ANALYSIS AND DESIGN OF PLASMA MONOPOLE ANTENNA

Li Wei, Qiu Jinghui and Suo Ying

Harbin Institute of Technology, Harbin, China
E-mail: liweihit@yeah.net

Abstract

Two kinds of plasma monopole antennas are simulated and analyzed in this paper. For different radius, reflection coefficient, radiation pattern and radiation efficiency of a cylindrical plasma monopole antenna are calculated respectively. According to actual situation, a conical plasma monopole antenna with different cone angle is simulated. Impedance and radiation characteristics of the plasma antenna are similar to the metal monopole antenna.

Keywords: Plasma antenna; Monopole antenna; Radiation characteristics

1. INTRODUCTION

A plasma antenna is able to radiate electromagnetic wave from the radiator made of plasma. The plasma antenna can be reconstructed with different electron density and collision frequency. And plasma antenna generated by explosion is a radiator for some high power microwave devices.

Principle of the plasma antenna has been researched recently. A plasma antenna is researched and measured in [1], and radiation characteristics are similar to metal antenna when signal is transmitted and received. The structure parameters and current distribution of a plasma antenna are researched in [2-4], and radiation efficiency of the antenna is about 25%. Experiments of electron density distribution, radiation patterns and noise characteristics are analyzed in [5-7].

In this paper, a cylindrical plasma monopole antenna with different radius are calculated and simulated. To broaden the bandwidth, a conical plasma monopole antenna is presented and simulated.

2. PRINCIPLE OF PLASMA MONOPOLE ANTENNA

The plasma characteristic frequency is increased as the electron density is heightened, while the skin depth of electromagnetic wave is very small. Transmission mode of electromagnetic wave in plasma column is similar to transmission mode in metal. So the plasma is able to conduct electromagnetic wave instead of metal in antenna design. The basic type of antenna with plasma radiator is a plasma monopole antenna. As the plasma is a kind of dispersion material, the impedance characteristics and radiation characteristics of the plasma monopole antenna are different with the metal monopole antenna.

The radio frequency signal can be coupled into the formative plasma by external excitation. The signal propagates along the plasma by surface wave format. The dispersion relation of the plasma surface wave in plasma column is given by (1).

$$\varepsilon_r T_0 I_1(T_p r) K_0(T_0 r) + T_p K_1(T_0 r) I_0(T_p r) = 0 \quad (1)$$

where ε_r is relative dielectric constant of plasma, ω_p is characteristic angular frequency of plasma, ν is collision frequency of plasma, ω is angular frequency of electromagnetic wave, $T_0^2 = k_p^2 - k_0^2$, $T_p^2 = k_p^2 - \varepsilon_r k_0^2$, I_n is the first order Bessel function while K_n is the second order Bessel function, r is radius of plasma column, k_p is wave number in plasma, k_0 is wave number in the vacuum, and the k_p is given by (2).

$$k_p = \beta - j\alpha \quad (2)$$

α is attenuation constant, β is phase constant. When ω_p is more than ω, for plasma with very high electron density α is small, and β is close to the wave number in vacuum. There is a surface wave mode at the boundary surface of the plasma and external environment. The vertical component of electromagnetic wave along the boundary surface attenuates fast while the parallel component can propagate along the boundary surface. The propagation mode of electromagnetic wave along the plasma column is similar to the propagation mode along the boundary surface of plasma and dielectric, where the velocity is close to light velocity. The current distribution induced by surface wave along a plasma column is also similar to the surface current in a metal antenna. The surface current distribution of cylindrical plasma monopole antenna is able to show in (3).

$$I(z) = I_0 \mathrm{e}^{jk_p z} - I_0 \mathrm{e}^{jk_p (2l - z)} \quad (3)$$

where I_0 is primary feeding current, l is length of a plasma column, k_p is used from 0 to l. Based on the antenna theory, radiation pattern of a cylindrical plasma monopole antenna can be shown in (4).

$$f(\theta) = \int_0^l I(z) \sin(\theta) \mathrm{e}^{jk_p z \cos(\theta)} \mathrm{dz} \quad (4)$$

A simplified cold plasma model is able to be chosen for the macroscopic analysis of the actual plasma with complex motion state and internal structure. Dielectric constant and electrical conductivity of the cold plasma model can be shown in (5) and (6).

$$\varepsilon = \varepsilon_0[1 - \frac{\omega_p^2}{\omega(\omega - j\nu)}] \tag{5}$$

$$\sigma = \frac{\varepsilon_0 \omega_p^2}{j\omega + \nu} \tag{6}$$

From homogeneous Helmholtz equation, attenuation constant α can be got, so the skin depth in a plasma column can be obtained $\delta = 1/\alpha$. And loss impedance of a plasma antenna can be given by (7).

$$R_l = l/(\sigma S) \tag{7}$$

where l is the effective length of a plasma antenna, and S is the loss sectional area from the skin depth. The radiation efficiency of the antenna can be obtained in (8) from the radiation impedance R_r.

$$\eta = R_r/(R_r + R_l) \times 100\% \tag{8}$$

3. CYLINDRICAL PLASMA MONOPOLE ANTENNA

To simulate the performance of a cylindrical plasma monopole antenna, CST MWS software based on finite integral technique is used. In this software, the behavior of the plasma is given by drude dispersion model. The drude dispersion model describes simple characteristics of an electrically conducting collective of free positive and negative charge carriers, where thermic movement of electrons is neglected. The dielectric constant of the drude dispersion model is given by (9).

$$\varepsilon = \varepsilon_0[\varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega - j\nu)}] \tag{9}$$

where ε_∞ is the relative dielectric constant at infinite frequency, generally $\varepsilon_\infty = 1$.

A basic dimension of antenna structure is selected: the radius of plasma column r=3mm, l=50mm, n=10^{20}/m^3, and the radius of circular floorboard R=20mm. The electron density in the plasma column is considered homogeneous, and the collision frequency is constant. For simulation of antenna, drude dispersion material is designed as: plasma characteristic frequency f_p=56.34$(n)^{1/2}$, ν=10^9Hz, relative magnetic permeability μ=1. The simulation structure of the cylindrical plasma monopole antenna is shown in figure 1, and impedance of feeding coaxial transmission line is 50 Ω. Reflection coefficient of cylindrical plasma monopole antenna and metal monopole antenna is shown in figure 2. It is seen that the reflection coefficient of cylindrical plasma monopole antenna is less than -10dB from 1.44GHz to 1.78GHz, while the impedance bandwidth of the metal monopole antenna with a same dimension of the structure is from 1.45GHz to 1.77GHz. So the impedance characteristics of the cylindrical plasma monopole antenna are similar to the metal monopole antenna. Based on equations (7) and (8), the radiation impedance R_r=56 Ω and the loss impedance R_l=45 Ω at 1.6GHz can be obtained. So the radiation efficiency of the plasma antenna is 55%.

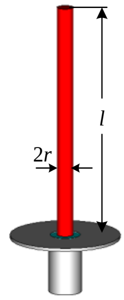


Fig. 1. Structure of cylindrical plasma antenna

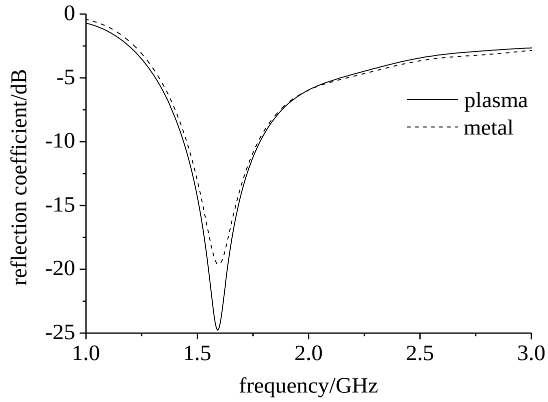


Fig. 2. Reflection coefficient of cylindrical plasma antenna

Based on the dimension in figure 1, the radius of the plasma column is changed from 1mm to 4mm with step of 1mm. As shown in figure 3, it is seen that resonant frequency of the plasma antenna is heightened as the radius become larger, and the impedance bandwidth is heightened with the radius enlarged.

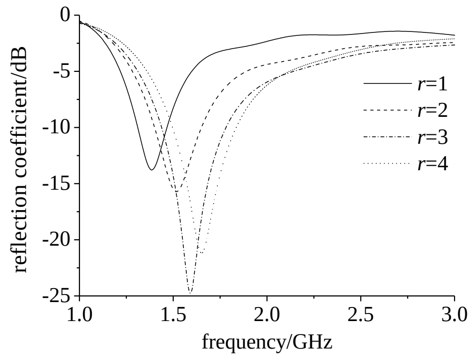
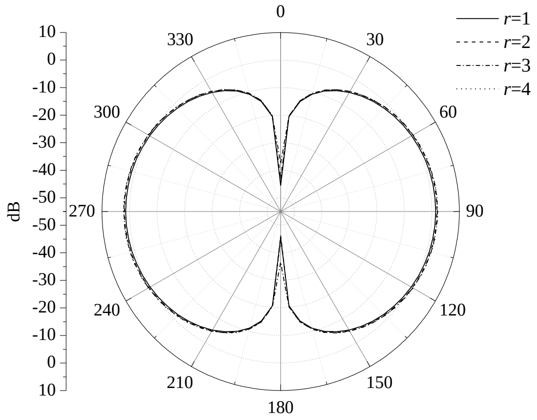
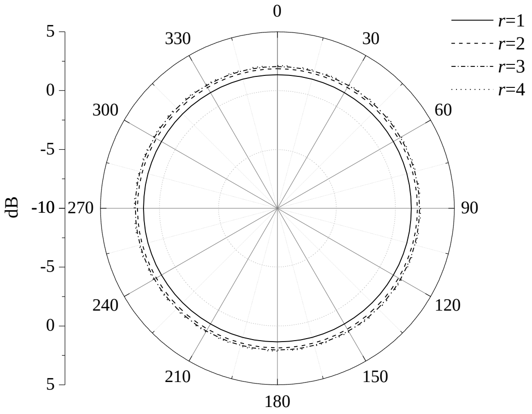


Fig. 3. Reflection coefficient of cylindrical plasma antenna with different *r*

Figure 4 show radiation patterns of the cylindrical plasma antenna with different radius of plasma column. As shown in radiation patterns, the gain is heightened with the radius enlarged. The gain stabilizes 2dB when r is 3mm or 4mm. And the radiation efficiency is about 50%~60%.



(a) E-plane



(b) H-plane

Fig. 4. Radiation patterns of cylindrical plasma antenna with different *r*

4. CONICAL PLASMA MONOPOLE ANTENNA

The plasma is in divergent status when it is generated by explosion and flame. At that time, the plasma is able to change to a circular cone. Simulation structure of the conical plasma monopole antenna is shown in figure 5, and α is cone angle. The different reflection coefficient of conical plasma monopole antenna with $\alpha=0^{\circ}$, $\alpha=10^{\circ}$, $\alpha=20^{\circ}$ and $\alpha=30^{\circ}$ when l=50mm, $n=10^{20}/m^3$, $v=10^9$Hz, r=3mm, and R=20mm are shown in figure 6.

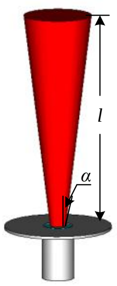


Fig. 5. Structure of conical plasma antenna

Resonant frequencies of the conical plasma monopole antenna with different cone angles are similar, and the maximal bandwidth is about 34%. The gain stabilizes about 2dB with different cone angles. The radiation impedance R_r=48 Ω and the loss impedance R_l=41 Ω at 1.6GHz can be obtained. So the radiation efficiency of the plasma antenna is 54%.

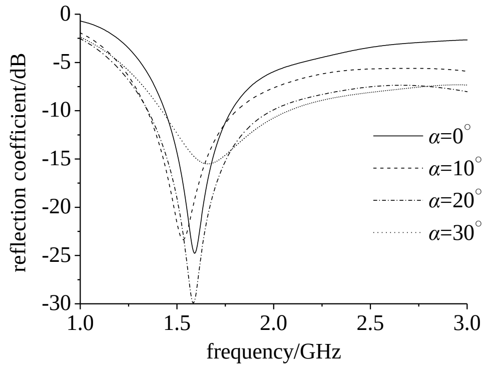


Fig. 6. Reflection coefficient of conical plasma antenna with different cone angle

5. CONCLUSION

Two kinds of plasma monopole antennas are designed and simulated. Resonant frequency of the cylindrical plasma monopole antenna is heightened as the radius become larger, and the impedance bandwidth is enlarged. The bandwidth of conical plasma monopole antenna is able to reach 34%. The gain stabilizes about 2dB, and the radiation efficiency is 50%~60%.

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