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Study on Pattern Reconfiguration of Plasma Antenna Excited by Surface Wave

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Abstract

For the purpose of anti-jamming communications, the radiation pattern reconfiguration of plasma antenna excited by surface wave were studied. The self-consistent model used to describe the relation between the pump signal and radiation pattern is put forward by combining the Boltzmann Equation and Maxwell Equation. And the correctness of the model is validated by using FDTD approach. The experiment system that used to measure the radiation pattern is established to validate the correctness of the self-consistent model. The investigation results show that the radiation pattern are reconfigurable by controlling the pump signal.

Keywords: *plasma antenna, reconfiguration, Boltzmann equation, FDTD*

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1. Introduction

Plasma antenna use partially or fully ionized gas as the conducting medium instead of metallic materials. With respect to conventional metallic antenna, plasma antenna has many peculiar properties. For instant, it can be rapidly switch on or off, this behavior makes plasma antenna suitable for use in stealth applications for military communications. Also, if this kind of antenna is used as the antenna array, the coupling between the elements is small. Especially, radiation pattern of plasma antenna is reconfigurable by changing the frequency and intensity of pump signal, gas pressure, vessel dimensions and so on. Because of the advantages above, many researchers and scientific communities show great interests about it.

At present, studies concerning plasma antenna consists of three aspects, experiment, theory, and numerical simulation. Theodore Anderson together with Igor Alexeff [1] designed a smart plasma antenna, and implement a wide range of plasma antenna experiments. Their studies proved that plasma antenna was highly reconfigurable. Rajneesh Kumar [2] designed a 30cm plasma antenna, and proved that the frequency and radiation pattern are able to alter with the frequency and power of the pump signal. Yang Lanlan [3] and Zhao Guowei [4] studied the dispersion of the surface wave along the plasma column by using the analytical method. Wu Zhenyu [5] and Xia Xinren [6] studied the radiation characteristic of plasma antenna through theoretical derivation. Zhaoyang Dai and Liu Shaobin [7] calculated the coefficients of reflection and transmission of electromagnetic wave in plasma by using FDTD numerical approach. Liang Zhiwei [8] simulated the radiation characteristic of cylindrical monopolar antenna by using FDTD method. P. Russo and G.G.Borg [9-13] established 1D and 2D self-consistent model and validated the correctness of the model by using FDTD method.

From the investigations above, we can draw a conclusion that plasma is so complicated that one can not find the real issues of the problem only in experimental approach. It is necessary to establish a rigorous mathematical model to investigate the reconfigurable characteristic of plasma antenna in theoretical approach. We did this work in section 2. Besides, the experiment investigation is implemented to validate the results of theoretical investigation. This part is introduced in section3.

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2. Theoretical Investigation

Plasma is created and sustained by a surface wave in this paper. The density of plasma along the tube is inhomogeneous. The electric parameters (ε, σ, μ) are different at different plasma region. And these parameters will change with the variation of pump signal. So the first thing we do in this part is to establish a model to describe the relation between the pump signal and the electric parameters. This model is used to calculate and load different electric parameters at different position of plasma tube. This part will be elaborated in section 2.1. The next work we do is to calculate the far field radiation pattern of plasma antenna by using the FDTD approach. The details of this part will be given in section 2.2. The object we studied is the cylindrical monopole as shown in Figure 1.

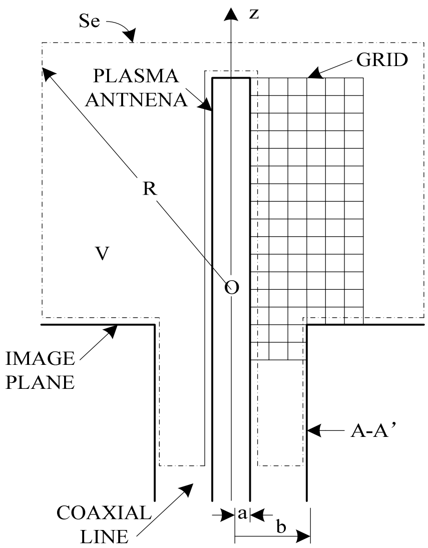


Figure 1. Geometry of Monopole Plasma Antenna

Figure 1 shows the geometry for a monopole plasma antenna fed through an image plane from a coaxial transmission line. The boundary of the space V is surrounded by the dash line. The image planes are assumed perfect electric conductor. a and b are the inner radius and outer radius of the transmission line, respectively. The ratio b/a=2.3, which corresponds to a characteristic impedance of 50Ω for the transmission line. The computational volume is surrounded by the perfectly matched layer (PML) to reduce the reflection of the radiated energy at the boundaries of the volume.

2.1. Establish the Self-consistent Model

The state of plasma is easily affected by the frequency and intensity of pump signal, the gas pressure, the shape of the vessel etc.. Among these factors that affect the reconfiguration performance of plasma antenna, the pump signal is picked up in this paper. The model is established to describe the relation between the pump signal and the radiation pattern of plasma antenna.

The relations between plasma state and pump signal can be considered as the interaction between plasma and electromagnetic wave. So, the propagation of an electromagnetic wave into a plasma is described by the Maxwell curl equation together with the Boltzmann equation.

The plasma state is determined by the movements of electron and ion. And these movements could be described by Boltzmann Equation [14].

$$\frac{\partial F}{\partial t}+\boldsymbol{v}\cdot\nabla_{\mathrm{r}}F+[-\frac{e}{m_e}(\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B})+\frac{F_{ext}}{m_e}]\cdot\nabla_{\mathrm{v}}F=(\frac{\partial F}{\partial t})_{coll} \tag{1}$$

Where F is electron distribution function (EDF). F_{ext} represents the external force put on the particles. $(\frac{\partial F}{\partial t})_{coll}$ represents the change rate of EDF with time.

Because the Boltzmann equation is nonlinear equation, the usual method to deal with it is to expand the EDF in spherical harmonics retaining only the first two terms, so that:

$$F(\boldsymbol{r},\boldsymbol{v},t) = F_0(v,\boldsymbol{r},t) + \frac{\boldsymbol{v}}{v}F_1(v,\boldsymbol{r},t) \tag{2}$$

Substituting (2) into the (1), an equation for each term is obtained and these are the ones that have to be solved self -consistently with the Maxwell equations.

$$\begin{cases} \frac{\partial F_0}{\partial t} = -\frac{v}{3}\nabla_r \cdot \boldsymbol{F_1} + \frac{e}{3m}\cdot\frac{\boldsymbol{E}}{v^2}\cdot\frac{\partial}{\partial v}(v^2\boldsymbol{F_1}) + C_0(F_0) \\ \frac{\partial \boldsymbol{F_1}}{\partial t} = -v\cdot\nabla_r F_0 + \frac{e}{m}\cdot\boldsymbol{E}\cdot\frac{\partial F_0}{\partial v} + C_1(\boldsymbol{F_1}) \\ \frac{\partial \boldsymbol{H}}{\partial t} = -\frac{1}{\mu}\nabla\times\boldsymbol{E} \\ \frac{\partial \boldsymbol{E}}{\partial t} = \frac{1}{\varepsilon}\nabla\times\boldsymbol{H} - \frac{1}{\varepsilon}\boldsymbol{j} \end{cases} \tag{3}$$

Where, $C_0(F_0)$ and $C_1(F_1)$ are the collision terms describing the EDF evolution due to elastic and ionization collisions.

The current density is calculated from the EDF as:

$$\boldsymbol{j} = -en\cdot\boldsymbol{u} = -en\cdot\left(\frac{1}{n}\int_v F\cdot\boldsymbol{v}d^3v\right) = -e\frac{4\pi}{3}\int_0^\infty v^3\boldsymbol{F_1}dv \tag{4}$$

To describe the ionization of weakly ionized plasma due to the perturbation introduced by the propagating electromagnetic field, also the continuity equation for the electron density n_e has been introduced in the model:

$$\frac{\partial n_e}{\partial t} = -\nabla_{\boldsymbol{r}}\cdot(n_e\boldsymbol{u}) + (<u^i> - \alpha\cdot n_{ion})n_e \tag{5}$$

Where, n_{ion} is the ion density and it is assumed to be equal to the electron density according to the quasi-neutrality assumption; $<u^i>$ and α are the ionization and recombination rates respectively, where:

$$<u^i> = \int_v v^i \cdot fd^3v \tag{6}$$

And α can be assumed to be a constant chosen according to the gas composition.

The complete plasma kinetic model is finally represented by Equation (3) and (4) together with Equation (5) .

In a steady-state condition (when the ionization-recombination balance is reached) and for a time harmonic field, the time-varying quantities J_x and E_x can be transformed into the corresponding quantities $\tilde{J}_x$ and $\tilde{E}_x$ in the frequency domain. In this way, the plasma electron parameters σ_p and ε_p can be obtained.

$$\begin{cases} \sigma_p = \mathrm{Re}[\tilde{J}_x / \tilde{E}_x] \\ \varepsilon_p = 1 + \dfrac{\mathrm{Im}[\tilde{J}_x / \tilde{E}_x]}{\varepsilon_0 \omega} \end{cases} \tag{7}$$

From the equations above, we know that most of the equation is nonlinear partial differential equations. It is difficult to solve these equations by using the analytic approach. The most feasible approach is numerical approach. The finite-difference time-domain (FDTD) method is adopted in this paper.

The model represented by the Maxwell curl equation, Boltzmann equation and the continuity equation can be resolved in an explicit way by using FDTD approach. The iterative equations of Boltzmann equation and the continuity equation after discretization are:

$$\begin{aligned} F_0 |_k^{n+1} = & F_0 |_k^n + \Delta t \frac{e}{3m} \frac{E_x |_k^n}{v^2} \frac{\partial}{\partial v} \left(v^2 F_{1x} |_{k+1/2}^{n+1/2} + \Delta t \frac{1}{v^2} \frac{\partial}{\partial v} \right) \\ & \times \left[\frac{m}{M} v^e(v) v^3 F_0 |_k^n + \frac{T_a}{M} v^e(v) v^2 \frac{\partial F_0 |_k^n}{\partial v} \right] \\ & + 4\Delta t \frac{v^i}{v} F_0 |_k^n (v^i) v^i (v^i) - \Delta t F_0 |_n^k v^i(v) \end{aligned} \tag{8}$$

$$F_{1x} |_{k+1/2}^{n+1/2} = (1 - \Delta t v^e(v)) F_{1x} |_{k+1/2}^{n-1/2} + \frac{e}{m} E_x \Big|_k^n \frac{\partial F_0}{\partial v} \Big|_k^n \tag{9}$$

$$n |_k^{n+1} = n |_k^n + \Delta t \left(\left\langle v^i \right\rangle - \alpha n_{ion} \right) n |_k^n \tag{10}$$

The discretization of Maxwell equation is omitted because it is well know in the electromagnetic community.

The Equation (8) to (10) together with the Maxwell iterative equation constitute a complete set of self-consistent equations to be solved simultaneously. The iterative procedure assuming starting approximate values for $E_i(r,t)$, Equation (8) and (9) can be solved to yield $F(\boldsymbol{r},\boldsymbol{v},t)$, using the calculated $F(\boldsymbol{r},\boldsymbol{v},t)$ in Equation (4) leads to values for the change and current densities J in the plasma, which can be substituted into Maxwell equations and solved for $E_i(r,t)$. These values are then plugged back into the Boltzmann equation, and so on. When plasma meets the steady-state condition, the electric parameters could be calculated through Equation (7).

To maintain the same accuracy and the same numerical structure as the standard FDTD, the anisotropic function is calculated in the same position and in the same instant of the magnetic field whereas the isotropic function and the electron density are calculated in a velocity grid.

2.2. Calculate the Radiation Pattern

The radiator in Figure 1 is rotationally symmetric and is excited by a rotationally symmetric source. Therefore, the electromagnetic field is independent of the cylindrical coordinate ϕ, and Maxwell equation can be expressed as two independent sets: one that involves can be expressed as two independent sets: one that involves only the components E_x, E_y, H_z, the transverse electric (TE) field. And one that involves only the components E_z, H_x, H_y, the transverse magnetic (TM) field. since the excitation for the antenna in Figure 1 is a TEM mode, which has only the field components E_z H_x, so, the TM model is selected. The iterative Equation [15] are as follows.

$$E_z^{n+1}(i,j) = C_{eze}(i,j) \times E_z^n(i,j) + C_{ezhy}(i,j) \times \left(H_y^{n+1}(i,j) - H_y^{n+1}(i-1,j) \right)$$
$$+ C_{ezhx}(i,j) \times \left(H_y^{n+1/2}(i,j) - H_y^{n+1/2}(i,j-1) \right) + C_{ezj}(i,j) \times F_{iz}^{n+1/2}(i,j) \tag{11a}$$

$$H_x^{n+1/2}(i,j) = C_{hxh}(i,j) \times H_x^{n-1/2}(i,j) + C_{hxez}(i,j) \times \left(E_z^n(i,j+1) - E_z^n(i,j) \right)$$
$$+ C_{hxm}(i,j) \times M_{ix}^n(i,j) \tag{11b}$$

$$H_y^{n+1/2}(i,j) = C_{hyh}(i,j) \times H_y^{n-1/2}(i,j) + C_{hyez}(i,j) \times \left(E_z^n(i+1,j) - E_z^n(i,j) \right)$$
$$+ C_{hym}(i,j) \times M_{iy}^n(i,j) \tag{11c}$$

Where, $C_{eze}(i,j)$, $C_{ezhy}(i,j)$, $C_{eze}(i,j)$,etc. represent the iterative coefficients of Maxwell equation.

On the cross section A-A' the incident electric field is:

$$E^i(t) = \frac{V^i(t)}{\ln(b/a)} \hat{r} \tag{12}$$

The spatial and temporal increments (Δx, Δz and Δt) are chosen to satisfy the 'Courant-Friedrichs-Lewy condition'.

$$c\Delta t \le \frac{1}{\sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta z)^2}}} \tag{13}$$

In this paper, the uniform spatial grid is used and we set $\Delta x = \Delta z$.

For obtain the electromagnetic wave in unbounded regions, an absorbing boundary condition (ABC) must be introduced to simulate the extension of the lattice to infinity. In this paper the PML is applied.

The PML updating equations are obtain as:

$$\begin{cases} \varepsilon_0 \dfrac{\partial E_{zx}}{\partial t} + \sigma_{pex} E_{zx} = \dfrac{\partial H_y}{\partial x} \\ \varepsilon_0 \dfrac{\partial E_{zy}}{\partial t} + \sigma_{pey} E_{zy} = -\dfrac{\partial H_x}{\partial y} \\ \mu_0 \dfrac{\partial H_x}{\partial t} + \sigma_{pmy} H_x = -\dfrac{\partial (E_{zx} + E_{zy})}{\partial y} \\ \mu_0 \dfrac{\partial H_y}{\partial t} + \sigma_{pmx} H_y = \dfrac{\partial (E_{zx} + E_{zy})}{\partial x} \end{cases} \tag{14}$$

Where, σ_{pex}, σ_{pmx}, σ_{pey}, σ_{pmy} are the electrical conductivity and the magnetic conductivity at the corresponding direction, respectively.

However, for many antenna applications, we want to know the electromagnetic field at a large distance from the antenna—the radiated field. this field can be obtain by applying a near-field to far-field (NFFF) transformation. To perform this transformation, a virtual surface is placed around the antenna. The field on this surface is obtained for the time period of interest. This radiation power of the field is then obtained by applying the surface equivalence theorem.

$$P_{rad} = \frac{1}{2} \mathrm{Re}\left\{ \int_s \boldsymbol{E} \times \boldsymbol{H} \cdot \hat{n} dS' \right\} \tag{15}$$

Here, the components $\boldsymbol{E}$ and $\boldsymbol{H}$ are the electric field and magnetic field on the virtual surface, respectively. Then, combining the FDTD approach and applying the image theory, we obtain the far field pattern.

2.3. Results

Firstly, we simulated the attenuation constant and phase constant of electromagnetic wave transmitting in plasma. The plasma region is characterized by these parameters: electron density $N_e = 1.86\times10^{18} m^{-3}$, neutral density $N_n = 6.24\times10^{23} m^{-3}$, temperature $T = 293K$ and a constant collision frequency $\tilde{v} = 1.5\times10^{8} Hz$. The variation of attenuation constant and phase constant with frequency range from 10GHz to 25GHz is simulated in this paper. The result is shown in Figure 2.

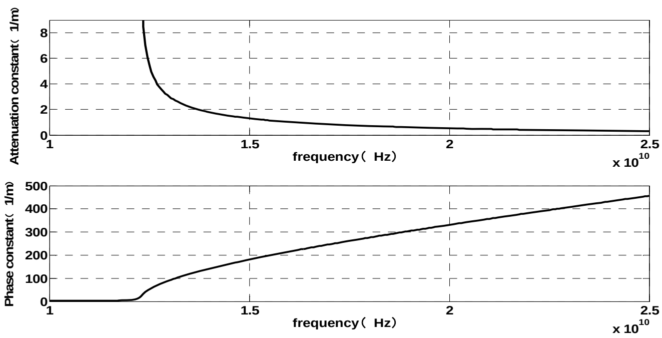


Figure 2. Attenuation Constant and Phase Constant of Electromagnetic Wave Transmitting in Plasma

From Figure 2 we can conclude that the attenuation constant decreases gradually with the increase of frequency. While the phase constant increases with the increase of frequency. The correctness of the self-consistent model established in section 2.1 is validated by simulating the process of electromagnetic wave (2GHz) transmitting in plasma from free space. The iteration times is 1600. The result is shown as Figure 3.

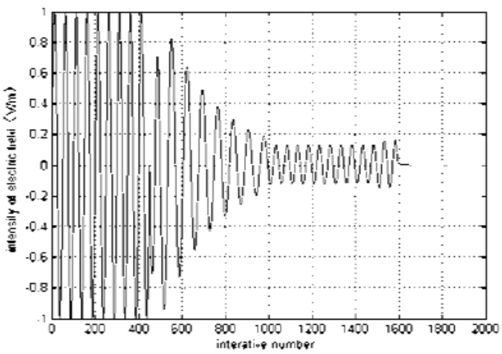


Figure 3. Propagation of Electromagnetic Wave from Free Space to Plasma

From Figure 3 we can see that the attenuation is happened obviously when the electromagnetic wave transmit into the plasma from free space. When electromagnetic wave transmitting in the free space the wave vector is a constant. There is no attenuation. While plasma is a kind of lossy medium, the wave vector is a complex number. Therefore, the amplitude of the electromagnetic wave attenuate gradually until to the air-plasma interface. From this result, we can conclude that the self-consistent model is correct.

3. Experimental Investigation
3.1. Experiment Setup

In order to check the correctness of the model proposed above. The system [16] used to measure the radiation pattern of plasma antenna array is established. In this system, the plasma antenna is constructed applying bursts of power to a discharge tube which filled with argon. The antenna-rotating method is adopted in this paper. The sketch diagram are as show in Figure 4.

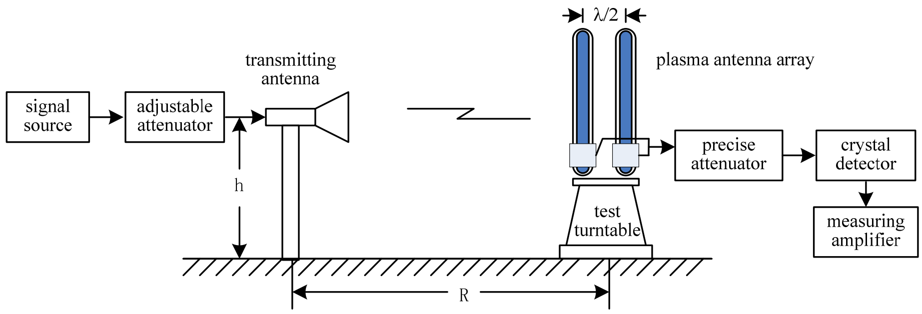
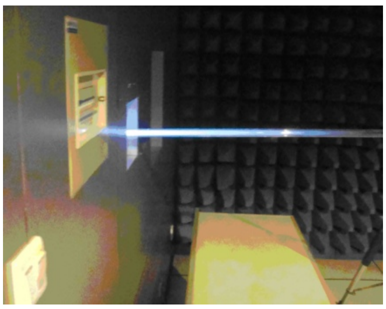
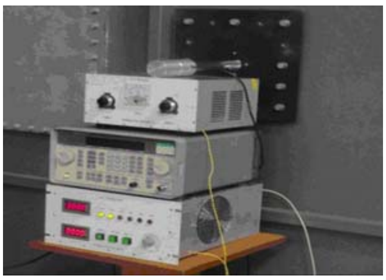


Figure 4. Sketch Diagram of Antenna-rotating Method

According to the reciprocity principle, the radiation pattern of transmitting antenna and receiving antenna is same. The horn antenna is adopted as transmitting antenna. And the plasma array is used as receiving antenna. The distance of the two elements is $\lambda/2$. The distance R satisfies the far field condition $\frac{2\pi R}{\lambda} \gg 1$. The photos related to the experiment are shown as Figure 5.


(a) anechoic chamber


(b) plasma antenna


(c) pump signal source

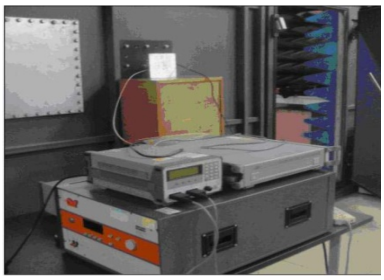

(d) signal source and amplifier

Figure 5. Photos Related to the Experiment

3.2. Experiment Results

We establish a plasma array, which has two elements. The frequency of excitation signal is 12.56MHz. The power of pump signal is adjustable with the range 0~120W. The transmitting signal frequency is 200MHz corresponding to the wavelength 37.5cm. The distance of the two elements is 75cm. In order to measure the field intensity, the field intensity indicator is placed at 30m away from the antenna array. Antenna array rotates once every 15 degree. We record the data of the radiation pattern by changing the power of the pump signal. The results are as shown in Figure 6.

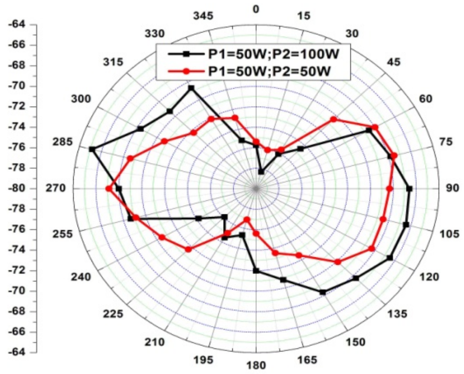


Figure 6. H Plane Radiation Pattern of Plasma Antenna Array

As shown in Figure 6, it is the H-plane radiation pattern of the two element plasma array. At the beginning, the applied power of two elements are both 50W. The radiation pattern is represented by the curve that consists of dot spot and short line. And then the applied power of one element changes from 50W to 100W. Company with the variation of applied power, the maximum radiation direction of the antenna array changes from 270 degree to 285 degree. The state of plasma change with the variation of the applied power. The electric parameters (ε , σ , μ) change with the state of plasma. A serial of changes lead to the change of surface current distribution of plasma antenna. Once the surface current distribution of plasma antenna changes, the radiation pattern will be affected.

4. Conclusion

The radiation pattern reconfiguration of plasma antenna is studied in theory and experiment aspect. First of all, we established the self-consistent model used to confirm the electric parameters of plasma antenna at different region. We validate the correctness of this self-consistent model by using the numerical approach. And then, we establish the experimental system used to measure the pattern of plasma antenna is set up. The radiation pattern of two elements plasma array was tested. The results show that the radiation pattern could be configured by changing the power of pump source. This characteristic makes the plasma useful in communication anti-jamming. This research result will have preferable application prospect and superior martial application value.

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