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THEORETICAL ASPECTS OF THE ELECTRONICAL DEVICES OPERATING DUE TO INTERACTION BETWEEN ANNULAR ELECTRON BEAMS AND THE AZIMUTHAL SURFACE WAVES

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Abstract

The paper considers physical basis of the electronical devices operating due to the beam or dissipative instability of the azimuthal surface waves (ASW). The ASW are the electromagnetic surface waves with extraordinary polarization (with field components E_r, E_φ, H_z), they propagate across the axial external steady magnetic field $\vec{B}_0 || \vec{z}$ in the metal cylindrical waveguide with cold plasma filling. The ASW fields are described by Maxwell equations. To solve the problem we use the Fourier method and numerical simulation of the obtained equations. The ASW excitation under the conditions of the beam and dissipative instabilities due to the electron beam motion is examined. We also study the correction to the ASW eigenfrequencies caused by the waveguide chamber noncircularity. The ASW delaing leads to the negative frequency correction. The ASW energy can be emited from the narrow slot in the metallic chamber of the waveguide. We found the optimum wavenumber range where increments values are much greater than those of the ASW decrement caused by their energy radiation.

Introduction

Theory of vacuum electronical devices has been developed completely enough till now: their working parameters are rather close to those theoretically predicted. Utilization of plasma insertions in waveguiding elements of electronical devices allows to achieve much better characteristics than those of vacuum devices. First, frequency range of the generating waves becomes more wide. Second, the top value of the current caused by the beam which is transporting in the device increases. Third, the possibility to control fluently the frequency of the generating waves arises, etc. At the last time annual beams of charged particles become to be used for increasing the efficiency of such electronical devices as gyrotron and laser on free electrons [1]. Increments of beam instabilities and efficiency of transformation of beam particles kinetic energy into the energy of radiating waves increase due to utilization of annual beams as compared with the case of longitudinal propagation of charged particles beams.

Interaction of annual electron beam, rotating between the cylindrical metallic chamber of the device and coaxial plasma insertion, with eigen modes of the waveguide is studied here. These modes propagate across external steady magnetic field with azimuthal wave number m and are called therefore as azimuthal surface waves. Let us consider cylindrical metallic waveguide of the radius R_2 with coaxial plasma insertion of the radius $R_1 < R_2$. Plasma can be gaseous or semiconductor one. Concentration n_p of plasma particles is much greater than that n_b of electrons in beam, $\xi = n_b/n_p << 1$. Electrons of the beam rotate either in steady magnetic field or in crossed $\vec{E}_0 \perp \vec{B}_0$ fields. In the latter case radial electric field $\vec{E}_0$ is produced in the region $R_1 < r < R_2$ with the help of special additional electrodes. The space is supposed to be uniform in z direction $(\partial / \partial z = 0)$.

Delaying of the surface waves in the noncircular chamber

If metal wall of the waveguide is not ring, $R_2 = R_0 \cdot (1 + h \cdot sin(n \cdot \varphi))$, then delaying of the ASW occurs as compared with the case of the ring, $h = 0$, waveguide. Here R_0 is mean value of R_2, the value h is small, $h << \Lambda = (R_0 - R_1) \cdot R_1^{-1}$, n is integer. Such approach allows to model any shape of the metal waveguide cross-section, for example, a magnetron - like one. Frequency correction $\Delta\omega(n)$, caused by the noncircularity of the metallic chamber, appears to be the small value of the second order,

$$\frac{\Delta\omega(n)}{\omega} \sim \frac{-h^2 \cdot \Lambda \cdot m^2 \cdot (m+n) \cdot (m+n)!}{16 \cdot \pi \cdot m! \cdot (\omega \cdot R_1 \cdot c^{-1})^{2+n}} \qquad (1)$$

Dispersion relation

Distribution of electromagnetic field of the ASW inside the chamber was determined from Maxwell equation. It was found that the main part of the ASW energy is located in the region $R_1 < r < R_2$, where $|H_z|, |E_r| > |E_\varphi|$. Dispersion relation, which describes excitation of the ASW by electron beam, is obtained due to applying linear boundary conditions. It has the following form [2],

$$\frac{I'_m(z)}{\psi \cdot I_m(z)} + \frac{m \cdot \varepsilon_2}{z \cdot \psi \cdot \varepsilon_1} + \frac{\Lambda}{k \cdot R_1}\left(k^2 \cdot R_1^2 - \frac{m^2}{\varepsilon_b}\right) = 0, \qquad (2)$$

here $z = k \cdot R_1 \cdot \psi$, $\psi = \sqrt{\varepsilon_1 - \varepsilon_2^2 \cdot \varepsilon_1^{-1}}$, $k = \omega / c$, $b = \gamma \cdot \omega / \omega_c$, $a = \dfrac{m \cdot v_0 \cdot \gamma}{\omega_c \cdot R_1}$,

$\gamma = \left(1 - v_0^2 / c^{-2}\right)^{-1/2}$, $I_n(z)$ is modified Bessel function, index means a derivative,

$$\varepsilon_b = 1 + \frac{2 \cdot \xi \cdot \Omega^2}{\omega_c^2} \sum_{n=0}^{\infty} \left[\frac{n^2 \cdot \gamma \cdot J_n^{2\prime}(a)}{\left(n^2 - b^2\right) \cdot a} + \frac{n^2 \cdot \gamma \cdot J_n^2(a) \cdot v_0^2}{\left(n^2 - b^2\right) \cdot a^2 \cdot c^2} \cdot \left(n^2 - b^2\right) \right]$$

v_0 is beam velocity, c is light velocity, Ω and ω_c are Langmuir and cyclotron electron frequencies respectively, ε_1 and ε_2 are components of the plasma dielectrical permeability tensor in hydrodynamical approach, $J_n(z)$ is the Bessel function. The ASW energy can be emitted through the narrow slot [3] in the metal wall of the waveguide. We found the optimum wave number range, $0,1 < |m| \cdot \delta / R_1 < 0,5$, in which increments of the beam and dissipative instabilities are greater than damping rates of the ASW caused by their energy radiation, here $\delta = \Omega / c$ is skin depth. The results of the numerical investigation of the considered problem are presented on fig.1.2 for the ASW with azimuthal wave numbers $m = -2$ and $m = -3$. Dependences of the ASW frequency and of the increments of beam Γ_b and dissipative Γ_d instabilities upon the effective wave number $k_0 = |m| \cdot \delta / R_1$ are drawn by lines marked by figures 1,2 and 3 respectively on the upper part of coordinate plane. Dependence of the ASW damping rate caused by their radiation through a slot in the metal screen with the following angular dimensions, $\Delta\varphi = 0,02 \cdot \pi$, is drawn on its lower part and is marked by figure 4. Here we represent the results of the numerical calculation which are concerned the case when $\Omega = 10 \cdot \omega_c, \xi = 0.01, \nu = 0.007 \cdot \Omega$, ν is effective value of the collisional frequency for plasma electrons. In the case of the dissipative instability the value of ν is much greater than the beam instability growth rate Γ_b. For reader's comfort we drawn the increments values Γ_b

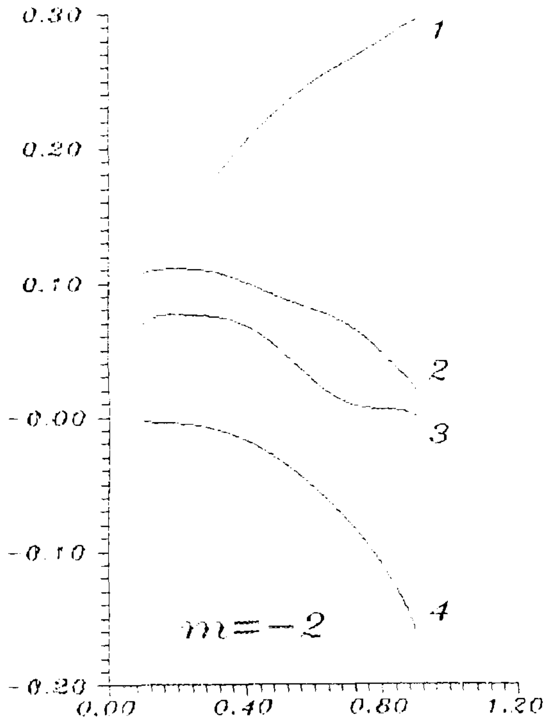

Fig.1

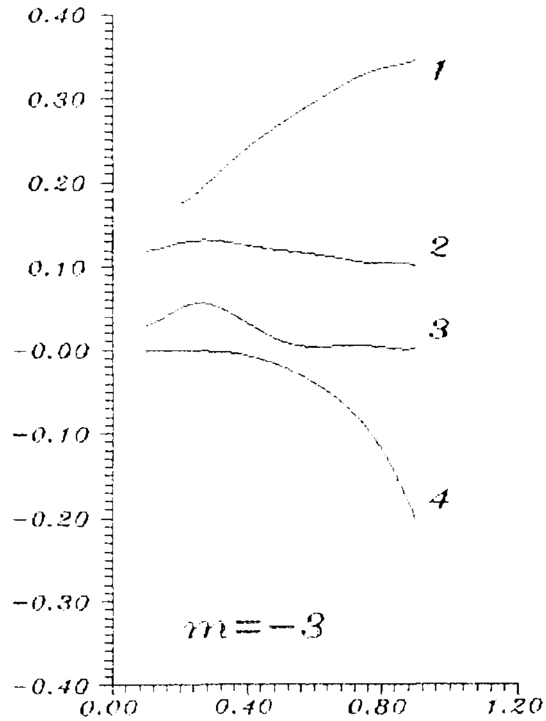

Fig.2

and Γ_d multiplied by *100* and devided by Ω. Curvers marked by 1 and 4 show us respectively the dependences of the ASW frequency and damping rate both devided by Ω on k_0 value.

Conclusion

In our opinion the construction of electronical devices proposed has such advantages and qualities: achievement of the short wavelength energy radiation, opportunity to change the radiation frequency in wide range, small longitudinal dimensions. Utilization of surface waves allows to hope that wave-beam interaction becomes more efficient as compared with the case of volume waves. ASW energy is located mainly in that region where the beam rotates, amplitudes of ASW fields monotonously decrease when going from plasma boundary R_1 to its axis.The utilization of annual electron beam has some advantages as compared with longitudinal beams, so our studies can be interesting for the plasma electronics.

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[3] Girka, V.O., Girka, I.O.:Sov.Journ. of Communic. Technol. and Electronics, **37** (1992) 32.