Analysis of Plasma Loop Antenna with Uniform and Nonuniform Distribution

Fatemeh Etesami[1], Farzad Mohajeri[1],

[1] Dept. of Electrical and Communication Eng.
School of Electrical and Computer Engineering, Shiraz University, Shiraz, Iran
{Etesami, Mohajeri}@Shirazu.ac.ir

Abstract. This paper presents the results of study of radiation pattern of surface wave plasma loop antenna using of numerical method. By solving electric field integral equation (EFIE) using moment method (MOM), the current distribution and then the radiation pattern of antenna is derived. The side lobes in the radiation pattern of nonuniform plasma antenna are more defined than uniform case. The simulation method of plasma antenna is described in both uniform and nonuniform case. The effect of various spaces between two larger sides of plasma and metal loop antenna on radiation pattern is studied. In VHF band, the radiation pattern of plasma loop antenna is elevated in both cases.

Keywords: Plasma loop antenna, plasma density, moment method, radiation patterns.

1 Introduction

Plasma antennas are usually radio frequency (RF) antennas base on plasma element instead of metal conductor. Recently they have achieved more attentions and have developed, since have attractive advantages over the conventional metal ones [1]. One important advantage is possibility of rapid changing of the effective length of the antenna by input RF power [3]. Plasma antenna can be reconfigurable with respect to shape, frequency and radiation parameters on very short time [5]. Plasma can switch on and off in microseconds and also can be a good electrical conductor when is energized, but is non-conducting when is de-energized. Therefore an unenergized plasma antenna can be difficult to detect by enemy radar. This property is useful for military communication [3]. Other unique property of plasma antenna is having variable impedance and broadband matching [7].

There are several plasma sources for plasma antenna that surface wave discharges comparing to others are the most flexible. In 1982 Moisan et al., have suggested the RF plasma surface technique for plasma discharging by one electrode in one end of tube. This technique not only doesn't have previous problems such as plasma contamination by electron erosion, but also is more acceptable in stability, lost, decreasing radar cross section (RCS) and simplicity of design [4, 5]. Recently base on this idea the plasma in antenna is rapidly created and destroyed by applying proper RF power pulses to discharge tube [2].

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In physical experiments, the possibility of changing dimensions and parameters of a structure is limited. Numerical simulations can solve this problem to some extent. So, in recent decade, attention to numerical methods and simulators for analysis of plasma antennas has increased.

In this paper, we implement a computer code base on MOM technique to solve electrical field integral equation (EFIE) for current distribution on a plasma loop antenna on infinite ground plane. The radiation patterns in two cases, uniform and nonuniform plasma, are studied. Also the effect of the changing of the space between two bases of antenna on the radiation pattern is shown.

2 Theory

2.1 Principle of plasma antenna

The isotropic cold plasma is a type of dispersive medium. The relative permittivity ε_{rp} of uniform cold plasma is as follow [7]

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

where ω is operating frequency [rad/s], $\omega_{pe} = \sqrt{ne^2 / m\varepsilon_0}$ the electron plasma frequency [rad/s], n the electron density [m^{-3}], ν_m collision frequency [Hz], m electron mass [kg], e charge of electron [C], ε_0 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 plasma permittivity is negative, electromagnetic wave not be allowed to propagate in plasma [5, 6]. 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

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

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

2.2 Plasma column parameters

In fact the plasma density in a tube is not uniform completely and decreases axially. In a given pressure p and for an input power of P_0, the plasma density along a column decreases in an approximately linear manner from the launcher to end of the column as given by [3]

$$n(z) \approx n_L - C v_m(p)(h-z) \tag{3}$$

where v_m is collision frequency, C a constant with a value $C \approx 5\times10^9 m^{-4} s$, z the position along the plasma column, h the length of plasma column and n_L is a characteristics number density at the plasma frequency corresponding to the radio frequency of the source, ω, that is given as

$$n_L = \frac{\varepsilon_0 m_e}{e^2}\omega^2(1+\varepsilon_g) \tag{4}$$

where ε_g is the dielectric constant of the insulator (usually glass) surrounding the plasma.
The length of plasma column, h, is proportional to square root of the applied input power as shown below

$$h = \frac{n_0}{C v_m(p)} = \frac{A(p)\sqrt{P_0}}{C v_m(p)} \tag{5}$$

where $v_m(p)$ and $A(p)$ are constant in a definite pressure and n_0 the density at the base of the column.

2.3 Formulation of numerical method

Generally the electric field integral equation (EFIE) is given by [9]:

$$-\frac{j}{\omega\mu}[\hat{t}(r).E^{i}(r)]=\hat{t}(r).\iiint_{V}[1+\frac{1}{k^{2}}\nabla\nabla.]J(r')G(r,r')dr' \tag{6}$$

where $\hat{t}(r)$ is the tangent unit vector at position r, $E^{i}(r)$ the radiation field in free space, k wave number in free space, μ free space permittivity, V the volume of source, J the volume density of current, ∇ and $\nabla.$ respectively gradient and divergence operator on the observation coordinates and $G(r,r')$ electro dynamic Green's function in three dimensions via

$$G(r,r')=\frac{e^{-jk|r-r'|}}{4\pi|r-r'|} \tag{7}$$

where r' and r are respectively source and observation points.

Because our antenna has junction, we need to consider the EFIE in an appropriate form for this geometry. In this form, the current will be linear and a vector function of position; therefore, the basis and weighting functions in moment method will also be vectors. So let us make the line current [11]

$$\vec{I}\ (r)=I(r)\hat{t}(r) \tag{8}$$

where $I(r)$ is replaced by $J(r)$ in (6) and integration is done on length of antenna.

3 Modeling

To study and analysis of plasma antenna, it is easy to assume that it is located on infinite ground plane. First plasma is considered uniform and then nonuniform. Fig.1 shows the geometry of our plasma loop antenna on the infinite ground plane where a is the radius of plasma column, L the length of total antenna, h the height of antenna and s is the spacing between two larger sides of antenna. In Fig.1, the samples of tangent unit vector $\hat{t}(r)$ are shown.

Since ε_{rp} and σ_{p} that is mentioned in theory part, are related to uniform plasma, we need to consider an appropriate model for our geometry. So for simulation of plasma loop antenna, the length of each larger sides of antenna, h, is subdivided into N segments of length $\Delta h = h/N$ .Then the plasma density at both end of each segment is calculated using equation (3) assuming P_{0} and p are constant. For plasma density in each section, the average amount of these two end density, n_{ave}, is considered. Now we can use the relative permittivity and the conductivity of uniform plasma in each segment [10]. The density of last segment must be considered n_L , where is the minimum value of n for which the wave propagates.

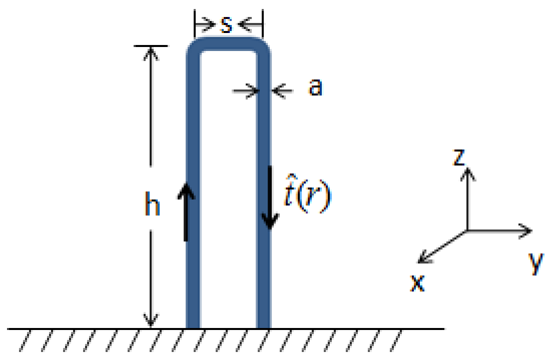

Fig. 1. The geometry of plasma loop antenna on infinite ground plane

We assume separated plasma sources for each larger side of antenna. Since the length of top slice of antenna is very smaller than two larger sides and wave length, the plasma density in it is supposed approximately uniform and equal n_L .

4 Simulation and Results

Here, we assume a = 12.5mm, the height of antenna 450mm and the space between two larger sides 100mm.The operating frequency range is in VHF band. For comparing, the aluminum (with a conductivity of $3.8\times 10^7 S/m$) antenna with the same size is applied. For a usual pressure of $400\,\mu b$, $A(p) = .016\times 10^{18}\,m^{-3}W^{-1/2}$ and $\nu_m = 500MHz$ **.** For uniform case the plasma density is assumed $n = 5\times 10^{17} m^{-3}$**.**

Fig.2 shows the normalized radiation power of plasma loop antenna in two cases, uniform and nonuniform density, at $f = 300MHz$ for $\nu_m = 500MHz$. It is obvious that the radiation power in side lobes is stronger for nonuniform case.

In Fig.3 the effect of changing the space between two larger sides of plasma and metal antennas, s , at f=300MHz is shown. Increasing this space leads to decrees of mutual effect of two sides and displacement of the main lobe of radiation pattern toward less angles. By comparing Fig.3 (a), Fig.3 (b) and Fig.3(c), one finds that the loop plasma antenna in uniform and nonuniform cases, possess radiation patterns similar to the metal one at each corresponding space. Note that the amounts of spaces are expressed in regard with wave length in Fig.3.

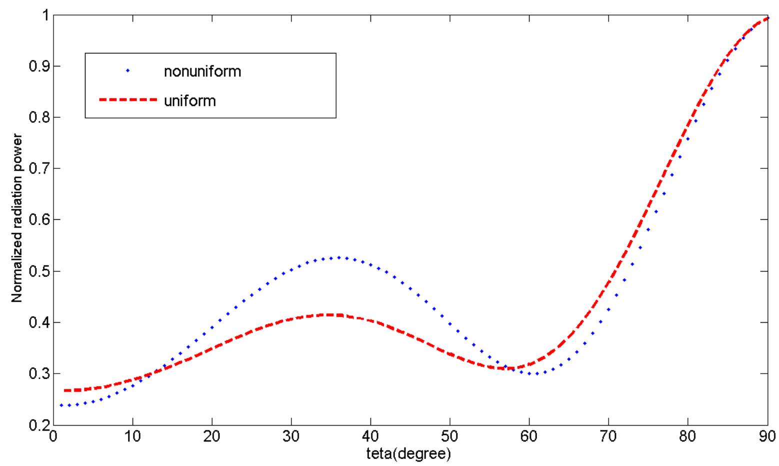

Fig. 2 The normalized radiation power at 300MHz for uniform and nonuniform plasma loop antenna

Comparing between the radiation power of the uniform and nonuniform plasma loop antenna and metal at 50*MHz*, 150*MHz*, 200*MHz*, 250*MHz* and 300*MHz*, is revealed in Fig.4. In this part the plasma density in uniform case is assumed $n = 1 \times 10^{18} m^{-3}$. Approximately the radiation pattern of plasma antenna in two cases follows the radiation pattern of metal one at most of frequencies. When frequency comes to 50MHz, the plasma antenna is electrically short, so the radiation pattern is intended to metallic one. For sake of better appreciation the radiation patterns of both antennas at variant frequencies are plotted in form of polar in Fig.5.

5 Conclusion

By employing the moment method for solving EFIE, the radiation pattern of uniform and nonuniform plasma loop antenna is studied. The side lobes in radiation pattern for nonuniform case are stronger than uniform one. Increasing the space between two larger sides of plasma and metal loop antenna leads to displacement of the peak of radiation pattern toward lower angles. By changing the operating frequency, the radiation pattern of plasma antenna follows metal one, approximately. Whit increasing the operating frequency the side lobes is appeared in the radiation patterns and difference between the radiation pattern of plasma and metal antenna becomes more evident.

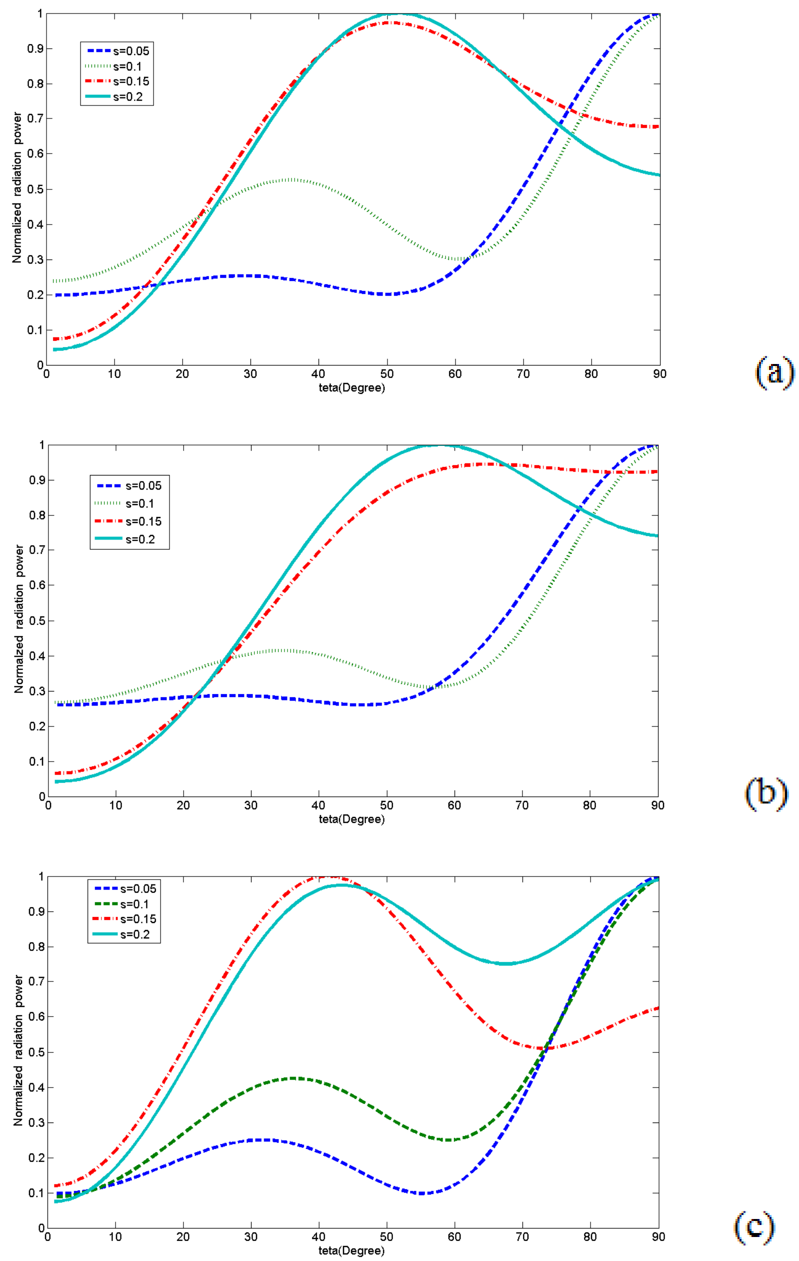

Fig. 3 The normalized radiation power of antenna for various *s* at f=300MHz.(a) nonuniform plasma antenna. (b) uniform plasma antenna. (c) metal antenna

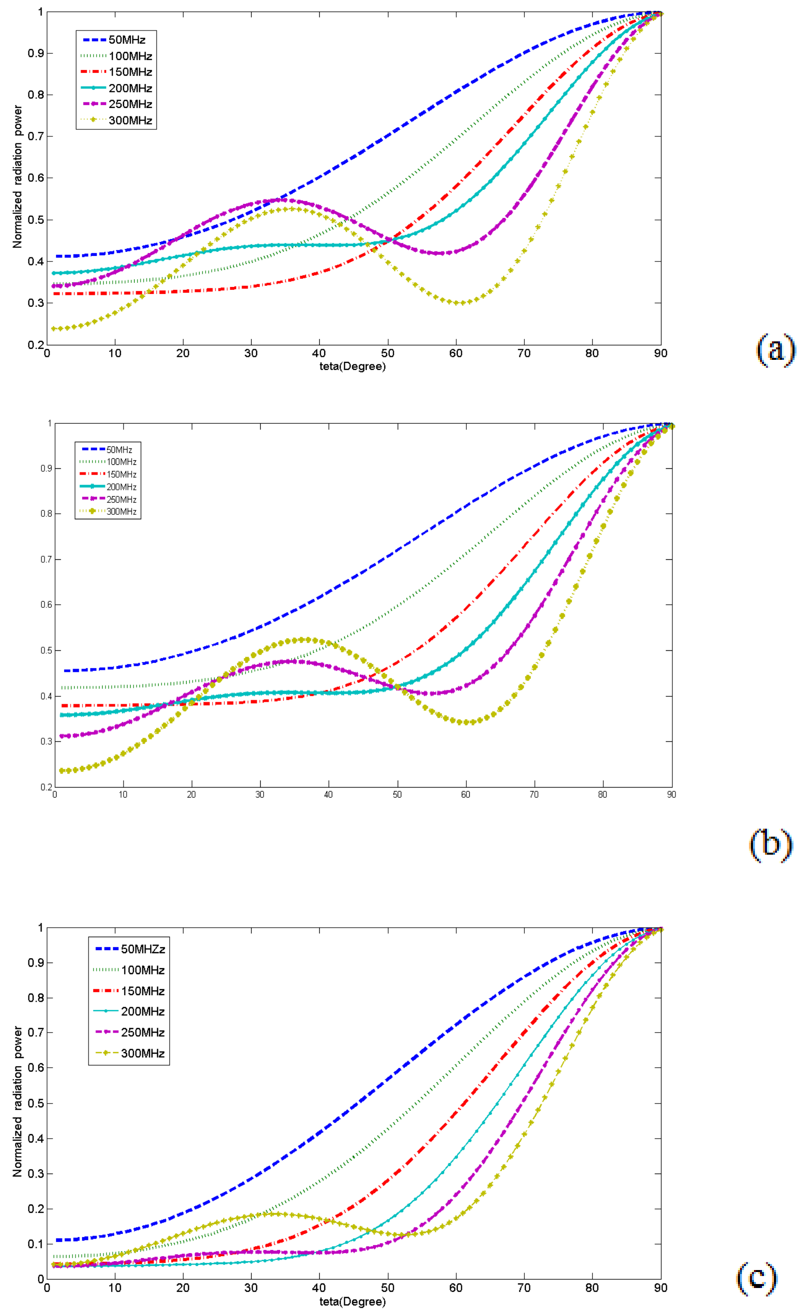

Fig. 4 The normalized radiation power for s =.1m at several frequencies of (a) nonuniform plasma antenna. (b) uniform plasma antenna. (c) metal antenna

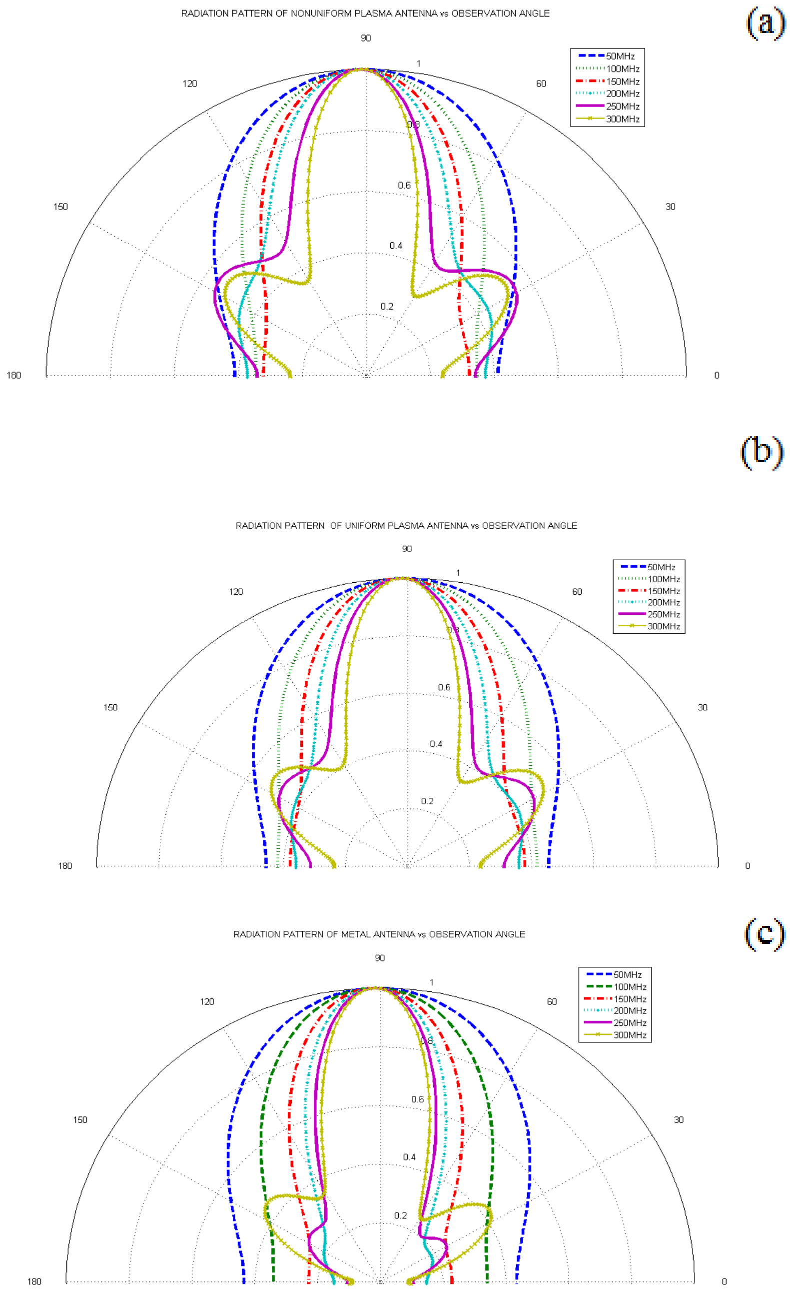

Fig. 4 The radiation pattern in observation angles for s =100mm at several frequencies of (a) nonuniform plasma antenna. (b) uniform plasma antenna. (c) metal antenna

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