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Terawatt femtosecond Ti:sapphire laser system

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Abstract. **A terawatt femtosecond laser system based on a most promising at present broadband laser medium, Ti-doped sapphire, is created. The system produces 80-fs pulses with energy of 80 mJ and a repetition rate of 10 Hz. The first applications of the laser system demonstrated in the paper are the formation of extended channels with the aspect ratio $\sim 10^4$ upon axicon focusing of laser radiation in transparent dielectrics and transformation of the pulse spectrum during propagation of the pulse in gas-filled low-pressure capillaries.**

Keywords: *femtosecond light pulse, terawatt laser system, superstrong electromagnetic fields.*

In the last decade one of the most interesting fields in modern physics has emerged – the study of the interaction of superstrong optical fields with matter during ultrashort time intervals. Progress in this field was mainly achieved due to the creation of compact terawatt femtosecond laser systems based on solid-state broadband active media Ti : Al_2O_3 (or Ti : sapphire). These laser systems are becoming an experimental basis for the development of new studies and applications in atomic physics, thermonuclear research, the physics of charged-particle accelerators, precision material machining, and for investigations of ultrashort-pulse sources and X-ray and UV lasers.

At present, there are several femtosecond laser systems world-wide that provide a peak pulse power of more than 10^{13} W (multiterawatt systems) and the radiation intensity up to 10^{20} W cm^{-2} [1 – 5]. Apart from a significant influence on the development of new scientific fields, the creation of such complexes demonstrates the prestige of a national science and the advanced technology level achieved in the country.

In this paper, we describe briefly a terawatt femtosecond Ti:sapphire laser system created at the Institute of Applied Physics, RAS (Nizhnii Novgorod), which is capable of producing 100-fs laser pulses with energy of $\sim$ 100 mJ, a pulse repetition rate of 10 Hz, and the intensity of focused radiation of 10^{18} W cm^{-2}.

The concept of the laser system design is traditional [6] and consists in the generation of femtosecond laser pulses, their subsequent temporal stretching, amplification of phase-modulated (chirped) wave packets in the system of broadband optical amplifiers, and the final recovery of the initial time profile of the ultrashort light pulse. This principle of producing superstrong optical fields has been used in all laser systems without exception created up to now. The block diagram of such a femtosecond laser system is presented in Ref. [7] and completely reflects the concept described above. Let us discuss briefly the principal elements of this diagram.

A master oscillator represents a passively Kerr mode-locked Ti : sapphire laser. A principal scheme of such an oscillator can be found in many papers devoted to femtosecond lasers (see, for example, [8, 9]). The laser resonator of length $\sim$ 3 m is formed by flat dielectric mirrors between which a pair of concave mirrors are mounted (with a radius of curvature of $\sim$ 100 mm). These mirrors form a misaligned resonator, which is close to a confocal resonator, with a $\sim$ 1-cm long Brewster active element placed at its centre. The flat mirrors (output and highly reflecting mirrors) close the inner 'confocal', forming the laser resonator. A dispersion compensator consisting of two Brewster prisms, separated by a certain distance and mounted with the oppositely directed apexes, is placed near the highly reflecting mirror. The distance between the apexes of the prisms was calculated from the condition of compensation for the second-order dispersion for a 1-cm long active element [10]. The angles between the 'confocal' axis and the beams emerging from it were chosen from the condition of compensation for astigmatism [11] introduced by a plane – parallel plate of the Brewster element.

The femtosecond laser was pumped by spatially single-mode (TEM$_{00q}$ mode) second-harmonic radiation from a cw solid-state laser. This radiation was focused into the active element so that the transverse size of the pump beam in the waist was slightly smaller than the minimum size of the fundamental mode of the laser cavity. The 'confocal' caustic should be made longitudinally coincident with the waist. These conditions are necessary for obtaining the Kerr mode locking in a Ti : sapphire laser.

The cw lasing threshold in our case (for the transmission coefficient of the output mirror equal to 80 % and the 10-mm long active element) was 1.5 – 2 W. The mode-locking threshold was $\sim$ 3 W. The stable generation of femtosecond pulses was observed up to the maximum available power of the pump laser (5.5 W). In this case, the average output power achieved 600 – 700 mW at a pulse repetition rate of $\sim$ 80 MHz and a pulse duration of $\sim$ 80 fs. A passage from the cw to pulsed lasing was achieved by the abrupt trans-

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verse displacement of one of the dispersion compensator prisms. The stable generation of femtosecond pulses persisted for several hours, which allowed us to align the entire optical scheme of the system and perform experiments with the objects under study.

A stretcher is a device that performs a strong (by 3–4 orders of magnitude) temporal stretching of an initial femtosecond pulse due to the phase modulation of a short wave packet propagating through it. In essence, in this device possessing a strong normal dispersion, an ultrashort light pulse acquires a monotonic variation of the carrier frequency within its envelope (chirp). As a result, the envelope of the initial laser pulse elongates, resulting in a decrease in the signal peak power. It is the idea of the amplification of chirped optical pulses, which was first proposed in Ref. [6], that made it possible to build tabletop laser sources for generating superstrong electromagnetic fields.

Diffraction gratings are used as elements with a strong dispersion. There are several designs of the stretcher (see, for example, [12, 13, 14]). However, in our opinion, the most convenient for the alignment and use is a scheme that uses one diffraction grating (1600 lines mm^{-1}, the angle of incidence is close to the autocollimation angle) and an additional flat mirror mounted in the focal plane of a spherical mirror, which reflects the diffracted beam back to the grating where it experiences the secondary diffraction. Apart from the convenience of the alignment, such a stretcher design allows one to exclude large-aperture achromatic lenses, which are used in the traditional scheme, and to use only one grating. The maximum coefficient of the pulse stretching is determined, as is known, by the linear size L of the grating in the diffraction plane. For our scheme (with $L = 100$ mm), this coefficient is 3×10^3, which corresponds to a pulse duration about of 200 ps.

A Faraday isolation performs simultaneously two tasks: it eliminates the reverse effect of the amplifying system on the master oscillator and directs the radiation amplified in a regenerative amplifier to a system of final amplifiers. This system contains an optical permanent magnet Faraday isolator, broadband polarisers, and phase plates for optical rotation.

A regenerative optical amplifier represents a Ti : sapphire laser with the external signal injection, which is pumped by the second harmonic from a repetitively pulsed Nd : YAG laser and has a fast intracavity electrooptical gate (with the switching time on no longer than 2 ns) for extracting a single amplified pulse. An active element used in the regenerator has the same size as that in the femtosecond master oscillator.

The pump laser radiation (with a pulse energy of ~ 10–12 mJ) is focused into the active element so that its transverse size coincides with the size of the fundamental mode of the regenerator cavity. If the input of the regenerative amplifier is blocked (free running regime) and the energy is not extracted from the cavity, the regenerator operates as a usual laser and emits a pulse of duration of several hundreds of nanoseconds. We used this lasing regime for the alignment of all final amplifiers and the object under study.

When a chirped pulse from the stretcher output was delivered to the amplifier input and the gate was switched off, the laser emitted a periodic train of short pulses. The repetition period was determined by the round-trip time of the light pulse in the regenerator cavity (the cavity lengths of the master oscillator and the regenerative amplifier were approximately the same).

The maximum of the envelope of this pulse train in the case of optimal alignment of the signal being amplified shifts by $\Delta t \sim 150 - 200$ ns compared to the pulse maximum in the free running mode. Therefore, the development time of lasing decreases in this case by Δt because lasing occurs from the injected signal level rather than from the quantum fluctuation level, as in the case of free running mode. This allows us to determine experimentally the optimal instant of time for the extraction of the amplified pulse.

An optimal number of round trips of the pulse in the cavity under our conditions was ~ 30, the output energy of the amplified pulse being 1.2–1.5 mJ. Therefore, the energy gain of the regenerative amplifier was approximately 10^6. The transverse structure of the output radiation was completely determined by the fundamental mode of the regenerator cavity, and the laser beam was naturally diffraction limited.

The repetition rate of amplified pulses was determined by the repetition rate of the pump-laser pulses (10 Hz). The regenerative amplifier was controlled by a synchronisation system, which determined the moment of injection of one of the pulses of the periodic pulse train from the femtosecond master oscillator to the regenerator cavity and the moment of its outcoupling after amplification. A train of femtosecond pulses emitted by the master oscillator was used as an internal 'clock' of the synchronisation system. The time instability (jitter) of the moment of outcoupling of an optical pulse amplified in the regenerator relative to the pump pulse was no more than half the repetition period $T \sim 12$ ns. This jitter proved to be quite satisfactory for further amplification of optical pulses in final stages, which were pumped by the second harmonic from the same Nd:YAG laser, because the population inversion lifetime of Ti:sapphire crystals was several microseconds.

Amplifiers for the subsequent amplification of the optical pulse energy were based on four- and three-pass schemes. The active elements were Brewster Ti : sapphire crystals of diameter 10 mm and length 15 mm. The four-pass amplifier was pumped, as mentioned above, by the second harmonic from the same Nd : YAG laser, which was used for pumping the regenerator. Because the spatial structure of radiation from this laser was close to a Gaussian only in the near-field zone, we had to build an optical system for imaging (with the reduction) of this zone on the amplifying element input. This provided a sufficiently smooth spatial distribution of the pump radiation on the input faces of the amplifying crystal, resulting in a substantial decrease in the radiation load.

To further decrease the radiation load at the active element, the pump beam was divided into two beams of approximately equal pulse energies, and both these beams were incident on the amplifier crystal in the opposite directions. The diameters of both beams were chosen so that the energy density at the input surfaces of the element did not exceed 4 J cm^{-2}. This value (according to the literature data and our experience) corresponds to the safe operation of the amplifier in respect of the optical damage. Correspondingly, the cross section of the signal beam being amplified was matched with that of the pump beam using a lens telescope.

The maximum pulse energy did not exceed 50 mJ at the pump energy ~ 200 mJ. Note that the transverse structure of the amplified beam was slightly distorted, resulting in the divergence of the output beam from the four-pass amplifier that exceeded the diffraction-limited divergence approximately by a factor of 1.4.

The final power amplifier was built based on the three-pass scheme. It was pumped with the help of an additional frequency-doubled optical laser system, which produced a smooth spatial radiation distribution in the near-field zone for the 1-J pulse, which was locked to the initial pulse.

To pump the final amplifier crystal, we also used the system for imaging the near-field zone, and, similarly to the previous case, the radiation was incident on the crystal from both its sides. The pump energy density also did not exceed 4 J cm^{-2} and the transverse sizes of the beam being amplified and the pump beam were matched. According to our calculations, the pump energy was sufficient for obtaining the output energy after the final amplifier of $\sim 200-220$ mJ, however, we obtained experimentally the output pulse energy less than 200 mJ. This discrepancy is probably explained by an imperfect spatial matching between the pump and amplified beams in the active medium.

A compressor is a necessary element of a terawatt complex, which recovers the time profile of the initial femtosecond pulse. This device represents a linear system with strong anomalous dispersion. To perfectly reconstruct the initial shape of a femtosecond pulse, it is necessary to know the frequency dependence of the phase incursion $\Phi(\omega)$ of the amplified chirped pulse over the entire optical path before the compressor.

The grating compressor can compensate only the most important quadratic and cubic terms in the expansion of $\Phi(\omega)$ in a Taylor series in the vicinity of the central frequency ω_0 because it has two free parameters: the distance between the gratings and the angle of radiation incidence on the first grating. For this reason, the shape of the pulse envelope is not reconstructed completely after the compressor and the residual phase modulation of the pulse is retained, resulting in its stretching compared to the initial pulse and in the appearance of 'wings'.

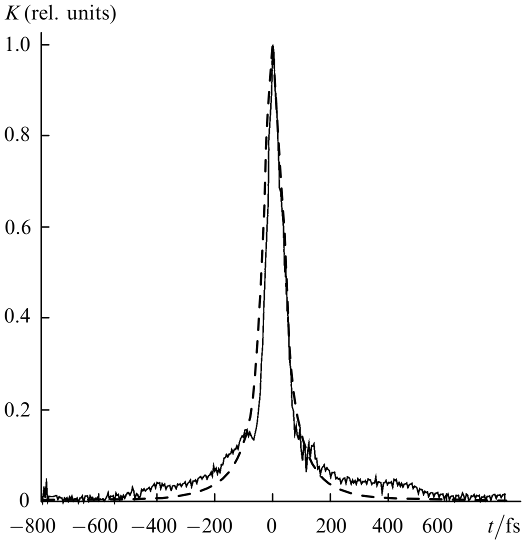

Figure 1. Single-pulse autocorrelation function of the output radiation intensity of the system (solid curve) and its approximation by a Lorentzian with the width 80 fs (dashed curve) for a pulse energy of 80 mJ.

In principle, the terms of the higher order than three in the expansion of $\Phi(\omega)$ can be compensated, resulting in the more exact recovery of the initial pulse, for example, using optical elements (mirrors) with controllable dispersion [15]. However, the fabrication of such elements is complicated and costly, and the measurement of phase characteristics of an optical pulse, which are required for such compensation, is also an intricate problem.

We used in our laser system a single-grating compressor, which can be simply aligned and used. Instead of the second grating, we used an angle reflector, which reflected (in the diffraction plane) radiation after the first diffraction back to the grating, where the radiation experienced the secondary reflection. The second angle reflector, which was mounted in the plane perpendicular to the diffraction plane, reflected radiation back and outcoupled the compressed pulse from the compressor. The total energy transmission coefficient of the compressor was 50 % and was mainly determined by an insufficiently large reflectivity of the grating used. Thus (Fig. 1), our femtosecond laser system can produce ~ 0.1 J, 100-fs pulses, i.e., the peak pulse power amounts to 10^{12} W.

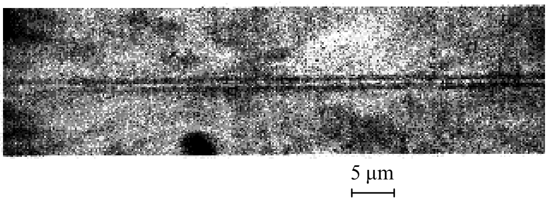

Figure 2. Channel produced in quartz upon axicon focusing of a 10-mJ single femtosecond pulse with the input beam diameter of 1 cm.

Consider some applications of the terawatt femtosecond system. Using this system, we performed a number of experiments on the modification of the structure of transparent dielectrics in the fields of focused femtosecond laser pulses with the aim of applications for material machining. In particular, we demonstrated for the first time the formation of microstructures of diameter ~ 1 μm with the aspect ratio up to 10^4 in the material bulk (see Fig. 2 in [7]). This result is very important for machining of superhard materials (like diamonds), the development of the elemental base for integrated and X-ray optics, artificial media with parameters of photonic crystals, etc.

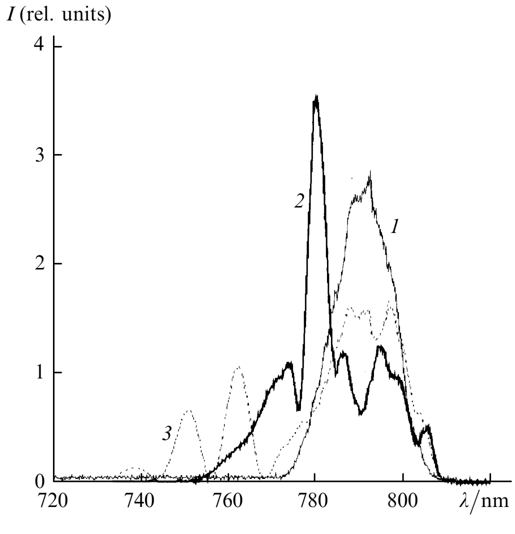

Figure 3. Emission spectra I at the output from an empty capillary (*1*) and from capillaries filled with Ar at a pressure of 1 Torr for the incident radiation energy equal to 2.4 (*2*) and 11.8 mJ (*3*). The capillary diameter is 100 μm and its length is 20 cm.

At present, the first results were obtained on channelling high-power single-mode ultrashort pulses in gas-filled microcapillaries in the presence of laser plasma. One of the aims of these studies is the optimisation of the parameters of the laser plasma for the creation of efficient X-ray sources and high-amplitude plasma waves for acceleration of electrons. Another aim is the obtaining of a very broad spectrum of an ionising laser pulse in a capillary and a subsequent compression of the pulse to the subfemtosecond duration. Fig. 3 shows the typical spectra of high-power femtosecond radiation propagated through a capillary filled with inert gas. One can see that the spectrum of incident radiation substantially broadens and shifts to the blue. The results of a theoretical analysis of this phenomenon based on the model of single-mode propagation of a powerful ultrashort pulse taking the gas ionisation into account qualitatively agree with the experiment.

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