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Self-Modulation of High Frequency Electric Field and Formation of Cavities in Plasma

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Abstract

The self-modulation of the oscillating electric field is observed when its frequency is near the electron plasma frequency. The localized field due to the self-modulation is found to make depression in the plasma density.

An intense high frquency electric field applied to a plasma introduces interesting nonlinear wave phenomena. The parametric decay instability has been intensively explored in connection with the heating of ionospheric and laboratory plasmas[1]. Observation of the oscillating two-stream instability[2] has, however, been reported only at the lower hybrid frequency[3]. Some evidence for this instability in a double plasma device without magnetic field has been observed[4]. The basic process involved in this instability is understood in terms of the ponderomotive force which is due to spatially nonuniform oscillating electric field[5]. This force expels the plasma from a region where the electric field is strong and makes a cavity in the plasma, which in turn traps the field. The present letter wishes to report an experimental observation of the self-modulation of the applied pump field near the electron plasma frequency and of the formation of localized depression in plasma density.

The high frequency electric field is excited in a cylindrical microwave cavity of 32 cm diam. and 1.5 m length. The argon plasma is produced by a double plasma source[6] and occupies one end of the cavity as shown in Fig.1(a). Typical plasma parameters as measured with Langmuir probes are the electron temperature $T_e \simeq 1.5$ eV, the electron density $n_0 \simeq 5 \times 10^9$ cm^{-3}, the ion temperature $T_i \lesssim 0.2$ eV, the argon pressure $p \simeq 2 \times 10^{-4}$ Torr, and the fluctuation level of the spontaneous background noise

$\delta n/n_0 < 10^{-3}$. The electron Debye length λ_D is 0.1 mm. An antenna placed at the other end of the cavity excites TE_{11} mode in the vacuum region; this mode couples to the dipole mode in the plasma region[7]. The plasma density is radially nonuniform so that a plane where the frequency of the pump $\omega_0/2\pi$ (= 0.64 GHz) equals the local electron plasma frequency $\omega_{pe}/2\pi$ stays in the plasma as shown by dotted line in Fig.1(a). Hereafter, we call this the cut-off surface. A conductor plate which is set in the cavity prevents harmful azimuthal rotation of the electric field. The quality factor of the cavity is 700 when the plasma is loaded. The density perturbations due to the instabilities are detected by observing the electron saturation current to the Langmuir probe, the high frequency electric field by observing the potential difference between two closely spaced wires. The probes are inserted into the plasma in such a way that the disturbance to the pump field is minimized.

In Fig.1(b), the radial distribution of the weak pump field measured by employing interferometer is plotted. We find that the direction of the electric field in a region where $r < r_0$ (specified in the figure) is opposit to that in a region where $r > r_0$. From the fact that E = const. along the electric field E and employing the dielectric constant of the cold plasma, we find the point $r = r_0$ is on the cut-off surface. The corresponding density profile as measured by the Langmuir probe is also shown.

The growth of the instability has been studied by gating the pump power. The typical distribution of the plasma density and of the high frequency field are plotted in Fig.2 at every 1 μ sec. step during the turn-on period of the pump. The power fed into the cavity is 20 W. The sampling technique was employed for this measurement. The plasma density start decreasing at a place near the cut-off surface; then the density depression - cavity - expands toward both the high density side and the low density side with the velocity ($\sim 2 \times 10^5$ cm/sec) which is approximately the same as the ion-acoustic velocity (1.8×10^5 cm/sec). The expanding front eventually forms narrow dip and at the same time another dip starts growing at the place where the former dip appeared. This process is repeated, and an oscillatory structure is eventually formed. The depth of the dip reaches to about 7 % of the unperturbed density. Since the correlation of the density perturbation between each shot of the gated pump is lost after a few repetition of the cycles mentioned above, the sampling technique does not work for a long time after switch-on of the pump.

Figure 2(b) shows the correlation of the intensity of the high frequency field (including self-consistent field) to the density perturbation. The field intensity E^2 is enhanced up to 5 times as large as the original intensity E_0^2 at the position where the density is decreased. The initial growth rate of the high frequency field in the unit of the electron plasma period γ/ω_{pe} is 3×10^{-4}. The growth rate is approximately proportional to the pump power.

In order to check the possibility of spurious effects due to the nonlinear behavior of the Langmuir probe immersed in a high frequency field, the pump power is turned-off after the instability is developed. The density distribution as measured by the electron staturation current is found to be undisturbed by the turning-off of the pump, whereas the high frequency field damps away, immediately after the turn-off. This observation excludes the possibility of detecting the change in the electron saturation current induced by the intense high frequency field through nonlinearity of the probe.

The parametric decay instability is found in the low density region ($\omega_0 > \omega_{pe}$), while the modulational instability mentioned above occurs in the high density region ($\omega_0 < \omega_{pe}$)[8]. The frequency spectra are measured by feeding the pump continuously. Figures 3(a) and (b) show the spectra of the signal detected in the low density region when the pump power is weak and no modulational instability grows. The spectra of the signal detected in the high density region is shown in Fig.3(c) and (d). The two types of instabilities reveal clearly different frequency spectra. The decay instability makes lower sidebands to the pump [Fig.3(a)] and excites an ion-acoustic wave at 0.5 MHz ($\simeq 0.2\ \omega_{pi}/2\pi$) [Fig.3(b)]. Stronger pump makes the spectrum broader. On the other hand, the modulational instability induces strong upper sideband [Fig.3(c)]; the spectrum of the low frequency perturbation is peaked around 150 kHz [Fig.3(d)].

The decay instability grows when the pump power exceeds (0.5-1) W. On the other hand, the threshold of the modulational instability is 5 W which is (5-10) times as large as that of the decay instability.

The measurements of the wave propagation by the interferometer have shown that the electron plasma waves (lower sideband) due to decay instability propagate to both higher and lower density sides. If we follow the spatial profile of the amplitude from the high density side, it sharply rises at the point where $\omega_0 = \omega_{pe}$ and stays fairly flat for 1 cm and then damps with the typical length of 1.5 cm. The damping is presumably due to the Landau damping because the plasma density decreases. The scale length of the density nonuniformity $n_0/(\partial n_0/\partial r)$ is 30 cm ($= 3 \times 10^3 \lambda_D$). The ion-acoustic waves mainly consist of the one propagating to the lower density side and are undamped during much longer distance than the damping length of the electron plasma wave. The ion-acoustic waves remain for a few ten micro-seconds even after the pump is turned off.

The theory of parametric instabilities[1,2] predicts that the oscillating two-stream instability sets in when $E_0^2/16\pi n T_e \geq 4\nu_e/\omega_e$, where ν_e and ω_e are the damping rate and the frequency of the high-frequency oscillation. If we assume a static ion response, the associated density dip becomes $\delta n \simeq n_0 E^2/16\pi n(T_e + T_i)$[9]. From the experimental value of $E^2/E_0^2 \simeq 5$ and from $\nu_e/\omega_e \sim 10^{-4}$ estimated from the collisional damping, we then find $\delta n/n_0 \sim 10^{-3}$ which is much too small as compared with the experimental value of 10^{-1}. However, when the envelope of the high-frequency oscillation and the density dip propagates at the ion-acoustic velocity as we have seen experimentally, a resonant dynamical response of ions takes place, and as a result the density dip increases to[10]

$$\delta n/n_0 \sim (E^2/16\pi n T_e)^{1/2}. \qquad (1)$$

This resonance is broadened by the ion Landau damping which causes a threshold for the occourrence of such a large density dip:

$$(E_0^2/16\pi n T_e)^{1/2} \gtrsim \nu_i/\omega_s, \qquad (2)$$

where ν_i and ω_s are the damping rate and the frequency of the ion-acoustic wave. Combining (1) and (2) and using $\nu_i/\omega_s \simeq 2 \times 10^{-2}$, the value obtained experimentally by the propagation of the ion-acoustic wave, we find $\delta n/n_0 \sim 5 \times 10^{-2}$ which is in reasonable agreement with the observed value.

The stationary solution derived in Ref.10 includes a rarefactory soliton in the overdense region ($\omega_0 < \omega_{pe}$).

The half width D of the soliton is given by

$$D = (18n_0/\delta n)^{1/2}\lambda_D. \qquad (3)$$

If we substitute $\delta n/n_0 = 7 \times 10^{-2}$ (the depth of the left-hand side dip in the bottom trace in Fig.2(a)) and $\lambda_D = 1 \times 10^{-2}$ cm into (3), we have D = 0.16 cm which is about a half of the experimental value. The width of the density dip observed under different conditions is always wider than the prediction of (3). This descrepancy may be due to the Landau damping of the high-frequency oscillation which tends to flatten the perturbation by cutting down the large wavenumber components.

In conclusion, the self-modulation of the oscillating electric field near ω_{pe} is observed. The localized field expels the plasma and makes plasma cavities. At the same time it is found that the modulational instability and the decay instability take place in the high density and the low density regions, respectively.

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Figure Captions

Fig.1. (a) Schematic of the experimental setup. Dotted line indicates the plane where the electron plasma frequency equals the pump frequency. (b) Radial density profile and the distribution of the pump field. A couple of traces indicate the interferometer output when the polarity of the reference signal is inverted.

Fig.2. Evolution of the density (a) and the field intensity (b) distributions. The pump is suddenly applied beginning from t = 0. Pump power = 20 W.

Fig.3. (a), (b) Spectra of the decay instability signal. Pump power = 2.5 W. (c), (d) Spectra of the modulational instability signal. Pump power = 20 W.

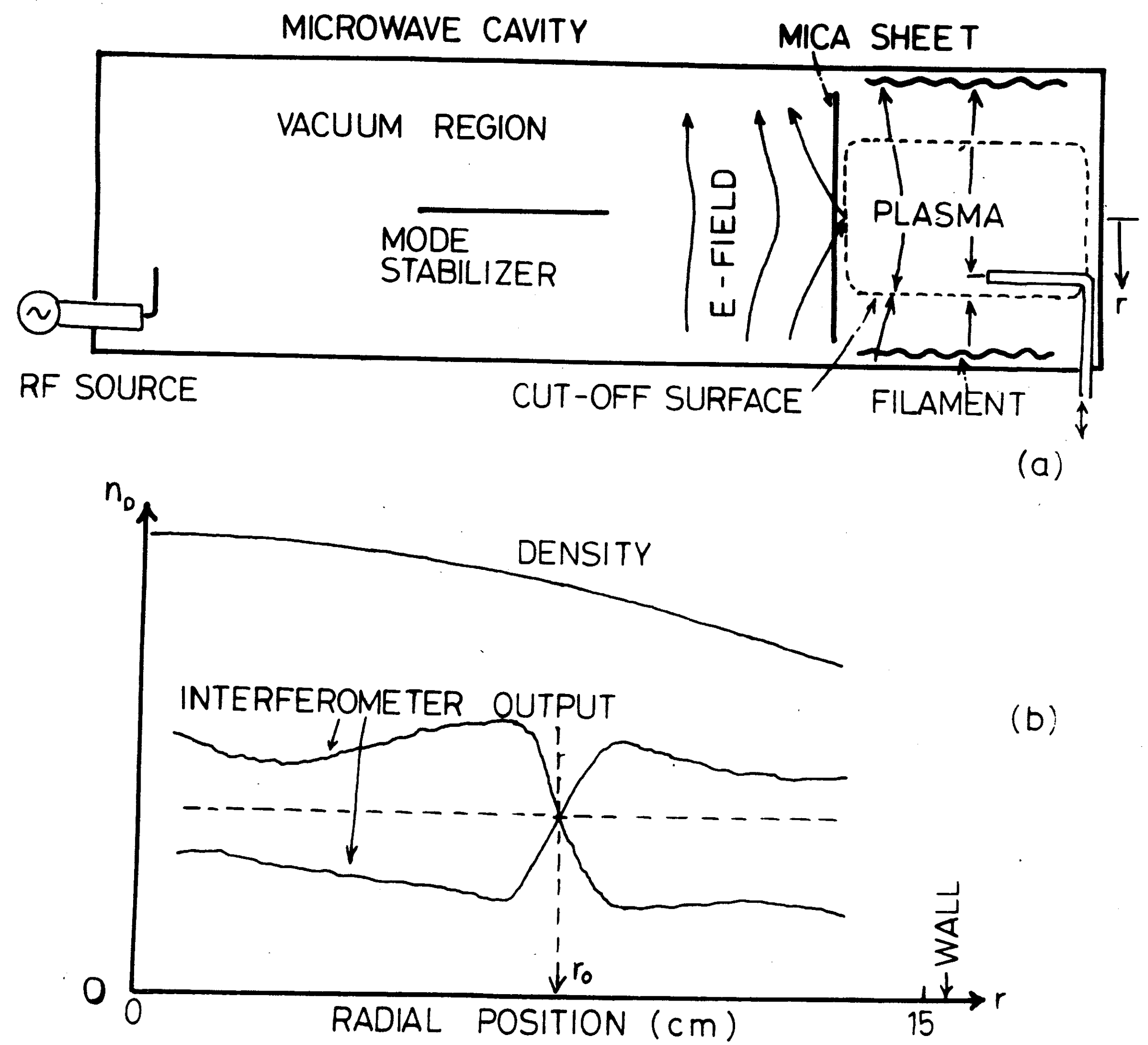
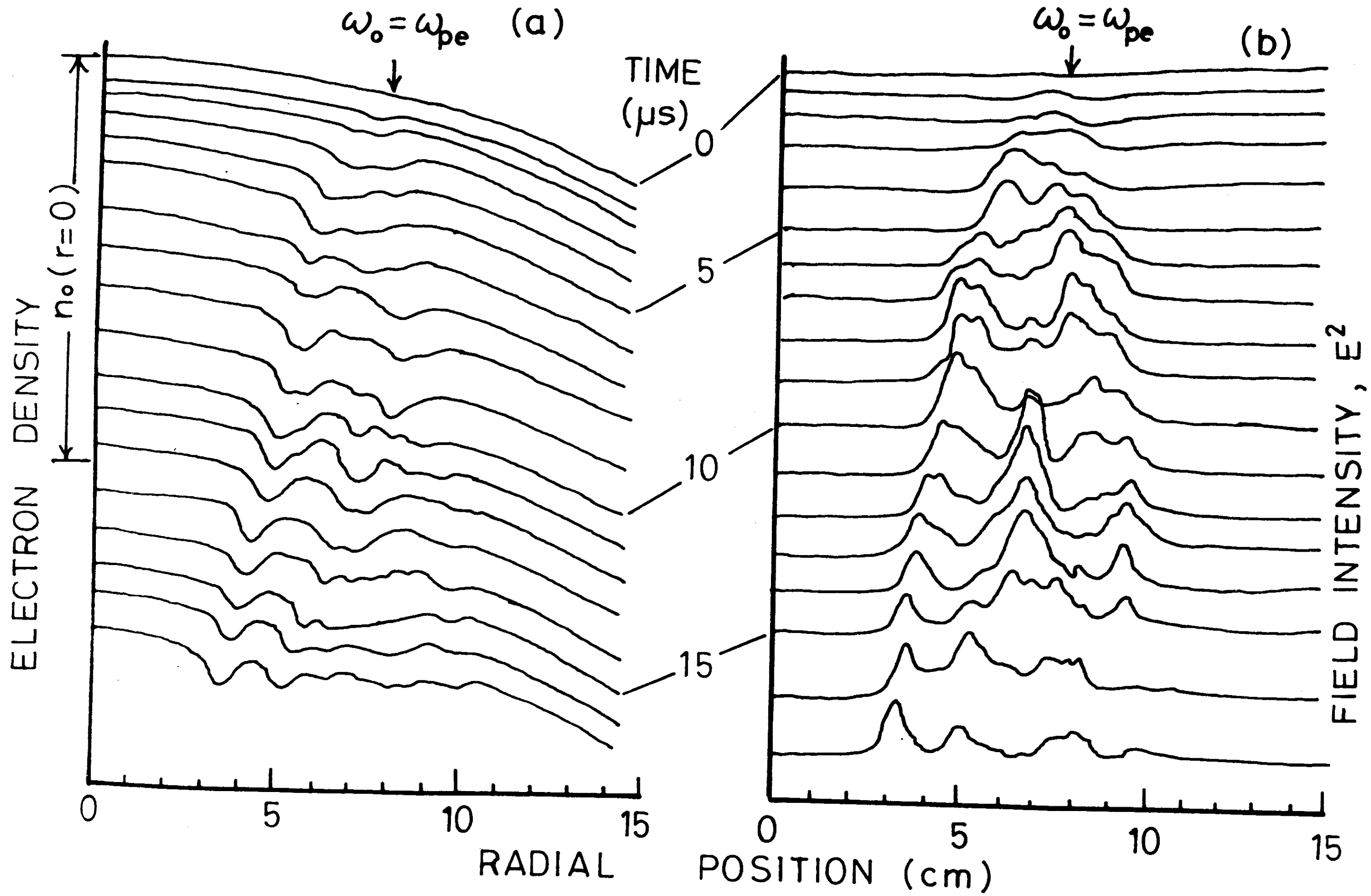

MICROWAVE CAVITY
MICA SHEET
VACUUM REGION
MODE
STABILIZER
E-FIELD
PLASMA
r
RF SOURCE
CUT-OFF SURFACE
FILAMENT
(a)
n_0
DENSITY
INTERFEROMETER OUTPUT
(b)
WALL
r_0
0
0
RADIAL POSITION (cm)
15
r

FIG. 1



ω₀ = ωpe
(a)
ELECTRON DENSITY
n₀(r=0)
0
5
10
15
RADIAL
TIME
(μs)
0
5
10
15
ω₀ = ωpe
(b)
FIELD INTENSITY, E²
0
5
10
15
POSITION (cm)

FIG. 2

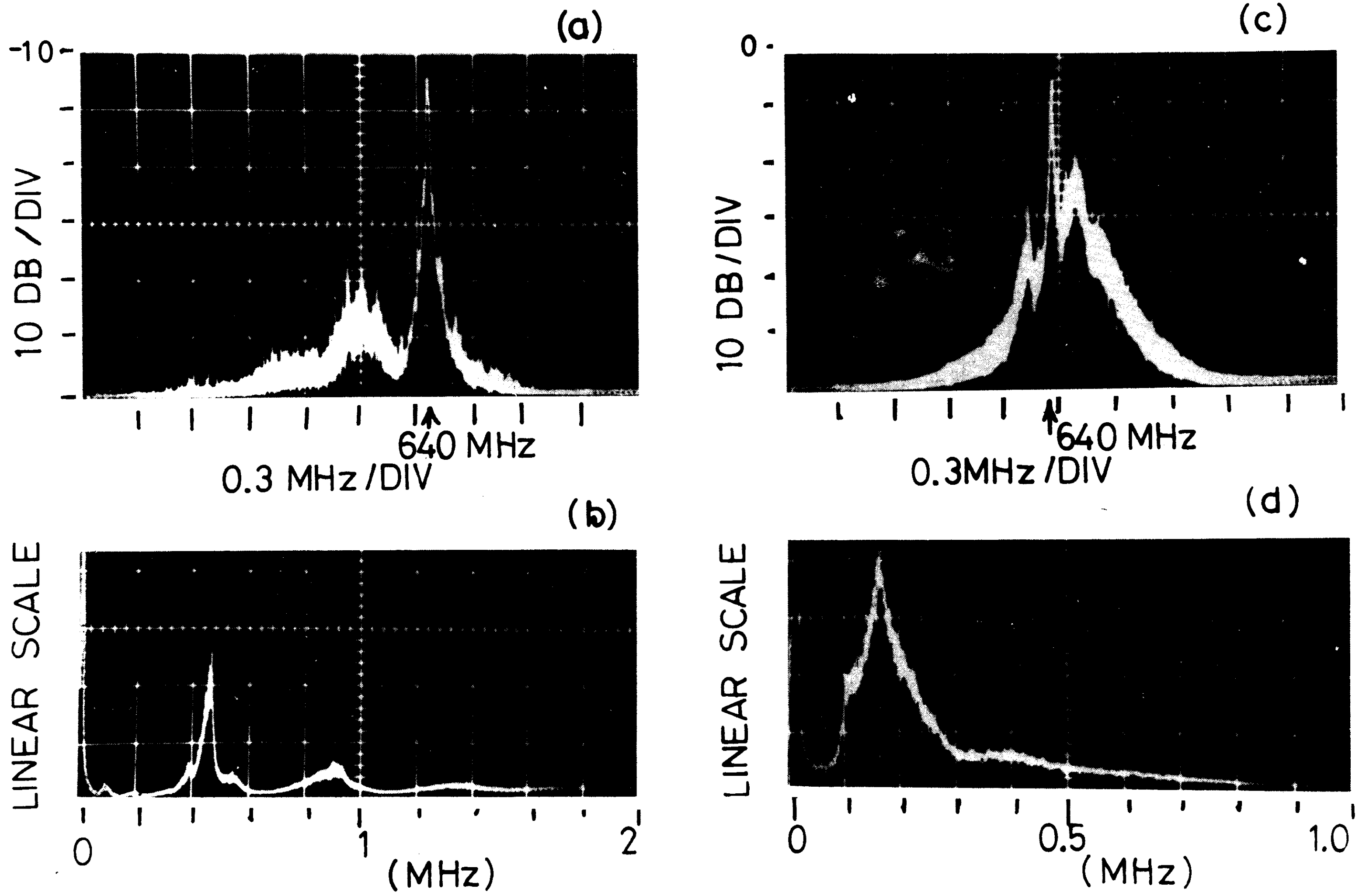

(a)
-10
10 DB / DIV
640 MHz
0.3 MHz / DIV
(b)
LINEAR SCALE
0
1
2
(MHz)
(c)
0
10 DB / DIV
640 MHz
0.3MHz / DIV
(d)
LINEAR SCALE
0
0.5
1.0
(MHz)

FIG. 3