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High-power pulsed ytterbium fibre laser with 10-μJ pulse energy

A.I. Trikshev, V.A. Kamynin, V.B. Tsvetkov, O.N. Egorova

Abstract. **An all-fibre pulsed fibre laser system emitting at a wavelength of 1093 nm with an average output power up to 10 W is presented. The system is assembled according to the master oscillator/fibre amplifier scheme. Pulses were generated with passive mode locking due to nonlinear polarisation rotation in a standard single-mode fibre. The main fibre amplifier was pumped by fibre-coupled semiconductor laser diodes at a wavelength of 976 nm with a maximum total power up to 50 W. The measured pump duration did not exceed 60 ps at a pulse repetition rate of about 1 MHz. The pulse energy was 10 μJ.**

Keywords: *pulsed fibre laser, nonlinear polarisation rotation; phase mode locking.*

1. Introduction

Ultrashort pulse (USP) lasers find wide application in many fields of science and technology. They occupy a special place in medicine [1, 2]. Fibre USP lasers are an alternative to solid state lasers, because they are inexpensive, reliable, and simple in production.

To stabilise USP generation, one uses nonlinear intracavity modulators to achieve passive mode locking [3, 4]. Such modulators can be semiconductor saturable absorber mirrors (SESAMs) [5, 6], saturable absorbers based on single-wall carbon nanotubes [7], nonlinear fibre mirrors [8], and modulators based on nonlinear polarisation ellipse rotation [9]. Each of these methods has its own advantages and drawbacks. SESAMs are relatively expensive and often fail to operate at high laser powers but provide the best stability. Nanotubes also demonstrate stable operation but degrade with time. Modulators based on nonlinear mirrors and nonlinear polarisation rotation have the minimum cost, but their working ability strongly depends on the environmental conditions, which, however, can be overcome by using polarisation-maintaining fibres [10, 11].

In this paper, we demonstrate an all-fibre pulsed laser system based on a ring-cavity laser, in which passive mode locking occurs due to nonlinear polarisation rotation, and several cascades of ytterbium-doped fibre amplifiers. The output pulse energy was about 10 μJ at a pulse repetition rate of 1 MHz, and the measured pulse duration did not exceed 60 ps.

A.I. Trikshev, V.A. Kamynin A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia; Ulyanovsk State University, ul. L. Tolstogo 42, 432017 Ulyanovsk, Russia; Photonics Laboratory, Perm Scientific Center, Ural Branch, Russian Academy of Sciences, ul. Lenina 13a, 614990 Perm, Russia; e-mail: trikshevgpi@gmail.com;
V.B. Tsvetkov A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia; National Research Nuclear University 'MEPhI', Kashirskoe sh. 31, 115409 Moscow, Russia;
O.N. Egorova Fiber Optics Research Center, Russian Academy of Sciences, ul. Vavilova 38, 119333 Moscow, Russia

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2. Experimental setup

The scheme of the experimental setup is shown in Fig. 1. The laser is designed according to the master oscillator/fibre amplifier scheme [12]. The master oscillator (*1*) was a pulsed ring laser mode-locked by nonlinear polarisation rotation. As an active medium, we used ytterbium-doped fibre with a multi-element first cladding (GTWave) [13]. The active core diameter was 6 μm, and the cladding diameter was 125 μm. The core numerical aperture was NA = 0.11. The absorption coefficient at the pump wavelength λ_p = 976 nm was 0.8 dB m^{-1}. The active fibre was 5 mm long. Pumping was performed by a semiconductor laser diode (λ_p = 976 nm). To achieve a pulse repetition rate of 1 MHz, a fibre delay line (FDL) based on a single-mode fibre about 180 m long was included in the cavity. The total cavity length was about 200 m. The operation regime of the master oscillator was adjusted using fibre polarisation controllers (FPCs). The laser radiation was coupled out of the cavity via a 9/1 fibre coupler, its weak arm returning a part of power to the cavity. The average output power of the master oscillator was 10 mW, which corresponds to a pulse energy of 9 nJ.

Fibre preamplifier (*2*) was an active ytterbium-doped GTWave fibre 16 m long, which was pumped by a laser diode with λ_p = 976 nm. So that the preamplifier power did not return to the master oscillator, we placed a fibre optic isolator (FOI) in front of the preamplifier. The average power at the exit from the amplifier was 350 mW, which corresponds to a pulse energy of 318 nJ.

High-power fibre amplifier (*3*) was based on a large-mode-area ytterbium-doped fibre [14] with a core diameter of 25 μm (NA = 0.07) and a cladding diameter of 250 μm (NA = 0.46). The absorption coefficient at a wavelength of 976 nm was 10 dB m^{-1}. The active fibre length was 2.7 m. The apertures of fibres of preamplifier (*2*) and high-power amplifier (*3*) were matched using a mode adapter based on a conical fibre with a smoothly changing core diameter. As a pump source, we used three multimode laser diodes with the total power up to 50 W. The pump radiation was coupled in using a (6 + 1) × 1 fibre combiner (three inputs remained

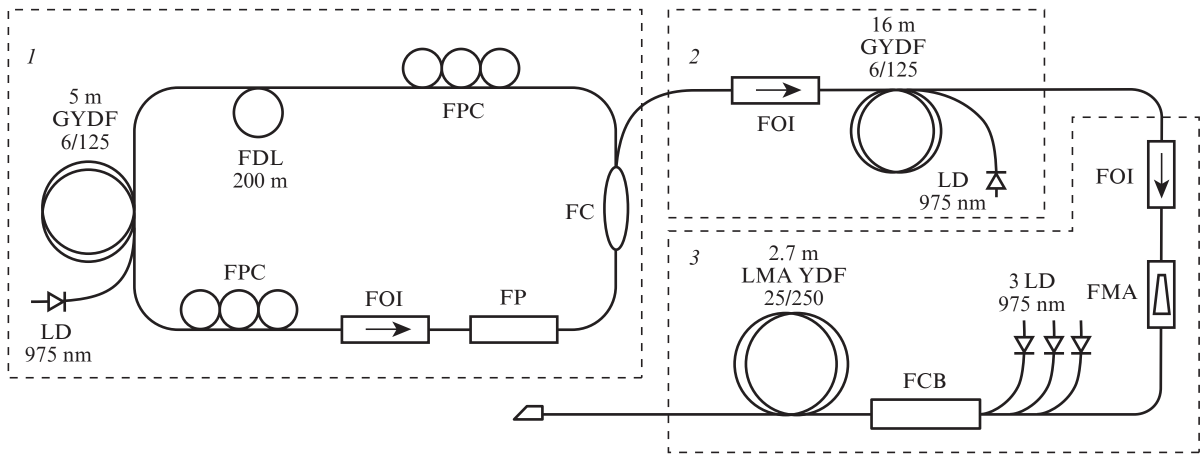

Figure 1. Experimental setup: (*1*) master oscillator; (*2*) preamplifier; (*3*) amplifier; (GYBF) ytterbium-doped GTWave fibre; (LMA YDF) large-mode-area ytterbium-doped fibre; (FDL) fibre delay line; (FPC) fibre polarization controller; (FOI) fibre optic isolator; (FP) fibre polariser; (FC) fibre coupler; (LD) pump laser diode; (FMA) fibre mode adapter (conical fibre); (FCB) fibre combiner.

unused). The output end of the active fibre was fused to a passive fibre 20 cm long. To remove unabsorbed pump power, the splice to the passive fibre was coated with a polymer. To prevent backward reflection, the output end of the passive fibre was cleaved at an angle of 8°. The average output power of the system at a pump power of 48 W was 10 W, which corresponds to a pulse energy of 10 μJ.

3. Experimental results

The master oscillator spectrum at an output power of 10 mW, which is shown in Fig. 2, corresponds to the spectrum of stochastic pulses [15]. The laser radiation peak lies at a wavelength of 1093 nm. The 1093-nm peak observed at a level of –12 dB from the laser peak corresponds to the first Stokes component in silica glass [16]. A similar peak in the spectrum of an all-fibre fibre laser mode locking by nonlinear polarisation rotation was observed for the first time in [17] at a laser pulse energy of 20 nJ.

The oscillogram of a laser pulse in the steady-state regime is shown in Fig. 3. The pulse duration at half maximum measured with a 16-GHz oscilloscope was about 60 ps at a pulse repetition rate of about 1 MHz. The negative pulse on the oscillogram is caused by the transient characteristic of the electric circuit between the photodiode and the oscilloscope. The pulse energy was 9 nJ.

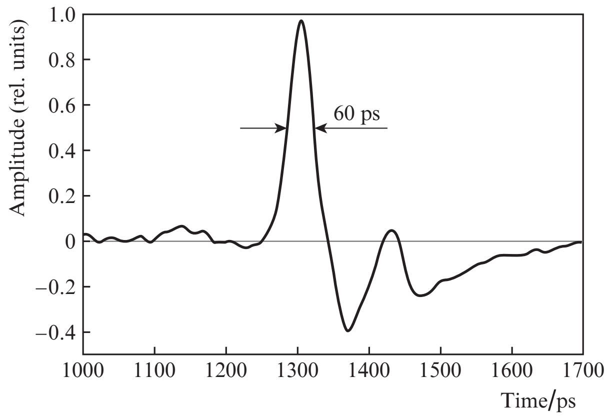

Figure 3. Master oscillator pulse oscillogram.

At a 3-W pump power of the preamplifier, its output power reached 350 mW, and a pulse energy increased to 318 nJ. The spectra of the fibre preamplifier at different pump powers normalised to the maximum value are shown in Fig. 4. One can see

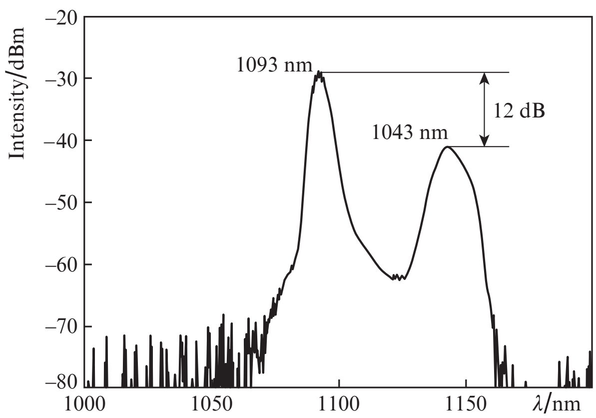

Figure 2. Master oscillator output spectrum.

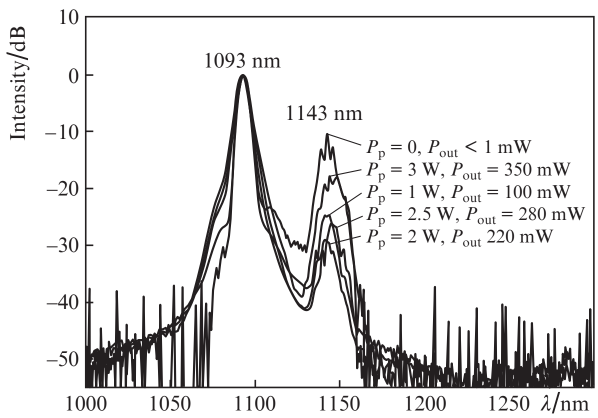

Figure 4. Preamplifier output spectra at different pump powers P_p.

that, as the ump power increases to 2 W, the intensity of the first Stokes component peak at first decreases with respect to the main laser peak and then increases. The decrease in the relative peak intensity is related to the fact that the main mechanism of its spectral profile formation at low signal powers is linear amplification. In our fibre, the most efficient amplification occurs at wavelengths close to 1090 nm. The increase in the peak intensity is related to an increase in the signal power and, as a result, to an increase in the contribution from nonlinear effects, in our case, from SRS.

Figure 5 shows the dependences of the output power of the main amplifier on its pump power. One can see that, to achieve the maximum efficiency at the given length of the active fibre, it is necessary to use pumping at a wavelength precisely coinciding with the active fibre absorption peak (975 nm). At a pump power of 48 W, the average output power was 10 W, which corresponds to a pulse energy of 10 μJ at a slope efficiency $\eta = 27\%$.

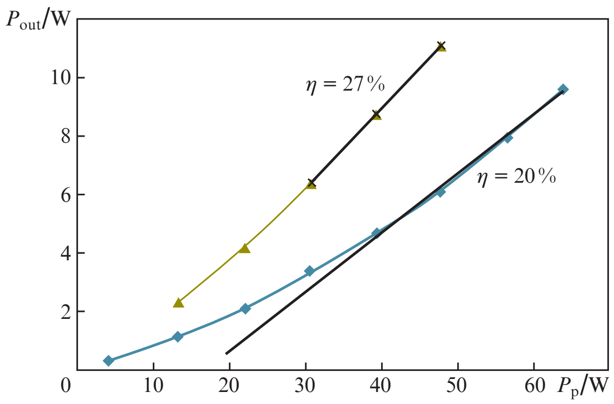

Figure 5. Dependence of the output power on the pump power at different pump wavelengths (η is the slope efficiency).

The output spectra of the system at different pump powers of the main amplifier are presented in Fig. 6. The spectrum contains, in addition to the main laser peak and the peak corresponding to the first Stokes component, a peak of unabsorbed pump radiation (966 nm) and a peak at 1033 nm, which corresponds to amplified spontaneous luminescence. The integration of power over the spectrum showed that about 95% of the entire power is concentrated in the main laser peak. The oscillogram of pulses at the exit from the system in a steady-state operation regime is given in Fig. 7. The measured pulse duration at half maximum was about 60 ps.

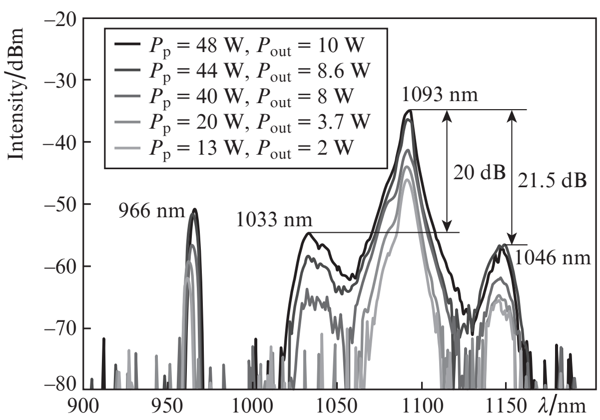

Figure 6. Output spectra at the exit from the system at different pump powers P_p.

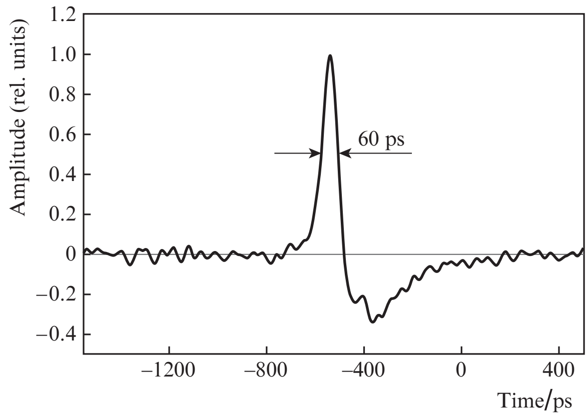

Figure 7. Pulse oscillogram at the output from the system.

Thus, we created an all-fibre laser passively mode-locked by nonlinear polarisation rotation, which is based on silica fibre and operates in the spectral range of ~1 μm. Amplification of pulses in the active fibre with multi-component cladding is demonstrated with a slope efficiency of 27%. The all-fibre system generates pulses with a duration of 60 ps, a repetition rate of about 1 MHz, and a pulse energy up to 10 μJ at an average power of 10 W at a wavelength of 1093 nm.

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