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THEORETICAL AND EXPERIMENTAL STUDIES OF MAGNETIC FIELD ON ELECTROMAGNETIC WAVE PROPAGATION IN PLASMA

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Abstract—A spacecraft will experience the well-known "blackout" problem in the re-entry into the Earth's atmosphere, which results in communication failures between the spacecraft and ground control center. It is important to study the blackout mitigation method. The effects of external magnetic field on electromagnetic wave propagation in plasma are studied by theoretical and experimental methods in this paper. The numerical results show that the attenuation of electromagnetic wave in plasma is reduced by the presence of a magnetized field. The propagation properties of electromagnetic wave in unmagnetized and magnetized plasma have been studied experimentally with plasma torch, and the experimental results are in good agreement with the theory. Both the theoretical and experimental results indicate that magnetic window is an alternative and promising way to improve the radio blackout issue.

1. INTRODUCTION

A plasma sheath is formed around the aircraft in the re-entry into the Earth's atmosphere. Radio signals can be reflected, refracted and absorbed by the plasma sheath, in serious cases the plasma sheath will completely interrupt transmission of radio signals, which is called the well-known "blackout" problem. In recent years, the phenomenon has attracted more and more attention [1–5], and research on transmission characteristics of electromagnetic waves in plasma has been carried out [6–10].

Currently, many methods have been suggested to solve the communication interruption [11] such as changing the aerodynamic

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shape, pro-electronic material, memory retransmission, etc., but they did not get a true technological breakthrough. The change of the aircraft aerodynamic shape will bring the increase in aerodynamic heat and the reduction in payload. There are some difficulties in using electron affinity substance in engineering. The way of memory retransmission cannot achieve real-time communication between the aircraft and ground control center.

Hodara proposed the external magnetic field can slow down attenuation of the right-hand circularly polarized electromagnetic wave in plasma [12]. Starkey theoretically analyzed the effects of external magnetic field on propagation of right-hand circularly polarized electromagnetic wave in plasma when the wave frequency is 10 GHz and 20 GHz [13]. Keidar and Kim et al. theoretically studied the influence of plasma on attenuation of electromagnetic wave with external magnetic field [14, 15]. They analyzed the influence of external magnetic field and electric field on plasma density. The studies show that the plasma density in the vicinity of the cathode is reduced to 10% compared with the original, however, they have not analyzed the reduction of attenuation with external magnetic field and electric field.

Therefore, for solving the blackout problem, it is significant to study the effects of external magnetic field on propagation of right-hand circularly polarized electromagnetic wave in plasma. However, most of the studies focused on theoretical research, but study verifying this theory through experiment is little. The effects of external magnetic field on propagation of right-hand circularly polarized electromagnetic wave in plasma are studied with theoretical and experimental methods in this paper.

2. PHYSICAL MODEL

The physical model used in this paper is as follows: The waves are incident vertically into the plasma along the positive direction of the Z-axis, which is depicted in Figure 1. The plasma is assumed to be homogeneous, steady-state and collisional. The thickness of the plasma is d, which is set to 45 mm in the following numerical simulations.

The electromagnetic wave equation in homogeneous plasma is as following [16, 17]:

$$\nabla^2 E + k^2 E = 0, \tag{1}$$

The uniform plane wave solution can be obtained from Equation (1):

$$E(z) = E_0 e^{-ikz}, \tag{2}$$

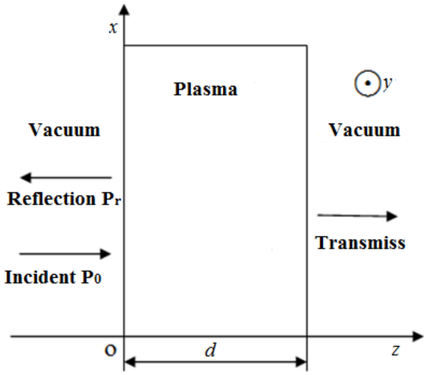

Figure 1. The physical model of the wave propagation in plasma.

where E_0 is the amplitude of incident electric field, respectively, $k = k_0\sqrt{\varepsilon_r} = \beta - i\alpha$ is the wave number in plasma, $k_0 = \frac{\omega}{c}$ is the wave number in vacuum, ω is the angular frequency of the wave, c is the speed of light in vacuum, ε_r is the relative permittivity of the plasma.

$$\beta = k_0 \mathrm{Re}(\sqrt{\varepsilon_r}) \quad (3)$$
$$\alpha = -k_0 \mathrm{Im}(\sqrt{\varepsilon_r}) \quad (4)$$

The relative permittivity of the unmagnetized plasma can be expressed as:

$$\varepsilon_r = 1 - \frac{\omega_p^2}{\omega^2 + \nu_{en}^2} - j\frac{\nu_{en}}{\omega}\frac{\omega_p^2}{\omega^2 + \nu_{en}^2} \quad (5)$$

The relative permittivity of the magnetized plasma if the magnetic field direction is along the positive Z-axis can be expressed as:

$$\varepsilon_r = 1 - \frac{\omega_p^2}{\omega^2\left[\left(1 - j\frac{\nu_{en}}{\omega}\right) \mp \frac{\omega_{le}}{\omega}\right]} \quad (6)$$

where "−", "+" correspond to the left-hand and right-hand polarized electromagnetic wave, respectively, $v_{en} = 2\pi f_{en}$, and f_{en} is the collision frequency of the plasma, $\omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}$ is the angular frequency of the plasma, $\omega_{le} = \frac{eB}{m_e}$ is the electron cyclotron frequency, n_e is the plasma electron density, e is the electron charge, m_e is the electron mass, ε_0 is the vacuum permittivity, B is the magnetic induction.

The electromagnetic waves are only reflected at the interface because there is no reflection of electromagnetic waves in uniform plasma. The reflected power can be expressed as:

$$P_r = P_0 \left| \frac{1-\sqrt{\varepsilon_r}}{1+\sqrt{\varepsilon_r}} \right|^2 \tag{7}$$

where P_0 is the incident power.

At a point (z, x) in the plasma, the electromagnetic power can be described as:

$$P(z) = \left| (P_0 - P_r) e^{-2ikz} \right| = (P_0 - P_r) e^{-2\alpha z} \tag{8}$$

Therefore, the attenuation of electromagnetic wave in plasma can be acquired and expressed as following:

$$Att = -10 \lg \frac{P(d)}{P_0} \tag{9}$$

3. NUMERICAL RESULTS AND ANALYSIS

3.1. The Effects of the Plasma Density on the Attenuation of Electromagnetic Wave Propagation

The variations of the attenuation of right-hand circularly polarized electromagnetic wave in unmagnetized and magnetized plasma along with the plasma density under fixed plasma collision frequency are obtained based on the physical model and theoretical analysis, which is depicted in Figure 2, where the electromagnetic wave frequency f is 2.4 GHz, and the magnetic induction of external magnetic field in magnetized plasma is 0.2 T.

We can see that there is a significant improvement in the attenuation of electromagnetic wave in plasma with 0.2 T external magnetic field, when the plasma collision frequency ranges from 5×10^8 Hz to 5×10^9 Hz. The attenuation of electromagnetic wave in unmagnetized plasma is almost more than 30 dB, and the maximum attenuation is up to 75 dB, when the plasma collision frequency $f_{en} = 5 \times 10^8$ Hz and the plasma density ranges from $10^{17}/\mathrm{m}^3$ to $10^{18}/\mathrm{m}^3$. But the attenuation of electromagnetic wave in plasma with 0.2 T external magnetic field is almost less than 30 dB. Therefore, the numerical results show that the attenuation of electromagnetic wave in plasma is obviously reduced by the presence of external magnetized field, and the biggest improvement reaches 40 dB.

3.2. The Effects of the Magnetic Field on the Attenuation of Electromagnetic Wave Propagation

The variations of the attenuation of right-hand circularly polarized electromagnetic wave in plasma along with the magnetic induction

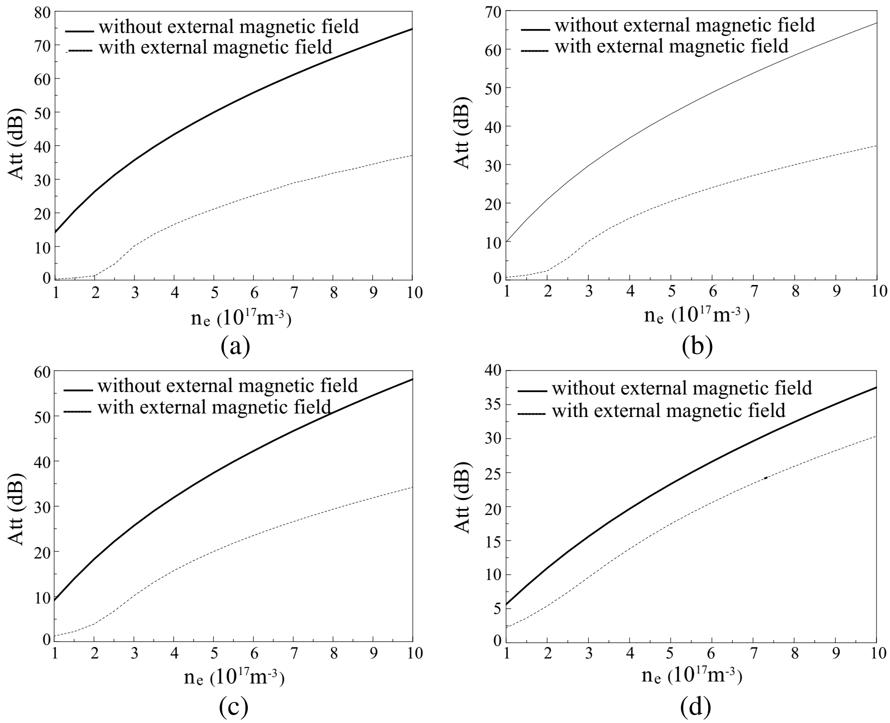

Figure 2. The variations of the electromagnetic wave attenuation along with the plasma density. (a) $f_{en} = 5 \times 10^8$ Hz; (b) $f_{en} = 10^9$ Hz; (c) $f_{en} = 2 \times 10^9$ Hz; (d) $f_{en} = 5 \times 10^9$ Hz.

of external magnetic field and the plasma density under fixed plasma collision frequency are obtained based on the physical model and theoretical analysis, which is depicted in Figure 3, where the electromagnetic wave frequency $f = 2.4$ GHz and the plasma collision frequency $f_{en} = 10^9$ Hz.

In Figure 3, we can find that the attenuation of electromagnetic wave in plasma decreases with increasing magnetic induction of external magnetic field for identical plasma collision frequency and plasma density. It can be explained as following: the electrons move as a circular motion with $\omega_{le} = \frac{eB}{m_e}$ cyclotron frequency in the plane which is perpendicular to the magnetic lines of force. The electromagnetic wave cannot propagate through a plasma when its frequency lies below the plasma frequency without an external magnetic field. The electron cyclotron orbit radius decreases with increasing magnetic induction of external magnetic field. The electron cyclotron orbit radius is zero

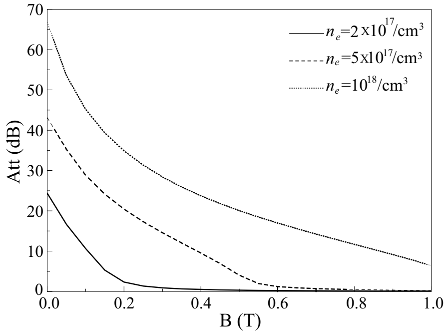

Figure 3. The variations of the electromagnetic wave attenuation along with the external magnetic field.

when the magnetic induction of external magnetic field is infinite, which can be regarded as that the electron is frozen in the plane. In that way, the right-hand circularly polarized electromagnetic wave can propagate through a plasma just as in vacuum because the electrons no longer interact with the plasma.

Furthermore, the magnetic induction of external magnetic field which reduces the attenuation of electromagnetic wave in plasma to 30 dB increases with increasing plasma density for identical plasma collision frequency. It needs 0.3 T external magnetic field to reduce the attenuation of electromagnetic wave in plasma to 30 dB when the plasma density n_e is $10^{18}/\mathrm{m}^3$.

4. EXPERIMENTAL RESULTS

The properties of electromagnetic wave in unmagnetized and magnetized plasma are studied experimentally with a plasma torch. The schematic diagram of the experimental setup is shown in Figure 4. The diameter of the plasma torch is 45 mm. The antenna is S-band right-hand circularly polarized microstrip antenna. The function of the metal baffle plate in schematic diagram is to prevent electromagnetic waves diffracting into the receiving antenna. The test has been done to estimate the efficiency of the metal baffle plate with vector network analyzer. The permanent magnet is Rubidium Iron Boron because of its strong magnetism. It can produce a uniform magnetic field of 0.2 T in the middle of the two permanent magnets, and the magnetic field direction is pointing from permanent magnets 1 to permanent magnets 2. A total of four effective experiments were carried out and we denote the experiments by numbers: 1, 2, 3, 4. The plasma densities and

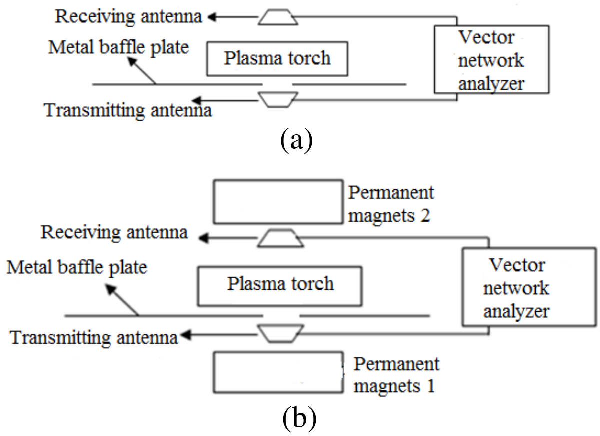

Figure 4. The experimental setup of the electromagnetic wave propagation in plasma. (a) Without external magnetic field, (b) with external magnetic field.

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

Number of the experiments	n_e (m^{-3})	f_{en} (Hz)
1	1.6×10^{17}	2.7×10^{9}
2	2.5×10^{17}	2.3×10^{9}
3	2.7×10^{17}	1.9×10^{9}
4	4.2×10^{17}	2.1×10^{9}

collision frequencies used in the experiments are presented in Table 1, which are calculated based on setting states of the plasma torch and spectrum diagnosis [18] in the experiments.

The theoretical and experimental comparisons of the electromagnetic wave attenuation in unmagnetized and magnetized plasma are respectively shown in Figures 5 and 6. The theoretical and experimental attenuations of right-handed circularly polarized electromagnetic wave in plasma with external magnetic field are less than the ones without external magnetic field for identical plasma collision frequency and plasma density. The maximum improvement of electromagnetic wave attenuation in plasma with external magnetic field can reach 13 dB in experiment. Therefore, the external magnetic field can slow down the attenuation of right-hand circularly polarized electromagnetic wave in

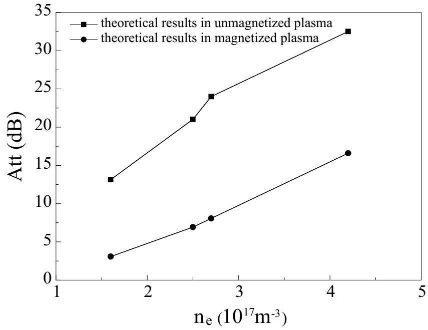

Figure 5. The theoretical comparison of the electromagnetic wave attenuation in unmagnetized and magnetized plasma.

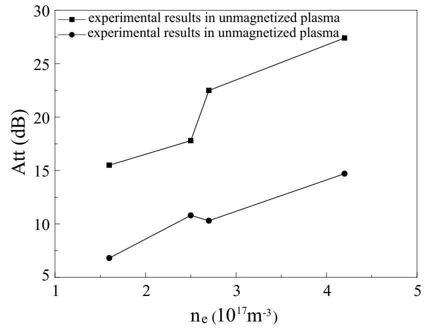

Figure 6. The experimental comparison of the electromagnetic wave attenuation in unmagnetized and magnetized plasma.

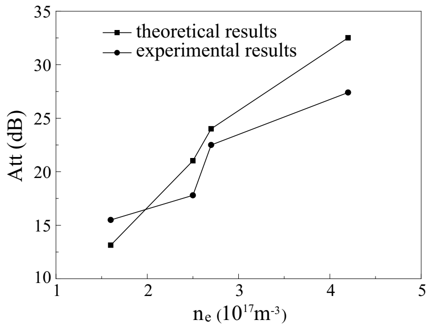

Figure 7. The comparison of the experimental and theoretical electromagnetic wave attenuation in unmagnetized plasma.

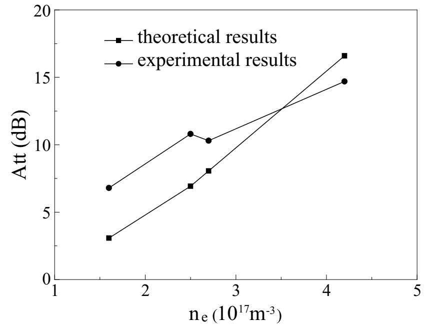

Figure 8. The comparison of the experimental and theoretical electromagnetic wave attenuation in magnetized plasma.

plasma. It provides an effective way to solve the blackout problem.

The comparison of the experimental and theoretical electromagnetic wave attenuations in unmagnetized plasma is shown in Figure 7, and the attenuations in magnetized plasma are shown in Figure 8. The experimental results match well with the theoretical ones which can be seen from Figures 7 and 8. 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. According to these reasons, the differences between the experimental and theoretical results are reasonable and understandable.

5. CONCLUSIONS

The effects of external magnetic field on electromagnetic wave propagation in plasma have been studied by theoretical and experimental methods in this paper. The results show that the attenuation of electromagnetic wave in plasma is obviously reduced by the presence of external magnetized field. We can find that the attenuation of electromagnetic wave in plasma decreases with increasing magnetic induction of external magnetic field, and the magnetic induction of external magnetic field which reduces the attenuation of electromagnetic wave in plasma to 30 dB increases with increasing plasma density for identical plasma collision frequency. The electromagnetic wave properties in unmagnetized and magnetized plasma are studied experimentally with a plasma torch, and the experimental results match well with the theoretical ones. Both the theoretical and experimental results show that external magnetic field can slow down the attenuation of right-hand circularly polarized electromagnetic wave in plasma. It provides a promising way to improve the radio blackout issue.

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