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TRANSMISSION AND ABSORPTION OF MICROWAVES BY AN INHOMOGENEOUS SPHERE PLASMA

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Abstract

The numerical calculation of the transmission and absorption of microwaves at an arbitrarily incident angle to the inhomogeneous spherically symmetric plasma is presented. The nonuniform sphere is modeled by a series of concentric spherical shells, and the electron density is constant in each shell. The overall density profile follows any given distribution function. By using the geometrical optics approximation and considering the propagation coefficient is complex, as well as the attenuation and phase coefficients are vectors, the detailed evaluation shows that the transmission and absorption of microwaves in the inhomogeneous spherically symmetric plasma depend on the electron and neutral particle collision frequency, central density, incident angle of the microwaves and density distribution profiles.

Key words Sphere plasma, Microwaves

1 Introduction

In 1960s, the experiments in ionosphere were observed that the weakly ionized plasma can absorb the microwaves[1]. It opens up a field for making the broadband microwave absorber. Recently, one of the most important issues is to explore the possibility of using artificial plasmas as the microwave absorbers[2]–[6]. It is well known that the artificial weakly ionized plasma objects can be different shapes such as slabs, cylinders, spheres, and so on. The difference of sphere plasma and planar plasma is that the microwaves diffract from sphere plasma, and the RCS of a target is reduced by refraction of microwaves in the plasma sphere[7]. Two techniques in Ref.[8], the Scattering Matrix Model (SMM) and the Impedance Boundary Condition (IBC) methods, are used to study the microwaves scattering

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by the nonuniform plasma sphere. The SMM method can only be used to study the normal incident microwaves, and the IBC method has its special application criteria. In this paper, we present the numerical calculation of the transmission and absorption of microwaves at an arbitrarily incident angle in the inhomogeneous spherically symmetric plasma. The effects of the central density, the collision frequency and the angle of propagation on the transmission and absorption of microwaves are evaluated for a large-scale plasma sphere ($R_0 = 80\,\mathrm{m}$), which becomes particularly interesting for making the microwave absorber.

In linear model, the absorption of microwaves by plasma is caused by collision and resonance. In the paper, we only consider the collision absorption.

2 Formulation

The nonuniform sphere is modeled by a number of concentric spherical shells. Let us suppose that each spherical shell has a uniform electron density, so it is agreed that the transmission of microwaves in the plasma sphere amounts to the transmission in the stratified plasma sphere. Fig.1 shows the transmission of microwaves in the stratified plasma sphere. In the calculation, we are dealing with the first reflection on each shell, and the effect of secondary reflection is ignored. Under the weakly ionized plasma conditions, and ignoring the ion momentum, we consider the effect of the electron and neutral particle collision. From the electron momentum equation and Maxwell equations, we can obtain the dispersion relation of microwaves as follows:

$$k(\omega) = \frac{\omega}{c}\sqrt{\tilde{\varepsilon}} = \frac{\omega}{c}\left[1 - \frac{\omega_{\mathrm{p}}^2}{\omega(\omega - \mathrm{i}\nu)}\right]^{1/2}, \tag{1}$$

where ν is the electron and neutral particle collision frequency, ω is the angular frequency of the incident microwaves, $\omega_{\mathrm{p}} = (4\pi n_{\mathrm{e}} e^2/m_{\mathrm{e}})^{1/2}$ is the electron plasma frequency, $\tilde{\varepsilon}$ is the complex dielectric constant. Due to the effect of the particles collision, the wave number $\boldsymbol{k}$ is given by

$$\boldsymbol{k} = \boldsymbol{k}_r - \mathrm{i}\boldsymbol{k}_i, \tag{2}$$

where $\boldsymbol{k}_r$ is the phase coefficient, and $\boldsymbol{k}_i$ is the attenuation coefficient. Noticing $\boldsymbol{k}$ is a vector, we cannot obtain the values of k_r and k_i only from Eq.(1). Starting from Eq.(1), we introduce the electromagnetic waves refraction law, and the relation between the refraction angle and the reflection angle on the sphere. The equations for the numerical computation are determined by

$$k_r^2(N) - k_i^2(N) = \frac{\omega^2}{c^2}\left[1 - \frac{\omega_{\mathrm{p}}^2(N)}{\omega^2 + \nu^2}\right], \tag{3}$$

$$k_r(N)k_i(N)\cos\left[\sum_{m=1}^{N-1}\varphi(m) - \sum_{m=2}^{N-1}\theta(m)\right] = \frac{1}{2c^2}\frac{\omega_{\mathrm{p}}^2(N)\omega\nu}{\omega^2 + \nu^2}, \tag{4}$$

$$k_r(N)r(N-1)\sin\varphi(N-1) = \frac{\omega}{\mathrm{c}}R_0\sin\theta_0, \tag{5}$$

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where θ_0 is the incident angle of microwaves, $\varphi(N)$ is the refraction angle in the N layer, R_0 is the radii of the plasma sphere, $k_r = |\boldsymbol{k}_r|$ and $k_i = |\boldsymbol{k}_i|$, respectively. In obtaining Eq.(4), we assume the plasma is a good conductor, so the direction of $\boldsymbol{k}_i$ is always along the normal direction of microwaves which is equal to the radial direction in the sphere. And we use the same reflection coefficient and transmission coefficient as being used in the slab[7], considering that the radii of the sphere is very large and the curvature of the sphere is small.

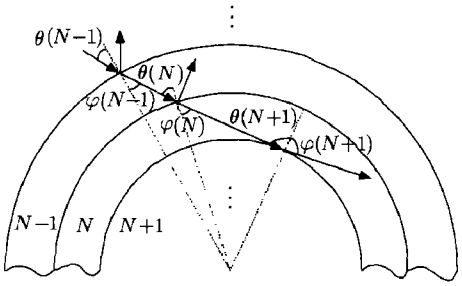

Fig.1 Transmission of microwaves in the stratified plasma sphere

In the geometrical-optical approximation, we don't care for the phases of microwaves. So the reflected power and the transmitted power are averaged in the total phase space. Assuming the absorbed power is P_{A} and the incident power is unity, one immediately obtains

$$P_{\mathrm{A}} = 1 - P_{\mathrm{R}} - P_{\mathrm{T}}, \tag{6}$$

where P_{R} and P_{T} is the reflected power and the transmitted power, respectively.

In the following analysis, we take the radii of the plasma sphere $R_0 = 80\,\mathrm{m}$. Three typical density distribution profiles are presented: the linear distribution n_{l}, the exponential distribution n_{exp} and the Epstein distribution n_{Ep}, as following

$$n_{\mathrm{l}} = N_0\Big[1 - \frac{r(N)}{R_0}\Big], \qquad n_{\mathrm{exp}} = N_0 \exp\Big[-5\frac{r(N)}{R_0}\Big],$$
$$n_{\mathrm{Ep}} = N_0\Big\{1 + \exp\Big[\frac{r(N) - R_0/2}{\sigma}\Big]\Big\}^{-1}, \tag{7}$$

where N_0 is the central density of plasma sphere, $r(N)$ is the radii of the Nth spherical shell, σ is a parameter which shows the characteristic of Epstein distribution, in our study, $\sigma = R_0/10$.

3 Numerical Results and Discussion

The density configuration of plasma shells will be approaching the given distribution profile with the increasing number of plasma shells. Fig.2 shows the absorbed power versus the number of plasma shells. It is clear from this figure that, the absorbed power is

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approximately constant with the increasing number of plasma shells when the number of plasma shells is over 2000. In that case, the precision of calculation is still good enough even if the parameters (N_0, θ_0, f, ν) are changed. More and more of computation time are required with the increasing number of plasma shells. In the paper, the plasma sphere is divided into 2000 concentric spherical shells, on this condition, we can take better precision of calculation and spend less time in computation.

Fig.3 shows the absorbed power versus the frequency of microwaves for three density distribution profiles, the plasma parameters are set to $N_0 = 1 \times 10^{12}\,\mathrm{cm}^{-3}$, $\nu = 10\,\mathrm{MHz}$, $\theta_0 = 10°$. On the given conditions, for the exponential profile, the linear profile and the Epstein profile there are the peak values of absorbed power where the frequencies are near 1.80 GHz, 6.89 GHz and 9.0 GHz, respectively. For Epstein profile starting from $f = 2\,\mathrm{GHz}$ and going to $f = 9\,\mathrm{GHz}$, there exists a broadband frequency region where the absorption of

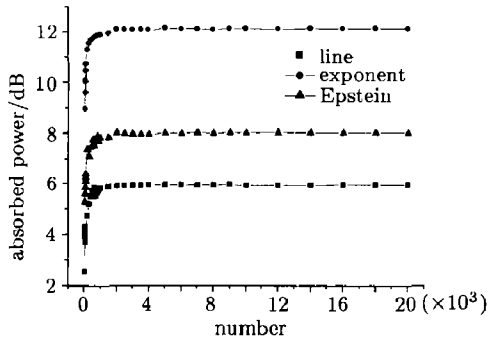

Fig.2 Absorbed power versus the number of plasma shells, $\nu = 20\,\mathrm{MHz}$, $\theta_0 = 10°$, $f = 1\,\mathrm{GHz}$, $N_0 = 1 \times 10^{11}\,\mathrm{cm}^{-3}$

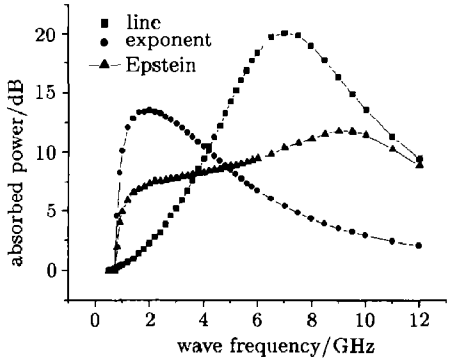

Fig.3 Absorbed power versus wave frequency for three distribution profiles, $N_0 = 1.0 \times 10^{12}\,\mathrm{cm}^{-3}$, $\theta_0 = 10°$, $\nu = 20\,\mathrm{MHz}$

microwaves slowly varies with the frequency. And the region still exists even when the plasma parameters (N_0, ν, θ_0) are changed. In other two profiles, we do not find this property. Therefore, it is worth noticing that the plasma following Epstein profile is a good candidate for making the microwave absorber with broadband frequency.

Fig.4 shows the absorbed power for Epstein profile versus the frequency of microwaves with $\nu = 20\,\mathrm{MHz}$ and $\theta_0 = 10°$ for three values of the central density $N_0 = 1 \times 10^9\,\mathrm{cm}^{-3}$, $1 \times 10^{10}\,\mathrm{cm}^{-3}$ and $1 \times 10^{11}\,\mathrm{cm}^{-3}$. It will be seen that, with increasing value of central density N_0, the effective frequency width of absorption becomes wider, the peak absorbed power moves toward the higher frequency. This result is the same as the slab model[6],[7]. The peak absorbed power for the values of central density $N_0 = 1 \times 10^9\,\mathrm{cm}^{-3}$, $1 \times 10^{10}\,\mathrm{cm}^{-3}$, and $1 \times 10^{11}\,\mathrm{cm}^{-3}$ are near the frequencies of 0.3 GHz, 0.9 GHz and 3 GHz, respectively. For the given distribution profile, the value of the plasma density of each spherical shell increases with the increasing value of the central density, and the cut-off frequency increases also, so the frequency corresponding to the peak absorbed power moves to the higher frequency. It is

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seen that the frequency corresponding to the peak absorbed power increases with increasing central density, but the value of absorbed power is nearly not changed, which is different from the slab model. A reasonable cause is that the absorption and reflection of microwaves interact with each other and reach a balance finally.

In Fig.5 the variation of the absorbed power with the collision frequency is shown for $N_0 = 1 \times 10^9\,\mathrm{cm}^{-3}$, $f = 2\,\mathrm{GHz}$ and $\theta_0 = 10°$. There is a peak value of absorbed power with the increasing collision frequency. Physically, this can be explained that the resonance absorption can appear in the plasma when the electron and neutral particle collision frequency approaches the frequency of incident waves.

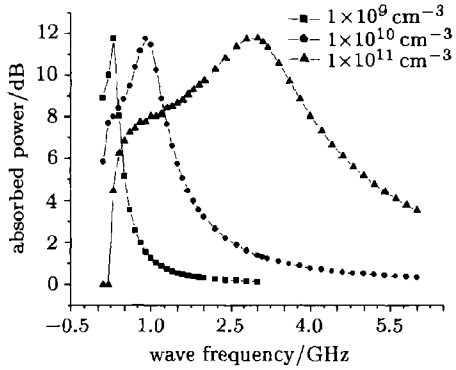

Fig.4 Absorbed power versus wave frequency with different values of central density for Epstein profile, $\theta_0 = 10°$, $\nu = 20\,\mathrm{MHz}$

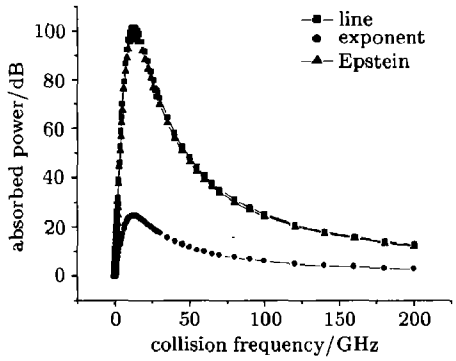

Fig.5 Absorbed power versus electron-neutral particle collision frequency for three distribution profiles, $\theta_0 = 10°$, $f = 2\,\mathrm{GHz}$, $N_0 = 1 \times 10^9\,\mathrm{cm}^{-3}$

An explicit numerical evaluation of the absorbed power as a function of central density is presented in Fig.6 for $f = 1\,\mathrm{GHz}$, $\nu = 10\,\mathrm{MHz}$, and for three values of the incident angle of microwaves, $\theta_0 = 0°$, $10°$, $20°$. There exists a value of central density corresponding to the peak absorption. It is because that when the value of central density is high enough,

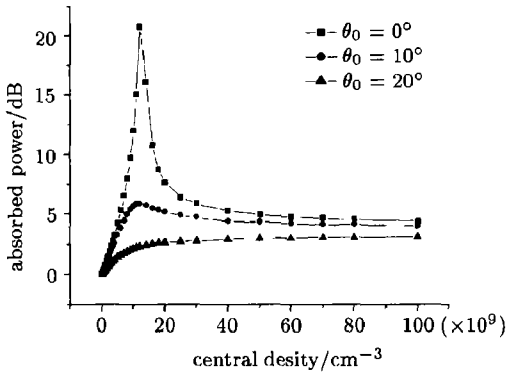

Fig.6 Absorbed power versus the values of central density for different incident angles of microwaves, $f = 1\,\mathrm{GHz}$, $\nu = 10\,\mathrm{MHz}$ and the density profile follows Epstein distribution

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namely, $\omega < \omega_p$, the absorbed power of microwaves mainly come from the cut-off layer, the reflection becomes larger and absorption becomes smaller. Otherwise, in Fig.6 one can also see that the value of the peak absorbed power decreases with the increasing incident angle of microwaves. It is seen that for small θ_0 we get more absorption.

4 Conclusion

We have presented a proper model for calculating the absorption and transmission of microwaves at an arbitrarily incident angle in the inhomogeneous spherically symmetric plasma. This model makes it easy to analyze the transmission, absorption and reflection of microwaves at an arbitrarily incident angle in the large size plasma sphere. The numerical calculation shows that the absorption property of plasma depends strongly on the wave frequency, central plasma density, the electron and neutral particle collision frequency and the incident angle of microwaves. For the Epstein distribution profile, there exists a broadband frequency region where the microwaves are slowly absorbed. Otherwise there is a peak value of absorbed power with the increasing collision frequency and central density. Choosing the suitable plasma parameters, we can get the optimum absorbed power. The results will give reference value to the study of the microwave absorber with broadband frequency.

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