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Advantages and Disadvantages of Different Coupling Methods of Plasma Antennas

Farzad Mohajeri[1*], **Mostafa Hadaegh**[2]
*Corresponding Author: mohajeri@shirazu.ac.ir

[1,2] Department of Communications and Electronics, School of Electrical and Computer Engineering, Shiraz University, Shiraz, Iran.

Abstract – *One of the very important challenges in plasma antennas is the coupling of the RF signals to the plasma column. RF signal coupling significantly affects the antenna efficiency, antenna implementation cost, structure implementation complexity, antenna pattern shape, and final structure size, weight, and volume. In this article, firstly the various methods of coupling were introduced, described, and compared. Then the capacitive coupling, direct coupling, and sleeve coupling were presented, and their advantages and disadvantages were mentioned and compared. A plasma-folded monopole antenna with sleeve coupling was designed, simulated, fabricated, and measured as a sample of this RF coupling method. By comparing these different coupling methods, one can conclude that the sleeve coupling method is the most suitable. This method has the least sensitivity to change the dimensions of the antenna. It is also easy and cheap to implement. In this type of RF signal coupling method, the efficiency of the Nesta antenna is suitable and the coupling structure adds very small weight and volume to the antenna structure.*

Keywords: *Collision frequency, Capacitive coupling, Direct coupling, Plasma, Plasma frequency, Sleeve coupling.*

1. Introduction

The controllable conductive-dielectric property of plasma has been known for decades. It 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 where the plasma is used as a parasitic element and plasma antennas where 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, the tube gas must be ignited to produce the plasma in it [13]-[17], and then the RF signal should be coupled to the plasma column with other equipment. For coupling the 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?

The advancement of modern telecommunications and radar systems has necessitated the exploration of innovative technologies that can enhance signal quality and adaptability. Among these emerging technologies is the concept of plasma antennas, which leverage ionized gas, or plasma, to facilitate wireless communication. The motivation behind coupling plasma antennas with traditional systems rests on several compelling factors: frequency agility, improved radiation properties, and the potential for miniaturization.

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 passes an electric current through a gas in 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 electrons in a plasma medium is based on the following second-order nonhomogeneous differential equation [11]:

$$m_e \frac{d^2x}{dt^2} - m_e v_c \frac{dx}{dt} = -eE \tag{1}$$

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 time-harmonic electric field is applied to the plasma. Then the phasor solution of this equation is:

$$X(\omega) = \frac{eE}{m_e(\omega^2 - jv_c\omega)} \tag{2}$$

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:

$$D = \varepsilon_0 E - \frac{ne^2E}{m_e(\omega^2 - jv_c\omega)} \tag{3}$$

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.

$$\varepsilon_{r_{plasma}} = \varepsilon_r' - j\varepsilon_r'' = 1 - \frac{\omega_{pe}^2}{\omega(\omega - jv_c)} = \left(1 - \frac{\omega_{pe}^2}{\omega^2 + {v_c}^2}\right) - j\left(\frac{\omega_{pe}^2 v_c}{\omega(\omega^2 + {v_c}^2)}\right) \tag{4}$$

Where

$$\omega_{pe} = \left(\frac{ne^2}{m_e\varepsilon_0}\right)^{\frac{1}{2}} \tag{5}$$

Where ω and ω_{pe} are the operating frequency and electron plasma frequency, respectively. In fact, ω_{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 the earth's ionosphere when signals are in FM and TV bands greater than 90 MHz.

It is obvious that for ω_{pe} and $v_c >> \omega$ equation (4) can be written as the following equation:

$$\varepsilon_{r_{plasma}} = \varepsilon_r' - j\varepsilon_r'' \cong 1 - j\frac{{\omega_{pe}}^2}{\omega v_c} = 1 - j\frac{\frac{ne^2}{m_e\varepsilon_0}}{\omega v_c} \tag{6}$$

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

$$\sigma = \omega\varepsilon_0\varepsilon_r'' = \frac{ne^2}{m_e v_c} \tag{7}$$

According to this equation, the conductivity of plasma can be altered by changing the frequency and collision frequency of the plasma [13].

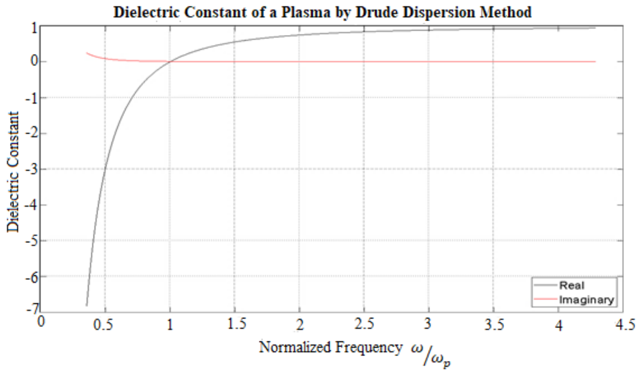


Figure 1. The dielectric constant of a plasma versus normalized frequency

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.

3.1 Capacitive Coupling

Fig. 2 shows a plasma antenna with capacitive coupling.

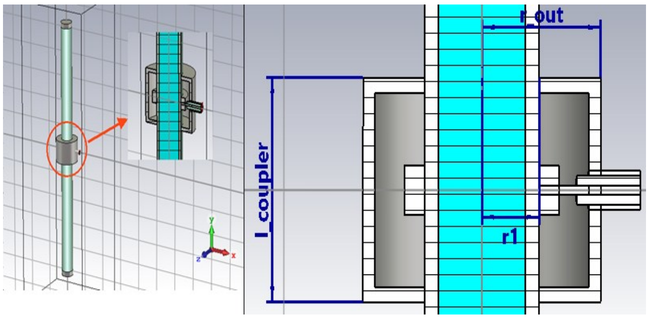


Figure 2. Capacitive coupling profile

In this coupler, the outer conductor of the RF coaxial cables is connected to a cylindrical metallic box, and the inner conductor of the 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, the 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 for 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 is perturbed with a plasma column are calculated. Comparing approximated results acquired from the perturbation method [7] with CST software results shows a good agreement between them. For example, in Fig. 3 variations of resonance frequency versus the inner radius of cavity (r_1) are shown in both simulated and approximated results.

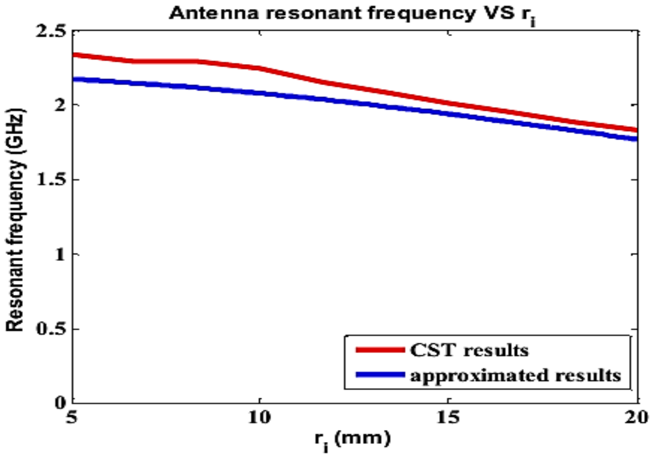


Figure 3. Approximated and simulated CST results for the resonance frequency of the capacitive coupling method versus r_1

3.2 Direct Coupling

As shown in Fig. 4, in this method, the RF signal is connected to the ends of a plasma element, directly. For igniting the plasma, a high voltage must be applied across two ends of the plasma element. Therefore, equipment for insulating RF signals 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 the 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].

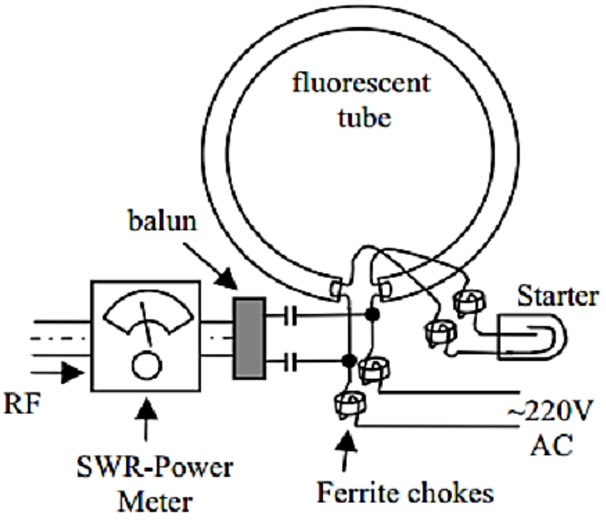


Figure 4. Direct coupling method [16]

$$\lambda_r = 1.9669L + 0.10981 \qquad (8)$$

Where λ_r is 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 the different lengths.

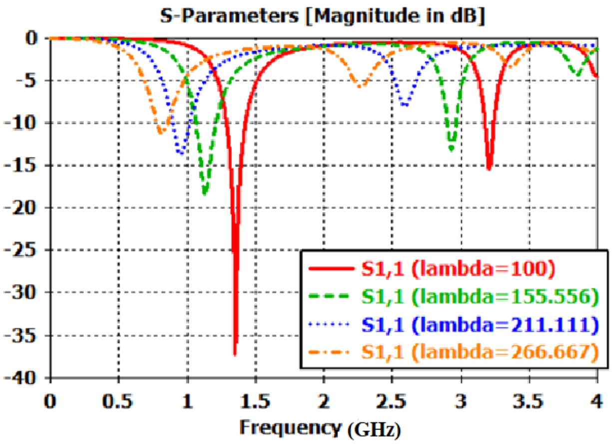
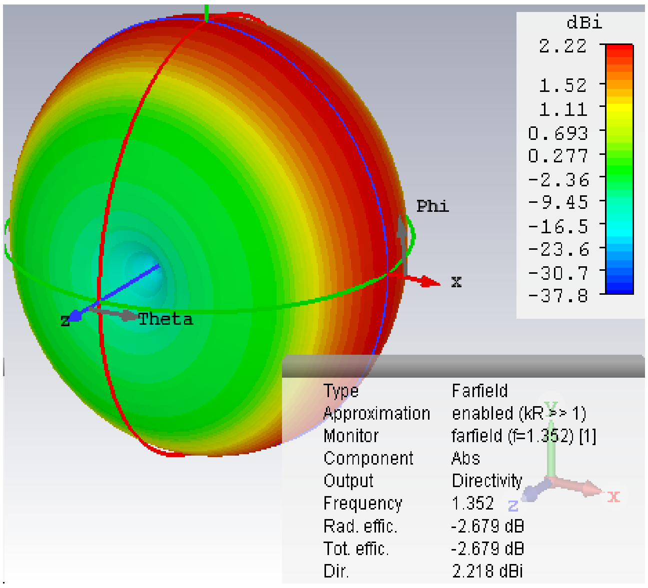


Figure 5. Variation of S_{11} versus frequency for different lengths of an antenna with direct coupling

The three-dimensional radiation pattern of this antenna with direct coupling is shown in Fig. 6, in which the collision frequency is $\nu_c = 900\ MHz$ and electron plasma frequency is f_{pe}=7 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 of the antenna. Also, the radiation efficiency of this antenna is about -1 to -3 dB which is suitable enough. In other words, the gain of this antenna is acceptable for usual applications.



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=1.352) [1]
Component	Abs
Output	Directivity
Frequency	1.352
Rad. effic.	-2.679 dB
Tot. effic.	-2.679 dB
Dir.	2.218 dBi

Figure 6. The three-dimensional radiation pattern of the antenna with direct coupling (f_{pe}=7 GHz, ν_c=900 MHz)

3.3 Sleeve Coupling

The other coupling method of the plasma antenna is sleeve coupling. In this method for coupling 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 this coupler.

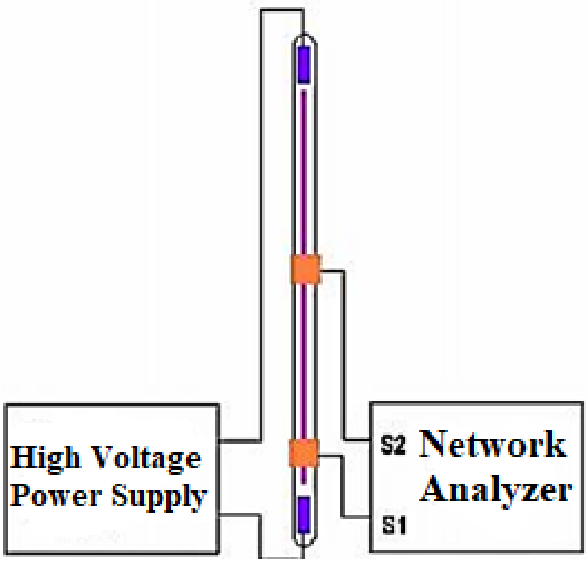


Figure 7. Sleeve coupling method [17]

For transmission of the RF signal to the sleeves, a structure similar to a T-match can be used. The resonance frequency of the antenna is dependent on the Z_1 (distance of two sleeves), X_min_C (distance of high voltage power supply from the antenna), L (length of the antenna), and r (radius of the 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_min_C*, the resonance frequency doesn't change noticeably. (Fig. 10)

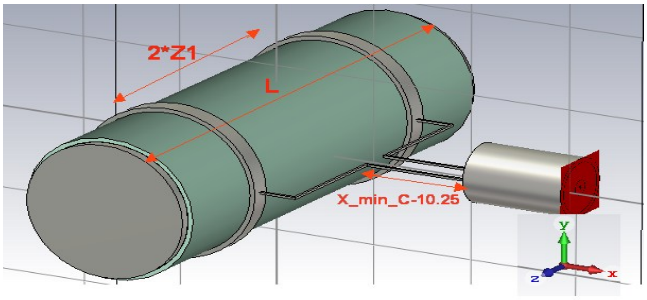


Figure 8. Simulated structure of the plasma antenna with sleeve coupling

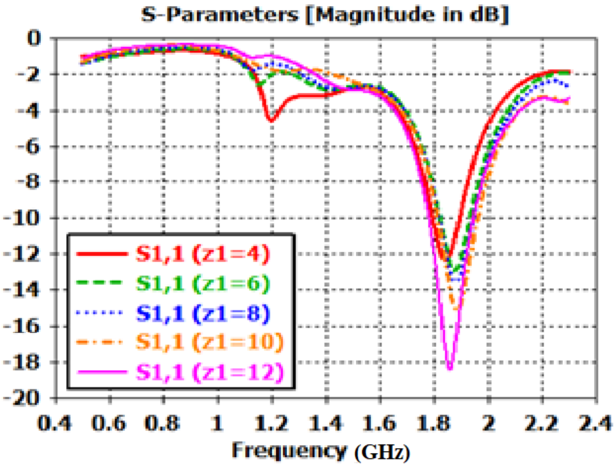


Figure 9. Variation of S_{11} versus frequency for different values of the distance between sleeves (X_min_C=10.5 m m, L=50 mm, r=8 mm)

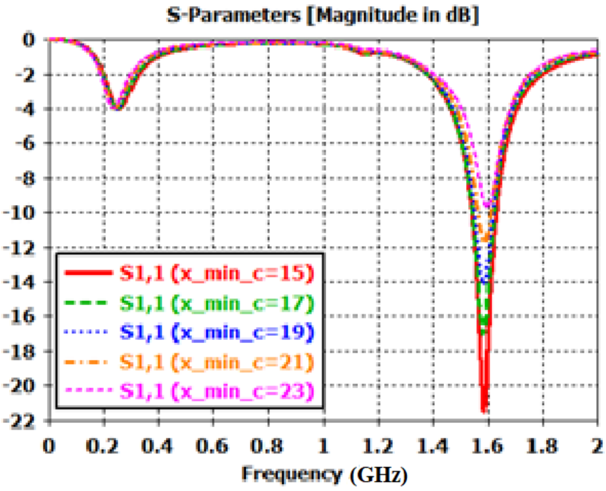


Figure 10. Variation of S_{11} versus frequency for different values of X_min_C (Z_1 =20 mm, L=50 mm, r = 8mm)

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

$$L = 0.8487\lambda_r + 127.11 \qquad (9)$$

Where λ_r is 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 are shown in Fig. 11.

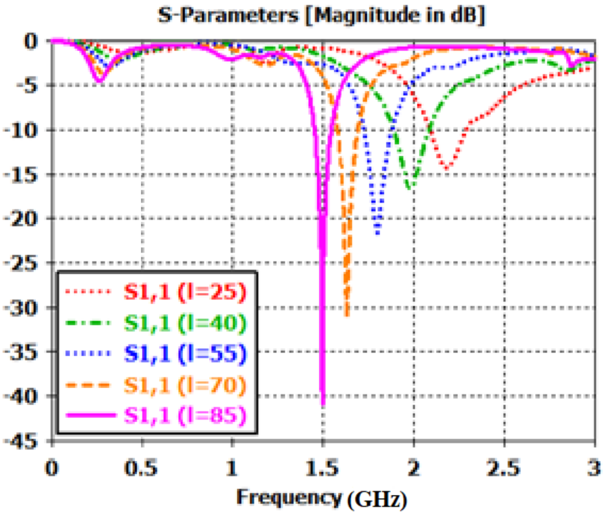


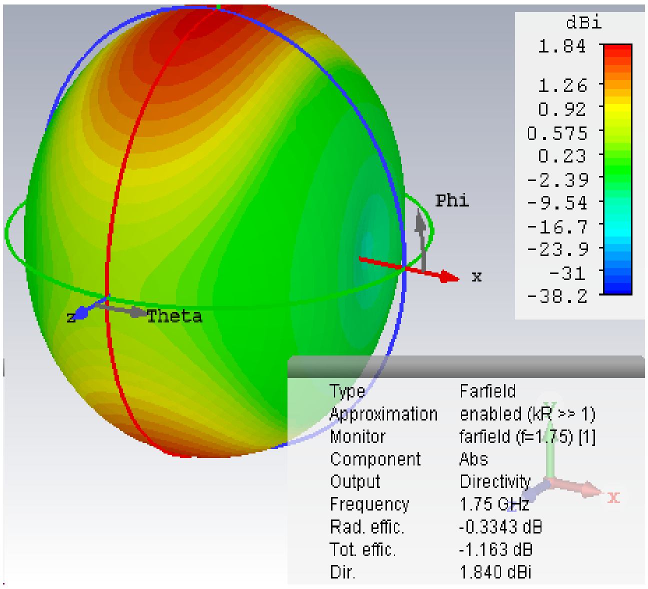
Figure 11. Variation of S_{11} versus frequency for different lengths of the antenna (L) with sleeve coupling

The three-dimensional radiation pattern of this antenna with sleeve coupling is shown in Fig. 12, in which the collision frequency is $\nu_c = 900\,MHz$ and electron plasma frequency is f_{pe}=7 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 of the antenna. Also, the radiation efficiency of this antenna is about -0.34 dB which is suitable enough. Another advantage of the sleeve coupling method is that this method is easy to implement and has a 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. 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.



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=1.75) [1]
Component	Abs
Output	Directivity
Frequency	1.75 GHz
Rad. effic.	-0.3343 dB
Tot. effic.	-1.163 dB
Dir.	1.840 dBi

Figure 12. The three-dimensional radiation pattern of the antenna with sleeve coupling (f_{pe}=7 GHz, ν_c=900 MHz)

B. Similarity to the Metallic Dipole Antenna:

The maximum value of the metallic dipole pattern occurs at θ=π/2 but in the capacitive coupling, there is a null at θ=π/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:

The radiation efficiency of the capacitive coupling is insufficient (Typically about -10 dB) but the radiation efficiency of the direct and the sleeve coupling is sufficient (Typically about -1 dB).

D. Comparison of the Coupler Dimensions and Volume:

One of the attractive capabilities of plasma antennas is their camouflage from waves. The antenna coupler is metallic and conflicts with this important property of plasma antennas. Therefore, the antenna with a small coupler is better. Moreover, the size and weight of the antenna structure must be as 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, a comparison of the advantages and disadvantages of the different coupling methods is 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 capacitive coupling is the worst method.

Table 1. Comparison of the Different Coupling Methods

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 a dipole antenna.

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, a radius of 7.5 mm, and a thickness is 1 mm. The power of these tubes is supplied by the electronic ballasts with specifications of 220V and 50Hz. The other parameters are shown in Table 2.

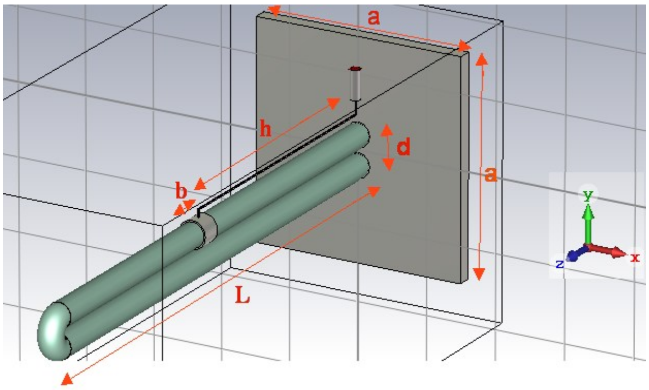


Figure 13. Structure of the folded monopole plasma antenna with sleeve coupling

Table 2. Dimension of the Fabricated Monopole Plasma Antenna

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 the 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 a 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 3.56×10^7 S/m.

5.2 Results and Discussion

Fig. 14 shows the fabricated folded monopole plasma antenna with sleeve coupling. The amplitude of the S_{11} is measured in the frequency range 400 MHz to 6 GHz and is shown in Fig. 15.

In the measurement process, by switching the plasma on, one resonance appears at 1.4 GHz, and receiving waves to the antenna are absorbed but by switching the plasma off, any resonance appears in the plasma and the waves are not absorbed, exactly, similar to when any antenna is present (Fig. 15).

Figure 14. Fabricated folded monopole plasma antenna with sleeve coupling

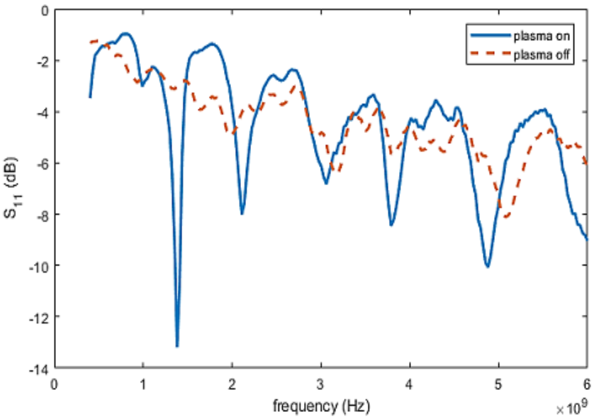


Figure 15. Comparison of the measured return loss of plasma antenna with sleeve coupling by switching plasma on and off

Discrepancies Between Theoretical Expectations and Experimental Results in Plasma Modeling As observed, the results obtained from plasma experiments exhibit significant deviations from the theoretical predictions typically anticipated. This divergence can be attributed to various approximations and discrepancies between theory and practice, which merit closer examination.

Firstly, it is essential to recognize that the model employed for electric permeability in plasma is a simplified representation of actual plasma behavior. The inherent complexities of plasma dynamics often render such models inadequate in capturing all relevant phenomena. Consequently, reliance on these approximations can lead to unexpected outcomes in experimental settings. Secondly, the specific tube utilized for plasma generation not only contains argon gas but also harbors impurities such as mercury vapor. These contaminants can significantly influence the behavior of the plasma, introducing factors that complicate both theoretical modeling and empirical observation. Additionally, there exists ambiguity regarding the diameter of the formed plasma within the tube. The non-uniform distribution of this plenum further complicates our understanding; hence, any assumptions made regarding its homogeneity may lead to flawed conclusions when correlating theory with experiment. Moreover, it is critical to consider that coupling equipment behaves analogously to a monopole antenna; therefore, during periods when plasma is inactive, its radiative pattern resembles that of a monopole antenna rather than an idealized state predicted by theoretical frameworks. Finally, several parameters assessed for plasmas, including electron collision frequencies and overall plasma frequency, are often estimated rather than precisely measured.

The advent of plasma antennas represents a significant advancement in the field of telecommunications and electromagnetic engineering. Unlike traditional wire-based antennas, plasma antennas utilize ionized gas, or plasma, as their radiating element. This innovative approach offers unique advantages such as reconfigurability, broad bandwidth capabilities, and the potential for stealth applications. As technology evolves, understanding the various applications of fabricated plasma antennas becomes paramount.

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. The capacitive coupling method suffers from bigness, complexity, bad pattern, and 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 patterns 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.

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