Advantages and Disadvantages of Different Coupling Methods of Plasma Antennas

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Advantages and Disadvantages of Different Coupling Methods of Plasma Antennas

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Abstract: One of the important challenges in plasma antennas, is the coupling of RF signal to the plasma column. RF signal coupling has a significant effect on antenna efficiency, antenna implementation cost, structure implementation complexity, antenna pattern shape, and final structure weight and volume. In this article, firstly the various methods of coupling were introduced. Then capacitive coupling, direct coupling and sleeve coupling were presented and their advantages and disadvantages were mentioned. As a sample, a plasma folded monopole antenna with sleeve coupling was fabricated and measured. By comparison of the different coupling methods and as a result, one can conclude that the sleeve coupling method is the most suitable method. This method has the least sensitivity to change the dimensions. It is also easy and cheap to implement. In this type of coupling, the efficiency of the Nesta antenna is suitable and the coupling structure adds small weight and volume to the antenna structure.

Key words: plasma, plasma frequency, collision frequency, capacitive coupling, direct coupling, sleeve coupling

1. INTRODUCTION

The controllable conductive-dielectric property of plasma has been known for decades, and makes it practical in many microwave applications, such as stealth reconfigurable antennas [1-4], frequency selective surfaces [5], lenses [6], waveguides, reconfigurable cavities [7], phase shifters [8] and attenuators [9]. Plasma elements can be reconfigured electrically, which is impossible to be done by a metal. Plasma antennas have a higher degree of freedom than metal antennas, which
provides a variety of capabilities for plasma antennas. Plasma antennas use ionized gas as an electron conduction medium. The advantages of plasma antennas are that they are highly reconfigurable and can be turned on and off. [10]. The plasma antenna can be classified into two groups: plasma antennas that the plasma is used in as a parasitic element and plasma antennas that the plasma is used as a driven element. Samples of the first group have been implemented. The most famous ones are [1], [11], and [12]. In the second group of plasma antennas, first the tube gas must be ignited to produce the plasma in it [13-17], then the RF signal should be coupled to the plasma column with another equipment. For coupling RF signal to the plasma column, these questions must be answered: What are the methods of RF coupling to the plasma column? What are the properties of these methods? What is the best method for the coupling? What are the optimized dimensions for the coupler?

2. PLASMA THEORY

Gas-discharge plasmas are weakly ionized plasmas [18, 19] that are one of the most used forms of plasmas [20]. The word "plasma" originates from blood plasma by I. Langmuir in 1923 [21]. A gas-discharge plasma is the result of passing an electric current through a gas under the presence of an external electric field [22]. Plasma is highly nonlinear and its detailed description requires a highly accurate computer model. However, its behavior can be described by continuity equations. Plasma is a dispersive medium. The motion of electron in plasma medium is based on the following second order nonhomogeneous differential equation [11]:

\[
m_e \frac{d^2x}{dt^2} - m_e v_c \frac{dx}{dt} = -eE
\]

(1)

Where \(e\) and \(m_e\) are the electric charge and mass of electrons, respectively and \(E\) is the applied electric field. Also \(v_c\) is the collision frequency. In plasmas with industrial applications energy transfer is neutralized by collisions of electrons and particles. Collision frequency \(v_c\) indicates this conflict. The collision frequency plays an important role in determining the amount of dispersion and attenuation. This quantity varies in different gases.

The solution of equation (1) shows the place of electrons versus time. Assume time harmonic electric field is applied to the plasma. Then the phasor solution of this equation is:

\[
X(\omega) = \frac{eE}{m_e(\omega^2 - jv_c\omega)}
\]

(2)
By involving this solution in the polarization equation \( P = -neX \) (where \( n \) is the density of electrons) and using \( D = \varepsilon_0 E + P \) the following equation can be obtained:

\[
D = \varepsilon_0 E - \frac{ne^2 E}{m_e(\omega^2 - j\nu_c \omega)}
\]  

(3)

From this equation, and constitutive relation \( D = \varepsilon E \) the dielectric relative permittivity of a non-magnetic, non-thermal plasma can be obtained through the following equation and is known as cold-plasma or Drude dispersion model, which is plotted in Fig. 1 versus normalized frequency.

\[
\varepsilon_{r_{plasma}} = \varepsilon'_r - j\varepsilon''_r = 1 - \frac{\omega_{pe}^2}{\omega(\omega - j\nu_c)} = \left(1 - \frac{\omega_{pe}^2}{\omega^2 + \nu_c^2}\right) - j\left(\frac{\omega_{pe}^2 \nu_c}{\omega(\omega^2 + \nu_c^2)}\right)
\]

(4)

Where

\[
\omega_{pe} = \left(\frac{ne^2}{m_e \varepsilon_0}\right)^{\frac{1}{2}}
\]

(5)

Where \( \omega \) and \( \omega_{pe} \) are the operating frequency and electron plasma frequency, respectively. In fact, \( \omega_{pe} \) is the frequency with which the electrons fluctuate between the ions. If the frequency of the incident wave to the plasma region is less than the plasma frequency, the reaction of the electrons in the plasma to the electric fields of the electromagnetic wave is in the form of energy absorption. Conversely if the frequency of the incident wave to the plasma region is greater than the plasma frequency, the electrons will be unable to react and will be fixed. So, the wave will pass without much reflection or loss. This phenomenon occurs in earth’s ionosphere when signals are in FM and TV bands greater than 90 MHz.

It is obvious that for \( \omega_{pe} \) and \( \nu_c \gg \omega \) the equation (4) can be written as the following equation:

\[
\varepsilon_{r_{plasma}} = \varepsilon'_r - j\varepsilon''_r \cong 1 - j\frac{\omega_{pe}^2}{\omega \nu_c} = 1 - j\frac{\frac{ne^2}{m_e \varepsilon_0}}{\omega \nu_c}
\]

(6)

So, the plasma acts like a metal and its conductivity is obtained by:

\[
\sigma = \omega \varepsilon_0 \varepsilon''_r = \frac{ne^2}{m_e \nu_c}
\]

(7)

According to this equation, the conductivity of plasma can be altered by changing the frequency and collision frequency of the plasma [24].
3. METHODS OF COUPLING

The RF signal can be coupled with a plasma column by different methods but, the most famous methods are capacitive coupling [11, 12], direct coupling [13] and sleeve coupling [14, 15]. These methods are explained in the following sections.

A. Capacitive Coupling

Fig. 2 shows a plasma antenna with capacitive coupling. In this coupler, the outer conductor of RF coaxial cables connected to a cylindrical metallic box and inner conductor of RF coaxial cable is connected to a metallic sleeve that surrounds the plasma column. For analyzing this coupler, it can be assumed that this coupler resembles a cylindrical resonant cavity that is perturbed by the plasma column. By calculating the cavity resonance frequencies, resonance frequencies of the capacitive coupler and therefore resonance frequencies of the plasma antenna are calculated. In some cases, the effect of such perturbations on the performance of the cavity can be calculated exactly, but often approximations must be made. One useful technique accomplishing this goal is the perturbation method, which assumes that the actual fields of a cavity with a small shape or material perturbation are not greatly different from those of an unperturbed cavity. In [7] resonance frequencies of a cylindrical cavity that perturbed with a plasma column is calculated. Comparing approximated results acquired from perturbation method [7] with CST software results shows a good agreement between them. For example, in Fig. 3 variations of resonance frequency versus inner radius of cavity ($r_1$) are shown in both simulated and approximated results.
B. Direct Coupling

As shown in Fig. 4, in this method, RF signal is connected to the ends of a plasma element, directly. For igniting of the plasma, a high voltage must be applied across two ends of the plasma element. Therefore, equipment for insulating RF signal from igniting power is needed. Using a high pass filter before the RF signal and a low pass filter before igniting power is one of the simplest solutions for this problem. In practice we can use a duplexer for this purpose.
For simulating this type of coupler, firstly a dipole antenna must be simulated. Because of the low conductivity of the plasma environment, the plasma dipole radius must be greater than usual metallic dipole. By various simulations, it is shown that the optimum radius of the antenna is 8 mm for the antenna with the plasma frequency equal to 7 GHz. Similarly, for the metallic dipole antenna, by performing various simulations, it can be found that the length of the dipole for the first resonance is related to the wavelength (Equation 8). Because the plasma parameters are not scaled whereas other parameters (frequency and length) are scaled, there is a constant term in this relation [13].

\[ \lambda_r = 1.9669L + 0.10981 \]  

(8)

Where \( \lambda_r \) the wavelength of the first resonance of the antenna and \( L \) is the antenna length.

Fig. 5 shows the simulated \( S_{11} \) results versus frequency for this antenna with direct coupling in different lengths.
Figure 5. Variation of $S_{11}$ versus frequency for different lengths of antenna with direct coupling

Three-dimensional radiation pattern of this antenna with direct coupling is shown in Fig. 6, which collision frequency is $\nu_c = 900 \text{ MHz}$ and electron plasma frequency is $f_{pe} = 7 \text{ GHz}$. It can be found that this pattern is similar to the pattern of a metallic dipole antenna. Both patterns are omnidirectional and the main lobe occurs in the normal plane to the antenna. Also, the radiation efficiency of this antenna is about -1 to -3 dB that is suitable enough. In other words, the gain of this antenna is acceptable for usual applications.

Figure 6. Three-dimensional radiation pattern of antenna with direct coupling. ($f_{pe} = 7 \text{ GHz}$, $\nu_c = 900 \text{ MHz}$)
C. Sleeve Coupling

The other coupling method of the plasma antenna is sleeve coupling. In this method for coupling of the RF signal to the plasma column, two sleeves are placed at the plasma tube, as shown in Fig. 7. A structure shown in Fig. 8 is suitable for simulating of this coupler.

![Figure 7. Sleeve coupling method [17]](image)

For transmission of the RF signal to the sleeves, a structure similar to T-match can be used. Resonance frequency of the antenna is dependent to the $Z_1$ (distance of two sleeves), $X_{\text{min}_C}$ (distance of high voltage power supply from antenna), $L$ (length of antenna) and $r$ (radius of antenna) [Fig. 7]. Therefore, the effect of these three parameters on the antenna resonance
frequency must be investigated. After the run of different simulations, it is found that the antenna resonance frequency is not sensitive to the distance of two sleeves ($Z_1$). Fig. 9 shows this property. Also, by varying the $X_{\text{min}_C}$, the resonance frequency doesn't change noticeably. (Fig. 10)

Figure 9. Variation of $S_{11}$ versus frequency for different values of the distance between sleeves ($X_{\text{min}_C}=10.5 \text{ mm}, L=50 \text{ mm}, r=8 \text{ mm}$)

Figure 10. Variation of $S_{11}$ versus frequency for different values of $X_{\text{min}_C}$ ($Z_1=20 \text{ mm}, L=50 \text{ mm}, r=8 \text{ mm}$)

As shown in Figs. 9 and 10, it is concluded that the resonance frequency of the plasma antenna
with sleeve coupling has a low sensitivity to the dimensions of structure.

Similar to the metallic dipole antenna, it can be found that the length of the dipole for the first resonance is related to the wavelength (Equation 9). There is a constant term in this relation because the plasma parameters are not scaled whereas other parameters (frequency and length) are scaled [15].

\[ L = 0.8487\lambda_r + 127.11 \]  

(9)

Where \( \lambda_r \) the wavelength of the first resonance of the antenna and \( L \) is the antenna length.

The simulated results for \( S_{11} \) of the plasma antenna with sleeve coupling in different antenna lengths is shown in Fig. 11.

![Figure 11. Variation of \( S_{11} \) versus frequency for different lengths of antenna (L) with sleeve coupling](image)

Three-dimensional radiation pattern of this antenna with sleeve coupling is shown in Fig. 12, which collision frequency is \( \nu_c = 900 \text{ MHz} \) and electron plasma frequency is \( f_{pe} = 7 \text{ GHz} \). It can be found that this pattern, approximately, is similar to the pattern of a metallic dipole antenna. Both patterns are omnidirectional and the main lobe occurs in the normal plane to the antenna. Also, the radiation efficiency of this antenna is about -0.34 dB that is suitable enough. Another advantage of the sleeve coupling method are that, this method is easy for implementation and has low cost.
4. COMPARISON OF THE COUPLING METHODS

A. Comparison of Complexity and the cost of Implementation

Because of the capacitive coupling structure, this method is the most complex and the most expensive method. Direct coupling needs the isolation circuit that must be designed and fabricated. So, this method is more complex than the sleeve coupling method. There it is concluded that the sleeve coupling method is the simplest and cheapest method for RF coupling in the plasma antenna.

B. Similarity to the Metallic Dipole Antenna

The maximum value of the metallic dipole pattern occurs at $\theta=\pi/2$ but in the capacitive coupling, there is a null at $\theta=\pi/2$ [11, 12]. Therefore, the radiation pattern of the capacitive coupling method is different from the metallic dipole. In the sleeve coupling, the pattern is a little different from the metallic dipole because of the T-match network and in the direct coupling the pattern is similar to the metallic dipole completely.

C. Comparison of the Radiation Efficiency

Radiation efficiency of the capacitive coupling is insufficient (Typically is about -10 dB) but the radiation efficiency of the direct and the sleeve coupling is sufficient (Typically is about -1 dB).
D. Comparison of the Coupler Dimensions and Volume

One of the attractive capabilities of plasma antennas is its camouflage from waves. The antenna coupler is metallic and is in conflict with this important property of plasma antennas. Therefore, the antenna with a small coupler is better. Moreover, the size and weight of antenna structure must be small as possible. The capacitive coupling coupler is large but the sleeve coupler includes less metal than the capacitive coupler and the direct coupler has the least metal [11-15].

E. Comparison of Dimension Sensitivity

Dimension sensitivity of the capacitive coupling is high but the sensitivity of the two other methods is low.

Now, comparison of advantages and disadvantages of the different coupling methods are shown in Table 1. Based on the topics discussed, it is concluded that sleeve coupling is the best method for coupling of RF signal to the plasma column and the capacitive coupling is the worst method.

| Performances                               | Capacitive Coupling | Direct Coupling | Sleeve Coupling |
|--------------------------------------------|---------------------|-----------------|-----------------|
| Complexity (Based on the equipment required for implementation) | high                | medium          | low             |
| Cost (Based on the equipment required for implementation)       | medium              | medium          | low             |
| Similarity to Dipole (Based on its radiation pattern)          | low                 | high            | medium          |
| Radiation efficiency (Based on simulations performed)           | low                 | medium          | medium          |
| Dimension and Volume (Based on physical structure)              | high                | low             | medium          |
| Sensitivity to Dimension (Based on simulations performed)       | high                | high            | low             |
5. IMPLEMENTATION OF THE SLEEVE COUPLING METHOD

5.1. Structure Parameters

Fig. 13 shows the structure of a folded monopole plasma antenna with sleeve coupling which is adjacent to the perfect electric conductor ground plane. This means that, by image theory, a monopole antenna with its image can be assumed as dipole antenna.

![Figure 13. Structure of the folded monopole plasma antenna with sleeve coupling](image)

The perfect electric conductor ground plane of the antenna is a square with sides equal to 150 mm (a=150 mm). The plasma elements consist of commercial fluorescent tubes with a Pyrex tube that its dielectric constant is 4.82, radius, 7.5 mm, and thickness is 1 mm. The power of these tubes is supplied by the electronic ballasts with specification of 220V, 50Hz. The other parameters are shown in Table 2.

| Parameter | Value   |
|-----------|---------|
| a         | 150 mm  |
| d         | 20 mm   |
| h         | 196.5 mm|
| L         | 370 mm  |
| b         | 15 mm   |

The structure of this antenna is simulated with CST microwave studio software. The cold plasma in this software is modeled with the Drude model. This model is a simple one for understanding electron behavior which was presented by Paul Drude in 1922. This model considers the electrons
of the environment as free and separable gas atoms and assumes that the positive ions of the atomic nucleus are immobile. In other words, in this model the sea of electrons surrounds the ions and moves around them. In summary Drude model assumptions in the simulation of plasma environment are:

1- In the absence of electromagnetic force, the electrons travel between the two collisions in a direct line.
2- The electron-electron interaction is ignored.
3- The electron-ion interaction is ignored.
4- The electrons reach thermal equilibrium in contact with the ion network and after collision in a random direction, they move at a speed corresponding to the ambient temperature. In the warmer environment, the temperature and energy of these electrons increase.
5- The system memory disappears after each collision and the electrons are under no external force when moving.

Although this model is valid for analysis of the metallic environments, with proper approximation it can be used for gas environments and electron plasmas.

In this model we substitute 900 MHz for electron-neutral collision frequency and 7 GHz for plasma frequency [9]. The metal is set as aluminum with conductivity equal to \( 3.56 \times 10^7 \) S/m.

5.2. Results and Discussion

Fig. 14 shows the fabricated folded monopole plasma antenna with sleeve coupling. The amplitude of \( S_{11} \) is measured in frequency range 400 MHz to 6 GHz and is shown in Fig. 15. In the measurement process, by switching plasma on, one resonance appears at 1.4 GHz and receiving waves to the antenna are absorbed but by switching plasma off, any resonance appears in plasma and the waves are not absorbed, exactly, similar to when any antenna is present (Fig. 15).
6. CONCLUSION

In this paper, the different coupling methods of RF signal to the plasma antenna were investigated. Three methods were introduced: capacitive coupling, direct coupling and sleeve coupling. It is shown that each method has advantages and disadvantages. Capacitive coupling method suffer from bigness, complexity, bad pattern, high sensitivity and has one benefit, good shielding for RF signals. Direct coupling suffers from additional equipment for isolation and has
some benefits, good radiation efficiency, and pattern similar to dipole, low weight and volume. Sleeve coupling has some benefits, good radiation efficiency, low weight and volume, low cost and simplicity of implementation. It is concluded that the sleeve coupling is the best method. A folded monopole plasma antenna with this coupling was fabricated and measured. An important result was observed that when plasma is turned on, a resonance for the antenna can appear. By this method, the antenna parameters can be changed electrically, without any mechanical changes in the antenna structures.

7. ACKNOWLEDGEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request. The authors declare that they have no conflict of interest.

8. DECLARATIONS

We declare that, there is no funding to report for this submission. Also, we wish to confirm that there are no known conflicts of interest associated with this publication and there has been no financial support for this work. Also, the data and code that support the findings of this study are available from the corresponding author upon reasonable request.

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