SYMMETRIC SURFACE WAVES IN CYLINDRICAL WAVEGUIDE STRUCTURES FILLED BY RADIALLY NON-UNIFORM COLLISIONAL PLASMA

V.P. Olefir, V.K. Galaydych, A.E. Sporov

V.N. Karazin Kharkov National University, Institute of High Technologies, Department of Physics and Technology, Kharkov, Ukraine, e-mail: olefir@pht.univer.kharkov.ua

This report is devoted to the investigation of the influence of electron collisions and radial non-uniformity of plasma density on phase characteristics, spatial attenuation and wave field structure of slow symmetric electromagnetic waves that propagate along cylindrical waveguide structure. It has been shown that collision rate and radial non-uniformity of plasma density for various parameters of waveguide structure and dielectric affect essentially on the wave characteristics and consequently, on the parameters of gas discharge that is sustained by this wave. The results obtained are of large importance for the construction of the theory of gas discharges that are sustained by the surface electromagnetic waves.

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1. INTRODUCTION

Electromagnetic surface waves (SW) that propagate in cylindrical waveguide plasma structures are widely used in HF electronics and in various plasma technologies, particularly for gas discharge sustaining [1-3]. At that, these SW are the eigen waves of discharge structure, so SW properties strongly influence on axial distribution of plasma parameters and vice versa. Frequently just symmetric waves (SW with azimuth wave number $m=0$) are used for this purpose [1]. Gas discharge plasma usually possesses radial non-uniform plasma density profile. The shape of this profile strongly influences on the efficiency of energy transfer from SW to gas discharge plasma and, therefore, on the discharge axial structure and stability [1, 2].

The aim of this report is to provide the extensive theoretical studies of the electron collision rate influence and influence of plasma density radial non-uniformity at various values of waveguide structure parameters on SW properties and on the stability of discharge sustained by such wave.

2. TASK SETTING

Let us consider the high frequency SW that propagate along plasma column of radius R_p that is placed in metallic waveguide with radius R_m ($R_p < R_m$). The region between plasma column and waveguide metallic wall is filled by dielectric with permittivity ε_d. Plasma is considered in hydrodynamic approximation as cold, slightly dissipative medium. It is supposed that effective electron collision rate ν is constant in the whole plasma volume.

Let consider the case, when only symmetric mode is excited in defined waveguide structure. In the case of rather long discharges with small plasma density axial gradients the solution of Maxwell system of equations can be found with the help of WKB method [4]. So the wave field amplitude, wavelength and plasma density vary slightly in axial direction at the distances of wavelength order.

In the specified case the system of Maxwell equations breaks into two independent subsystems. One of them describes slow E-wave with (E_z, H_φ, E_r) components [2]. In the region of radial non-uniform plasma the wave field components are govern by the system of ordinary differential equations:

$$\frac{dH_\varphi^P(r)}{dr} = -ik\varepsilon_p E_z^P(r) - \frac{H_\varphi^P(r)}{r},$$

$$\frac{dE_z^P(r)}{dr} = i\frac{\kappa^2}{k\varepsilon_p} H_\varphi^P(r); \quad E_r^P(r) = \frac{k_3}{k\varepsilon_p} H_\varphi^P(r), \quad (1)$$

where $k=\omega/c$, k_3 is axial wavenumber, $\varepsilon_p = 1-\omega_p^2/[\omega(\omega+i\nu)]$, ω is wave frequency, c is light velocity, ω_p is electron plasma frequency, $\kappa^2 = k_3^2 - k^2\varepsilon_p$.

In the dielectric region the wave field components can be written with the help of modified Bessel functions of the first and second kind I_m and K_m, respectively:

$$H_\varphi^D(r) = iB\frac{k\varepsilon_d}{\psi}\mathrm{Q}(r);$$

$$E_z^D(r) = B\,\mathrm{F}(r); \qquad E_r^D(r) = iB\frac{k_3}{\psi}\mathrm{Q}(r), \qquad (2)$$

where $B = \frac{E_z^P(R_p)}{F(\psi R_p)}$, $\mathrm{F}(r) = \frac{\mathrm{K}_0(\psi r)}{\mathrm{K}_0(\psi R_m)} - \frac{\mathrm{I}_0(\psi r)}{\mathrm{I}_0(\psi R_m)}$,

$\mathrm{Q}(r) = \frac{\mathrm{K}_1(\psi r)}{\mathrm{K}_0(\psi R_m)} + \frac{\mathrm{I}_1(\psi r)}{\mathrm{I}_0(\psi R_m)}$, $\psi^2 = k_3^2 - k^2\varepsilon_d$.

With the help of boundary conditions, that consists in continuity of tangential electric and magnetic wave field components at plasma-dielectric interface and vanishing of the tangential electric wave field component at the waveguide metallic wall, the local dispersion equation can be written in the following form:

$$\frac{H_\varphi^P(R_p)}{E_z^P(R_p)} - i\frac{k\varepsilon_d}{\psi}\frac{Q(R_p)}{F(R_p)} = 0, \qquad (3)$$

where $H_\varphi^P(R_p)$, $E_z^P(R_p)$ are electric and magnetic wave field components in plasma region at plasma - dielectric interface, that are obtained with the help of numerical solution of the system (1).

3. MAIN RESULTS

For the arbitrary parameters of waveguide structure the local dispersion equations (3) can be solved only with the help of numerical methods. In contrast to ordinary differential equation the local dispersion equation (3) connects the local value of plasma density and the wavelength at the specified point along the axis of waveguide structure. To study the wave properties let use the dimensionless parameter ω / ω_p, that at the fixed wave frequency ω is determined by the local plasma density value ω_p, and dimensionless axial wave number $k_3 R_p$. The real part of it determines the wavelength, and imaginary part determines wave spatial damping coefficient α along the propagation direction.

The results of the numerical investigation of equation (3) for different ν / ω values in the case of radial uniform plasma are shown on the Figs.1, 2. The numerical solution of the local dispersion equation (3) has shown, that when effective collision rate is small $\nu / \omega < 0.1$ the growth of ε_d value leads to the decrease of parameter ω / ω_p value (curve 1 Fig.1).

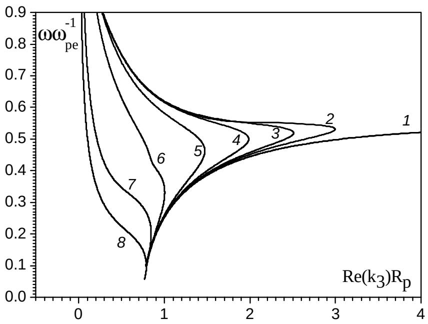

Fig. 1. The dependence of local dispersion on parameter ν / ω for radial uniform plasma with $\sigma = 0.5$, $R_m / R_p = 3.0$, $\varepsilon_d = 2.0$. The numbers 1-8 corresponds to the values of ν / ω: 0.001, 0.15, 0.2, 0.3, 0.5, 1.0, 2.0, 5.0

At that case only wave with $k_3 R_p > k_{3cr} = \sigma \sqrt{\varepsilon_d}$ ($\sigma = R_p \omega / c$) can propagate along the axis of such structure. Thus, for slightly collision plasma the increase of ε_d value results in the contraction of SW region of existence and in the decrease of α value. The increase of parameter R_m / R_p leads to the growth of ω / ω_p and to the decrease of α. The decrease of dielectric thickness under the fixed value of parameter σ offer no influence on the k_{3cr} value. The decrease of parameter σ leads to the increase of ω / ω_p, growth of α and to the decrease of k_{3cr}. It has been shown that when $\nu / \omega > 0.1$ the SW can propagate also in the region when $k_3 R_p < k_{3cr}$ (curves 2-8 on the Fig.1). The adduced dependence qualitatively coincides with the dependence, that was observed earlier for the case of plasma cylinder, that is placed in unbounded dielectric under the conditions of the large electron collision rate [5].

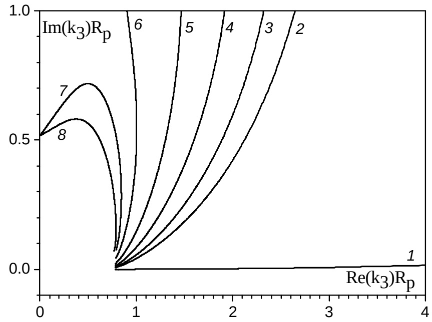

Fig. 2. The dependence of the coefficient of spatial attenuation α on the parameter ν / ω in the case of radial uniform plasma. The notation is the same as on the Fig. 1

The results of the numerical solutions of the local dispersion equations (3) in the case of radial non-uniform plasma are shown at Figs. 3,4. Plasma density radial profile was chosen in the form $n(r) = n(0) J_0(\mu r / R_p)$, where J_0 is Bessel function of the zero order, and parameter μ determines the radial profile of plasma density ($0 < \mu < 2.405$) [1,6]. In the case of strong radial non-uniformity ($\mu \geq 2$) the dependence ω / ω_p on $\mathrm{Re}(k_3 R_p)$ possesses rather complex behavior (see curves 4,5 on the Fig. 3). Note, that the parameter ν / ω influences on the spatial attenuation coefficient similar to the non-uniformity parameter μ.

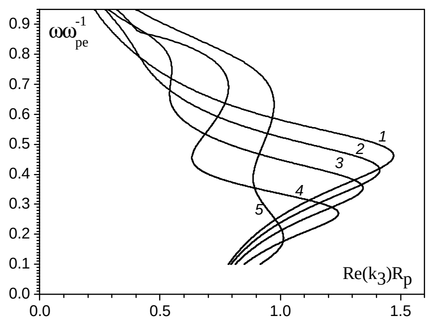

Fig. 3. The dependence of the local dispersion on the parameter μ. $\sigma = 0.5$, $\nu / \omega = 0.5$, $R_m / R_p = 3.0$, $\varepsilon_d = 2.0$. The numbers 1-5 corresponds to the following parameter values $\mu = 0; 1; 1.5; 2; 2.4048$

In the case of radial uniform collisionless plasma the wave field culminates its maximum at plasma-dielectric interface ($r = R_p$). With the increase of the dimensionless collision rate ν / ω or non-uniformity parameter μ the wave field changes its radial structure to one, which is typical for volume wave. It has been obtained that in collisional plasma the direction of the wave energy flux does not coincide with wave propagation direction. Also it was shown, that the value of radial component of the wave energy flux depends as on effective electron collision rate, as on plasma density radial profile. The increase of non-uniformity parameter value or collision rate value leads to the increase of radial component of the wave energy flux.

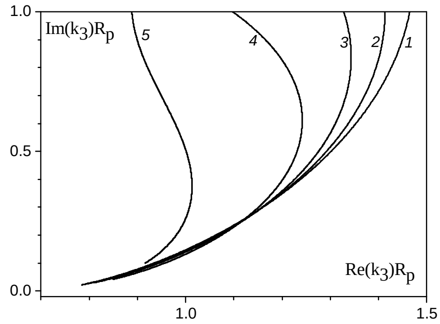

Fig. 4. The dependence of the coefficient of spatial attenuation α on the parameter μ value. The notation is the same as on the Fig. 3

It is necessary to mention that it is possible to estimate the region of stable discharge existence based on the dependence of spatial attenuation coefficient upon local plasma density value. According to the criterion, obtained in the paper [7] it has been shown that the increase of collision rate or non-uniformity parameter leads to the decrease of the region of plasma density, where it is possible to obtain stable symmetric wave sustained gas discharge.

CONCLUSIONS

The properties of symmetric wave that propagates in waveguide structure that consists of radial non-uniform isotropic dissipative plasma column, surrounded by dielectric and included into metal waveguide were studied. It was studied combined influence of plasma parameters and dielectric properties, and also geometrical parameters of the waveguide structure on the phase characteristics, spatial damping and distribution of electromagnetic wave field component of slow symmetric wave. It was shown that varying of effective electron collision rate and radial plasma density profile essentially influences on the wave energy flux components. It was investigated the influence of the effective electron collision rate and radial plasma density profile on stability of gas discharge sustained by symmetric SW.

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СИММЕТРИЧНЫЕ ПОВЕРХНОСТНЫЕ ВОЛНЫ В ЦИЛИНДРИЧЕСКИХ ВОЛНОВОДНЫХ СТРУКТУРАХ, ЗАПОЛНЕННЫХ РАДИАЛЬНО НЕОДНОРОДНОЙ СТОЛКНОВИТЕЛЬНОЙ ПЛАЗМОЙ

В.П. Олефир, В.К. Галайдыч, А.Е. Споров

Исследовано влияние эффективной частоты столкновений электронов и радиальной неоднородности плотности плазмы на фазовые характеристики, пространственное затухание и структуру поля медленных симметричных электромагнитных волн, распространяющихся вдоль цилиндрической структуры. Полученные результаты важны для построения теории газовых разрядов, поддерживаемых электромагнитными волнами поверхностного типа.

СИМЕТРИЧНІ ПОВЕРХНЕВІ ХВИЛІ В ЦИЛІНДРИЧНИХ ХВИЛЕВОДНИХ СТРУКТУРАХ, ЩО ЗАПОВНЕНІ РАДІАЛЬНО НЕОДНОРІДНОЮ ПЛАЗМОЮ З ЗІТКНЕННЯМИ

В.П. Олефір, В.К. Галайдич, О.Є. Споров

Досліджено вплив ефективної частоти зіткнень електронів та радіальної неоднорідності густини плазми на фазові характеристики, просторове загасання та структуру поля повільних симетричних електромагнітних хвиль, що розповсюджуються вздовж циліндричної структури. Отримані результати важливі для побудови теорії газових розрядів, що підтримуються електромагнітними хвилями поверхневого типу.