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Self-mode-locked all-fibre erbium laser with a low repetition rate and high pulse energy

V.I. Denisov, B.N. Nyushkov, V.S. Pivtsov

***Abstract*. Self-starting mode locking is demonstrated for the first time in an all-fibre erbium laser with a cavity length above 1 km and high positive (normal) intracavity dispersion. The unconventional cavity design, with polarisation instability compensation, ensures stable operation and good frequency stability. The laser generates pulses with a record low repetition rate (82.4 kHz) and record high energy (564.3 nJ).**

Keywords: *fibre laser, mode locking, low pulse repetition rate, high pulse energy, normal dispersion, linear ring cavity.*

All-fibre self-mode-locked lasers are very reliable, compact sources of short pulses with good frequency stability and high beam quality. Initially, the pulse repetition frequency, f, of such lasers was from a few to tens of megahertz and their pulse energy did not exceed a few nanojoules. Many practical applications (e.g. lidar measurements, optical telecommunication systems and precision machining), however, require lower (sub-megahertz) pulse repetition rates and considerably higher pulse energies. Very recently, the first all-fibre passively mode-locked lasers with a sub-megahertz pulse repetition rate were demonstrated [1 – 5]. The only erbium-doped one among them [5] was mode-locked by a semiconductor saturable absorber mirror (SESAM) and had a maximum pulse energy of 14 nJ at $f = 250.7$ kHz.

In this paper we report a stable all-fibre self-mode-locked erbium laser with a sub-megahertz repetition rate, maximised pulse energy and high beam quality, fabricated from standard telecommunication fibre and fibre-optic components.

Most single-mode telecommunication fibres suitable for the fabrication of long cavities for sub-megahertz operation have anomalous chromatic dispersion at $\lambda = 1.55$ μm. As is well known, mode locking in the case of anomalous intracavity dispersion leads to soliton generation. Soliton energy quantisation imposes stringent limitations on the maximum pulse energy. Raising the intracavity energy above a certain level brings the laser into a multiple pulse regime [5 – 7]. At the same time, passive mode locking in the case of all-normal intracavity dispersion enables generation of so-called dissipative solitons [8], which have no such limitations on the maximum pulse energy. Dissipative soliton operation has recently been demonstrated in all-fibre erbium lasers [9, 10]. Wu et al. [9] achieved a pulse energy of 281.2 nJ at $f = 1.225$ MHz.

We have fabricated an all-fibre erbium laser with high positive intracavity dispersion using single-mode DCF fibre, which is ususally applied in optical fibre communication systems to compensate for the dispersion of standard single-mode fibres (SMFs). The configuration of the laser is shown in Fig. 1. Basic to the laser design is the linear ring cavity [11], which combines the advantages of linear and ring cavities, such as ease of tuning, travelling-wave operation, optimised light outcoupling, minimum mode frequency spacing and the possibility of polarisation instability com-

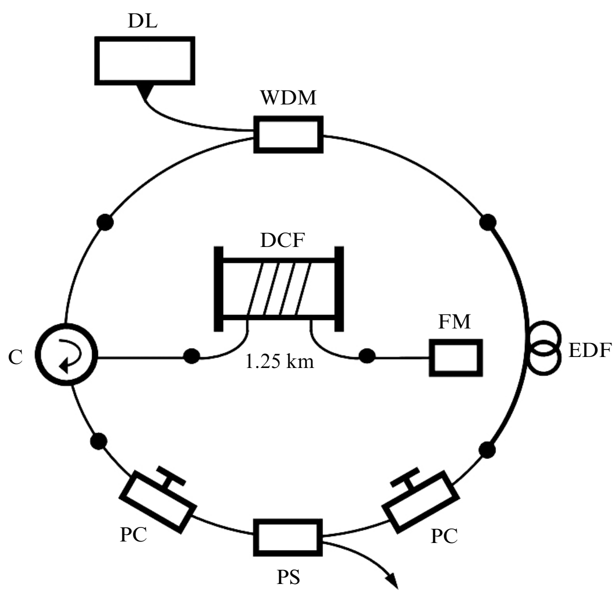

Figure 1. Laser configuration: (DL) diode laser pump; (WDM) wavelength-division multiplexer; (EDF) erbium-doped fibre; (PC) polarisation controller; (PS) polarisation splitter; (C) circulator; (DCF) 1.25 km of spooled normal-dispersion single-mode fibre; (FM) Faraday mirror.

V.I. Denisov, B.N. Nyushkov, 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. Karla Marksa 20, 630092 Novosibirsk, Russia; e-mail: denisov@laser.nsc.ru

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pensation. The linear part of the cavity includes a Sumimoto N-DCFM-C-10-FA dispersion-compensating module: 1.25 km of spooled normal-dispersion single-mode DCF fibre ($\beta_2 \approx 217$ ps^2 at 1.55 μm). This part of the cavity is terminated with a 100 % Faraday mirror, which rotates the plane of polarisation of the input light through 90°, thereby compensating for the polarisation instability over almost the entire length of the cavity (the ring part of the cavity is no longer than 3 m). The two parts are coupled together by a fibre-optic circulator, which also serves as an optical diode for the ring part, ensuring unidirectional operation.

The gain medium is a 1.8-m-long Liekki heavily erbium-doped fibre with an absorption coefficient of 40 ± 4 dB m^{-1} at 1530 nm, incorporated into the ring. This fibre has normal dispersion at the lasing wavelength. The laser is pumped at 980 nm; the maximum pump power is 450 mW. Like in classic femtosecond fibre lasers, mode locking is enabled by nonlinear polarisation evolution [6, 7]. The fibre polarisation splitter placed before the doped fibre in the ring is used as a polarisation discriminator and output coupler. None of the anomalous-dispersion fibres in the cavity (pigtails of the fibre-optic components) is longer than 20 cm. The net dispersion introduced by them at 1.55 μm is approximately -0.04 ps^2.

Pump powers above 150 mW ensure self-starting mode locking. By adjusting the settings of the polarisation controllers, both multiple-pulse (harmonic mode locking) and single-pulse operation can be achieved. The pulse shape and duration also depend on these settings. Below, we specify the optimal characteristics which ensure stable pulse generation at the fundamental frequency with the maximum pulse energy and minimum duration.

The centre wavelength of the laser is 1560 nm, and the full width at half maximum of its optical spectrum is approximately 7 nm (Fig. 2). The pulse repetition time, measured with an oscilloscope, is ~ 12 μs (which corresponds to the cavity round-trip time) and the pulse duration is about 5 ns (Fig. 3). Examination of intermode beating spectra (Fig. 4) using an rf spectrum analyser showed good spectral purity and frequency stability. Even high-order beat harmonics (~ 10 MHz) have a signal-to-noise ratio of at least 50 dB, linewidth no more than 10 Hz (analyser resolution) and temperature frequency drift within 60 Hz× min^{-1}. The measured mode frequency spacing (intermode frequency) is ~ 82.4 kHz. At the maximum pump power, the average output power of the laser reaches 46.5 mW. Accordingly, the maximum pulse energy is ~ 564.3 nJ. This lasing mode is very stable: under laboratory conditions, it persists for a working day, even with no thermal stabilisation and no vibration isolation.

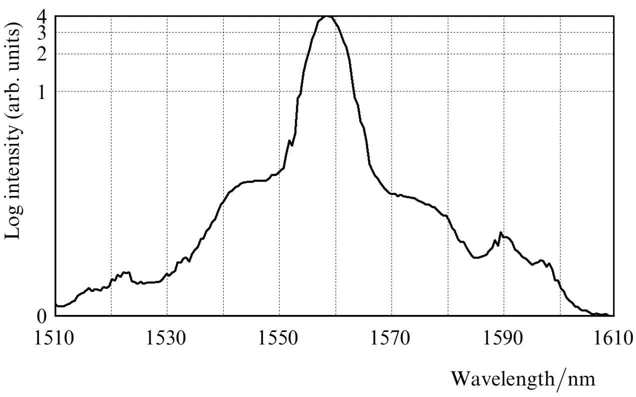

Figure 2. Optical spectrum of the laser on a logarithmic scale.

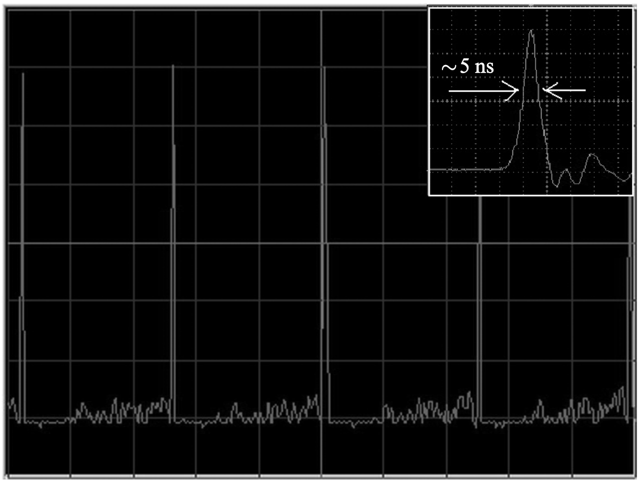

Figure 3. Oscilloscope trace showing a sequence of pulses (time base, 5 μs div^{-1}). Inset: one pulse (time base, 5 ns div^{-1}).

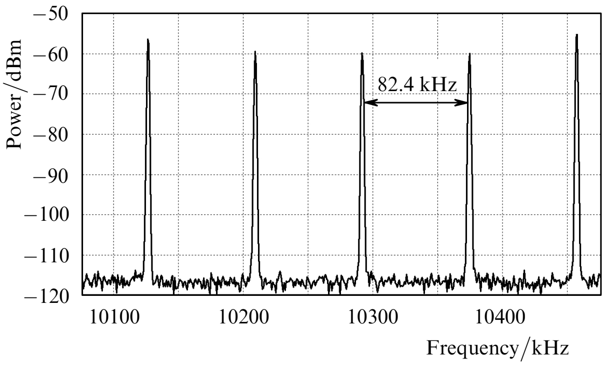

Figure 4. Intermode beating spectrum of the laser (1 kHz resolution).

Thus, using standard telecommunication fibre and fibre-optic components, we have fabricated an all-fibre self-mode-locked erbium laser with a sub-megahertz pulse repetition rate. Owing to the high positive intracavity dispersion and very low pulse repetition rate, we achieved a record high pulse energy for such lasers, 564.3 nJ, limited by pump power. The unconventional cavity design, with polarisation instability compensation, ensures good performance stability in spite of the long cavity length and the use of non-polarisation-maintaining fibre. The use of only single-mode fibres in the cavity ensures high beam quality, corresponding to the fundamental spatial mode.

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