Effect of Plasma on Electromagnetic Wave Propagation and THz Communications for Reentry Flight

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Abstract **─** The spacecraft will experience the well-known "blackout" problem when it re-enters into the Earth's atmosphere, which results in communication failures between the spacecraft and the ground control center. It is important to study the effect of the plasma on electromagnetic wave (EMW) propagation. The properties of EMW propagation in plasma based on theoretical analysis have been studied in this paper, which indicate that communications using terahertz (THz) wave is an alternative method for solving the blackout problem. The properties of 0.22 THz EMW propagation in plasma have been studied experimentally with shock tube, and the experimental results are in good agreement with the theoretical ones. Both the theoretical and experimental results indicate that communications using THz wave is an alternative and effective way to solve the blackout problem.

Index Terms **─** Blackout, EMW propagation, plasma, THz.

I. INTRODUCTION

The spacecraft will experience the well-known "blackout" problem [1-3] when it re-enters into the Earth's atmosphere, which results in communication failures between the spacecraft and the ground control center. This phenomenon has attracted more and more attention recently [4-8].

A number of approaches have been proposed to solve the blackout problem, such as aerodynamic shape modification, quenchant injection, magnetic window and so on; however, the true technological breakthough has not been achieved.

One of the major reasons for communication failures is that the plasma frequency is greater than the EMW frequency. The plasma density may reach $10^{21}/\text{m}^3$ and the corresponding plasma frequency is 0.284 THz, which are typical data of the RAM C (Radio Attenuation Measurement C) flight [9]. Besides, 0.2 THz has been specified for the next intersatellite communications by the International Telecommunication Union. For these reasons, communications using THz wave is an alternative method for solving the blackout problem and the great advance in THz source technology recently provides a great opportunity for this issue [10-14]. Moreover, it is possible to solve the blackout problem using THz wave with the development of THz technology.

Therefore, it is important to study the properties of THz wave propagation in plasma. However, most published works were limited in microwave frequency (<100 GHz) and focus on theory and numerical simulations [15-19].

The effect of plasma on EMW propagation has been studied theoretically and the properties of 0.22 THz EMW propagation in plasma have been studied experimentally with shock tube in this paper.

II. PHYSICAL MODEL

The physical model used in this paper is as follows: the EMW incident vertically into the plasma along the *z*-axis, which is depicted in Fig. 1. The plasma is assumed to be homogeneous and unmagnetized. The electric field is parallel to the *x*-axis and the magnetic field is parallel to the *y*-axis. The thickness of plasma is *d*.

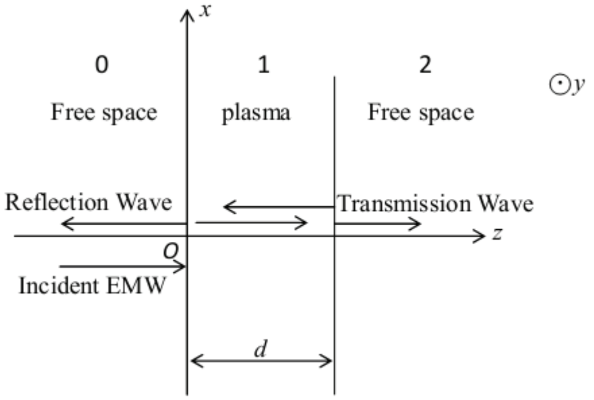

Fig. 1. The physical model of EMW propagation in plasma.

The Maxwell's equations are the following [20-24]:

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

where $\vec{E}$ and $\vec{H}$ are the electric field and magnetic field, respectively, μ_0 is the permeability of vacuum, ε is the permittivity, $\omega = 2\pi f$, and f is the frequency of the incident EMW.

The electric field of the incident EMW can be expressed as: $E_x = E_0 e^{-jk_0 z}$, 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 obtain the magnetic field of the incident EMW: $H_y = -\frac{1}{j\omega\mu_0}\frac{\partial E_x}{\partial z}$.

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

$$\begin{aligned} E_{0x} &= E_0 \left(e^{-jk_0 z} + r e^{jk_0 z} \right) \\ H_{0y} &= \frac{k_0}{\omega\mu_0} E_0 \left(e^{-jk_0 z} - r e^{jk_0 z} \right) \end{aligned}, \tag{2}$$

where r is the reflection coefficient.

Similarly, the electric and magnetic fields in medium 1 can be expressed as:

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

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 the following:

$$\begin{aligned} E_{2y} &= E_T e^{-jk_0 z} \\ H_{2x} &= \frac{k_0}{\omega\mu_0} E_T e^{-jk_0 z} \end{aligned}, \tag{4}$$

where 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:

$$\begin{aligned} E_{0x}\big|_{z=0} &= E_{1x}\big|_{z=0} \\ H_{0y}\big|_{z=0} &= H_{1y}\big|_{z=0} \\ E_{1x}\big|_{z=d} &= E_{2x}\big|_{z=d} \\ H_{1y}\big|_{z=d} &= H_{2y}\big|_{z=d} \end{aligned}, \tag{5}$$

i.e.,

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

The reflection coefficient r and transmission coefficient t can be obtained from equation (6):

$$\begin{aligned} r &= \frac{1 - \varepsilon_r}{2\sqrt{\varepsilon_r}\coth(jk_p d) + \varepsilon_r + 1} \\ t &= \frac{E_T}{E_0} = \frac{2\sqrt{\varepsilon_r} e^{jk_0 d}}{2\sqrt{\varepsilon_r}\cosh(jk_p d) + (\varepsilon_r + 1)\sinh(jk_p d)} \end{aligned}, \tag{7}$$

where ε_r is the relative permittivity of plasma.

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

$$\begin{aligned} R &= \left| r \right|^2 \\ T &= \left| t \right|^2 \\ Att &= -10\log_{10} T \end{aligned}. \tag{8}$$

III. NUMERICAL SIMULATION RESULTS

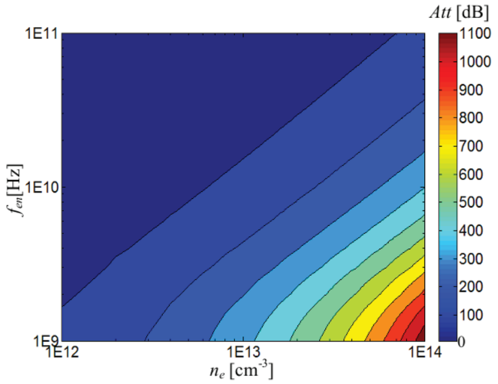
The attenuation of the EMW versus plasma density and collision frequency at different EMW frequency are calculated and illustrated in Fig. 2, in which the thickness of the plasma d is 0.08 m.

As shown in Fig. 2, the attenuation decrease with EMW frequency for identical plasma density and collision frequency. The mechanism responsible for this phenomenon can be explained through the electrons' response to the electric field: the electrons will no longer be able to response to the electric field as the EMW frequency increases; hence, the EMW energy absorbed by electrons decrease and then the attenuation is decreased.

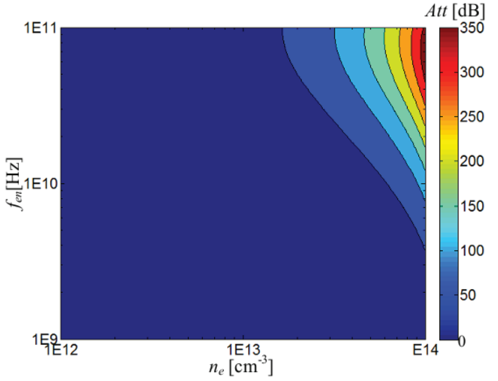
The maximum attenuation for $f = 1.5$ GHz, $f = 0.1$ THz and $f = 0.22$ THz are 1100 dB, 350 dB and 100 dB, respectively, which can be seen from Fig. 2. The EMW attenuation is less than 30 dB for 0.22 THz EMW at most region when $n_e = 10^{12}/\text{cm}^3 \sim 10^{14}/\text{cm}^3$, $f_{en} = 10^9\text{Hz} \sim 10^{11}\text{Hz}$. For this reason, communications using THz wave can be considered for solving the blackout problem.

From Fig. 2, we can also see that the attenuation increase with plasma density, which is because there are more electrons in plasma with higher plasma density, and then more EMW energy is absorbed by electrons and passed to neutral particles through collisions, i.e., the EMW attenuation is increased.

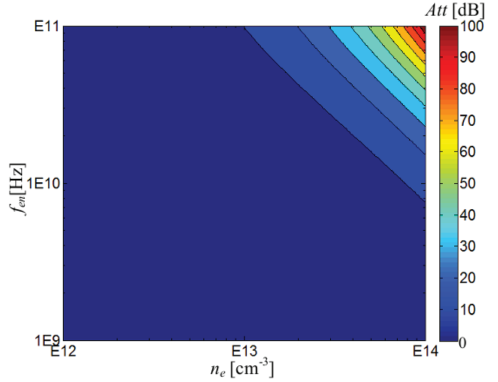
Figure 2 also shows that the attenuation decreases with plasma collision frequency when $f < f_p$ while increases with plasma collision frequency when $f > f_p$. The reason is that the electrons are oscillating at EMW frequency when $f < f_p$, the acceleration time of electrons before collision with neutral particles is so short that there is little time for the electrons to receive energy from the electric filed with increasing plasma collision frequency, so the attenuation is decreased. However, the electrons are oscillating at the inherent frequency when $f > f_p$, and the collision probability between the electrons and neutral particles increases and the energy passed to neutral particles is increased for higher plasma collision frequency, then the attenuation is increased.



(a) f = 1.5 GHz



(b) f = 0.1 THz



(c) f = 0.22 THz

Fig. 2. The attenuation of EMW versus plasma density and collision frequency for various EMW frequency.

IV. EXPERIMENTAL RESULTS

The 0.22 THz EMW propagation properties in the plasma are studied experimentally with shock tube. The shock tube is a cylindrical device and it can produce approximate uniform plasma, which are usually used to simulate the plasma near the aircrafts [25,26]. The schematic diagram of the experimental setup is illustrated in Fig. 3. The diameter of the shock tube is 0.08 m. The original wall of the shock tube was replaced by Teflon in order to reduce the reflection. A total of five effective experiments were carried out and we denoted the experiments by numbers: 1, 2, 3, 4 and 5.

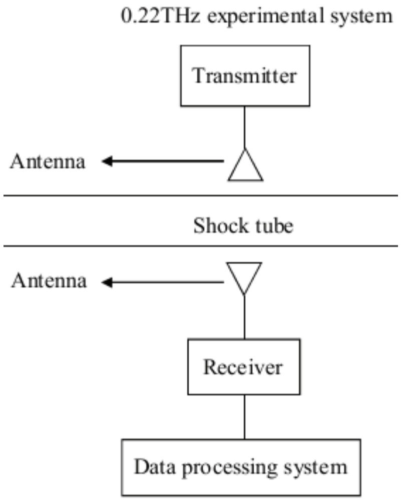


Fig. 3. The experimental setup of the 0.22 THz EMW propagation in the plasma.

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.

A chemical reaction model consisting of 7 chemical reactions among 7 compounds was used in the calculation, which includes the reactions as follows:

$$\begin{cases} O_2 + M_1 \Leftrightarrow O + O + M_1 \\ N_2 + M_2 \Leftrightarrow N + N + M_2 \\ N_2 + N \Leftrightarrow N + N + N \\ NO + M_3 \Leftrightarrow N + O + M_3 \\ O + NO \Leftrightarrow N + O \\ O + N_2 \Leftrightarrow N + NO \\ N + O \Leftrightarrow NO^+ + e^- \end{cases}, \tag{9}$$

where M is the collider in the reactions, and the reaction rate is presented in reference [27,28]. The theoretical plasma density n_e can be obtained from these reactions.

The collision frequency of the plasma f_{en} was acquired from equation (10):

$$f_{en} = 3.67\times10^{-15}\omega_p^2 T, \tag{10}$$

where $\omega_p = \sqrt{n_e e^2 / \varepsilon_0 m_e}$, e is the charge of the electron, ε_0 is the vacuum permittivity, m_e is electron mass, and T is the temperature of the plasma which was measured in the experiments.

The experimental EMW attenuation is acquired from the power of the receiver, which is proceeded by the "data processing system".

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

Number of the Experiments	n_e (m^{-3})	f_{en} (Hz)
1	9.0×10^{17}	8.2×10^{10}
2	3.0×10^{18}	9.2×10^{10}
3	3.2×10^{18}	9.7×10^{10}
4	7.3×10^{18}	1.0×10^{11}
5	2.4×10^{19}	1.2×10^{11}

Figure 4 shows the comparison of the experimental results and theoretical ones of the 0.22 THz EMW attenuation. The experimental results match well with the theoretical ones, which can be seen from Fig. 4. However, there are some differences between the experimental results and theoretical ones, which may be attributed to the errors of the experimental systems and the calculation errors of plasma densities and collision frequencies. The theoretical and experimental results are both smaller than 30 dB even if the plasma density reach as high as 2.4×10^{19}/m^3 and the plasma collision frequency is 1.2×10^{11}Hz. According to these results, it can be deduced that communications using THz wave is an effective way to solve the reentry blackout problems.

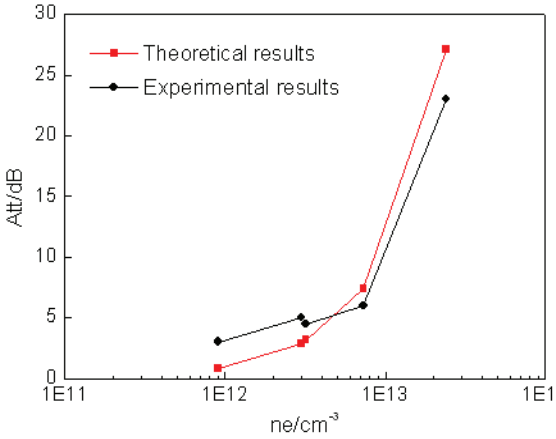


Fig. 4. The comparison of the experimental and theoretical results of 0.22 THz EMW attenuation.

V. CONCLUSIONS

The effect of plasma on EMW propagation have been studied theoretically in this paper, which indicate that communications using THz wave is an alternative method for solving the blackout problem. The 0.22 THz EMW propagation properties in the plasma have been studied experimentally with shock tube and the experimental results match well with the theoretical ones. Both the theoretical and experimental results indicate that communications using THz wave is an alternative and effective way to solve the reentry blackout problems.

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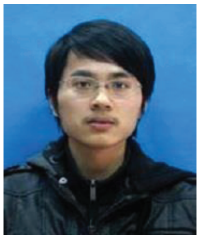

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