INFLUENCE OF COLLISIONS AND PLASMA RADIAL NON-UNIFORMITY ON ELECTROMAGNETIC WAVE IN COAXIAL STRUCTURE WITH AZIMUTH EXTERNAL MAGNETIC FIELD

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This report is devoted to the investigation of dispersion properties, attenuation coefficient and radial wave field structure of high-frequency electromagnetic wave that propagates in coaxial magnetized waveguide structure with non-uniform azimuth magnetic field, partially filled by radial non-uniform collisional plasma. The influence of geometric parameters of waveguide structure, plasma non-uniformity, effective collision rate, direction and value of azimuth magnetic field on phase characteristics, attenuation coefficient and radial wave field structure of the considered wave is studied. It was shown that it is possible to control effectively the dispersion properties and spatial attenuation of the considered wave by varying the value and direction of external azimuth magnetic field.

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1. INTRODUCTION

The study of eigen electromagnetic waves of plasma filled metal waveguide structures is of a great importance for plasma electronics, various plasma technologies, etc. Among different types of plasma filled waveguide structures it is possible to separate the cylindrical devices with coaxial elements. The realized experimental study of coaxial waveguide structures with central metallic rod have shown that properties of electromagnetic waves and gas discharge plasma maintained by these waves, differ considerably from the corresponding properties of cylindrical plasma – metal waveguide structures without central conductor [1]. Properties of plasma maintained in coaxial structure with dielectric rod inside have been study in paper [2]. It is necessary to note that in spite of perfect plasma parameters obtained in experimental devices with coaxial structures, theoretical study of eigen wave properties of coaxial waveguide structures and efficiency of such structure use in various applications is insufficient. This especially concerns the theoretical study of plasma density, radial non–uniformity and electron collision rate influence on the phase characteristics and spatial attenuation of electromagnetic eigen waves of coaxial structure with central metal conductor. These circumstances greatly determine the urgency of theoretical study of eigen wave properties of coaxial structures.

2. TASK SETTING

Let us consider the axially–symmetric (azimuth wavenumber $m = 0$) high–frequency electromagnetic wave that propagates in the cylindrical coaxial magnetized waveguide structure, partially filled by radial non–uniform dissipative plasma. Let suppose that the wave propagates along z – axis of cylindrical coordinate system (r, φ, z), which is directed along the axis of waveguide structure The waveguide structure consists of metal rod of radius R_1, which is placed at the axis of plasma column. The direct current J_z flows along this rod, creating radial non–uniform azimuth magnetic field $H_0(r)$. This rod is enclosed by the cylindrical plasma layer with radius R_2. The vacuum region ($R_2 < r < R_3$) separates the cylindrical plasma layer from waveguide metal wall with radius R_3. It was supposed, that plasma density is radial non–uniform and possesses the bell–shaped profile of the following form:

$$n(r) = n(r_{\max})\exp\left(-\mu(r - r_{\max})^2 r_\delta^{-2}\right). \qquad (1)$$

Here, $r_{\max}$ – is the radius value where plasma density culminates its maximum, parameters r_δ and μ ($0 \le \mu \le 1$) describes the width and the slope of the bell–shaped profile, respectively. Plasma was considered in the hydrodynamic approach as cold medium with collisions, that were characterized by the effective collision rate ν. This quantity is constant in the whole volume of cylindrical plasma layer and is supposed to be small ($\nu/\omega < 1$, where ω is wave frequency).

From the system of Maxwell equations one can find, that the electromagnetic field of considered axially symmetric E–wave consists of only three components E_z, E_r and H_φ. In the region of cylindrical plasma layer ($R_1 < r < R_2$) the equations that govern these components of E–wave can be written in the form [3]:

$$\begin{cases} E_r = \dfrac{k_3}{k\varepsilon_1} H_\varphi + i\dfrac{\varepsilon_2}{\varepsilon_1} E_z \\ \dfrac{dE_z}{dr} = -k_3 \dfrac{\varepsilon_2}{\varepsilon_1} E_z + i\dfrac{\kappa_p^2}{k\varepsilon_1} H_\varphi \\ \dfrac{dH_\varphi}{dr} = ik\dfrac{\varepsilon_2^2 - \varepsilon_1^2}{\varepsilon_1} E_z + \left(k_3\dfrac{\varepsilon_2}{\varepsilon_1} - \dfrac{1}{r}\right) H_\varphi \end{cases}, \qquad (2)$$

where $\varepsilon_1 = 1 - \dfrac{\omega_p^2(r)\omega'}{\omega\left((\omega')^2 - \omega_c^2(r)\right)}$, $\varepsilon_2 = \dfrac{|\omega_c(r)|\omega_p^2(r)}{\omega\left((\omega')^2 - \omega_c^2(r)\right)}$, $\varepsilon_3 = 1 - \dfrac{\omega_p^2(r)}{\omega\omega'}$, $\omega' = \omega + i\nu$, $\omega_p(r)$ and $\omega_c(r)$ are electron plasma and cyclotron frequencies, respectively, $\kappa_p^2 = k_3^2 - k^2\varepsilon_1(r)$, $k = \omega/c$ is the vacuum wavenumber, k_3 is complex axial wavevector, real part of it determines the wavenumber and imaginary part determined wave attenuation coefficient.

It is necessary to mention, that in spite of low value of effective electron collision frequency ($\nu < \omega$) it is necessary to keep imaginary terms in the expressions for components of permittivity tensor of magnetized plasma. This imaginary terms give the possibility to carry out numerical integration of the system (2) in the region where the conditions of upper hybrid resonance may take place [4].

In the cylindrical vacuum region ($R_2 < r < R_3$) the wave components $E_z(r)$, $E_r(r)$ and $H_\varphi(r)$ can be analytically expressed in terms of Bessel functions:

$$\begin{cases} E_z &= C_1 I_0(\kappa_v r) + C_2 K_0(\kappa_v r) \\ H_\varphi &= -i\dfrac{k}{k_v}\left(C_1 I_1(\kappa_v r) - C_2 K_1(\kappa_v r)\right), \\ E_r &= \dfrac{k_3}{k} H_\varphi \end{cases} \quad (3)$$

where $\kappa_v^2 = k_3^2 - k^2$, $I_{0,1}$, $K_{0,1}$ are Bessel functions of the first kind and second kind, C_1 and C_2 are the wave field constants. The boundary conditions for $E_z(r)$ and $H\varphi(r)$ consisting in continuity of these quantities at plasma-vacuum interface ($r = R_2$) give the linear system for the matching constants C_1 and C_2.

The boundary condition for $E_z(r)$ wave field component at the waveguide metallic wall $r = R_3$ consisting in the vanishing $E_z(R_3)$ gives the dispersion equation that can be written in the following form:

$$C_1 I_0(\kappa_v R_3) + C_2 K_0(\kappa_v R_3) = 0, \quad (4)$$

The initial conditions for integration of the system of ordinary differential equations (2) can be obtained from the conditions at the inner conductive rod.

The obtained dispersion equation (4) is solved in complex algebra. For this purpose the system of ordinary differential equations was numerically solved with the help of Badler and Deuflhard version of semi-implicit extrapolation method [5]. This method gives the possibility to obtain accurately numerical solution even in the region where the conditions of upper hybrid resonance take place. The dispersion equation (4) was solved with the help of Muller method [5].

3. MAIN RESULTS

In the case when external current flows along the propagation direction of the considered wave the dispersion equation (4) possesses two solutions with different values of frequency for the fixed value of dimensionless wavenumber $\mathrm{Re}(k_3)R_1$. One of them with comparatively more high frequency will be called further high frequency (HF) wave, and other — low frequency (LF) wave. Properties of these waves substantially determined by the value and direction of direct current. Thus, in the limiting case, when the azimuth magnetic field $H_0(r)$ trends to zero the LF wave vanishes. The increase of the direct current leads to the decrease of the HF wave frequency and to the increase of the LF wave frequency. So, for rather high dimensionless direct current value ($j = eJ_z/(2m_e c^3) \approx 2.0$) the frequencies of HF and LF waves for rather high $\mathrm{Re}(k_3)R_1$ values are close.

The influence of parameter ν/ω value on the dispersion and attenuation properties of HF and LW waves was study for the case of radial uniform plasma ($\mu = 0$). For rather small values of effective collision rate ($\nu/\omega < 1$) the increase of ν/ω value leads to the increase of the LF dimensionless frequency ω/ω_p and attenuation coefficient $\mathrm{Im}(k_3)R_1$. Dispersion and attenuation properties of HF wave depend on the ν/ω parameter much weaker. It is necessary to note that the attenuation coefficient value of LF wave is approximately of one order greater than the value of attenuation coefficient of LF wave.

The influence of plasma density radial profile (non-uniformity parameter μ value) on the dimensionless frequency and attenuation coefficient for HF and LF wave at fixed point of dispersion curve (for $\mathrm{Re}(k_3)R_1 = 0.01$) is shown on Fig. 1. Other external parameters were equal to $r_1 = R_1\omega_p(r_{\max})/c = 4.0$, $r_2 = R_2\omega_p(r_{\max})/c = 5.0$, $r_3 = R_3\omega_p(r_{\max})/c = 6.0$, $\nu/\omega = 0.001$, $r_{\max} = 4.5$, $r_\delta = 0.1$, $j = eJ_z/(2mc^3) = 2.0$. One can see that the increase of non–uniformity parameter μ leads to the increase of the dimensionless wave frequency of HF wave and to the decrease of the dimensionless wave frequency of LF wave. The wave attenuation coefficient shows more complicated behaviour (Fig. 2). The calculations carried out have shown that the spatial attenuation coefficient for HF wave possesses the maximum in the range of rather small μ values ($\mu \approx 0.2$). In contrast, the attenuation coefficient for LF possesses the minimum for approximately the same μ values. Such complicated dependence may be very important for the determination of the frequency range, where the considered wave can maintain the stable discharge [6].

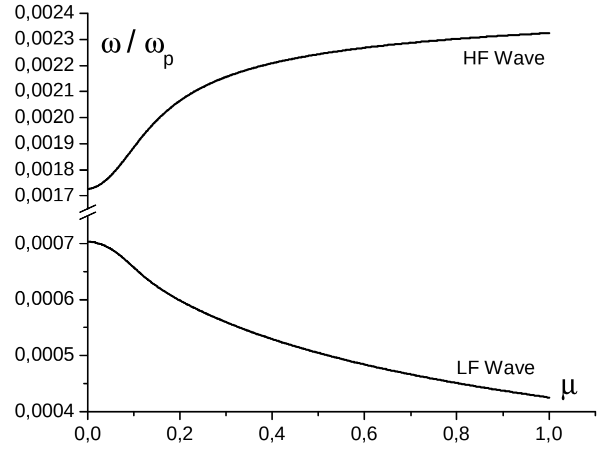

Fig. 1. The dependence of dimensionless wave frequency ω/ω_p on the non–uniformity parameter μ for the fixed point on the dispersion curve ($\mathrm{Re}(k_3)R_1 = 0.01$*)*

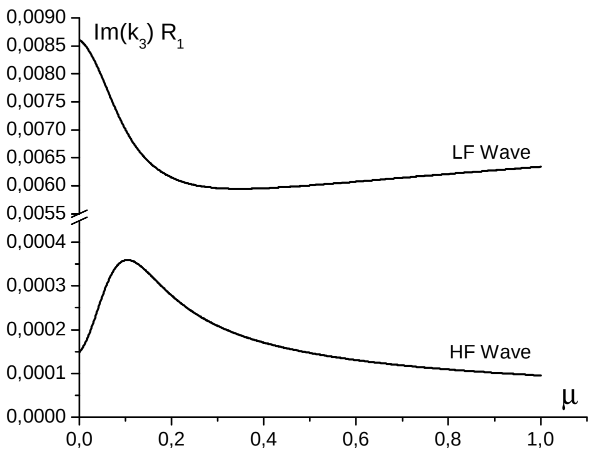

Fig. 2. The dependence of attenuation coefficient $\mathrm{Im}(k_3)R_1$ *on the non–uniformity parameter* μ *for the fixed point on the dispersion curve (* $\mathrm{Re}(k_3)R_1 = 0.01$ *)*

CONCLUSIONS

The influence of plasma density radial non–uniformity, electron effective collision frequency, direction and direct current value on phase characteristics, attenuation coefficient and radial wave field structure of the considered wave was studied. It was shown that it is possible to control effectively the dispersion properties of E–wave by varying the value and direction of direct current. The influence of dimensionless collision rate on the dispersion and attenuation properties of HF and LF waves was studied as well. It was shown that LF wave attenuates more effectively than HF wave. It was shown also that in the case of bell–shaped radial plasma density profile the increase of plasma density radial non–uniformity results in the growth of wave frequency of HF wave and in the decrease of wave frequency of LF wave.

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ВЛИЯНИЕ СТОЛКНОВЕНИЙ И РАДИАЛЬНОЙ НЕОДНОРОДНОСТИ ПЛАЗМЫ НА ЭЛЕКТРОМАГНИТНЫЕ ВОЛНЫ В КОАКСИАЛЬНОЙ СТРУКТУРЕ С ВНЕШНИМ АЗИМУТАЛЬНЫМ МАГНИТНЫМ ПОЛЕМ

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Исследованы дисперсионные свойства, коэффициент пространственного затухания и радиальная структура поля высокочастотной электромагнитной волны, распространяющейся в коаксиальной волноводной структуре, частично заполненной радиально неоднородной столкновительной плазмой, которая находится в радиально неоднородном азимутальном магнитном поле. Изучено влияние геометрических параметров волноводной структуры, радиальной неоднородности плотности плазмы, эффективной частоты столкновений электронов, величины и направления постоянного тока на фазовые характеристики, коэффициент пространственного затухания и радиальную структуру поля рассматриваемой волны. Показана возможность эффективного управления дисперсионными свойствами и коэффициентом пространственного затухания путем изменения величины и направления постоянного тока.

ВПЛИВ ЗІТКНЕНЬ ТА РАДІАЛЬНОЇ НЕОДНОРІДНОСТІ ПЛАЗМИ НА ЕЛЕКТРОМАГНІТНІ ХВИЛІ В КОАКСІАЛЬНІЙ СТРУКТУРІ З ЗОВНІШНІМ АЗИМУТАЛЬНИМ МАГНІТНИМ ПОЛЕМ

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Досліджено дисперсійні властивості, коефіцієнт просторового загасання та радіальну структуру поля високочастотної електромагнітної хвилі, що розповсюджується в коаксіальній магнітоактивній хвилевідній структурі з радіально неоднорідним азимутальним магнітним полем, частково заповненою радіально неоднорідною плазмою із зіткненнями. Вивчено вплив геометричних параметрів хвилевідної структури, радіальній неоднорідності густини плазми, ефективної частоти зіткнень електронів, напрямку та величини постійного току на фазові характеристики, коефіцієнт просторового загасання та радіальну структуру поля досліджуваної хвилі. Показано можливість ефективного керування дисперсійними властивостями та коефіцієнтом просторового загасання зміною величини та напрямку постійного струму.