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All-fibre high-energy chirped-pulse laser in the 1 μm range

L.V. Kotov, M.E. Likhachev, M.M. Bubnov, D.S. Lipatov, A.N. Gur'yanov

Abstract. **We report an all-fibre 1030-nm ultrashort (100 ps with the possibility of compression to 430 fs) chirped pulse laser configuration based on a seed oscillator that includes a semiconductor saturable absorber mirror, and demonstrate amplification of its pulses to an energy of 0.6 μJ, with the possibility of pulse compression to 650 fs.**

Keywords: *fibre laser, self-phase modulation, SESAM, femtosecond pulses.*

1. Introduction

Recent years have seen increasing interest in ultrashort pulse (USP) fibre lasers owing to their reliability, efficiency and compactness. USP lasers in the 1 μm range are currently the most attractive in terms of peak and average powers, because the possibility of doping the fibre core with high concentrations of ytterbium allows one to reduce the working length of amplifiers and minimise the influence of nonlinear effects (relative to erbium and thulium USP lasers). Nevertheless, it is the unwanted nonlinear effects in the output amplification stage that impose limitations on the maximum peak power achievable in a fibre amplifier. The amplification of chirped pulses that have a time delay varying linearly with wavelength (linear chirp) due to propagation through a high group velocity dispersion (GVD) medium enables the threshold for nonlinear effects to be considerably raised (by several orders of magnitude). When their duration considerably exceeds that of transform-limited pulses of the same spectral width, chirped pulses can be effectively compressed (e.g. using a grating pair) to the transform-limited pulse duration.

There are several approaches to making such lasers. Note, first of all, schemes that include the generation of femtosecond pulses with a large spectral width, which are then passed through a high-dispersion element.

The best results so far have been obtained by Eidam et al. [1]: stretching femtosecond pulses to a 3 ns duration, followed by amplification in a microstructured fibre and compression to a subpicosecond duration enabled a pulse energy of about 2 mJ and peak power near 3.8 GW to be achieved. However, Eidam et al. [1] used bulk elements (Ti : sapphire seed oscillator, lenses with three-axis positioners, diffraction gratings and others) to generate, compress and stretch pulses and launch them into amplifiers. This approach nullifies the main advantages of fibre lasers – compactness and reliability – and makes such devices difficult to use in practice.

It is worth pointing out that the generation of femtosecond pulses possessing a sufficient spectral width in the 1 μm range and intended for further amplification in fibres presents much more difficulties than that in the longer wavelength range around 1.55 μm [2]. The reason for this is that there are no standard fibres with anomalous GVD in this spectral range, even though such fibres are a necessary component of seed oscillators based on intracavity dispersion management. One can, of course, place bulk elements – prism pairs [3], grating pairs [4] or hollow-core fibre [5] – in a cavity for dispersion compensation, but such configurations have no advantages of all-fibre systems; in particular, they lack reliability.

An alternative approach, attracting more and more interest, is the generation of highly chirped pulses (several tens to hundreds of picoseconds in duration) just at the output of a seed oscillator. However, a stably operating seed oscillator is then difficult to realise, and the problem becomes more severe with increasing chirped pulse duration. The longest pulse duration obtained in such systems to date is 150 ps, with the possibility of pulse compression to 880 fs [6]. At the same time, as pointed out by Kharenko et al. [7, 8] generation in such systems is unstable and only changes in seed oscillator design allow one to achieve stable generation of 30-ps chirped pulses [8].

The next step in the development of this idea was the generation of relatively short chirped pulses and subsequent pulse stretching in a long length of optical fibre. For example, Mukhopadhyay et al. [9] demonstrated an all-fibre amplifier system where pulses were first stretched to 30 ps and then amplified to an energy of ~0.25 μJ. Note that all the above pulsed laser configurations, which ensure the generation of picosecond pulses with a broad spectrum (sufficient for pulse compression to a femtosecond duration), rely on nonlinear polarisation rotation. However, because of the necessity to adjust the polarisation controller, the long-time reliability of such configurations is considerably lower that that of configurations that employ a semiconductor saturable absorber mirror (SESAM).

L.V. Kotov Fiber Optics Research Center, Russian Academy of Sciences, ul. Vavilova 38, 119333 Moscow, Russia; Moscow Institute of Physics and Technology (State University), Institutskii per. 9, 141700 Dolgoprudnyi, Moscow region, Russia;
e-mail: alterlk@yandex.ru;
M.E. Likhachev, M.M. Bubnov Fiber Optics Research Center, Russian Academy of Sciences, ul. Vavilova 38, 119333 Moscow, Russia;
D.S. Lipatov, A.N. Gur'yanov G.G. Devyatykh Institute of Chemistry of High-Purity Substances, Russian Academy of Sciences, ul. Tropinina 49, 603950 Nizhnii Novgorod, Russia

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The purpose of this work was to use an all-fibre SESAM-based seed oscillator for the generation of highly chirped pulses, followed by pulse amplification and compression to a subpicosecond duration. The distinctive feature of this study is the use of commercially available SESAM-based all-fibre systems that are the simplest to implement and ensure the generation of transform-limited picosecond pulses (with a spectral width under 1 nm) at a wavelength of ~1 μm (see e.g. Ref. [10]).

2. Principle of chirped pulse generation

The output of a laser that can serve as a seed oscillator for an amplifier system allowing one to reach high subpicosecond-pulse energies should have a relatively broad spectrum. This will offer the possibility of compressing pulses after amplification to a short duration and reducing the total dispersion needed for obtaining a chirped pulse of long duration. At the same time, as pointed out above the simplest and most reliable 1-μm seed oscillator configurations are SESAM-based systems generating transform-limited pulses several picoseconds in duration.

It is well known that, in the case of transform-limited pulses, a considerable increase in their spectral width and a nearly linear chirp can be ensured through self-phase modulation (SPM), which occurs when relatively short pulses with a relatively high peak power propagate through a nonlinear Kerr medium. In an all-fibre system, the fibre itself can be used as such a medium. For an effective spectral broadening of pulses, the nonlinear length of the fibre should considerably exceed its dispersion length. At the same time, for a subsequent GVD-induced increase in pulse duration, with no additional distortion of the spectrum of the pulse, the opposite relationship should hold: the nonlinear length of the fibre should be shorter than its dispersion length. Generally, both spectral broadening and stretching of a pulse can be performed in a single fibre, but it is then rather difficult to control the chirped pulse duration and obtain pulses of predetermined (long) duration. For this reason, the spectral broadening and stretching processes were separated in this study and took place sequentially, in different fibres.

3. Experimental results

The seed oscillator used was a commercially available all-fibre laser (Fianium) that included an SESAM and generated polarised 11-ps pulses at a repetition rate of 20 MHz and average power of 2.5 mW. The laser emission bandwidth was ~0.1 nm (Fig. 1). To broaden the spectrum through SPM, the average power of the seed laser was increased to 140 mW using two fibre amplifier stages. The core diameter in the single-mode fibres used in the amplifier stages (ytterbium-doped fibres, multiplexers and isolators) was 6 μm, and their total length was ~2.5 m. The fibres used in this and all subsequent stages were polarisation-maintaining. After amplification, the spectrum broadened to ~0.8 nm (Fig. 1). Next, the amplified signal was passed through a 50-m length of fibre with a core diameter of 6 μm, where the pulse bandwidth increased to ~8.5 nm (Fig. 1). The chromatic dispersion D of that fibre and the fibres used to fabricate all the other optical components was –40 ps nm^{-1} km^{-1} at a wavelength of 1030 nm. It is worth noting that, owing to the normal GVD of the fibres, the pulses obtained had a positive chirp and their duration after spectral broadening was 32 ps (Fig. 2). A grating pair ensured compression of those pulses to 430 fs.

To increase the pulse duration, the pulses were then passed through a 250-m length of a single-mode fibre. To reduce the influence of nonlinear effects (i.e. to increase the nonlinear length relative to the dispersion one), the fibre core diameter was increased to 10 μm (chromatic dispersion D = –35 ps nm^{-1} km^{-1}) and the power coupled into the fibre was decreased to 10 mW by laterally displacing the fibre cores relative to each other at the fusion splice. Next, the average pulse power was again amplified to ~100 mW. The output pulse duration was ~100 ps, the emission spectrum of the pulses was almost unchanged, and the pulses could also be compressed to 430 fs (Fig. 3).

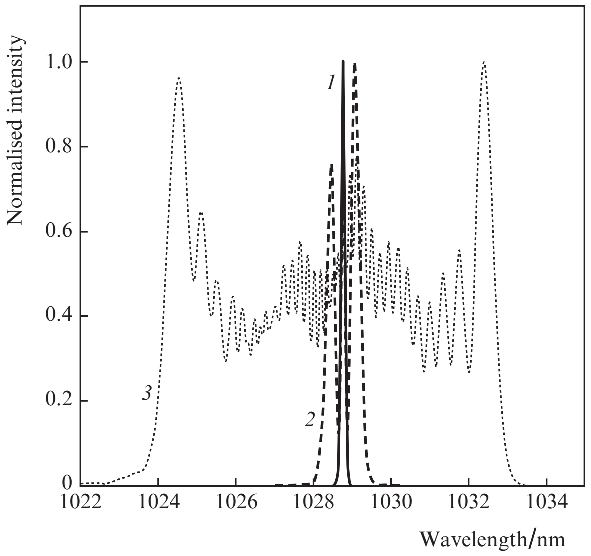

Figure 1. Spectra of the (*1*) picosecond laser output, (*2*) amplified emission and (*3*) amplified emission after spectral broadening.

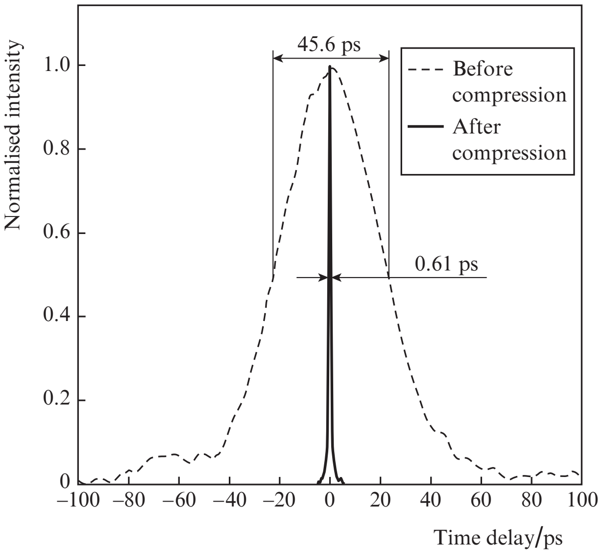

Figure 2. Intensity autocorrelation traces of spectrally broadened pulses before and after compression by a grating pair. The pulse duration is $\Delta\tau = 45.6/1.41 = 32.3$ ps before compression and $\Delta\tau = 0.6/1.41 = 0.43$ ps after compression.

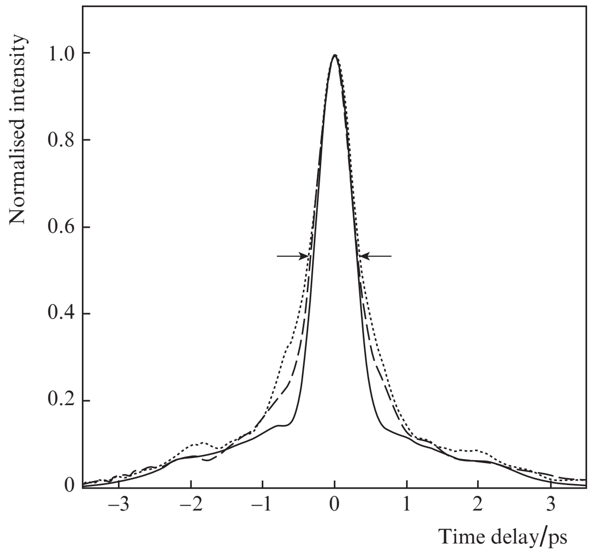

Figure 3. Intensity autocorrelation traces of pulses before the AOM (solid curve, $f = 20$ MHz, $\Delta\tau = 0.61/1.41 = 0.43$ ps) and behind it (long-dashed curve, $f = 20$ MHz, $\Delta\tau = 0.61/1.41 = 0.43$ ps; short-dashed curve, $f = 1$ MHz, $\Delta\tau = 0.76/1.41 = 0.54$ ps).

To control the pulse repetition rate, we used an acousto-optic modulator (AOM) with an additional amplifier stage behind it (to compensate the losses in the AOM and at the fusion splices). The AOM enabled the pulse repetition rate to be varied in the range 50 kHz to 20 MHz. The average power at the amplifier output was ~40 mW at a pulse repetition rate of 20 MHz and 5 mW at 50 kHz. The intensity autocorrelation traces of a compressed pulse behind the AOM at 20 and 1 MHz are presented in Fig. 3.

In the output amplifier stage, the fibre was pumped through the first reflective cladding by the multimode 976-nm output of a diode laser. Chirped pulses with a repetition rate of 1 MHz and the pump beam were coupled through a fibre coupler into an ytterbium-doped fibre (core and cladding diameters of 25 and 250 μm, $D = -30$ ps nm^{-1} km^{-1}, length of 0.7 m), where the pulses were amplified to an average power of 0.6 W, which corresponded to a pulse energy of 0.6 μJ. The diode pump power was 3.5 W. The spectrum and autocorrelation trace of a compressed pulse are presented in Fig. 4. At higher pump powers, the spectrum was substantially distorted by nonlinear effects and amplified pulses could not be compressed.

4. Conclusions

We have proposed and demonstrated a new technique for the generation of USPs with a large linear chirp for high-pulse-energy, subpicosecond lasers. The technique uses a simple, reliable (due to an SESAM) seed source of transform-limited picosecond pulses. We have created an all-fibre source of ~100-ps chirped pulses of 0.6 μJ energy with the possibility of pulse compression to 650 fs by a grating pair. Note that the chirped pulse duration obtained by us (100 ps) is not a limit: it is only determined by the performance of the instruments used, namely, by the range of the autocorrelator and the width of the diffraction gratings. Therefore, the pulse energy obtained (0.6 μJ) is not a limit and can be raised by using longer chirped pulses.

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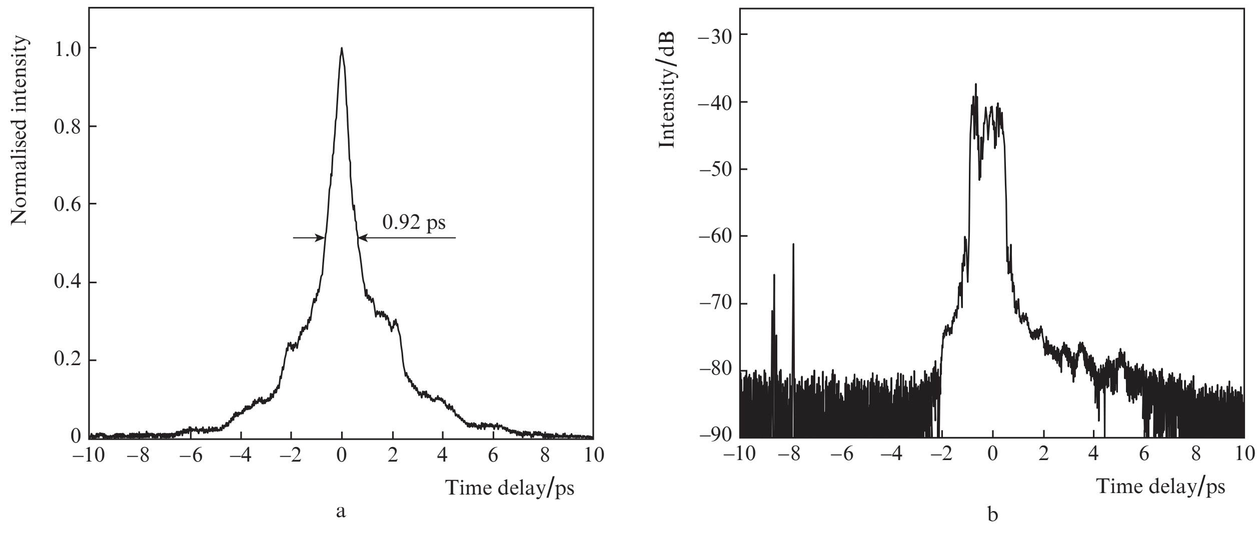

a

b

Figure 4. (a) Intensity autocorrelation trace and (b) emission spectrum of amplified compressed pulses. Pulse duration $\Delta\tau = 0.92/1.41 = 0.65$ ps.

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