Periodic bursts of stimulated Madel'shtam–Brillouin scattering in the self-focusing of laser beams in a plasma

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The dynamics of stimulated Mandel'shtam–Brillouin scattering and of the self-focusing in a plasma is studied. The scattered light takes the form of intense, periodic bursts.

The effect of self-focusing of laser beams on the stimulated scattering processes and, in particular, on the stimulated (Mandel'shtam)–Brillouin scattering (SBS) was initially discussed in the 1960s (see, e.g., Refs. 1 and 2). It has recently become a topic of special relevance, as applied to plasma, in view of the progress in research on controlled thermonuclear laser fusion (CTLF) (Ref. 3).

In considering this problem, the model of steady-state self-focusing is usually used (see, e.g., Refs. 4 and 5). However, in a hot plasma, in which the basic physical mechanisms which determine the nonlinear response are linked with the redistribution of the density, it takes a rather long time to establish it.

In analyzing the strictional nonlinearity, most typical for a hot plasma, we have considered in this experimental study the dynamics of the density perturbation which arises during the self-focusing. We have shown that a joint development of self-focusing and stimulated Brillouin scattering occurs in such a way that the scattered light takes the form of short, intense, periodic flashes, although the time-averaged scattering level is rather low. There are many experimental data on hot plasma[3] which can be clearly explained in terms of the stimulated Brillouin scattering.

Let us consider a layer of transparent plasma of thickness l, on which an axisymmetric beam of electromagnetic radiation with a frequency ω, wave number $k_z = k$, amplitude ϵ_1, and radial dimension a is incident normal to the boundary from the left ($z=0$). Let us also consider a beam of backscattered light (due to the stimulated Brillouin scattering) with an amplitude ϵ_{-1} and frequency $\omega - \Delta\omega$, where $\Delta\omega \simeq 2kv_s$ (here v_s is the speed of sound). These beams produce two types of density perturbations in the plasma: small-scale acoustic waves ($k_s \simeq 2k$), which are associated with SBS, and large-scale perturbations, which are linked with self-focusing. To describe the first kind of perturbation, we will use the so-called damping-sound approximation (the mean free path of sound is shorter than the amount by which its amplitude changes). To describe the second kind of perturbation, the slower density perturbation, δN, we will use the equations of the acoustic theory, with driving ponderomotive force. Under such assumptions, the basic system of equations has the form

$$\left[i\left(\beta\frac{\partial}{\partial\tau}+\sigma\frac{\partial}{\partial z}\right)+\Delta_\perp - A - i\sigma G|E_{-\sigma}|^2\right]E_\sigma = 0\,, \tag{1}$$

$$\left(\frac{\partial^2}{\partial\tau^2}+2\hat{\Gamma}_s\frac{\partial}{\partial\tau}-\Delta_\perp\right)A = \alpha\Delta_\perp\sum_{\sigma=\pm1}|E_\sigma|^2, \tag{2}$$

where $\sigma = \pm 1$, $\tau = tv_s/a$, $\Delta_\perp = (1/\rho)(\partial/\partial\rho)[\rho(\partial/\partial_\rho)]$, $\rho = r/a$, z is the longitudinal coordinate normalized to $2ka^2$, $E_\sigma = \epsilon_\sigma/E_0$, E_0 is the maximum amplitude of the beam incident on the $z=0$ boundary, $A = (\omega a/c)^2\delta N/N_0$, $\alpha = (\omega_p a v_E/2cv_{T_e})^2$, $\beta = 2\omega a v_s/c^2$, $v_E = eE_0/m\omega$, $v_{T_e} = eE_0/m\omega$, $v_{T_e} = \sqrt{T_e/m}$, T_e is the temperature of the plasma electrons, $\hat{\Gamma}_s = a\hat{\gamma}_0/v_s$, $\hat{\gamma}_0$ is an operator which takes into account the damping due to the viscosity and ion–ion collisions, $G = kv_s\alpha/\gamma_s$ is a coefficient which describes the interaction of the beams due to the SBS, and γ_s is the attenuation rate of the scattered sound.

The incident beam ($\sigma = 1$) is assumed to be Gaussian at the boundary, with a plane phase front [$E_1(\rho;z=0;\tau) = f(\tau)\exp(-\rho^2)$, where $f(\tau)$ characterizes the change in the boundary amplitude as a function of time]. The scattering amplitude of the beam ($\sigma = -1$) also has a Gaussian distribution at the boundary:

$$E_{-1}(\rho;L;\tau) = E_b\exp(-\rho^2/a_0^2), \tag{3}$$

where E_b is the "seed" amplitude, and a_0 is the dimensionless width. At $a_0 \gg 1$, the amplitude (3) is nearly constant at the width of the incident beam.

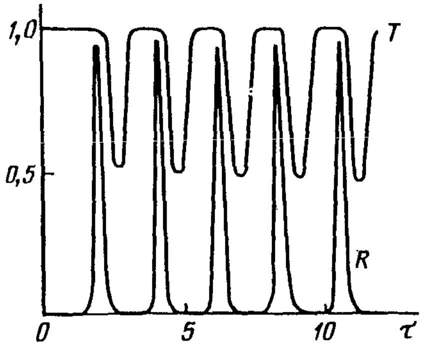

FIG. 1. Time dependence of the SBS reflection R and of the transmission T.

The boundary conditions of the transverse coordinate correspond to the field symmetry and density perturbations at the axis $\rho = 0$, and to their decay at infinity (in reality, at $\rho_{\max} \gg 1$). The initial conditions correspond to the absence of a perturbed density.

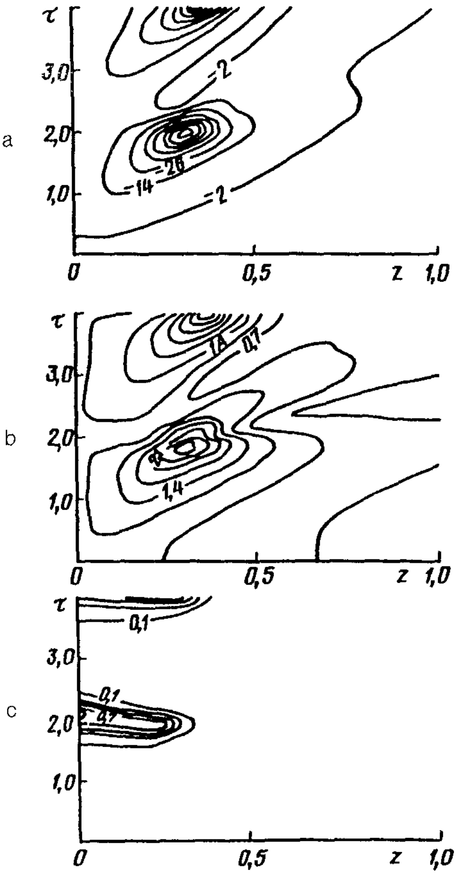

FIG. 2. Lines of (a) the density level and of the amplitude of the light (b) incident on and (c) scattered by the z,τ plane at $\rho = 0$.

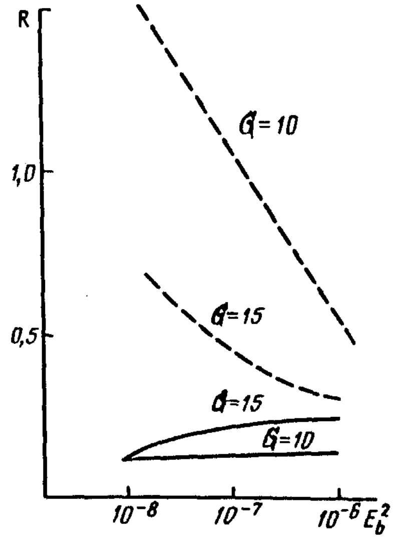

FIG. 3. Average SBS reflection (solid curves) and maximum SBS reflection (dashed curves) versus the seed level E_b^2 for two values of the parameter G.

In solving the posed problem, it is legitimate to use the results of the basic, steady-state theory of SBS as a guideline.[1] According to this theory, the amplitudes $E_{\pm 1}$ do not depend on the time τ or on the transverse coordinate ρ; $A=0$, $G=0$ in Eq. (1) when $\sigma=1$. For $f(\tau)=1$, it follows from Eq. (1) that the dimensionless energy density of the SBS which escapes through the boundary $z=0$ is $I_{-1}=I_0 \exp \times[(G \tan^{-1} 4L)/2]$, where $I_0=E_b^2/8\pi$. In the limit $L \gg 1$, the reflection coefficient of SBS is commensurate with unity for $E_b^2 \simeq 10^{-7}$ when $G \simeq 20$.

In the solution of the posed problem we will use the values of G in the interval 10–15. In the case of seed intensity, 10^{-6}–10^{-8}, and disregarding the self-focusing, these values of G correspond to the small coefficient of the SBS (10^{-3}). The parameter α is assumed to be 8.4, which is slightly higher than the value at which, according to the steady-state theory (disregarding SBS), self-focusing should arise[2] ($\alpha_{\text{th}}=7.54$).

Figure 1 shows the time dependence of the reflection coefficients ($f=1$ at $\tau>0$) $R=\int_0^{\rho_{\max}} d\rho\rho|E_{-1}(z=0;\tau,\rho)|^2/S_0$ and transmission coefficients $T=\int_0^{\rho_{\max}} d\rho\rho|E_1(z=L;\tau;\rho)|^2/S_0$, integral in the transverse coordinate, where $S_0=\int_0^{\rho_{\max}} d\rho\rho|E_1(z=0;\rho,\tau)|^2$. We used the parameter values $G=10$, $\beta=1$, and $E_b^2=10^{-7}$, which correspond specifically to the interaction of the laser beam of wavelength 0.5 μm, intensity 10^{14} W/cm^2, and radius 60 μm, with the plasma of density 2×10^{19} cm^3 and temperature $T_e=500$ eV. We see that SBS emission occurs periodically (every 0.6 ns) as short bursts (60 ps), which correspond to the decrease in the transmission of the light incident on the plasma slab.

The physical reason for such a pulsed SBS mode can be understood by examining Fig. 2, which plots the lines of constant values of the density and amplitude of the light which is incident on the z,τ plane and scattered by it at $\rho=0$. At first, before the large-scale change in the plasma density begins, the SBS reflection is small and all of the light passes through the layer. The density dip, which is caused by the beam initially near the $z = 0$ boundary and which is involved in focusing the light, moves away from it and increases in magnitude. The intensity peak, which creates the density dip and which maintains it, therefore also moves away from the boundary.[6] At the time $t \simeq 2a/v_s$ ($\tau = 2$), the intensity peak is situated at the point $z_0 \simeq 0.6ka^2$ and is so large that it causes a considerable stimulated Brillouin scattering. Because it depends exponentially on $|E_1|^2$, this process is triggered abruptly, and in a time $\sim z_0/c$ nearly all of the incident-beam light in the region between 0 and z_0 is scattered. The density dip which is not supported by the electromagnetic field pressure undergoes a relaxation before the next portion of light arrives. As a result, the system returns to the ground state, and the process begins again.

Experimental observation of SBS light bursts in plasma was reported in Refs. 7–10.

An important feature of the dynamic SBS regime which we are considering is the fact that the time-averaged reflection, $\overline{R} = \int_0^{\tau_0} R(\tau) d\tau$ (τ_0 is the time between the bursts) depends only slightly on the parameter G, which is determined by the intensity of the pump wave, and on the seed energy (Fig. 3). Such a weak dependence at the 1–10% level has indeed been frequently observed experimentally,[3] which is indirect confirmation of the existence of the self-adjusting scattering mechanism which we have been discussing.

There have been many experimental studies,[3] in which stimulated Raman scattering radiation bursts and bursts at the harmonic $3/2\omega$ have been observed in plasma. It is possible that these effects are a manifestation of the time evolution of the intensity of radiation in a plasma which we have studied.

We believe that SBS bursts, similar to those observed by us, occur as a result of the filamentation of a laser beam.[10]

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