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SELF-INTERACTION OF HIGH-FREQUENCY SURFACE WAVES IN PLANAR PLASMA WAVEGUIDE.

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ABSTRACT

The process of self-interaction of high-frequency surface wave (SW) in plasma-metal waveguide structure is considered in a weak nonlinearity approximation. The estimates for the contributions of two main nonlinearity mechanisms to nonlinear frequency shift of the SW are carried out. Solutions for the nonlinear SW field envelope are treated for stability in respect to longitudinal and transverse perturbations.

The problem of investigations of several types of antennas immersed in magnetoplasma, stimulated theoretical and experimental studies of surface waves propagation along the interface between a metal surface and magnetoactive plasma. The earlier works [1,2] are devoted to studies of dispersion characteristics of SW, propagating along a thin metal wire, immersed along the external magnetic field $\vec{H}_0$ in magnetized plasma. In more recent work [3] theoretical and experimental studies of SW at planar plasma-metal antenna boundary are presented. In this work the results are presented in the linear in respect to the wave amplitude approximation. We also consider wave properties in planar plasma-metal structures [4,5] in the same approximation. The aim of the present paper is to study some nonlinear properties of high frequency (HF) SW im planar magnetoactive plasma-metal structure.

The waveguide structure considered is formed by homogeneous plasma, occupying the half-space $x > 0$ bounded at the plane $x = 0$ by an ideally conductive metal surface. An external magnetic field $\vec{H}_0$ is applied parallel to plasma-metal boundary at z direction. In this paper we consider electromagnetic HF SW, propagating at y direction across the external magnetic field. The frequencies of the SW considered satisfy the following inequality $\omega > \omega_1$, where ω_1 is the upper hybrid frequency. The problem of self-interaction of these waves is treated in a weak nonlinearity approximation (the parameter $\mu = v_E / v_{ph}$ is supposed to be small compared with unity, where v_E is an electron oscillation velocity in the field of SW, v_{ph} is the phase velocity of the SW). In the first in respect to the SW amplitude approximation the dispersion relation between the frequency ω and the wavenumber k_2 of the SW in a dense plasma has the following form

$$\omega_0 = \Omega_e [1 + (c k_2 / \Omega_e)^2]^{1/2} \qquad (1)$$

where Ω_e is tne electron plasma frequency. In the frequency range of our interest the SW are nonreciprocal ($k_2 > 0$).

Under consideration of the SW second harmonic generation we suppose that the latter is not the eigenwave of the strucrture. In this case the amplitude of the signal of frequency 2ω is $\mu^{-1} \gg 1$ times less than the amplitude of the first harmonic and the influence of the second harmonic to the first one is negligible. This is valid if $k_2(2\omega) \neq 2 k_2(\omega)$. In the case considered the second harmonic of the SW is a superposition of the surface type ($\sim exp(-2 \varkappa_1 x)$) and the volume type ($\sim exp(i \varkappa_2 x)$) perturbations. Here

$$\varkappa_1^{-1} \simeq [\omega_e \Omega_e / c \omega \Omega]^{-1}$$

is the skin depth of the SW, $\varkappa_2 \simeq \sqrt{3}\, \Omega_e / c$ is the transverse wavenumber of the second harmonic volume wave, ω_e is the electron cyclotron frequency, $\Omega^2 = \omega^2 - \Omega_e^2$. Thus, in the second approximation alongside with the process of the second harmonic generation of surface type perturbations into volume type ones and a nonlinear energy dissipation, connected with this process take place.

In the second in respect to the SW field amplitude it is necessary to take into account the ponderomotive force action, which leads to the appearence of the static surface perturbations (process $\omega - \omega = 0$), i.e. a process of zero frequency signal generation. Analogously to the second harmonic, static surfase perturbations are not the eigenwaves of the system, and they disappear with the pump wave switch off.

In the third approximation in respect to the SW amplitude one can obtain nonlinear dispersion equation

$$\omega \simeq \omega_0 + Re\, Q |E|^2 + i\, Im\, Q |E|^2 \qquad (2)$$

where ω_0 is defined by expression (1), the second term is a nonlinear frequency shift of the SW and the third term is responsible for nonlinear damping of the SW. It is possible to show that in the task considered here, there are three self-interaction mechanisms:

$$2\omega(s) - \omega = \omega\,,\ 2\omega(v) - \omega = \omega\,,\ 0 + \omega = \omega$$

The first process acts through the surface part of the second harmonic, and the second one acts through the volume part of the second harmonic. The third process acts through the static surface perturbations. All these proceses lead to the appearence of nonlinear response on the main frequency ω . One can show that the imaginary part of Q . is due to interaction $2\omega(v)-\omega=\omega$, and the real part of Q is due to all three above mentioned processes. Investigations of all processes contributions to the SW self-interaction show, that in the considered case the influence of nonlinear energy dissipation is considerable. This means that a presence of an additional energy source is necessary for realization of self-interaction effects. It is also possible to show that the process $0+\omega=\omega$ gives the main contribution to nonlinear frequency shift, and the latter changes its sign near the frequency $\omega = 1,8\Omega_e$ (if $\omega < 1,8\Omega_e$ then $Re\, Q<0$, and if $\omega > 1,8\Omega_e$, then $Re\, Q>0$).

Following the method, presented in [6], we obtain nonlinear Shredinger equation, which corresponds to nonlinear equation (2):

$$i\left(\frac{\partial E}{\partial t} + v_g \frac{\partial E}{\partial y}\right) + P_{\parallel}\frac{\partial^2 E}{\partial y^2} + P_{\perp}\frac{\partial^2 E}{\partial z^2} + i\nu E = = (Re\, Q + i\, Im\, Q)|E|^2 E + f \tag{3}$$

where v_g is the SW group velocity , ν - linear decrement of collisional damping, f - is an external source of electromagnetic signal, which compensates dissipation losses in the system, $P_{\perp} = c^2/\omega_0$, $P_{\parallel} = \Omega_e^2 c^2/2\,\omega_0^3$.

One can show that the solutions of (3) are stable in in the frequency range $\omega > 1,8\Omega_e$, and unstable in respect to longitudinal and transverse perturbations if $\omega < 1,8\Omega_e$. The evolution of unstable transverse perturbations leads to formation of the structure with a soliton profile of intensity

$$E = B_1\, ch^{-1}\left[B_1\sqrt{\theta_1}\,(z-z_0)\right] exp\left[i\,\frac{\theta_1 B_1^2 (y-y_0)}{2\,\kappa_{20}}\right]$$

where $\theta_1 = -\kappa_2\, Re\, Q/v_g$. For the SW, which are unstable in respect to longitudinal perturbations, the following solution is valid

$$E_1 = \sqrt{2}\; B_2\, ch^{-1}\left[B_2\sqrt{\theta_2}\,(\xi-\xi_0)\right].$$

$$\cdot \exp(i \, Re \, Q \, B^2 t)$$

where

$$\theta_2 = - Re\, Q / 2P_{11} \, , \quad \xi = y - v_g t \, , \quad \xi_0 = \xi(t=0).$$

A stationary state with antisoliton density profile is a result of evolution of the stable transverse perturbations, and the antisoliton state realizes for stable longitudinal perturbations.

Note, that in the absence of the external energy source f, the dissipation-type instability may occur in the structure considered.

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