Observation of laser scattering at ω_0 and $2\omega_0$ by a plasma region with a density well below the critical density

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Experiments on spherical heating of fusion targets in the Del'fin-1 device reveal laser scattering at frequencies of ω_0 and $2\omega_0$ by a plasma region with a density well below the critical density. For each of the frequencies, the size of the emission region is roughly four times the initial target diameter, and the region has a sharp boundary. Some possible explanations for the observations are proposed.

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The generation of harmonics of the fundamental frequency of a laser beam in a plasma has attracted much interest because a study of the generation mechanism can yield information about the processes which operate in a plasma as it is heated by intense laser radiation. Generation of the second harmonic of the incident beam has been studied quite thoroughly both experimentally and theoretically,[1-3] but this research has dealt with the generation at the frequency $2\omega_0$ in the plasma region with the critical density.

In this letter we report a study of the scattering of laser radiation at the frequencies ω_0 and $2\omega_0$ by a low-density plasma ($n_e \sim 10^{19}$ cm^{-3}) in the Del'fin device.[4,5] The experimental arrangement is shown in Fig. 1. The scattered light is detected by two

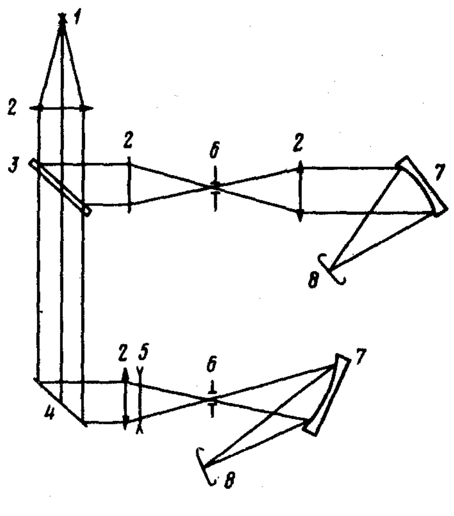

FIG. 1. Basic optical arrangement for detecting the light scattered by the plasma at the frequencies ω_0 and $2\omega_0$. 1—Target; 2—aspherical lenses; 3—beam splitter; 4—rotating mirror; 5—correcting lens; 6—diaphragms; 7—grating holograms; 8—photographic film.

different systems with diffraction spectrographs. An image of the plasma is directed to the entrance slit by means of aspherical optics with a speed $D_0/f_0 = 1/2$ ($f_0 = 120$ mm) at a unit magnification.

As dispersive elements we use concave grating holograms with dimensions of 50×50 mm, a speed $D/f = 1/2$, and 1500 lines/mm.

In the first detection system the spectrograph has the Rowland arrangement. Astigmatism is cancelled by a negative cylindrical lens with $f_k = 100$ mm. The spatial resolution in the image plane, δ, is no worse than 50 μm; the linear dispersion $d\lambda/dl$ is 26 Å/mm; and the magnification β of the optical system is 2.5.

The second-signal spectrograph has a Wadsworth arrangement in which the diffraction angle is 0°; correspondingly, the image of the object in this direction is stigmatic. The characteristics of the optical system are $\delta = 90$ μm, $d\lambda/dl = 40$ Å/mm, and $\beta = 1.25$.

A necessary condition for detection of the light under study is

$$E\tau > s, \tag{1}$$

where $E = \pi\eta B_s(\delta\lambda/\Delta\lambda)(1/\beta)\sin^2\theta$ is the illuminance of the image, τ is the exposure time, and s is the sensitivity of the photographic material. Here B_s is the brightness of the emission source, η is the transmission coefficient of the optical system, $\delta\lambda$ is the spectral width of the instrumental function, $\Delta\lambda$ is the width of the spectral line, and θ is the entrance aperture angle.

The experimental results are shown in Figs. 2a–2c. We see that the emission at both frequencies is observed from a region with a sharp spatial boundary and a dimension $r_{em} \sim 4r_t$, where r_t is the initial radius of the target.

These observations cannot be explained on the basis of mechanisms which lead to harmonic generation in the plasma region with the critical density, since even if it is assumed that all the mass of the target evaporates and occupies a volume $V_{em} = 4/3\pi r_{em}^3$ the average density remains below the critical value:

$$\rho_{av} = \frac{3}{A}\rho\left(\frac{r_t}{r_{em}}\right)^3 < \rho_{cr},$$

where ρ is the density of the target material, and A is the aspect ratio. For the typical parameters of the targets used in the Del'fin experiments [$2r_t = 400$ μm, $A = 150$–250, $\rho = 2.7$ g/cm^3 (SiO_2), and $\rho_{cr} = 3.33\times 10^{-3}$ g/cm^3] we find $\rho_{av} = 6.5\times 10^{-4}$ g/cm^3.

Calculations of the plasma density profile show that at the point $r = r_{em}$ the electron density n_e is $\sim 10^{19}$ cm^{-3} (the critical density for a neodymium laser is $n_c = 10^{21}$ cm^{-3}).

What mechanisms can we call upon to explain these results? It is natural to suggest that the emission at ω_0 results from Thomson scattering. For isotropic emission, the source brightness can be written $B_s = (1/\pi)q_l\sigma n_e\Delta r$, where q_l is the laser power density, σ is the Thomson scattering cross section, and Δr is the thickness of the emitting plasma layer. For the parameter values $q_l \sim 10^{14}$ W/cm^2, $\sigma = 6.5\times 10^{-25}$ cm^{-2}, $\Delta r = 2\times 10^{-2}$ cm, $\eta = 0.2$, $\delta\lambda/\Delta\lambda = 4.3\times 10^{-2}$, $\tau = 3$ ns, and $s = 10^{-6}$ J/cm^2

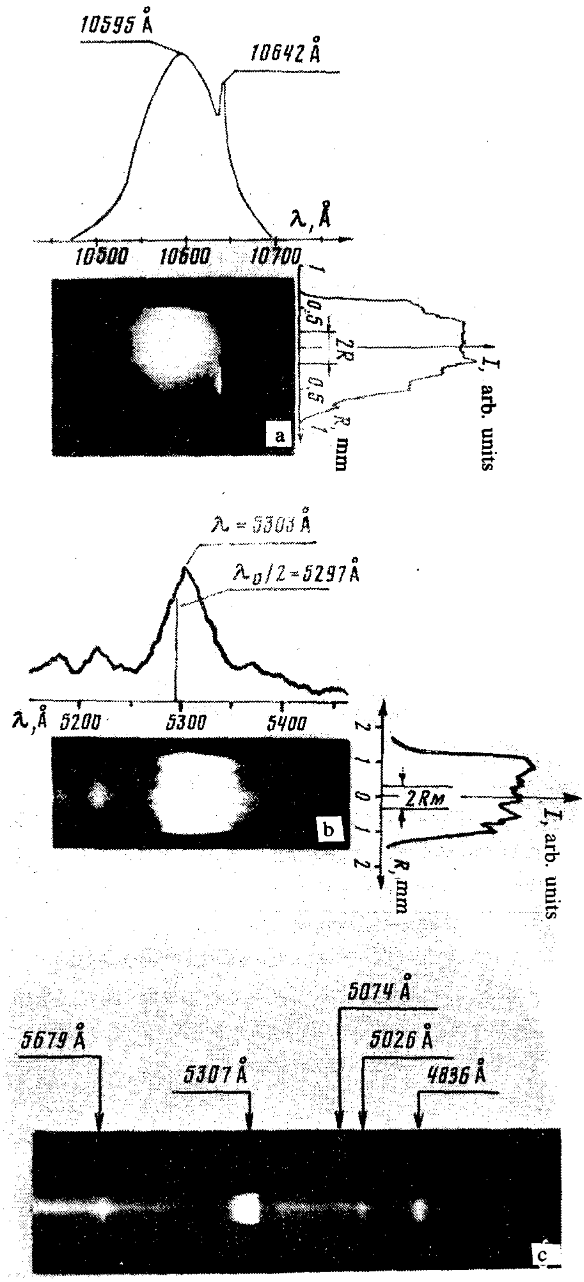

FIG. 2. Spectral and spatial distributions of the light intensity in the observed spectra. a—ω_0; b—$2\omega_0$; c—panoramic spectrum at $2\omega_0$.

we then find $E\tau = 10^{-5}$ J/cm$^2 > s$. These estimates show that the Thomson scattering mechanism can explain the experimental results on the scattering at the fundamental frequency.

We turn now to the generation at the frequency $2\omega_0$ at $n_e \sim 10^{19}$ cm^{-3}. This effect might occur because of the particular way in which an electron moves in an intense electromagnetic wave.[6]

To determine E_T we use the values $\delta\lambda/\Delta\lambda = 6.7\times10^{-2}$, $\eta = 3\times10^{-2}$, and $s = 3\times10^{-8}$ J/cm^2 for this case. With these numerical values for the parameters we find $E_T = 3\times10^{-10}$ J/cm^2.

Consequently, although this mechanism can formally explain the possibility of generation at the frequency $2\omega_0$ at $n_e \sim 10^{19}$ cm^{-3}, the energy is still too low for detection under the assumption of isotropic scattering. We are thus led to the possibility that the scattering at $2\omega_0$ is anisotropic. To resolve this question, however, we need to carry out a detailed study of the directional pattern of the emission.

We have a few comments to offer regarding the sharp boundary of the emission region. The presence of a sharp boundary means that the motion of the electrons is spatially bounded. A reason might be the generation of magnetic fields by the charged-particle currents and the formation of filaments in the laser plasma.[7]

It may be that there is some average field in the plasma volume over the observation time interval which begins to have an important effect on the nature of the electron motion as the plasma expands, curving the trajectories traced out by the electrons in the direction of the center of the target. This field is easily estimated:

$$H_{\rm av} \sim \frac{m_e v^*_{T_e} c}{eR},$$

where R is the radius of curvature at the turning point, and $v^*_{T_e}$ is the thermal velocity of the electrons at the temperature $10\,kT_e$.

With $R = 200\ \mu$m and $v^*_{T_e} \sim 6\times10^9$ cm/s ($kT_e \sim 1$ keV) we have

$$H_{\rm av} \sim 2\cdot10^4\ \mathrm{G}.$$

The energy density of this field would be $W = H^2_{\rm av}/8\pi \sim 1.6\times10^7$ erg/cm^3. The plasma volume ($V_{\rm pl} = 4.2\times10^{-3}$ cm^3) thus contains an energy corresponding to the field $H_{\rm av}$: $\sim 7\times10^{-3}$ J. This energy is well below the absorbed energy ($E_{\rm abs} = 300$–500 J). Magnetic fields up to several tens of kilogauss may thus be generated in the plasma corona.

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[1]N. G. Basov, Yu. V. Bychenkov, O. N. Krokhin, *et al.*, Kvant. Elektron. (Moscow) **6**, 1829 (1979) [Sov. J. Quantum Electron. **9**, 1081 (1979)].
[2]E. A. McLean, J. A. Stamper, B. H. Ripin, H. R. Ghiem, J. M. McMahon, and S. E. Bodner, Appl. Phys. Lett. **33**, 825 (1977).
[3]M. B. Isihenko and V. V. Yan'kov, Phys. Lett. **90A**, 248 (1982).
[4]N. G. Basov, A. E. Danilov, B. V. Kruglov, *et al.*, Kvant. Elektron. (Moscow) **9**, 395 (1982) [Sov. J. Quantum Electron. **12**, 225 (1982)].
[5]N. G. Basov, A. E. Danilov, M. P. Kalashnikov, *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **37**, 109 (1983) [JETP Lett. **37**, 134 (1983)].
[6]L. D. Landau and E. M. Lifshitz, Teoriya polya, Nauka, Moscow, 1973, p. 504 (The Classical Theory of

Fields, Pergamon, Oxford, 1975).
[7]Yu. M. Aliev, V. Yu. Bychenkov, and A. A. Frolov, Preprint No. 189, P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow, 1982, p. 7.

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