The image of a nanosecond laser plasma in its own optical radiation

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Abstract. The results of experiments on the interaction of nanosecond laser radiation (wavelength of 1.06 μm and a radiation power density of 10^{12}–10^{13} W/cm²) with targets from various materials (Cu, (C_{2}H_{4})_{n}, TAC) are presented in the paper. In the experiments images of the plasma in own optical radiation in the wavelength range 0.4–1.1 μm were obtained. In one shot of laser images at wavelengths corresponding to the radiation of the harmonics 2\omega_0, 3/2\omega_0, 5/2\omega_0, and at the frequency of laser radiation \omega_0 were recorded. Using the obtained images the spatial characteristics of the radiating regions of the plasma, as well as the radiated energy for each of the harmonics, were estimated.

1. Introduction

At laser-matter interaction it is essential problem to effectively expend such highly organized form of energy as laser radiation. The scattering processes lead to the loss of part of the laser radiation energy. In modern studies, there is a fundamental task of comprehensive study of the processes of harmonic generation, Raman scattering, stimulated Raman scattering (SRS), and stimulated Brillouin scattering (SBS) in a plasma [1–5].

In the plasma formation process the laser radiation energy is absorbed in a plasma region with a critical electron density n_c. Exactly in this region radiation scattering is occurring at the fundamental laser frequency \omega_0 and integer harmonics, for example, 2\omega_0 are generating [6]. Another important region for the interaction of laser radiation with the plasma corona is the region with an electron density n_c/4. In its vicinity, the frequency of the laser is close to twice the plasma frequency, and it is possible to resonantly excite plasma waves, and as a consequence, an anomalous absorption of laser energy in plasma occurs. At the same time, due to the nonlinear interaction in this region, the generation of half-integer harmonics 1/2\omega_0, 3/2\omega_0, 5/2\omega_0 are possible. In the region n_c/4 the main process responsible for the emission of harmonics is Raman scattering [7], wherein emission occurs at the frequencies 1/2\omega_0, 3/2\omega_0. In the next order in the pump wave amplitude, the Raman scattering process describes radiation emission at a frequency 5/2\omega_0. Also in same region of the plasma the developing of the stimulated Raman scattering can lead to the direct generation of the harmonics 1/2\omega_0, 3/2\omega_0 in the form of the Stokes and anti-Stokes scattering components [7].

On the one hand, in studies on inertial confinement fusion the stimulated Raman scattering is potentially dangerous, and can lead to an acceleration of electrons, and premature heating of the
irradiated target, on the other hand, it is potentially as a beneficial mechanism for optical pulse compression in plasma-based Raman amplifiers [7–9].

In case the wavelength laser irradiated the matter is 1.06 μm, the harmonics at frequencies $2\omega_0$, $3/2\omega_0$, $5/2\omega_0$ generated in the plasma fall into the optical range of the wavelengths of 0.4–1.1 μm. The most important characteristics of harmonics radiation generated in the plasma are spatial localization and spectral distribution. The study of the emission of harmonics emergence region makes it possible to diagnose the dynamics of the plasma region with a critical and a quarter of the critical electron densities $n_c$ and $n_c/4$.

2. Experimental data

Experiments on the interaction of laser radiation with matter were performed on the "Channel-2" facility [10]. The source of radiation was a neodymium-glass laser operating in a multimode regime. In experiments, the parameters of laser radiation were the following: pulse duration 2.5 ns, spectral width 20 Å, laser output energy 1–100 J, laser power density at target surface $10^{12}$–$10^{13}$ W/cm$^2$, focal spot size ~350 μm. The used targets were metal foils made of copper Cu, polyethylene ($C_2H_4)_n$ in the form of a film, a film of cellulose triacetate (TAC), and low density volume-structured targets from TAC. The density of the films from the TAC was ~1300 mg/cm$^3$, while the density of low-density target TAC varied from 2 to 10 mg/cm$^3$.

A four-frequency polarization microscope was used to record the image of laser plasma in the optical range 0.4–1.1 μm [11]. Microscope allows to record four images of laser plasma with the same spatial resolution the specified spectral range. The diagnostic channel with a microscope was located at an angle of 18° to the axis of the heating laser beam, measurements were made at a solid angle corresponding to the aperture of the microscope, and integrally over the entire time of the plasma emission. Laser radiation came along the normal to the plane of the target. For one shot of the laser, a plasma image was recorded at four wavelengths corresponding to the plasma radiation at the frequencies of the harmonics $2\omega_0$, $3/2\omega_0$, $5/2\omega_0$ and at the fundamental frequency $\omega_0$ (at wavelengths 0.53, 0.71, 0.42 and 1.06 μm, respectively). Also used microscope allows to estimate the size of the emission region, and the amount of energy radiated by the plasma at the harmonic frequency into the solid angle of the recording channel.

Figures 1–4 show the plasma images obtained by means a four-frequency polarization microscope for the investigated targets: A – low-density TAC target, B – film TAC target with density 1300 mg/cm$^3$, C – polyethylene ($C_2H_4)_n$ film, D – metal foils made of copper.

![Figure 1. Images of plasma emission on fundamental frequency $\omega_0$.](image1)

![Figure 2. Images of plasma emission on harmonic frequency $2\omega_0$.](image2)
3. Discussion of experiments
For all types of targets, the radiation of the harmonics $2\omega_0$, $3/2\omega_0$, $5/2\omega_0$ and at the fundamental frequency $\omega_0$ was registered. A study of the plasma image with spatial resolution at the frequencies of the harmonics and the fundamental frequency showed that in the observation direction the emission distribution of the plasma has a complex character. According to plasma images, the localization size of the emitting regions was estimated. For emission area of the plasma the inhomogeneity intensity regions exist. And these areas can take different shapes and sizes with each laser shot.

In experiments, the plasma emission areas at frequencies $2\omega_0$ and $\omega_0$ in size correspond to the size of the focusing spot of laser radiation. As a rule, for all types of studied targets an inhomogeneous structure of the plasma emission in second-harmonic radiation was obtained in the experiments. This inhomogeneity indicates fluctuations in the electron density $n_e$ in the formed plasma, and is probably related to the formation in the plasma of regions corresponding to the most optimal second-harmonic generation conditions due to linear transformation process. At a frequency of $3/2\omega_0$, the characteristic size of the radiation localization is smaller than the size of the focusing spot of the laser radiation and depends on the target type and the laser radiation energy. For all types of studied targets, the emission area at the frequency $3/2\omega_0$ was the smallest region in comparison with the emission areas at the harmonic frequencies $2\omega_0$, $5/2\omega_0$ and at the fundamental frequency $\omega_0$.

Table 1 presents the results of processing plasma images by estimating the energy of the harmonics $2\omega_0$, $3/2\omega_0$, $5/2\omega_0$ and at the fundamental frequency $\omega_0$.

The coefficient of transformation of the laser radiation into the plasma harmonics was determined as the ratio of the energy of the harmonic recorded at the solid angle of diagnostic channel registration to the energy of the laser radiation incident on the target. The energy density emitted at a frequency of $3/2\omega_0$ exceeds this index for the frequency $5/2\omega_0$, in spite of the fact that the radiation region for $3/2\omega_0$ is much smaller than the radiation region for $5/2\omega_0$. This is because the process of harmonic generation $5/2\omega_0$ is of the next order of smallness in comparison with Raman scattering, and the harmonic intensity $5/2\omega_0$ should be less than the radiation intensity of the harmonic $3/2\omega_0$ [7].

Despite the small volume density of the volume-structured TAC target, the energy of the scattered radiation at frequencies $2\omega_0$, $3/2\omega_0$, $5/2\omega_0$, recorded in experiments, is comparable with the data for solid targets.

If we compare the results obtained for low-density TAC target and TAC films with a density of ~1300 mg/cm³, then it turns out that the harmonic energy and harmonics transformation coefficient are large for targets with a density of 1300 mg/cm³. According to the formulas for the transformation coefficient of the heating radiation into the second harmonic, the transformation coefficients are proportional to the scale of the density variation in the vicinity of the critical density [6], other
parameters can be considered identical. Since for TAC target films the coefficient of transformation into the second harmonic is greater than for low-density TAC target, it can be concluded that the value of the characteristic size of density inhomogeneity for TAC target with a density of 1300 mg/cm$^3$ is greater than for low-density TAC target.

**Table 1.** Results of energy estimating of the harmonics $2\omega_0$, $3/2\omega_0$, $5/2\omega_0$ and at the fundamental frequency $\omega_0$.

| Type of target → | Low-density TAC | TAC film | (C$_2$H$_4$)$_n$ | Cu |
|------------------|-----------------|----------|-----------------|----|
| Target density, mg/cm$^3$ → | 9               | 1300     | 950             | 8900 |
| Laser radiation energy, J → | 17.8            | 28.8     | 22.6            | 18.7 |
| Harmonics ↓ | Energy, scattered in solid angle of diagnostic channel, J | | | |
| $2\omega_0$ | $3.1 \times 10^{-11}$ | $5.7 \times 10^{-10}$ | $6.8 \times 10^{-10}$ | $7 \times 10^{-11}$ |
| $3/2\omega_0$ | $1.5 \times 10^{-9}$ | $10^{-9}$ | $5.4 \times 10^{-10}$ | $2.6 \times 10^{-9}$ |
| $5/2\omega_0$ | $2.6 \times 10^{-10}$ | $1.8 \times 10^{-10}$ | $1.5 \times 10^{-10}$ | $3.1 \times 10^{-10}$ |
| $\omega_0$ | $2.8 \times 10^{-6}$ | $1.9 \times 10^{-6}$ | $1.3 \times 10^{-6}$ | $2.3 \times 10^{-5}$ |
| Harmonics ↓ | Energy density, scattered in solid angle of diagnostic channel, J/cm$^2$ | | | |
| $2\omega_0$ | $4.2 \times 10^{-7}$ | $8.2 \times 10^{-7}$ | $9.7 \times 10^{-7}$ | $3.9 \times 10^{-7}$ |
| $3/2\omega_0$ | $1.8 \times 10^{-5}$ | $6.5 \times 10^{-6}$ | $3.4 \times 10^{-6}$ | $1.6 \times 10^{-5}$ |
| $5/2\omega_0$ | $2 \times 10^{-7}$ | $1.1 \times 10^{-7}$ | $1.1 \times 10^{-7}$ | $5.6 \times 10^{-8}$ |
| $\omega_0$ | $3.6 \times 10^{-3}$ | $3.9 \times 10^{-3}$ | $4.1 \times 10^{-3}$ | $7.8 \times 10^{-2}$ |
| Harmonics ↓ | Transformation coefficient of laser radiation into the harmonics | | | |
| $2\omega_0$ | $3.8 \times 10^{-12}$ | $2 \times 10^{-11}$ | $3 \times 10^{-11}$ | $3.7 \times 10^{-12}$ |
| $3/2\omega_0$ | $2.3 \times 10^{-10}$ | $3.6 \times 10^{-11}$ | $2.4 \times 10^{-11}$ | $1.4 \times 10^{-10}$ |
| $5/2\omega_0$ | $2.1 \times 10^{-11}$ | $6.3 \times 10^{-12}$ | $6.8 \times 10^{-12}$ | $1.7 \times 10^{-12}$ |
| $\omega_0$ | $1.8 \times 10^{-7}$ | $6.5 \times 10^{-8}$ | $5.6 \times 10^{-8}$ | $1.2 \times 10^{-6}$ |

For the TAC targets, a theoretical estimate of the value of the transformation coefficient of the heating radiation into the second harmonic was made, assuming that the $2\omega_0$ generation process is due to a linear transformation. This estimate gives a value of $\sim 10^{-6}$, which is much higher than the value obtained experimentally. Here it should be noted that the harmonics radiation was registered in the limited solid angle of the diagnostic channel, and at an angle to the axis of the heating laser radiation.

4. Conclusion

As a result of the experiments on the nanosecond laser radiation interaction with metal foils of copper Cu, polyethylene (C$_2$H$_4$)$_n$ in the form of a film, films of cellulose triacetate (TAC) and low-density bulk-structured targets from TAC, Components corresponding to radiation at harmonic frequencies $2\omega_0$, $3/2\omega_0$, $5/2\omega_0$ for all types of targets studied. Radiation of the plasma at harmonic frequencies is localized in different spatial regions. An analysis of the experimental data indicates the emergence and development of parametric instabilities in the plasma regions, both with the critical density of electrons and a quarter of the critical one.

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