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Generation of dissipative solitons in an actively mode-locked ultralong fibre laser*

N.A. Koliada, B.N. Nyushkov, A.V. Ivanenko, S.M. Kobtsev, P. Harper, S.K. Turitsyn, V.I. Denisov, V.S. Pivtsov

Abstract. **A single-pulse actively mode-locked fibre laser with a cavity length exceeding 1 km has been developed and investigated for the first time. This all-fibre erbium-doped laser has a normal intracavity dispersion and generates dissipative 8-ns solitons with a fundamental repetition rate of 163.8 kHz; the energy per pulse reaches 34 nJ. The implemented mode locking, based on the use of intracavity intensity modulator, provides self-triggering and high stability of pulsed lasing. A possibility of continuous tuning of the centre lasing wavelength in the range of 1558–1560 nm without any tunable spectral selective elements in the cavity is demonstrated. The tuning occurs when controlling the modulation signal frequency due to the forced change in the pulse repetition time (group delay) under the conditions of intracavity chromatic dispersion.**

Keywords: *active mode locking, ultralong fibre laser, dissipative solitons.*

1. Introduction

In recent years, ultralong (with 1-km long or even longer cavities) passively mode-locked (PML) fibre lasers have been actively developed and investigated in many laboratories of the world. These lasers can generate regular trains of short pulses with high energy (up to several μJ) and low repetition rate (~100 kHz or less). The first demonstration of such a laser with a relatively high energy per pulse [1] was followed by a series of studies aimed at developing and analysing ultralong ytterbium- and erbium-doped fibre lasers having various cavity configurations and PML mechanisms [2–8]. The interest in this field was caused by both the nontrivial physics the pulse generation dynamics in ultralong fibre cavities is based on and many important applications of these laser sources in metrology, industry, and telecommunications.

The pulsed lasing in mode-locked fibre lasers is determined by the complex dynamic balance between the dispersion and nonlinear effects, as well as the dissipative and regenerative processes occurring in the fibre cavity. If the dispersion phase delay dominates when a pulse is formed (for example, in fibre lasers with completely normal intracavity dispersion), the so-called dissipative optical solitons can be generated [9–11]. These are pulses characterised by a monotonic change in the instantaneous frequency (chirp) and a peculiar optical spectrum with steep edges. A very large normal intracavity dispersion in ultralong lasers leads generally to a giant chirp [2] and, correspondingly, to a relatively wide (up to several nanoseconds) pulse. However, specifically the possibility of scaling the chirp makes it possible to accumulate relatively high energy in dissipative solitons without their decay, in contrast to other types of pulses generated in PML fibre lasers [11]. In certain cases the instantaneous pulse frequency changes almost linearly, due to which generated pulses can be compressed to picosecond durations afterwards [12]. On the whole, the formation of stable single pulses in lasers with ultralong fibre cavities is a more difficult nonlinear problem than in the case of conventional short fibre lasers. Hence, step-by-step analysis of different ways of stable generation in ultralong lasers is very urgent.

To date, the highest pulsed energy was obtained in ultralong fibre lasers where PML is implemented due to the nonlinear polarisation evolution (NPE) in the fibre (see, for example, [1–4]). However, NPE-induced mode locking in these lasers may lead (under certain conditions) to generation of nanosecond trains of pulses with quasi-stochastic filling by femtosecond pulses [6, 13]. To implement single-pulse generation, one must perform precise tuning of the optomechanical elements (polarisation controllers). The NPE-induced mode locking cannot be maintained for a long time without periodic tuning of fibre polarisation controllers because of the relaxation of stress in the amorphous material (glass) under a long-term mechanical load. Other drawbacks of NPE are high sensitivity of mode locking and output laser characteristics to external perturbations because of the large cavity length, significant influence of polarisation instability, and the absence of stable self-triggering. In addition, when it is necessary to stabilise (synchronise) the pulse repetition rate with respect to an external generator, one must implement

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N.A. Koliada, V.I. Denisov Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 13/3, 630090 Novosibirsk, Russia; e-mail: denisov@laser.nsc.ru;
B.N. Nyushkov Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 13/3, 630090 Novosibirsk, Russia; Novosibirsk State University, ul. Pirogova 2, 630090 Novosibirsk, Russia; Novosibirsk State Technical University, prosp. K. Marksa 20, 630092 Novosibirsk, Russia; e-mail: nyushkov@laser.nsc.ru;
A.V. Ivanenko, S.M. Kobtsev Novosibirsk State University, ul. Pirogova 2, 630090 Novosibirsk, Russia; e-mail: kobtsev@lab.nsc.ru;
P.Harper, S.K. Turitsyn Aston Institute of Photonic Technologies, Electronic Engineering, Aston University, Birmingham, B4 7ET, UK;
V.S. Pivtsov Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 13/3, 630090 Novosibirsk, Russia; Novosibirsk State Technical University, prosp. K. Marksa 20, 630092 Novosibirsk, Russia

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dynamic monitoring of the cavity length and use a system of automatic frequency tuning in lasers of this type.

The purpose of this work was to experimentally demonstrate and perform preliminary analysis of single-pulse active mode locking (AML) in an ultralong fibre laser with normal dispersion for stable generation of high-energy pulses. The basic aspects of AML approval is the possibility of applying this regime to ensure more reliable triggering, maintain pulsed lasing for a long time, increase resistance to external effects and stability of output laser characteristics, and solve the problem of frequency locking (stabilisation) with an external generator. In addition, we demonstrate and discuss the dispersion mechanism of lasing wavelength tuning, which is accompanied by a change in the pulse repetition rate. AML, which makes it possible to generate pulses with fundamental repetition rate, is applied to the first time in ultralong fibre lasers. All the above-mentioned aspects of AML application in lasers of this type are investigated for the first time.

2. Experimental setup

The laser under study had an all-fibre (without bulk optical elements) ring cavity (Fig. 1). A heavily doped 2.5-m-long erbium fibre (LIEKKI Er30-4/125) having absorption of 30 dB m^{-1} at a wavelength of 1530 nm was used as an active light guide. The active fibre was pumped by a diode laser at λ = 980 nm through a fibre multiplexer. The maximum pump power was 300 mW. The large length and normal group-velocity dispersion (GVD) of the cavity were ensured by a long segment of a special telecommunication fibre on a reel. We used a ~1.25-km-long dispersion-compensating N-DCFM-C-10-FA Sumitomo fibre with a normal GVD ($\beta_2 \geqslant 0$) equal to +217 ps^2 at λ = 1.55 μm. The optical loss introduced by the reeled fibre did not exceed ~1.3 dB. The lengths of the optical fibres with anomalous GVD we had to use (pigtails of fibre element and the active fibre) were minimised so as to make negligible the total dispersion introduced by them (to a level of about –0.05 ps^2 at a wavelength of 1.55 μm).

The generated radiation was extracted from the cavity using a 30% fused fibre coupler. A polarisation-insensitive optical isolator with fibre pigtails was applied to maintain the unidirectional travelling wave regime in the ring cavity. To implement AML in the cavity, we used a telecommunication electro-optical intensity modulator (based on the Mach–Zehnder interferometer scheme) with fibre pigtails. The input radiation must be linearly polarised to provide correct operation of modulator; therefore, a polarising element – fibre polarisation splitter – was installed before the modulator. The splitter and modulator were connected by a polarisation-maintaining fibre. The polarisation controller, installed before the polarisation splitter, was used to destroy the self-locking mode (in the case of its occurrence) due to the NPE effect and to optimise the energy laser characteristics.

The modulator was controlled by a digital functional RF oscillator, frequency-tunable with a step of 0.1 Hz. Active mode locking was triggered when the frequency of oscillator periodic signal approached the fundamental (intermodal) laser frequency (163.8 kHz); the latter was determined by the optical cavity length. Using a fast photodetector and oscilloscope, we recorded the generation of a regular train of laser pulses with the aforementioned repetition rate. The train of pulses was synchronised with the master RF signal. The most reliable mode locking was obtained using saw-tooth and sinusoidal modulation signals. Both these types of modulation signals lead to similar pulse parameters; hence, we report below the laser characteristics obtained with sinusoidal modulation.

3. Results and discussion

The laser pulse duration and repetition time were, respectively, 8 ns and 6.1 μs (Fig. 2). The measurements were performed with an oscilloscope having a resolution of 0.4 ns. The intermodal frequency measured with an RF spectrum analyser was found to be 163.8 kHz. The signal-to-noise ratio in the RF intermode beat spectrum (Fig. 3) reached 40 dB. The measurement results indicate that pulses were generated with the fundamental repetition rate; i.e., the mode locking was single-pulse (one pulse per cavity period). When the master RF oscillator was switched off, a regular train of pulses immediately stopped to be generated and passed to a quasi-continuous stochastic regime. This behaviour confirmed the very important role of AML in the formation of pulses and the absence of direct influence of NPE. In the case of AML, the optical emission spectrum broadened and acquired a peculiar

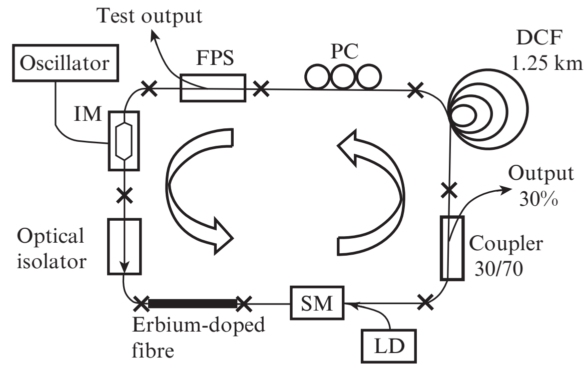

Figure 1. Schematic of an ultralong actively mode-locked erbium-doped fibre laser:
(LD) pump laser diode, (SM) spectral multiplexer, (IM) intensity modulator, (FPS) fibre polarisation splitter, (PC) polarisation controller, and (DCF) dispersion-compensation fibre (fibre with normal chromatic dispersion).

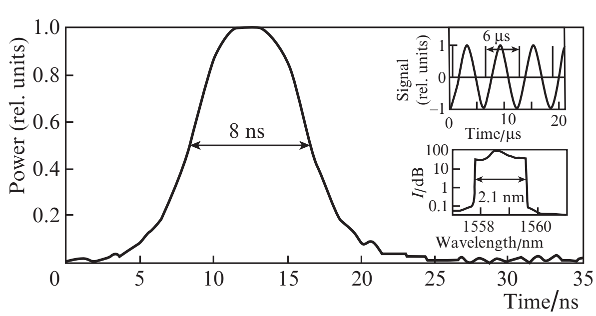

Figure 2. Oscillogram of a pulse of an ultralong actively mode-locked erbium-doped fibre laser. The upper and lower insets show, respectively, the oscillogram of a regular train of pulses mode-locked with the RF modulation signal and the laser optical spectrum $I(\lambda)$ under the single-pulse AML conditions.

shape with steep, almost vertical edges, which is characteristic of dissipative optical solitons [10, 11, 13] (Fig. 2, inset). The spectrum was recorded using an optical analyser with a resolution of 0.02 nm. The spectral width under the AML conditions was 2.1 nm (at a level of 0.1), and the centre radiation wavelength was near 1559 nm. When adjusting the RF modulation frequency, the lasing wavelength was smoothly tuned. Changing the RF frequency, we could control the pulse repetition rate in the range of 163808–163816 Hz without suppressing mode locking and inducing any significant changes in the pulse shape and width. The observed effect of repetition frequency pulling confirms the active nature of mode locking. The change in the pulse repetition rate was accompanied by a change in the centre lasing wavelength in the range of 1558–1560 nm (Fig. 4).

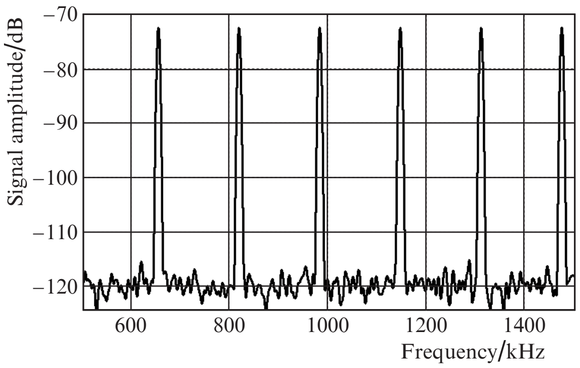

Figure 3. RF intermode beat spectrum of a laser under the single-pulse AML conditions.

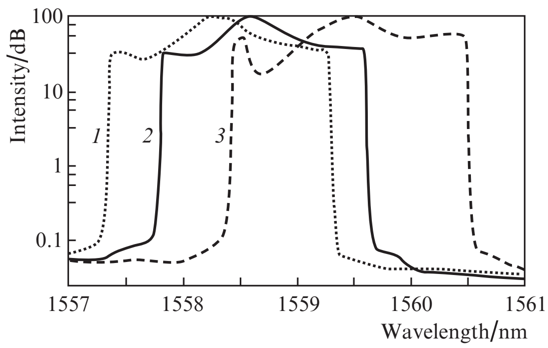

Figure 4. Tuning of the lasing wavelength under the single-pulse AML conditions with a change in the pulse repetition rate. The optical spectra were recorded at repetition rates of (*1*) 163808, (*2*) 163810, and (*3*) 163816 Hz.

This effect can be explained as follows: only due to the change in the lasing wavelength under the intracavity GVD conditions the group delay in the cavity and, therefore, the pulse repetition period/rate may change at invariable structural parameters of the cavity. The similar dispersion mechanism of wavelength tuning when adjusting the pulse repetition rate was previously observed and investigated in fibre lasers with high-frequency AML [14, 15]. However, this tuning in ultralong fibre lasers with single-pulse AML and a pulse repetition rate lying in the kHz range has been analysed for the first time. Having expressed the change in the fundamental pulse repetition rate in terms of the differential group delay in the cavity near the centre lasing wavelength, we arrive at a relation that makes it possible to determine the sensitivity of lasing wavelength to a change in the repetition rate, depending on the intracavity dispersion:

$$\frac{\Delta\lambda}{\Delta f} = \frac{1}{2\pi c}\frac{\lambda^2}{f^2}\frac{1}{\beta_2},$$

where c is the speed of light; λ is the lasing wavelength; f is the pulse repetition rate; and β_2 is the total intracavity GVD. Substitution of the numerical values of the laser characteristics and parameters into this relation yields $\Delta\lambda/\Delta f \sim 0.23$ nm Hz^{-1}, which is in good agreement with the experimental observations.

The maximum pump power at which stable single-pulse lasing was still retained amounted to 117 mW and the average output power reached 5.6 mW. An increase in the pump power reduced lasing stability: the regular train of pulses decayed and the laser passed to unstable multipulse regime. This phenomenon can be explained by the fact that a decrease in the energy of dissipative solitons is always accompanied by an increase in the pulse chirp. As a result, the efficiency and quality of intracavity modulation with the aid of interferometric electro-optical modulator decrease. Thus, the maximum energy per pulse reached 34 nJ in the case of single-pulse AML. To increase the pulse energy even more, one should gain a deeper insight into the nonlinear dynamics of pulsed generation under AML conditions; the laser parameters should be optimised as well [16].

If the master RF frequency remained set in correspondence with the fundamental pulse repetition rate, each switch on of the modulator led to self-triggering of the single-pulse AML regime. This regime was maintained under laboratory conditions throughout the working day until the modulator was switched off.

For comparison we also investigated the laser operation under the PML conditions. To this end, the intensity modulator was removed from the cavity. The mode locking was implemented due to the NPE effect in the fibre. A polarisation splitter played the role of polarisation discriminator. Depending on the settings of the polarisation controllers and the specified pump laser power, both multipulse lasing and PML with one pulse per cavity period (single-pulse regimes) could be implemented in the cavity. The same settings were used to control the pulse shape and width.

The single-pulse lasing under the PML conditions at a pump power of 47 mW and an average output power of 1.5 mW was optimum from the point of view of stability and minimum pulse width. With an increase in power the lasing became unstable and multipulse. In the single-pulse PML regime described here the pulse repetition rate was fundamental (163.8 kHz). The characteristic profile of optical spectrum (with steep edges) gives grounds to assign the generated pulses (Fig. 5) to dissipative solitons, as in the case of AML. However, we observed a significant shift of the centre lasing wavelength to the short-wavelength range of erbium-doped fibre amplification (to 1533 nm). The short-wavelength edge of the spectrum was distorted (most likely, because of the strong inhomogeneity of the fibre amplification near the lasing wavelength and due to the boundedness of the spectral transmission band of the fibre elements used in the laser, with a working wavelength of 1550 nm). The minimum pulse duration under the PML conditions was 1.2 ns. The pulse narrowing (with respect to AML) is related to the decrease in the pulse energy. The pulse energy reached only 9 nJ under the above-described PML conditions. As was mentioned above, the scaling of dissipative-soliton energy is fundamentally related to the chirp scaling and, therefore, to the pulse duration. On the whole, the stability of single-pulse PML turned out to be much worse than that of AML. Strong external perturbations (acoustic and vibrational) suppressed the PML regime, which is in principle critical to polarisation instability. To launch PML, we had to tune polarisation controllers each time when switching on the laser.

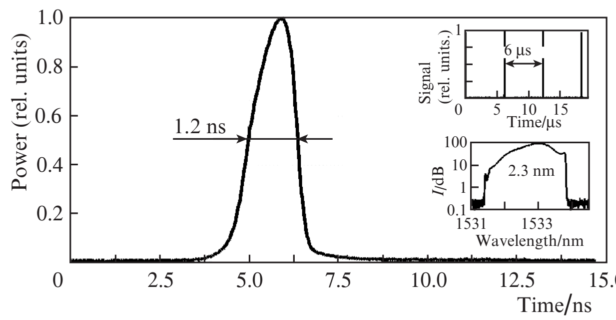

Figure 5. Oscillogram of a pulse of an ultralong passively mode-locked erbium-doped fibre laser. The upper and lower insets show, respectively, the oscillogram of a regular train of pulses and the laser optical spectrum $I(\lambda)$ under the single-pulse PML conditions.

4. Conclusions

We experimentally demonstrated for the first time the possibility of generating high-energy dissipative solitons in ultralong actively mode-locked fibre lasers. It was shown that AML in ultralong lasers has a number of advantages over passive mode locking due to the NPE, specifically: self-triggering and high stability of single-pulse lasing, synchronisation of the pulse repetition rate with the RF reference frequency, and the possibility of smooth, electronically controlled tuning of lasing wavelength applying no spectral selective elements. We should also note that the effect of pulse repetition rate pulling and the dispersion mechanism of wavelength tuning under AML conditions in ultralong fibre lasers were investigated for the first time.

Based on the results obtained, we can suggest that the transition to AML in ultralong fibre lasers will expand their application range beyond the laboratory.

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