Energy absorption effects of the electromagnetic waves in collisional dusty plasmas

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Energy absorption of electromagnetic (EM) waves in collisional dusty plasmas has attracted much attention from researchers due to its applications in many fields, such as plasma antennas, blackout research during reentry, plasma stealth technology, and the design of microwave transmission in plasmas. In this paper, the propagation characteristics, in particular, the energy absorption effects of EM waves in partially ionized unmagnetized collisional dusty plasmas, are investigated. The results show that the effective energy absorption of EM waves is mainly due to the interaction between electrons and waves, and the plasmas with proper collisional frequencies can be used as a broadband frequency EM wave absorption medium with moderate absorption efficiency. Quantitative analyses of the characteristics of the EM waves that propagate in the collisional dusty plasmas are also included in this study.

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I. INTRODUCTION

Partially ionized unmagnetized collisional dusty plasmas have the features of high collisional frequency, adjusted percentage of electrons and other negative particles, high number density of atoms/molecules, and so on. Such characteristics make them widely applicable in many research fields, including the interaction with electromagnetic (EM) waves, materials processing, and plasma-biotechnology.1-3 The propagation of EM waves in such plasmas has attracted much attention from researchers in the past decades because many applications, such as plasma stealth of hypersonic vehicles and plasma antenna technologies, are related to such research.4-18 For example, the air around a spacecraft surface is at high temperature and it is ionized to form a plasma slab during reentry at high speed in the near space, and the interaction between the plasma slab and the EM wave will seriously interfere or even completely block the vehicle communication; thus, the blackout phenomenon is formed. Simultaneously, the energy absorption effect of the EM waves in plasma can be used for the elimination of radar reflections by the plasma slab with proper parameters. The physical characteristics of such a phenomenon can be attributed to the issue of EM wave propagation in high number density, weakly ionized, and nonmagnetized collisional dusty plasmas.11-16 In the nonmagnetized collisional dusty plasmas, electron-neutral collisions are responsible for dissipating the wave energy into the neutral gas background, and the EM wave energy is mainly transported to the electrons and dissipates when colliding with the neutral gases.17-21 Thus, the collision effect for EM wave energy absorption is an issue for both investigations of the plasma physics and extending the applications of the EM wave energy absorption effects in collisional dusty plasmas.

In fact, there is already a fairly substantial amount of published work on the propagation characteristics of EM waves in nonuniform collisional plasma slabs (i.e., reflection, absorption, and transmission characteristics). Different models and solving methods are introduced in this field, including Wentzel-Kramers-Brillouin (WKB), Finite-Difference Time-Domain (FDTD), Scattering Matrix Method (SMM), and theoretical analysis. Previous works indicated that the geometrical-optical approximation is an effective way to study the EM wave propagation process in collisional dusty plasmas,22-24 and
the absorption, reflection, and transmission of EM waves can be revealed using such a research technique. However, the characteristics of the plasma slabs are quite different from case to case, and the parameters of the EM waves vary a lot, so investigations of the propagation characteristics of EM waves in collisional dusty plasmas are a complicated issue.

In this paper, the key physical propagation process of EM waves in collisional dusty plasmas is considered and calculations on the energy absorption effects are performed. All the calculations are performed using normalized parameters compared with the plasma frequency (\(\omega_{pe}\)) so that the physical essence can be revealed more clearly. The calculation results will be useful for deep understanding of the transmission behaviors of typical EM waves in nonuniform collisional dusty plasmas, and they are the guide for the design of broadband EM wave absorption media with moderate efficiency.

The layout of the paper is as follows: models are described in Sec. II, and the calculation results and discussion are described in Sec. III. Finally, the paper is summarized in Sec. IV by concluding remarks.

II. MODEL DESCRIPTIONS

The geometrical optics model is adopted in this paper, which is the same as that described in Ref. 26. The schematic diagram of the EM wave propagation model is shown in Fig. 1. In this model, the electromagnetic wave is assumed to be a plane wave launched at a vertical angle of incidence to the plasma slab. The total power incident from the air into the plasma is \(P_i\), and \(P_a\), \(P_r\), and \(P_t\) represent absorbed, reflected, and transmitted power, respectively. Thus, \(P_i = P_a + P_r + P_t\) at the interface between plasma and air. In this study, the skin depth is much smaller than the thickness of the plasma slab, and the wave propagates perpendicular to the air-plasma interface, so the geometrical-optical approximation is applicable for the calculation of the propagation characteristics of the EM waves. Maxwell’s equations are applicable as follows when the electromagnetic wave propagates in the plasma slab:

\[
\nabla \times E = -j\omega \mu_0 H,  \tag{1}
\]

\[
\nabla \times H = j\omega \varepsilon_0 E,  \tag{2}
\]

where \(\varepsilon_r = 1 - \frac{n_p^2}{\nu_m^2}\) is the plasma complex dielectric coefficient. The dispersion relation can be obtained when the wave propagates in the \(x\) direction, i.e., \(E = E_0 \exp(j\omega t - \vec{\nu} \cdot \vec{r})\). Thus, it can be expressed as

\[
\tilde{\nu}^2 = -\varepsilon_0 \frac{\omega^2}{c^2},  \tag{3}
\]

where \(\tilde{\nu}\) is the complex propagation constant that is expressed as \(\tilde{\nu} = \alpha + j\beta\). \(\alpha\) and \(\beta\) are the attenuation coefficient and the phase coefficient, respectively,

\[
\tilde{\nu}_p = 1 - \left(\frac{\omega^2}{\omega^2 + \nu_m^2} + \frac{\omega^2}{\omega^2 + \nu_m^2} + \frac{\omega^2}{\omega^2 + \nu_m^2}\right) - j \left(\frac{\omega^2 \nu_m}{\omega^2 + \nu_m^2} + \frac{\omega^2 \nu_m}{\omega^2 + \nu_m^2} + \frac{\omega^2 \nu_m}{\omega^2 + \nu_m^2}\right),  \tag{4}
\]

where \(\omega_{pe} = (n_e^2 \gamma_m^2)^{1/2}, \omega_{p_e} = (n_e^2 \gamma_m^2)^{1/2},\) and \(\omega_{p_m} = (n_m^2 \gamma_m^2)^{1/2}\) and the charge neutrality condition is applied as \(n_e = n_m + n_n\).

At the air-plasma interface (\(z = 0\)), the initial reflection power can be expressed as

\[
P_{\text{br}} = \frac{1 - \sqrt{\varepsilon_r}}{1 + \sqrt{\varepsilon_r}} P_i \equiv \lambda P_i,  \tag{5}
\]

where \(\lambda = \left(1 - \sqrt{\varepsilon_r}\right)/\left(1 + \sqrt{\varepsilon_r}\right)\) is the air-to-plasma reflection ratio, while \(\lambda' = \left(\sqrt{\varepsilon_r} - 1\right)/\left(\sqrt{\varepsilon_r} + 1\right)\) is the plasma-to-air reflection ratio. The power of the electromagnetic wave inside the plasma slab can be expressed as follows:

\[
P(z) = P_i \exp(-2\alpha z) = (P_i - P_{\text{br}}) \exp(-2\alpha z) = (1 - \lambda)P_i \exp(-2\alpha z) = (1 - \lambda)P_i \delta,  \tag{6}
\]

where \(\delta\) is the absorption power, and the total transmission power can be expressed as

\[
P_t = (1 - \lambda)^2 \delta[1 + \left(\lambda^2 \delta^2\right) + (\lambda^2 \delta^2)^2 + \cdots]P_i = \left[(1 - \lambda)^2 \delta/(1 - \lambda^2 \delta^2)\right]P_i.  \tag{7}
\]

Then, the total reflection of the electromagnetic wave on the plasma surface (the air-plasma interface) can be expressed as

\[
P_r = \lambda P_i + P_t (1 - \lambda)^2 \times \lambda \delta^2[1 + (\lambda^2 \delta^2)^2 + (\lambda^2 \delta^2)^3 + \cdots].  \tag{8}
\]

As \(\lambda \delta < 1\), the above formula can converge to

\[
P_r = \lambda P_i + P_t (1 - \lambda)^2 \lambda \delta^2 / (1 - \lambda^2 \delta^2).  \tag{9}
\]

Then, the total absorption of the plasma layer is

\[
P_a = P_i - P_r = P_t (1 - \lambda)(1 + \lambda \delta)/(1 - \lambda^2 \delta^2).  \tag{10}
\]

Thus, the absorbed, reflected, and transmitted power can be obtained from the expressions mentioned above.

III. RESULTS AND DISCUSSIONS

Based on the model described above, simulations are performed to investigate the influences of the dusty plasma components and the collisional frequency between electrons and neutral gases on the energy absorption effects of the electromagnetic waves. The plasma density \(n_p\) is set to be \(10^{17}\) cm\(^{-3}\) (a moderate plasma...
density in the experiment), and the plasma frequency ($\omega_{pe}$) is calculated to be $1.8 \times 10^{10}$ Hz. The dusty plasma in this study consists of positive ions, electrons, and negative ions (formed by the dust in the plasma). Generally, the EM wave frequency ($\omega_0$) should be higher than the plasma frequency, so that the EM wave can penetrate the plasma slab and the propagation characteristics can be investigated. In this paper, the EM wave frequency is set to be $9 \times 10^{10}$ Hz ($5\omega_{pe}$) to study the influence of the plasma slab thickness and plasma component on the absorption of the EM wave energy.

Figure 2(a) shows the energy absorption of the EM wave with different $\eta$, where $\eta = n_e/n_p$ stands for the electron percentage in the dusty plasmas. Other negative charges are negative ions formed by the dust in the plasma, and the plasma thickness is fixed to be 10 cm. It can be seen that the higher $\eta$ is, the higher the absorption peak value is. Simultaneously, wider absorption broadening is also accompanied by higher $\eta$. The energy absorption effect becomes weaker with the decrease of $\eta$, which means that the effective energy absorption of the EM wave is mainly due to electrons (not the negative ions). The difference between electrons and negative ions is the mass of the particle, and electron with smaller mass can respond to the changes in the electromagnetic field with time, and the energy absorbed from the EM waves can be transformed into thermal energy by collisions between electrons and neutral particles. Figure 2(b) shows the curves of energy absorption values with different components, where the collisional frequencies are set to be $v_{en} = 5\omega_{pe}$, $v_{en} = 10\omega_{pe}$, and $v_{en} = 50\omega_{pe}$, and the plasma slab thickness is 10 cm. It can be seen that the nonlinear relationship of the absorbed energy is applicable with the increase of $\eta$ for a given collisional frequency, and the nonlinear relationships are quite different for different collisional frequencies. If the electron percentage ($\eta$) is too low, the EM wave energy can hardly be absorbed. From this point of view, some kinds of dust in plasma which absorb electrons to form negative ions can decrease the EM wave absorption effectively. In fact, free electrons are usually absorbed by adding substance for the relief of blackout phenomenon during spacecraft reentry process based on this principle.

Figure 3(a) shows the energy absorption of the EM wave in plasma slabs with different thicknesses (where $\eta$ is fixed to be 1), and the thicknesses of the slab are set to be 0.1 m, 0.3 m, 0.5 m, and 1.0 m. As the plasma density is $10^{11}$ cm$^{-3}$, the skin depth ($d_e$) is calculated to be 1.68 cm, so the subwavelength effect can be neglected.
The energy absorption effects of the EM wave changing with collisional frequencies at different EM wave frequencies are shown in Fig. 4. Without loss of generality, the negatively charged particle component is assumed to be electrons only (namely $\eta = 1$). In fact, the EM wave energy is absorbed mainly by the electrons rather than the ions or the negative ions because the mass of the electron is much smaller than that of the ion or negative ion, so the electron response to time-variant EM field changes fast and they lose energy by means of collisions with the heavy particles (ions and atoms). In addition, the role of negative ions is similar to the role of ions as they have the same mass during EM wave propagation in the dusty plasmas. The energy absorption peaks appear at the resonance absorption points where the EM wave frequencies are the same values as collisional frequencies. Also, the differences of energy absorption among different collisional frequencies decrease with the increase of collisional frequencies. For example, the difference of energy absorption is large when the collisional frequency is less than $10\omega_{pe}$, while the difference is quite small when the collisional frequency is close to $30\omega_{pe}$. Hence, the collisional frequency is an issue for the energy absorption of EM wave propagation in the plasma slab. To further investigate the influence of collisions on the energy absorption effect of EM waves, the collisional frequency is studied in detail below.

Figure 5 presents the EM wave energy absorption effects changing with EM wave frequencies at different collisional frequencies, where the inset (a) shows the energy absorption at the broadband collisional frequency and the inset (b) shows the energy absorption curves for the moderate collisional frequencies (at around $10\omega_{pe}$) that are concerned with the broadband EM wave absorption medium. It can be seen from Fig. 5(a) that the energy absorption peaks appear at the resonance absorption points where the EM wave frequencies are the same values as plasma frequencies ($\omega_0 = \omega_{pe}$), and the absorption peak broadening becomes wider with increasing collisional frequencies. For the case of weaker collisional frequencies ($\omega_{en} < \omega_{pe}$), the energy absorption of EM waves exhibits selections for the absorption effects of the wave frequency. While for the case of stronger collisional plasmas, the energy can be absorbed in a wide EM wave frequency range; however, the total energy absorption values are at a lower level compared with the energy absorption peak value of the weaker collisional plasmas. Also, the total energy absorption value is at a very low level when the collisional frequency...
FIG. 6. EM wave energy absorption effects changing with plasma slab thickness and the wave frequency at different collisional frequencies (η = 1), where \( \nu_{en} = 5\omega_{pe} \) for inset (a), \( \nu_{en} = 10\omega_{pe} \) for inset (b), \( \nu_{en} = 15\omega_{pe} \) for inset (c), and \( \nu_{en} = 20\omega_{pe} \) for inset (d).

is too high (e.g., \( \nu_{en} > 30\omega_{pe} \)) because in that case, the plasma characteristics for the EM waves are rather weak. Thus, for the plasma with moderate collisional frequency, it can be used as a good absorption medium in a wide frequency spectrum to some extent, which will be helpful in EM wave absorption applications. In particular, the plasmas with proper collisional frequencies (about several to 20 times the plasma frequency) can be regarded as such a kind of a broadband EM wave absorption medium for the working conditions in this paper. Energy absorption curves for the plasma slab with collisional frequencies ranging from \( 5\omega_{pe} \) to \( 30\omega_{pe} \) are shown in Fig. 5(b), and it can be observed that the energy of EM waves with broadband (up to \( 10\omega_{pe} \)) frequencies can be absorbed effectively (\( \geq 20\%) \) when the collisional frequency is between \( 5\omega_{pe} \) and \( 20\omega_{pe} \), when the plasma slab thickness is 10 cm, and the plasma number density is \( 10^{11} \text{ cm}^{-3} \).

Further investigations are carried out to reveal the EM wave energy absorption effects at different plasma slab thicknesses, where the negatively charge particle is assumed to be electrons only, and the results are shown in Fig. 6 for four typical collisional frequencies. It can be seen that for the broadband frequency EM wave absorption plasma slabs, the high energy absorption area is in the region with the thicker plasma slab and lower EM wave frequency, and such an area becomes smaller as the collisional frequency increases. However, all the energy of the EM waves with the frequency ranging up to \( 10\omega_{pe} \) can be absorbed, at least 20% of their initial energy, after propagating in the collisional plasma slabs. For the plasma parameters in this study, the plasma slab with the collisional frequency ranging from \( 5\omega_{pe} \) to \( 20\omega_{pe} \) can be used as a broadband frequency EM wave absorption medium.

IV. CONCLUDING REMARKS

This paper presents the typical results of the energy absorption effects of electromagnetic waves in collisional dusty plasmas. It is shown that the effective energy absorption of EM waves is mainly due to electrons, and the EM wave energy can hardly be absorbed if the electron percentage is too low. Besides, collisional frequency is an issue in the energy absorption effects of the EM wave, and the absorption peak broadening becomes wider with increasing collisional frequencies. For the case of weaker collisional frequencies (for example, \( \nu_{en} < \omega_{pe} \)), the energy absorption of EM waves exhibits selections for the absorption effects of the wave frequency. For the case of strong collisional plasmas, the energy can be absorbed in a wide EM wave frequency range with low absorption efficiency, while for the plasma slab with moderate collisional frequency, both broadband frequency and acceptable absorption efficiency can be obtained simultaneously. Thus, the dusty plasma slabs with proper collisional frequencies can be used as a good absorption medium in a wide frequency spectrum with moderate absorption efficiency. Further technical investigations of the adjustment of collisional frequency in the plasma slab should be carried out in order to use the broadband frequency EM wave absorption medium better.

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