Observation of a coherent generation of an anti-Stokes component of scattered microwave radiation in a plasma

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The generation of an anti-Stokes component of scattered microwave radiation has been observed. The effect stems from the excitation of a coherent parametric process—an absolute $l \to l' + s$ instability—in the inhomogeneous magnetized plasma.

According to Refs. 1 and 2, a spatial inhomogeneity of a plasma leads to not only an increase in the thresholds for parametric decay instabilities, because of a convective transfer of energy out of the narrow region in which the three-wave mixing occurs, but also a saturation of these instabilities even in the linear approximation. The parametric instabilities reduce to an incoherent process: a convective growth of the equilibrium plasma-wave noise. At the same time, many possibilities for the excitation of a coherent parametric process—an absolute instability—in an inhomogeneous plasma have been pointed out in the literature. In general, such processes occur if at least some of the energy removed from the region of the three-wave mixing by convection can return to this region, i.e., if there is a feedback loop. This possibility was first pointed out by Rosenbluth.[2] This situation arises if the decay conditions for the three-wave mixing, $k_0(\omega_0,z) = k_1(\omega_1,z) + k_2(\omega_2,z)$, are satisfied at two points, rather than at just one, and if the group velocities of the waves are in opposite directions. This mechanism for the excitation of an absolute instability has been studied experimentally[3] in the particular case of the stimulated Raman scattering of laser light in a plasma with a parabolic density profile. The stimulated Raman scattering was observed under conditions such that there clearly existed two synchronization points for the process $t \to t' + l$, and a feedback loop was possible. However, Villeneuve and Baldis[3] did not report any unambiguous evidence for the excitation of specifically the absolute instability $t \to t' + l$. In particular, they did not establish that the process was coherent.

In the experiments that we are reporting here, the mechanism proposed in Ref. 2 for the excitation of an absolute instability was studied for the case $l \to l' + s$, which occurs in an inhomogeneous magnetized plasma. We used the experimental apparatus of Ref. 4, in which an argon plasma was produced by electron cyclotron breakdown. This plasma was inhomogeneous both radially and axially: $\omega_{pe} = \omega_{pe}(r,z)$. The values of the experimental parameters were $B = 3$ kHz, $T_e = 2$ eV, $p_{\mathrm{Ar}} = (1\text{–}2) \times 10^{-2}$ Torr, and $n_e = 10^{12}\text{–}10^{10}$ cm^{-3}. An oblique plasma wave (Langmuir wave) l_0 (the fundamental Trivelpiece-Gould radial mode of an axially nonuniform plasma-filled waveguide) was launched in the plasma by a waveguide launching device at the frequency $f_0 = \omega_0/(2\pi) = 2350$ MHz. Near the point $\omega_{pe}(0,0) = \omega_0$, where the relation

$\omega_{pe}^2/\omega_0^2 = 1 - (z/a) - (r^2/b^2)$ holds ($a \simeq 5$ cm, $b \simeq 0.4$ cm), the wave is converted into a "warm" plasma wave, and there are sharp increases in the field and the longitudinal wave number k_0, the latter being found from the equation

$$3r_d^2 k_m^2 - \frac{z}{a} - \frac{2(2m+1)}{k_m b} = 0 \qquad (1)$$

with $m = 0$.

In this region we had previously observed[5] the excitation of a stimulated-backscattering instability $l_0 \rightarrow l_0' + s$, which occurs at $P_0 \sim 10$ mW and which gives rise to a Stokes component in the scattering spectrum with a frequency shift $f_0 - f_0' \simeq 3$ MHz. At a higher power, $P_0 \gtrsim 100$ mW, the Stokes component is suppressed, and at the same time an anti-Stokes component with a frequency shift $f_0' - f_0 \simeq 0.8$–1 MHz appears in the scattering spectrum. Under certain discharge conditions, the suppression of the Stokes component of the scattering occurs near the threshold, even at $P_0 \lesssim 20$ mW, and this suppression is total. In this case the scattering spectrum has a series of very narrow, uniformly spaced lines (Fig. 1a). The appearance of an anti-Stokes component in the spectrum can be linked in a natural way with a scattering by an ion acoustic wave of frequency $f_s \simeq 1$ MHz propagating opposite the pump wave: $l_0 + s \rightarrow l_0'$. One possible mechanism for the excitation of such a wave is an ionic acoustic instability excited in the plasma by an electron current which compensates for the loss of fast electrons accelerated by the wave.[6] However, that mechanism is incapable of explaining the very high coherence of the scattered signal, which is seen in the

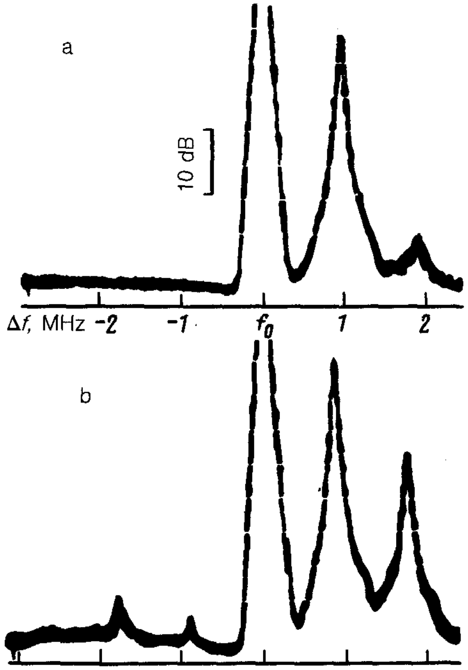

FIG. 1. Spectrum of the scattered signal. a—Without; b—with the effect of the multigrid analyzer.

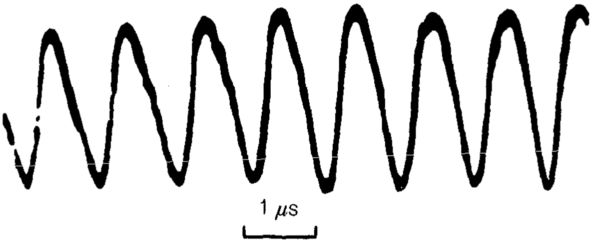

FIG. 2. Oscilloscope trace of the signal from the microwave detector.

sinusoidal shape of the beats of the pump and the scattered wave. These beats were observed with a microwave detector in a waveguide (Fig. 2).

An alternative mechanism for the excitation of an ion acoustic wave propagating opposite the pump wave is a parametric instability of a stimulated forward scattering, $l_0 \to l_1' + s$. This process would result in the excitation of the first radial mode l_1', at the frequency $f_0 - f_s$, in addition to the ion acoustic wave. This wave would propagate in the same direction as the pump wave and would be absorbed in the plasma. Calculations from Eq. (1) show that the decay conditions for the process $l_0 \to l_1' + s$, specifically, $k_0(z) = k_1(z) + k_s$, $k_s < 0$, can be satisfied at two spatial points, z_1 and z_2 (Fig. 3). A coherent parametric process—an absolute instability—may be excited as a result, by the mechanism predicted in Ref. 2. The curves of $k_0(z)$ and $k_0(z) - k_s$ are tangent at the frequency $f_s \simeq 0.9$ MHz, and the frequency of the ion acoustic wave

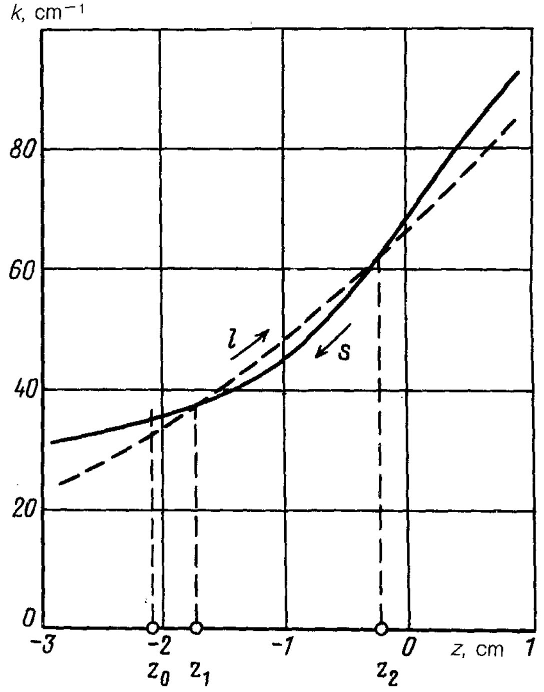

FIG. 3. Dispersion curves of $k_1(z)(l)$ and $k_0(z) - k_s(s)$. The arrows show the directions of the group velocities of the waves (dimensionless units).

corresponding to the excitation of a high-index natural mode of the feedback loop, $m \gg 1$, is determined by

$$\int_{z_1}^{z_2} (k_0 - k_1 - k_s) dz = 2\pi (m + \frac{1}{2}). \tag{2}$$

A numerical calculation has shown that with $m = 0$ we would have $f_s \simeq 0.85$ MHz. The threshold for the excitation of the absolute instability $l_0 \to l_1' + s$ is determined by the inhomogeneity of the plasma and by the damping of the ion acoustic wave:

$$S_{sl}(z_1) S_{ls}(z_2) \exp[-k_s''(z_2 - z_1)] = 1, \tag{3}$$

where S_{sl} and S_{ls} are the parametric-conversion coefficients at decay points z_1 and z_2, and k_s'' is the damping rate of the acoustic wave. The numerical value predicted by (3), $P_{\text{th}} \simeq 12$ mW, is close to the value found experimentally: $P_0 \approx 20$ mW.

Note that the coherent anti-Stokes component of the scattering which is observed is a result of the secondary scattering process $l_0 + s \to l_0'$, which occurs at the point z_0, outside the feedback loop, where the condition $2k_0(z_0) = k_s$ holds (Fig. 3). As was mentioned above, the first Stokes component of the scattering, l_1', is not observed in this formulation of the experiment, since it is propagating in the direction opposite the waveguide. To detect it, we carried out a special experiment. A fast-particle analyzer was moved along the axis of the system. When the surface of this analyzer approached the mixing region (this time was identified on the basis of the longitudinal distribution of the plasma glow), the wave l_1' was reflected, and a Stokes component appeared in the spectrum of the scattered signal, at the position symmetric with respect to that of the anti-Stokes component (Fig. 1b).

In summary, this experiment has resulted in the first observation of a coherent regime of an absolute parametric instability of an inhomogeneous plasma, excited by the mechanism proposed by Rosenbluth.[2]

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