

## THEORETICAL AND EXPERIMENTAL STUDIES OF 35 GHz AND 96 GHz ELECTROMAGNETIC WAVE PROPAGATION IN PLASMA

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**Abstract**—The 35 GHz and 96 GHz electromagnetic wave propagation characteristics in plasma are studied theoretically and experimentally in this paper. The variations of the electromagnetic wave attenuation along with the plasma density, plasma collision frequency and electromagnetic wave frequency are acquired based on the physical model. The electromagnetic wave propagation properties in plasma are studied experimentally with the shock tube and the experimental results match well with the theoretical results. Both the theoretical and experimental results indicate that increasing the electromagnetic wave frequency is an alternative and effective method to solve the reentry blackout problem.

### 1. INTRODUCTION

The velocity of the aircraft is very high, i.e., nearly several tens of the speed of sound, when the spacecraft reentry into the Earth's atmosphere. The ultrahigh velocity results in the formation of a shockwave. Owing to the compression of the shockwave and the conglutination of the atmosphere, a part of the kinetic energy of the aircraft changes into thermal energy. The temperature near the aircraft may reach as high as 10000 to 12000 Kelvin, which lead to the ionization of the surface materials and the ambient air. Then a plasma

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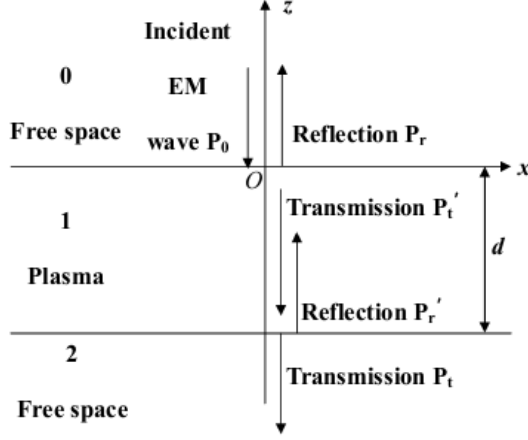
sheath is formed. The plasma sheath severely affects the propagation of the incident electromagnetic (EM) wave and cause severe EM wave attenuation, which results in the communication failures between the aircraft and the ground control center. What's more, it will lead to the loss of radar targets and threaten the lives of astronauts, which is known as "reentry blackout" and has attracted more and more attention recently [1–5]. Several solutions have been proposed to the problem, for example,  $\vec{E} \times \vec{B}$  cross-field configuration technology [1, 4], the electrostatic plasma sheath technology [4], the moving-window technology [2], the magnetic window technology [5] and so on.

In such a situation, it is important to study the properties of the EM wave propagation in plasma [6–8]. However, most of the published works focus on theories and numerical simulations [9–14] while little experimental studies on this issue have been carried out presently.

In this paper, the EM wave propagation characteristics in plasma are studied both theoretically and experimentally. The remainder of the paper is organized as follows: first of all, the physical model of the EM wave propagation in plasma is introduced. The simulation results of the EM wave propagation characteristics in plasma, including the effects of plasma density, plasma collision frequency and EM wave frequency on the reflectance, transmission and attenuation of the incidence EM wave are exhibited and analyzed in Section 3. Following this, the experimental studies of the EM wave propagation in plasma with the shock tube are presented. The conclusions of this paper are presented in Section 5.

## 2. PHYSICAL MODEL

The EM wave propagation properties are usually acquired by analyzing the permittivity of plasma [15–20]. The physical model used in this paper is as follows: the linearly polarized EM wave incident vertically into plasma along the negative  $z$ -axis, which is depicted in Figure 1. The plasma is assumed to be homogeneous, non-magnetized, steady-state and collisional. The electric field is parallel to the  $y$ -axis and the magnetic field is parallel to the  $x$ -axis. The media are denoted by numbers: medium 0 (free space), medium 1 (plasma), and medium 2 (free space). The thickness of the plasma is  $d$ , which is set to 80 mm in the following numerical simulations. The multiple reflections occur at the interfaces  $z = 0$  and  $z = -d$ .



**Figure 1.** The physical model of the EM wave propagation in plasma.

The Maxwell's equations are as following [21, 22]:

$$\begin{cases} \nabla \times \vec{E} = -j\omega\mu_0\vec{H} \\ \nabla \times \vec{H} = j\omega\varepsilon\vec{E} \\ \nabla \cdot (\varepsilon\vec{E}) = 0 \\ \nabla \cdot \vec{B} = 0 \end{cases} \quad (1)$$

where  $\vec{E}$  and  $\vec{H}$  are the electric field and magnetic field, respectively,  $\mu_0$  is the permeability of the vacuum,  $\varepsilon$  is the permittivity,  $\omega = 2\pi f$ , and  $f$  is the frequency of the incident EM wave.

The electric field of the incident EM wave can be expressed as:  $E_y = E_0 e^{jk_0 z}$ , where  $E_0$  is the amplitude of the incident electric field and  $k_0$  is the wave number in free space

From the Maxwell's equations, we can receive the magnetic field of the incident EM wave:  $H_x = \frac{k_0}{\omega\mu_0} E_0 e^{jk_0 z}$ .

Then the electric field and magnetic field in medium 0 can be expressed as

$$E_{0y} = E_0 \left( e^{jk_0 z} + r e^{-jk_0 z} \right) \quad H_{0x} = \frac{k_0}{\omega\mu_0} E_0 \left( e^{jk_0 z} - r e^{-jk_0 z} \right) \quad (2)$$

where  $r$  is the reflection coefficient.

Similarly, the electric and magnetic fields in medium 1 are

expressed as

$$\begin{aligned} E_{1y} &= \left( E_{PT}e^{jk_p z} + E_{PR}e^{-jk_p z} \right) \\ H_{1x} &= \frac{k_p}{\omega\mu_0} \left( E_{PT}e^{jk_p z} - E_{PR}e^{-jk_p z} \right) \end{aligned} \quad (3)$$

where  $E_{PT}$  and  $E_{PR}$  are the amplitudes of the transmission and reflection electric fields in medium 1, and  $k_p$  is the wave number in plasma.

The electric field and magnetic field in medium 2 are presented as following:

$$E_{2y} = E_T e^{jk_0 z} \quad H_{2x} = \frac{k_0}{\omega\mu_0} E_T e^{jk_0 z} \quad (4)$$

Here,  $E_T$  is the amplitude of the transmission electric field in medium 2.

The continuity boundary conditions of the electric and magnetic fields can be described as:

$$\begin{aligned} E_{0y} |_{z=0} &= E_{1y} |_{z=0} \\ H_{0x} |_{z=0} &= H_{1x} |_{z=0} \\ E_{1y} |_{z=-d} &= E_{2y} |_{z=-d} \\ H_{1x} |_{z=-d} &= H_{2x} |_{z=-d} \end{aligned} \quad (5)$$

i.e.,

$$\begin{aligned} E_0(1+r) &= E_{PT} + E_{PR} \\ \frac{k_0}{\omega\mu_0} E_0(1-r) &= \frac{k_p}{\omega\mu_0} (E_{PT} - E_{PR}) \\ E_{PT}e^{-jk_p d} + E_{PR}e^{jk_p d} &= E_T e^{-jk_0 d} \\ \frac{k_p}{\omega\mu_0} \left( E_{PT}e^{-jk_p d} - E_{PR}e^{jk_p d} \right) &= \frac{k_0}{\omega\mu_0} E_T e^{-jk_0 d} \end{aligned} \quad (6)$$

where  $r$ ,  $E_{PT}$ ,  $E_{PR}$  and  $E_T$  are unknown. The reflection coefficient  $r$  and the transmission coefficient  $t$  can be obtained from Equation (6):

$$\begin{aligned} r &= \frac{1 - \varepsilon_r}{2\sqrt{\varepsilon_r} \cot h(jk_p d) + \varepsilon_r + 1} \\ t &= \frac{E_T}{E_0} = \frac{2\sqrt{\varepsilon_r} e^{jk_0 d}}{2\sqrt{\varepsilon_r} \cos h(jk_p d) + (\varepsilon_r + 1) \sin h(jk_p d)} \end{aligned} \quad (7)$$

where  $\varepsilon_r$  is the relative permittivity of the plasma.

Then the reflectance, transmission and attenuation of the EM wave, i.e.,  $R$ ,  $T$  and  $Att$  can be acquired and expressed as following:

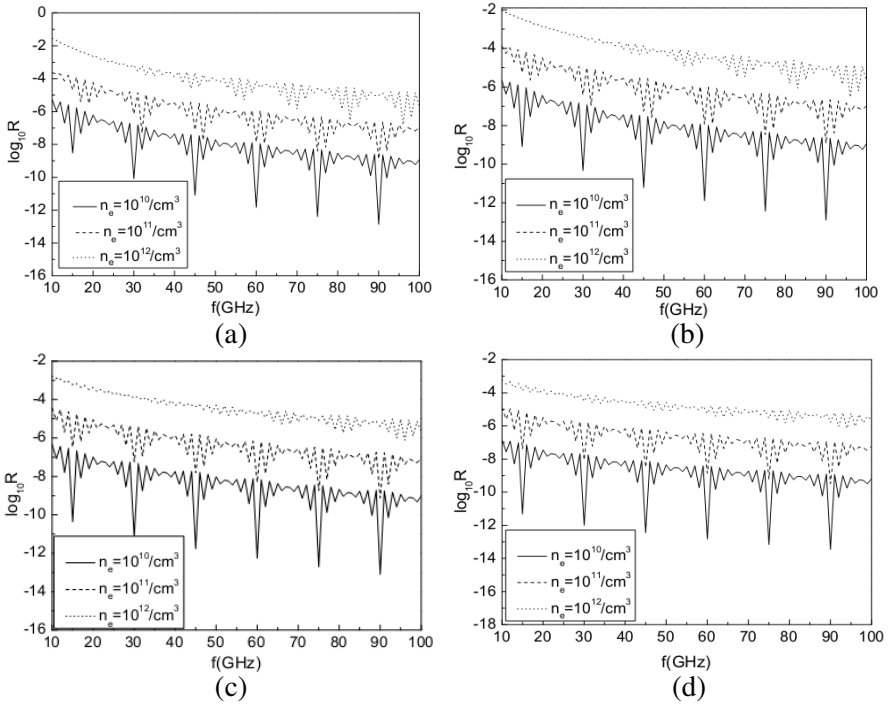
$$R = |r|^2 \quad T = |t|^2 \quad Att = -10 \log_{10} T \quad (8)$$

### 3. NUMERICAL SIMULATION RESULTS

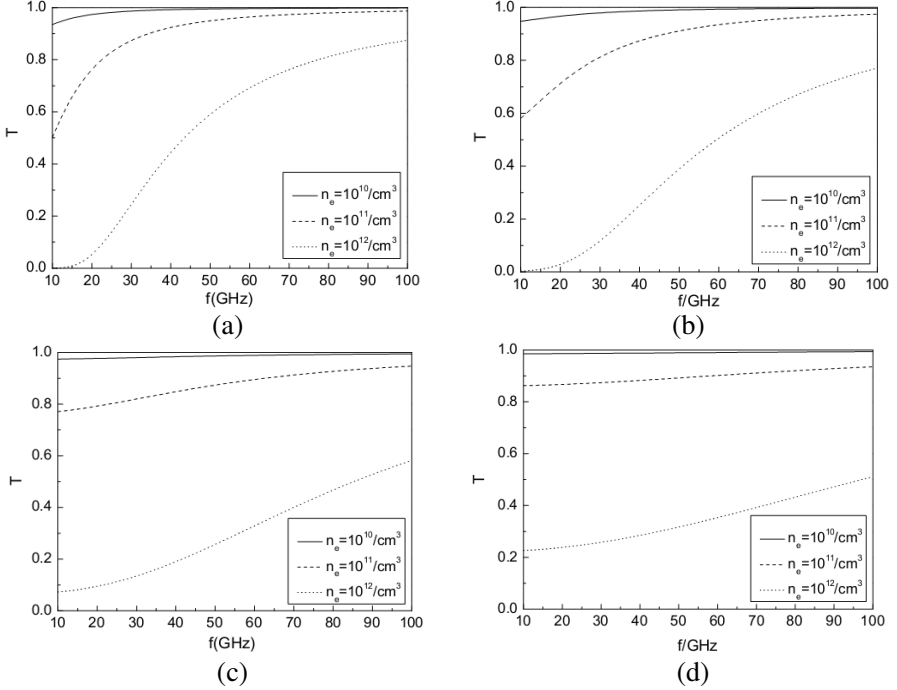
#### 3.1. The Effects of the Plasma Density on the EM Wave Propagation

The variations of the EM wave reflectance, transmission and attenuation along with the EM wave frequency and plasma density under fixed plasma collision frequency are obtained based on the physical model and theoretical analysis, which are depicted in Figure 2, Figure 3 and Figure 4, respectively.

Figure 2 shows the variations of the EM wave reflectance along with the EM wave frequency and plasma density. We can see that the EM wave reflectance decreases in general with increasing EM wave frequency for identical plasma collision frequency and plasma density. Furthermore, it can be seen that the EM wave reflectance increases with increasing plasma density for identical plasma collision frequency and EM wave frequency. The EM wave reflectance increases by two



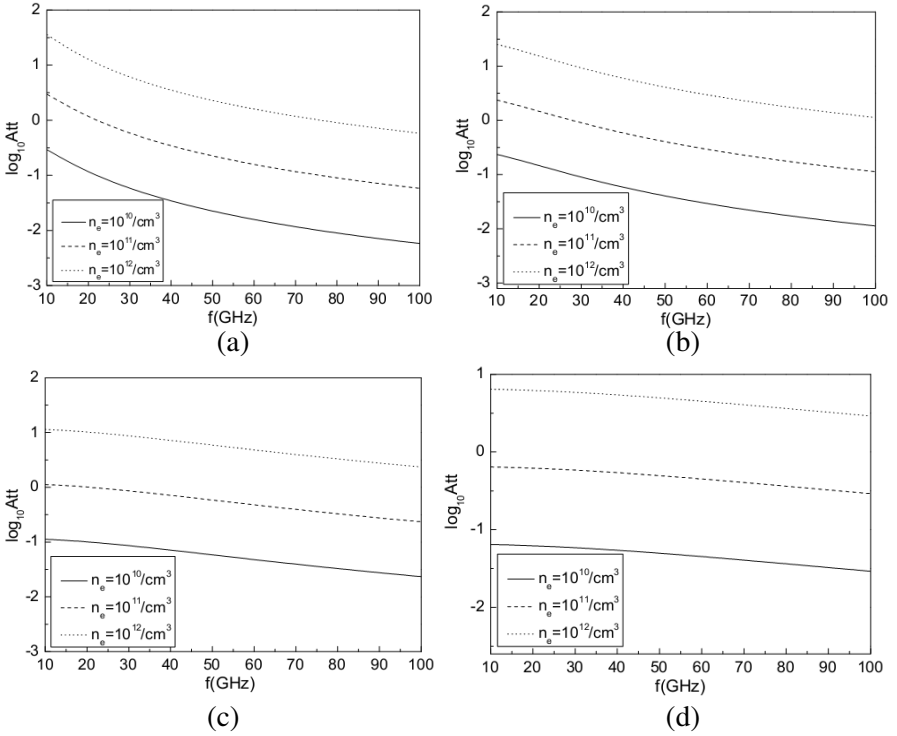
**Figure 2.** The variations of the EM wave reflectance along with the EM wave frequency and plasma density. (a)  $f_{en} = 10$  GHz. (b)  $f_{en} = 20$  GHz. (c)  $f_{en} = 50$  GHz. (d)  $f_{en} = 90$  GHz.



**Figure 3.** The variations of the EM wave transmission along with the EM wave frequency and plasma density. (a)  $f_{en} = 10$  GHz, (b)  $f_{en} = 20$  GHz, (c)  $f_{en} = 50$  GHz, (d)  $f_{en} = 90$  GHz.

orders of magnitude with the plasma density increases by one order of magnitude. Moreover, there are several valleys on the reflectance curves and the values of the valleys decrease while the corresponding EM wave frequency increase with increasing plasma density. The phenomenon is owing to the cavity resonance effects [15], however, the effects of the plasma density on the resonance was not described by Yuan. The cavity resonance has a more obvious effect on the EM wave reflectance for higher EM wave frequency, while the effect becomes less obvious for higher plasma density. In essence, the cavity resonance effect is attributed to the multiple EM wave reflections at the interfaces  $z=0$  and  $z=-d$ .

The EM wave transmission increases and the attenuation decreases with increasing EM wave frequency for identical plasma collision frequency and plasma density, which are presented meticulously in Figure 3 and Figure 4. The mechanism responsible for this phenomenon is complicated and maybe it can be explained through the electrons' response to the electric field. Under higher EM wave fre-



**Figure 4.** The variations of the EM wave attenuation along with the EM wave frequency and plasma density. (a)  $f_{en} = 10$  GHz. (b)  $f_{en} = 20$  GHz. (c)  $f_{en} = 50$  GHz. (d)  $f_{en} = 90$  GHz.

quency, the electrons will no longer be able to respond to the electric field, hence, the EM wave energy absorbed by the electrons is decreased and the attenuation of the EM wave will be decreased.

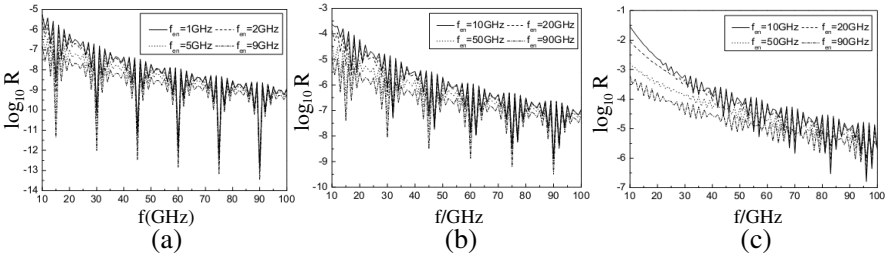
In Figure 3 and Figure 4, we can also find that the EM wave transmission decreases and the attenuation increases with increasing plasma density for identical plasma collision frequency and EM wave frequency. Moreover, the EM wave attenuation increases by one order of magnitude with plasma density increases an order of magnitude. The reason is that with higher plasma density, there are more electrons in the plasma and more EM energy is absorbed by the electrons and passed to neutral particles through collisions, i.e., the EM wave attenuation in the plasma is increased.

### 3.2. The Effects of the Plasma Collision Frequency on the EM Wave Propagation

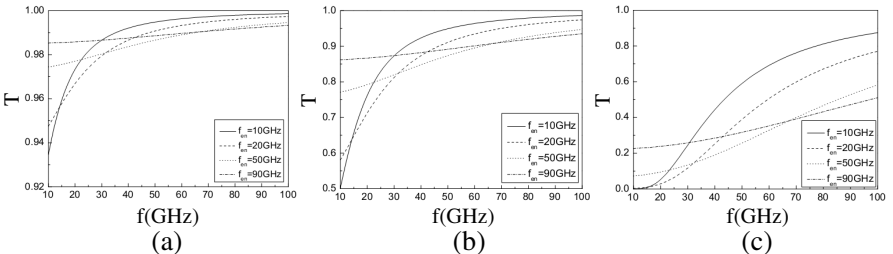
The variations of the EM wave reflectance, transmission and attenuation along with the EM wave frequency and plasma collision frequency under fixed plasma density are obtained based on the physical model and theoretical analysis, which are shown in Figure 5, Figure 6 and Figure 7, respectively.

Figure 5 shows the variations of the EM wave reflectance along with the EM wave frequency and plasma collision frequency. We can see that the EM wave reflectance decrease in general with increasing EM wave frequency for identical plasma density and plasma collision frequency. Moreover, the EM wave reflectance decreases with increasing plasma collision frequency under identical plasma density and EM wave frequency. The cavity resonance effects are also involved in these conditions.

The EM wave transmission increases and the attenuation decreases with increasing EM wave frequency under identical plasma

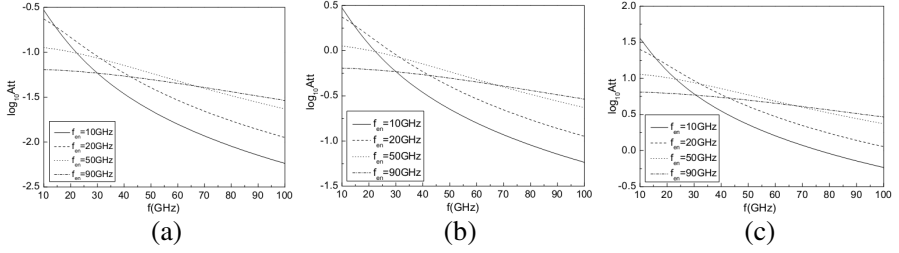


**Figure 5.** The variations of the EM wave reflectance along with the EM wave frequency and plasma collision frequency. (a)  $n_e = 10^{10}/\text{cm}^3$ . (b)  $n_e = 10^{11}/\text{cm}^3$ . (c)  $n_e = 10^{12}/\text{cm}^3$ .



**Figure 6.** The variations of the EM wave transmission along with the EM wave frequency and plasma collision frequency. (a)  $n_e = 10^{10}/\text{cm}^3$ . (b)  $n_e = 10^{11}/\text{cm}^3$ . (c)  $n_e = 10^{12}/\text{cm}^3$ .





**Figure 7.** The variations of the EM wave attenuation along with the EM wave frequency and plasma collision frequency. (a)  $n_e = 10^{10}/\text{cm}^3$ . (b)  $n_e = 10^{11}/\text{cm}^3$ . (c)  $n_e = 10^{12}/\text{cm}^3$ .

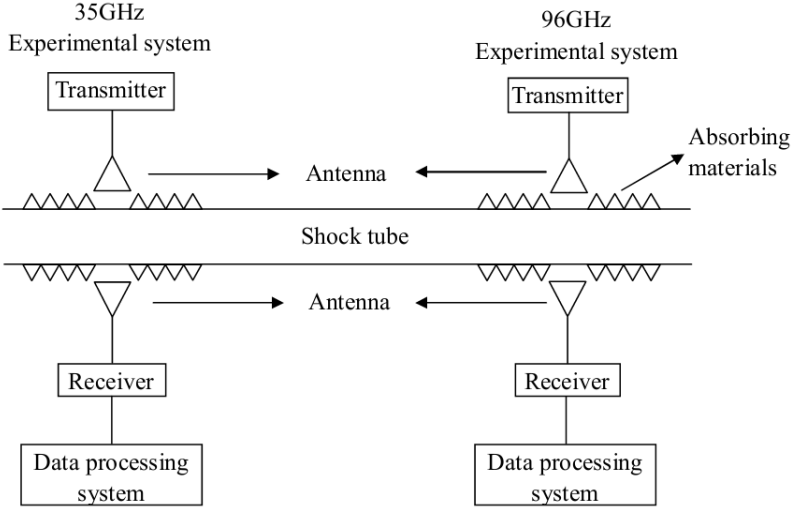
density and plasma collision frequency, which can be seen in Figure 6 and Figure 7. The reasons have been given in the previous section.

In Figure 6 and Figure 7, we can also find that the EM wave transmission first decreases and then increases while the attenuation first increases and then decreases with increasing plasma collision frequency for identical plasma density and EM wave frequency. The performance of the incident EM wave can be explained through the effects of the plasma collision frequency: under higher plasma collision frequency, the collision probability between the electrons and neutral particles increases and the energy passed to the neutral particles is increased, then the attenuation of the incident EM wave increases. However, when the collision frequency is too high, the acceleration time of the electrons before collision with the neutral particles is so short that there is little time for the electron to receive energy from the electric field, so the attenuation decreases on the contrary.

#### 4. EXPERIMENTAL RESULTS

The EM wave propagation properties in plasma are studied experimentally with the shock tube. The shock tube is a cylindrical device and it can produce approximate uniform plasma, which can be used to simulate the plasma near the aircrafts for simplify. The schematic diagram of the experimental setup is shown in Figure 8. The diameter of the shock tube is 80 mm. The absorbing materials were set around the antennas and the test section of the original shock tube wall was replaced by Teflon in order to reduce the reflection. The 35 GHz and 96 GHz experimental systems were used to measure the attenuation of the plasma at the same time. The theoretical EM wave attenuation is achieved based on the physical model in Section 2 and the experimental EM wave attenuation is acquired from the power of

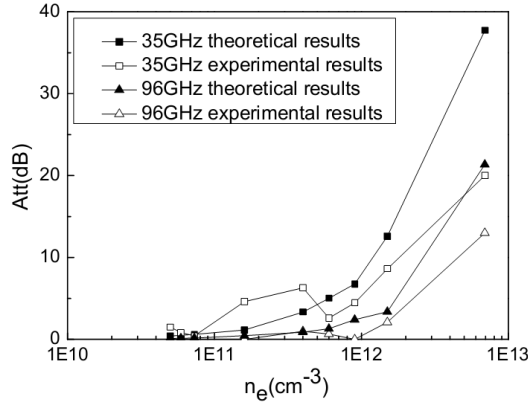
the receiver and can be obtained from the “Data processing system”. A total of nine effective experiments were carried out and we denoted the experiments by numbers: 1, 2, 3, . . . , 9. The plasma densities and collision frequencies used in the experiments are presented in Table 1, which are calculated based on the physical states of the shock tube in the experiments.



**Figure 8.** The experimental setup of the EM wave propagation in plasma.

**Table 1.** The plasma densities and collision frequencies used in the experiments.

Number of the experiments	$n_e$ ( $\text{cm}^{-3}$ )	$f_{en}$ (Hz)
1	$5.0 \times 10^{10}$	$4.0 \times 10^{10}$
2	$5.9 \times 10^{10}$	$4.0 \times 10^{10}$
3	$7.3 \times 10^{10}$	$4.2 \times 10^{10}$
4	$1.6 \times 10^{11}$	$6.1 \times 10^{10}$
5	$4.0 \times 10^{11}$	$4.1 \times 10^{10}$
6	$6.0 \times 10^{11}$	$4.0 \times 10^{10}$
7	$9.0 \times 10^{11}$	$5.7 \times 10^{10}$
8	$1.5 \times 10^{12}$	$4.2 \times 10^{10}$
9	$6.9 \times 10^{12}$	$9.7 \times 10^{10}$



**Figure 9.** The comparison of the experimental and theoretical EM wave attenuation at 35 GHz and 96 GHz.

Figure 9 shows the comparison of the experimental and theoretical EM wave attenuation at 35 GHz and 96 GHz. The theoretical and experimental EM wave attenuation at 35 GHz are both larger than that at 96 GHz. According to this, it can be deduced that increasing the EM wave frequency is an alternative and effective method to solve the reentry blackout problems.

The experimental results match well with the theoretical results, which can also be seen from Figure 9. However, there are some differences between the experimental and theoretical results, which may be attributed to the errors of the experimental systems or the calculation errors of the plasma densities and collision frequencies. The EM wave propagation characteristics are strongly affected by the plasma density and collision frequency, for example, the EM wave attenuation increase by one order of magnitude with plasma density increases an order of magnitude. According to these reasons, the errors between the experimental and theoretical results are reasonable and understandable.

## 5. CONCLUSIONS

The EM wave propagation characteristics in plasma at 35 GHz and 96 GHz are studied theoretically and experimentally in this paper. The variations of the EM wave attenuation along with the plasma density, collision frequency and EM wave frequency are acquired: (1) the EM wave attenuation increases by one order of magnitude with the plasma density increases an order of magnitude; (2) the EM wave attenuation first increases and then decreases with increasing

plasma collision frequency; (3) the EM wave attenuation decrease with increasing EM wave frequency. The EM wave propagation properties in plasma are studied experimentally with the shock tube and the experimental results match well with the theoretical results. Both the theoretical and experimental results indicate that increasing the EM wave frequency is an alternative and effective method to solve the reentry blackout problem.

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