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Model of a Miniature Plasma Antenna

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Abstract* − *In this work we report results from theoretical modeling of miniature plasma antenna at low gas pressure working at a frequency of 2.45 GHz. The plasma antenna is investigated for the first time as a cylindrical dielectric resonator antenna (DRA) with known electric and magnetic fields on the wall surfaces. The plasma column in a finite length vessel is sustained by azimuthally symmetric surface wave (TM_{00}-mode) and this plasma antenna works as an asymmetrical electrical dipole above the metal plane. The dispersion relation of the surface waves in the plasma column is solved numerically and their wavelength, damping rate and field distribution are obtained. Antenna radiated power depends on the value of the axial component of the electric field on the boundary plasma-air. Results show that the antenna radiation from cylindrical plasma column at low gas pressure is similar to a dielectric resonator antenna.

Index Terms*—*antenna, dielectric resonator, plasma, surface waves

I. INTRODUCTION

The plasma antennas have promising features as steerable and adaptive antennas [1-4]. The possibilities for rapid adjustments of their working frequency, for control of the radiation pattern and for beam forming make them competitive to the smart antennas. Plasma antennas with plasma column sustained by surface waves can work in the microwave S-band as asymmetrical dipoles and they are subjected of many experimental and theoretical studies [5–10]. The plasma column in these antennas is a dielectric with negative permittivity and low conductivity, which values depend on the electron density. Their properties and parameters usually are compared with these of the metal antennas, although plasma antennas generally operate at low gas pressures and plasma columns have a much lower electron concentration.

In our study is modeled miniature cylindrical plasma antenna on the basis of surface wave discharge at low gas pressure (p~3.5 Pa) in argon [11]. A signal at the frequency 2.45 GHz from the generator is fed to the antenna structure which has surface wave exciter [12]. This coaxial structure excites an azimuthally symmetric surface waves (TM_{00} - plasma mode [13]) which create a plasma in a quartz capillary with finite length. Standing-wave regime is realized in the capillary if it is completely fulfilled with plasma and the surface wave is reflected from the end of the capillary. At specific value of the plasma density the plasma column will have a length comparable to quarter or half wavelength of the surface wave and the antenna becomes a resonant structure, which effectively radiates at the frequency of 2.45 GHz. Grounded metal plane is taken into account in the model in order to obtain radiation pattern and directivity of the monopole plasma antenna.

II. MODEL OF PLASMA ANTENNA

Plasma antenna is modeled as a cylindrical dielectric rod-cylindrical plasma column with radius of R (homogeneous in radial and axial directions) and length of d with very thin quartz wall (width of the wall D). It is assumed that plasma is sustained by surface wave discharge at frequency of 2.45 GHz ($\omega=2\pi f$). The relative plasma permittivity ε (Drude model) depends on the plasma frequency ω_p and electron neutral collision frequency ν:

$$\varepsilon = 1 - \frac{\omega_p^2}{\omega(\omega - j\nu)} \qquad (1)$$

where $\omega_p = (n.e^2/\varepsilon_0 m)^{1/2}$, n is the plasma density, e - elementary charge, m - electron mass, ε_0 - dielectric constant of vacuum. We assume that plasma density vary from n = 2×10^{18} m^{-3} to 12×10^{18} m^{-3} and plasma column can be described as a dielectric with negative plasma permittivity (from ε= -33 to -160) and low conductivity (from 14 mS to 52 mS). The estimation of the skin depth ($\delta = c/\omega_p$ = 1.6×10^{-3} m-3.3×10^{-3} m) of EM field show that it is larger than the plasma column radius ($\delta \geq R$).

Wavelength of surface waves sustaining the plasma column as a function of plasma density is investigated by solving the dispersion relation in a system plasma-dielectric-air for a infinite tube. These waves propagate along the plasma column with propagation constant $\gamma = \alpha + j\beta$, where β is a phase constant and α - space damping rate, j- imaginary unit.

This procedure is correct for finite length tube if $\alpha \ll \beta$ as can be seen below. Material of the capillary tube and width of the wall have small effect on the distribution of the electromagnetic field of surface wave and on the space damping rate α and phase constant β because we assume that D<<R. Dispersion relation [14] of surface waves sustaining the plasma column is used for calculations of α and β:

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$$-\frac{\kappa_d \varepsilon}{\kappa_p \varepsilon_d}\frac{I_1(\kappa_p R)}{I_0(\kappa_p R)} = \frac{\delta_1 + (\frac{\kappa_d}{\varepsilon_d})Z_2\delta_2}{\delta_3 - (\frac{\kappa_d}{\varepsilon_d})Z_2\delta_4}$$

$$Z_2 = \frac{1}{\kappa_v}\frac{K_1(\kappa_v(R+D))}{K_0(\kappa_v(R+D))}$$

$$\delta_1 = K_1(\kappa_d R)I_1(\kappa_d(R+D)) - I_1(\kappa_d R)K_1(\kappa_d(R+D))$$

$$\delta_2 = I_1(\kappa_d R)K_0(\kappa_d(R+D)) + I_0(\kappa_d(R+D))K_1(\kappa_d R)$$

$$\delta_3 = I_0(\kappa_d R)K_1(\kappa_d(R+D)) + K_0(\kappa_d R)I_1(\kappa_d(R+D))$$

$$\delta_4 = I_0(\kappa_d R)K_0(\kappa_d(R+D)) - I_0(\kappa_d(R+D))K_0(\kappa_d R)$$

)

where R is a radius of the plasma column and D is the width of the tube wall. Dielectric constants are ε, ε_d, ε_v and quantities κ_p, κ_d, κ_v characterize a radial distribution of the field in the plasma, dielectric tube and air, respectively. The functions I_0, I_1, K_0, K_1 are modified Bessel functions. In the dispersion relation is taken into account electron neutral collision frequency but its ratio to the frequency of the surface wave is very low (ν/ω << 1) at the low gas pressure. Therefore the damping rate is about 1000 times smaller than the phase constant (α << β) and the surface waves are weakly damped waves at these conditions (Fig. 2). In this case we assume that the surface waves reflect at the end of the antenna tube and standing wave regime will appear. At these conditions the length of the surface waves (λ_g=2π/β) changes from 0.029 m to 0.074 m with increase of the plasma density while the wavelength in the free space is 0.1224 m.

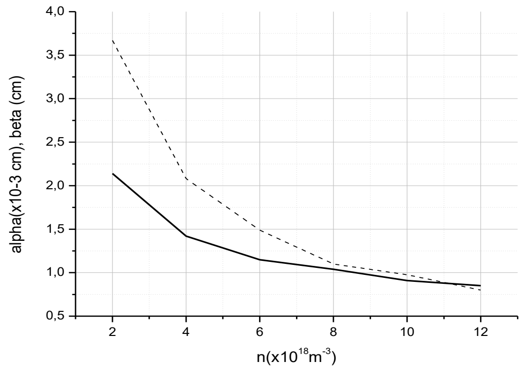

Fig. 2 Dependence of damping rate α (dashed line) and phase constant β (continuous line) of surface waves on the plasma density *n* at R=0.001 m, D=1.10^{-6} m.

These results show that the ratio of the wavelength of surface wave to the wavelength in the free space λ changes with the value of the plasma density from λ_g/ λ= 0.23 to 0.6.

More important for standing wave regime and work of the plasma antenna as a dielectric resonator antenna (DRA) is the ratio of the length of the plasma antenna d to the wavelength of surface wave λ_g. In the model this ratio is assumed d/ λ_g ≤1/4. In the experiments [11] the plasma column of the antenna is sustained by azimuthally symmetric surface mode (TM_{00} - plasma mode) and the same mode is taken into account in the analysis of the work of antenna as a DRA. Antenna is positioned above the infinite grounded plane (Fig.1). In this case the method using the magnetic wall model for a simple analysis of cylindrical DRA [15] is applied for determination of radiated fields of plasma antenna in the far-field zone.

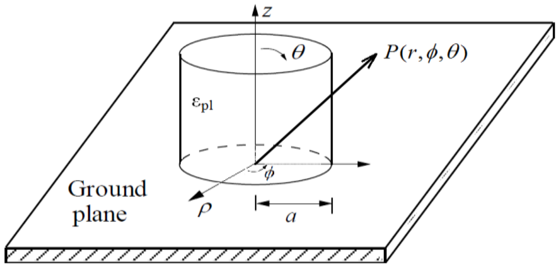

Fig. 1 Plasma antenna above the grounded plane in a polar co-ordinate system.

The ratio R/d< 0.1 is assumed and the radiation from the top and the bottom walls is neglected. There is not conductivity current J_s on the dielectric wall and only the equivalent magnetic surface current is considered. The azimuthally symmetric surface mode has components E_r, E_z, H_φ and therefore the magnetic surface current is:

$$\vec{M}_S = \vec{E}_z \times \vec{n} = E_z\vec{\varphi} \ , \tag{2}$$

where $E_z = E_{z_0}\left(r=R\right)\cos\left(\pi z/2d\right)$ is the electric field along the dielectric wall of the plasma antenna. The electric vector potentials due to this current is:

$$\mathbf{F}_M = \frac{\varepsilon.a}{4\pi}\iint_S M_S \frac{e^{-jkR}}{R}ds' = \frac{\varepsilon e^{-jkr}}{4\pi R}L \tag{3}$$

where

$$L = \int_S M_S e^{jkr'\cos\varphi}ds' \ .$$

The far-fields are usually expressed in spherical coordinates (r, θ, φ) and the transformed source currents are:

$$\begin{aligned} M_r &= M_{\rho'}\sin\theta + M_{z'}\cos\theta \\ M_\theta &= M_{\rho'}\cos\theta - M_{z'}\sin\theta \\ M_\varphi &= M_{\varphi'} \end{aligned} \tag{4}$$

The expressions for the components of the vector potential are:

$$F_\theta = \frac{\varepsilon e^{-jkr}}{4\pi r}R\iint_S M_\varphi \cos\theta \sin\left(\varphi-\varphi'\right)e^{jk\rho'\sin\theta\cos(\varphi-\varphi')} e^{jkz'\cos\theta}d\varphi' dz' \tag{5}$$

$$F_\varphi = \frac{\varepsilon e^{-jkr}}{4\pi r}R\iint_S M_\varphi \cos\left(\varphi-\varphi'\right)e^{jk\rho'\sin\theta\cos(\varphi-\varphi')} e^{jkz'\cos\theta}d\varphi' dz' \tag{6}$$

where S is the sidewall surface.

In order to simplify analysis a dipole dielectric antenna is considered. The calculations show that F_θ=0 and F_φ≠0 in the far-field zone. Applying formulas from [16] for integral form of Bessel functions, the expressions for far-field component of EM field in P(r, θ, φ) are calculated:

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$$E_{\theta} = \kappa E_{z0} \frac{e^{-jkr}}{4\pi r} 2\pi.\mathrm{R}.d \frac{4\pi \cos\left(\kappa_0 d \cos\theta\right)}{\pi^2 - 4d^2\kappa_0^2 \cos^2\theta} J_1\left(\kappa_0 R \sin\theta\right) \quad (7)$$

$$H_{\varphi} = -j\omega F_{\varphi} = \omega\varepsilon \frac{e^{-jkr}}{4\pi r} E_{z0} \cdot 2\pi.\mathrm{R}.d \frac{4\pi \cos\left(\kappa_0 d \cos\theta\right)}{\pi^2 - 4d^2\kappa_0^2 \cos^2\theta} J_1\left(\kappa_0 R \sin\theta\right) \quad (8)$$

where $k_0 = 2\pi/\lambda$. This result show that the EM field radiated by the plasma antenna with column sustained by azimuthally symmetric surface wave has two components in the far-field zone - E_θ and H_φ . Radiation pattern is similar to the radiation pattern of wire electric dipole but the value of the fields depend on the value of the electric field on the sidewall and these values are not directly connected with the current in the plasma. Radiation pattern of the plasma monopole calculated as a DRA above the infinite grounded plane is presented in Fig.3.

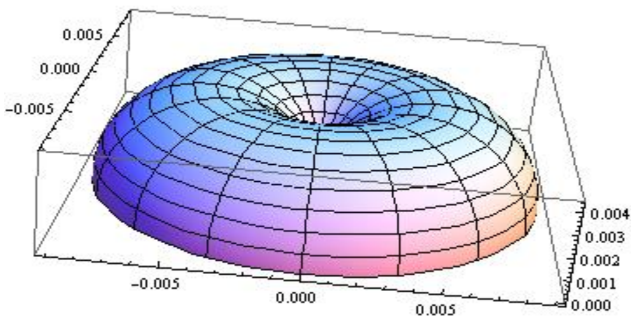

Fig. 3 Radiation pattern of plasma antenna as a DRA.

This result could be a reasonable explanation of the effective work of the vibrator plasma antennas at low gas pressures [5] where the amplitude of the discharge current is low.

III. Conclusion

The model of plasma antenna as a DRA for the ratio of R/d< 0.1 is developed. The expressions for the components of EM field in the far-field zone are obtained and their values depend on the value of the electric field on surface of side-wall.

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