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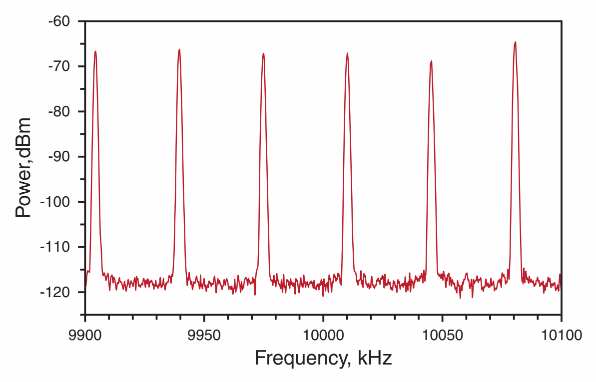
Abstract: We report on the record-high pulse energy of nearly 1.7 μJ obtained directly from a self-mode-locked all-fiber erbium laser with a linear-ring cavity owing its extreme elongation up to several kilometers. Specially selected telecommunication fibers, providing large normal net cavity dispersion in the vicinity of 1.55 μm, have been used for this purpose. Along with compensation for polarization instability in the longer linear arm of the cavity, such approach has ensured stable wave-breaking-free mode-locked lasing with an ultra-low pulse repetition rate of 35.1 kHz.



Intermode beats spectrum

Generation of 1.7-μJ pulses at 1.55 μm by a self-mode-locked all-fiber laser with a kilometers-long linear-ring cavity

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1. Introduction

The possibility of a substantial increase of pulse energy in a passively mode-locked laser by a significant elongation of its cavity using conventional telecom fibers was primarily proposed and demonstrated in [1]. First of all this approach has been used to create ytterbium-based high-energy pulsed fiber lasers whose generation wavelengths lie within 1.0 – 1.1 μm [1–6]. By now it has allowed reaching a pulse energy level as high as 4 μJ [5,6] at moderate pump and average laser powers without resorting to Q-switching, cavity dumping, or an extra optical power amplification. Besides ease of implementation, the direct generation of high-energy pulses by means of passively mode-locked long-cavity lasers has the potential advantage of well-defined pulse repetition frequency and short pulse duration. A gigantic chirp of generated pulses, which increases with the cavity length, may be considered as a drawback of this approach. However, it has been experimentally discovered that this chirp is predominantly linear [7]. This feature allows presuming that an efficient pulse compression is possible.

The similar approach being applied to erbium-based mode-locked fiber lasers has not yet resulted in the similar dramatic increase of pulse energies. The wavelength-

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depending dispersion properties of optical fibers make pulsed regimes of Er-based fiber lasers differ from those of Yb-based fiber lasers. Conventional low-cost telecommunication single-mode fibers (SMFs) that are the most natural candidate for laser cavity elongation, exhibit normal chromatic dispersion at the lasing wavelengths of Yb-fiber lasers, but the anomalous one within the spectral range of Er-fiber lasers (1.5 – 1.6 μm). Stable generation of wave-breaking-free high-energy pulses in mode-locked Yb-fiber lasers is enabled by all-normal intracavity dispersion [8–10]. Pulses generated in such lasers are often referred to as dissipative solitons [11,12]. Their physics does not impose fundamental limitations on the maximum pulse energy, as opposed to soliton-like pulses generated in mode-locked fiber lasers with anomalous intracavity dispersion [13–16]. In the all implemented types of long-cavity Er-based passively mode-locked lasers constructed from conventional anomalous-dispersion SMFs the output pulse energy is limited to values less than 20 nJ [17–19]. Due to the phenomena attributable to non-dissipative solitons, such as energy quantization and decay of high-order solitons [20], any attempts to raise pulse energy above this level bring the lasers into a multiple-pulse regime or turn them to a harmonic mode-locking. To avoid such negative effects and to scale up the pulse energy by analogy with the ytterbium-based lasers the intracavity dispersion in the erbium-based lasers has to be normal as well. Feasibility of passively mode-locked Er-fiber lasers with net-normal cavity dispersion that operate in the dissipative soliton regime has recently been demonstrated in [21–25]. Such lasing regime has allowed reaching a pulse energy level as high as 0.56 μJ in a self-mode-locked Er-fiber laser with a 1.25-km-long cavity [25]. The laser cavity has been elongated by a dispersion compensating fiber module (DCFM), which is normally used in fiber-optics communication lines to compensate for the anomalous dispersion of conventional SMFs. Though such approach has resulted in high-performance lasing, the very high cost of DCFMs, as compared with most SMFs, may be a limiting factor for further cavity scaling up.

In this work we aim to develop a low-cost long-cavity erbium-fiber laser operating in a stable single-pulse mode-locked regime, which provides output pulse energies in excess of 1.0 μJ with a kilohertz-scale repetition rate at a 1.55-μm wavelength. Pulsed laser radiation with such characteristics is required for many practical applications (e.g. lidar measurements, long distance atmospheric communications, and biomedicine technologies).

2. Experimental setup

A linear-ring all-fiber resonator, successfully tested in our previous work [25], has been used as the base configuration to build the higher-energy mode-locked Er-fiber laser. The specific feature of such a resonator (Fig. 1) is given by insertion of an optical-fiber circulator into an originally ring cavity. This circulator diverts the radiation into a long linear arm and also plays the role of an optical diode, thereby enforcing the unidirectional generation mode within the ring part of the cavity. The linear arm is terminated by a Faraday mirror, which compensates for linear birefringence in this arm. Thus, an efficient compensation for polarization instability and polarization mode dispersion, which might be accumulated over the long linear arm, is provided. In principle, the ratio between the lengths of the ring and the linear arms of the resonator may be arbitrary. Therefore such a combined resonator might be either predominantly ring or almost linear one.

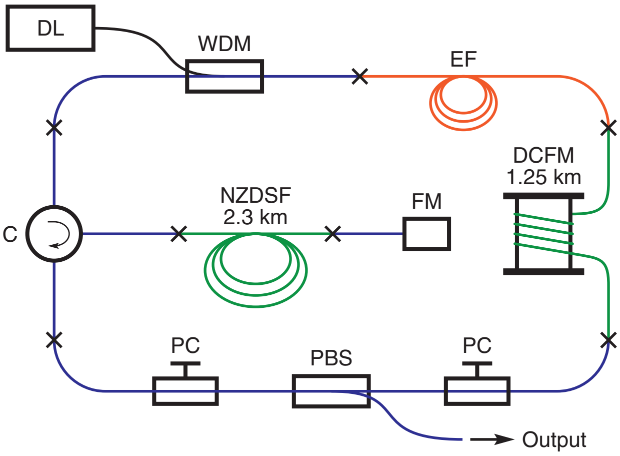

Figure 1 (online color at www.lphys.org) Schematic of the laser: DL – pumping diode laser, WDM – wavelength-division multiplexer, EF – erbium-doped fiber, DCFM – dispersion compensating fiber module, PC – polarization controller, PBS – polarizing beam-splitter, C – circulator, NZDSF – non-zero dispersion-shifted fiber, and FM – Faraday mirror

The active medium of the laser is a 2.2-m-long highly-doped erbium fiber "LIEKKI™ Er30-4/125" (absorption 30±3 dB/m at 1530 nm), which is placed in the ring part of the cavity. The laser is pumped at a wavelength of 980 nm by a fiber-coupled diode laser. The maximum pump power is 450 mW. The pump radiation is injected through a wavelength-division multiplexer.

Self-mode-locking in this laser is achieved by exploiting nonlinear polarization evolution [13,14]. A fiber-optical polarization beam splitter located in the ring part of the cavity is used as a polarization discriminator and simultaneously as an output coupler.

In the vicinity of 1.55 μm the erbium fiber has a normal chromatic dispersion comparable in magnitude with the dispersion of conventional SMFs. All intracavity SMFs with anomalous dispersion (the pigtails of fiber-optical elements) are no longer than 25 cm each. Their total contribution to the overall group velocity dispersion of the cavity ($\Sigma\beta_2$) has been estimated as only – 0.05 ps^2.

Unlike [25], the linear arm of the laser cavity has been elongated by a 2.3-km-long single-mode telecommunica-

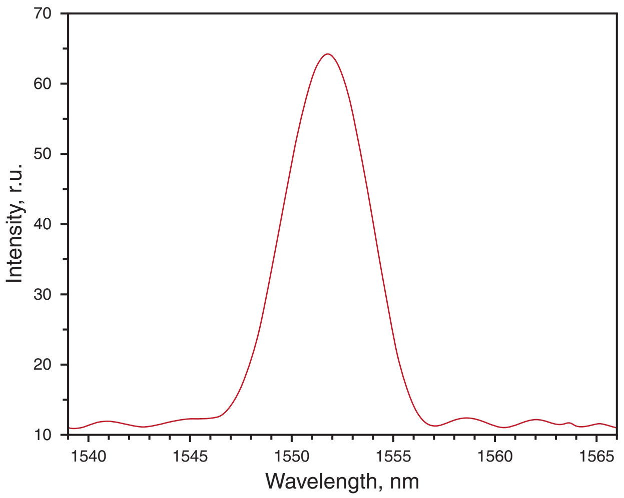

Figure 2 (online color at www.lphys.org) Optical spectrum of the laser

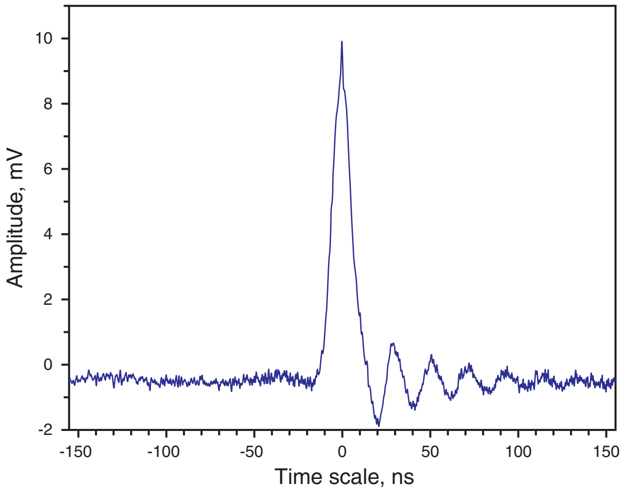

Figure 3 (online color at www.lphys.org) Oscillogram of a single pulse

tion fiber, which complies with the ITU-T G.655 standard. This is a so-called non-zero dispersion-shifted fiber (NZDSF). The measured zero-dispersion wavelength of this fiber is 1,598 nm, which is almost at the boundary of the operating spectral range of erbium lasers. At 1.55 μm this fiber exhibits a slightly normal chromatic dispersion ($D \approx -3$ ps/nm/km). Its contribution to the overall group velocity dispersion of the cavity is about $+17.6$ ps^2.

The laser cavity has been also supplemented with a dispersion compensating fiber module “N-DCFM-C-10-FA” made by Sumitomo. This module contains a 1.25-km-long special single-mode fiber with a large normal chromatic dispersion ($\beta_2 \approx +217$ ps^2 at 1.55 μm). Its dispersion curve does not approach zero within operating spectral range of erbium lasers. The optimal location of the DCFM has been found experimentally. The highest energy efficiency of the laser has been reached with the DCFM located in the ring part of the cavity (as shown in Fig. 1). The main reason for that is significant optical loss introduced by the DCFM (up to 1.9 dB per pass).

Thus, the net cavity dispersion has been made a large normal one over the whole spectral band of the laser active medium.

3. Results and discussions

Mode-locking is self-triggered when the pump power exceeds ~ 150 mW. Depending on the adjustments of the polarization controllers, ether a multi-pulse operation (harmonic mode-locking) or single-pulse regime (one pulse per resonator period) can be initiated. The shape and duration of pulses also depend on the settings of the polarization controllers. The parameters specified below correspond to the optimal mode-locked lasing regime, in which a stable generation of pulses with the fundamental repetition rate, the highest energy, and the shortest duration is sustained.

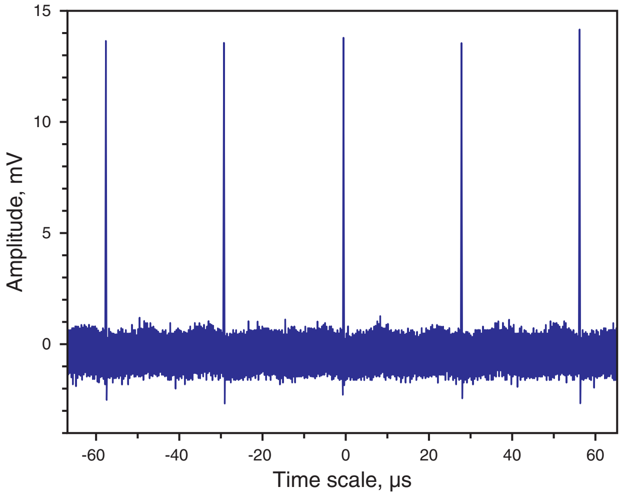

Figure 4 (online color at www.lphys.org) Oscillogram of a pulse train

The laser radiation spectrum registered by an optical spectrum analyzer is shown in Fig. 2. The center wavelength is near 1552 nm, and the spectral width is about 6 nm. It corresponds to a sub-picoseconds transform-limited pulse width. In spite of that, the actual output pulse duration measured by means of a fast photodiode and a broadband oscilloscope is around 13 ns (Fig. 3). Thus it indicates very strong pulse chirping. Shown in Fig. 4 is an oscilloscope trace of the generated pulse train. The train has a uniform interpulse interval of ~ 28.5 μs corresponding to the cavity round-trip time.

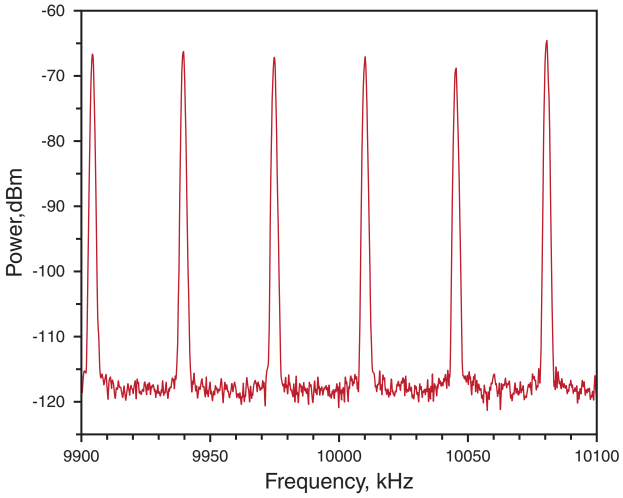

Figure 5 (online color at www.lphys.org) Intermode beats spectrum

Examination of intermode beats spectra using a broadband RF spectrum analyzer showed high spectral purity and good frequency stability. Even for high-order beats (at frequencies ~ 10 MHz) the signal/noise ratio is higher than 45 dB (Fig. 5). The measured intermode frequency is ~ 35.1 kHz. It corresponds to the fundamental pulse repetition frequency.

The average output power is about 22 mW at the triggering pump power (150 mW), and it reaches 58.2 mW at the maximum pump power (450 mW). Thus the maximum output pulse energy can be estimated as 1.66 μJ. It is pertinent to note that the average output power experiences almost linear growth with increase of the pump power. This allows concluding that the maximum pulse energy, obtained in this laser, is limited by the available pump power.

The described lasing regime is sufficiently stable: under laboratory conditions it was continuously maintained during several hours, despite the absence of any thermal stabilization and vibroacoustic isolation of the laser.

Thus self-mode-locking in the considered laser configuration involving a kilometers-long non-zero dispersion-shifted fiber along with a dispersion compensating fiber module allows reaching pulse energies in excess of 1.0 μJ. The large normal net cavity dispersion enables stable wave-breaking-free lasing, but also leads to very strong pulse chirping. The linear-ring cavity design with compensation for polarization instability in the kilometers-long linear arm facilitates reliable self-mode-locking based on nonlinear polarization evolution.

To the best of our knowledge the achieved pulse energy (1.66 μJ) sets a new record for passively mode-locked erbium fiber lasers not assisted by Q-switching or cavity dumping. Furthermore, the demonstrated pulse repetition rate (35.1 kHz) is record-low for passively mode-locked lasers with pulse energies exceeding 1.0 μJ.

4. Summary

We have demonstrated stable self-mode-locking in an all-fiber erbium-based laser with a kilometers-long net-normal-dispersion cavity. It has resulted in direct generation of short laser pulses with an ultra-low repetition rate of 35.1 kHz and a very high energy of nearly 1.7 μJ at a wavelength of 1.55 μm. Since no output saturation and no wave-breaking effects have been observed at the maximum available pump power (450 mW), a further pulse energy scaling up seems to be possible.

The laser cavity has been fabricated from commercially-available telecom fibers and optical-fiber elements. Its unconventional linear-ring design with compensation for polarization instability ensures high reliability of the self-mode-locking operation, despite the use of nonpolarization-maintaining fibers.

The laser characteristics make it suitable for many applications (e.g. various lidar measurements, long-distance atmospheric communications, and biomedicine technologies).

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