

Ultra-low repetition rate mode-locked fiber laser with high-energy pulses

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Abstract: This paper reports on the results of research into passively mode-locked fiber laser with a record-setting optical length of the resonant cavity amounting to 3.8 km. Significant elongation of the laser resonator led to more than two orders of magnitude increase in the output pulse energy at the same pump radiation power. At ultra-low (for mode-locked lasers) pulse repetition rate (77 kHz) and pulse duration of 3 ns the energy per pulse reached 3.9 μ J. At this moment this is the highest pulse energy on record generated directly from a mode-locked laser without Q-switching, cavity dumping techniques, or additional optical amplifiers.

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

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1. Introduction

For generation of relatively high pulse energies of laser radiation (1 μJ –1 mJ and higher) Q-switched lasers are usually applied with comparatively low pulse repetition rates (~ 10 –100 kHz) or mode-locked lasers with high repetition rates (~ 10 –100 MHz) and low pulse energies, which can be further increased by using additional optical amplifiers. The combined Q-switching and mode-locking in one cavity is also successfully employed for generation of high-energy pulses of laser radiation [1, 2]. Another way to increase per-pulse energy of output radiation is cavity dumping technique [3], which can be used in all mentioned types of lasers. Cavity dumping consists in using a totally reflective resonator in order to increase intra-cavity pulse energy and inserting a so-called cavity dumper that allows picking single high-energy pulses out of the cavity at a certain frequency, which is lower than the original pulse repetition rate. Per-pulse energy in passively mode-locked lasers may also be increased by means of the pump power rise, but it may be realised at definite combination of pulses and cavity parameters only [4,5].

Higher per-pulse energy of output in mode-locked lasers may be also achieved by simple elongation of the laser cavity. The pulse repetition rate of a mode-locked laser is inversely proportional to its resonator length, this is why longer cavities lead to lower pulse repetition rates and, consequently, to higher pulse energy at the same average power of radiation.

First experiments on considerable cavity elongation up to 100 m in solid-state [6] and fiber [7, 8] mode-locked lasers have shown that in such comparatively long resonators is it possible to achieve stable passive mode locking. Thereby the pulse repetition frequency can be reduced by more than an order of magnitude (down to ~ 1.7 MHz) and the per-pulse energy can be raised by the same factor at the same average output power of radiation.

In the present work we have studied the possibility of further considerable resonator elongation in a mode-locked fiber laser aimed at increasing the energy of generated pulses without resorting to resonator Q-switching or cavity dumping techniques. As it is demonstrated in the following discussion, we have succeeded in generating stable mode locking in a fiber laser with optical length of the cavity 3.8 km. To our knowledge, at this moment this is the longest mode-locked laser in the world.

2. Experiment

Our studies were based on a laboratory sample of a ring Yb fiber laser, the diagram of which is given in Fig. 1. Pumping of 7-m active Yb-doped fiber with a 7- μm core was performed through its sides (GTWave technology [9]) with a 980-nm laser operating at up to 1.5 W of CW output power. The Yb-doped GTWave fiber used in the laser is a convenient choice because it allows using inexpensive diode lasers with multi-mode 100- μm output fiber for pumping.

Microscope objectives were used in order to guide radiation in and out of the free-space laser resonator with discrete elements. The ring configuration of the free-space portion of the resonator was created by three broad-band ($\Delta\lambda \sim 100$ nm) highly-reflective mirrors. Output of radiation from the resonator was done with a polarisation beam splitter that also provided linear polarisation of the output radiation. Laser generated unidirectional radiation pulses despite the fact that no optical diode was used in the resonant cavity. The propagation direction of generated pulses coincided with that of the pumping radiation inside the active fibre.

Mode locking of the laser was achieved by using the effect of non-linear rotation of radiation polarisation [10-12]. Control over the polarisation was carried with the help of three phase plates inserted into the laser cavity. Upon initial alignment of these plates and start of mode locking this operation was henceforth self-activated as soon as pumping was switched on.

We did not use in the laser cavity any elements with negative dispersion in spectral range of generation. Mode-locked regime of generation was obtained in all-positive-dispersion laser configuration.

At minimal length of the resonator 9.4 m the laser generated single chirped pulses with 3.5-ps duration (Fig. 2(a)) and 300-mW average output power at 1075 nm. The pulse repetition rate was 22 MHz, the spectrum width being 2 nm. Extra-cavity pulse compression by two diffraction gratings (1,200 lines/mm, spaced by ~15 mm from each other) lead to reduction of the output pulse duration to 550 fs (Fig. 2(b)). The ratio $\Delta\nu\Delta\tau\sim 0.33$ demonstrates that compressed pulses were transform-limited. The highest per-pulse energy reached 14 nJ. It is relevant to note that a stable mode-locked operation of this laser was achieved without using any additional elements for limitation of laser radiation spectrum, unlike it was in Refs [13, 14].

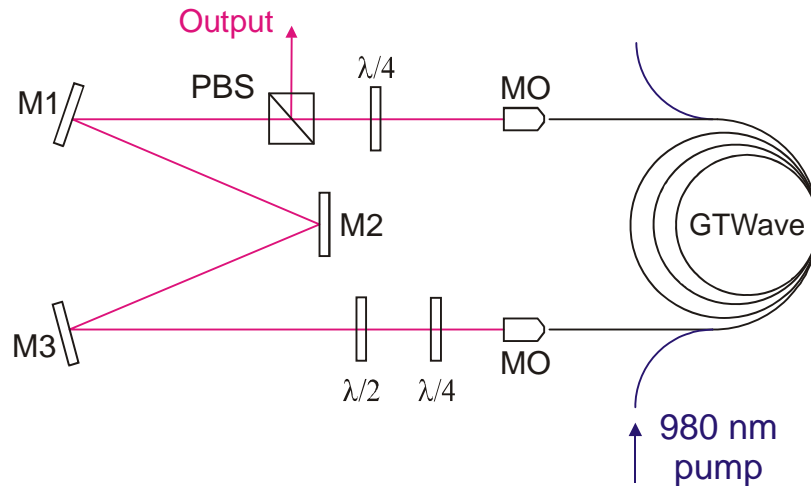


Fig. 1. Schematic of fiber laser: MO - microscope objective, PBS – polarizing beam splitter, M1-M3 – high-reflectivity mirrors, $\lambda/4$ – quarter-wave plate, $\lambda/2$ – half-wave plate.

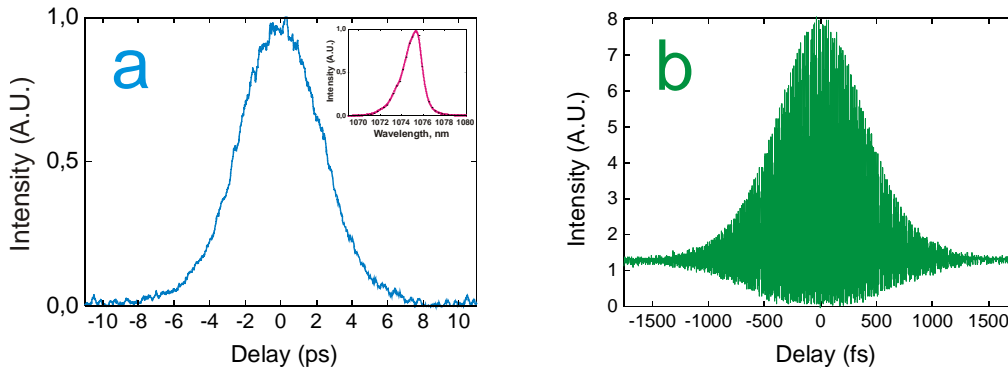


Fig. 2. (a) Background-free autocorrelation trace of chirped pulses from laser output, insertion: optical spectrum of the laser; (b) Interferometric autocorrelation trace of the dechirped laser pulses.

In order to elongate the laser cavity we used a 2.6-km All-Wave (Lucent) fiber stretch. At this length of the fiber the optical length of the laser cavity was 3.8 km. The laser diagram with elongated cavity is given in Fig. 3. Pumped with the same amount of power (1.5 W) the laser generated unchanged average output radiation power, 300 mW. However, mode-locked

operation of this laser with ultra-long cavity behaved differently depending on the setting of the phase plates (Fig. 4).

It was possible to run the laser stably both in the mode of single nanosecond pulses (Fig. 4(a)) or a train of nanosecond pulses (Fig. 4(b)) and in the mode of nanosecond pulses with noticeable microsecond pedestal (Fig. 4(c)). When generating trains of nanosecond pulses, the train duration was up to 300 ns and the train contained up to 20 pulses, each about 1 ns long. When generating single nanosecond pulses, their duration was 3 ns, repetition rate 77 kHz, and per-pulse energy 3.9 μ J. As far as we are informed, the energy of pulses we have generated (3.9 μ J) is the highest to-date achieved directly from a mode-locked fiber laser without application of Q-switching or/and cavity dumping techniques.

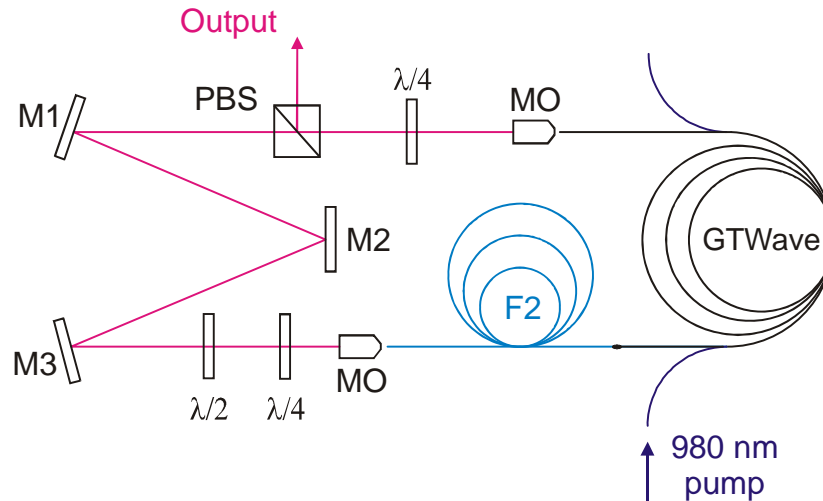


Fig. 3. Schematic of extra-long mode-locked fiber laser: F2 – All-wave fiber, length of 2,6 km.

In Fig. 5 radiation spectra of ultra-long mode-locked laser generating single pulses and multiple pulse trains are shown. These spectra differ significantly in width. The spectrum width of laser radiation in the case of single pulses (Fig. 5(left)) amounted to 0.35 nm, suggesting that the obtained pulses can be subsequently compressed into picosecond range, which however, was not experimentally verified in the course of this study. Spectrum width of multiple pulse trains radiation (Fig. 5(right)) was almost 20 nm and this indicates that these pulses have different radiation wavelengths. Radiation spectra of these pulses overlap and form relatively wide resulting spectrum. It should also be noted \sim 11-nm shift of laser spectrum in long-wavelength range in the case of multiple pulse trains generation. Laser spectra of single pulses radiation both in short and ultra-long cavity are quite smooth-shaped and these spectra do not have steep sides with peaks at the edges which are typical for all-normal-dispersion fiber lasers with strong spectral filtering.

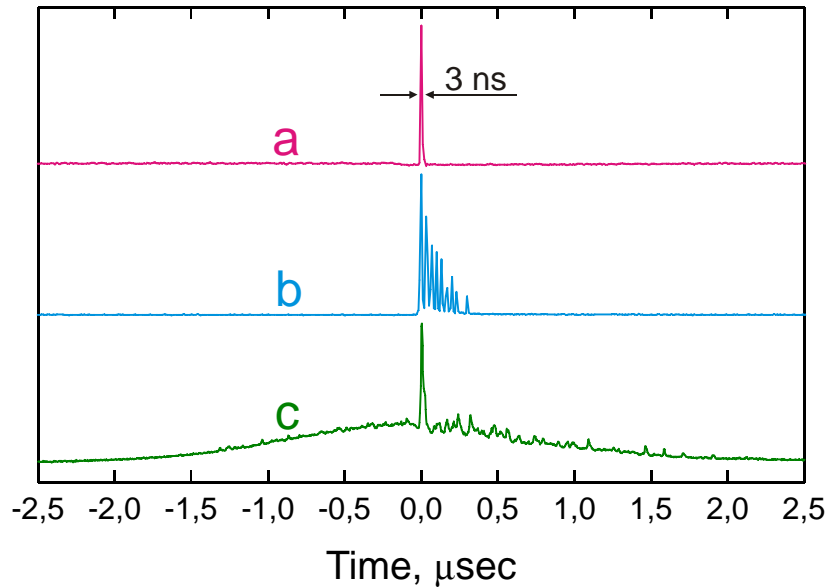


Fig. 4. Temporal distribution of laser radiation intensity in different types of mode-locked operation: a – generation of single 3-ns pulses, b – generation of multiple nanosecond pulse trains, c – generation of single nanosecond pulses with noticeable microsecond-long pedestal. For all types of operation the pulse period (or period of pulse trains in case b) was $\sim 13 \mu\text{s}$.

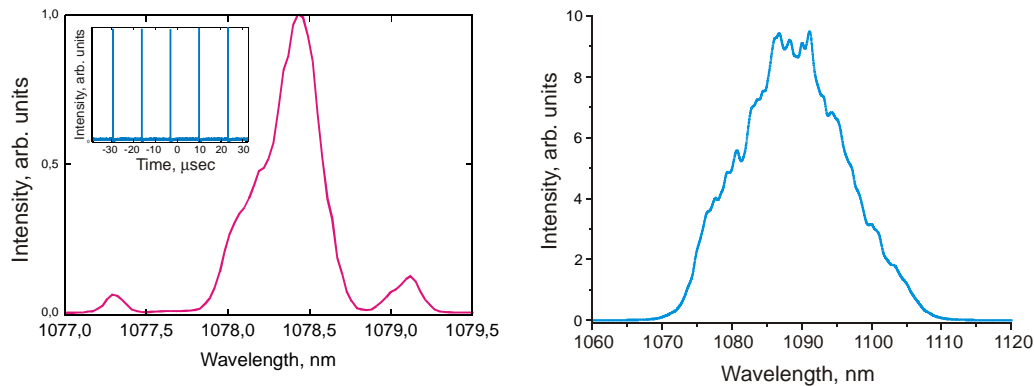


Fig. 5. Optical spectra of ultra-long mode-locked Yb-doped fiber laser: on the left: spectrum in the case of single 3-ns pulses generation, insertion: real-time oscilloscope trace of single pulse train; on the right: spectrum in the case of multiple nanosecond pulse trains generation.

3. Conclusion

In the course of this investigation, a fiber laser was developed for the first time with mode-locked operation in an ultra-long cavity whose optical length equals 3.8 km. Elongation of the optical path of the laser's ring resonator from 12.5 m to 3.8 km led to the increase in the output pulse energy by more than two orders of magnitude up to $3.9 \mu\text{J}$, which is a record-breaking achievement for pulses generated directly by a mode-locked fiber laser without application of Q-switching, cavity dumping techniques, or additional optical amplifiers. The minimal duration of output pulses was 3 ns at the pulse repetition rate 77 kHz and the average output power 300 mW at wavelength 1078 nm. It is important to note that for the laser cavity elongation a fiber was used, which is not single-mode at the laser output wavelength and does

not maintain radiation polarisation. Nevertheless, the extra-long ring fiber laser using this fiber has demonstrated reliable and stable mode-locked operation because of non-linear rotation of radiation polarisation. Remarkably low requirements to the parameters of fiber used for elongation of the laser cavity suggest that the proposed resonator configuration has a significant potential for further increase of the cavity length and, consequently, for higher energies of pulses generated in such mode-locked fiber laser.