Generation of double-scale femto/pico-second optical lumps in mode-locked fiber lasers

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Abstract. We observed generation of stable picoseconds pulse train and double-scale optical lumps with picosecond envelope and femtosecond noise-like oscillations in the same Yb-doped fiber laser with all-positive-dispersion cavity mode-locked due to the effect of non-linear polarization evolution. In the noise-like pulse generation regime the auto-correlation function has a non-usual double (femto- and picosecond) scale shape. We discuss mechanisms of laser switching between two operation regimes and demonstrate a good qualitative agreement between experimental results and numerical modeling based on modified nonlinear Schrödinger equations.

OCIS codes: (140.4050) Mode-locked lasers; (140.3510) Lasers, fiber; (140.7090) Lasers and laser optics: Ultrafast lasers.

References and links

1. K. Tamura, H. A. Haus, and E. P. Ippen, “Self-starting additive pulse mode-locked erbium fiber ring laser,” Electron. Lett. **28**, 2226-2228 (1992).
2. C. J. Chen, P. K. A. Wai, and C. R. Menyuk, “Soliton fiber ring laser,” Opt. Lett. **17**, 417-419 (1992), http://www.opticsinfobase.org/ol/abstract.cfm?uri=ol-17-6-417.
3. V. J. Matsas, T. P. Newson, D. J. Richardson, and D. N. Payne, “Selfstarting passively mode-locked fiber ring soliton laser exploiting non linear polarisation rotation,” Electron. Lett. **28**, 2226–2228 (1992).
4. A. Chong, W. H. Renninger, and F. W. Wise, “Propeties of normal-dispersion femtosecond fiber lasers,” J. Opt. Soc. Am. B **25**, 140-148 (2008), http://www.opticsinfobase.org/josab/abstract.cfm?uri=josab-25-2-140.
5. F. W. Wise, A. Chong, and W. H. Renninger, "High-energy femtosecond fiber lasers based on pulse propagation at normal dispersion," Laser Photonics Rev. **1-2**, 58-73, (2008).
6. V. L. Kalashnikov, E. Podivilov, A. Chernykh, and A. Apolonski, “Chirped-pulse oscillators: theory and experiment,” Appl. Phys. B **83,** 503-510 (2006).
7. S. Kobtsev, S. Kukarin, and Yu. Fedotov. “Ultra-low repetition rate mode-locked fiber laser with high-energy pulses,” Opt. Express **16**, 21936-21941 (2008).
8. S. Kobtsev, S. Kukarin, S. Smirnov, A. Latkin, and S. Turitsyn. “High-energy all-fiber all-positive-dispersion mode-locked ring Yb laser with 8 km optical cavity length,” CLEO-Europe/EQEC-2009, CJ8.4. Munich, Germany, 14-19 June 2009.
9. M. Horowitz, Y. Barad, and Y. Silberberg, “Noiselike pulses with a broadband spectrum generated from an erbium-doped fiber laser,” Opt. Lett. **22(11),** 799–801 (1997).
10. M. Horowitz and Y. Silberberg. “Control of noiselike pulse generation in erbium-doped fiber lasers,” IEEE Phot. Technol. Lett. **10**, 1389-1391 (1998).
11. L. M. Zhao, D. Y. Tang, J. Wu, X. Q. Fu, and S. C. Wen. “Noise-like pulse in a gain-guided soliton fiber laser.” Opt. Express **15,** 2145-2150 (2006). http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-15-5-2145
12. S. Chouli and Ph. Grelu, “Rains of solitons in a fiber laser,” Opt. Express **17**, 11776-11781 (2009). http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-17-14-11776
13. A. I. Chernykh and S. K. Turitsyn, “Soliton and collapse regimes of pulse generation in passively modelocking laser systems,” Opt. Lett. **20,** 398-400 (1995).
14. A. B. Grudinin, D. N. Payne, P. W. Turner, L. J .A. Nilsson, M. N. Zervas, M. Ibsen, and M. K. Durkin, “Multi-fiber arrangements for high power fiber lasers and amplifiers,” United States Patent 6826335, 30.11.2004.

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15. G.P. Agrawal, *Nonlinear fiber optics*, (Academic Press, 2001).
16. A. Komarov, H. Leblond, and F. Sanchez, "Quintic complex Ginzburg-Landau model for ring fiber lasers," Phys. Rev. E **72**, 025604 (2005).
17. N. Akhmediev, J. M. Soto-Crespo, and G. Town, "Pulsating solitons, chaotic solitons, period doubling, and pulse coexistence in mode-locked lasers: Complex Ginzburg-Landau equation approach," Phys. Rev. E **63**, 056602 (2001).

1. Introduction

Nonlinear polarisation evolution (NPE) [1–4] is a commonly employed mechanism used to achieve stable mode-locking and ultra-short pulse generation in an all-positive dispersion cavity. In comparison to systems using semiconductor saturable absorbers, the NPE-based lasers are relatively easier to assemble and they are more robust against power damage. In addition, NPE-based laser systems allow simple adjustment of the saturable absorber action, and as a result, they can be effectively used for studies of different pulse generation regimes. Compared to soliton generation in the anomalous group velocity dispersion (GVD) regime, use of the normal dispersion allows one to achieve higher pulse energies without wave breaking [4-6]. The key to achieving stable generation of high energy pulses is the management of nonlinear propagation effects in the cavity. Another new promising approach to ultra-high energy pulse generation just in fiber master oscillators introduced in [7] is to elongate a mode-locked laser cavity in order to achieve extremely low pulse repetition rates with considerable increase in pulse energy. Applying this technique we have recently demonstrated the generation of highly chirped short pulses with few-nanosecond envelope width and energy as high as 3.9 μJ [7] and 4 μJ [8] both in a hybrid (consisting of both bulk elements and fiber sections) and all-fiber master oscillators with optical length of the long-cavity amounting to 3.8 and 8 km, respectively. Mode-locked fiber laser generating high energy pulses typically presents a multi-parametric nonlinear system that by changing device parameters might operate in a range of regimes: conventional soliton, dispersion-managed soliton (stretched pulse), self-similar pulse regime, all-normal dispersion highly-chirped pulse, multiple-pulse regimes and so on. In this work we present in more detail an unusual mode of operation of all-positive dispersion fiber lasers and demonstrate how a change of system parameters leads to switching between standard stable pulse train generation and more exotic regimes. In particular, we study both experimentally and numerically a generation of a double-scale picosecond lump envelope and a femtosecond scale noise-like oscillations inside the larger wave-packet. Such a lasing mode is characterised by an unusual double-feature shape with an auto-correlation function (ACF) comprising of a femtosecond-scale peak on a picosecond-scale pedestal. Though noise-like pulse generation regime has been studied for Er-doped fiber lasers [9-12], the nature of fine structure oscillations is not yet completely clear. In [10], the noise-like pulse generation was attributed to large birefringence of the laser cavity in a combination with the nonlinear field evolution. In [11], similar noise-like pulse operation was demonstrated in erbium-doped fiber laser with weak birefringence. It was conjectured in [11] that the formation of the noise-like oscillations is caused by the pulse collapse effect [13] and that such dynamics is a generic feature of a range of the passively mode-locking systems. The pulse collapse effect studied in [13] is an intermediate dynamical process that is caused by the third-order nonlinear gain term in the Taylor expansion of the nonlinear response of the effective saturable absorber. For some range of parameters, initially smooth field distribution is engaged in an explosive-like growth of the amplitude with corresponding compression. The collapse effect dynamics is more sensitive to initial conditions and as a result the forming field structures tend to be more random and complex compared to non-collapse pulse generation regimes. Though, evidently such fast growth of the field amplitude is saturated at some level by the higher terms in the expansion and other high-order effects, the resulting noisy and random asymptotic state could be quite different from more smooth regimes of the radiation intensity growth. Here we present experimental and numerical studies of the double-scale femto-pico-second optical lumps generation in Yb fiber laser and discuss in detail physical

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mechanisms behind the generation of mode switching in mode-locked all-positive-dispersion fiber lasers.

2. Experimental setup

The experimental set-up of the considered all-fiber ring-cavity laser is shown in Fig. 1. A 7-m long active ytterbium fiber with a 7-μm core was used as the laser active element. This fiber was pumped from one of the ends of the twinned fiber (GTWave technology [14]) with 1.5 W of 980-nm radiation from a laser diode. In order to couple the generated radiation out of the resonant cavity, a fiber-based polarisation beam splitter (FPBS) was used. In order to ensure uni-directional generation, a polarisation-independent fiber optical isolator (PIFI) was also introduced into the cavity. Mode locking was achieved due to the effect of non-linear polarisation evolution [1–4]. For control of the polarisation state in the layout, two fiber-based polarisation controllers PC1 and PC2 were employed.

For elongation of the laser cavity and boosting of the output pulse energy a stretch of passive SMF-28 fiber was inserted, so that the full resonator length came to 11.2 m (round trip time τ = 54 ns). All optical fibers in this layout had normal dispersion within the working spectral range of the laser. The average output power of the laser was limited by the power rating of FPBS and did not exceed 150 mW.

3. Numerical simulations

In the theoretical analysis of operation of considered laser schemes a standard approach is to apply numerical modelling based on the system of coupled modified non-linear Schrödinger Eqs. (1) [15]:

$$\begin{aligned}\frac{\partial A_x}{\partial z} &= i\gamma\left\{\left|A_x\right|^2 A_x + \frac{2}{3}\left|A_y\right|^2 A_x + \frac{1}{3}A_y^2 A_x^*\right\} + \frac{g_0/2}{1+E/\left(P_{sat}\cdot\tau\right)}A_x - \frac{i}{2}\beta_2\cdot\frac{\partial^2 A_x}{\partial t^2},\\ \frac{\partial A_y}{\partial z} &= i\gamma\left\{\left|A_y\right|^2 A_y + \frac{2}{3}\left|A_x\right|^2 A_y + \frac{1}{3}A_x^2 A_y^*\right\} + \frac{g_0/2}{1+E/\left(P_{sat}\cdot\tau\right)}A_y - \frac{i}{2}\beta_2\cdot\frac{\partial^2 A_y}{\partial t^2}\end{aligned} \quad (1)$$

where A_x, A_y are the orthogonal components of the field envelope, z is a longitudinal co-ordinate, t – time, γ = 4.7×10^{-5} (cm·W)$^{-1}$ – non-linear coefficient, g_0 – unsaturated gain coefficient, β_2 = 23 ps^2/km– dispersion coefficient, P_{sat} – saturation power for the active fiber, τ – time of cavity round trip. In our calculations we neglected the higher-order dispersion and linear birefringence of the fiber. The amplifier parameters were estimated from experimental measurements and taken equal to g_0 = 540 dB/km, P_{sat} = 52 mW. To improve convergence of the solution to the limiting cycle, the numerical modelling included a spectral filter with a 30-nm band-width, which exceeds considerably the typical width of generated laser pulses. The effect of polarisation controllers was taken into account by introduction of corresponding unitary matrices (see e.g. recent publication [16] and references therein). In the numerical modelling, in order to reduce the required computational time we shortened the laser cavity to 6 m. Furthermore we only varied three of the 6 possible polarisation controller parameters (α, β, ψ) using following matrices (2,3) for PC1,2 at $\varphi = 2\psi + \pi/4$:

$$PC_1 = \begin{pmatrix} \cos\alpha & -i\cdot\sin\alpha \\ -i\cdot\sin\alpha & \cos\alpha \end{pmatrix} \quad (2)$$

$$PC_2 = \begin{pmatrix} \cos\beta - i\sin\beta\cos 2\phi & -i\sin\beta\sin 2\phi \\ -i\sin\beta\sin 2\phi & \cos\beta + i\sin\beta\cos 2\phi \end{pmatrix}\cdot(-i)\cdot\begin{pmatrix} \cos 2\psi & \sin 2\psi \\ \sin 2\psi & -\cos 2\psi \end{pmatrix} \quad (3)$$

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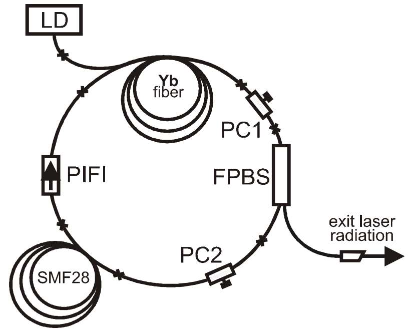

Fig. 1. Experimental laser scheme: PC - polarization controller, PIFI - polarization-independent fiber isolator, FPBS - fiber polarization beam splitter, LD - pump laser diode.

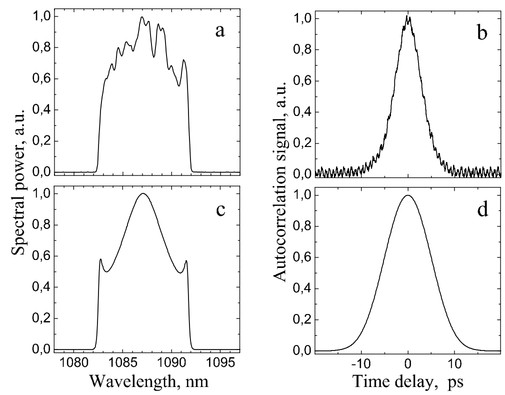

Fig. 2. Stable single-pulse generation: a,b - experimental results, c,d - simulations; a,c - spectra, b,d - ACFs.

Results in Figs. 2 and 3 correspond to (α, β, ψ) = (25.1°, 40.9°, 37.9°) and (53.0°, 68.4°, 40.5°) respectively. In spite of simplifications we made the modelling allowed us to reproduce qualitatively the experimental results.

4. Results and discussion

A remarkable feature of the system under consideration - a laser mode-locked due to NPE - is a possibility to obtain generation in a variety of ways and using different tuning of polarisation controllers, which is borne out by both the numerical modelling and experiment. Depending on phase shifts introduced by the polarisation controllers the energy and duration of laser pulses at the output may change their values by up to an order of magnitude. An immense variety of results generated in experiments and in modelling may be divided into two main types of generation regimes. The first type presents a well-known generation of isolated pulses (Figs. 2(b), 2(d)) with bell-shaped auto-correlation function (ACF) and steep spectral edges (see Figs. 2(a), 2(c)). As the numerical modelling has shown, the pulse parameters obtained in this generation regime are stable and do not change with round trips after approaching those asymptotic values after the initial evolution stage. Since the cavity has all-positive dispersion, the generated laser pulses exhibit large chirp [4-6] and may be efficiently compressed with an external diffraction-grating compressor, which is confirmed by both the numerical results and the experiment.

The more interesting, however, is that in addition to this standard generation regime, the considered laser scheme exhibits a different type of operation. For this second type of operation, an unusual double-structured ACF (femto- and pico-second) can be observed, see Figs. 3(b), and 3(e). Experimentally measured laser generation spectra of this type usually has

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a smooth bell-shaped appearance (see Fig. 3(a)). However, as the numerical simulation demonstrates, such smooth spectra are a result of averaging over a very large number of pulses, whereas the spectrum of an individual pulse contains an irregular set of noisy-like peaks (see the un-averaged spectrum in Fig. 3(d) shown with a grey line). In the temporal representation this type of generation corresponds to a picosecond wave packet consisting of an irregular train of femtosecond sub-pulses (see Fig. 3(f)). Peak power and width of such sub-pulses stochastically changes from one round trip along the cavity to another, also leading to fluctuations in the wave packet parameters easily noticeable when observing the output pulse train in real time on the oscilloscope screen during experiments (see Fig. 3(c)). We do not observe any systematic change in generation parameters such as power or wave-packet duration even after several hours of generation. The absence of systematic drift of pulse parameters is typical for numerical simulations as well (in the latter case however much shorter pulse train of about only 5×10^4 was examined.) The discussed regime presents an interesting symbiotic co-existence of stable solitary wave dynamics and low-dimension stochastic oscillations. Note that similar structures have been studied in different context numerically in the complex cubic-quintic Ginzburg-Landau model in [17]. The co-existence of stable steady state pulses and pulsating periodic, quasi-periodic or stochastic localised structures is a general feature of multi-parametric dissipative nonlinear system. Each particular nonlinear dynamic regime exists in a certain region of parameter space. Therefore, in systems that possess a possibility to switch operation from one region of parameters to another, one can observe very different lasing regimes. The regions of parameters where pulsating (periodic, quasi-periodic or stochastic) localized structures do exist might be comparable or even larger than regions of existence of conventional steady state solitons. Note that in the multi-dimensional space of parameters of the considered laser scheme, it is almost impossible to explore all possible operational regimes via direct modelling.

Both experiment and simulation show that wave-packets generated in the double-scale femto-picosecond regime can be compressed only slightly and pulses after compression remain far from spectrally limited. As our experiments have demonstrated, after extra-cavity compression of these complex wave packets with the help of two diffraction gratings ACF of the resulting pulses has qualitatively the same double-feature shape.

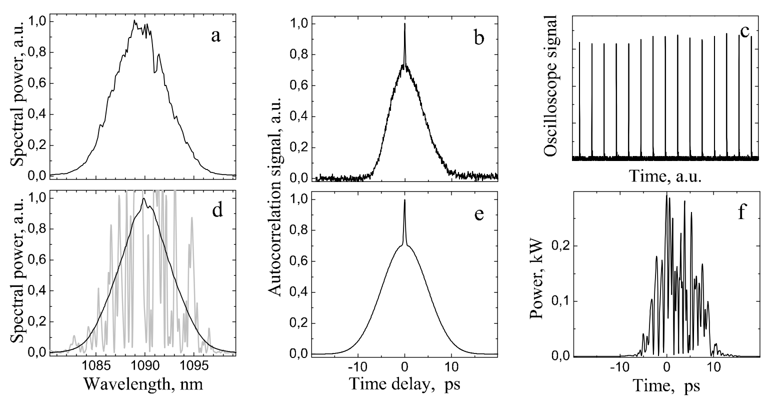

Fig. 3. Quasi-stochastic generation regime: a-c – experimental results, d-f – simulations; a,d – spectra, b,e – ACFs, c – pulse train from oscilloscope, f – non-averaged intensity distribution.

Switching between different modes of laser generation was done by changing the parameters of polarisation controllers. In order to clarify the physical mechanisms leading to quasi-stochastic oscillations and mode switching we have carried out numerical simulations of laser operation in the vicinity of the boundary of the stable single-pulse generation. While performing calculations, we introduced into the cavity fixed-duration pulses with different energies and analysed the resulting gain coefficient for the pulse over one complete round trip

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over the resonator (see black line in Fig. 4). At the input power $P = 1$ (in arbitrary units) the one-trip gain coefficient equals unity, which at negative curve slope corresponds to stable generation. Starting with $P \sim 1.75$ a.u. single-pulse generation becomes unstable (corresponding to positive slope of the black curve in Fig. 4). In this region an exponential growth of small intensity fluctuations can be observed and, over only several round trips of the cavity, an isolated picosecond pulse is decomposed into a stochastic sequence of femtosecond pulses. Because in this process a substantial change in the pulse form takes place the gain curves in Fig. 4 no longer correspond to the real situation. Exponential power growth is quickly quenched and over a number of trips along the cavity (as a rule, from dozens to hundreds) an isolated picosecond pulse with stable parameters is formed in the cavity again. So, in our numerical results there was no bi-stability, which could be expected on the basis of the curve shapes in Fig. 4: at any fixed set of cavity parameters at most only one of the two generation types could be stable irrespective of the initial field distribution within the resonator.

For reliable switching of the generation type it is necessary to adjust polarisation controllers or to change other cavity parameters. For instance, curves 1–3 in Fig. 4 correspond to different resonator length (12.0, 12.3 and 12.6 m accordingly). It can be seen that as the resonator parameters are shifted towards the boundary of single-pulse generation, the width of the stable domain is reduced. Indeed, for curve 3 in Fig. 4 the unity-gain point almost coincides with the extremum, so that even small intensity fluctuations may bring the system into the unstable region and lead to decay of the pulse. If the resonator length is further increased the stable single-pulse generation becomes impossible and the laser starts generating quasi-stochastic wave packets.

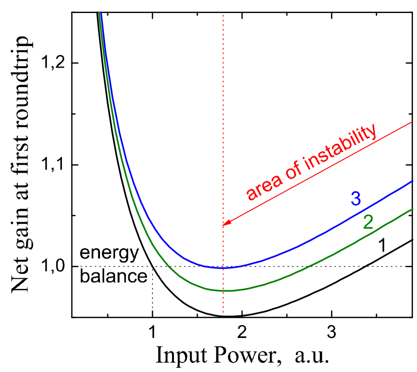

Fig. 4. Net gain per roundtrip vs. initial pulse power. Curves 1-3 correspond to slightly different cavity parameters close to boundary of single-pulse generation regime area.

Conclusions that we drew on the basis of the above-conducted analysis are also valid for the effect of generation type switching observed in our experiments due to changing the parameters of polarisation controllers. It should also be noted that the set of curves presented in Fig. 4 for dependence of gain per round-trip on the pulse power is qualitatively very well reproduced in analytical treatment of laser generation, in which every optical element of the laser corresponds to a 2×2 matrix. The detailed analytical study of these phenomena will be published elsewhere.

5. Conclusion

To the best of our knowledge we present for the first time a noise-like generation regime in ytterbium fiber laser with all-positive dispersion and mode locking due to non-linear polarisation evolution. Both the experimental and numerical studies show an unusual feature typical of this new generation type that is a double-structured (pico- and femto-second) non-

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collinear ACF (intensity ACF). Applying extensive numerical modelling we have shown that a possible physical mechanism underlying the new generation regime is an instability leading to decomposition of isolated pico-second pulses into a stochastic sequence of femtosecond sub-pulses. This effect makes it difficult to generate regular trains of isolated ultra-short pulses in long-resonator mode-locked all-positive-dispersion fiber lasers and very careful adjustment of the system parameters is required in this case. On the other hand, pico-second scale optical lumps with femto-second oscillatory structures and broadband spectrum might be attractive for a range of practical applications.

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