THEORY OF GAS DISCHARGE MAINTAINED BY THE ELECTROMAGNETIC SYMMETRIC SURFACE WAVE ALLOWING FOR RADIAL NON–UNIFORMITY OF THE MAGNETIZED PLASMA

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This report is devoted to the theoretical study of the phase characteristics, attenuation coefficient and axial electron density distribution in gas discharge maintained by symmetric high frequency electromagnetic wave in the diffusion controlled regime. The wave considered propagates along the waveguide structure that consists of a non–uniform plasma column, enclosed by dielectric tube that is surrounded by vacuum and placed within a cylindrical metal waveguide. The external steady magnetic field is directed along the axis of the waveguide system. Plasma is considered as a cold and weakly absorbing medium with constant value of effective electron collision frequency. The phase and attenuation surface wave characteristics, and the axial electron density distribution were considered in the approach of slightly axial non–uniformity plasma density. It was shown that the plasma density non–uniformity greatly influences on the wave characteristics and gas discharge axial structure.

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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. Up to now, the SW properties and gas discharge axial structure were mainly studied for the waveguide structures with uniform plasma filling. However, 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 symmetric SW in diffusion controlled regime. The wave considered possesses all six components of electromagnetic field. Because of that, general numerical method was used for the determination of the phase characteristics, attenuation coefficient and spatial wave field structure under the conditions of arbitrary plasma density radial profile, external magnetic field values and parameters of waveguide system.

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 outer radius R_d and thickness Δ that is surrounded by vacuum and placed within a cylindrical metal waveguide with radius R_m ($R_p < R_d < R_m$). External steady magnetic field 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 $n(r) = n(0)\, J_0\left(\mu\, r R_p^{-1}\right)$. The parameter of non–uniformity μ varies from $\mu = 0$ (radially uniform profile) to $\mu = 2.4$ (perfect ambipolar diffusion profile). The SW propagation is governed by the system of Maxwell equations. This wave possesses all six components of electromagnetic field. In the case of non–uniform plasma density radial distribution this system, for arbitrary discharge parameters (plasma density radial profile, external magnetic field value, geometrical parameters of discharge structure), 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 wave length order, the solution of the system of Maxwell equations in cylindrical coordinate system (r,φ,z) for SW field components E, H can be found in WKB form:

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

where k_3 and 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 [3]. General solution of the system reduced may be written as the linear combination of two linearly independent vectors of solutions ($E_z^{1,2}$, $E_\varphi^{1,2}$, $H_z^{1,2}$, $H_\varphi^{1,2}$), that satisfy the boundary conditions at the axis of waveguide system [3]. When $r = 0$ tangential components of SW electric and magnetic fields turn to zero. The fulfillment of boundary conditions at the waveguide metal wall (vanishing of SW electric field tangential components) leads to the system of two linear equations. The existence conditions of this system give the local dispersion equation in the form:

$$E_z^1(R_m)\,E_\varphi^2(R_m) - E_z^2(R_m)\,E_\varphi^1(R_m) = 0\,. \qquad (2)$$

Due to the SW symmetry properties, one can choose such vectors $(1,0,0,0)$ and $(0,0,1,0)$, as linear independent vectors of solutions [3]. 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 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. Therefore, the complex local dispersion equation (2) 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 (2) one must firstly solve the system of ordinary differential equations with the help of Gear method under the fixed values of k_3 and ω . Then, with the help of Muller method, one can 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 θ 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:

$$\frac{dN}{d\xi} = -\frac{2N\alpha}{\nu\omega^{-1}\left(1-(d\alpha/dN)N\alpha^{-1}\right)}, \qquad (3)$$

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

3. DISCUSSION

It is necessary to find the phase properties of the wave and attenuation coefficient for the determination of the plasma density axial distribution. 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. The results of numerical solution of the local dispersion equation for different external discharge parameters are presented in the figures 1–4. The calculations were carried out for the dimensionless parameters $\Omega = \omega_c\omega^{-1}$, $\sigma = R_p\omega c^{-1}$, $\delta = \Delta R_p^{-1}$ and $\eta = R_m R_p^{-1}$ (where ω_c is electron cyclotron frequency, c is light velocity in vacuum). Figures 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 (figure 1)

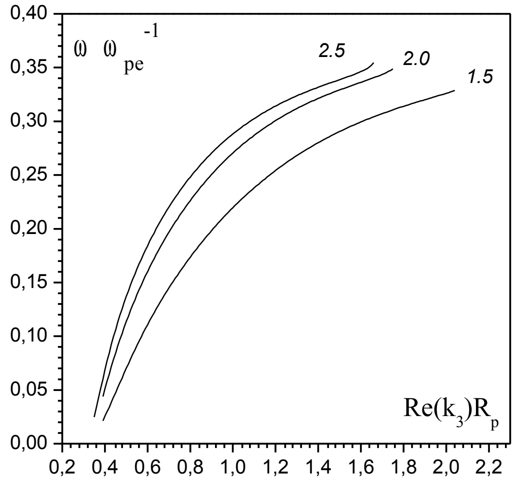

Fig. 1. The dependence of the SW phase properties on the value of the vacuum gap thickness: numbers at the curves corresponds to the parameter η value. Other dimensionless parameters are equal to $\mu = 2.2$, $\nu = 0.04$, $\varepsilon_d = 4.5$, $\Omega = 0.7$, $\sigma = 0.3$ and $\delta = 0.05$

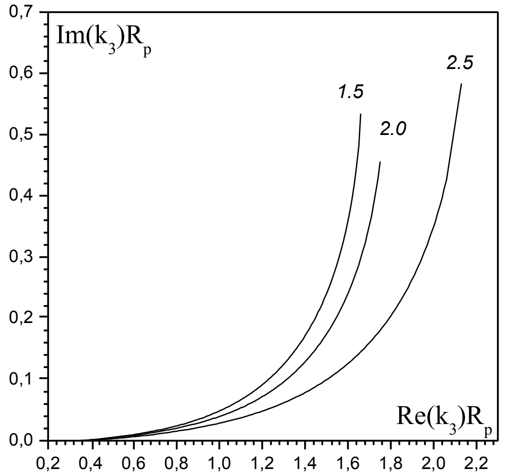

Fig. 2. The dependence of the SW attenuation coefficient α on the value of the vacuum gap thickness. The parameters are the same as in Fig. 1

and to the increase of its attenuation coefficient α (figure 2). Such dependence is rather weak in the case of the uniform plasma. When the non–uniformity parameter μ grows the thickness of vacuum gap becomes more determinative parameter. The increase of the glass tube thickness leads to the decrease of the SW phase velocity and to the increase of the attenuation coefficient α . It is necessary to stress that this dependence is more essential in the case of radial non–uniform plasma.

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 figures 3, 4.

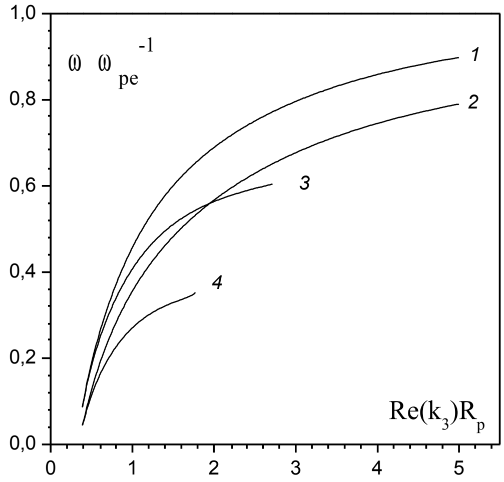

Fig. 3. The dependence of the SW phase properties on the external magnetic field value: curves 1, 2 correspond to $\mu = 0.0, 2.2$*, respectively and to the* $\Omega = 2.0$ *value; curve 3,4 correspond to* $\mu = 0.0, 2.2$ *and* $\Omega = 0.7$*. Other parameters are equal to* $\delta = 0.05$*,* $\nu = 0.04$*,* $\varepsilon_d = 4.5$*,* $\sigma = 0.3$*.*

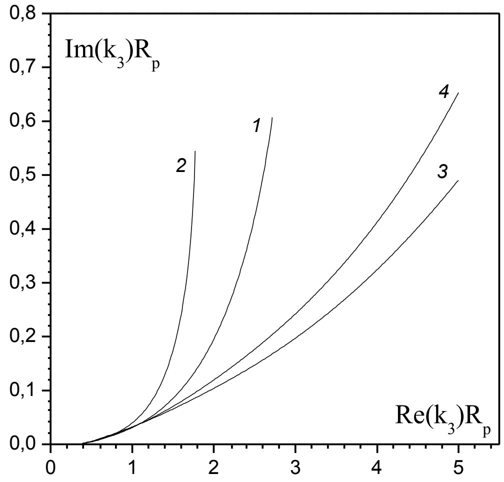

Fig. 4. The dependence of the SW attenuation coefficient α *on the external magnetic field value(the parameters are the same as in Fig. 3)*

The study has shown that in the case of small external magnetic field values ($\Omega < 1$) the increase of the non–uniformity parameter μ results in the retardation of the wave and the growth of the its attenuation coefficient. The similar dependence takes place in the case of strong external magnetic fields ($\Omega > 1$). It was obtained that attenuation coefficient essentially increases when the wave frequency became close to the upper hybrid frequency.

The next step of our study is the determination of plasma density axial distribution in the SW sustained discharges. It is necessary to mention that the SW phase and attenuation properties mainly determine the axial distribution of the discharge parameters in the framework of the approach applied. To find the regions in phase diagrams where the SW considered can sustain the stable discharge it is necessary to check the fulfillment the Zakrzewski's stability condition [1]. The study has shown that this stability condition is fulfilled at the whole range of SW existence. Plasma density axial profile was determined as the function of the dimensionless axial coordinate ξ that is measured from the generator exit up to the end of the discharge. In such consideration the dimensionless plasma density N in the region just near to the generator can be determined from the phase diagrams at the fixed external discharge parameters.

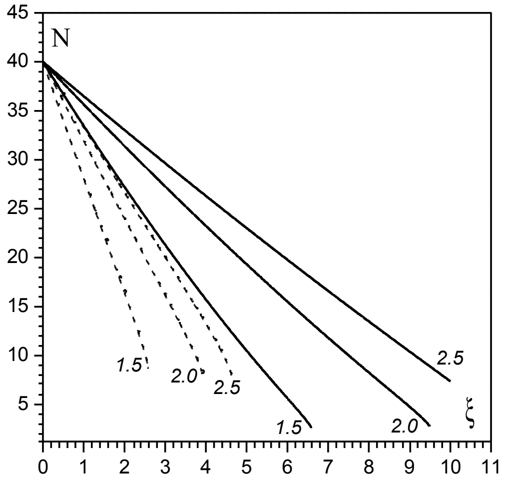

Fig. 5. Plasma density axial profiles for the case of uniform (solid curves) and non–uniform (dashed curve, $\mu = 2.2$*) plasma(the numbers at the curves correspond to the* η *value; other parameters are the same as in Fig. 1)*

The plasma density axial profiles for different non–uniformity parameters μ and vacuum gap thickness are presented in the figure 5. It is shown that the increase of the μ value leads to the attenuation coefficient growth (figure 2) and consequently to the decrease of the dimensional length of the discharge (figure 5, see solid and dashed curves). The increase of the vacuum gap thickness results in the discharge length growth and in the decrease of the axial plasma density gradient.

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REFERENCES

[1] M. Moisan, Z. Zakrzewski// *Journal of Physics D: Applied Physics*, 24, 1991, p.1025.

[2] I. Peres, M. Fortin, J. Margot// *Phys. Plasmas*, 3, 1996 p.1754.

[3] N.I. Karbushev, U.A. Kolosov, A.I. Polovkov// *Phisica Plasmy//* 18, 1992,p. 54.

ТЕОРІЯ ГАЗОВОГО РОЗРЯДУ, ЩО ПІДТРИМУЄТЬСЯ ЕЛЕКТРОМАГНІТНОЮ СИМЕТРИЧНОЮ ПОВЕРХНЕВОЮ ХВИЛЕЮ ПРИ УРАХУВАННІ РАДІАЛЬНОЇ НЕОДНОРІДНОСТІ МАГНІТОАКТИВНОЇ ПЛАЗМИ

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Дана робота присвячена теоретичному вивченню фазових характеристик, коефіцієнта просторового загасання симетричної високочастотної електромагнітної хвилі, а також аксіального розподілу густини плазми при дифузійному режимі протікання газового розряду, що підтримується цією хвилею. Розглянуто хвилю, що розповсюджується уздовж хвилеводної структури, яка складається з неоднорідного плазмового стовпа, що знаходиться в діелектричній трубці, яка оточена вакуумною областю та розташована в циліндричному металевому хвилеводі. Зовнішнє стале магнітне поле спрямоване уздовж вісі хвилеводної системи. Плазма розглядається як холодне та слабко поглинаюче середовище зі сталим значенням ефективної частоти зіткнень електронів. В наближенні слабкої аксіальної неоднорідності густини плазми розглянуто фазові властивості та просторове загасання хвилі, а також аксіальний розподіл густини плазми у розряді. Показано, що радіальна неоднорідність густини плазми суттєво впливає на властивості хвилі та аксіальну структуру розряду.

ТЕОРИЯ ГАЗОВОГО РАЗРЯДА, ПОДДЕРЖИВАЕМОГО ЭЛЕКТРОМАГНИТНОЙ СИММЕТРИЧНОЙ ПОВЕРХНОСТНОЙ ВОЛНОЙ ПРИ УЧЕТЕ РАДИАЛЬНОЙ НЕОДНОРОДНОСТИ МАГНИТОАКТИВНОЙ ПЛАЗМЫ

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Данная работа посвящена теоретическому изучению фазовых характеристик, коэффициента пространственного затухания симметричной высокочастотной электромагнитной волны, а также аксиального распределения плотности плазмы при диффузионном режиме протекания газового разряда, который поддерживается этой волной. Рассматриваемая волна распространяется вдоль волноводной структуры, состоящей из неоднородного плазменного столба, помещенного в диэлектрическую трубку, которая окружена вакуумной областью и помещена в цилиндрический металлический волновод. Внешнее постоянное магнитное поле направлено вдоль оси волноводной системы. Плазма рассматривается как холодная и слабо поглощающая среда с постоянным значением эффективной частоты столкновений электронов. В приближении слабой аксиальной неоднородности плотности плазмы рассмотрены фазовые свойства и пространственное затухание волны, а также аксиальное распределение плотности плазмы в разряде. Показано, что радиальная неоднородность плотности плазмы существенно влияет на свойства волны и аксиальную структуру разряда.