

# Two-Dimensional Models of Cylindrical Monopole Plasma Antenna Excited by Surface Wave

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**Abstract:** The numerical calculation model of cylindrical monopole plasma antenna excited by surface wave is proposed in the paper. The wave propagation model of the plasma antenna is also investigated. The models are both analyzed in two-dimension and calculation equations of models are given and deduced. The detailed analysis of models and the calculation results have been obtained. The two models are testified through the specific experiments. The results show that the measured results agree well with the calculated ones which help to verify validity of the proposed models.

**Key-Words:** - Monopole Cylindrical Plasma Antenna; Surface Wave; Two-Dimensional Model; Numerical Calculation

## 1 Introduction

In the present research of plasma antenna, the plasma antenna is considered as metal antenna with the same current distribution, recent experiments have demonstrated that plasma antennas can be efficient and generate sufficiently low noise as to be useful for narrow band high-frequency (HF) (3–30MHz) and very high-frequency (VHF) (30–300MHz) communications.

Plasma elements have a number of potential advantages over conventional metal elements for antenna design as they permit electrical, rather than mechanical control of their characteristics [1-7].

But the density and current distribution of plasma antenna are non-uniform. In each part of the plasma, the energy absorption from the surface wave also is unequal[8],and its energy coefficient presents nonlinear distribution [9-10].When density of the plasma is about  $10^{11} / cm^3 - 10^{20} / cm^3$ , the plasma can be regarded as good conductive material, Borg G. G. calculates the radiation patterns of the plasma antenna according to current distribution of the mental antenna, and the premise of calculation is that the plasma is uniform distributed and the frequency of plasma is higher than the signal frequency transmitted [11]. John Phillip gives out the axial distribution and the attenuation coefficient of the plasma antenna approximately [12], Zhao G. W. calculates the radiation patterns under certain

distribution of the surface current [13], they all regard the plasma antenna as working in traveling wave work mode.

The assumption of plasma antenna working in traveling wave work mode has many limitations, sometimes will leads to be errors. The researchers have found that when plasma density is low, the wave attenuation of plasma is large, then plasma antenna approximately has no reflection wave, under this condition the assumptions above mentioned are reasonable and practicable [14-15].The calculation methods of the plasma antenna parameters according to method of mental antenna have many approximations and they can not reflect the characteristics of the plasma antenna accurately[16].When plasma antenna presents some distribution, the real part and imaginary part of the wave vector of the signal transmitted, and the parameters of plasma antenna are determined by inner state of plasma. The physical parameters of plasma antenna such as the conductivity, dielectric tensor, etc. can not be calculated precisely through using transitional method.

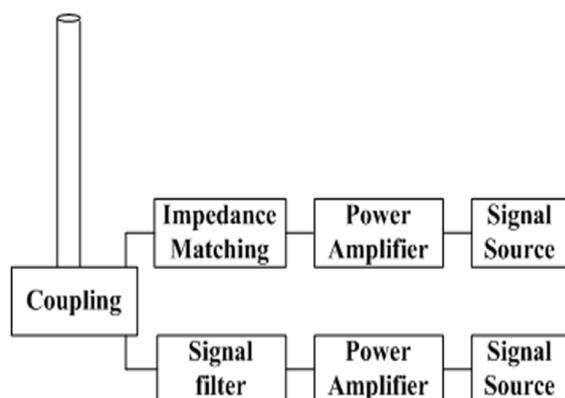
To numerically evaluate the radiation pattern, many variations of the numerical electromagnetic code (NEC) method of Moments computer packages can be used. Several are available from <http://www.qsl.net/wb6tpu/swindex.html>. NEC is widely used for modeling antennas and their

environment. The antenna structure is broken down into short wires and small surface areas, from which the current distribution and the radiation pattern may be found. Using a computer program, the conductivity of the small current elements that comprise the antenna structure can be changed easily [11].

But the real-time characteristic is ignited in the method, and it cannot predict the state of the plasma.

So the accurate modeling study of plasma antenna is very necessary, and the wave propagation model of the plasma antenna should be investigated. In the wave propagation model the incidence electric field and reflected electric field should both be taken into consideration. The detailed analysis and the calculation have been made in the paper. The two models are verified through the specific experiment of plasma antenna.

## 2 Structure of the Plasma Antenna



**Fig.1** The structure of cylindrical monopole plasma antenna excited by surface wave

Fig.1 shows the schematic diagram of cylindrical monopole plasma antenna excited by surface wave.

The plasma antenna system consists of two parts, one is the excited power circuit part and the other is the transmitting signal circuit part. The two circuits are made up of signal source, power amplifier, filter, and impedance matching part, etc. as shown in Fig.1. The measurement of the plasma antenna in near field and far field can adopt the measure methods of the metal antenna with modifying in the measure equipments and environment.

The plasma is created by the RF excitation power. Electromagnetic power is coupled into the antenna through RF coils. The inductive magnetic field presents axial distribution and the inductive electric field presents radial distribution around the plasma antenna. The inductive magnetic field

presents axial reverse symmetric distribution.

As the state of plasma antenna is determined by power and frequency of the excitation electromagnetic field, and the gas pressure and composition of discharged gas and other parameters are also the influence factors of plasma antenna [13]. In addition, in order to describe the interaction mechanism between the electromagnetic field and the plasma, it is necessary to understand how plasma changes with the work conditions which are adopted in the paper. The plasma phenomenon can be kinetically modeled with equations including the Maxwell curl equations and the Boltzmann equation [14]. The Boltzmann equation can illustrate the time, space, and velocity evolution of the electron distribution function (EDF), which is expressed as  $f(t, r, v)$ , where  $t$  is the time,  $r$  is the location,  $v$  is the velocity of particle. The describe of the EDF is the key point to define plasma state, all the macroscopic quantities involved in the problem such as electron density and plasma conductivity etc. can be analyzed with some analytical manipulation from the EDF.

## 3 Numerical Calculation Model of Plasma Antenna

Fig.2 illustrates cylindrical plasma which can be divided into many subsections in axial direction, the length of each part is  $\Delta z$ ,  $e^{-i\omega t}$  is the time factor,  $\omega$  is the electromagnetic frequency,  $L$  is the length of plasma antenna. If neglecting the influence of axial density gradient in the plasma, assumptions of the calculation model are as following:

- (1).each unit of the plasma is uniform distributed.
- (2).the frequency of RF power far outweighs ion oscillation frequency of the plasma.
- (3).the density of plasma is high enough, the Debye sheath near the surface cylindrical is very short, and is far less than radius of plasma antenna; therefore the influence of the sheath can be neglected.
- (4).the mirror reflection of electronic wave is happened in the boundary of the plasma antenna.

According to the above assumptions, the electric field presents column symmetrical, in cylindrical coordinates system the electric field can be expressed as

$$E_f(r, t) = E_\phi(r, z)e^{-j\omega t} \quad (1)$$

Where  $E_f(r, t)$  is the inductive electric field,  $E_\phi(r, z)$  is the electric field,  $Z$  represents the axial direction and  $r$  represents the radial direction. The expression of electric field can be written as follows

$$E_{\phi}(r, z) = \sum_{j=1}^{\infty} \sum_{k=-\infty}^{\infty} e_{jk} J_1(p_j r / R) \sin(K_k z) \quad (2)$$

Where  $e_{jk}$  is the spread coefficient,  $J_1$  is the Bessel function,  $p_j$  and  $K_k$  satisfies the type  $J_0(p_j) = 0$ ,  $k_k = k\pi/L$ , and  $k$  is the integer.

According to the hypothesis given above, the electronic velocity distribution function can be described as the following Boltzmann equation

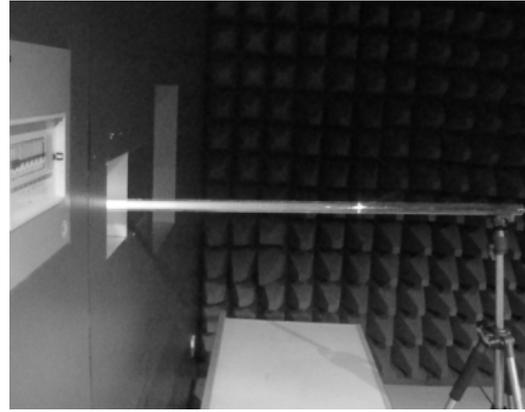
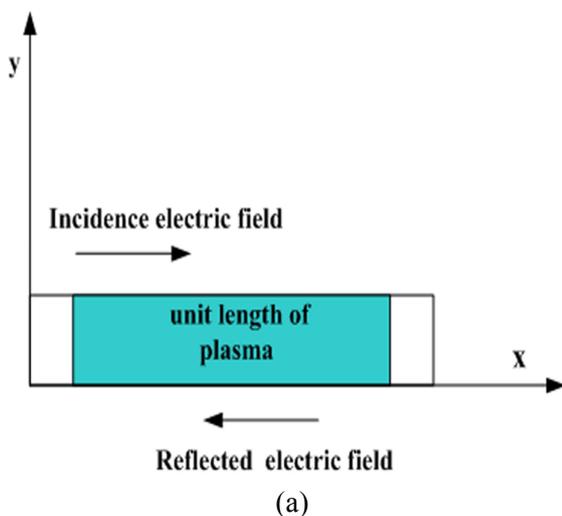
$$\frac{\partial f}{\partial t} + v \frac{\partial f}{\partial r} - \frac{eE_{rf}}{m_e} \cdot \frac{\partial f}{\partial v} = S(f) \quad (3)$$

Where  $f$  is the electron distribution function (EDF),  $v$  is the velocity of electron and the  $S(f)$  is the collision integral.

Based on the Boltzmann equation and assumptions of the proposed model, the physical parameters of plasma antenna such as the conductivity, dielectric tensor, etc. can be deduced and calculated.

#### 4 Wave Propagation Model of Plasma Antenna

Based on the discussions above, in the wave propagation model of the plasma antenna, it can be divided into many parts in two-dimensional coordinate system. In each part, the distribution of plasma is approximate uniform as shown in Fig.2 (a). The axial attenuation character of the given plasma antenna is shown in Fig.2(b). The influence of transmitted signal to the plasma can be neglected. According to the antenna theory, the axial current plays a key role in the antenna, and the value of electric field is the sum of incidence and reflection electric field. On the top point of the plasma antenna, the current is nearly zero due to the incident current and the reflect current are



(b)

**Fig.2** (a) Wave propagation model of the plasma antenna,

(b) Uniform distribution in axial direction of the plasma antenna equal in value and opposite in direction.

The Maxwell equation of the model in cylindrical coordinates system can be expressed as

$$\frac{d^2 E(r)}{dr^2} + \left(\frac{1}{r}\right) \frac{dE(r)}{dr} - \gamma(r)^2 E(r) = 0 \quad (4)$$

Where  $E(r)$  is the sum of incidence and reflection electric field,  $\epsilon_r$  is dielectric constant of the unit length of in the plasma,  $\gamma(r)$  is the composite wave vector.

According to the assumptions above, in each unit of plasma antenna, the boundary condition is that, it is limited in center place and finite in infinity place and the borders is continuous. So the expression of the wave transmitted and the dispersion relations in the plasma antenna can be obtained. The dispersion relationship of the plasma can be expressed by equation (5) given in [11].

$$\epsilon_r \gamma_0 I_1(\gamma_p a) K_0(\gamma_0 a) + \gamma_p K_1(\gamma_0 a) I_0(\gamma_p a) = 0 \quad (5)$$

Where  $\gamma_p^2 = k^2 - \epsilon_r k_0^2$ ,  $\gamma_0^2 = k^2 - k_0^2$ ,  $k$  is the wave vector in plasma and  $k_0$  is the wave vector in free space.

The symmetry and initial conditions of the proposed model can be described as equations (6), (7), and (8).

$$\begin{cases} E_{f,r} / r=0,t=0 = E_{f0,r0} \\ E_{f,r} / r=0 = 0 \end{cases} \quad (6)$$

$$E_{f,r}(r, z) = E_{f0,r0} \cdot I_0(\gamma_p \cdot r) e^{\pm ik(z) \cdot z - i\omega t} \quad (7)$$

$$\begin{aligned} J_{f,r}(r, z) &= \sigma(z) \cdot E_{f,r}(r, z) \\ &= \sigma(z) \cdot E_{f0,r0} \cdot I_0(\gamma_p \cdot r) e^{\pm ik(z) \cdot z - i\omega t} \end{aligned} \quad (8)$$

Where the equation (6) is boundary condition,  $E_{f,r}(r, z)$  is the electric field around plasma antenna in axial direction,  $J_{f,r}(r, z)$  is the current of the point  $\Delta z$  on the plasma antenna in  $Z$  direction,  $t$  represents time, the current can be expressed as equation (9).

$$J(r, z, t) = J_f - J_r$$

$$= \sigma(z) \cdot I_0(\gamma_p \cdot r) \cdot (E_{f0} \cdot e^{ik(z)z} - E_{r0} \cdot e^{-ik(z)z}) \cdot e^{-i\omega t}$$
(9)

The bottom current and top current of the plasma antenna are as (10), (11).

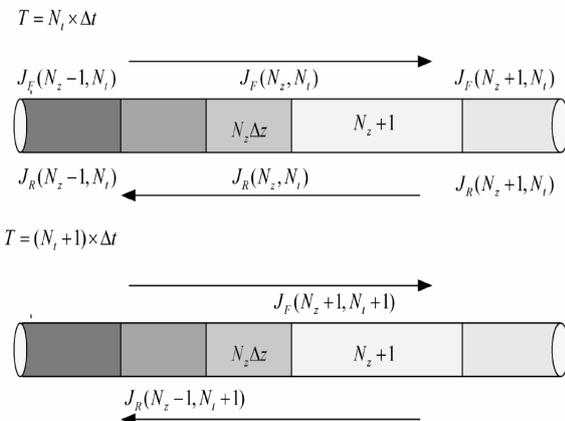
$$J_F \Big|_{r=0, z=0} = J_0 e^{-i\omega t}$$
(10)

$$J_F \Big|_{z=l} = -J_r \Big|_{z=l}$$
(11)

According to the theory of electromagnetic field, there exists absorption and attenuation of electromagnetic wave in the plasma which is similar to the electromagnetic wave transmitted in other medium. In each subsection part of the plasma, plasma presents uniform distribution, the incidence power is  $P_i$  and reflection power is  $P_r$ , then the power at point  $z$  on the plasma antenna can be written as equation (12).

$$p(z) = (p_i - p_r) \exp(-2k_r z)$$
(12)

The parameters of the propagation wave model need to be calculated in each part of the plasma antenna is as shown in Fig.3 including the current, plasma density, dielectric coefficient, position, space intervals, incident wave amplitude and phase, reflected wave amplitude and phase, wave vector. When the interval  $\Delta t$  is very small, the approximate equation can be expressed as (13).



**Fig.3** Subsection of the cylindrical monopole plasma antenna

$$\begin{cases} J(N_z, N_t + 1) = J_F(N_z, N_t) \times e^{j(k(N_z) \cdot \Delta z - \omega \Delta t)} \\ \quad - J_R(N_z, N_t) \times e^{j(k(N_z) \cdot \Delta z - \omega \Delta t)} \\ E(N_z, N_t + 1) = J(N_z, N_t + 1) / \sigma(N_z) \end{cases}$$
(13)

Where  $J$  is the current in axial direction, and  $E$  is the electrical field in axial direction  $\sigma$  is the conductivity of plasma.

Based on discussions and the parameters given above including the electric field, plasma length, time interval, signal frequency and radius of plasma antenna, the surface current in each unit of the antenna can be calculated.

### 5 Numerical Calculation and Results Discussions

When the axial distribution of density of the plasma is obtained, the power of signal transmitted on the plasma antenna is far less than the excitation power. The wave vector distribution of transmission signal can be got from related formulation given by equation (14).

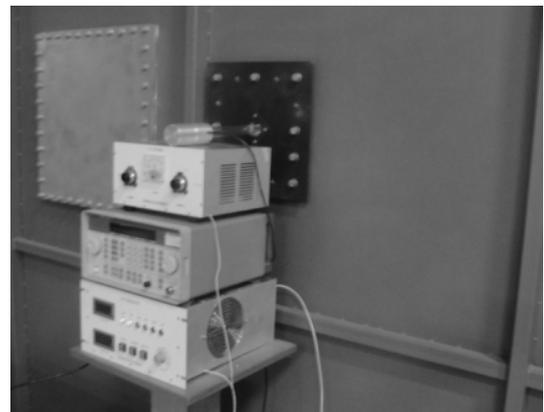
$$\vec{k}_s(z) = k_{sr}(z) + i \cdot k_{si}(z)$$
(14)

According to the model proposed, the surface current distribution of plasma antenna can be expressed as equation (15).

$$J(z, t) = \int_0^z e^{-\int_0^z k_{sr}(\tau) d\tau} \cdot e^{-\int_0^z k_{si}(\tau) d\tau} - e^{-\int_0^z k_{sr}(\tau) d\tau} \cdot e^{-\int_0^z k_{si}(\tau) d\tau} \cdot e^{j\omega t} dz$$
(15)

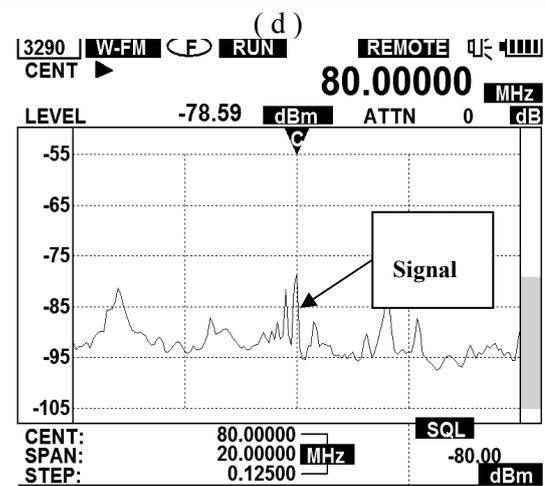
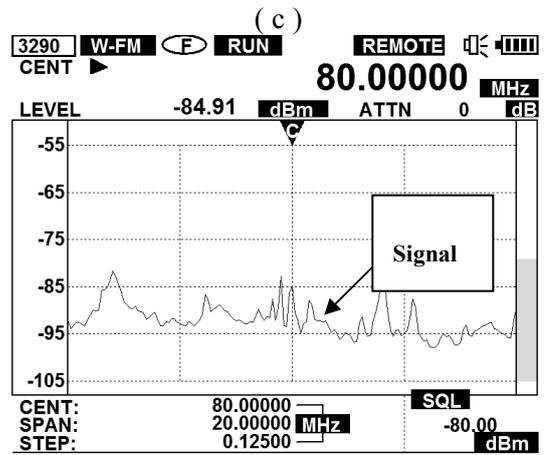
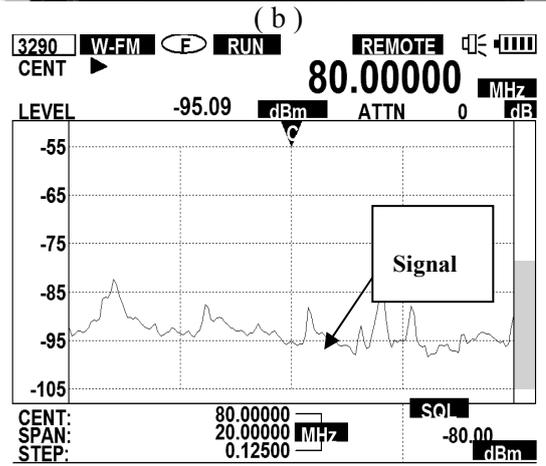
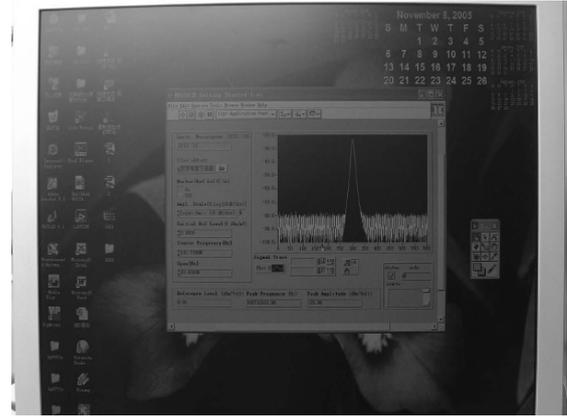
Therefore, the radiation patterns of the plasma antenna in the article can be obtained through the equation which can be described as (16).

$$F(\theta) = \int_0^l e^{-\int_0^z k_{sr}(\tau) d\tau} \cdot e^{-\int_0^z k_{si}(\tau) d\tau} - e^{-\int_0^z k_{sr}(\tau) d\tau} \cdot e^{-\int_0^z k_{si}(\tau) d\tau} \cdot \sin(\theta) \cdot e^{jk_0 z \cos(\theta)} dz$$
(16)

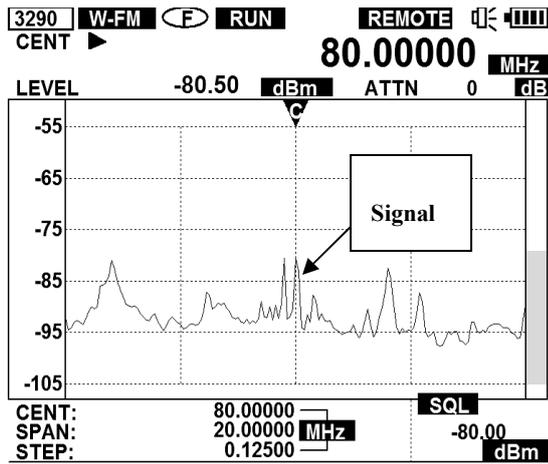




(a)

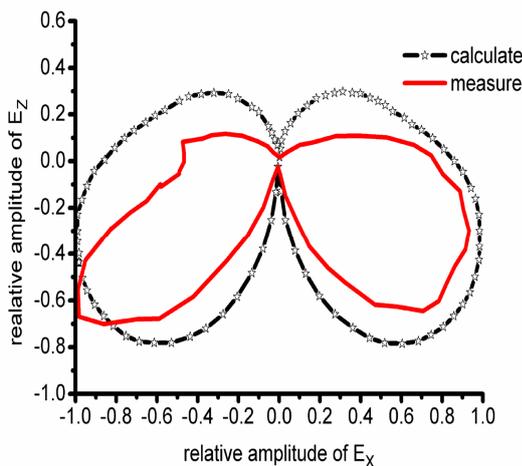


(e)



(f)

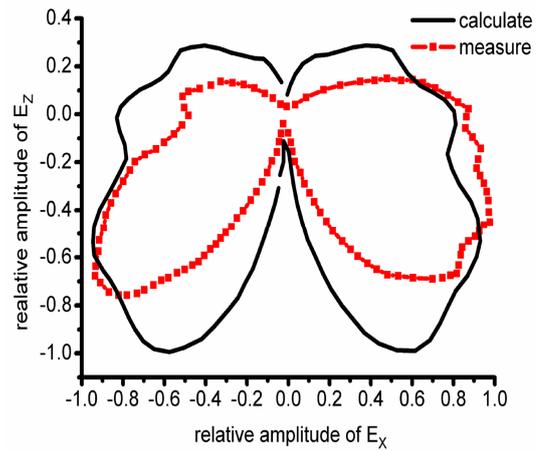
**Fig.4** (a) The measurement of radiation pattern in near field  
 (b) The measurement of radiation pattern in far field  
 (c) The strength of the transmission signal when the plasma antenna is not excited  
 (d) (e) (f) The strength of the transmission signal in different measure point



(a)

The proposed model has been measured and calculated to verify the effectiveness of the deduced equations. The radiation characteristics of the model in the near and far field are presented by using the plasma antenna measurement devices in the optics and electronic department of Mechanical Engineering College. And the measured results are shown in Fig.4.

Fig.4 (a) and Fig.4 (b) show the results of radiation pattern in near field and far field respectively, the measurement setup is consistent with the standard condition. Fig.4 (c) describes that the frequency of measure signal is 80MHz. The



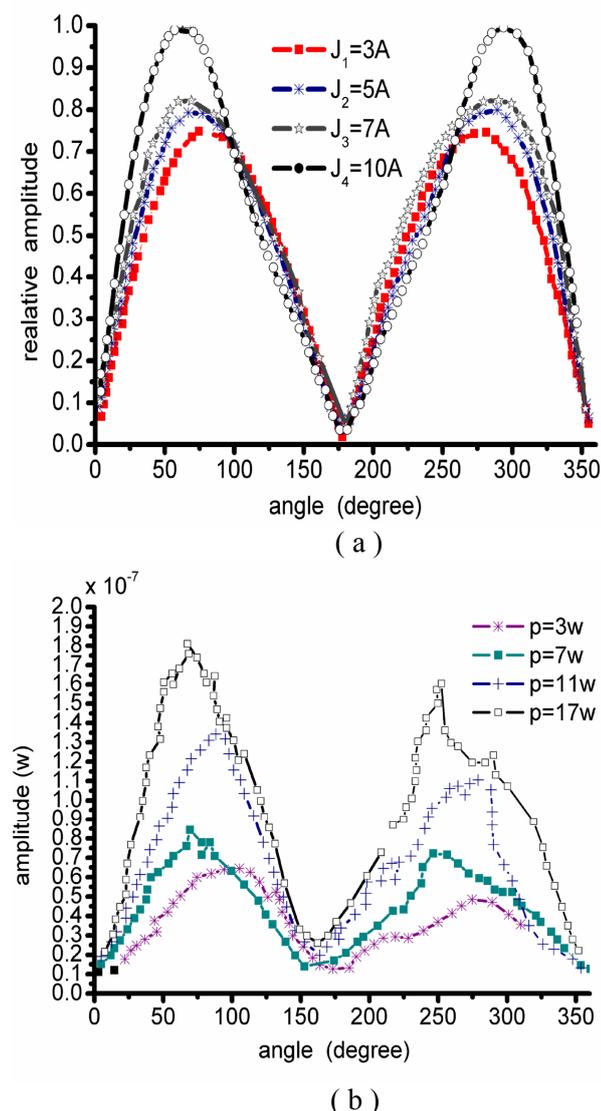
(b)

**Fig. 5** (a) Calculated and measured radiation pattern in near field  
 (b) Calculated and measured radiation pattern in far field

signal strength is about -95dBm when the plasma antenna is not excited. Fig.4(d), (e), (f) are the signal strength in different measure point, which are about -78dBm, -84.9dBm and -80.5dBm, when the plasma antenna is ignited. During the measurement, the noise strength of environments is the same which are also shown in the Fig.4. It can be seen from Fig.4, the radiation power of the plasma antenna varies with the changing of the measure point. The density distribution of plasma antenna in axial direction can be got from the plasma model, the calculation of the radiation patterns can be carried out by using the wave propagation model of the plasma antenna.

The radiation patterns can also be obtained from numerical calculation given in equation (15) and (16). The radiation pattern of the plasma antenna has been given numerically and experimentally by fixed the frequency of the signal on 80MHz. And the results are shown in Fig.5. From Fig.5, we can see that the measured results agree well with calculated ones which also certify the effectiveness of the proposed model. The minor errors between measured results and the calculated ones may be attributed to the larger energy absorption in plasma antenna and the non-uniform distribution of its conductivity, which cause the abnormality in the left and right lobe of the radiation pattern as seen in the measured curve of (a),(b) in Fig 5. As to defined experiment, the type of gas, antenna radius, and gas pressure of the plasma antenna can not be changed, only the excitation power can be easily controlled by using the external

circuits. If the excitation power is changed, the calculated and measured radiation patterns are



**Fig.6** (a) Calculation results of radiation patterns  
(b) Experimental results of radiation patterns shown in Fig.6. The numerical calculation and experimental results is obtained by varying the plasma density. The radiation patterns are almost the same with little error except the signal amplitude which is not consistent due to the power used in the experiment. If the incentive power is increased to certain extent, the radiation patterns change accordingly and obviously.

## 6 Conclusions

This paper proposes the calculation model according to the Boltzmann Equation and Maxwell Equations. The model can be worked out in precision through using the deduced equations. The research of wave propagation model of plasma

antenna is also given by dividing the plasma antenna into many parts in axial direction, in which the time interval is equal and each length is unequal.

The proposed models are also testified by the experiments of plasma antenna. The calculated and measured results show that the energy absorption of the surface wave is large which caused the error between the calculated results and the measured ones. And the results meet well in the radiation patterns in general.

When the excitation power and plasma density is low, the radiation patterns of plasma antenna are unchanged or changed little. Only when the plasma density is increased to a certain extent, the radiation patterns change obviously. The experiment results validate the proposed models' analysis and calculation which can help us to do the further related research.

Our investigations have shown that although there is some loss of radiation efficiency due to the lower conductivity of the plasma antenna, this loss is not serious and may be easily made up by slightly boosting the power used in transmission. We also found that the tapered conductivity profile has little effect on the resulting radiation pattern.

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