parameters of such low-lying isomers of stable and long-lived nuclei (lifetimes, spin, energy, decay channels, etc.) by conventional methods of nuclear spectroscopy present considerable problems.

The main excitation channels of low-lying isomers in the FLP — excitation by X-ray radiation of the plasma itself, electron-impact excitation, and reverse internal electron conversion — were discussed in papers [22–24]. The excitation energy of most stable isomers exceeds 5 keV [23]. Therefore, the increase in the temperature and concentration of hot electrons observed in the FLP should increase the probability of the experimental detection of excitation of the isomer nuclear level in the laser plasma.

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Experimental investigation of the influence of subterawatt femtosecond laser radiation on transparent insulators at axicon focusing

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(1) The extensive recent development of lasers generating powerful femtosecond pulses has made it possible to study the interaction of intense radiation (which can produce electromagnetic fields of the order of or even higher than intra-atomic fields) with matter. As a result, new classes of physical phenomena have been experimentally investigated, such as the generation of large-amplitude plasma waves [1, 2], the obtaining of picosecond bursts of soft X-ray radiation [3], the generation of high harmonics extending to the soft X-ray region [4], etc. In this paper, we describe a subterawatt Ti:sapphire laser setup developed in the Institute of Applied Physics, Russian Academy of Sciences, and report the results of experimental studies of the action of intense laser radiation focused with an axicon lens on transparent dielectric targets.

(2) Figure 1 shows a block diagram of the femtosecond laser setup. The driving oscillator was pumped by a CW argon laser and produced a train of 100-fs pulses of 3 nJ energy and a repetition rate of 110 MHz at the wavelength $\lambda_0 \approx 795$ nm. The pulses were amplified using the common scheme [5]. To avoid nonlinear distortions and breakdowns in optical elements of the amplifier, the femtosecond pulses generated by the driving oscillator were stretched in time to approximately 150 ps with the help of a pulse stretcher. Then, the stretched pulses were first amplified in a regenerative oscillator and then in the output amplifier. The amplified pulses with a repetition rate determined by the repetition rate of the pump Nd:YAG laser were compressed in the diffraction compressor. The operation of separate units of the setup was synchronized with an accuracy of 1 – 2 ns with the help of a specially devised synchronization scheme. The diagnostic setup included a spectrograph (for current monitoring the spectrum of the driving oscillator), an autocorrelator (for continuous monitoring of the pulse duration of the driving oscillator), and a single-pulse autocorrelator (to control the duration of amplified pulses). All the output signals of the diagnostic setup were fed into a computer and were processed using an L-305 data acquisition and processing card.

The output pulses of the laser setup had the following parameters: pulse duration $\tau \approx 120-140$ fs, repetition rate $f = 10$ Hz, pulse energy $W \leqslant 20$ mJ, corresponding to the radiation power $P \leqslant 0.15$ TW. The diameter of the output radiation beam was $d \approx 8$ mm.

The laser radiation was focused by a conic axicon lens with an angle $\beta = 20°$ at the base. It is known [6] that an axicon focuses the incident radiation beam into a filament directed along its axis. The maximum radiation intensity on the axicon axis in our experiments was $I \sim (1-5) \times 10^{14}$ W cm^{-2}. The focusing scheme is shown in Fig. 2. A target made of a transparent dielectric was located in the region of maximum intensity. In most experiments, it was mounted on a rotating table, which provided irradiation of a given spot on the target by only one laser pulse.

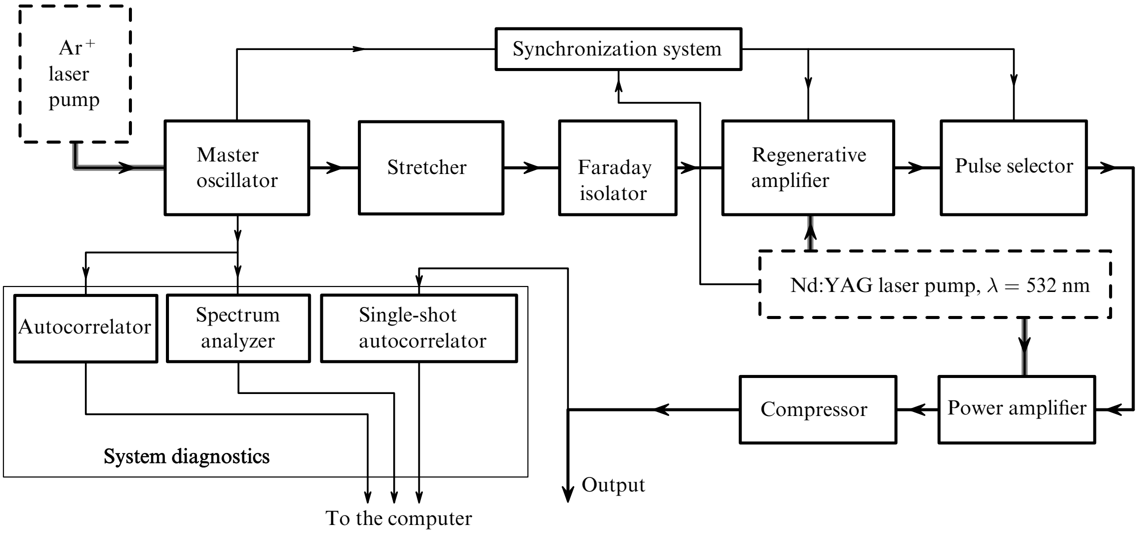

Figure 1. Block diagram of the laser setup.

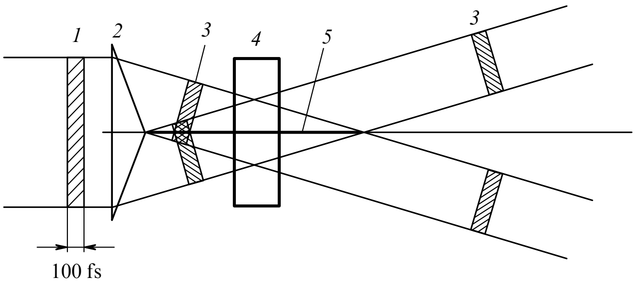

Figure 2. Scheme of focusing the femtosecond pulse by an axicon lens onto a dielectric target: (*1*) incident femtosecond pulse; (*2*) axicon; (*3*) refracted pulse; (*4*) dielectric target; (*5*) axicon caustic.

(3) When the energy of the laser pulse focused on the transparent dielectric target exceeded a threshold value, we observed a bright luminous filament in it. The observation of this region under the microscope showed that a hollow channel was formed in the target (Fig. 3a), whose diameter was $d = 1.5$ μm and the length could exceed 1 cm, being equal to the target thickness. If the target was not rotated, and several tens of pulses irradiated the same spot on the target, the channel collapsed into separate bubbles (Fig. 3b).

The radiation transmitted through the target exhibited a system of concentric multicolored rings separated by dark rings (Fig. 4). The inner ring corresponded to the fundamental harmonic ω_0 of the laser radiation and was always observed. The external rings appeared when the pulse energy exceeded a threshold value, which in turn exceeded the threshold for the appearance of the luminous filament in the dielectric. The radiation wavelength decreased with increasing ring diameter, the radiation inside a ring being almost monochromatic. In the case of a target made of K-8 optical glass, the ring that follows the fundamental-harmonic ring has the frequency $\omega_{(3/2)\omega} \approx (3/2)\omega_0$, and the ring with still larger diameter has the frequency $\omega_{2\omega} \approx 2\omega_0$, corresponding to the second harmonic. Upon irradiation of targets made of other materials, rings of different colors were also observed.

Figure 5 shows the spectrum of the $(3/2)\omega_0$ harmonic detected with a spectrometer. Also, the spectrum of the second harmonic of Nd:YAG laser radiation is presented as a reference ($\lambda_0 = 532$ nm), which corresponds to the exact

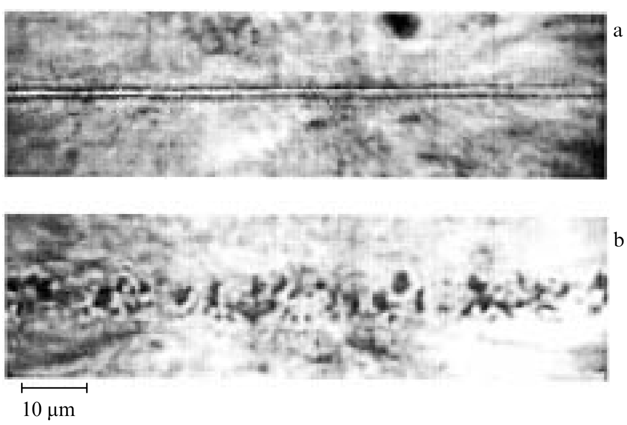

Figure 3. View of the channel in K-8 glass: (a) channel is formed by a single laser pulse; (b) channel after irradiation by approximately 30 pulses.

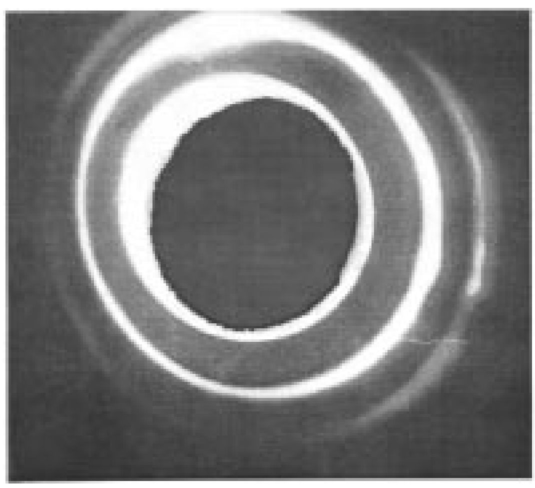

Figure 4. Spatial structure of radiation transmitted through the plasma filament.

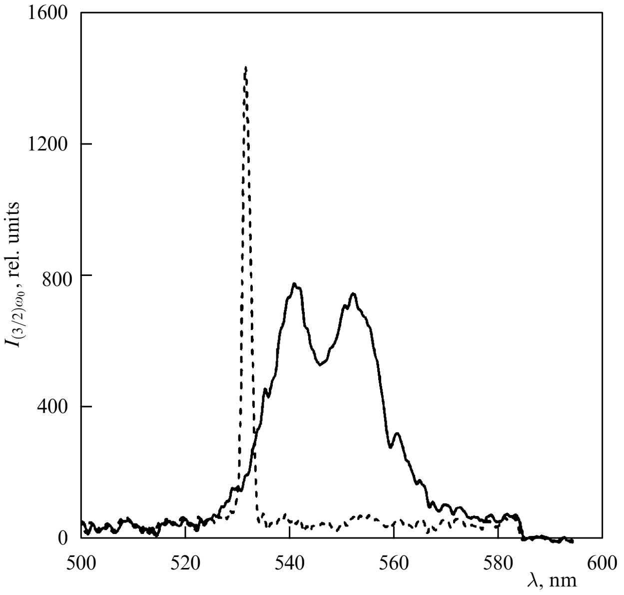

Figure 5. Spectrum of the $(3/2)\omega_0$ harmonic; the narrow 532-nm peak is the spectrum of the second harmonic of an Nd:YAG laser.

meaning of $(3/2)\omega_0$. The spectrum width was about 20 nm with the mass center shifted at $\Delta\lambda \approx 20$ nm to the 'red'. The fine structure of the spectrum has fluctuated from shot to shot.

The polarization of harmonics coincided with that of the incident laser radiation (both in the cases of linear and circular polarizations). The intensity of the harmonics was almost independent of the polarization of the incident radiation.

Figure 6 shows the dependence of the relative intensity of the $(3/2)\omega_0$ harmonic on the incident-radiation intensity I_0. One can see that the harmonic-generation threshold is $I_{(3/2)\omega_0} \approx 10^{14}$ W cm^{-2}, while the harmonic intensity is approximately proportional to the incident-radiation intensity: $I_{(3/2)\omega_0} \sim I_0$. Similar measurements gave for the second harmonic the threshold $I_0 \approx 10^{14}$ W cm^{-2} and the dependence $I_{2\omega} \sim I_0^{1.2}$. The efficiency of conversion to harmonics was measured with a photodiode calibrated at the corresponding wavelength with the help of an absolute pulsed power meter. We found that the conversion efficiency was $\eta_{(3/2)\omega_0} \sim 10^{-3}$ and $\eta_{2\omega} \sim 10^{-3}$ for $I_0 \approx 4 \times 10^{14}$ W cm^{-2}.

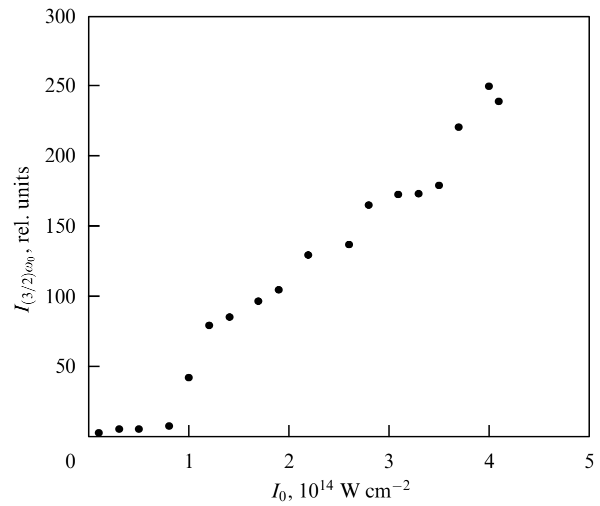

Figure 6. Dependence of the relative intensity of the $(3/2)\omega_0$ harmonic on the incident-radiation intensity (material: K-8 glass).

(4) Let us discuss our results. We believe that the formation of hollow channels in dielectrics and the generation of harmonics of the fundamental laser frequency are related to the appearance of a plasma inside the dielectric upon axicon focusing. The geometry of axicon focusing makes it possible to achieve a radiation intensity $I_0 \geqslant 10^{14}$ W cm^{-2} inside the target, avoiding (due to small transverse dimensions of the region of high radiation intensity) self-focusing effects. At such high radiation intensities, the target material becomes ionized at the leading edge of the laser pulse. First, the plasma concentration increases to the critical value for the incident radiation on the axicon axis. Then, because of the radiation screening, the plasma concentration ceases to increase here. Further, the plasma concentration increases at the periphery and the plasma propagates from the axicon axis as the front of the ionization wave. The typical transverse size of the plasma thus formed is determined by the characteristic scale of the electromagnetic-field decay and is about 1 μm.

The formation of long hollow channels in transparent dielectrics represents an interesting physical problem, which may find practical applications in the future. However, at present this experimental effect requires further studies.

The generation of harmonics upon laser irradiation of the solid surface is an old problem, which originally appeared in studies of the possibilities of the achievement of inertial thermonuclear synthesis. We suppose that theoretical concepts developed in the field may be used for interpretation of our experiments. According to the accepted notion, the generation of the $(3/2)\omega_0$ harmonics occurs in two stages [7]. First, the incident electromagnetic radiation with frequency ω_0 is decomposed, because of the parametric instability, into two plasma waves with frequencies $\omega_0/2$ in the region of the plasma concentration equal to one fourth of the critical concentration, and then the $(3/2)\omega_0$ harmonic is generated owing to the interaction between the incident and plasma waves.

According to the theory [7], the intensity of the $(3/2)\omega_0$ harmonic should be described by the relation $I_{(3/2)\omega_0} \sim I_0^{3/2} T_e^{3/2}$, where T_e is the electron temperature of the plasma. The weaker dependence of the harmonic intensity on the incident-radiation intensity, which was observed in our experiments ($I_{(3/2)\omega_0} \sim I_0$), can be explained by the decrease in the local electron temperature in the plasma with the increasing incident-radiation intensity, which in turn is determined by the dynamics of propagation of the ionization front. Another reason may be the change in the characteristic scale of the plasma in the region of one fourth of the critical concentration [8].

The efficiency of generation of the $(3/2)\omega_0$ harmonic in our experiments was several orders of magnitude higher than, for example, in Ref. [7]. This is probably explained by the fact that in our experiments, in contrast to Ref. [7], there is a spatial scale ($\sim \lambda_0$) determined by the transverse size of the plasma channel formed in the dielectric. For this reason, the wavelength of the excited plasma wave is close to the channel diameter, i.e., λ_0, which ensures the fulfillment of the law of conservation of momentum $\mathbf{k}_{(3/2)\omega} = \mathbf{k}_0 + \mathbf{k}_p$ during the interaction of the waves, where $\mathbf{k}_{(3/2)\omega}$, $\mathbf{k}_0$, and $\mathbf{k}_p$ are the wave vectors of the $(3/2)\omega_0$ harmonic, the incident radiation, and the plasma wave, respectively. This results in the resonance generation of the $(3/2)\omega_0$ harmonic. According to the law of conservation of momentum, efficient generation of the $(3/2)\omega_0$ and $(2\omega_0)$ harmonics will occur at a certain angle between the wave vectors of the incident wave and harmonic, resulting in the ring system observed in experiments. The characteristic wavelength of the plasma wave can be estimated from the law of conservation of momentum and experimental data on the harmonic radiation diagram (see the ring structure in Fig. 5). We found that $\lambda_p \approx 1$ μm, i.e., indeed, the wavelength of the plasma wave is close to the channel radius. According to the estimate, under experimental conditions [7] the wavelength of the excited plasma waves is much smaller than that of the pump wave ($\mathbf{k}_p \gg \mathbf{k}_0$), and nonresonance generation of the harmonic occurs.

The interpretation of the experimental spectrum shown in Fig. 5 is particularly difficult. The great width of the observed spectrum may be connected with the high collision frequency of plasma electrons with atoms and ions. According to estimates [13], the electron collision frequency in the conditions of a solid-state plasma is about the laser radiation frequency. This causes the wide spectrum of plasma waves, and, as a result, the wide spectrum of harmonics. The presence of small spatial scales ($\sim \lambda$) and the non-ideal cold dense plasma may lead to the harmonic spectrum shift relative to $(3/2)\omega_0$.

The second-harmonic generation is theoretically explained by excitation of plasma waves in a laser plasma region with the critical concentration due to a linear transformation of the laser radiation [9]. In this case, the frequency of plasma waves proves to be close to that of the incident radiation, and the subsequent interaction of longitudinal plasma waves with the laser pump wave results in the second-harmonic generation. As in the case of the $(3/2)\omega_0$ harmonic, a weaker dependence of the second-harmonic intensity on the incident-radiation intensity (the experimental dependence is $I_{2\omega} \sim I_0^{1.2}$, whereas, according to the theory, $I_{2\omega} \sim I_0^2$) may be related to the dynamics of the plasma front. In earlier papers, the efficiency of conversion to the second harmonic reached $\eta \sim 10^{-4}$ for $I_0 \approx 10^{13} - 10^{14}$ W cm^{-2} for nanosecond laser pulses [10, 11] and for $I_0 \sim 10^{16}$ W cm^{-2} upon irradiation of a target by femtosecond pulses [12]. The high conversion efficiency to the second and $(3/2)\omega_0$ harmonics in our experiments is probably explained by the fulfillment of the synchronism condition.

(5) Therefore, the study of the interaction of intense femtosecond radiation with a transparent dielectric upon axicon focusing revealed a number of interesting effects related to plasma formation. We have demonstrated the formation of long hollow channels of the transverse size 1 μm and length up to 1 cm in dielectrics. We have obtained highly efficient (for plasma experiments) generation of harmonics of the fundamental laser frequency, which is likely to be related to the resonance interaction of the waves involved in the harmonic generation.

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