Generation of subharmonics and higher harmonics of ion acoustic waves in a laser plasma

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The spectrum of the light scattered by a laser plasma into the aperture of a focusing lens during the application of a pulse with a power density of 5×10^{14} W/cm^2 from a CO_2 laser to a target has been measured. The results are reported. A Fourier analysis demonstrates that the spectra contain frequencies corresponding to the generation of subharmonics of ion acoustic waves in the plasma.

According to the present understanding, nonlinear mechanisms for the absorption and scattering of the laser light play an important role in the interaction of intense beams from CO_2 lasers with plasmas. Several experimental studies have revealed a broadening of the spectrum of the scattered light; this broadening has usually been attributed to stimulated Brillouin scattering (or "stimulated Mandel'shtam-Brillouin scattering").[1,2] A simple model does not always suffice for explaining even the width of the spectrum, and there is a particular division of opinion regarding the fine details of the spectra, e.g., the line structure.[1–4]

The theoretical analysis of stimulated Brillouin scattering for a bounded system with a reflecting boundary which was proposed in Ref. 5 seems to us to correspond most comprehensively to the experimental situation in the case of high-power densities of the light from a CO_2 laser ($I \gtrsim 10^{14}$ W/cm^2). Radiation pressure begins to play an important role here, causing a pronounced steepening of the density profile; the interaction regime becomes very nonlinear. Under such conditions, a critical-density surface can serve as a reflecting boundary. According to Ref. 5, the intensity of the scattered light in the nonlinear regime exhibits a random behavior in time, and the spectrum acquires frequencies corresponding to harmonics and subharmonics of the ion acoustic frequency.

In this letter we report studies of the spectrum of the light scattered by a laser plasma into the aperture of the focusing lens for targets with various values of Z. In order to identify the spectral components corresponding to harmonics and subharmonics of the ion sound, we have carried out a numerical Fourier analysis of the experimental spectra.

For the measurements we use the TIR-1 CO_2 laser apparatus, which is described in detail in Ref. 6. In the present experiments the energy of the laser beam is 50 J; its wavelength is $\lambda = 10.591\ \mu$m (10P20); the length of the pulse at the half-intensity level is 2 ns; and the energy contrast is $> 10^7$. The good quality of the beam wavefront permitted focusing of the beam with an aspherical NaCl lens (F/3) with a focal length $F = 550$ mm in a spot 70 μm in diameter. Correspondingly, the power density of the light at the target ranges up to 5×10^{14} W/cm^2. Figure 1 shows the measurement arrangement. The laser beam scattered by the plasma into the aperture of the focusing lens (1) is reflected from one surface of a NaCl wedge (2) and sent to a diffraction grating (3) with 100 lines/mm and dimensions of 100×100 mm.[2] A distinctive feature of this arrangement is the high spectral resolution, achieved by eliminating aber-

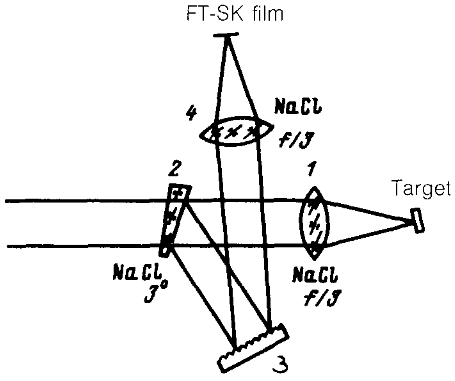

FIG. 1.

rations almost completely. The resolution is determined in our case by the size of the source of the scattered light, ~10 Å. A time-integrated spectrum is measured by sensitizing FT-SK photographic film to IR light.[7] An absolute calibration of the wavelength scale is carried out on the basis of results calculated for the relative angular positions of the −17th and −16th diffraction orders for a He-Ne laser, placed in the beam from the CO_2 laser, and the −1st diffraction order of the beam from the CO_2 laser. The maximum deviation of the measured wavelength from the actual wavelength is determined by the precision of the procedure by which the beams are brought into coincidence; it does not exceed ±10 Å. Figure 2 shows spectra of the incident light (Fig. 2a) and of the scattered light, for targets made of polyethylene (Fig. 2b), aluminum (Fig. 2c), and lead (Fig. 2d). All the spectra of the scattered light are significantly broadened; their width at half-intensity does not depend on the target

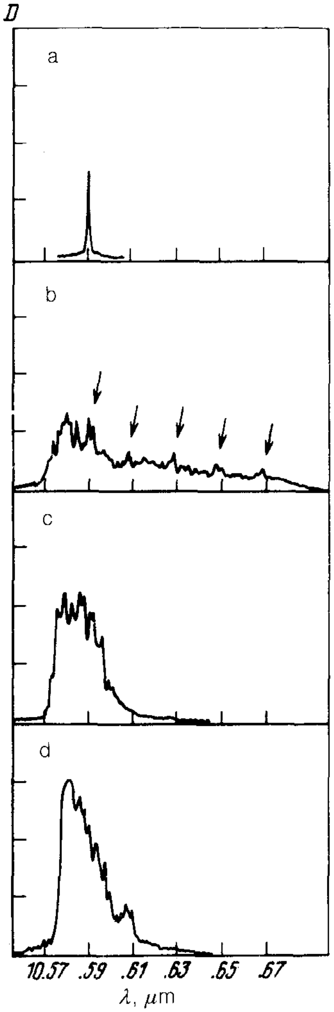

FIG. 2

material, having the value ~ 160 Å (50 GHz) at a power density of 5×10^{14} W/cm^2. On the other hand, the width of the spectra at the level of 1/10 of the intensity varies significantly with the value of Z of the target, having the values ~ 250, ~ 300, and ~ 800 Å for Pb, Al, and $(CH_2)_n$, respectively. We should point out that a line structure is characteristic of all of the spectra.

To digitize the raw data for numerical processing, we use an AMD-1 automatic microdensitometer. The step of the scan is 10 μm. At a linear dispersion of 166.25 Å/mm of the spectrograph, this step corresponds to a spectral shift of 1.6625 Å, which is much smaller than the experimental resolution. We selected this scanning step in order to improve the resolution of the numerical scheme and correspondingly eliminate the effect of the scan step on the results of the processing. At the spectral width used, the number of digitized points ranges from 300 to 900. The purpose of the processing was to generate a modulation spectrum. For this purpose we used 1024-point "fast" Fourier transforms. For the analysis we selected the "red" and "blue" parts of the spectra separately, on the basis of the suggestion that different physical mechanisms contribute to the "blue" and "red" broadening. Figure 3, a–c, shows Fourier spectra of the red parts of the initial experimental spectra, obtained during the illumination of (CH_2), Al, and Pb targets, respectively. On the spectra obtained through the use of lead targets we can clearly see maxima at 6, 12, and 24 GHz, which correspond to the first, second, and third subharmonics of the ion acoustic frequency, since the frequen-

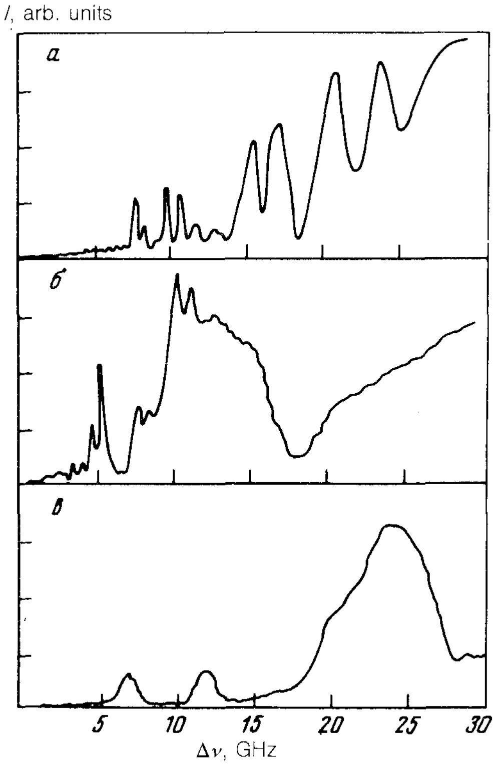

FIG. 3.

cy shift of the Stokes component of the stimulated Brillouin scattering is $\Delta\omega = 2K_0c_s \simeq 50$ GHz, according to previous measurements of the electron temperature,[8] $T_e \sim 800$ eV. As we go to targets of lighter elements, we find that the spectra become substantially more complex, and a clear identification of subharmonics becomes impossible.

Walsh and Baldis[9] have carried out experiments on the heating of a plasma by the beam from a CO_2 laser and have observed generation of first and second harmonics of the ion acoustic frequency. In our experiments, we observe maxima in the spectrum corresponding to higher harmonics, up to the fifth, of ion acoustic waves during illumination of polyethylene targets. The number of harmonics apparently determines the width of the red part of the spectra, which is at a maximum in the case of the light target, polyethylene ($\Delta\lambda = 600$ Å), and is substantially smaller in the cases of the aluminum and lead targets.

According to Feigenbaum's theory,[10] one possibility for the development of turbulence is the sequential growth of harmonics of the fundamental frequency, subharmonics of the fundamental frequency, and their harmonics.

Figures 2 and 3 provide qualitative confirmation of the conclusions of Ref. 10: As the spectrum becomes richer in harmonics of the fundamental frequency, the number of components with $\omega < \omega_0$ also increases. We should stress, however, that it is not possible to directly compare the experimental results with the conclusions of the theory of Ref. 10 or the numerical calculations of Ref. 11, since under our experimental conditions the onset of the ion acoustic turbulence occurs in a bounded and highly inhomogeneous region. A correct interpretation of the experimental data will require a joint numerical solution of a system of equations for coupled modes analogous to the system of equations of, for example, Ref. 5, and equations describing the hydrodynamics of a laser plasma at power densities $\sim 10^{15}$ W/cm^2.

Nevertheless, the experimental data allow us to assert that these experiments have revealed the first generation of subharmonics and higher harmonics of the ion acoustic frequency in a laser plasma at a power density $\sim 5 \times 10^{14}$ W/cm^2 of the beam from a CO_2 laser.

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