Observation of coherent anomalous parametric reflection of microwave power from a plasma

V. I. Arkhipenko, V. N. Budnikov, E. Z. Gusakov, and L. V. Simonchik
A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, Leningrad;
Institute of Physics, Academy of Sciences of the Belorussian SSR

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A coherent parametric scattering of microwave power by a plasma has been observed. This scattering occurs both near the threshold for the onset of the absolute parametric instability $l \rightarrow l' + s$ and well above this threshold, where the anomalous reflection of microwave power is nearly total.

According to a widespread point of view, the application to a plasma of electromagnetic radiation at a power level well above the threshold for a parametric instability excites a large number of internal degrees of freedom in the plasma, which goes into a turbulent state characterized by broad spectra of excited waves.[1,2] The coherent wave processes which are so important in (for example) nonlinear optics are regarded as negligible in this approach to the description of the wave interaction in a plasma.

In the present letter we describe an experiment in which, in contrast, the spatial and temporal coherence of the interacting waves appears to play a governing role. This experiment was carried out in a weakly ionized argon plasma produced in a glass tube about 1 m long and 2.5 cm in diameter immersed in a longitudinal magnetic field $H = 3$ kOe. The plasma was inhomogeneous in both the radial and axial directions[3]: $n_e = n_e(r,z)$, $n_e < 10^{12}$ cm^{-3}, $T_e = 2$ eV. An oblique plasma wave (or "oblique Langmuir wave") was excited by a waveguide device in the plasma in the form of the fundamental radial Trivelpiece-Gould mode l_0 at the frequency $f_0 = 2350$ MHz. The dispersion relation for this mode is $K_\perp^2 = [(\omega_{pe}^2/\omega^2) - 1]K_\parallel^2$. Near the point of the linear conversion of the oblique plasma wave into a warm plasma wave (the focus), where the condition $n_e(o,z) = n_c = \pi f_0^2 m_e/e^2$ holds, the wave slows substantially,

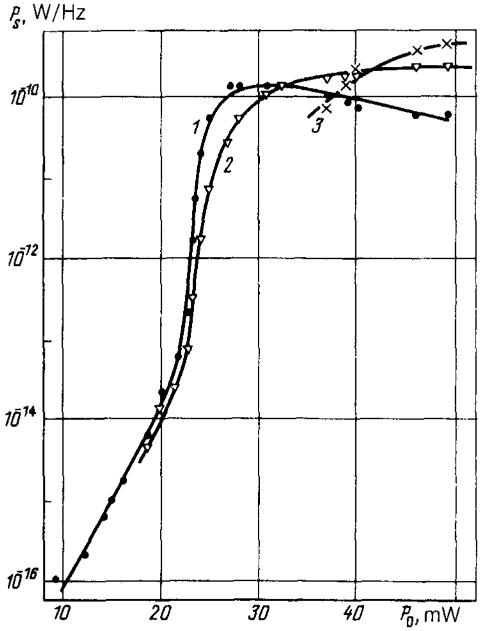

FIG. 1. Amplitude of the components of the spectrum of the scattered signal versus the power.

and its electric field reaches a maximum. Here the parametric instability $l_0 \to l_0' + s$ is excited first at $P_0 > 10$ mW. At a low power level, $P_0 < 20$ mW, the parametric interaction is incoherent and reduces to the spatial amplification of the equilibrium ion acoustic noise near the point of the resonance for the process $l_0 \to l_0' + s - z_0$, where the condition $2k_{\parallel 0}(z_0) = 2\pi f_s / c_s$ holds. A backscattered fundamental radial Trivelpiece-Gould mode, l_0', at the frequency f_0-f_s is excited in this process. This backscattered mode is detected in the waveguide system as a satellite on the fundamental frequency f_0. The spectrum of the scattering signal is noisy and wide ($\delta f \cong 1$ MHz); its frequency shift corresponds to $f_s \cong 3$ MHz; and the satellite amplitude p_s is an exponential function of the pump power (Fig. 1).

With increasing power of the pump wave, $P_0 > 20$ mW, the dependence $p_s(P_0)$ becomes substantially steeper (curve 1 in Fig. 1). In the plasma a coherent wave process—an absolute parametric instability—is excited by means of the $l_0 \to l_0' + s$ spatial amplification. The mechanism for this instability appears to rest on a multimode nature of the pump wave.[4] The "feedback loop" around the amplifier at the points $z = z_0$ is closed at the point $z = z_1$ as a result of the process $l_1 \to l_0^1 + s$, in which the first radial pump mode, l_1, interacts with the l_0^1 wave and excites an ion acoustic wave, which returns energy to the region of the decay $l_0 \to l_0^1 + s$. A narrow line appears at the frequency $f \cong f_0$—3.5 MHz in the spectrum of the scattered signal when the threshold for the absolute instability is exceeded. Continuous measurements of the spectrum in discharge regimes with small fluctuations of the plasma density reveal 100 kHz $< \delta f <$ 200 kHz (curve 1 in Fig. 2). This value is only an upper estimate of the actual linewidth and is apparently determined by changes in the frequency

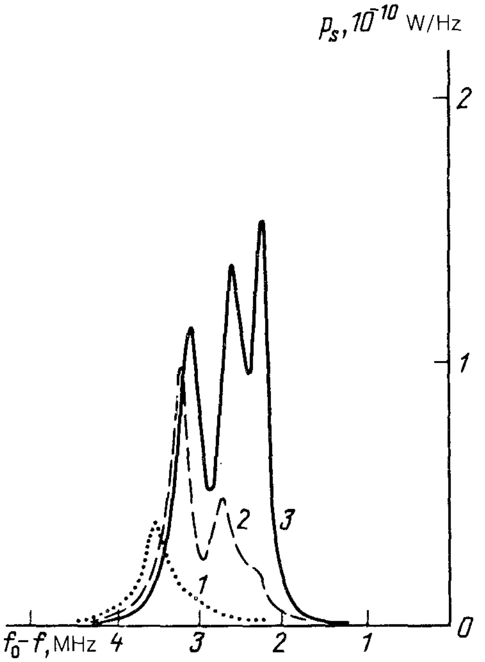

FIG. 2. Shape of the spectrum at various pump power levels.

of the line due to variations in the parameters of the plasma over long times. Pulsed measurements over the time $\tau = 10$ μs yield the estimate $\delta f < 100$ kHz for the linewidth of the scattered signal. At $P_0 > 30$ mW the increase in the amplitude of the satellite reaches saturation at a level $p_s = 2 \times 10^{-10}$ W/Hz. An estimate shows that this scattering level corresponds to a nearly total parametric reflection of a wave near the focus. At this power level, a second narrow line, shifted $f_0 - f = 2.8$ MHz (curve 2 in Fig. 2), appears in the spectrum of the scattered signal. Curve 2 in Fig. 1 shows the P_0 dependence of the amplitude of this second line. At $P_0 > 30$ mW the amplitude of the first line begins to decrease, while the amplitude of the second line increases. The strong parametric reflection is also coherent, but in a denser plasma, in scattering by sound of frequency $f_s = 2.8$ MHz.

When the power is raised further, we see the next stage in this peculiar series of events. Yet another narrow line, at a frequency $f = f_0 - 2.4$ MHz, appears in the spectrum, and it gradually becomes higher than the other lines (curve 3 in Fig. 2).

It is natural to link discrete lines in the spectrum of the scattered signal with frequency of natural modes of the feedback loop, i.e., of the coherent resonant structure which arises in the plasma in the field of a multimode pump wave and which leads to an absolute parametric instability. The frequency of the ion acoustic waves that are excited is determined by the quantization condition on the phase shift of the waves in the feedback loop. A calculation shows that the frequency difference between adjacent lines in the spectrum is determined by the propagation time of the ion sound in the loop: $\Delta f = f_1 - f_2 = c_s/(z_0 - z_1)$. The length of the feedback loop depends on the

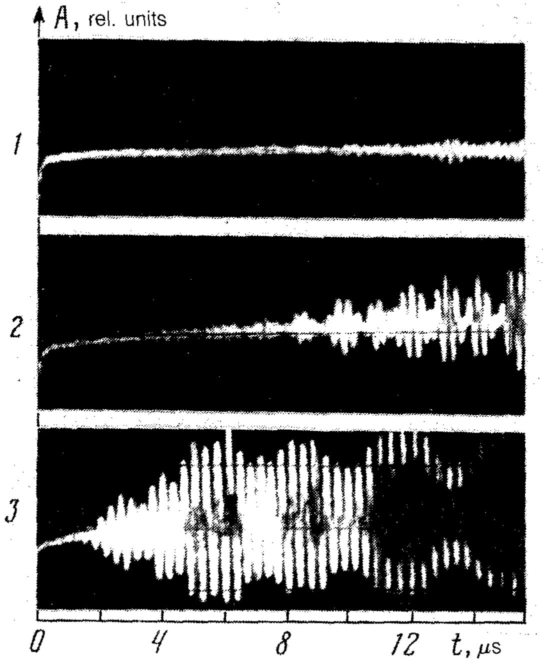

FIG. 3. Onset of the scattered signal.

frequency of the acoustic wave, so that we have $\Delta f = 0.5$ MHz at $f_s = 3$ MHz and $\Delta f = 0.3$ MHz at $f_s = 2$ MHz. The spectra found experimentally (Fig. 2) agree with this estimate.

At a pump-wave power $P_0 = 30$ mW, the frequency of each of the lines in the scattered signal begins to decrease smoothly (Fig. 2). This behavior is apparently due to an increase in the longitudinal length scale of the plasma variations and a proportionate increase in the length of the feedback loop, $z_0 - z_1$, due to additional ionization at the focus.

We studied the dynamics of the scattered signal by measuring the time evolution of the amplitude of the detected signal in the waveguide system, $A(t)$. It can be seen from oscilloscope trace 1 in Fig. 3 that slightly above the threshold ($P_0 = 25$ mW) the rise time of the sinusoidal component of the signal is long ($\tau = 12$ μs), apparently because of the small growth rate of the absolute instability near the threshold. As the power is increased, the wave amplitude increases, and the rise time of the waves decreases to $\tau = 7$ μs at $P_0 = 30$ mW (trace 2 in Fig. 3). In this case the $A(t)$ dependence becomes more complicated: beats of sinusoidal signals of approximately the same frequency. The scattered signal remains coherent and sinusoidal even at a high power level, $P_0 = 40$ mW (trace 3 in Fig. 3), but the rise time of the signal decreases to 2–3 μs when the threshold is exceeded by this amount.

In the experiments which we have described here the coherent interaction of waves was manifested clearly and could be seen easily because of the particular features of the experimental situation: A large number of radial oscillation modes are not excited in the system. It may be that coherent phenomena are also important in other cases involving the interaction of intense waves with plasmas, but an identification of the role played by these effects may be complicated by the large number of degrees of freedom that are excited.

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