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Generation and subsequent amplification of few-cycle femtosecond pulses from a picosecond pump laser

I.B. Mukhin, I.I. Kuznetsov, O.V. Palashov

Abstract. **Using a new approach, in which generation of femtosecond pulses as short as a few field cycles is implemented directly from the radiation of a picosecond pump laser, pulses with the microjoule energy, the repetition rate 10 kHz, and the duration less than 26 fs are generated in the spectral range 1.3 – 1.4 μm. In the process of generating this radiation, use was made of a method providing passive phase stabilisation of the carrier oscillation of the electromagnetic field and its slow envelope. The radiation spectrum was converted into the range of parametric amplification in the BBO crystal by the broadband second harmonic generation; the pulse was parametrically amplified up to the microjoule level and compressed by chirped mirrors to a duration of 28 fs.**

Keywords: *femtosecond pulses, supercontinuum generation, passive phase stabilisation, parametric amplification.*

1. Introduction

The construction of terawatt and petawatt femtosecond lasers is one of the most demanded activities in laser physics. The set of parameters important for their practical use includes the pulse repetition rate, efficiency, stability, contrast, etc. Many of the parameters are determined by the combination of characteristics of the pump laser and the source of femtosecond radiation. For example, their optical locking allows a significant increase in the stability of a high-power femtosecond laser, and the phase stabilisation between the electromagnetic field oscillation and its slow envelope is important for the generation of secondary radiation. The radiation bandwidth of a femtosecond source determines the minimal possible duration and, correspondingly, the maximal peak power, and the thermal effects in the pump laser restrict the pulse repetition rate in a high-power femtosecond laser.

In Refs [1 – 3], a new design of high-power femtosecond lasers based on a relatively broad gain band of ytterbium lasers is proposed and implemented. According to the new approach, femtosecond pulses are directly produced from picosecond laser radiation by generating a supercontinuum with a sufficiently broad band due to the short duration of the initial signal. Then, after subsequent parametric conversions, appropriate spectral components of the supercontinuum are amplified, and generation of a difference frequency allows one to obtain the radiation with passive locking of the envelope phase of the electromagnetic field [4]. In Ref. [1], the supercontinuum generation was implemented using relatively short pulses (350 fs using additional regenerative amplifier with the active Yb:KYW element). The parametric amplifiers were pumped by Nd:YAG lasers with a pulse duration of 50 ps. In Ref. [3], long (800 fs) pulses directly from a high-power picosecond disk laser were used to generate the supercontinuum. The second approach significantly simplifies the signal-pump optical locking, thus allowing the use of picosecond pumping and stretching/compression of femtosecond pulses by chirped mirrors; however, it restricts the spectral composition of the generated supercontinuum. Therefore, to generate the supercontinuum, the authors of Ref. [3] used additional generation of a cross-polarised pulse having a duration of 466 fs.

The present paper combines the main ideas of Refs [1, 3], which demonstrated the possibility of generating broadband radiation in the near-IR range (700 – 900 nm) using the method of passive phase stabilisation of the electromagnetic field and its slow envelope directly by a picosecond pulse of the pump laser. In the first part of the paper we present the results of measuring the characteristics of the supercontinuum generated from the radiation of a picosecond laser with a Yb:YAG crystal final amplifier. The next part contains the description of the optical scheme and the results on the difference frequency generation using the radiation of the supercontinuum and pump source. In the last part of the paper we present the results on the parametric amplification of the second harmonic of the difference frequency up to the submicrojoule energy.

2. Supercontinuum generation using a picosecond pump laser

A schematic of the developed laser setup is presented in Fig. 1. As a source of radiation, we used a fibre subpicosecond laser (FPL) with the output energy above 1 μJ and the pulse repetition rate 3 MHz. The signal at the output of the fibre laser was stretched up to the duration of 50 ps, the spectral width being 8 nm at the centre wavelength 1030 nm. By means of a Pockels cell (PC) with the frequency 10 kHz, two pulses were sequentially cut from the pulse train. The first pulse was used for amplification in the hybrid laser system with the disk final amplifier [5], and the second pulse, following nearly in 300 ns (which is necessary to compensate for a greater optical path length in the high-power laser under the optical locking) served as a trigger signal for the femtosecond part of the setup. The trigger signal was amplified in the four-pass amplifier with the active element in the form of a thin rod [6] of

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I.B. Mukhin, I.I. Kuznetsov, O.V. Palashov Institute of Applied Physics, Russian Academy of Sciences, ul. Ul'yanova 46, 603950 Nizhny Novgorod, Russia; e-mail: mib_1982@mail.ru

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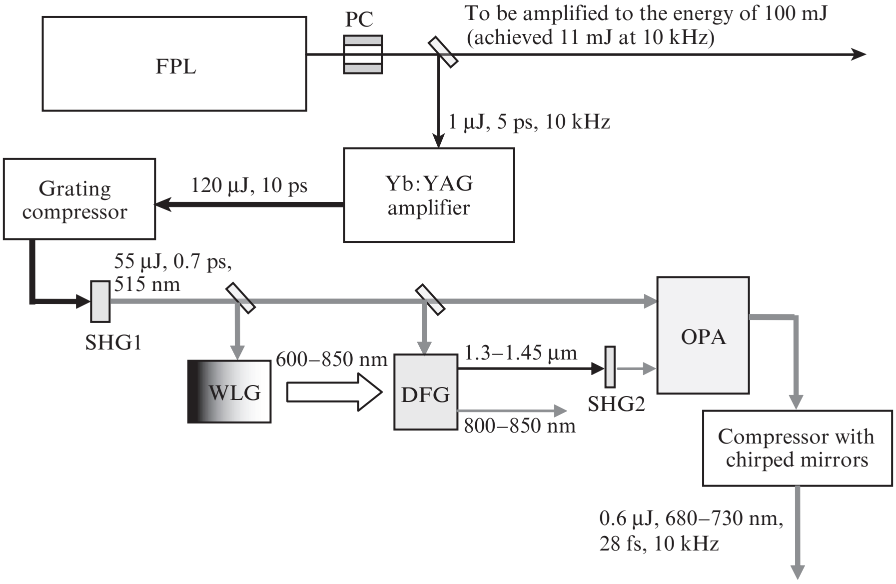


Figure 1. Schematic of the developed laser setup with the indication of achieved radiation characteristics.

yttrium aluminium garnet (Yb:YAG) to the energy of $\sim$120 μJ with the spectrum narrowing to about 1.5 nm, and then compressed by a grating compressor to a duration of 0.9 ps. The pulse duration was measured by a scanning autocorrelator, based on the non-collinear second harmonic generation. The root-mean-square deviation of the pulse energy amounted to 2.5%.

In the present paper, one of the key moments in the implementation of few-cycle femtosecond pulses is the generation of the difference frequency between the signal at the carrier wavelength and the radiation of the supercontinuum produced by this signal. This approach provides passive phase stabilisation between the carrier electromagnetic field and its slow envelope (carrier-envelope phase (CEP) stabilisation [4]), which is an important advantage for many applications. It is also necessary to keep in mind that the majority of high-power femtosecond lasers operate in the near-IR range (in particular, because of the availability of pump lasers providing a sufficiently high power). Therefore, to avoid the transfer of difference frequency generation to the mid-IR range, the amplified and 'compressed' signal is converted into a pulse at the wavelength of the second harmonic (SHG1 in Fig. 1). The energy of the second harmonic radiation pulse amounted to 55 μJ. This signal is divided into three parts and used both for the supercontinuum generation and for further parametric conversion of the radiation.

Part of the second harmonic signal ($\sim$5 μJ) is used to generate the supercontinuum in the YAG crystal (the WLG unit in Fig. 1). To this end, the signal beam with the diameter 2 mm (at the intensity half-maximum) is focused using the spherical mirror (f = 15 cm), and then, after the supercontinuum generation, collimated using the mirror with f = 5 cm. The pulse energy of the supercontinuum radiation amounted to 2 μJ with the root-mean-square deviation of 3.7%, and the spectral width of the long-wavelength part of the supercontinuum varied from 515 to 850 nm (Fig. 2). Note that in Ref [1] the supercontinuum spectrum of similar width was generated using a signal with the duration $\sim$300 fs, and in Ref. [3] the spectral width of the long-wavelength part of the supercontinuum was within the range 515–770 nm, the pulse duration being 460 fs. The wide supercontinuum generation band was achieved due to the careful choice of the pulse energy and the beam diameter of the second harmonic signal, as well as due to the choice of the focal length of the mirror for the give crystal length, which is in good agreement with the results of Ref. [7].

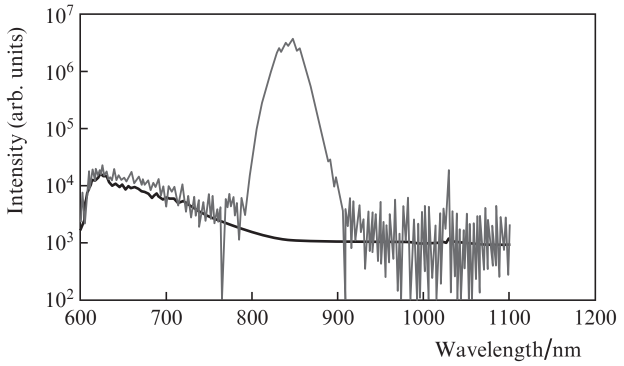


Figure 2. Long-wavelength part of the supercontinuum radiation spectrum before (black curve) and after (grey curve) parametric amplification for the difference frequency generation.

3. Generation of difference frequency in BBO crystal

For CEP stabilisation, the supercontinuum signal parametrically interacts with part of the pump signal (20 μJ) to generate the difference frequency (DFG unit in Fig. 1). The beams of supercontinuum and second harmonic radiation are superposed at a dichroic mirror and collinearly focused into the BBO crystal by means of a silver mirror (f = 17.5 cm) to provide their coupling under the matching condition of the first type. A delay line provides the temporal coincidence of the two beams. The thickness of the BBO crystal with the orientation $\theta = 23.4^\circ$, $\varphi = 90^\circ$ amounts to 4 mm; with respect to the incident radiation, the nonlinear crystal is tuned to provide the efficient parametric amplification in the range 800–900 nm. For additional broadening of the radiation spectrum at the difference frequency, the nonlinear crystal was passed twice with a small difference of the angles of incidence (~2°). This approach allowed the generation of the radiation at the difference frequency in the range 1250–1450 nm (Fig. 3), as well as the significant increase in the pulse energy due to more efficient conversion, the supercontinuum signal in the range 800–900 nm being rather weak. After the radiation filtering with an IR filter, the pulse energy at the difference frequency amounted to 2 μJ.

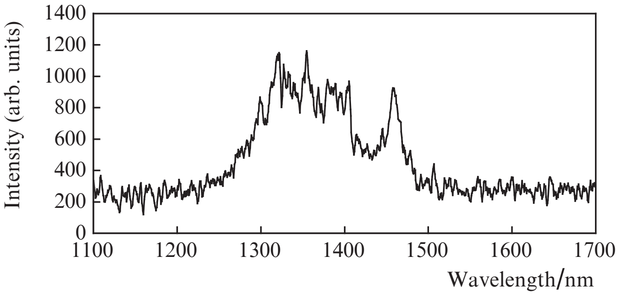
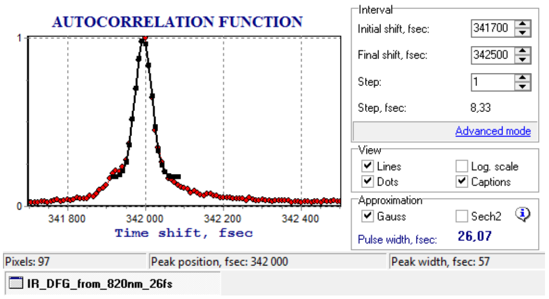


Figure 3. Spectrum of difference-frequency radiation.

We also measured the pulse duration by a scanning autocorrelator that operates based on the noncollinear second harmonic generation. The minimal step of the autocorrelator was equal to 8.3 fs; a 0.2-mm-thick KDP crystal was used for the measurements. Unfortunately, the resolution of the autocorrelator does not allow precision measurement of the pulse duration in the range of a few field cycles (10 fs and less). However, it allows durations greater than 20 fs to be estimated with good accuracy. At the output of the difference-frequency generator, the pulse duration amounted to 96 fs, which is explained by the presence of a minor chirp in the signal. By adding a fused silica etalon having the optimal thickness (2 cm) to the optical path, it was possible to compress the pulse to a duration of 26 fs (Fig. 4), which is close to the transform-limited pulse duration (see Fig. 3).



Interval
Initial shift, fsec: 341700
Final shift, fsec: 342500
Step: 1
Step, fsec: 8,33

View
☑ Lines ☐ Log. scale
☑ Dots ☑ Captions

Approximation
☑ Gauss ☐ Sech2
Pulse width, fsec: 26,07

Pixels: 97 | Peak position, fsec: 342 000 | Peak width, fsec: 57

IR_DFG_from_820nm_26fs

Figure 4. Autocorrelation function and difference-frequency signal duration after the compression (autocorrelator software screenshot).

4. Parametric amplification of the second harmonic of the difference-frequency radiation

In Ref. [1], the difference-frequency radiation was converted to the near-IR range by one more stage to generate the supercontinuum from the difference-frequency pulse. This method allows one to provide very broadband radiation (more than an octave), but the efficiency of this conversion is rather small. Moreover, in high-power multiterawatt laser systems the spectral width of the amplified femtosecond radiation amounts to a few tens of nanometres and rarely exceeds 200–300 nm. In the present paper, we propose and implement an alternative approach that allows much more efficient conversion of the difference frequency into the near-IR range using the second harmonic generation (SHG).

Figure 5 presents the spectral distributions of the second harmonic radiation measured at the output of a 1-mm-thick BBO crystal. Note that by tuning the crystal generating the difference frequency (DFG unit) and the BBO crystal providing the second harmonic of this frequency one can vary both the centre wavelength and the bandwidth of the radiation in the range of more than 100 nm (grey curve in Fig. 5), which is enough for many high-power laser systems. Even a wider radiation bandwidth can be obtained using the noncollinear generation of the difference frequency, as shown in Ref. [3]. In the present paper, the wavelengths in the DFG and SHG2 units are chosen to provide the best visualisation of radiation and the highest quantum efficiency.

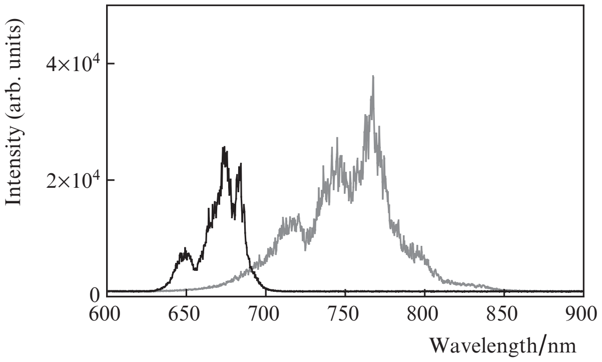


Figure 5. Spectral distributions for the signal of the second harmonic of the difference frequency radiation for two different tunings of nonlinear crystals, providing the difference frequency and second harmonic generation.

The signal of the second harmonic of the difference frequency radiation is further amplified parametrically using the remaining part of the pump radiation (OPA unit in Fig. 1). The interacting beams are focused into the BBO crystal using the silver mirror ($f = 15$ cm) at the angle ~3° for noncollinear parametric amplification with type I phase-matching. The delay line provides the temporal coincidence of two beams. The thickness of the BBO crystal with the orientation $\theta = 23.4°$, $\varphi = 90°$ amounts to 1 mm. The nonlinear crystal is tuned with respect to the incident radiation to provide the efficient parametric amplification in the range 600–800 nm. The spectrum of the second harmonic radiation is close to the one shown in Fig. 5 (black curve). To increase the conversion efficiency, two passes through the nonlinear crystal are organised with a small difference of angles of incidence (~0.5°) in the non-sensitive plane, which allowed the pulse to be amplified to the energy 0.6 μJ with the spectral distribution presented in Fig. 6. Note that the root-mean-square deviation of the pulse energy amounted to 6%, and the transverse distribution of the beam intensity was close to the Gaussian one.

The pulse duration was measured using the scanning autocorrelator mentioned above. The pulse duration at the

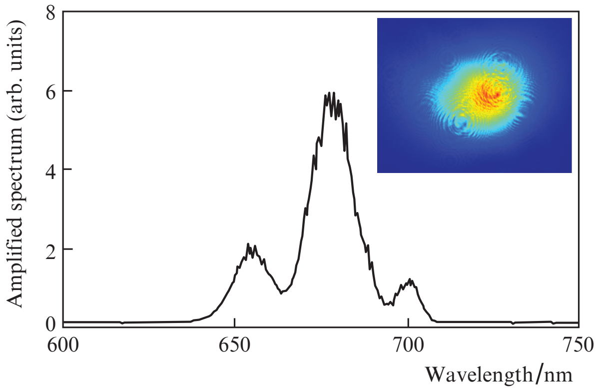


Figure 6. Spectral distribution of the signal of the second harmonic of the difference frequency after parametric amplification. The inset shows the transverse distribution of intensity of the amplified beam.

output of the parametric amplifier amounted to 144 fs (in the presence of positive chirp). Therefore, after the parametric amplification the signal was directed to the compressor based on a couple of chirped mirrors with the dispersion 100 fs^2. Figure 7 presents the dependence of the pulse duration on the number of reflections from the chirped mirrors. The minimal pulse duration amounted to 28 fs (Fig. 8), which is close to the duration of a bandwidth-limited pulse (see Fig. 6).

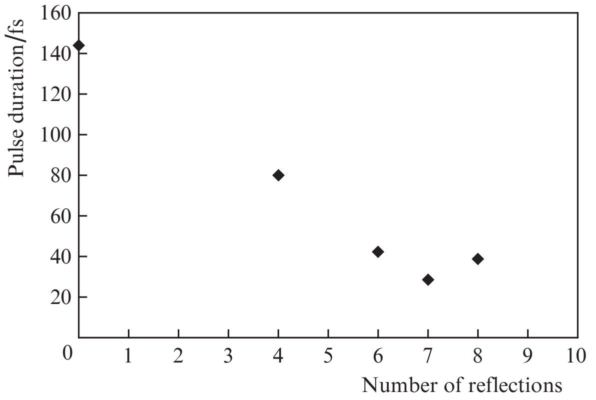
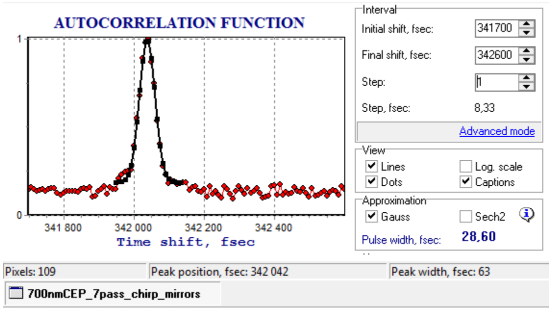


Figure 7. Dependence of the output pulse duration on the number of reflections from the chirped mirrors.



Interval
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View
☑ Lines ☐ Log. scale
☑ Dots ☑ Captions

Approximation
☑ Gauss ☐ Sech2
Pulse width, fsec: 28,60

Pixels: 109 | Peak position, fsec: 342 042 | Peak width, fsec: 63

700nmCEP_7pass_chirp_mirrors

Figure 8. Autocorrelation function and duration of the output signal after the compressor (autocorrelation software screenshot).

5. Conclusions

We present the results of developing the front-end part of a multiterawatt laser system with a high (units of kilohertz) repetition rate of laser pulses. Based on a new approach to the generation of few-cycle femtosecond pulses directly from the radiation of a picosecond pump laser, we obtained the radiation of the microjoule pulse energy with the pulse repetition rate 10 kHz and the duration less than 30 fs in different spectral regions. To this end, we implemented the method of passive carrier-envelope phase stabilisation. The possibility of broadband generation of the supercontinuum from picosecond laser pulses was experimentally demonstrated, and the alternative method of converting the difference-frequency radiation into the range 600–1000 nm 'traditional' for femtosecond lasers by means of second harmonic generation was implemented.

The optical quality of the laser beam at the output is close to the diffraction-limited one, and the stability of energy from pulse to pulse is within 6%, mainly determined by the stability of the thin rod amplifier pump. The developed laser system with the microjoule pulse energy can be used for research purposes in ultrafast laser spectroscopy, and, after a planned further increase in power, also for the high-order harmonic generation. As the next step, the present signal is planned to be parametrically amplified up to submillijoule energies using the pump from a picosecond laser with the pulse energy 10 mJ, optically synchronised with the developed femtosecond system.

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