Effects of DC Discharge Type on Plasma Collisional Absorption of Electromagnetic-Wave

Runhui Wu, Shengjun Zhang, Jiaqi Liu, Aimin Ren, Gang Meng, and Hongyan Liu

***Abstract*—In this paper, the collisional absorption mechanism of electromagnetic-wave in plasma for DC discharge type is studied with numerical method. The computation model of the electromagnetic-wave collisional absorption in the DC discharge plasma is founded. The FDTD method is presented for simulating the collisional absorption of electromagnetic-wave energy in the one-dimensional inhomogeneous plasma by DC discharge generator. The emulational results illustrate that the inhomogeneous plasma electron density which is produced by DC discharge around the opening space could be approximate to 1014-1015cm-3, and the plasma can absorb the energy of electromagnetic-wave in the wide bandwidth by collisional absorption.**

***Index Terms*—Plasma, DC discharge, electromagnetic-wave, collisional absorption.**

I. Introduction

As one of the important factors in electromagnetic energy attenuation researchers have conducted many theory and experimental works in the Electromagnetic-wave collision absorption effect in plasma. The physical and mathematic model of the Electromagnetic-wave collision absorption in the homogeneous and inhomogeneous plasma is developed by D.J.Gregolre etc. [1], ShuGuo Xie [2] studies the effects of the plasma parameter on the Electromagnetic-wave absorption and reflection in the inhomogeneous plasma on the PEC plane. FaLun Song [3] gives the numerical analysis of the Electromagnetic-wave propagation in the weakly ionized plasma with strong collision. The relationship among the plasma density collision frequency Electromagnetic-wave frequency and collision absorption in the inhomogeneous unmagnetized plasma is committed by Ping Wu[4]. FuHua Zeng [5]-[6] studied the factors that affect the plasma absorption technology and proposed the optimal scheme in the stealth application.

The results of the above suggest the absorbant of Electromagnetic-wave in plasma theoretically but few of them reported about the Electromagnetic-wave absorption in the inhomogeneous plasma generated by the plasma generator. In this paper, the Electromagnetic-wave collision absorption character in the plasma generated by the DC discharge plasma generator in the frequency band between 0.4GHz and 12GHz was analyzed. The FDTD method is used in the simulation of wideband absorption in the inhomogeneous plasma. The results are obtained from the simulation analysis.

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II. Propagation Character of Electromagnetic-Waves in Plasma

According to the relation between Electromagnetic-wave and the plasma could be categorized into three aspects [7].

When the plasma frequency is larger than wave frequency, the Electromagnetic-wave could not propagate in the plasma.

When the plasma frequency is less than wave frequency, the Electromagnetic-wave could propagate in the plasma.

When the plasma frequency is equal to the wave frequency, the Electromagnetic-wave would be fully reflected on the boundary, and the energy would be mostly absorbed. the cutoff density of corresponding plasma is:

$$n_{ec} = 1.23 \times 10^{10} f^2 \quad (1)$$

where n_{ec} unit is cm^{-3}, f is the Electromagnetic-wave frequency ,and its unit is GHz.

III. Principle of the Plasma Generation

The common method to acquire plasma is gas discharge [8]-[9] such as DC discharge, AC discharge, RF discharge, electromagnetic-wave discharge and ECR discharge etc. The supersonic expansion DC discharge principle of generating plasma in open space is discussed in this paper.

Using the DC discharge scheme, the principle of generating the supersonic expansion plasma in opening vacuum is illustrated in Fig. 1. The basic components include DC power source, cathode, anode, working gas filling area and working gas discharge area. In the vacuum space, the DC discharge power source is connected with cathode and anode of generation respectively .The ionized plasma goes through the supersonic channel and form the inhomogeneous plasma area. In this scheme, the factors that affect the plasma electron density(its symbol is "n_e"), collision frequency(its symbol is "v_{en}") and spatial size(its symbol is "L") include the degree of ionization(its symbol is "*alfa*"), working gas flux(its symbol is "G") and the power of the discharge power source. The generated plasma has the characteristics of supersonic expansion and large size. The distributions in three-dimensional space are all inhomogeneous. With the specific working gas, larger electron density requires larger degree of ionization and working gas flow. The maximum plasma electron density at the nozzle could reach to $10^{14}cm^{-3} \sim 10^{15}cm^{-3}$ and it will attenuate with the distance from the nozzle.

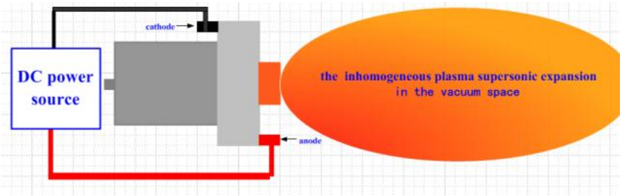

Fig. 1. DC discharge of the vacuum opening space

IV. Electromagnetic-Wave Collision Absorption Model in Plasma

A. Mathematical Model of the Electromagnetic-Wave Collision Absorption in Plasma

For the inhomogeneous plasma with specific spatial size, if the Electromagnetic-wave with power *Pi* propagates in the plasma to the location denoted as *Z* the Electromagnetic-wave power at *Z* due to the collision absorption is calculated as [7]:

$$P(Z) = P_i e^{-2\alpha Z} \tag{2}$$

where α represents the attenuation coefficient due to the energy absorption caused by the particle collision in plasma. It is determined by the Electromagnetic-wave frequency, angular frequency of the plasma and the collision frequency of the plasma [7]:

$$\alpha(z) = \frac{\omega}{c}\left\{-\frac{1}{2}\left[1-\frac{\omega_p(z)^2}{\omega^2+v(z)^2}\right]+\frac{1}{2}\left[\left(1-\frac{\omega_p(z)^2}{\omega^2+v(z)^2}\right)^2+\left(\frac{\omega_p(z)^2}{\omega^2+v(z)^2}\frac{v(z)}{\omega}\right)^2\right]^{\frac{1}{2}}\right\}^{\frac{1}{2}} \tag{3}$$

where *c* is the speed of light, ω is the angular frequency of the incident Electromagnetic-wave, $\omega_p(z)$ is the angular frequency of the plasma in the specific location, *v(z)* is the plasma collision frequency in the specific location. The angular frequency of the plasma has the connection with the plasma electron density $n_e(z)$ [10]:

$$\omega_p(z) = \sqrt{\frac{n_e(z)e^2}{m_e \varepsilon_0}} \tag{4}$$

where ε_0 is the permittivity in free space, me is the mass of the electron, e is the electric quality of the electron.

The plasma collision frequency should include the collision between electron and ion, electron and neutral particle. For the collision between the electron and ion, the coulomb collision model is taken to calculate the collision frequency [11]:

where N_i and *Z* are the ion density and the number of ion charge; m_e, e and T_e are the mass of the electron, electron charge and the temperature of the electron; $\ln\Lambda$ is the logarithm of the coulomb.

$$\nu_{ei} = \frac{4\sqrt{2\pi}}{3} N_i \left(\frac{Ze^2}{kT_e}\right)^2 \left(\frac{kT_e}{m_e}\right)^{\frac{1}{2}} \ln\wedge \tag{5}$$

As for the collision between electron and neutral particle, the collision frequency is calculated as [11]:

$$\nu_{en} = \langle \sigma v \rangle \mathrm{N_m} \tag{6}$$

where $\langle \sigma v \rangle$ is the effective collision speed coefficient, N_m is the neutral particle density.

The total collision frequency of the plasma is calculated by the combination of Equation (5) and Equation (6):

$$\nu_{en}{}^{t} = \nu_{ei} + \nu_{en} \tag{7}$$

B. FDTD Model of the Electromagnetic-Wave Propagation in One Dimensional Plasma

In one dimensional case assuming the electromagnetic-wave propagates along the z-axis(illustrates in Fig. 2), the medium parameter and the field has no connection with *x*, *y* components, hence the Maxwell equations could be interpreted as [12]:

$$\begin{cases} -\dfrac{\partial \mathrm{H_y}}{\partial \mathrm{z}} = \varepsilon \dfrac{\partial \mathrm{E_x}}{\partial \mathrm{t}} + \sigma \mathrm{E_x} \\ \dfrac{\partial \mathrm{E_X}}{\partial \mathrm{z}} = -\mu \dfrac{\partial \mathrm{H_y}}{\partial \mathrm{t}} - \sigma_{\mathrm{m}} \mathrm{H_y} \end{cases} \tag{8}$$

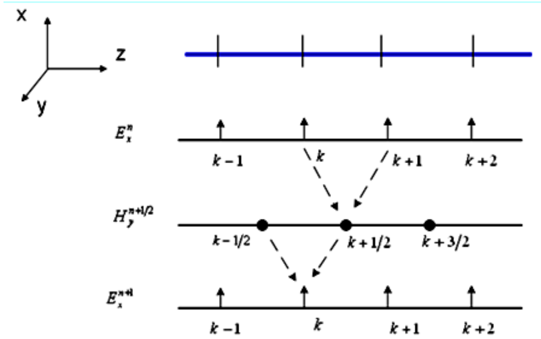

Fig. 2. The Electromagnetic-wave propagation in one dimensional plasma

Fig. 2 illustrates the sample method of *E*, *H* components in space and time axis. The FDTD discretization of equation (8) is:

$$E_x^{n+1}(k) = \mathrm{CA}(m)E_x^n(k) - \mathrm{CB}(m)\left[\frac{H_y^{n+1/2}(k+\frac{1}{2}) - H_y^{n+1/2}(k-\frac{1}{2})}{\Delta z}\right] \tag{9}$$

$$H_y^{n+1}(k+\frac{1}{2}) = \mathrm{CP}(m)H_y^{n-1/2}(k+\frac{1}{2}) - \mathrm{CQ}(m)\left[\frac{E_x^n(k+1) - E_x^n(k)}{\Delta z}\right] \tag{10}$$

where CA(*m*), CB(*m*) , CP(*m*) and CQ(*m*) are:

$$CA(m) = \frac{1 - \dfrac{\sigma(m)\Delta t}{2\varepsilon(m)}}{1 + \dfrac{\sigma(m)\Delta t}{2\varepsilon(m)}} \quad (11)$$

$$CB(m) = \frac{\dfrac{\Delta t}{\varepsilon(m)}}{1 + \dfrac{\sigma(m)\Delta t}{2\varepsilon(m)}} \quad (12)$$

$$CP(m) = \frac{1 - \dfrac{\sigma_m(m)\Delta t}{2\mu(m)}}{1 + \dfrac{\sigma_m(m)\Delta t}{2\mu(m)}} \quad (13)$$

$$CQ(m) = \frac{\dfrac{\Delta t}{\mu(m)}}{1 + \dfrac{\sigma_m(m)\Delta t}{2\mu(m)}} \quad (14)$$

Taking into account the equation (9)~(14), the reflection coefficient *R* and transmission coefficient *T* are calculated using:

$$R = 20\lg\frac{E_r}{E_i} \quad (15)$$

$$T = 20\lg\frac{E_t}{E_i} \quad (16)$$

In (15) and (16), E_i is the incident Electromagnetic-wave field, E_r is the reflected field, E_t is the transmitted field.

V. Results and Analysis of the Collision Absorption

A. Calculation Parameters

The plasma and Electromagnetic-wave parameters given by the DC discharge mode are listed in Table I.

TABLE I: The Plasma and Electromagnetic-Wave Parameters Given by the DC Discharge Mode

alfa	G(g/s)	n_e (cm^{-3})	v_{en}(Hz)	L (m)	f(GHz)
0.1	0.05	10^{14}–10^{7}	10^{12}–10^{5}	75	0.4–12
0.1	0.1	10^{14}–10^{7}	10^{12}–10^{5}	110	0.4–12
0.1	0.2	5×10^{14}–10^{7}	8×10^{12}–10^{5}	150	0.4–12
0.5	0.05	10^{15}–10^{7}	10^{13}–10^{5}	158	0.4–12
0.5	0.1	10^{15}–10^{7}	10^{13}–10^{5}	227	0.4–12
0.5	0.2	5×10^{15}–10^{7}	4×10^{13}–10^{5}	345	0.4–12

In Table I, alfa and *G* are the symbols of degree of ionization and gas flux for DC discharge plasma generator; n_e, v_{en} and *L* are the symbols of approximation electron density, approximation collision frequency and plasma scale for the DC discharge mode; *f* is the symbol of Electromagnetic-wave frequency.

B. Simulation Model of the Electromagnetic-Wave Energy Attenuation in One Dimensional Plasma

In Fig. 3, the simulation for the Electromagnetic-wave energy absorption in the plasma is demonstrated for the DC discharge model.

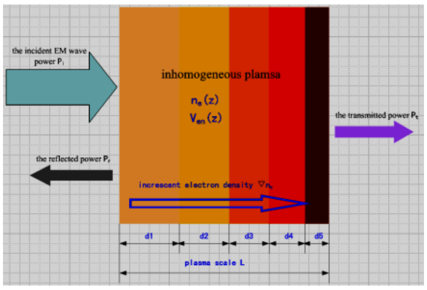

Fig. 3. The simulation model for the Electromagnetic-wave energy absorption in the DC discharge plasma

C. Results and Analysis

The results of DC discharge plasma diffusion and its collisional absorption for Electromagnetic-wave were obtained in Fig. 4 to Fig. 9 according to the parameters of Table I. All left figures, *x*-axis shows the distance between the plasma and the DC discharge plasma generator, *y*-axis shows the electron density(black line) and collision frequency (red line) results with the distance at *x*-axis. All right figures, *x*-axis shows the Electromagnetic-wave frequency, *y*-axis shows the change of the Electromagnetic-wave for the collisional absorption of the plasma by DC discharge generator.

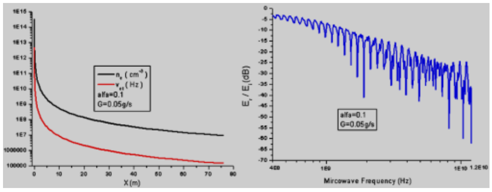

Fig. 4. DC discharge plasma diffusion(in the left figure ,alfa=0.1,G=0.05g/s) and the energy attenuation of Electromagnetic-wave(in the right figure) as the collisional absorption of plasma

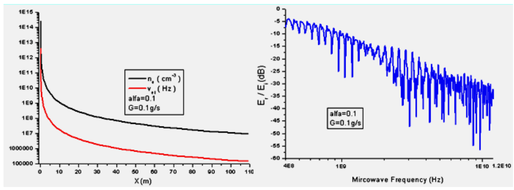

Fig. 5. DC discharge plasma diffusion(in the left figure ,alfa=0.1,G=0.1g/s) and the energy attenuation of Electromagnetic-wave(in the right figure) as the collisional absorption of plasma

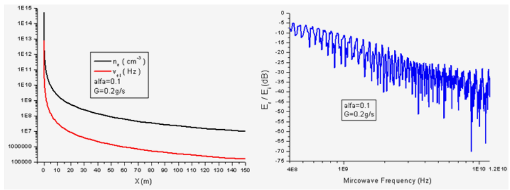

Fig. 6. DC discharge plasma diffusion(in the left figure ,alfa=0.1,G=0.2g/s) and the energy attenuation of Electromagnetic-wave(in the right figure) as the collisional absorption of plasma

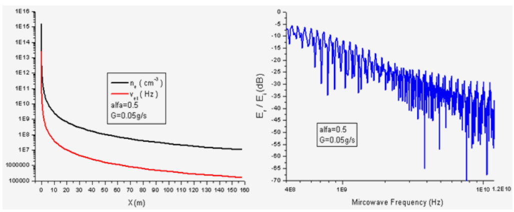

Fig. 7. DC discharge plasma diffusion(in the left figure ,alfa=0.5,G=0.05g/s) and the energy attenuation of Electromagnetic-wave(in the right figure) as the collisional absorption of plasma

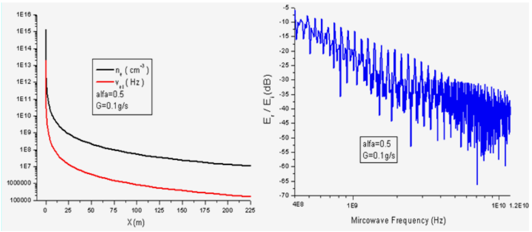

Fig. 8. DC discharge plasma diffusion(in the left figure ,alfa=0.5,G=0.1g/s) and the energy attenuation of Electromagnetic-wave(in the right figure) as the collisional absorption of plasma

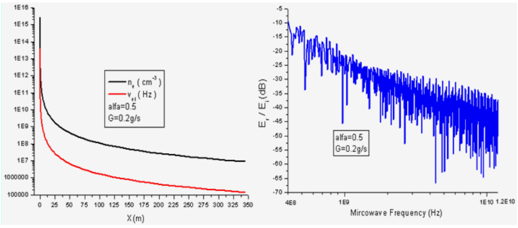

Fig. 9. DC discharge plasma diffusion(in the left figure ,alfa=0.5,G=0.2g/s) and the energy attenuation of Electromagnetic-wave(in the right figure) as the collisional absorption of plasma

The energy attenuation results of Electromagnetic-wave in the different parameters of plasma were illustrated in Table II.

TABLE II: THE DC DISCHARGE PLASMA GENERATOR PARAMETERS AND THE ENERGY ATTENUATION RESULTS OF ELECTROMAGNETIC-WAVE

alfa	G(g/s)	Electromagnetic -wave frequency(GHz)	the energy attenuation of Electromagnetic-wave E_r/E_i(dB)
0.1	0.05	0.4-12	4-35
0.1	0.1	0.4-12	6.5-40
0.1	0.2	0.4-12	8-43
0.5	0.05	0.4-12	10-45
0.5	0.1	0.4-12	12.5-47
0.5	0.2	0.4-12	17-50

Fig. 4 to Fig. 9 and Table II showed that the higher the degree of ionization the greater the energy attenuation of Electromagnetic-wave, and also the bigger the gas flux the greater the energy attenuation of Electromagnetic-wave.

VI. CONCLUSION

The Electromagnetic-wave collision absorption in plasma generated by DC discharge plasma generator of different parameters with frequencies from 0.4 to 12GHz is simulated and analyzed .It is shown that:

1) The max electron density of plasma that is produced by DC discharge plasma generator could be approximate to 10^{14}-$10^{15}cm^{-3}$ by designing the degree of ionization and the gas flux of plasma generator.
2) The inhomogeneous characteristic of DC discharge plasma generator made for the result that the Electromagnetic-wave energy was absorbed in the wide bandwidth.

The inhomogeneous plasma not only can absorb the energy of electromagnetic-wave but also can refract the incident Electromagnetic-wave. And the energy of Electromagnetic-wave will also be attenuated by the refraction of plasma.

REFERENCES

[1] D. J. Gregolre, J. Santoru, and R. W. Schumacher, “Electromagnetic-Wave Propagation in unmagnetized plasmas,” *AD-A250*, vol. 710, pp. 7-10.
[2] S.-G. Xie and D.-L. Lin, “Broadband Absorption of Electromagnetic-waves in Collisional Plasma,” *Journal of Telemetry Tracking and Command*, vol. 29, no. 5, September 2008, pp. 4-8.
[3] F.-L. Song, J.-X. Cao, and G.-A. Wang, “Model of the absorption of electromagnetic-waves by weakly ionized plasma and the numerical calculation,” *ACTA PHYSICA SINICA*, vol. 54, no. 2, February, 2005, pp. 807-810.
[4] P. Wu and S.-B. Liu, “The WKB Method of Plasma Stealth Technology,” *Journal of Natrual Science*, Nanchang University vol. 30, no. 4, August 2006, pp. 331-337.
[5] F.-H. Zeng and Z.-D. Liu, “Numerical Simulation of Power Absorption in Plasma Absorption Stealth Technique,” *Natrual Science*, Nanchang University, vol. 32, no. 2, April 2008, pp.183-185.
[6] F.-H. Zeng and Z.-D. Liu, “The eechnique of controllable plasma stealth with absorption and refraction effect,” Optical Technique, vol. 32, Suppl, August 2006, pp. 257-260.
[7] A. Sun, *Some problems of low temperature plasma application*, Paper of doctor degree, 2000.
[8] J. Jian, *Electron engineering of plasma*, Science Publishing Company,2002.
[9] X.-J. Xu and D.-C. Zhu, *The physics of gaseous discharge*, Fudan University Publishing House, 1996.
[10] F. F. Chen, *The physics theoretics of plasma*, Demotic Education Publishing House, 1981.
[11] R.-H. Wu, A.-M. Ren, G. Meng *et al.*, “Research on the plasma collisional absorption of electromagnetic-wave upper the aerosphere,” *Journal of CAEIT*, vol. 3, no. 5,Oct. 2008.
[12] J.-J. Mo, “The Research on the stealth target electromagnetic scattering characteristic both low frequency and wide bandwidth,” The National Defence Science and Technology University, Paper of doctor degree, Changsha, 2004.

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