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Radiation of Monopole Microwave Plasma Antenna

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***Abstract:** The radiation of cylindrical plasma monopole at low gas pressure is theoretically investigated by applying the theory for dielectric resonator antenna (DRA). The plasma column is placed in a thin dielectric tube with a longitudinal length equal to half wavelength of the surface wave which sustains the discharge. The resonance wavelength of the TM_{011} mode at frequency 2.45 GHz is obtained by dielectric waveguide model (DWM) in which dielectric is replaced by plasma medium. The expression for electric field in far-field zone of this plasma monopole is derived and the result shows that its radiation pattern is similar to that of metal dipole antenna. The radiated field strength of plasma monopole is greater than that of metal antenna with the same electrical conductivity and dimensions.*

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

I. INTRODUCTION

Plasma antennas operating at low pressure are actively exploring in the last decade because of their capability to be invisible to radar systems [1, 2] and to ensure high-speed transfer of information in modern mobile communications. Plasma antennas are a new alternative to conventional metal antennas in wireless communications and they are quickly gaining popularity. Instead of metal wires these antennas use plasma columns. Particular attention attracted monopole plasma antennas created by high-frequency surface waves which sustain the plasma column in vessel with finite dimensions [3-6]. Plasma discharge appears as a complex impedance load for the microwave generator – load, which changes its value depending on the plasma density. Plasma density is dependent on the absorbed microwave power and power θ required to sustain an electron-ion pair in the vessel [7]. Furthermore, part of the delivered to the discharge power is radiated into the free space as EM waves and the experimentally obtained radiation pattern is similar to the metal antenna [3]. At low gas pressures, the electrical conductivity in the plasma is low and the plasma antenna can be better described as a dielectric resonator antenna [8]. The radiation pattern of DRA with excited $TM_{01\delta}$ mode is also similar to the radiation pattern of electric dipole [9]. The investigation of cylindrical DRA with TM_{011} and TM_{012} modes attract attention with the possibility of constructing of omnidirectional dual-band antennas [10]. In this paper the half-wavelength plasma antenna above grounded metal plane, with column sustained by azimuthally-symmetric surface wave (TM_{011}), is analyzed. The expressions for electric field and radiation pattern in the far-field zone of plasma antenna are obtained. They are compared to the electric field and radiation pattern of metal antenna with same dimensions and electrical conductivity of the plasma column.

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II. MODEL OF PLASMA ANTENNA

In our study is modeled microwave plasma antenna with plasma column at low gas pressure (p~ 3.5 Pa) in argon, sustained by surface wave discharge [3]. Surface wave coaxial launcher [11] is used for excitation of azimuthally symmetric surface waves in a quartz capillary with finite length at the frequency of 2.45 GHz. If the capillary is completely fulfilled with plasma a standing wave regime is observed [12]. At specific value of the plasma density the capillary will have a length approximately equal to the half wavelength of the surface wave and the antenna becomes a resonant structure. Plasma antenna is positioned above grounded metal plane and it is analyzed as a dielectric resonator antenna (Fig. 1).

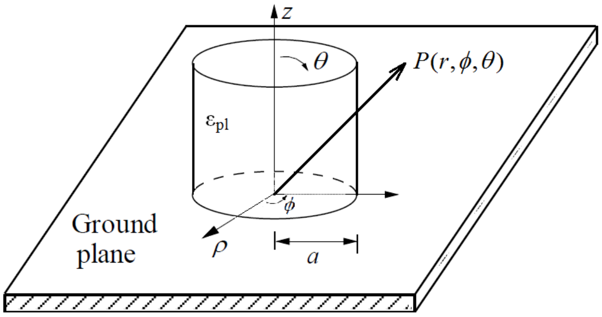

Figure 1. Cylindrical plasma antenna above the grounded plane.

In the model is assumed that the cylindrical plasma column with radius R of 1 mm is homogeneous in radial and axial directions. It is positioned in quartz tube with length d of 16 mm with very thin wall (width of the wall D= 1.10^{-6} m).
Drude model for the plasma column is used and the relative plasma permittivity ε is:

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

where ω is the signal frequency, ν is the electron neutral collision frequency, $\omega_p = (n.e^2 / \varepsilon_0 m)^{1/2}$, n is the plasma density, e - elementary charge, m - electron mass, ε_0 - dielectric constant of vacuum.

At small ratio R/d, the resonant wavelength at 2.45 GHz is obtained by applying the dielectric waveguide model (DWM) [10] in which the dielectric is replaced by plasma medium.
Dispersion relation [13] of azimuthally symmetric (TM_{01}) surface waves sustaining the plasma column is:

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

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

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

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

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

$$\delta_4 = I_0(\kappa_d R)K_0(\kappa_d(R+D)) - I_0(\kappa_d(R+D))K_0(\kappa_d R) \tag{2}$$

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:

$$\kappa_p = \sqrt{k_z^2 - k_0^2\varepsilon}\,,$$

$$\kappa_d = \sqrt{k_z^2 - k_0^2\varepsilon_d}\,,$$

$$\kappa_v = \sqrt{k_z^2 - k_0^2} \tag{3}$$

where $k_z=\beta+j\alpha$, β-phase constant, α-space damping rate of surface wave, $k_0=\omega/c$ – is the free-space wave number. The functions I_0, I_1, K_0, K_1 are modified Bessel functions.

The wavelength of the surface waves ($\lambda_g=2\pi/\beta$) is shorter than the signal wavelength in the free space (λ= 0.1224 m) and it depends on the plasma density in the quartz tube (Fig. 2). The resonant length of the surface wave λ_g at frequency of 2.45GHz is obtained from Figure 2. At specific value of the plasma density the tube length is equal to the half wavelength of the surface wave ($d = \lambda_g/2$) and the plasma antenna works as a DRA with TM_{011} mode.

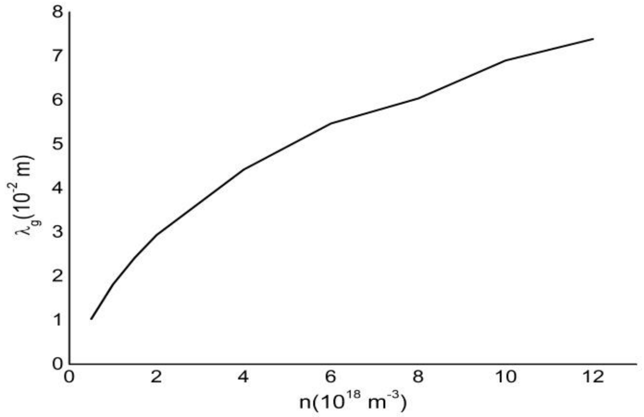

Figure 2. Dependence of wavelength of surface waves on the plasma density n at signal frequency of 2.45 GHz.

In the dispersion relation of surface waves is taken into account electron neutral collision frequency. At low gas pressure $\nu/\omega \ll 1$ and the results show that the damping rate α is much smaller than the phase constant β ($\alpha \ll \beta$) [8].

In our study the method for analyzing of cylindrical DRA [9] is applied for determination of fields of plasma antenna [3] in the far-field zone. In our model d/R>10 and the radiation from the top wall of the cylindrical tube is neglected. As in the previous model of plasma antenna [8], only the equivalent magnetic surface current is considered on the quartz tube surface area S. The azimuthally-symmetric surface wave mode (TM_{011}) has components E_r, E_z, H_φ and therefore the magnetic surface current is:

$$\vec{M}_S = \vec{E}_z \times \vec{n} = E_z\vec{\varphi}\,. \tag{4}$$

In order to simplify analysis a dipole dielectric antenna is considered and $E_z=E_{z0}(r=R).\sin[\beta\,|\,d-z\,|\,)]$ is the electric field along the dielectric wall of the plasma antenna. The electric vector potential due to this current is:

$$\mathbf{F}_M = \frac{\varepsilon.a}{4\pi}\iint_S M_S\frac{e^{-jkR}}{R}ds' = \frac{\varepsilon e^{-jkr}}{4\pi R}L \tag{5}$$

where [14]:

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

The magnetic current (4) and far-fields are expressed in spherical coordinates (r, θ, φ) as in [9]. The expression for the component F_φ of the vector potential is:

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

$$e^{jkz'\cos\theta}d\varphi' dz'$$

where S is the sidewall surface.

Applying formulas from [14] for integral form of Bessel functions, the expressions for far-field components of EM field radiated by half-wavelength plasma antenna at the point P(r, θ, φ) are calculated as:

$$E_\theta = E_{z0}\frac{\kappa_0 e^{-jkr}}{4\pi r}4\pi.\mathrm{R}.\frac{\left[\cos\left(\kappa_0 d\cos\theta\right)-\cos(\xi\kappa_0 d)\right]}{\xi.\kappa_0(1-\cos^2\theta/\xi^2)}\times$$

$$\times J_1\left(\kappa_0 R\sin\theta\right) \tag{7}$$

$$H_\varphi = -j\omega F_\varphi = \omega\varepsilon\frac{e^{-jkr}}{4\pi r}E_{z0}\times$$

$$\times 4\pi.\mathrm{R}\frac{\left[\cos\left(\kappa_0 d\cos\theta\right)-\cos(\xi\kappa_0 d)\right]}{\xi.\kappa_0(1-\cos^2\theta/\xi^2)}\,, \tag{8}$$

where $k_0==2\pi/\lambda$, $\xi=\beta/k_0$. This result shows that the EM field in the far-field zone has two components (E_θ and H_φ), which depend on the value of the electric field E_{z0} on the sidewall [8] and the surface area of the antenna. Therefore, the radiation from half-wavelength plasma antenna above grounded plane, at low gas pressure in the quartz tube, is similar to that of half-wavelength dielectric resonator antenna. On the other hand, the radiation pattern of DRA with TM_{011} mode is similar to the radiation pattern of electric dipole antenna [9] with length equal to λ. If the parameter ξ = 1, the radiation pattern of this plasma antenna approaches the radiation pattern of metal electric dipole antenna [14]. Distribution of the electric field of the half-wavelength plasma antenna (7) is calculated with estimated value of E_{z0} [3] and it is presented in figure 3. The distribution of the electric field of a small metal antenna [14] whose parameters are identical to those of the plasma antenna (length of 16 mm, radius of 1 mm and the same electrical conductivity) is also calculated (Fig. 4).

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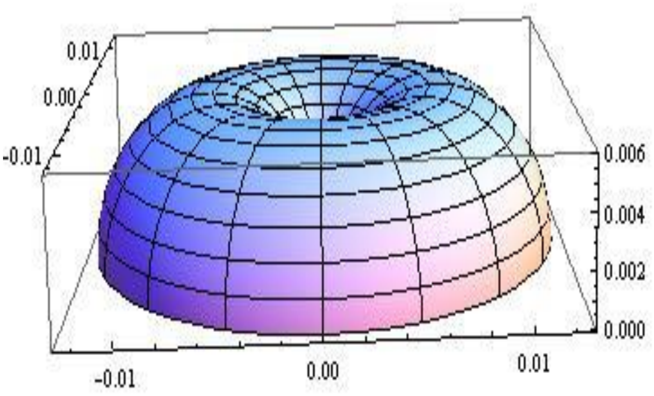

Figure 3. E_θ-field distribution in the far-field zone of half-wavelength plasma antenna above the metal plane.

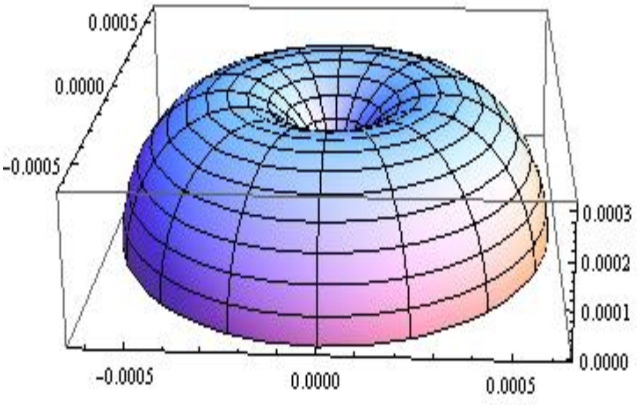

Figure 4. E_θ-field distribution in the far-field zone of the metal antenna with dimensions and electrical conductivity identical to those of the plasma antenna.

Obtained results show that the electric field strength in the far-field zone of the plasma antenna is many times greater than that radiated by the metal antenna with identical dimensions.

III. CONCLUSION

Radiation of the half-wavelength plasma antenna in the far field zone is obtained by the model developed on the basis of the theory of dielectric resonator antennas. The expressions for the components of EM field in the far-field zone are obtained and result shows that they depend on the value of the electric field on the side-wall and surface area of the plasma antenna. If the parameter ξ is close to one, the radiation pattern of half-wavelength (related to the surface wavelength) plasma antenna approaching that of metal dipole antenna.

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