Propagation Properties of Electromagnetic Wave in a Plasma Slab*

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Abstract In this paper, the calculated results about the propagation properties of electromagnetic wave in a plasma slab are described. The relationship of the propagation properties with frequencies of electromagnetic wave, and parameters of plasma (electron temperature, electron density, dimensionless collision frequency and the size of the plasma slab) is analyzed.

Keywords: electromagnetic wave, plasma slab

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1 Introduction

Research on the propagation of electromagnetic wave in plasmas has been kept on for many years as a result of its development applications, such as broadcast communication, radio astronomy and plasma diagnostics with microwave [1~5]. The propagation properties of electromagnetic wave in plasma are related to many factors, such as the frequency of electromagnetic wave, electron density, electron temperature, collision frequency and size of the plasma slab. In this paper, some calculated results about propagation properties of electromagnetic wave in a plasma slab are presented. The effects of the electromagnetic wave and some parameters of plasma on the power transmissivity (T), reflectivity (R) and absorptivity (A) have been analyzed.

2 Calculation of propagation properties of electromagnetic wave

2.1 Basic relations

Maxwell's equations are

$$\begin{aligned}\nabla \cdot D &= \rho,\\ \nabla \cdot B &= 0,\\ \nabla \times E &= -\frac{\partial B}{\partial t},\\ \nabla \times H &= J + \frac{\partial D}{\partial t},\end{aligned} \tag{1}$$

where ρ is the volume density of free charge and J the explicit current density.

In the following, we will consider the case of plasma medium and $\rho = 0, J = 0$. In this case, the relationships between D and E, B and H are

$$\begin{aligned}D(\omega) &= \varepsilon(\omega)E(\omega),\\ B(\omega) &= \mu(\omega)H(\omega),\end{aligned} \tag{2}$$

where ω is the frequency of the electromagnetic wave.

In a plasma medium, we can consider the permeability $\mu = \mu_0$ and the complex dielectric constant ε as functions of electrons density, collision frequency

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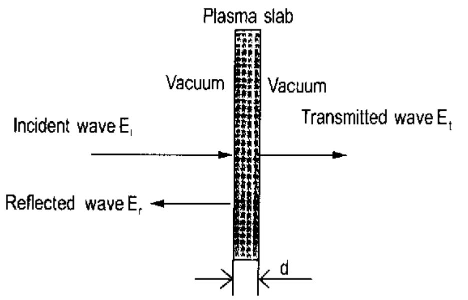

Fig.1 One-dimension model for calculation

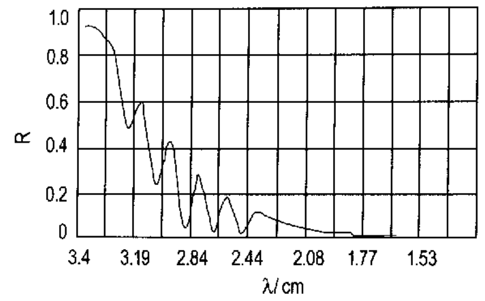

Fig.2 The relationship between the wavelengths λ and the reflectivity of plasma R (T_e =1.5 eV, n_e = $1 \times 10^{12}/\mathrm{cm}^3$, $\nu/\omega = 0.1$, $d = 3$ cm)

of plasma and frequency of electromagnetic wave

$$\varepsilon = \varepsilon_0\Big[\big(1 - \frac{\omega_p^2}{\omega^2+\nu^2}\big) + \mathrm{i}\frac{\nu\omega_p^2}{\omega(\omega^2+\nu^2)}\Big], \qquad (3)$$

where ν is the collision frequency of plasma, ω_p is the frequency of plasma, ε_0 is the dielectric constant in vacuum.

In this calculation, we assume:

a. The electromagnetic wave is a plane wave and has a single frequency.

b. The plasma slab is a homogeneous medium.

c. The incident wave travels vertically on the plasma slab.

d. The effects of electromagnetic wave on plasma can be neglected for the low-power electromagnetic wave.

In this case, the propagation properties of electromagnetic wave (power reflectivity, transmissivity and absorptivity) in a plasma slab can be calculated.

2.2 Calculated results

Fig. 1 shows the one-dimension calculation model of electromagnetic wave propagation in a plasma slab.

The power reflectivity, transmissivity and absorptivity for the plasma slab are

$$R = \big(\frac{E_r}{E_i}\big)^2,$$

$$T = \big(\frac{E_t}{E_i}\big)^2, \qquad (4)$$

$$A = 1 - R - T,$$

where E_r, E_t and E_i are the electric fields for the reflected wave, transmitted wave and incident wave, respectively.

The R, T and A can be caculated with the above relations.

In the following, we will present some calculated results of the propagation of the electromagnetic wave in a plasma slab. Fig. 2 shows the relationship between the wavelengths and the reflectivity of plasma. It can be seen from Fig. 2 that for the electromagnetic wave from a longer wavelength plasma slab has a higher reflectivity. The conditions for the calculation are as follows: the electron temperature of the plasma is 1.5 eV; the electron density is $1 \times 10^{12}/\mathrm{cm}^3$; the dimensionless collision frequency v/ω of plasma is 0.1.

Fig. 3 shows the relationship between the wavelengths and the transmissivity for the wave of a shorter wavelength plasma slab has higher transmission coefficient.

Fig. 4 shows the relationship between the wavelengths and the absorptivity of plasma. It can be seen from Fig. 4 that only the wave of a certain wavelength can be absorbed. The wave of a longer wavelength will be reflected by the plasma slab, and the

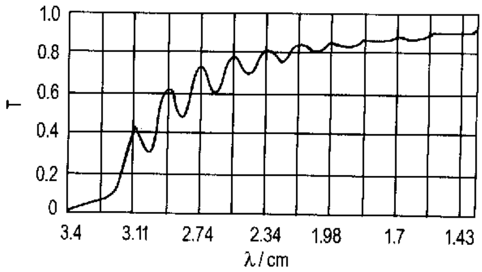

Fig.3 The relationship between the wavelengths λ and the transmissivity T ($T_e = 1.5$ eV, $n_e = 1 \times 10^{12}/\mathrm{cm}^3$, $\nu/\omega = 0.1$, $d = 3$ cm)

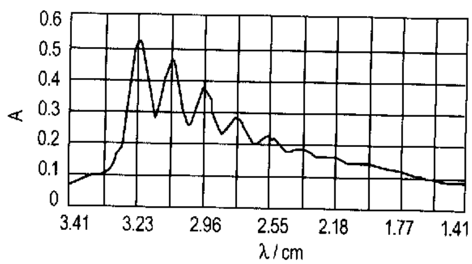

Fig.4 The relationship between the wavelengths λ and the absorptivity A ($T_e = 1.5$ eV, $n_e = 1 \times 10^{12}/\mathrm{cm}^3$, $\nu/\omega = 0.1, d = 3$ cm)

wave of a shorter wavelength will transmit through the plasma slab. The phenomena show that if we want to get a much more absorption of the wave, the parameter of the plasma must match the wavelength of the electromagnetic wave.

Fig. 5 shows the relationship between the wavelengths and the absorptivity when the dimensionless collision frequency (ν/ω) is 0.5. It can be seen from Fig. 5 that when the plasma has a higher collision frequency, it will have a higher absorptivity. And under this condition the absorptivity of plasma can reach 0.9. So the collision frequency (ν) is a very important factor for the absorptivity.

Fig. 6 shows the relationship between the thickness of the plasma slab and R, T, A, respectively. It can be seen from Fig.6 that when the thickness of

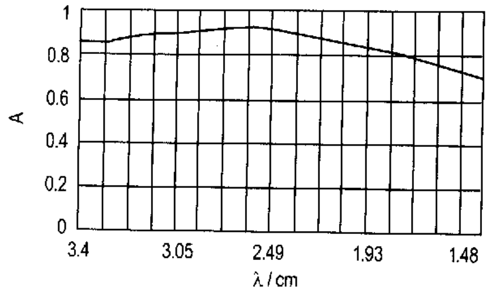

Fig.5 The relationship between the wavelengths λ and the absorptivity A ($n_e = 1 \times 10^{12}/\mathrm{cm}^3, d = 3$ cm, $T_e = 1.5$ eV , ν/ω =0.5)

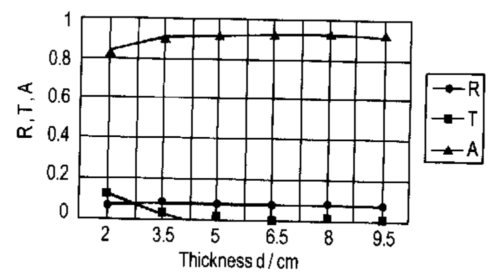

Fig.6 The relationship between the thickness of the plasma slab d and R, T, A, respectively ($\nu/\omega = 0.5, n_e = 1 \times 10^{12}/\mathrm{cm}^3, \lambda = 3$ cm, $T_e = 1.5$ eV)

the plasma slab is more than one to two wavelengths, the effects of the plasma thickness on the parameters (R, T, A) is not very obvious.

Fig. 7 shows the relationship between the electron densities and R, T, A, respectively. It can be seen from Fig. 7 that the reflectivity will increase with the increase in electron density, and the absorptivity will decrease with the increase in electron density.

Fig. 8 shows the relationship between the dimensionless collision frequencies of plasma (ν/ω) and R, T, A. It can be seen from Fig. 8 that the absorptivity will increase with the increase in collision frequency of plasma. In reverse, the transmissivity and the reflectivity will decrease with the increase in dimensionless collision frequency of plasma.

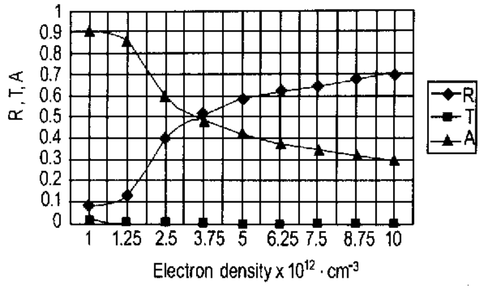

Fig.7 The relationship between the electron densities n_e and R, T, A, respectively (λ = 3 cm, d = 3.5 cm, T_e = 1.5 eV, $\nu/\omega = 0.5$)

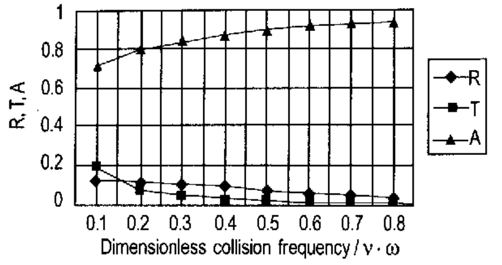

Fig.8 The relationship between the dimensionless collision frequencies of plasma (ν/ω) and R, T, A, respectively ($n_e = 1 \times 10^{12}/\text{cm}^3$, d = 3.5 cm, λ = 2 cm, T_e = 1.5 eV)

When the plasma is inhomogeneous in propagation direction, the stratified layer model can be used for calculation of propagation characteristics of the electromagnetic wave. The research work on this area will be described on the next paper.

3 Discussion

When we consider the propagation properties of the electromagnetic wave of a low-power plasma, the effects of electromagnetic wave on the plasma can be neglected. So the main phenomena of the electromagnetic wave propagating in plasmas are reflection, transmission and absorption. The power reflectivity, transmissivity and absorptivity are related to frequencies of the electromagnetic wave and properties of plasma (electron temperature, electron density, dimensionless collision frequency and the size of the plasma slab).

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