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Research paper

A Study on the Effect of the Radius of a Cylindrical Plasma Antenna on its Radiation Efficiency

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Abstract

The aim of this study is to examine the effect of the tube radius in a cylindrical plasma antenna on the radiation efficiency of the antenna and on some of the physical characteristics of the plasma. It is shown that density of the plasma at the excitation point and also the height of the column varies proportionally to the square root of the ratio of the inner radius to the outer one, provided the length of the tube is longer than the height of the excited plasma. Plasma density and antenna height in the column with a smaller radius derived by the analytical approach lead to a more efficient antenna in a lower working frequency and narrower bandwidth.

Keywords: *cylindrical plasma antenna; radius; efficiency*

1. Introduction

Over the past few years, a number of different investigations to analyze plasma antennas have been published [1-5]. Some of these publications are solely based on experimental results [1,2], whereas some other studies consist of estimation of electrical parameters of the plasma column using global models along with experimental results, which models the physical characteristics of a surface wave driven cylindrical plasma antenna [3]. The majority of other investigations are based on numerical analysis of a specific type of a plasma antenna [4, 5].

Following the analysis of [6], broadband characteristics can be obtained by increasing the diameter of the antenna while its resonant length decreases.

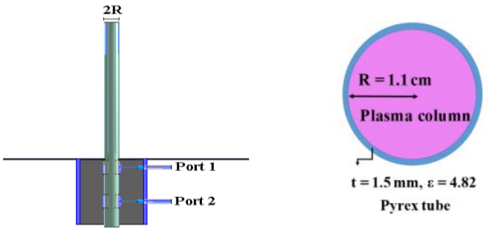
A recent work experimentally studied the effect of different values of radius in a plasma antenna. However, the study was focused on the resonance frequency of the plasma column, and its effect on the efficiency of the antenna is not considered [7]. Another numerical work examined the effects of the plasma column radius on the radiation characteristics of a cylindrical plasma antenna in the VHF/UHF frequency range [8]. However, the study only covered the static variations of the radius of the plasma column assuming that all the physical characteristics of the plasma are constant.

In this paper, we have carried out an analytical and numerical analysis to investigate the effects of the tube radius on the radiation characteristics of a cylindrical plasma antenna. Since the key quality of an antenna is its acceptable radiation characteristics, these parameters need to be known at different tube radii of the antenna.

The rest of this paper is organized as follows. In section II, the structure of the antenna is described. The height and density of a plasma column as a function of radius of the antenna are determined in section III. In section IV we analyze numerically the effect of the radius of a plasma column on its radiation characteristics. We summarize this investigation in section V.

2. The Antenna Structure

The focus of this study is on a cylindrical plasma antenna, which is excited by surface wave. An illustration of the structure is shown in Fig. 1. The antenna consists of a cylindrical column of radius R_1=1.1 cm surrounded by a Pyrex tube with relative permittivity of ε=4.82, thickness of t = 1.5 mm and length of 1 m which is partially inserted in a metallic box for excitation purposes. The structure also includes a horizontally placed metallic sheet as a ground plane. The tube is filled with argon at a nominal pressure of p = 0.3 Torr. The electron-neutral collision frequency is ν_m = 500 MHz. To launch surface wave at the interface between the plasma and the column, RF power with the frequency of f_{exc}= 450 MHz is applied to port 1.



(a) (b)

Fig. 1: Geometry of the antenna: a) side view b) top view

A second port is mounted below the excitation port to send/receive communication signals to/from the antenna.

3. Theory

To determine the height and density of a plasma column as a function its radius, analyses are undertaken for different tube radii. To this end, formulations of a surface wave driven cylindrical plasma antenna are presented in this section.

Note that the plasma column considered here is a long cylindrical column, which is excited using a surface wave. Therefore, the distribution of the plasma density (n) is not uniform along the column. Plasma density decreases linearly from an initial value at the excitation point in the base of the antenna to the cut off density at the end of the antenna. Considering the plasma column across the z axis, wave power $P(z)$ along the column as a function of location z is defined as:

$$P(z) = P_0 e^{-2\alpha(z)} \tag{1}$$

where P_0 is excitation power at the base of the antenna (z = 0), and $\alpha(z)$ is the attenuation coefficient at position z.

Therefore, the wave power absorbed by the plasma per unit length at a position z along the column is given by [3]

$$A(z) = -\frac{dP(z)}{dz} = -\nabla_z P(z) = 2\alpha(z)P(z) \tag{2}$$

The attenuation coefficient can be estimated from the dispersion relation of surface waves and as a reasonable approximation can be expressed as:

$$a = a(n,z) = \frac{C\nu_m(p)}{n - n_D} \tag{3}$$

where C is a constant, $\nu_m(p)$ is the electron-neutral collision frequency and n_D is the cut off plasma density, which depends on the frequency of excitation and is given by:

$$n_D = 1.242' \ 10^4 (1+ e) f_{exc}{}^2 cm^{-3} \tag{4}$$

Note that for densities below n_D, the surface wave no longer propagates. Moreover, the plasma density at the base of the antenna is

$$n_0 = A(p)\sqrt{P_0} \tag{5}$$

where A(p) is a function of the pressure and is defined as:

$$A(p) = \sqrt{\frac{2C\nu_m(p)}{K(p)}} \tag{6}$$

and

$$K(p) = u_B(p) A_{eff}(p) \xi_L(p) \tag{7}$$

In this equation, u_B is the Bohm velocity and is a function of pressure, ξ_L is the energy loss per electron ion pair and $A_{eff} = 2\pi R\, k_R(p)$ is the effective area per unit length of the column. $k_R(p)$ is a factor that relates the electron density at the edge of the column to its value at the centre of the column and R is the radius of the column.

Antenna length is given by

$$h = \frac{n_0 L_0}{n_D} - L_0 \tag{8}$$

where L_0 is a characteristic length scale given by

$$L_0 = \frac{n_D}{C\upsilon_m} \tag{9}$$

Assuming $h >> L_0$, and combining (4) to (9) the length of the antenna can be written as:

$$h \; ; \; B(p)\sqrt{P_0} \tag{10}$$

where

$$B(p) = \sqrt{\frac{2}{C\nu_m(p)K(p)}} \tag{11}$$

Consequently, equations (6) and (11) show that for a given pressure and excitation power, if C is assumed constant, the length of the antenna and also the plasma density at the excitation point are both functions of $K(p)$. However, $K(p)$ is a linear function of radius. As a result, if the pressure is assumed constant in two columns with radius R_1 and R_2, and identical power and frequency is applied to excite both structures, the length of the two antennas are inversely proportional to the square root of the radii of the columns:

$$\frac{h_2}{h_1} = \frac{B_2(p)}{B_1(p)} = \frac{\sqrt{\dfrac{2}{C\nu_m(p)K_2(p)}}}{\sqrt{\dfrac{2}{C\nu_m(p)K_1(p)}}} = \sqrt{\frac{K_1(p)}{K_2(p)}} = \sqrt{\frac{R_1}{R_2}} \tag{12}$$

Also, the plasma density at the base of the antennas is inversely proportional to the square root of the radii of the columns:

$$\frac{n_{02}}{n_{01}} = \sqrt{\frac{K_1(p)}{K_2(p)}} = \sqrt{\frac{R_1}{R_2}} \tag{13}$$

4. Numerical Results

The effect of radius of a cylindrical plasma antenna on its radiation characteristic is numerically investigated in this section. To this end, two antennas with different radius are numerically simulated using Finite Integration Technique (FIT). The required parameters for the simulation of the antennas are extracted from the analytical relations of the previous section.

In all the simulations of this section it is assumed that the plasma is already excited and the gas is ionized through the excitation port (port 1). Also, a filter is placed in series with the port 1 such that it acts as an open circuit at the frequency of the communication signal.

Upon substituting f_{exc} = 450 MHz and ε = 4.82 in (4), the cut off plasma density will be $n_D = 1.41\times10^{16}$ m^{-3}. Following [9], in the nominal pressure of 0.3 Torr and when the radius of the antenna equals to 1.1 cm, $A(p) = (0.16 \pm 0.01) \times 10^{18}$m^{-3}W$^{1/2}$ and $B(p) = 6.77 \pm 0.04$ cm/W$^{1/2}$. For the excitation power of P_0 = 33 W, using (5), the plasma density at the base of the antenna is $n_{01} = 0.87\times10^{18}$ m^{-3}. Equation (10) estimates the length of the antenna to be $h_1 \approx 37$ cm.

Considering the second case, where the radius of the plasma tube is decreased to R_2 = 0.6 cm. Using (12) and (13), the plasma density at the base of the antenna and the antenna height can be found to be:

$$n_{02} = n_{01}\sqrt{\frac{R_1}{R_2}} = 1.17' \ 10^{18} \quad m^{-3} \tag{14}$$

$$h_2 = h_1\sqrt{\frac{R_1}{R_2}} = 49.95 \quad cm \tag{15}$$

An illustration of the effect of the column radius on the height and density of the plasma is shown in Fig.2.

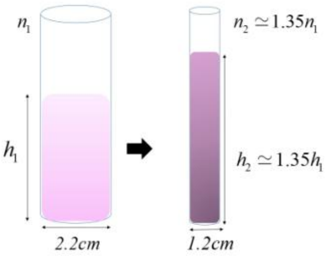
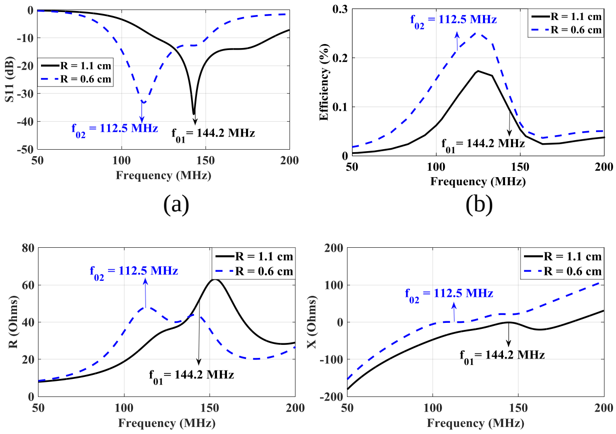


Fig. 2: View of the density and height variations of a plasma antenna when the radius of the antenna decreases from 1.1 cm to 0.6 cm.

Fig. 3 shows the radiation characteristics of the two antennas, namely, the antennas with radius R_1 = 1.1 cm and R_2 = 0.6 cm. It is observed in Fig. 3(a) that by decreasing the radius of the antenna, the working frequency (f_0) decreases. This effect is expected since the antenna with smaller radius is longer than the one with larger radius. Fig. 3(b) shows that decreasing the radius of the plasma column also results in an increase in the radiation efficiency of the antenna. The increase in the antenna efficiency is due to the increased density of the plasma in the column. Figs 3(c) and 3(d) show the real and imaginary parts of the impedance of the antennas.

Note that since capacitive coupling mechanism is used to feed the signal to port 2, an inductor is placed in series between the signal sources to achieve a better impedance matching. The values of the inductors used in the two cases are listed in Table 1.

Table 1 also presents the designed dimensions and performance of the two plasma antennas. It can be concluded here that a plasma antenna with smaller tube radius benefits from a higher radiation efficiency. Regarding the antenna size, while the narrower antenna is longer, it has a lower resonance frequency. It can be shown that the electrical length of the narrower antenna is 7% longer. It must be noted that despite the advantage of the narrower antenna in terms of the efficiency, manufacturing a dielectric vessel with a very small radius and its delicacy may be considered as its drawbacks.



(a) (b)

(c) (d)

Fig. 3: Variation of: (a) reflection coefficient, (b) antenna efficiency, (c) input resistance and (d) input inductance, versus frequency for different plasma tube radii.

5. Conclusion

Theoretical analysis of the effects of the radius of a plasma tube on the physical characteristics of the plasma confined in the tube has been presented. It has been shown that the length of the antenna and also the plasma density at the base of the column are inversely proportional to the square root of the radii of the antennas. From these results, the radiation characteristics of cylindrical plasma antennas with different radii have been numerically studied. The results show that decreasing the radius of a plasma antenna can be used to increase its radiation efficiency while the electrical length of the antenna is slightly increased.

Table 1: Summary of Antenna Characteristics

Parameters	R_1 = 1.1 cm	R_2 = 0.6 cm
Antenna Height (cm)	37	49.5
n_0 (m^{-3})	0.87×10^{18}	1.17×10^{18}
n_D (m^{-3})	1.41×10^{16}	1.41×10^{16}
Pressure (Torr)	0.3	0.3
ν_m (MHz)	500	500
f_{exc} (MHz)	450	450
f_0 (MHz)	144.2	112.5
Efficiency (%)	9.5	21.5
Inductor value (nH)	19.4	75.7

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