Radiation Characteristics of Plasma Triangular Antenna

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Abstract

This paper presents the results of a study on the radiation characteristics of a plasma triangular antenna in the VHF band (30-300MHz) applying the method of moment. Deriving the current distribution of the antenna, it shows the relationship between radiation characteristics of the plasma antenna and the plasma parameters. Both theoretical and numerical results indicate that if the plasma frequency is sufficiently higher than the operating frequency and the collision frequency is correspondingly low, the radiation treatment of the plasma antenna will be close to a metal one. Also the consequence of simulations reveals the proposed plasma antenna has better peak gain than the conventional plasma column on the operating band. The results of the current study are checked by using full wave HFSS simulator.

Keywords: Current Distribution, Method of Moment, Plasma Antenna, Radiation Patterns.

1. Introduction

Plasma antennas are usually radio frequency (RF) antennas based on the plasma element instead of the metal conductor. The plasma antennas have developed recently [1] because of their attractive advantages compared to conventional metal ones, Unfortunately, a few papers have been published on this subject but they lack sufficient information on the plasma antennas [2]–[4]–[5]. In fact, most these studies were covered by patents. The main advantage of the plasma antennas is that they permit electric, rather than the mechanical control of their characteristics. For example, the effective length of an antenna can be changed by controlling the input RF power [2]. When the plasma antenna is energized, it can conduct as a metal antenna but when it is de-energized, the antenna behaves as a dielectric tube with reduced reflection [2]–[3]. The plasma antenna can switch on and off rapidly. So it can be difficult to detect this antenna by hostile radar and it is energized only when communication takes place. This property can be useful for the military communication [2].

The plasma antenna is usually constructed using an insulating tube filled with low pressure gas. There are various methods to generate plasma for this type of antennas. In previous experiments, two electrodes were used at opposite ends of the tube containing a suitable gas. But this method encountered problems such as plasma contamination by electron erosion [4]. In 1982, Moisan et al. suggested the RF plasma surface wave technique for plasma discharging by an electrode at the one end of the tube [5]. This technique did not have the previous problems and was more stable too. Moreover this method decreased the radar cross section (RCS) and had other advantages like simplicity of design [4]–[5]. Recently, based on this idea, the plasma in antenna is rapidly created and destroyed by applying proper RF power pulses to discharge tube.

In practical experiments, changing of dimensions and parameters of a structure is limited because of some problems such as time-consuming and cost factors, while the use of numerical simulations can overcome these limitations. As such, numerical methods for analysis of plasma antennas are more desirable in recent decades [6]–[7]. Among them, FDTD analysis is being used more, because in this time-domain method, a wide frequency response can be easily obtained by taking the FFT of the results. However, to increase the accuracy, the FDTD might need much memory. Also simulation has to run for a longer time in order to record low frequency components [6]. In some works, the method of moment (MOM) is used for calculating current distribution on a plasma column from an integral equation (IE) [8]. This method is more exact than the FDTD but not as simple as it is.

In this paper, we implement a computer code based on the MOM technique to solve electric field integral equation (EFIE) for current distribution on a triangular plasma antenna. For that matter, the radiation patterns and the relationship between radiation characteristics of the plasma antenna and the plasma parameters and also antenna bend angle

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are studied. Finally simulations are compared with the results of the HFSS software and an acceptable matching between them is observed.

2. Theory

A. Principle of Plasma Antenna

The isotropic cold plasma is a type of dispersive medium. The relative permittivity ε_{rp} of uniform plasma is as follows [9]

$$\varepsilon_{rp} = 1 - \frac{\omega_{pe}^2}{\omega(\omega - j\nu_m)} = 1 - \frac{\omega_{pe}^2}{\omega^2 + \nu_m^2} - j\frac{\omega_{pe}^2 \nu_m}{\omega(\omega^2 + \nu_m^2)} \quad (1)$$

where ω is the operating frequency [rad/s], $\omega_{pe} = \left(n_e e^2 / m\varepsilon_0\right)^{1/2}$ is the electron plasma frequency [rad/s], n_e is the electron density [m^{-3}], ν_m is the collision frequency [Hz], m is the electron mass [kg], e is the charge of electron [C], ε_0 is the free space electric permittivity [F/m].

For electromagnetic waves propagating in cold plasma, it behaves like a dielectric with permittivity less than unity for frequencies above the plasma frequency. But for frequencies below the plasma frequency, where the real part of the plasma permittivity is negative, electromagnetic wave is not allowed to propagate in plasma [5]–[6]–[7]. Therefore plasma is a high pass filter.

For a time harmonic wave with a time dependence of $e^{j\omega t}$ propagating in cold plasma, the propagation constant can be expressed as

$$\gamma = j\omega(\mu\varepsilon)^{1/2}\left(1 + \frac{\sigma_p}{j\omega\varepsilon}\right)^{\frac{1}{2}} = \alpha + j\beta \quad (2)$$

where $\varepsilon = \varepsilon_0$, $\mu = \mu_0$ is free space magnetic permeability [H/m], $\sigma_p = \varepsilon_0\omega_{pe}^2 / (\nu_m + j\omega)$ is the complex conductivity of plasma [S/m], α is the attenuation constant [Np/m] and β is the phase constant [rad/m].

When $\omega << \omega_{pe}$, plasma can have different behaviors for various collision frequencies. In this case, when the plasma is bounded by a dielectric of positive permittivity (that permittivity of the bounding medium is less than the absolute value of the plasma permittivity), if the collision frequency is sufficiently low, reflection coefficient of plasma will be predominantly real and close to -1. This means that the plasma acts as a metal. Fig. 1 shows the real and imaginary components of the plasma reflection coefficient on the VHF band (30-300MHz) and for different collision frequencies. It is obvious that the reflection coefficient is closer to -1 for smaller collision frequencies [11]–[12].

For $\omega << \nu_m$, ε_{rp} is predominantly imaginary and the real and imaginary parts of the complex refractive index of plasma are comparable. In this case, the plasma is mainly absorbing [11].

The complete set of field equations for non-magnetized cold plasma is given by [6]

$$\nabla \times \vec{E} = -\mu_0\, \partial\vec{H}/\partial t \quad (3)$$

$$\nabla \times \vec{H} = -\varepsilon_0\, \partial\vec{E}/\partial t + \vec{J} \quad (4)$$

$$\partial\vec{J}/\partial t + \nu_m\vec{J} = \varepsilon_0\omega_{pe}^2\vec{E} \quad (5)$$

where $\vec{E}$ and $\vec{H}$ are the electric [V/m] and magnetic [A/m] fields and $\vec{J}$ is the plasma current density [A/m^2].

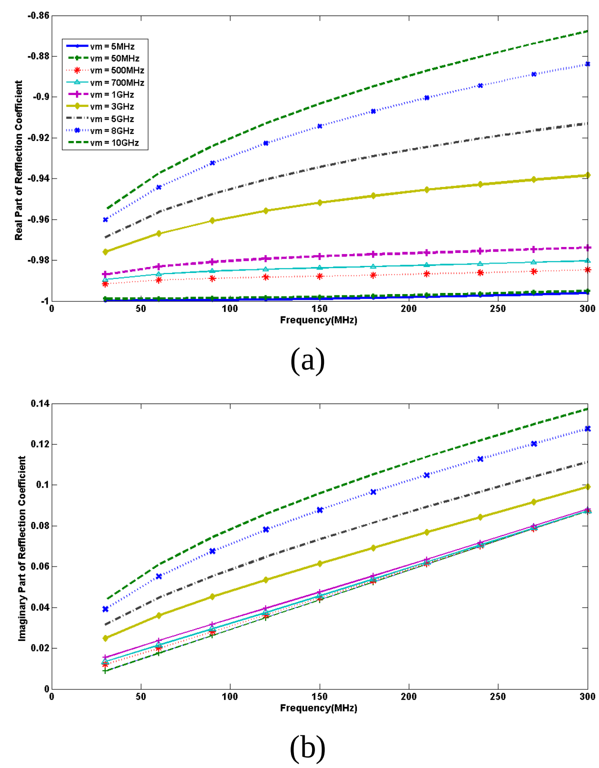


Fig. 1 The reflection coefficient of the plasma on the VHF band and for different collision frequencies. (a) Real component, (b) Imaginary component.

B. Formulations

The electric field can be obtained everywhere in the source-free region via expression [11]

$$\vec{E}(r) = -j\omega\vec{A}(r) - \frac{j}{\omega\mu\varepsilon}\nabla\left(\nabla\cdot\vec{A}(r)\right) \quad (6)$$

where ∇ and $\nabla.$ are respectively the gradient and divergence operator, r is radial position and $\vec{A}(r)$ is the magnetic vector potential as follows:

$$\vec{A}(r) = \mu\iiint_V G(r,r')\vec{J}(r')dr' \quad (7)$$

where V is the volume of source, $\vec{J}$ is the volume current density and $G(r,r')$ is electro dynamic Green's function in three dimensions via:

$$G(r,r') = \frac{e^{-jk|\vec{r}-\vec{r}'|}}{4\pi|\vec{r}-\vec{r}'|} \quad (8)$$

where k is the wave number in free space, $\vec{r}'$ and $\vec{r}$ are respectively the position vectors of the source and observation points. Let $R = |\vec{r}-\vec{r}'|$ that is the distance between any point of the source to the observation point. By replacing (7) in (6)

$$-\frac{j}{\omega\mu}\vec{E}(r) = \iiint_V [1+\frac{1}{k^2}\nabla\nabla.]\vec{J}(r')G(r,r')dl' \quad (9)$$

For our triangular plasma antenna, the radius of the plasma column is very smaller than the wavelength and the length of each side of the antenna. On the other hand, the structure has an axial symmetry on each side of the triangle with respect to the axis of that side. So, it is acceptable to apply line current instead of volume current density in (9). Since our antenna has bend and junction, we need to consider (9) in an appropriate form for this geometry. In this form, the current will be a vector function of the position; hence, the basis and weighing functions of the method of moment will also be vectors. So let us make the line current as [11]

$$\vec{I}(r) = I(r)\hat{t}(r) \quad (10)$$

here $\hat{t}(r)$ is the tangent unit vector on the antenna at the position r. Substituting (10) into (9), yields [10]

$$-\frac{j}{\omega\mu}\vec{E}(r) = [1+\frac{1}{k^2}\nabla\nabla.]\int_L I(r')\hat{t}(r')G(r,r')dl' \quad (11)$$

Note that the basis and weighing functions should be vector functions that are tangent to the antenna everywhere. Using the method of moment (11), we will have

$$\int_L \vec{f}_m(r).\vec{E}(r)dl = \int_L \vec{f}_m(r).(-j\omega\mu[1+\frac{1}{k^2}\nabla\nabla.]\sum_{n=1}^{N} a_n\int_{f_n}\vec{f}_n(r')G(r,r')dl')dl \quad (12)$$

where $\vec{f}_n(r)$ and $\vec{f}_m(r)$ are the basis and the weighing vector functions, respectively, N is the number of basis functions needed to cover the length of antenna and a_n are the expansion coefficients that must be obtained. If the weighing functions are considered as $\vec{f}_m(r) = f_m(r)\hat{t}(r)$ then $\hat{t}(r).\vec{E}(r)$ in (12) will be V_i/D for the excitation place and $Z_{sp}I(r)/D$ for the surface of antenna where V_i is the terminal voltage, Z_{sp} is the surface impedance of plasma and D is the length of a section of the divided length of antenna.

In this paper, the center between two bases of the antenna is regarded as an origin. The place and the angle of corners are specified by position vectors ($\vec{r}'$, $\vec{r}$) that influence on tangent unit vector $\hat{t}(r)$ and consequent basis and weighing vector functions. In corners, due to increase of the accuracy in calculating current coefficients, deviations are considered smaller.

As the minimum difference between current coefficients of our antenna and a metal one is appropriate, the MOM is converged when the minimum difference is obtained.

Using the method of moment (11), the electric current distribution along the plasma triangular antenna and consequent the radiation pattern is obtained.

3. Modeling

To study and analyze the plasma antenna, it is easy to assume that it is located on an infinite ground. Plasma is considered uniform. Fig. 2 shows the proposed geometry of the triangular plasma antenna on the infinite ground plane where a is the radius of the plasma column, L is the length of the total antenna, h is the height of the antenna and β is the angle of each lateral side with respect to the horizon that is named bend angle. In Fig. 2, the samples of the tangent unit vector $\hat{t}(r)$ are shown on each side.

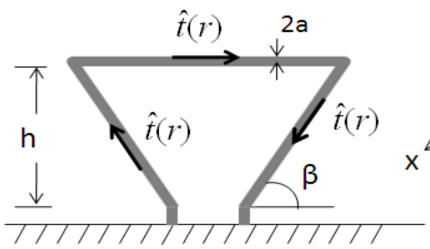


Fig. 2 The geometry of the triangular plasma antenna on the infinite ground plane.

4. Numerical Results and Discussion

Here, we assume a =12.5mm and the length of the antenna (L) is 1m. The simulation has involved several parameters that are the electron density ($n_e \leq 10^{18}$ m^{-3}), the collision frequency (50$MHz \leq \nu_m \leq$ 10GHz) and the bend angle ($75^o \leq \beta \leq 90^o$). The VHF band is our operating frequency range. For comparison, the copper (with a conductivity of 5.8×10^7 S/m) antenna as long as the proposed antenna is considered that is simulated by HFSS. The mentioned ranges are given according to the previous works [2]–[3]–[6].

Fig. 3 shows the normalized magnitude of the electric current distribution at f =300MHz for ν_m = 500MHz, β = 75^o and different electron densities. It is clear that when the electron density increases, the current distribution approaches to the metal one. The increase of n_e leads to the improvement of the approximation ω_{pe} >> ω that is a necessary condition for having metal characteristics.

The normalized magnitude of the electric current distribution on part of the triangular plasma antenna (along the right side) at the operating frequency 300MHz and for n_e=$6.1\times10^{15}m^{-3}$, β =75^o and different collision frequencies is plotted in Fig.4. An increase of the collision frequency brings about larger surface impedance and therefore more difference between the current distribution of plasma and metal antennas; also leads to get far away the reflection coefficient from the suitable amount.

The effect of various plasma densities and collision frequencies on the radiation power of a plasma antenna is shown in Fig. 5 and Fig. 6, respectively. When the plasma density is sufficiently high that leads to being satisfied the necessary condition ω_{pe} >> ω and if the collision frequency is corresponding low, the radiation behavior of the plasma will be similar to the metal one.

When n_e =10^{18}m^{-3} and ν_m = 500MHz, the radiation patterns of the plasma triangular antenna by using the method of moment and HFSS software at 250MHz and for bend angles 75^o, 80^o, 85^o and 90^o are shown in Fig. 7. For comparison, the radiation pattern of the metal antenna is also plotted for each case. From Fig. 7, one can find that our numerical results are close to the results of HFSS and both of them acceptably follow the metal one at each corresponding bend angle.

Fig. 8 shows the peak gain of a metal and plasma triangular antenna and also a plasma column with length of 1m for n_e=10^{18}m^{-3}, ν_m =500MHz, and β =75^o on VHF band. As it can be seen, although the peak gain of the triangular plasma antenna is lower than the metal one, it is higher than the results of the plasma conventional column on our operating band.

5. Conclusion

Plasma parameters influence on the current distribution and therefore the radiation pattern of the triangular plasma antenna. By changing the bend angle of the antenna, the radiation pattern of the plasma antenna follows the metal one. The peak gain of our plasma antenna is higher than a plasma column with the same length. Overall, an acceptable matching exists between our results and HFSS ones.

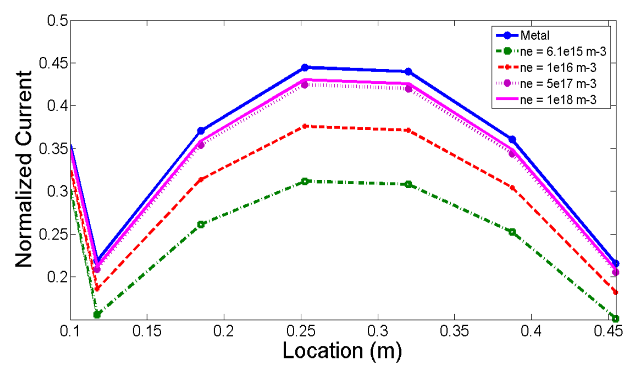


Fig. 3 The normalized magnitude of the electric current distribution of a part of the triangular plasma antenna length (along the left side) at f = 300MHz for ν_m = 500MHz and β = 75^o.

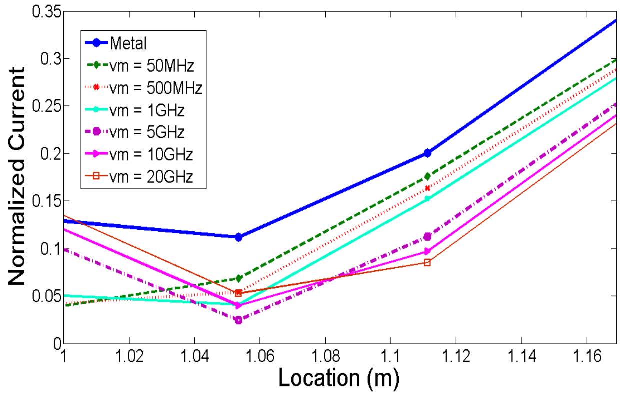


Fig. 4 The normalized magnitude of the electric current distribution of a part of the triangular plasma antenna (along the right side) at f = 300*MHz* for $n_e = 6.1 \times 10^{15} m^{-3}$ and β = 75°.

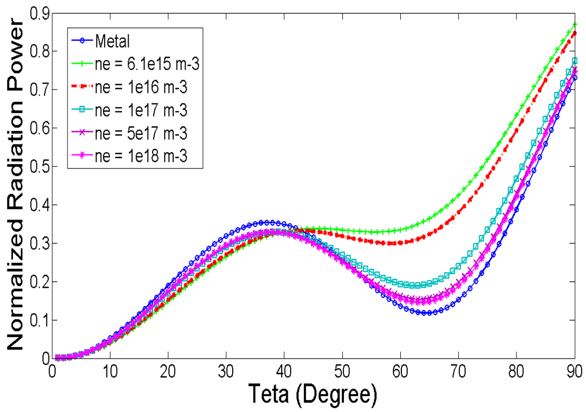
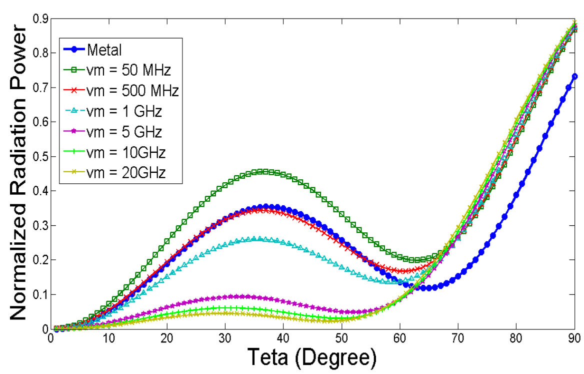


Fig. 5 The normalized radiation power of the triangular plasma antenna at f = 300*MHz* for ν_m = 500*MHz* and β = 75°.



FiFig. 6 The normalized radiation power of the triangular plasma antenna at f = 300*MHz* for $n_e = 6.1 \times 10^{15} m^{-3}$ and β = 75°.

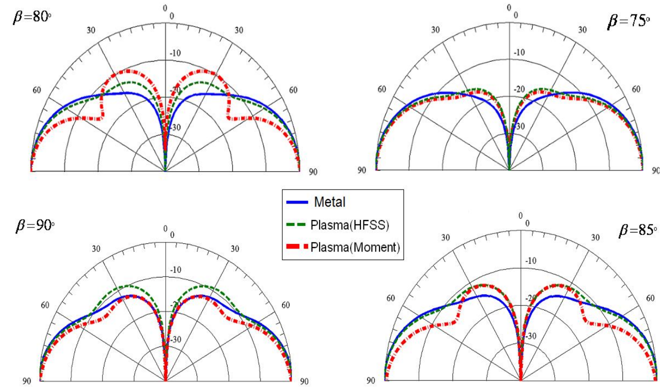


Fig. 7 The radiation patterns of the plasma triangular antenna for some bend angles at f = 250*MHz* ($n_e = 10^{18} m^{-3}$, ν_m= 500*MHz*) by using the method of moment and HFSS software and comparing them with a metal one.

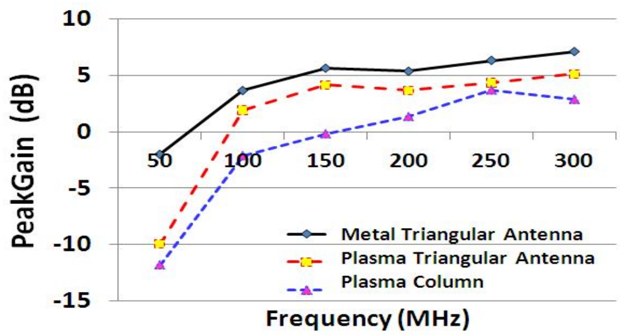


Fig. 8 The comparison of the peak gain of the plasma and metal triangular antenna and the plasma column.

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