Experimental Research on Electromagnetic Wave Attenuation in Plasma

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***Abstract*- The power loss of electromagnetic wave in plasma is analyzed and calculated in this paper. An experiment scheme is proposed to measure the electromagnetic wave attenuation in plasma. The experiment scheme includes a plasma flat slab consist of several plasma tubes. The attenuation characteristics of electromagnetic waves in plasma are measured by horn antenna.**

I. INTRODUCTION

When a high speed spacecraft flies in reentry aerosphere stage, the plasma is generated by the interaction between spacecraft and aerosphere, and a phenomenon of electromagnetic wave attenuation increase is able to occur. The plasma is a main cause of electromagnetic wave attenuation. Plasma is a kind of electric liquid with high electron density, collision frequency and dispersive characteristic. The electromagnetic wave attenuation caused by plasma is consisted with the electromagnetic wave absorption and reflection of plasma, and gain reduced by mismatch of antenna impedance.

The attenuation of GPS signal by reentry plasma is analyzed in [1]. In [2,3] Kim calculates the attenuation values of remote sensing signal in reentry, and he gets the refractive index of electromagnetic wave with different electron density and collision frequency, and attenuation values on 1.575GHz. The attenuation effect in plasma layer with incident frequency, electron density and collision frequency is studied in [4]. In [5] the electromagnetic wave attenuation and reflection is measured by a experimental system, and the results are analyzed.

To verify the results of theory and simulation analysis, an experiment scheme is proposed to measure the electromagnetic wave attenuation of plasma. The experimental scheme includes a plasma flat slab consist of several plasma tubes by low voltage gas discharge. The plasma flat slab can simulate the reentry plasma characteristics. After determine the average electron density of the plasma flat slab, the plasma slab is put on the transmitting antenna, and the electromagnetic attenuation values are measured by transmitting and receiving horn antenna.

II. ELECTROMAGNETIC WAVE ATTENUATION CALCULATION

The electromagnetic wave attenuation caused by plasma is consisted with the electromagnetic wave absorption and reflection of plasma, and gain reduced by mismatch of antenna impedance. The electromagnetic wave attenuation can be calculated.

If the electromagnetic wave incidence is vertical, the attenuation of electromagnetic wave is

$$A = 8.68\alpha d - 10\lg\left(1 - \left|\frac{1-\sqrt{\varepsilon_r}}{1+\sqrt{\varepsilon_r}}\right|^2\right) \qquad (1)$$

α is attenuation coefficient,

$$\alpha = \frac{\omega}{c\sqrt{2}}\sqrt{\sqrt{\left(1-\frac{\omega_p^2}{\omega^2+{v_e}^2}\right)^2 + \left(\frac{\omega_p^2}{\omega^2+{v_e}^2}\cdot\frac{v_e}{\omega}\right)^2} - \left(1-\frac{\omega_p^2}{\omega^2+{v_e}^2}\right)}$$

where ω is angular frequency of incident electromagnetic wave, c is velocity of light, v_e is collision frequency, ω_p is characteristic frequency of plasma, and

$$\omega_p = \sqrt{\frac{N_e q_e^2}{\varepsilon_0 m_e}} \qquad (2)$$

N_e——electron density,
q_e——electronic charge,
m_e——electron mass.

To describe the macro graphic characteristic of plasma, the Drude dispersion model is able to employ to analyze the interaction of electromagnetic wave and plasma. In Drude dispersion model, the relative dielectric constant is

$$\varepsilon_r = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega - jv_e)} \qquad (3)$$

where ε_∞ is relative dielectric constant when operating frequency is infinite, generally $\varepsilon_\infty = 1$.

The electromagnetic wave attenuation with different electron density in plasma is shown in figure 1, where the thickness of homogeneous plasma layer is d=0.02m, and the collision frequency is v_e=1GHz. And the electron density N_e is $1\times10^{18}/m^3$、$3\times10^{18}/m^3$ and $1\times10^{19}/m^3$. As shown in figure 1, the higher the electron density of plasma is, the larger the value of electromagnetic wave attenuation is. The values of attenuation increase first and decreased afterwards, and there is a maximum value of attenuation. Figure 2 show the values of electromagnetic wave attenuation when $N_e=3\times10^{18}/m^3$ and d=0.02m with different collision frequency v_e, and v_e is 1GHz、5GHz and 10GHz. As shown in figure 2, the higher is the collision frequency of plasma, the smaller the values of electromagnetic wave attenuation is when the operating frequency is less than 14GHz. The higher the collision frequency of plasma is, the larger the value of electromagnetic wave attenuation is when the operating frequency is more than 14GHz. The values of attenuation increase first and decreased afterwards, and there is a maximum value of attenuation.

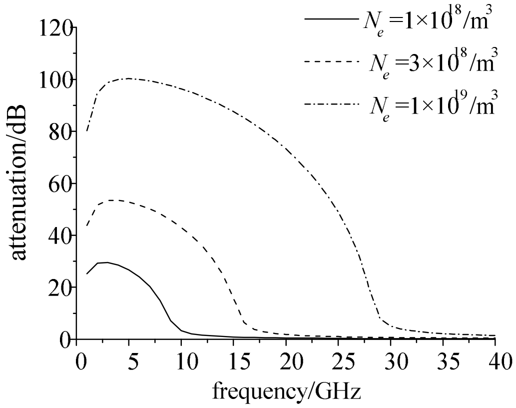

Figure 1.Electromagnetic wave attenuation with different electron density in plasma

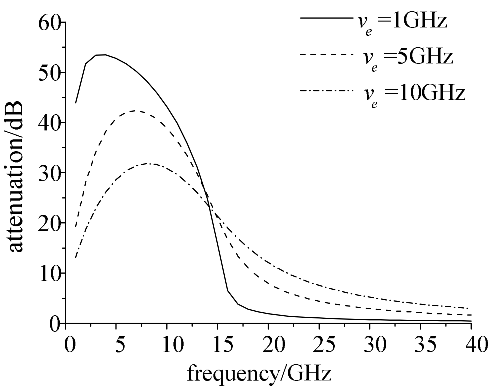

Figure 2.Electromagnetic wave attenuation with different collision frequency in plasma

The electromagnetic wave attenuation with different thickness of plasma layer is shown in figure 3, where the electron density is N_e=3×10^{18}/m^3, and the collision frequency v_e=1GHz. And the thickness is d is 0.02m, 0.03m and 0.05m. As shown in figure 3, the larger the thickness of plasma layer is, the larger the value of electromagnetic wave attenuation is. The values of attenuation increase first and decreased afterwards, and there is a maximum value of attenuation.

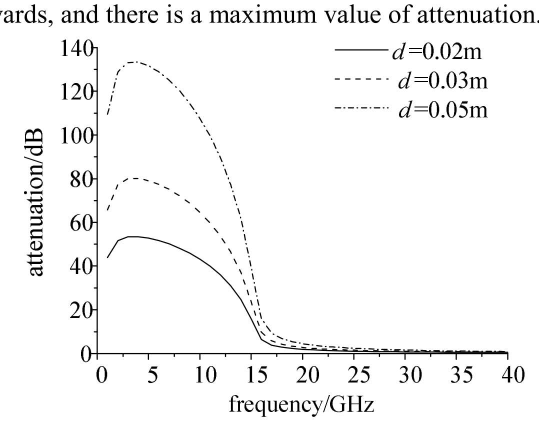

Figure 3.Electromagnetic wave attenuation with different thickness in plasma

III. ELECTROMAGNETIC WAVE ATTENUATION MEASUREMENT

In experimental research of electromagnetic wave attenuation measurement, the plasma is generated by direct current discharge under low atmospheric pressure. The glass tube is used in the experiment and the radius is 15mm. The air in the tube is extracted by a vacuum pump. The metal electrode is installed on two ends of the tube after the gas pressure is less than 10^{-2}Pa. The mixed air with Ar gas and Hg vapor is filled in the glass tube until the gas pressure reaches 10mmHg. A high voltage DC power (the output voltage is about 7000V and the power is about 60W) is connected with both ends of the electrode. The mixed gas is broken down when the electrodes discharge, and the plasma is generated by Penning Effect. The length of each plasma tube is about 1m. And a plasma flat slab is required in this experiment, so several plasma tubes can be arranged with series feeding. Figure 4 shows the plasma flat slab in the experiment. The plasma flat slab is made by 10 plasma flat slabs where the interval of two tubes is about 10mm.

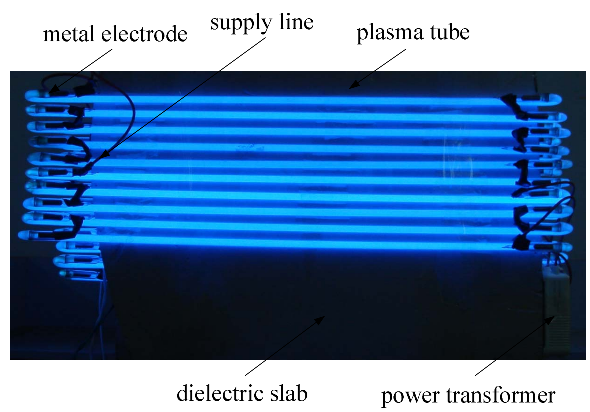

Figure 4.Slab made by plasma tubes

The measurement system of electromagnetic wave transmission is shown in figure 5. The system is consisted with a signal generator, a vector network analyzer, a directional coupler, a transmitting antenna and a receiving antenna. The electromagnetic wave attenuation by plasma is

$$10\lg\frac{P_{R2}(f)}{P_{R1}(f)}=10\log\frac{P_{R2}(f)}{P_T(f)}-10\log\frac{P_{R1}(f)}{P_T(f)}$$
$$=|S_{21b}|-|S_{21a}|(\text{dB}) \quad (4)$$

where S_{21a} is the S parameter measured by the vector network analyzer when plasma is generated, and S_{21b} is the S parameter measured by the vector network analyzer when plasma is not generated. $P_T(f)$ is the power at the plasma interface transmitted by the transmitting antenna, $P_{R1}(f)$ is the power received by receiving antenna when plasma is generated, and $P_{R2}(f)$ is the power received by receiving antenna when plasma is not generated,

$$|S_{21a}|(\text{dB})=20\log[S_{21a}(f)]=10\lg\frac{P_{R1}(f)}{P_T(f)},$$

$$|S_{21b}|(\text{dB})=20\log[S_{21b}(f)]=10\lg\frac{P_{R2}(f)}{P_T(f)}.$$

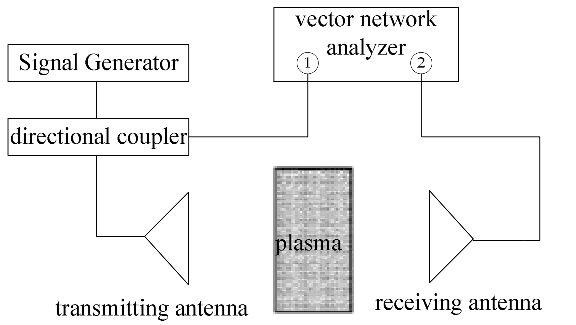

Figure 5.Measurement system of electromagnetic wave transmission

The electromagnetic wave attenuation is calculated where N_e=5×10^{16}/m^3, v_e=1×10^8Hz, d=50mm, and the operating frequency in from 0.9GHz to 1.3GHz. The value of attenuation is shown in figure 6. And the gain of the horn antenna with plasma layer can be simulated by the model in figure 7 by CST MWS studio. The value of the gain with plasma and the gain without plasma is shown in table 1.

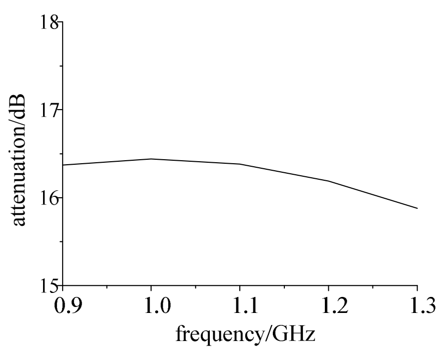

Figure 6.Calculation of electromagnetic wave attenuation in plasma

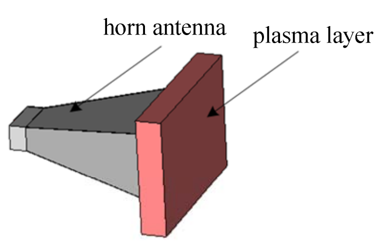

Figure 7.Simulation model of horn antenna with plasma

Table 1 Gain of horn antenna with or without plasma

Frequency/GHz	0.9	1.0	1.1	1.2	1.3
Gain without plasma/dB	13.0	14.6	16.2	17.2	18.9
Gain with plasma /dB	4.5	7.6	9.4	10.6	11.8

The total calculated value of electromagnetic wave attenuation is shown in figure 8. The value includes electromagnetic wave attenuation and the decrease of antenna gain. The measured value shown in figure 8 is got by formula (4). There is difference between calculated value and measured value for the electromagnetic wave reflection on the boundary of plasma, and the plasma is unstable and inhomogeneous.

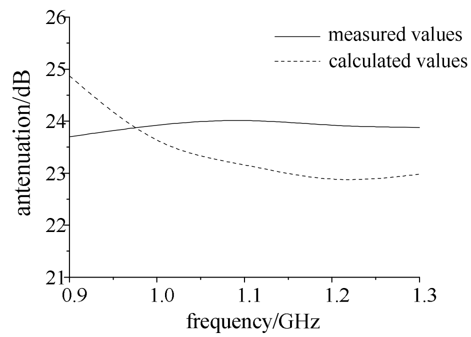

Figure 8.Measurement value of total electromagnetic wave attenuation

IV. CONCLUSION

An experiment system is presented to measure the electromagnetic wave attenuation of plasma. The system is consisted with a signal generator, a vector network analyzer, a directional coupler, a transmitting antenna and a receiving antenna. The experimental scheme includes a plasma flat slab consist of several plasma tubes by low voltage gas discharge. The calculated value and measured value of electromagnetic wave attenuation is given.

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to CST Ltd. Germany., for providing the CST Training Center (Northeast China Region) at our university with a free package of CST MWS software. The authors would like to express their sincere gratitude to funds supported by “the National Natural Science Funds” (Grant No. 61201014), and “the Fundamental Research Funds for the Central Universities” (Grant No. HIT.NSRIF.2012025).

REFERENCES

[1] D. S. Frankel, P. E. Nebolsine, M. G. Miller and J. M. Glynn. “Re-entry plasma induced pseudorange and attenuation effects in a GPS simulator”. SPIE Defense and Security Symposium, 2004:12~16

[2] M. Kim, M. Keidar and I. D. Boyd. “Effectiveness of an electromagnetic mitigation scheme for reentry telemetry through plasma”. 46th AIAA Aerospace Sciences Meeting and Exhibit, 2008:1~11

[3] M. Kim, M. Keidar and I. D. Boyd. “Analysis of an electromagnetic mitigation for reentry telemetry through plasma”. Journal of Spacecraft and Rockets. 2008,45(6): 1223~1229

[4] Liu Minghai, Hu Xiwei, Jiang Zhonghe, Liu Kefu, Gu Chenglin, Pan Yuan. “Property of electromagnetic wave attenuation in the artificial plasma of atmosphere”. Acta Physica Sinica. 2002,51(6):1317~1320

[5] Yuan Zhongcai, Shi Jiaming, Wang Jiachun. “Experimental studies of the interaction of microwaves with mixture burning plasmas in the atmosphere”. High Power Laser and Particle Beams. 2005,17(5):225~228

[6] D. M. Pozar Microwave Engineering 2005:555~556