Reconfigurable Characteristics of the Monopole Plasma Antenna and Its Array Driven by Surface Wave

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Abstract: - Reconfigurable characteristics of monopole plasma antenna are investigated in the paper, related analysis and experiments on the reconfigurable characteristics of the plasma antenna e.g., working frequency, radiation pattern are completed and many experimental results are obtained. The research results show that the reconfigurable characteristics of monopole plasma antenna can be realized and optimized under certain external excited conditions. The radiation parameters the plasma antenna array also can be reconfigured through changing variable parameters of the plasma elements, the related analysis and simulations are presented.

Key-Words: -Monopole Plasma Antenna, Plasma Antenna Array; Reconfigurable Characteristics, Surface Wave, Research

1 Introduction

Plasma antenna is usually driven by radio frequency (RF) power, when the insulated tube filled with inert gas is discharged thus the plasma is created. The RF power is propagated between plasma and tube in surface wave mode, and the plasma column is also sustained by the energy of surface wave. The plasma has the properties which make it can be used as conducting medium; Plasma can be rapidly created through applying bursts of RF power to discharge the inert gas, and the plasma antenna can be rapidly switched on and off in microsecond, when it is off, it behaves like a dielectric material, when it is on, plasma can be used as the conductor, therefore, the power supplied ionizes the gas providing the conductive medium for the signal to be radiated , so it also can be applied as the conducting medium for propagating the RF signals; in plasma antenna application two signals are needed: the pump signal that creates and sustains the plasma column, and the signal to be radiated that has to be coupled to the plasma element.[1-5].As known that plasma is a kind of dispersion medium, its electric parameters e.g., conductivity and permittivity are no longer the constant, parameters of the plasma mentioned above will be changed according to the plasma frequency, strength of driven power, the coupling methods and location of the power coupling on plasma antenna, etc [6-7]. Its parameters e.g., surface current distribution, radiation pattern, gain, conductivity and wave vector are entirely determined by the particle interactions of the plasma, and the dynamic movements of particles in plasma are governed by the external electrical fields, which make the plasma antenna have reconfigurable properties [8]. Reconfigurable methods of plasma antenna can be developed and obtained through related experiments and analysis. The physical characteristics of the plasma antenna e.g., the distribution of plasma density, antenna resonance length, noise and the radiation pattern under certain conditions are already analyzed and summarized in papers [9, 10, 11]. The researchers of the plasma antenna laboratory of Canberra University in Australia find that the changing of variable parameters of plasma antenna will lead to the changing in its radiation pattern [9-12]. Rayner finds that the length of plasma is directly proportional to the square root of excitation power, and the density of plasma along the antenna presents linear distribution. Many fundamental properties of the plasma antenna have already been investigated and many important results are obtained and which demonstrate the reconfigurable characteristics of plasma antenna [13-18].

A rigorous representation has been obtained for the current distribution on an infinitely long plasma antenna. It is also found that the stability of resonant frequency increases with the increasing in frequency of the power supplied [19-23].

From the related research works mentioned above, it can be concluded that the reconfigurable characteristics of the plasma antenna are the important advantage over the metallic antenna and the thorough and effective research work should be investigated. In this paper, the reconfigurable characteristics of the monopole plasma antenna are

presented through theory analysis, simulations and experiments.

2 Reconfigurable Characteristic of Monopole Plasma Antenna

2.1 Structure of Monopole Plasma Antenna Driven by Surface Wave

Experimental devices of plasma antenna include discharge tube, RF power source, band-pass filter, RF transmission and coupling device, etc. The experimental diagram is as shown as Fig.1; the coupling arrangement of the plasma antenna and the experimental equipments are illustrated as Fig. 2 and Fig. 3.
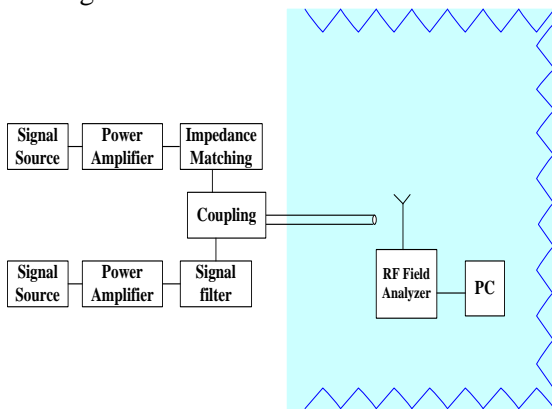

Fig.1. Experimental diagram of the plasma antenna

(a)   (b)

(c)   (d)
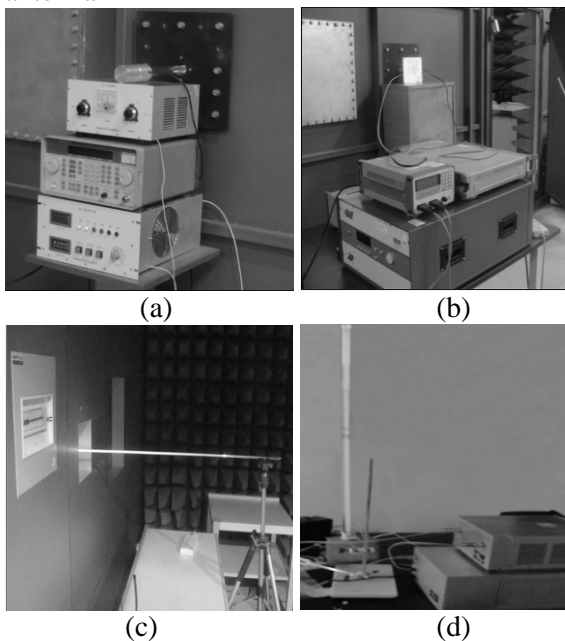
Fig.2. Photos of monopole plasma antenna driven by the surface wave

When the plasma is in low electron temperature state, the interactions between neutral atoms and molecules are not most important; as known that the plasma properties are affected by the movements of particles [8]. If there is no external magnetic field around the plasma antenna and the inductive

magnetic field is not taken into consideration, the conductivity of plasma is a scalar, otherwise, the state of plasma will become very complex, experiments of plasma antenna in this paper are also made in the environment where there is no external magnetic field and the inductive magnetic field is ignored.

In the reconfigurable experiments of the plasma antenna, while parameters of plasma antenna need to be changed simultaneously, so the impedance matching of the plasma antenna system is very important. The key point in the realization of plasma elements to be used as plasma antennas is the ignition of the plasma column: the pump signal network has to be optimized in order to obtain the highest plasma conductivity with the lowest power at the same time; the realization of the feeding network must not degrade the antenna radiating properties. We adopted the automatic impedance matching equipment in the experiments to ensure the impedance of plasma antenna in real time and it can realize the impedance matching of plasma antenna in one second or one second and a half and this impedance equipment makes related experiments easy to be carried out. And the coupling method of the plasma antenna is shown as Fig.3.
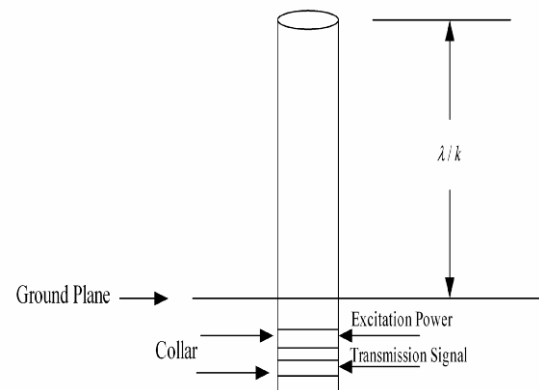

Fig.3. Coupling arrangements of the plasma antenna

2.2 Reconfigurable Characteristics of the Working Frequency

When the state of plasma is steady, the energy that per unit of plasma absorbs from the surface wave is equal to the energy loss from absorption, migration and compounding of electrons in the plasma [9].

$$n_0 \approx A(p)\sqrt{p_0} \qquad (1)$$

$$A(p) \approx \sqrt{\frac{2CV_m(p)}{k(p)}} \qquad (2)$$

The equations (1),(2) represent the relationships between the plasma density, gas pressure and the

collision frequency, respectively. From the equations above mentioned, it can be found that the numerical value of plasma density is related with the gas pressure p, $A(p)$ is a constant under certain inner pressure of the tube, C denotes the coefficient which is related to the specific experimental structure, the coefficient $k(p)$ represents the power loss of electron when the plasma pressure is p, and the V_m represents the collision frequency of electron and neutral particles in plasma [10]. When inner pressures of plasma antenna and excitation power are the constant, the plasma density is directly proportional to the square root of RF power. As the Fig. 4 shows, in the experiments we adopted plasma antenna with the different radius and different inner pressure. The radius of the plasma antenna ranges from 2.5cm to 1.2cm and inner pressure of the plasma antenna ranges from 5pa to 150pa in the experiments.
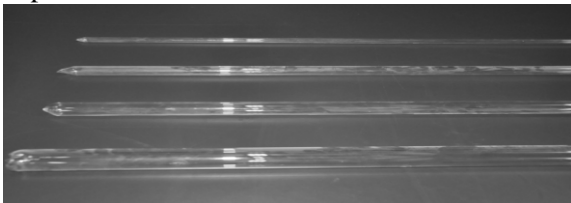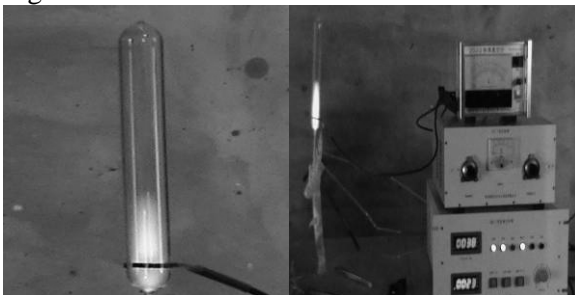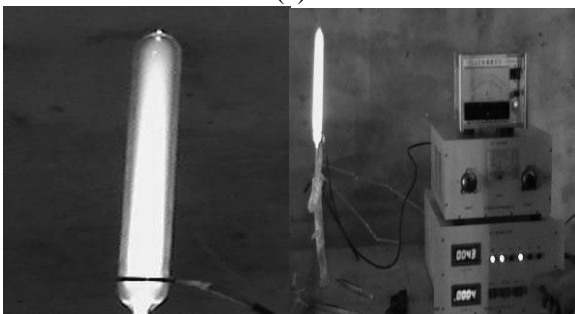

Fig.4. Plasma antennas with different radius

(a)

(b)

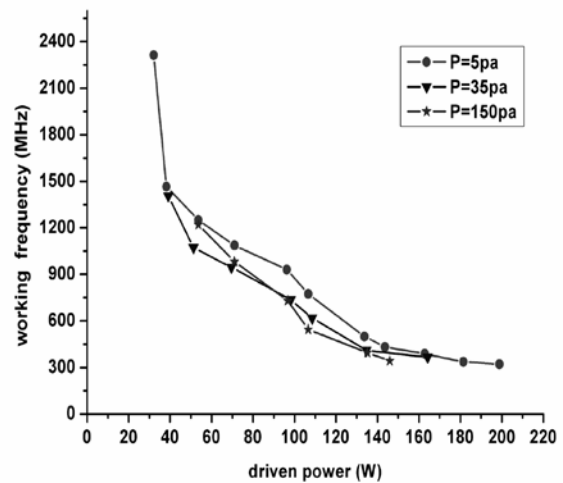Fig.5. (a) Plasma antenna when driven power is 15w, (b) Plasma antenna when driven power is 39w.

Fig.6.Relationships between the driven power and the working frequency with different inner pressure
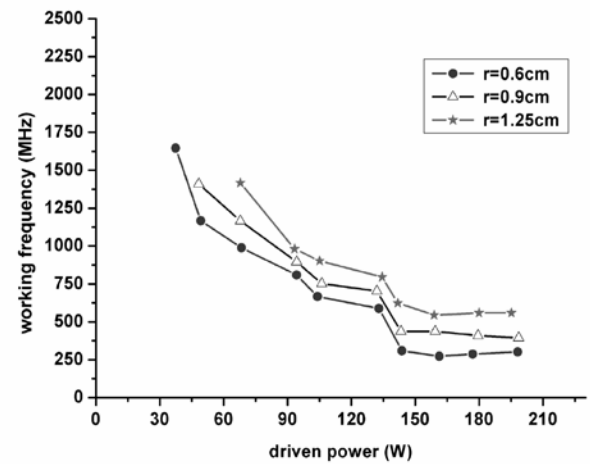

Fig.7. Relationships between the driven power and the working frequency with different radius of the antenna

It is known that the working frequency and the radiation efficiency of the plasma antenna are strongly affected by the resonance length of the plasma antenna according to the antenna theory. And relationships between the resonance length of plasma antenna and external excitation power in certain conditions have been discussed in papers [2-4].In the experiment shown as Fig.5, when the excited power is strengthened from the 30W to 200W, the working frequency of the plasma antenna is changed from 2400MHz to 280MHz as Fig. 6 illustrated, and the inner pressure of the plasma antenna is changed from 5pa to150pa, from the Fig. 7, we can find that the ranges of the working frequency are reduced with the increase of inner pressure of plasma antenna.

The relationship between the external excited power, inner pressure and the working frequency

when the radius of tube is 1.2cm which are illustrated as Fig. 6, when the strength of excitation power is changed from 30W to 200W, and the working frequency of plasma antenna is from 1750MHz to 250MHz, with increase of the radius of plasma antenna, the range of working frequency is reduced accordingly. So from the results of related experiments in monopole plasma antenna if we want to get a large reconfigurable range of working frequency, the radius of plasma antenna should be small and the inner pressure of it should be low.

2.3 Reconfigurable Characteristics of Radiation Pattern

As the composition of gas, radius, and pressure of plasma antenna can not be changed if the plasma antenna has been produced and these parameters only can be changed in the producing process of the plasma antenna. Numerical calculations results demonstrate that when the excitation power is small, plasma density is not high; the reconfigurable properties of radiation pattern are unobvious. The experimental results show that if the plasma density is increased, the radiation pattern will be changed apparently with the increase of plasma density and excitation power. As it is known that the dispersion relationships of the plasma are very complicated and the related research has been investigated in our paper [24, 25]. Analyses of reconfigurable characteristics of the radiation pattern are made under a certain known dispersion relationship. From the theory of antenna, when the propagation signals are coupled in the middle of plasma antenna, plasma antenna can be regarded as center–fed dipole antenna, if the surface current of plasma antenna presents the sinusoid distribution approximately, the center point can be regarded as the zero point, and the symmetry axis is the z axis which are schematically indicated in Fig. 8.
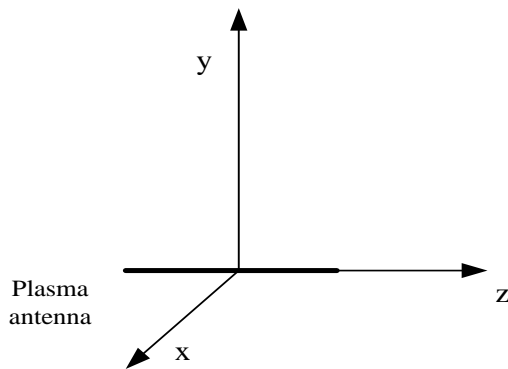

Fig.8. Coordinate system of the plasma antenna
The surface current of the antenna can be expressed as (3).

$$\begin{cases} I = j_z = I_0 \sin(k(L/2 + z)e^{j\omega t} & z < 0 \\ I = j_z = I_0 \sin(k(L/2 - z)e^{j\omega t} & z > 0 \end{cases} \qquad (3)$$

In the cylindrical coordinate system, the electrical field of the plasma antenna can be written as (4).

$$E_\theta = \int_0^l i \frac{\eta_0 k_0 I(z)}{4\pi r} \sin(\theta) e^{-ik_0 r} e^{ik_0 z \cos(\theta)} dz \qquad (4)$$

When the plasma antenna works in the traveling-wave mode, the surface current of it can be expressed as (5).

$$I = j_z = I_0 e^{-i(kz - \omega t)} \qquad (5)$$

Where ω represents the frequency of the signal, if the amplitude of current is independent on the wave vector k, i.e., when the value of k is changed, the amplitude change of the current can be neglected, then the electrical field can be obtained through (6),

$$E_\theta = i \frac{\eta_0 k_0 I_0}{4\pi r} e^{i\omega t} e^{-ik_0} \sin(\theta) \frac{e^{il(k_0 \cos(\theta) - k)} - 1}{k_0 \cos(\theta) - k} \qquad (6).$$

The un-normalized direction function of E_θ is expressed as (7), in the traveling-wave mode, the radiation pattern will be changed with different value of $n = k/k_0$, here k represents wave vector, and $k_0 = \omega/c$, $c = 3 \times 10^8 m/s$, It can be found that with changing of n, the radiation pattern and the number of wave beam of the plasma antenna will be changed accordingly. When $n = k/k_0$, the $f(\theta)$ can be expressed as (8).

$$f(\theta) = \left| \sin(\theta) \frac{e^{il(k_0 \cos(\theta) - k)} - 1}{k_0 \cos(\theta) - k} \right|$$

$$= \left| \sin(\theta) \frac{\sin(\frac{k_0 l \cos(\theta) - kl}{2})}{k_0 \cos(\theta) - k} \right| \qquad (7)$$

$$f(\theta) = \left| \frac{\sin(\theta) \sin(\frac{k_0 l}{2}(n - \cos(\theta)))}{n - \cos(\theta)} \right| \qquad (8)$$

The un-normalized direction function of the E_θ of the plasma antenna then can be written as below,

$$f(\theta) = \left| \int_{-L/2}^{0} \sin(\theta) \times \sin(k(L/2+z))e^{ik_0 z \cos(\theta)} dz \right| +$$
$$\left| \int_{0}^{L/2} \sin(\theta) \times \sin(k(L/2-z))e^{ik_0 z \cos(\theta)} dz \right| \quad (9)$$

as the plasma antenna is driven by surface wave, from the dispersive relationships of plasma, the wave vector $k = k_r + k_i$ can be obtained. If the item of $2/k_0$ is neglected, the (10) can be obtained.

$$f(\theta) = \left| \frac{n \times \sin(\theta)}{n^2 - \cos^2(\theta)} (\cos(\frac{k_0 l \cos(\theta)}{2}) - \cos(\frac{n k_0 l}{2})) \right| \quad (10)$$

It can be found that the effects of $n - \cos(\theta)$ and $\cos(\theta)$ on the $f(\theta)$ becomes weaker with increasing of the value of n, $f(\theta)$ then can be simplified written as (11),

$$f(\theta) = \left| \sin(\theta) \sin(\frac{k_0 l}{2} n) \right| \quad (11).$$

From equation (11) we see that it is a periodic function, the cycle is $2\pi/k_0 l$, $f(\theta)$ presents the periodic change with changing of the n .In the metallic medium ($n=1$) and other medium ($n \neq 1$), the values of are unchangeable. But in the plasma antenna, because the value n is not a constant, so if the density of plasma is changed, the value of n will be changed accordingly, which leads to the variation of radiation efficiency. From the (a)(b)(c)(d) of Fig. 9, it can be seen that with the increase of value of n, the right lobe of radiation pattern becomes larger ,if the value of n changes continuously, the radiation pattern will present periodic changing .
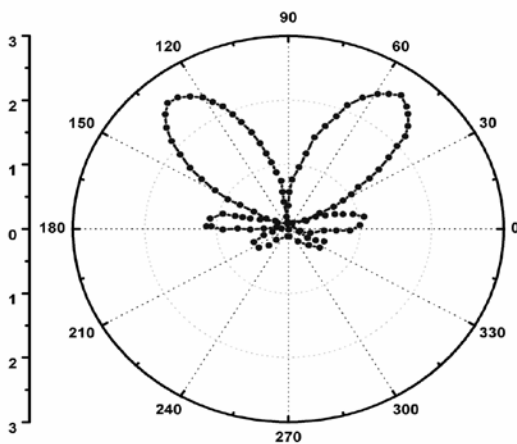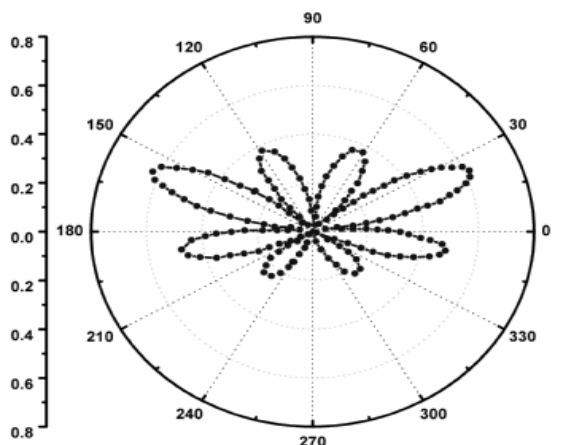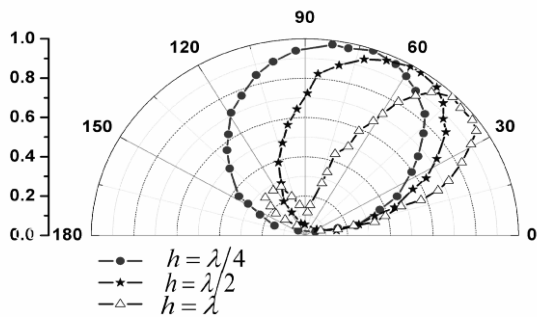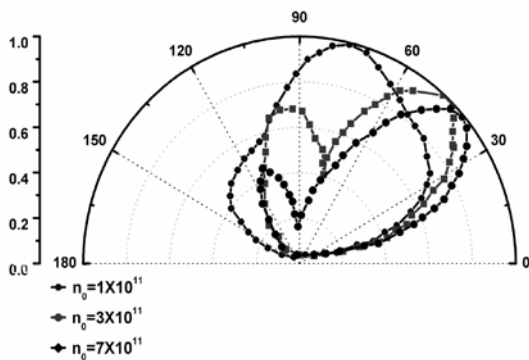

(a) n=1
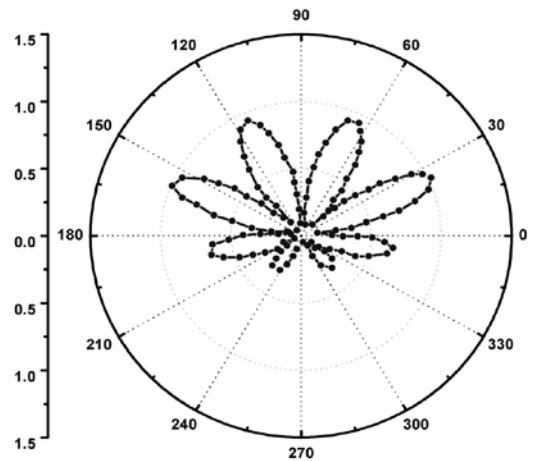
(b) n=1.3
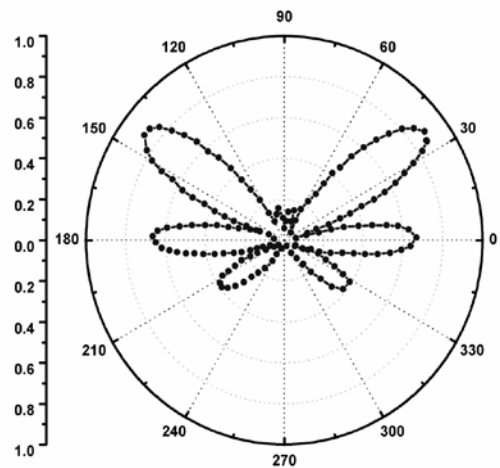
(c) n=1.5

(d) n=1.7

Fig.9. Radiation pattern of the plasma antenna with different n

When the resonance length of the plasma antenna and the density of the plasma antenna are different, radiation patterns of the plasma antenna

also show many differences, which are presented as the (a) (b) of the Fig.10. So the reconfigurable characteristics of the plasma antenna can be realized through changing the density of plasma and its effective length. The collision frequency of plasma antenna is anther important influence factor on the radiation pattern indicated as the Fig.11, the reconfigurable characteristics of plasma antenna are affected by many factors, and we should take all these factors into consideration in the application of reconfigurable characteristics of plasma antenna.

(a)

(b)

Fig.10. Radiation pattern of the plasma antenna with different density of the plasma
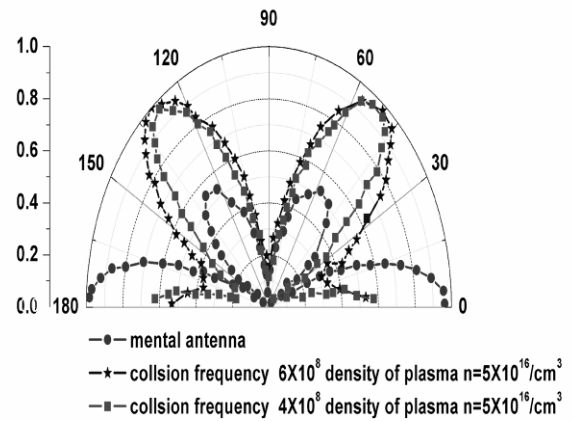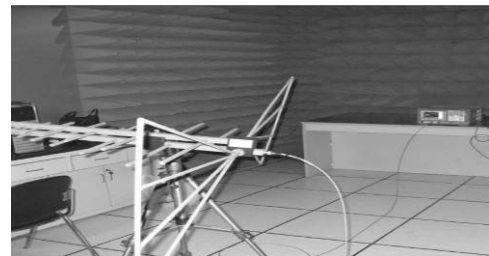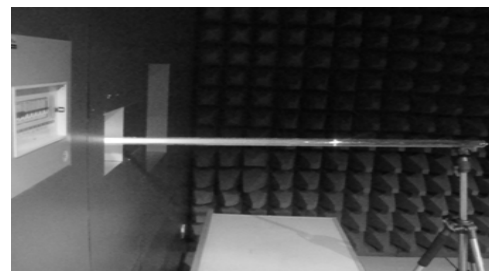

Fig.11. Radiation pattern of the plasma antenna with different density and collision frequency
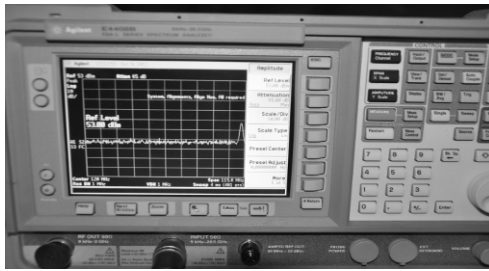

(a)

(b)

(c)

(d)

(e)

(f)

Fig.12.Experiment photos of the plasma antenna

In the reconfigurable experiments of the working frequency, with changing of the driven power which ignites the plasma antenna, the frequency of propagation signal will also be changed accordingly as illustrated in Fig. 12, photo (a) is a metallic antenna which is performed as received antenna and it is connected with the spectrum analyzer; photo (b) is the plasma antenna which is behaved as transmitting antenna, photo (c) (d) (f) are the received signals of different frequency which are shown in spectrum analyzer, photo (e) is the spectrum analyzer receives signals with the existence of interference signals in the environment. When the plasma antenna is not be excited, the plasma antenna has no propagation ability of the RF signals, as (c) of Fig.12 indicates , the signals received by mental antenna are the noise signals of environment, While the plasma antenna is ignited, the mental antenna received the signal simultaneously as (d) Fig 12 shows.

The propagation signal is produced by Agilent signal source, and amplitude of it is set in 10dBm,

when driven power is changed, the length of the plasma antenna and density of the plasma antenna will be changed accordingly, so the radiation efficiency of the plasma antenna is changed simultaneously as (f) of Fig.12 shows, different positions of signal in the spectrum analyzer screen denote the different frequency of signal. From the results of experiments, we can see that the plasma antenna nearly has the same capability of propagation different frequency signals. With the jamming signals of different frequency existing, the working frequency of plasma can be reconfigured to the frequency band where the interference signals are absence through some controlling strategies.

3 Reconfigurable Characteristic of Plasma Antenna Array

As known that reconfigurable characteristics of the mental antenna can be realized through the metallic antenna array, many mental antenna units are arranged in certain method thus form the antenna array called the phased array antenna. The phase array antenna has strong reconfigurable ability, but it need to be designed and controlled precisely and properly. There many forms of antenna array e.g., the line arrays, plane arrays, and circle arrays, etc.

In the paper we investigate the monopole plasma antenna circle arrays, each of the monopole plasma antenna are located in same distance around the circle, if parameters of one plasma element of the plasma array are changed, the parameters of the plasma antenna array may be changed apparently, thus the reconfigurable characteristics of the plasma antenna array can be realized through changing physical states of one or more plasma elements of the antenna array. In the paper we adopt the commercial software CST Microwave Studio to simulate electromagnetic field behavior of the plasma antenna array.

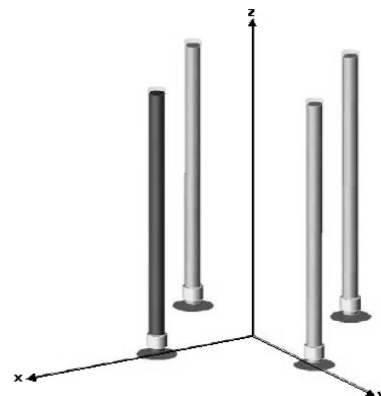## 3.1 Four-element plasma antenna array
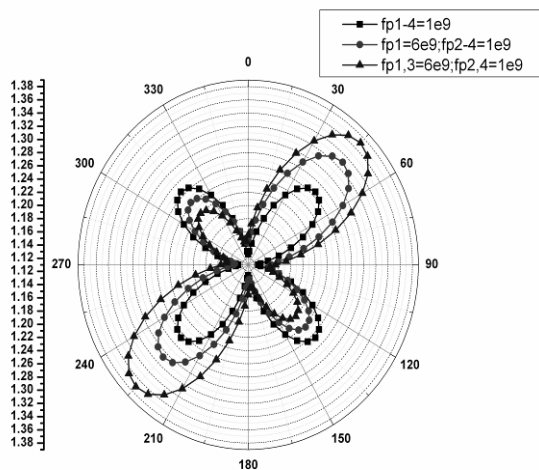
Fig.13. Four-element plasma antenna array

Fig.14. Radiation pattern of four-element plasma antenna array

The plasma antenna has many unique characteristics; the radiation pattern of it can be reconfigured in 360 degrees of the azimuth angle, as the plasma antenna can be ignited very quickly, so the radiation pattern of the plasma antenna can be reconfigured with very high speed. In the four-element plasma array shown as Fig.13, the simulations are made under assumptions below:

(1) The frequency of plasma elements are both set at $1GHz$ and the collision frequency of them are at 150MHz.

(2) The plasma frequency of element in azimuth angle $\Phi = 0°$ is $6GHz$, and plasma frequencies of other three antenna elements are not changed.

(3) The frequency of elements in azimuth angle $\Phi = 0°$, $\Phi = 180°$ are $6GHz$, and plasma frequency of other two plasma elements are not changed.

The radiation patterns of the plasma array under these assumptions are shown as Fig.14, it can be found that with changing of the plasma frequency in certain angles, the radiation pattern will be strengthened in the certain direction thus the plasma array can be reconfigured through the method.
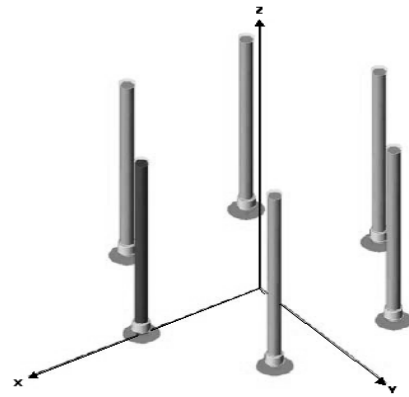
3.2 Six-element plasma antenna array

Fig.15. Six-element plasma antenna array

In the reconfigurable characteristic analysis of the six-element plasma antenna array shown as Fig.15, the simulation assumptions are as follows:

(1)The frequency of the elements of plasma array is $1GHz$.

(2)The frequency of the plasma element azimuth angle $\Phi = 0°$ is $3GHz$, and frequency of other five elements in the array is $1GHz$.

(3)The frequency of the plasma element azimuth angle $\Phi = 0°$ is $6GHz$, and frequency of other five elements is $1GHz$.
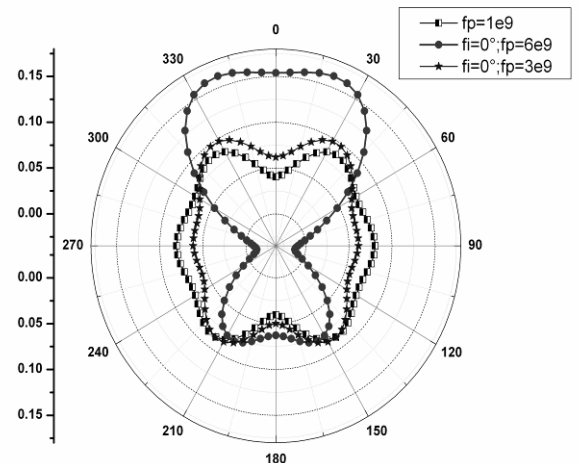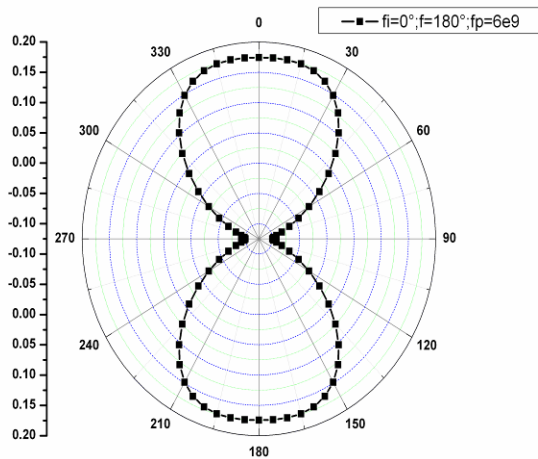

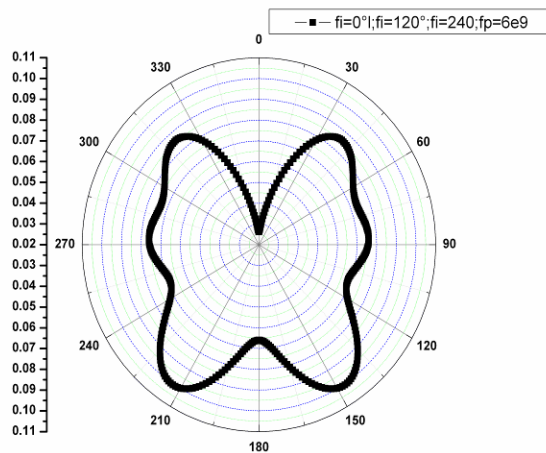**Fig.16.** Radiation pattern of six-element plasma antenna array

From the simulation results we can find that the six-element plasma antenna is nearly an Omni-directional antenna as shown in Fig.16, with increasing of the frequency in azimuth angle $\Phi = 0°$, the radiation pattern is strengthened apparently in this direction, and the radiation pattern is also

changed obviously, so we can adopt the method of controlling frequency of the plasma to change radiation properties of plasma array.

As shown in the (a),(b) of Fig.17, the multi-wave in radiation pattern also can be achieved through methods mentioned above.

(a)

(b)

Fig. 17. Multi-beam in radiation pattern of six-element plasma antenna array

3.3 Eight-element plasma antenna array

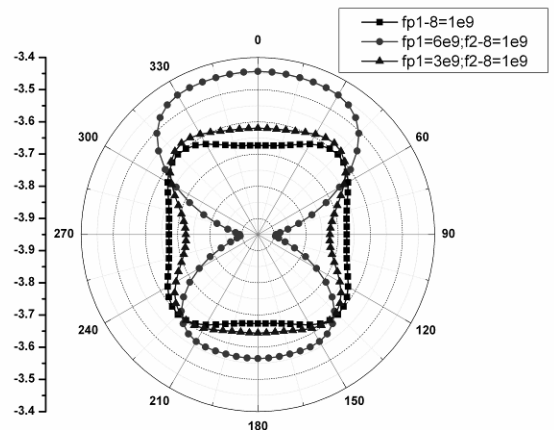Fig.18.Radiation pattern eight-element plasma antenna array

Fig.19.Radiation pattern of eight-element plasma antenna array

The eight-element plasma array is shown as Fig.18, simulation methods are the same as the one of four-element and six-element plasma array. From the Fig.19, we can find that the scanning ability of plasma antenna array in far-field can be realized through changing plasma frequency, as the plasma array has many elements, so there will be more choices of the angle in the radiation pattern. Elements of the plasma antenna array is increased to eight, the radiation ability of plasma antenna array also will be stronger than four-element and six-element plasma antenna array, the gain of plasma antenna will be also improved obviously. The eight-element radiation pattern also has more angle choices than the four-element and six-element plasma antenna array. It can form the multiple beams in the radiation pattern as Fig.20 shows.
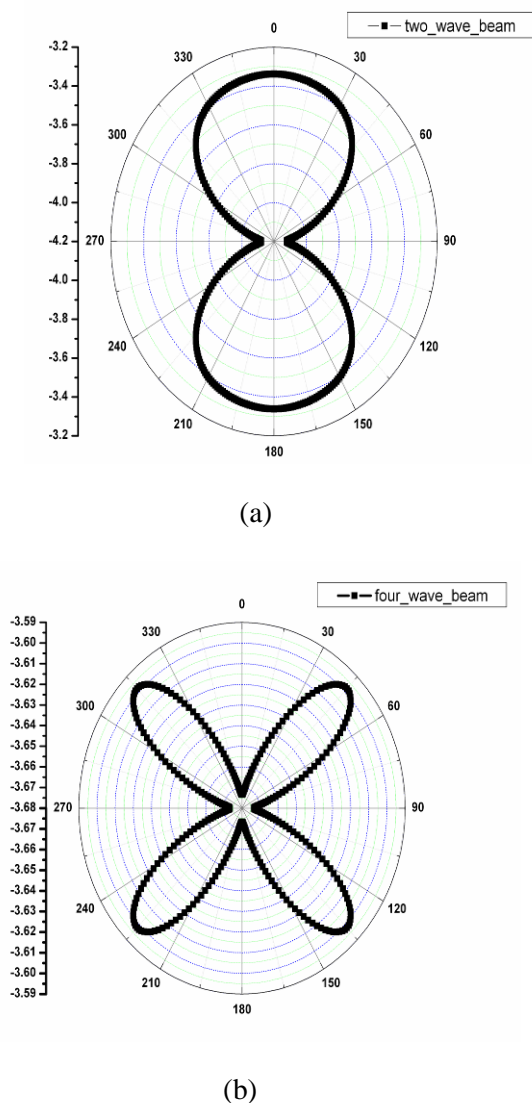
(a)

(b)

Fig.20.Multi-beam in radiation pattern of eight-element plasma antenna array

The research and analysis of the monopole plasma antenna demonstrate that changing of parameters of plasma antenna can lead to changing of radiation pattern and gain of it. The gain of plasma antenna array in certain directions can be promoted by changing the related physical parameters of plasma; the radiation pattern of plasma antenna array also can scan at very high speed and functions of multi-beam antenna also can be performed by the plasma antenna array. So the plasma antenna array has broad applications in the communication e.g., radar and aeronautic field etc, and more reconfigurable investigation should also be carried out in the future research.

4 Conclusion

The reconfigurable characteristic of the monopole plasma antenna and its array are analyzed through the experiments and the simulations. The reconfigurable results of the working frequency and the radiation pattern of the monopole plasma antenna are obtained, the reconfigurable characteristic of the four-element, six-element and eight-element of the plasma antenna array are analyzed. The experiments and research results of the paper are useful to the further application of plasma antenna and its array.

Acknowledgement

References:

[1] WANG Shi-qing, XIANG Qian, LIU Jian, "Conductivity and Excitation of Surface Wave Plasma Column," Journal of Applied Sciences, 2009,04,015.
[2] CHEN Zong-sheng,SHI Jia-ming,WANG Jia-yin,YUAN Zhong-cai, "Research on Parameters of the Plasma Column Source for the Surface Wave Plasma Antenna," Vacuum Electronics, 02(009),2008.
[3] Rayner John Phillip, Whichello Adrian Phili. "Physical characteristics of plasma antennas", IEEE Transactions on Plasma Science, Vol.32 (1), 2004,pp269～281.
[4] G. G. Borg, J. H. Harris, D. G. Miljak, and N. M. Martin, "Application of plasma columns to radiofrequency antennas," Appl. Phys. Lett., vol.74, May 1999,pp. 3272–3274.
[5] G. G. Borg, J. H. Harris, N. M. Martin, D. Thorncraft, R. Milliken, D. G.Miljak, B. Kwan, T. Ng, and J. Kircher, "Plasmas as antennas Theory, experiment and applications," Phys. Plasmas, vol. 7, July 200,pp. 2198–2202.
[6] Zhao Guo-Wei,Xu Yue-Min，Chen Cheng，"Calculation of dispersion relation and radiation pattern of plasma antenna," Acta Physica Sinica, 09(051),2007.
[7] Zhao Guo-Wei，Wang Zhi-Jiang，Xu Yue-Min，Liang Zhi-Wei，Xu Jie "Numerical simulation of plasma nonlinear phenomena driven by radio-frequency wave using FDTD method," Acta Physica Sinica, ,09(052), 2007.
[8] LI Sheng, "Theoretical analysis of Characteristics of Plasma Antennas droven by Surface Wave," Journal of Nanhua University Science and Technology, 02(008),2007.

[9] Hargreave M., Rayner J.P., Cheetham A.D., et al. Coupling power and information to a plasma antenna [A]. In: International Congress on Plasma Physics . Sydney, Australia: Australian Institute of Physics, 2003: 388-391.

[10] Rayner J.P., Whichello A.P., Cheetham A.D. Physical characteristics of a plasma antenna. 11th International Congress on Plasma Physics. Sydney, Australia: American Institute of Physics, 2003: 392-395.

[11] Rayner J.P., Whichello A.P., Cheetham A.D. Physical characteristics of plasma antennas[J]. IEEE Transactions on Plasma Science, 2004, 32 (1): 269-281.

[12] Whichello A.P., Rayner J.P., Cheetham A.D. Plasma antenna radiation patterns . In:11th International Congress on Plasma Physics . Sydney, Australia: American Institute of Physics, 2003: 396-399.

[13] Shokri B., Niknam A.R. Field profiles of symmetric surface waves in diffusion-controlled regime of a non-isothermal plasma columns . Plasma Physics and Controlled Fusion, 2005, 47 (10): 1805-1816.

[14] Volodin K.S., Minaev I.M., Rukhadze A.A., et al. Plasma control of the directional pattern of a multislot waveguide antenna . Plasma Physics Reports, 2009, 35 (1):50-53.

[15] Kumar R., Bora D. A ReconFig.urable Plasma Antenna. Journal of Applied Physics,2010, 107 (5): 1-9.

[16] J.Manzanares-Martinez Analytic Expression for the Effective Plasma Frequency RE in One-Dimensional Metallic-Dielectric Photonic Crystal. Progress In Electromagnetic Research M, Vol. 13, 189-202, 2010.

[17] C. S. GÄurel, E. ÄOncÄu Characteristic of Electromagnetic Wave Propagation through A Magnetized Plasma Slab With Linearly Varying Electron Density. Progress In Electromagnetics Research B, Vol. 21, 385-398, 2010.

[18] R. S. Pandey R. P. Pandey, K. M. Singh, and N. M. Mishra Cold Plasma Injection on VLF Wave Mode For Relativistic Magneto Plasma With A.C. Electric Field.Progress In Electromagnetics Research C, Vol. 2, 217–232, 2008.

[19] Z. H. Qian and R. S., Chen K. W. Leung H. W. Yang FDTD Analysis of Microstrip Patch Antenna Covered by Plasma Sheath.Progress In Electromagnetics Research, PIER 52, 173–183, 2005.

[20] A. V. Kudrin and E. Yu. Petrov G. A. Kyriacou T. M. Zaboronkova Insulated Cylindrical Antenna in a Cold .Magneto plasma Progress In Electromagnetics Research, PIER 53, 135–166, 2005.

[21] R. Otin ,Numerical Study of the Thermal Effects Induced by a RFID Antenna in Vials of Blood Plasma. Progress In Electromagnetics Research Letters, Vol. 22, 129-138, 2011.

[22] G. V. Jandieri A. Ishimaru N. N. Zhukova, T. N. Bzhalava, and M. R. Diasamidze On the Influence of Fluctuations of the Direction of an External Magnetic Field on Phase and Amplitude Correlation Functions of Scattered Radiation by Magnetized Plasma Slab. Progress In Electromagnetic Research B, Vol. 22, 121-143, 2010.

[23] V. Kumar , M. Mishra, and N. K. Joshi. Study of a Fluorescent Tube as Plasma Antenna Progress In Electromagnetic Research Letters, Vol. 24, 17-26, 2011.

[24] Junwei Lv, ZiliChen, Yingsong Li. Two-Dimensional Models of the cylindrical monopole plasma antenna excited by the surface wave ,WSEAS Transactions on Communications,Issue11,Volume10,November, 2011.

[25] Junwei Lv, ZiliChen, Yingsong Li. A Self-Consistent Model on Cylindrical Monopole Plasma Antenna Excited by Surface Wave Based on the Maxwell-Boltzmann Equation, Journal of Electromagnetic Application and Analysis, Vol.3,No.8, August,2011.