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Amplification of dissipative solitons with a polarisation-maintaining tapered fibre amplifier

A.G. Kuznetsov, D.S. Kharenko, S.A. Babin

Abstract. **The generation of strongly chirped dissipative solitons offers great opportunities for generating high-power laser pulses of short duration. We demonstrate the possibility of amplifying such pulses in a polarisation-maintaining tapered fibre having 32 μm mode diameter at the output end. Highly chirped pulses with a repetition rate of 14.3 MHz and a duration of 10 ps at 1055 nm centre wavelength are amplified in an all-fibre circuit to 2.11 μJ energy and compressed by diffraction gratings to a duration of ~297 fs. Reducing the pulse repetition rate to 1 MHz allows a 16.5 μJ output pulse energy to be achieved without manifestations of SRS and self-phase modulation in the spectrum.**

Keywords: *mode locking, dissipative soliton, femtosecond laser, taper, optical fibre, ytterbium amplifier.*

1. Introduction

Currently, femtosecond lasers with a high pulse repetition rate (PRR) and high peak power are in demand in such applied areas as microprocessing and photomodification of materials, engraving, etc. The use of disk lasers makes it possible to generate femtosecond pulses with an average power of a few tens of watts directly in the laser cavity [1, 2]. An alternative approach is to use a fibre laser source of ultrashort pulses having a relatively low power and one or a few amplifying stages to achieve high peak powers.

One of the promising methods for generating stable ultrashort pulses is the use of an all-fibre cavity design based on a short single-mode fibre with nonlinear polarisation rotation and a long polarisation-maintaining fibre, in which a dissipative soliton is formed. Such an approach allows generating pulses with a large chirp and high energy [3]. The pulse energy in lasers based on standard fibres is limited to ~20 nJ, above which a noise pulse is formed in another spectral region due to the effect of stimulated Raman scattering (SRS) [3].

To increase the pulse energy, amplifiers based on optical fibres with a large mode area (LMA) are often used, which allows a significant increase in the thresholds of various nonlinear effects (SRS, self-phase modulation, etc.). For example, Qi et al. [4], using three amplification stages with LMA fibres, amplified a chirped pulse with 120 ps duration to an energy of 1.85 μJ; however, a further increase in the pulse energy was accompanied by strong nonlinear effects. The use of microstructured photonic crystal fibres (PCFs) makes it possible to achieve even greater peak powers, up to several gigawatts after pulse compression [5]. However, the use of such fibres is complicated by the fact that the assembling of optical circuits based on them is very laborious and in most cases requires the use of bulk optic elements for the input and output of radiation. In addition, PCFs are sensitive to all sorts of bends, torsions and other deformations, and so they are usually to be aligned along a straight line, which makes it difficult to fabricate compact devices. Active tapered fibres with a core diameter smoothly changing with the length [5, 6] are a relatively new type of amplifiers that allow high peak signal powers to be reached without various nonlinear effects and maintaining the high quality of the output beam [7, 8].

The purpose of this work is to study the possibility of amplifying strongly chirped dissipative solitons with subsequent compression using an ytterbium fibre amplifier based on a tapered polarisation-maintaining fibre.

A.G. Kuznetsov Institute of Automation and Electrometry, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Koptyuga 1, 630090 Novosibirsk, Russia; e-mail: leks.kuznecov@gmail.com;
D.S. Kharenko, S.A. Babin Institute of Automation and Electrometry, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Koptyuga 1, 630090 Novosibirsk, Russia; Novosibirsk State University, ul. Pirogova 2, 630090 Novosibirsk, Russia

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2. Experimental setup

Figure 1 presents a schematic of the generator of chirped dissipative solitons. The master oscillator is implemented as a loop containing a short (~1.5 m) piece of a standard single-mode (SM) fibre (Nufern XP1060), in which mode locking occurs due to nonlinear rotation of polarisation, and a long (~10 m) piece of polarisation-maintaining (PM) fibre, in which a dissipative soliton is formed [3]. The PM part incorporates the following: a double-clad gain fibre doped with Yb^{3+} (Nufern PM-YB-5/130); a pump combiner that couples

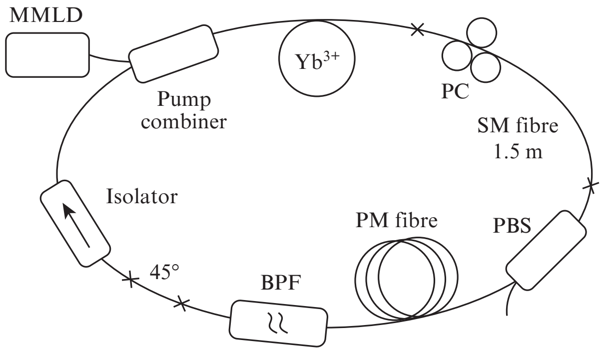

Figure 1. Schematic of a laser source of dissipative solitons.

the radiation of pump multimode laser diodes (MMLD) with nearly 3 W power at 980 nm wavelength into the outer cladding of the gain fibre, a polarisation beam splitter (PBS), a Lyot fibre spectral filter, implemented by splicing a PM fibre section at 45° angle, a polarisation controller (PC), an additional band pass filter (BPF) with 8 nm bandwidth, fixing the centre wavelength of radiation at 1055 nm. A PM fibre pigtailed polarising optical isolator sets the direction of propagation of radiation through the fibre.

To reduce the influence of nonlinear effects due to the high peak power, the pulses were pre-stretched before amplification with a fibre stretcher implemented as a PM fibre coil ~200 m long. The stretched chirped pulses were launched into a taper amplifier, the circuit diagram of which is similar to that described in Ref. [8] (shown in Fig. 2). The Yb^{3+} ion-doped tapered PM fibre made in the Fibre Optics Research Centre of the Russian Academy of Sciences (FORC RAS, Moscow) is a double-cladded cone-shaped light guide 2.5 m long with 9 μm input and 32 μm output core diameter (Fig. 3). The absorption of pump radiation at 976 nm wavelength in the cladding of the tapered fibre was ~23 dB m^{-1}. For pumping, a 60 W multimode laser diode was used, the collimated radiation of which was injected into the tapered fibre through its output end.

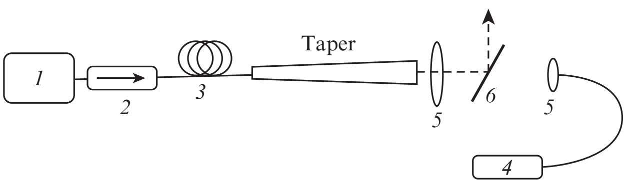

Figure 2. Schematic of the amplifier:
(*1*) generator of chirped pulses; (*2*) isolator; (*3*) stretcher; (*4*) pump multimode laser diode at 976 nm with a power up to 60 W; (*5*) collimator; (*6*) dichroic mirror.

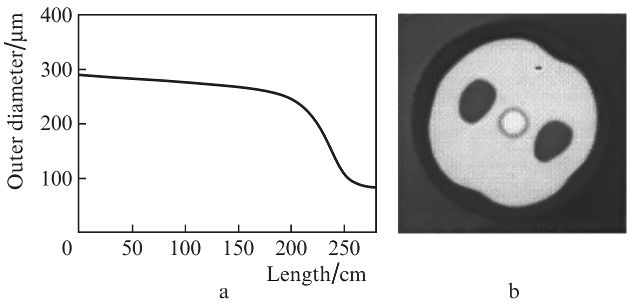

Figure 3. (a) Diameter of the outer cladding vs. length and (b) cross section of the tapered PM fibre.

The amplified useful signal from the taper output was directed by a dichroic mirror to a double-pass compressor with a pair of diffraction gratings (1500 lines mm^{-1}), and the compressed pulse was analysed using the FROG system (similar to that described in Refs [3, 9]).

3. Results and discussion

The master oscillator, schematically presented in Fig. 1, emitted a train of chirped pulses with 1055 nm centre wave-

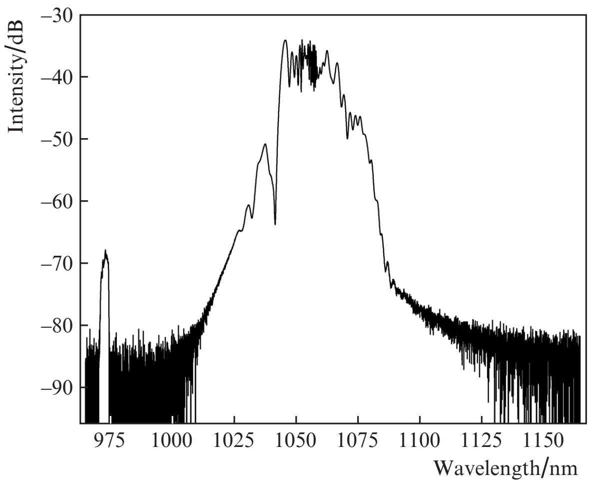

Figure 4. Emission spectrum of the master oscillator.

length (Fig. 4), 10 ps duration, and 14.3 MHz pulse repetition rate (PRR). The average power of the master oscillator was 20 mW, which corresponds to a pulse energy of 1.4 nJ. The pump power and cavity length were chosen to ensure maximum stability of the radiation in the absence of the generation of SRS pulses.

After passing the fibre-based pulse stretcher, the pulses were stretched to 130 ps and coupled into the tapered gain fibre. At a pump power of 51 W, the output power of the useful signal was 30.2 W, which corresponds to a pulse energy of 2.11 μJ; its spectrum is shown in Fig. 5. Figure 6 presents the dependence of the power at the output of the amplifier on the power of the diode pumping introduced from the wide end of the taper.

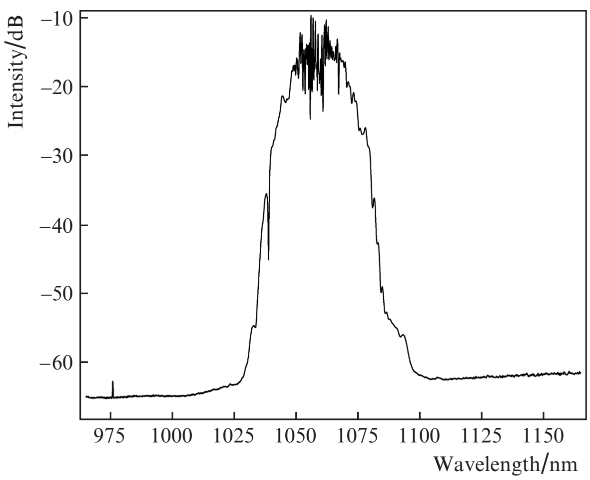

Figure 5. Spectrum of amplified radiation. The output power is 26.7 W.

Decreasing the repetition rate of the pulses to 1 MHz with an acousto-optic modulator leads to an increase in pulse energy at the same level of pump power. Figure 7 shows the power output from the amplifier as a function of the LD pump current and Fig. 8 presents the output spectrum at 1 MHz pulse repetition rate. The maximum pulse energy in this case was 16.5 μJ, while the spectrum did not exhibit the

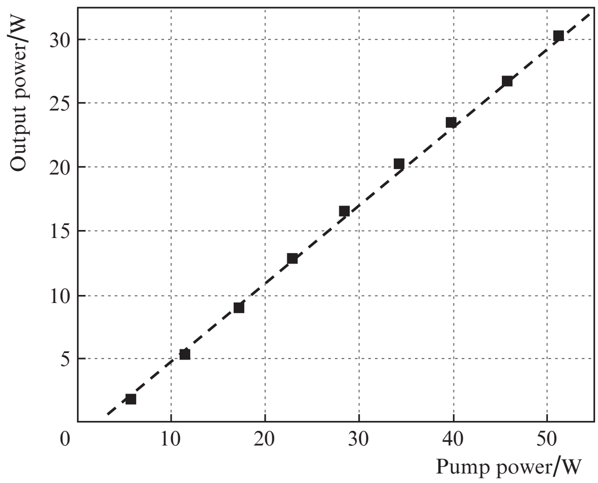

Figure 6. Dependence of the output signal power on the pump power at a PRR of 14.3 MHz.

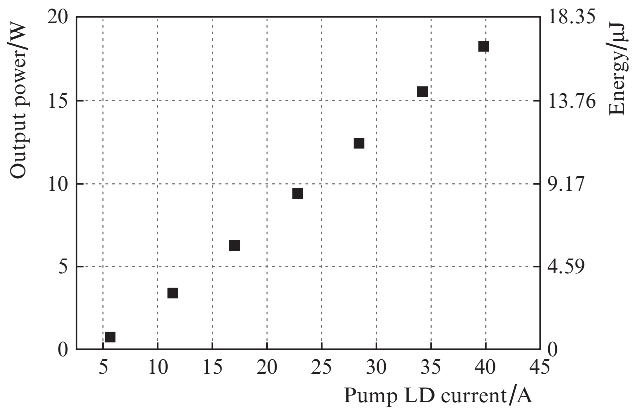

Figure 7. Dependence of the output signal power on the LD pump current at a PRR of 1 MHz.

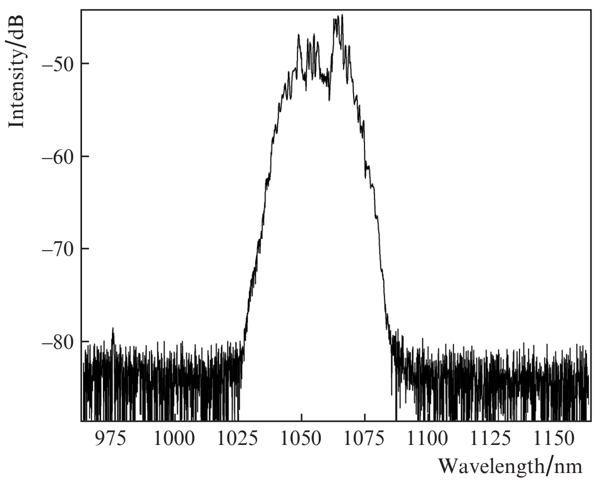

Figure 8. Spectrum of amplified radiation at 1 MHz PRR and 18.2 W output power.

influence of stimulated Raman scattering and there was no noticeable broadening of the spectrum due to self-phase modulation.

The amplified pulses were compressed by means of an external compressor based on diffraction gratings; their autocorrelation function (ACF) and FROG traces are shown in Fig. 9. The measured duration of a compressed pulse with an output power of 13 W and a PRR of 14.3 MHz was 297 fs.

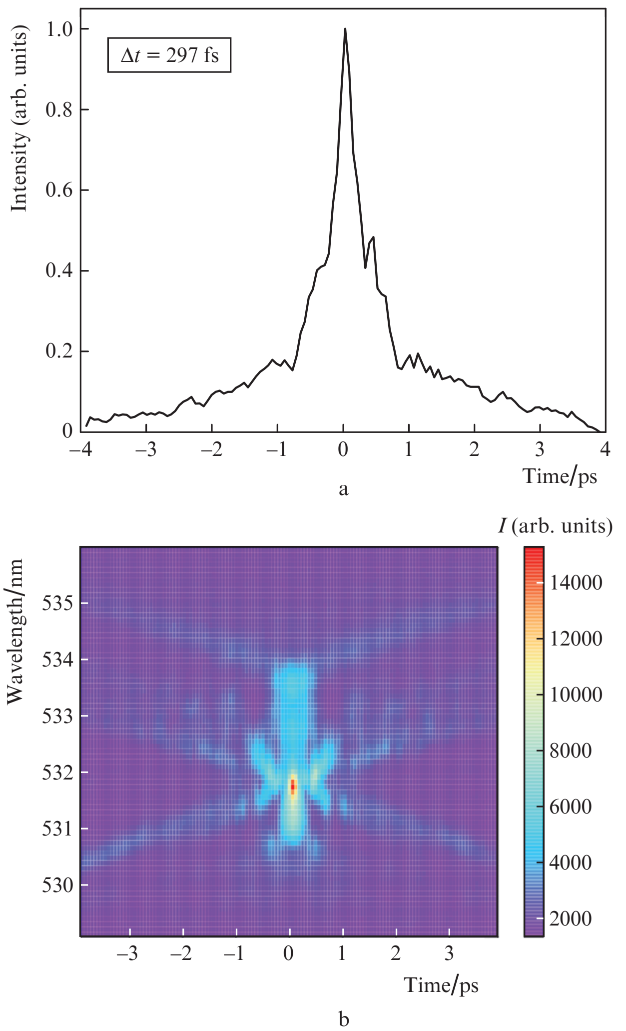

Figure 9. (a) ACF and (b) FROG traces of the pulses compressed after the amplifier.

In contrast to previous studies (see, e.g., [6]), in this work a taper polarisation-maintaining fibre was used, which makes the laser more stable and facilitates the compression of optical pulses. A PM taper was also used in Ref. [7]; however, along with it, a complicated master oscillator design with several stages of preamplifiers was used, and the resulting output pulse energy was ~1 μJ.

4. Conclusions

The paper demonstrated the amplification of highly chirped pulses with a duration of 130 ps and repetition rate of 14.3 MHz to an energy of 2.11 μJ in an all-fibre circuit with a tapered fibre amplifier. With a decrease in the repetition rate to 1 MHz, the energy of the amplified pulses reaches 16.5 μJ, while the spectrum shows no manifestation of the stimulated Raman scattering. Using a double-pass compressor with a pair of diffraction gratings, the pulses were compressed to a duration of about 300 fs. Note that when the signal is amplified, there is some distortion of the spectrum of chirped pulses and an increase in the noise already present at the output of the master oscillator. This leads to an increase in the pedestal in the ACF of the compressed pulse (see Fig. 9). Nevertheless, the achieved characteristics of the laser allow its use for micro-processing, engraving and photomodification of materials, e.g., for recording fibre Bragg gratings in a volume of silica glass [10] or periodic structures on the surface of metals [11].

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