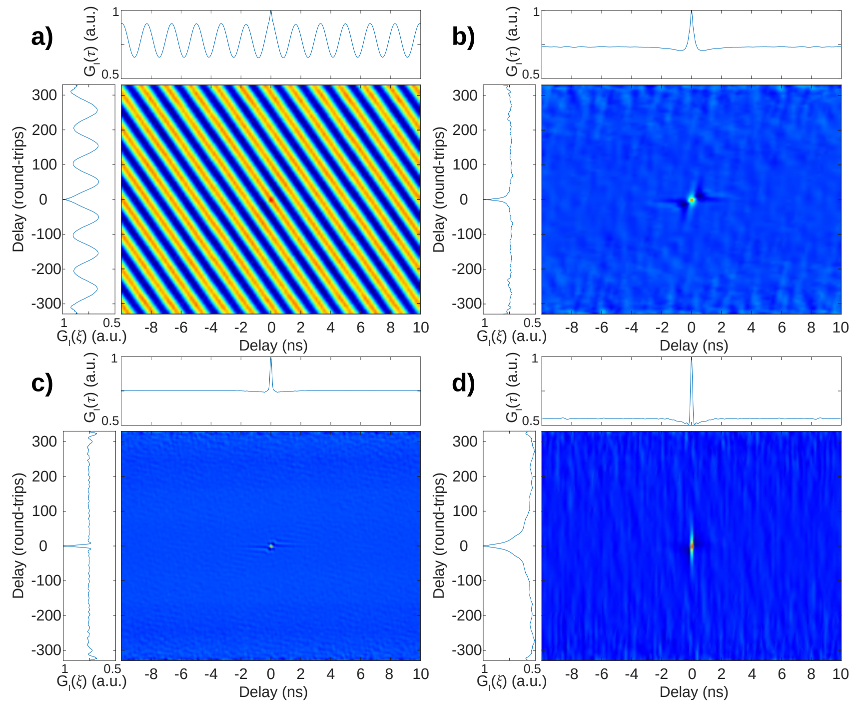

Fig. 4. 2D intensity ACFs over time and evolution coordinate $G_I(\tau,\xi)$, calculated from the measured intensity spatio-temporal dynamics for **a)** 1.5 W, **b)** 2 W, **c)** 3 W, and **d)** 3.25 W.

is still some background pattern in both turbulent regimes which properties could be further analyzed. Finally, at high power the two-dimensional ACF has a very different shape: there is a stripe-like central peak which width over the evolution coordinate gives an average lifetime of the emerged pulses, Fig. 4(d). Pulses live in average about 50 round-trips (which corresponds to the propagation length of 100 km) and are still $\sim$150 ps wide over the fast time.

4. Conclusion

To conclude, we experimentally investigate the different generation regimes in quasi-CW Raman fiber laser by making measurements in spatio-temporal domain. We found that despite intensity dynamics could be very similar in temporal domain, the generation regimes are differ substantially in their spatio-temporal properties. The same laser depending on the pump power generates in a regime of passive mode-locking of noise-like pulses, in irregular turbulent regimes and in a regime of emerged short-lived intense pulses over stochastic background. The two-dimensional auto-correlation analysis allow to reveal periodicity properties both over time and evolution coordinate and track the changes in the average temporal width and life-time (over evolution coordinate) of emerged typical spatio-temporal structures over the power.

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