ELECTROMAGNETIC DIPOLAR WAVE IN MAGNETIZED NON-UNIFORM PLASMA COLUMN

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It has been carried out theoretical study of phase characteristics, attenuation coefficient and wave field radial structure of the dipolar high frequency electromagnetic wave that propagates along the waveguide structure that consists of a slightly collisional non-uniform magnetized plasma column, enclosed by dielectric tube that is surrounded by vacuum and placed within a cylindrical metal waveguide. External steady magnetic field is directed along the axis of the waveguide system. The axial electron density distribution of gas discharge maintained by the wave considered in the diffusion controlled regime was studied as well.
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1. INTRODUCTION

The intensive theoretical and experimental studies of gas discharges sustained by high-frequency travelling surface wave (SW) are stipulated by their wide practical using in numerous technological applications [1]. The SW that sustains the discharge is the eigen wave of discharge structure. This is the characteristic feature of such discharges and leads to the strong influence of the SW properties on the axial distribution of discharge parameters. In real discharge systems plasma density is always non-uniform in radial direction and the conditions of upper hybrid resonance may take place at the periphery of plasma column [2]. The efficiency of energy transfer from SW into gas discharge plasma can be increased substantially in such regions, where electromagnetic waves transform into plasma waves [3]. This process can affects greatly the plasma density axial structure in SW sustained gas discharges. The main aim of this report is to determine the influence of plasma density radial profile on the SW properties and on the plasma density axial structure in the discharges sustained by the dipolar SW in diffusion controlled regime.

2. THEORETICAL FORMULATION

The SW considered propagates in magnetized waveguide structure that consists of radially non-uniform plasma column with radius R_p enclosed by dielectric tube with thickness Δ that is surrounded by vacuum and placed within a cylindrical metal waveguide with radius R_m. External steady magnetic field $\vec{B}_0$ is directed along the axis of the waveguide structure. Plasma is considered in hydrodynamic approximation as cold and slightly absorbing medium with constant effective electron-neutral collision frequency ν in the discharge volume. In the considered case this frequency is much less than SW generator frequency ω. Plasma density radial profile $n(r)$ was chosen in Bessel–like form given by $n(r)=n(0)\,J_0\left(\mu\, r\, R_p^{-1}\right)$, where J_0 is the Bessel function and μ is the parameter, which characterizes the plasma density non-uniformity. This non-uniformity parameter μ can varies from $\mu=0$ (radially uniform profile) to $\mu=2.405$ (perfect ambipolar diffusion profile). The SW propagation is governed by the system of Maxwell equations. This wave possesses all six components of electromagnetic field. For arbitrary discharge parameters (plasma density radial profile, external magnetic field value, geometrical parameters of discharge structure) in the case when waveguide is filled by radially non-uniform magnetized plasma this system can be solved only with the help of numerical methods. In the case considered, when plasma density, SW wavelength and it's amplitude vary slightly along the discharge column at the distances of the wave length order, the solution of the system of Maxwell equations in cylindrical coordinate system (r,φ,z) for SW field components $\vec{E}, \vec{H}$ can be found in WKB form:

$$\vec{E},\ \vec{H}(r,\varphi,z,t)=\vec{E},\ \vec{H}(r)\exp\left(i\left[\int_{z_0}^{z} k_3(z')\,dz'-\omega t\right]\right), \qquad (1)$$

where k_3 is SW axial wavenumber.

Applying expression (1) to the system considered one can reduce it into the system of four ordinary differential equations for the tangential SW components in plasma column ($0<r<R_p$). In spite of the low value of collision frequency $(\nu<<\omega)$ it is necessary to keep imaginary addends in the expressions of the permittivity tensor $\varepsilon_{1,2,3}$ of magnetized plasma. These imaginary addends give the possibility to carry out the numerical integration of the system of ordinary differential equations in the region when upper hybrid resonance occurs. In dielectric and vacuum regions the system of Maxwell equations can be solved analytically and one can obtain the expressions for tangential wave field components [4]. The local dispersion equation can be obtained by applying the conditions of continuity of the tangential field components at the plasma-glass tube and glass tube-vacuum region interfaces. The condition of vanishing of the SW electric field at the waveguide metallic wall is also applied.

Therefore, the complex local dispersion equation is obtained, the real part of its complex solution for wavenumber gives wavelength and imaginary part gives SW attenuation coefficient. To solve the dispersion equation one must firstly solve the system of ordinary differential equations under the fixed values of k_3 and ω . Then, one solve the local dispersion equation and find the eigen value of k_3 or ω .

In the case considered it is possible to obtain axial electron density variation as an intricate function of attenuation coefficient. The axial profile of dimensionless density $N=\omega_{pe}^2\omega^{-2}$ can be theoretically determined from the energy balance equation of gas discharge stationary state in diffusion controlled regime [1]. When mean power that maintains an electron in the discharge and electron effective collision frequency for momentum transfer ν are constant in discharge volume, one can obtain equation that governs plasma density axial distribution in the form:

$$\frac{d\ N}{d\ \xi}=-\frac{2N\alpha}{\nu\omega^{-1}(1-(d\alpha/dN)N\alpha^{-1})}, \quad (2)$$

where $\alpha=\mathrm{Im}(k_3)R_p$ is the dimensionless attenuation coefficient and $\xi=\nu z(\omega R_p)^{-1}$ is the dimensionless axial coordinate [1].

It is necessary to mention that the SW can maintain the stable discharge in diffusion regime only at the regions in the phase diagrams where the Zakrzewski's stability condition is fulfilled. In dimensionless variables this condition can be written as [1, 5]:

$$\frac{d}{dN}\frac{|\alpha|}{N}<0 . \quad (3)$$

3. DISCUSSION

To determine axial distribution of plasma density in gas discharge it is necessary firstly to find the phase properties and attenuation coefficient of the wave. Unlike the usual dispersion equation connecting wave frequency and wave length under the fixed value of plasma density, the local dispersion equation in the considered case, (when wave frequency is fixed and is determined by the generator's frequency ω), connects local value of plasma density and wavelength. Some results of numerical solution of the local dispersion equation for different external discharge parameters are presented in the Fig. 1-4. The calculations were carried out for the dimensionless parameters $\Omega=\omega_c\omega^{-1}$, $\sigma=R_p\omega c^{-1}$, $\delta=\Delta R_p^{-1}$, $\eta=R_m R_p^{-1}$ and $\tilde{\nu}=\nu\omega^{-1}$ (where ω_c is electron cyclotron frequency and c is light velocity in vacuum).

Fig. 1, 2 present the influence of the vacuum gap thickness on the SW properties. The numerical calculations have shown that at a fixed wavelength the decrease of the vacuum gap thickness leads to the decrease the wave phase velocity (Fig. 1) and to the increase of its attenuation coefficient α (Fig. 2), as in the case of symmetric waves. It is necessary to mention the fact that at some value of parameter η the SW attenuation coefficient increases sharply (curves corresponds to $\eta=1.7\div1.74$ at Fig. 2), but the wavenumber remains finite. Thus, variation of the parameter η value strongly affects the region on phase diagrams where SW can maintain the stable discharge in diffusion controlled regime. At all figures the boundaries of the stable regions on phase and attenuation diagrams are marked by circles (left boundary) and triangles (right boundary). The existence on the same phase curve the regions with two opposite slopes leads to the strong restriction of the stable discharge region (compare the curves corresponds to $\eta=1.5, 1.6$ and $\eta=1.7\div1.74$ on Figs. 1, 2).

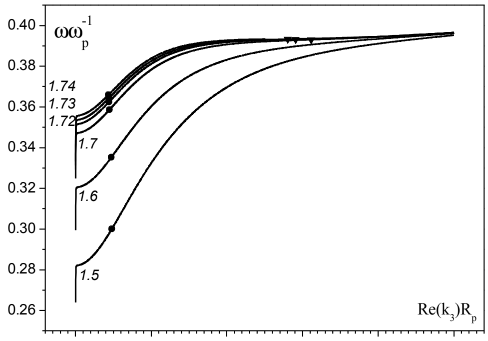

Fig. 1. The dependence of the SW phase properties on the value of the vacuum gap thickness for radially uniform plasma. Numbers at the curves correspond to the parameter η value. Other dimensionless parameters are equal to $\tilde{\nu}=0.001$, $\varepsilon_d=4.5$, $\Omega=0.2$, $\sigma=0.3$, $\delta=0.3$ and $m=-1$

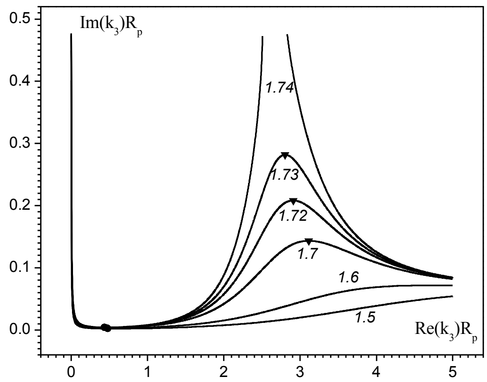

Fig. 2. The dependence of the SW attenuation coefficient α on the value of the vacuum gap thickness for radially uniform plasma. The parameters are the same as in Fig. 1

The increase of dimensionless plasma column radius σ (when $\sigma<1$) leads to the decrease of SW phase velocity and SW attenuation coefficient. The analysis has shown that one can mark out the regions with two different SW behavior. When parameter σ is rather small ($\sigma<\sigma_{cr}$) the dispersion equation possesses the solutions with $\mathrm{Re}(k_3)R_p=0$. When $\sigma>\sigma_{cr}$ there is a region on the phase curve at small $\mathrm{Re}(k_3)R_p$ values where SW cannot exist.

In real conditions the dimensions of discharge vessel are fixed and they are determined by the diameter of dielectric and metal tubes, where the discharge occurs.

So, it is possible to control discharge parameters due to variation of an external magnetic field value. The dependence of the phase and attenuation properties of the wave on the several values of dimensionless magnetic field value Ω are given in Fig. 3, 4. The study has shown that the increase of the parameter Ω results in the retardation of the wave in the region of small $\mathrm{Re}\left(k_3\right)R_p$ values and acceleration of SW in the region of large $\mathrm{Re}\left(k_3\right)R_p$ (Fig. 3). The SW attenuation coefficient grows with the increase of the parameter Ω value (Fig. 4).

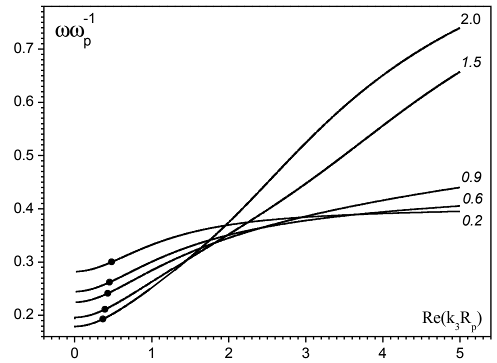

Fig. 3. The dependence of the SW phase properties on the external magnetic field value for radially uniform plasma. Numbers at the curves corresponds to the parameter Ω value. Other parameters are equal to $\delta=0.3$, $\eta=1.5$, $\tilde{\nu}=0.001$, $\varepsilon_d=4.5$, $\sigma=0.3$ and $m=-1$

Also it was shown that the increase of the non-uniformity parameter μ value leads to the decrease of the SW phase velocity and to the attenuation coefficient α growth. It was obtained that α essentially increases when the wave frequency became close to the upper hybrid frequency. The maximum possible density that can be maintained in the discharge by the SW considered grows with the increase of parameter μ value. At the same time the dimensional length of the discharge becomes smaller.

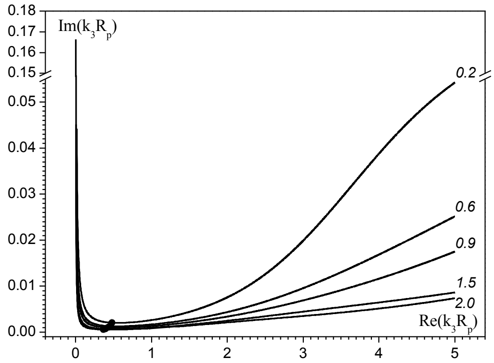

Fig. 4. The dependence of the SW attenuation coefficient α on the external magnetic field value for radially uniform plasma. The parameters are the same as in Fig. 3

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ЭЛЕКТРОМАГНИТНАЯ ДИПОЛЬНАЯ ВОЛНА В МАГНИТОАКТИВНОМ НЕОДНОРОДНОМ СТОЛБЕ ПЛАЗМЫ

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Проведено теоретическое исследование фазовых характеристик, коэффициента пространственного затухания и радиальной структуры поля дипольной электромагнитной волны, распространяющейся вдоль структуры, состоящей из слабостолкновительной неоднородной магнитоактивной плазмы, ограниченной диэлектрической трубкой, окруженной вакуумом и помещенной внутрь цилиндрического металлического волновода. Внешнее магнитное поле направлено вдоль оси структуры. Исследовано также аксиальное распределение плотности плазмы в разряде, поддерживаемом дипольной волной и протекающем в диффузионном режиме.

ЕЛЕКТРОМАГНИТНА ДИПОЛЬНА ХВИЛЯ В МАГНІТОАКТИВНОМУ НЕОДНОРІДНОМУ СТОВПІ ПЛАЗМИ

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Проведено теоретичне дослідження фазових характеристик, коефіцієнта просторового загасання та радіальної структури поля дипольної електромагнітної хвилі, що розповсюджується вздовж структури, яка складається з неоднорідної магнітоактивної плазми з малою частотою зіткнень електронів, обмеженої діелектричною

трубкою, оточеною вакуумом та розташованою всередині циліндричного металевого хвилеводу. Зовнішнє магнітне поле спрямоване вздовж осі структури. Досліджено також аксіальний розподіл густини плазми в розряді, що підтримується дипольною хвилею та протікає в дифузійному режимі.