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Design and Analysis of Circular Monopoly Plasma Antenna in Microwave band and Study of Plasma Parameters

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Abstract – *In this paper circular monopoly plasma antenna that is excited by surface wave is designed and simulated by using HFSS. The radiation pattern is compared with the antenna made of aluminum with the same dimensions. Also, the dependence of plasma parameters on radiation characteristics of the designed antenna will be investigated.*

Keywords: Plasma antenna, Circular monopoly antenna, Microwave band

1. Introduction

The plasma antennas are used for different antenna concepts that link some of the uses of ionized environments with antenna concepts. In recent years plasma antennas as a new technology for metal antennas replacement with more efficient are designed and have been built. Plasma antennas can produce the radiation pattern with a good approximation that same metal antennas can be produced. Plasma is a quasi-neutral gas of charged particles and neutral which have collective behavior [1]. It is often said that 99 % of matter in nature, is in plasma case, that's mean in the form of conduct electricity gas that atoms decomposed to positive ions and negative electrons. The gases that ionized well are good conductors of electricity [2].

In 1919, first Hettinger suggested that the ionized gas can be used to send and receive wireless signals [3]. Plasma antenna is composed of a coverage containing gas that by giving energy, the gas is converted into plasma. High density of electrons in plasma makes it a good conductor and plasma can behave like metal. Of course, by using plasma, antenna design is more complicated. The superiority of plasma antenna than metal, the ability to turn on and off quickly and hide from radars, re-configurability, improving the sensitivity and ownership, have a degree of freedom and guided pattern, can be noted; Which makes use of the antennas in applications of municipal services, particularly for wireless systems [4] and also has military applications. It can be said that changes in plasma antenna radiation characteristics can be changed in electronic form, unlike metal antennas which depends on the size of the antenna. The first concept on plasma antenna was started in 1997 [5]. In 2002 a project was registered with the plasma antenna where a comprehensive plan by feeding on surface waves, was brought [6]. Articles about plasma antenna since 2004 began by examining the physical properties of these antennas [7]. Then also presented papers on how to stimulate the plasma antenna [8], [9] & [10] and so far about the various forms of plasma antennas such as a column [11], a triangular loop [12], spiral [13] and antenna arrays [14] have been studied. Surface wave propagation on the surface of the plasma column and the surrounding dielectric discovered about 1959 [15] and from 1970 to use it as a means of maintaining a plasma column pushed. Surface wave properties mainly it depends on the power absorbed in the plasma unit and it depends on discharge conditions such as: the type of plasma, gas pressure, chamber dimensions, chamber dielectric material and also mode and frequency of surface wave [16]. In this paper, a loop of plasma antenna that is perpendicular to the ground plan and acts at a frequency of 200 MHz, we have designed and simulated using a simulator HFSS. Loop antenna is one of simple, inexpensive and versatile of antennas. Circular loop because of the simplicity in the analysis and structure is the most common form of the loop antenna. Usually, these antennas are used in reception mode, also these antennas as a searcher for measuring field and as directional antennas for radio navigations, are used. Basically, big loops electrically, are used in the directional arrays, such as spiral antennas and Yagi Yoda antennas [17]. In the following, we will discuss the theory of plasma and relationships needed. Then how to design and simulation methods are described and then we will study the physical characteristics of plasma during plasma loop antenna. Then also, radiation characteristics of antenna designed, compared with metal samples and the effect of plasma parameters on radiation characteristics of

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plasma antenna designed, will review. At the end, we examined the effect of dielectric constant plasma shielding material on the performance of the antenna.

2. Methodology

As mentioned, plasma environment under certain conditions can be replaced metal. This environment in terms of electromagnetic properties is inhomogeneous, nonlinear and dispersive, and parameters magnetic permeability, electrical conductivity and permittivity coefficient that are μ, σ and ε respectively, in it, in terms of frequency and other factors, can vary [18]. Also, electromagnetic waves in a collision with plasma environment absorb, scatter and are passed. Plasma has the inherent frequency is called frequency plasma which is different from operating frequency of the antenna (ω) and depends electron density (n_e), electron mass (m_e) and charge of the electron (e) and is defined [2]:

$$\omega_p = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}} \tag{1}$$

For $\omega \ll \omega_p$, the reflection coefficient is -1 and transmission coefficient is zero, that is, the incident wave to the plasma reflected with the same amplitude and phase reverse, so that plasma is replaced with a full conductor. Dielectric constant for plasma is defined by [7]:

$$\varepsilon_p = \varepsilon' - j\varepsilon'' = 1 - \frac{\omega_p^2}{\omega(\omega - j\upsilon_m)} \tag{2}$$

Where, υ_m is the collision frequency of plasma. Most laboratory plasmas have ε_p larger than one. Other quantities that are important to the wave propagation in the plasma are propagation constant and complex refractive index which is defined by:

$$k = \frac{\omega}{c}\tilde{n} = \frac{\omega}{c}\sqrt{\varepsilon_p} = \beta - i\alpha \tag{3}$$

Where α are the attenuation coefficient and β phase coefficient and are [19]:

$$\alpha = k_0\left\{\frac{1}{2}\left[-\varepsilon_p' + \left(\varepsilon_p'^2 + \varepsilon_p''^2\right)^{\frac{1}{2}}\right]^{\frac{1}{2}}\right\} \tag{4}$$

$$\beta = k_0\left\{\frac{1}{2}\left[\varepsilon_p' + \left(\varepsilon_p'^2 + \varepsilon_p''^2\right)^{\frac{1}{2}}\right]^{\frac{1}{2}}\right\} \tag{5}$$

Where $k_0 = \frac{\omega}{c}$ and complex refractive index is [20]:

$$\tilde{n} = \left(1 - \frac{\omega_p^2}{\omega(\omega - j\nu_m)}\right)^{\frac{1}{2}} = n - j\chi \tag{6}$$

In generally, specific conductivity of plasma is defined:

$$\sigma = \frac{\varepsilon_0 \omega_p^2}{\nu_m + j\omega} \tag{7}$$

That in the above relations, ω is the antenna operating frequency, ω_p is the plasma frequency, υ_m is the plasma collision frequencies, ε_0 is the vacuum permittivity coefficient and c is the speed of light. To obtain a wave dispersion equation in loop plasma antenna, we will consider plasma circular loop which is in the x-y plane and its radius is a and b, that a>b. Assuming there is symmetry in the problem and using the cylindrical coordinate system and knowing that the wave propagating in the z direction, the general form of fields as follows:

$$\vec{E} = \left[E_r\hat{r} + E_\varphi\hat{\varphi} + E_z\hat{z}\right]e^{[i(k_z z + m\varphi - \omega t)]} \tag{8}$$

$$\vec{B} = \left[B_r\hat{r} + B_\varphi\hat{\varphi} + B_z\hat{z}\right]e^{[i(k_z z + m\varphi - \omega t)]} \tag{9}$$

In the symmetry state m=0, TE mode can satisfy the boundary conditions because the component E_φ there must be, so that, through the surface wave, keep the plasma stable.

$$\vec{B} = B_r(r)\hat{r} + B_z(r)\hat{z}\,, \vec{E} = E_\varphi\hat{\varphi} \tag{10}$$

By applying the boundary conditions that are the continuity of the fields tangential component and continuity of radius components of electric displacement vector at r=a and r=b bounds, dispersion equation of surface wave propagation in the plasma loop, will be calculated as follow:

$$-\frac{k_p}{\varepsilon_p}K_0(k_v b)\left[K_1(k_p b) + I_1(k_p b)\right] + \frac{k_p}{\varepsilon_p}I_0(k_v a)\left[I_1(k_p a) - K_1(k_p a)\right] = k_v K_1(k_v b)\left[K_0(k_p b) + I_0(k_p b)\right] + k_v I_1(k_v a)\left[I_0(k_p a) + K_0(k_p a)\right] \tag{11}$$

Where $k_v = \sqrt{k_z^2 - k_0^2}$, $k_p = \sqrt{k_z^2 - k_0^2 \varepsilon_p}$ and $k_0 = \frac{\omega}{c}$ is the wave number in vacuum. In addition, K_0, K_1, I_0 and I_1 are the generalized Bessel functions. Using the dispersion equation, we can calculate wave number for a given frequency ω.

3. Design and simulation methods

Circular plasma antenna shown in Fig.1 is designed for the frequency of 200 MHz, using equations and graphs that there are in [17]. For simulation the software HFSS is used. The radius of the loop is 30.2 cm and the container is made of glass and its dielectric coefficient is 5.5 that the inner radius is 4.9 mm and an outer radius of it 5.9 mm is considered. Ground page is made of copper with a radius of 80 cm.

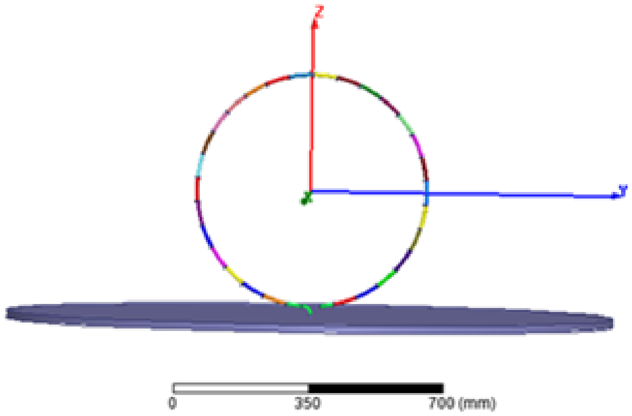

Figure 1. Scheme of designed plasma antenna

Gas pressure inside the chamber, excitation frequency and excitation power are three major and influential quantity in the plasma antenna performance. The gas in the chamber is argon and at a pressure of 0.4 mbar is selected that in this pressure collision frequency is 500 MHz.

Simulation referred to the way in [21] and was performed for the 30 sections and the density achieved per section:

$$n = n_0 - C v_m z \qquad (12)$$

Where, $n_0 = A(p)\sqrt{P_0}$ is density at the point of excitation and P_0 is the power of excitation. z is the length of plasma column that for loop is the size of the environment which was divided into 30 sections and specified on based of the angle. C and A(p) are coefficients, which in constant pressure and frequency, their values are clear [7]. After the plasma density was calculated for each section, from (2) and (7) relationships, the coefficient of permittivity and conductivity of plasma, will be calculated. The conductivity coefficient is calculated for the plasma loop, and its chart shown in Fig.2, and as is known, its value from the excitation point that is at zero degree towards the end of the tube, is reduced. Also, the penetration depth of electromagnetic waves to the designed loop containing plasma at frequencies of 50, 100 and 200 MHz calculated and shown in Fig.3. As the charts show, the conductivity of plasma inside the glass loop has a value between $9.68 < \sigma < 106.82$, and the penetration depth of wave for the frequency of 200 MHz is lower, and this means that in this frequency plasma is more similar to the metal. To excite the gas inside the loop, is used the surface wave method through capacitive couplers that are beneath the earth and surrounded glass.

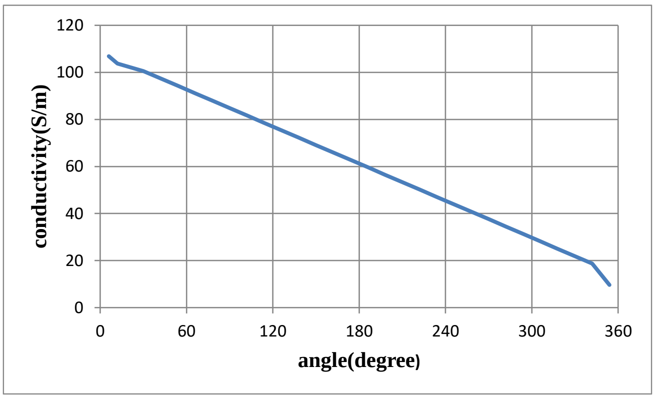

Figure 2. The amount of plasma conductivity along the loop

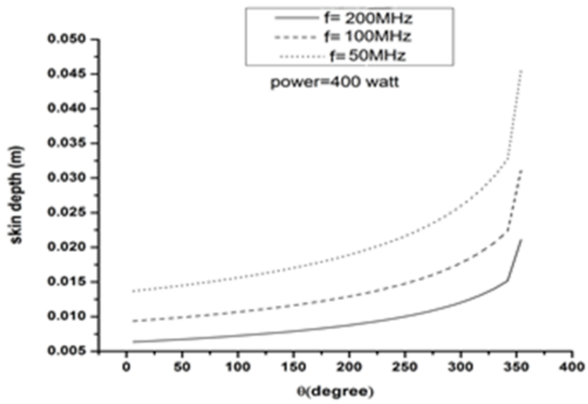

Figure 3. The penetration depth of electromagnetic waves to the designed loop containing plasma at different frequencies

4. Simulation results and the effect of changes in plasma parameters

The intended antenna then designs and carry out the necessary calculations, simulated and its radiation pattern of gain forφ=0, is plotted in Fig.4, and compared with a metal antenna made of aluminum and similar in size. Fig.4 indicates that the radiation pattern of metal and plasma antenna largely match together and the plasma antenna produces pattern that same metal antenna has produced, that's it, is indicative of the fact that the plasma environment, has the ability to replace metal for antenna applications. Of course, due to much lower plasma conductivity coefficient than metal such as aluminum, the plasma antenna gain is less than similar metal antenna gain. To investigate the effect of changing the plasma parameters on the radiation characteristics of designed loop plasma antenna, the two states have considered. First, we have examined the change of radiation characteristics of antenna for different excitation powers to production the plasma, and then, the effect of the collision frequency has reviewed, and in Figures 5 and 6 directivity charts for different excitation powers and graphs of antenna gain for different collision frequencies have drawn respectively.

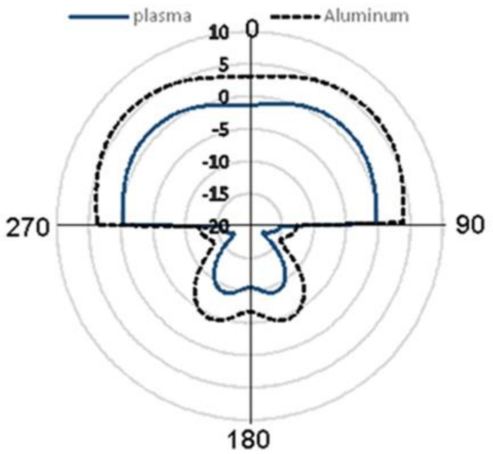

Figure 4. Comparison between radiation patterns of plasma antenna with the same metal antenna

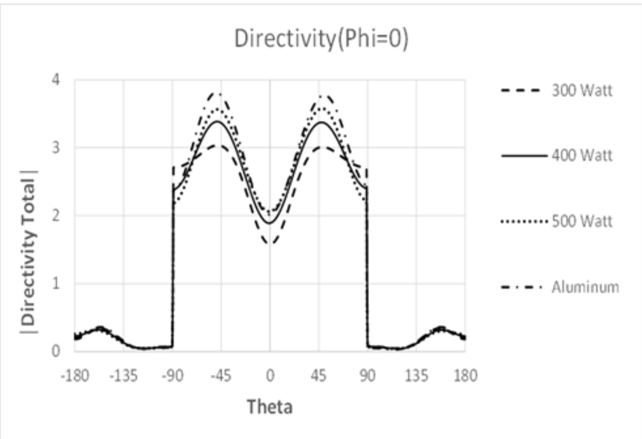

Figure 5. directivity of loop plasma antenna for different excitation powers and compared with metal antenna

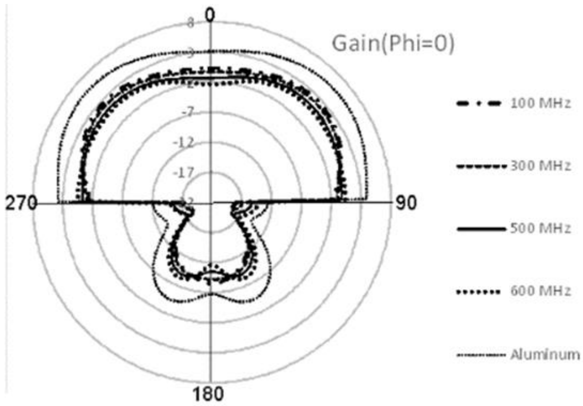

Figure 6. The gain of circular plasma antenna at different collision frequencies and compared with the metal antenna

From the above figures, to this point we realized that whatever exciting power to produce plasma is more, the amount of antenna directivity increases. Also, reduction in collision frequency due to increasing the gain of antenna, but the pursuit of low collision frequencies, according to the used initial density that are in this design 5.6×10^{18} electrons per cubic meter, it is almost impossible.

5. The effect of dielectric material involving the plasma on performance of antenna

In this section, we investigate the effect of changing on dielectric material which surrounds the plasma environment. Of course, this part when the antenna acts, cannot be changed, and before making the antenna, suitable material must be determined. For this purpose, we have used three materials of glass, Teflon and silicon nitrate with dielectric constant of 2.1, 5.5 and 7, and we have done simulation, and we have exhibited the graph of returned power in Fig.7. Shape indicates that it is important to select a material with a dielectric constant of between 2 and 3, is more suitable material for containing chamber of ionized gas and materials with dielectric constant above of 7 are not suitable for this use. Of course, for design we have used the glass because it has more generality, but if the goal is to achieve more frequency bandwidth and better be returned power or VSWR, we can use materials with lower dielectric constant.

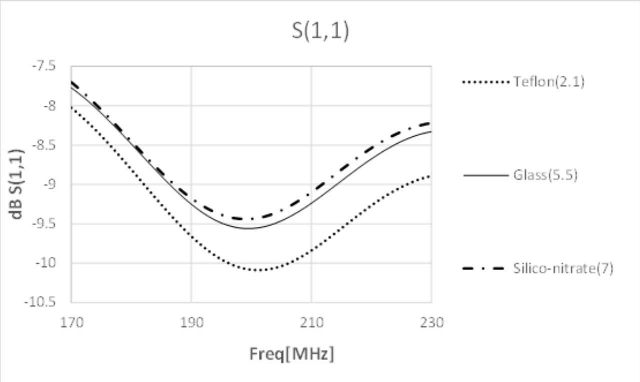

Figure 7. Be returned power of circular plasma antenna for different materials for container

Of course, the choice of dielectric material has not any effect on radiation characteristics of antenna such as directivity and gain.

6. Conclusion

In this paper, we could by introduce the environment plasma, design a plasma loop antenna in the VHF band and its radiation characteristics compared to the antenna with similar dimensions and made of aluminum, that matched radiation pattern showed that the plasma environment has ability to replacement the metal for antenna applications. Also, the size of loop plasma antenna is smaller than the metal antenna that this could be one of the advantages of the plasma environment than metal. Low gain and directivity in plasma antenna than the metal antenna due to low conductivity of plasma than the metal, that we can partly offset this case by using more exciting power or decreasing the collision frequency. The choice of dielectric material for shielding of ionized gas; we can be used materials with a dielectric constant of between 2 and 3 to achieve be returned power, VSWR and better frequency bandwidth, however, this case does not effect on the gain and directivity and other radiation characteristics of antenna. About the resonant frequency of the plasma antenna must say that since at the loop antenna, resonant frequency depends on the radius of the loop, so the change of plasma parameters does not much impact on the resonance frequency.

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