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Formation and amplification of 50-ps pulses in a THL-100 hybrid laser system

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Abstract. **Results of investigations of a THL-100 visible hybrid laser system consisting of a Ti : sapphire front end and a photodissociation XeF(C – A) amplifier are reported. The front end generates linearly chirped second harmonic pulses with a duration of 50 ps, an energy up to 5 mJ, and a high beam quality. Saturation of the XeF(C – A) amplifier at an input energy exceeding 2 mJ is demonstrated, and the output energy of 3.2 J is obtained, which makes it possible to achieve a peak power of about 50 TW in a 50-fs pulse.**

Keywords: *hybrid femtosecond system, XeF(C – A) amplifier, second harmonic generation, visible spectral region.*

1. Introduction

At present, multiterawatt and petawatt laser systems are developed based mainly on solid-state Ti : sapphire or parametric amplifiers and on amplification of positively chirped pulses, i.e., pulses stretched in time to a duration of 0.5 – 1 ns by linear frequency modulation [1]. These systems operate in the IR spectral region (0.8 – 1 μm). Expansion of the spectral range of these systems allows one to extend the field of their application and, in some cases, may increase the efficiency of femtosecond radiation – matter interaction [2, 3]. A known way to advance into the visible and UV spectral regions is the generation of the second and third harmonics of IR radiation. Unfortunately, the possibility of conversion of ultra-high-power IR beams to these spectral regions is restricted by technological problems of fabricating thin (thinner than 1 mm) nonlinear crystals with sufficiently large diameters (larger than 10 cm), which are needed to overcome the problems related to the broad spectrum and high intensity of femtosecond radiation [4]. The 4-TW power of the second harmonic (400 nm) of a Ti : sapphire laser achieved ten years ago [5] still remains maximum for this method.

An alternative way to obtain multiterawatt laser beams in the visible region is the hybrid approach to the design of femtosecond systems, which is presently being developed at the Lebedev Physics Institute (Moscow) and the Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences (Tomsk) based on THL-30 and THL-100 hybrid laser systems, respectively [3, 6 – 13]. These systems include solid-state and gaseous active media, namely, a Ti : sapphire femtosecond front end and a photodissociation XeF(C – A) amplifier. A THL-100 pulse power of 14 TW, which is record-high for the visible region, has already been obtained [3, 8 – 11], and there exists a possibility of increasing this power to 50 – 100 TW with a high time contrast (10^{12} – 10^{13}) [14].

These laser systems can in principle operate with the use of two optical schemes. The first one is based on amplification of a negatively chirped picosecond pulse in a gas amplifier and subsequent time compression in bulk glass. The possibility of using this scheme arises from the comparatively low optical nonlinearity of the medium of the used gas amplifier of picosecond pulses. This approach used in experiments yielded a 14-TW peak power of THL-100 femtosecond system [3, 8 – 11], in which a negative chirp of the pulse injected in the gas amplifier was formed using a prism pair. Further development of this approach in order to achieve higher peak powers requires using chirped (Bragg) mirrors both at the early stage of negative chirping of the injected pulse and in combination with recompression in the bulk glass to reduce the laser beam self-action.

Another possible scheme of hybrid systems is based on the traditional approach to amplification of positively chirped subnanosecond pulses with subsequent chirp suppression in a diffraction grating compressor. It is this approach that is used in the present paper to form a linearly chirped pulse of the second harmonic of the Ti : sapphire front end (470 nm) and amplify it in the rear-end XeF(C – A) amplifier of the THL-100 femtosecond system.

2. Experimental

The THL-100 laser system includes a Start-480M femtosecond Ti : sapphire front end (Avesta Project) and a photodissociation XeF(C – A) amplifier developed and fabricated at the Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences in cooperation with the P.N. Lebedev Physics Institute, Russian Academy of Sciences. The facility used in this study consisted of a Ti : sapphire femtosecond master oscillator pumped by a 532-nm cw pump laser (Verdi-8), a grating stretcher, a regenerative and two multi-

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pass amplifiers pumped by 532-nm repetitively pulsed lasers, and a second harmonic generator based on a 2-mm-thick type-I KDP crystal.

In the conventional scheme of a Start-480M front end system, a nonlinear crystal generates the second harmonic of transform-limited 50-fs pulses after the grating compressor [3, 6–13]. In the present work, the 940-nm radiation amplified in multipass amplifiers fell on the nonlinear crystal by passing through the compressor. In this case, the first harmonic pulses had an energy up to 50 mJ, a duration (FWHM) of 100 ps, and a spectral width corresponding to transform-limited pulses with a duration of 50 fs. The laser beam diameter at e^{-2} of intensity maximum was 3.7 mm. After the second harmonic generation, the beam was expanded in diameter by a mirror telescope and injected to the XeF(C–A) amplifier. At the same time, the beam had a small angle of divergence for the geometric matching with the multipass scheme of the amplifier (see below).

The XeF(C–A) amplifier, which was described in detail in [7, 9, 10, 13], is excited by the VUV radiation of an electron-beam converter, which converts the electron-beam energy to xenon radiation at a wavelength of 172 nm. This radiation is injected into a laser cell through CaF_2 windows and causes photodissociation of XeF_2 vapours with the formation of the excited state XeF(C). Amplification occurs during 33 passes through the active medium of the amplifier due to the reflection from 32 mirrors with gradually increasing diameters, which are placed inside the laser chamber cell over the perimeter of its inner flanges. The beam makes two roundtrips over the inner perimeter of the laser cell. The reflection coefficient of the mirrors is 99.5%–99.7%. To reduce the effect of the beam diffraction at the edges of mirrors, we placed at the entrance to the amplifier a serrated aperture with an inner diameter of 13 mm and the tooth height-to-pitch ratio $h/d = 6$, which cut off the central part of the Gaussian beam at the level e^{-2} and led to a sharper decrease in intensity at the beam edges. The injected laser beam, as was mentioned above, had a small divergence angle, because of which it steadily increased in diameter from 15 mm at the entrance to 60 mm at the penultimate mirror. The penultimate convex mirror (R = 5 m) directed the beam to a plane mirror 100 mm in diameter placed on the optical axis. After reflection from this mirror, the beam propagated along the optical axis of the cell and was coupled out having a diameter of 120 mm and a divergence angle of 24 mrad. The experimental optical scheme is shown in Fig. 1.

The output beam was focused by a lens and incident on a fused silica wedge. The beam diameter on the wedge was 2.5 cm. The beam energy of the reflected from one face of the wedge was recorded by an OPHIR energy meter. A footprint of the laser beam was recorded on photographic paper behind the wedge. All measurements were performed in the first pulse in a new gas mixture, because the active medium gain in the second pulse decreased by approximately 20% due to decomposition of XeF_2.

The second harmonic energy was measured by a Gentec energy meter using two selective mirrors with a maximum reflection in the region of 475 nm to suppress the first harmonic. The duration and spectrum of the positively chirped first and second harmonic pulses at the exit from the front end were measured using a Hamamatsu C10910 streak camera with a time resolution better than 1 ps equipped with a Spectra-Pro spectrograph (wavelength range 200–1200 nm, spectral resolution 0.1 nm).

3. Experimental results and discussion

Figure 2 shows a dependence of the energy efficiency of fundamental-to-second harmonic conversion in the front end on intensity. The conversion efficiency within the region of working intensities, which do not exceed 12 GW cm^{-2}, reached 12%, which allowed us to achieve a pulse energy up to 5 mJ at

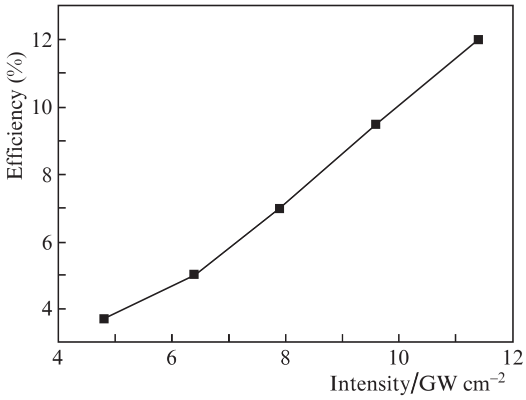

Figure 2. Dependence of the energy efficiency of the front end fundamental frequency conversion to the second harmonic on the intensity.

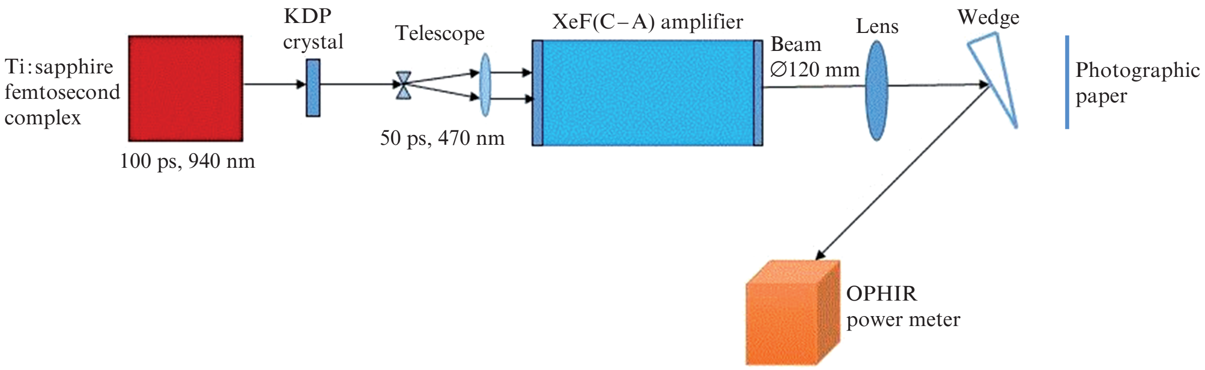

Figure 1. Optical scheme of the experiment.

the second harmonic wavelength. It is necessary to note that, in the conventional scheme of the femtosecond front end Start-480M, the efficiency of conversion of 50-fs transform-limited pulses to the second harmonic is 35 %–40 % at an intensity of 0.5 TW cm^{-2}. The decrease in the chirped pulse conversion efficiency is a 'payment' for in the high homogeneity of the second harmonic beam. Figure 3 presents the second harmonic beam profiles recorded in the femtosecond and subnanosecond regimes at intensities of about 0.5 TW cm^{-2} and 10 GW cm^{-2}, respectively. The cubic polarisation of the nonlinear crystal leads to a degradation of the beam quality at high intensities typical for the femtosecond regime, and almost does not affect the beam quality in the second regime. The beam quality degradation in the femtosecond regime requires spatial filtration of the beam after the nonlinear crystal. The weak effect of the cubic nonlinearity in the case of a long pulse allows one to retain the linear chirp of the pulse at the second harmonic wavelength, which is seen from the spectral-time scan of the beam intensity shown in Fig. 4. Note that the spectral width corresponded to the 50-fs duration of the transform-limited second harmonic pulse. The second harmonic pulse FWHM was 50 ps at the fundamental harmonic pulse duration of 100 ps (Fig. 5).

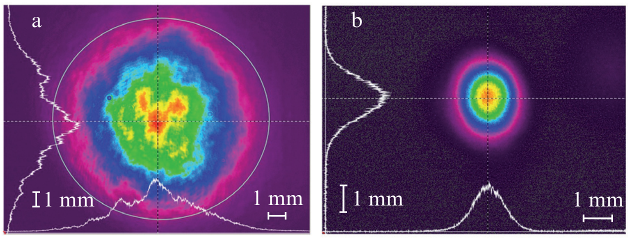

Figure 3. Profiles of the second harmonic beams recorded in (a) femtosecond and (b) subnanosecond regimes at intensities of about 0.5 TW cm^{-2} and 10 GW cm^{-2}, respectively.

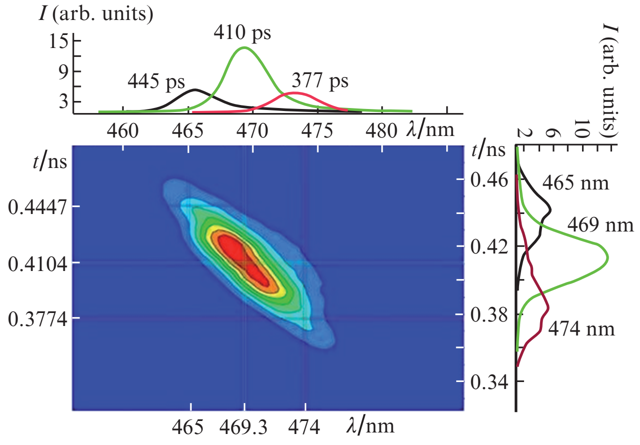

Figure 4. Spectral-time scan of the beam intensity.

The generated second harmonic pulse was amplified in the XeF(C–A) amplifier, whose laser chamber was filled with a mixture $N_2 : XeF_2 = 0.5$ atm : 0.2 Torr. The pulse energy at the entrance to the amplifier varied from 2 to 3.5 mJ, but the output amplifier energy remained almost unchanged and reached 3.2 J. A laser beam spot on photographic paper is presented in Fig. 6.

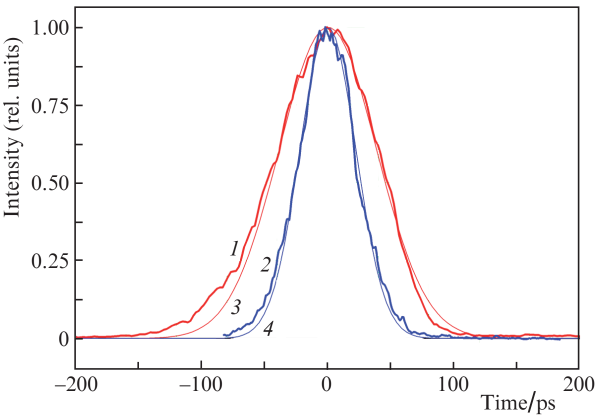

Figure 5. (*1*) First and (*2*) second harmonic pulses and their approximation by the Gaussian functions (*3*) $\exp(-x^2/3000)$ and (*4*) $\exp(-x^2/1000)$, respectively.

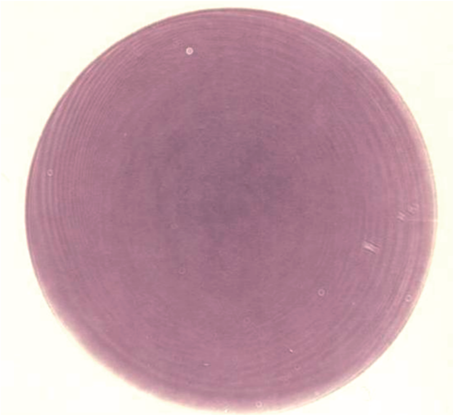

Figure 6. Footprint of a laser beam with an energy of 3.2 J.

The obtained energies well agree with the calculated results. Figure 7 shows the calculated dependence of the output amplifier energy on the injected signal energy and the experimental output energies achieved at different injected pulse energies. The calculations were performed based on the

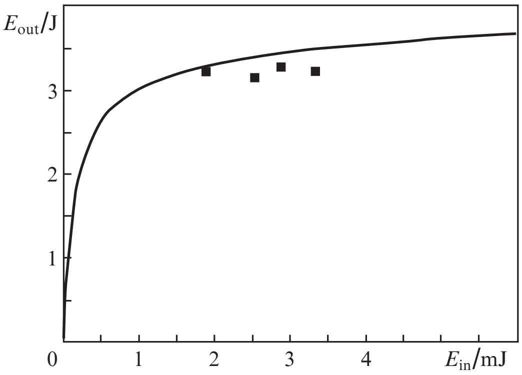

Figure 7. Calculated (curve) and experimental (points) dependences of the output energy of the XeF(C–A) amplifier on the incident energy for $N_2 : XeF_2 = 380 : 0.2$ Torr and $E_{VUV} = 270$ J.

active medium model described in [9]. The difference between the calculated curve shown in Fig. 7 and the dependence obtained in [9] is caused by the fact that the upgrade of the electron-beam converter described in detail in later work [13] allowed us to increase the total small-signal gain in the multipass amplifier by an order of magnitude, i.e., to $(5-6)\times10^4$ [3]. The calculated and experimental data presented in Fig. 7 indicate the possibility of a considerably decrease in the input saturation energy of the XeF(C–A) amplifier, which allows one to manipulate with the input beam so that its profile was super-Gaussian and to broaden the spectrum of the femtosecond pulse to decrease its duration.

4. Conclusions

Thus, we have found a regime of second harmonic generation in the Ti:sapphire front end of the THL-100 hybrid femtosecond system which allows one to form a linearly chirped subnanosecond pulse with a high beam quality at the entrance to the XeF(C–A) amplifier. It was experimentally and theoretically shown that, despite a comparatively low second harmonic generation efficiency (below 12%) at the used fundamental harmonic intensities, the second harmonic pulse energy considerably exceeds 1–2 mJ required for saturation of the XeF(C–A) amplifier. The obtained results make it possible to develop a scheme with an output compressor based on diffraction gratings with aluminium or silver coatings having a high reflection coefficient in the visible region. At present, these gratings with dimensions of 154 × 206 mm and an efficiency in the first diffraction order of 90% and higher are commercially available. It should be noted that a similar scheme was successfully used for the first time in [15], in which a pulse of the second harmonic of a chirped pulse of a Ti : sapphire system was compressed to 26 fs in a grating compressor.

The output pulse energy of 3.2 J experimentally achieved in the present work indicates that the peak power of the THL-100 system can reach approximately 50 TW in the case of the amplified pulse compression to a duration of 50 fs.

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