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Zhaoying Wang(王召迎), Lixin Guo(郭立新)†, and Jiangting Li(李江挺)

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Attenuation characteristics of obliquely incident electromagnetic wave in weakly ionized dusty plasma based on modified Bhatnagar–Gross–Krook collision model*

Zhaoying Wang(王召迎), Lixin Guo(郭立新)†, and Jiangting Li(李江挺)

School of Physics and Optoelectronic Engineering, Xidian University, Xi'an 710071, *China*

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The attenuation characteristics of obliquely incident electromagnetic (EM) wave in L-Ka frequency band in weakly ionized dusty plasma are analyzed based on the modified Bhatnagar–Gross–Krook (BGK) collision model. According to the kinetic equation and the charging theory, the total complex dielectric constant of the weakly ionized dusty plasma is derived by considering that the minimum velocity of the electron accessible to the dust particle surface is non-zero and the second potential part of the collision cross-section contributes to the charging. The attenuation characteristics within the modified model are compared with those within the traditional model. The influence of the dusty plasma parameters and the incident angle of EM waves on the attenuation in weakly ionized dusty plasma is further analyzed. Finally, the influence of different reentry heights on the attenuation characteristics of the obliquely incident EM wave is discussed. The results show that the effect of the minimum electron velocity and the second term of the collision cross-section on the attenuation characteristics of EM waves cannot be ignored. When the dust density and dust radius are changed, the trends of the attenuation of obliquely incident EM waves are consistent, but the influence of dust density is weaker than that of dust radius due to the constraint of orbit-limited motion (OLM) theory. The plasma thickness, electron density, and incident angle are proportional to the attenuation amplitude of EM waves. The effect of different reentry heights on the attenuation obliquely incident EM waves is related to the electron density and plasma thickness.

Keywords: dusty plasma, electromagnetic wave absorption, electromagnetic propagation, plasma sheaths

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1. Introduction

Unlike ordinary plasma, dusty plasma is formed by ordinary plasma and suspended dust particles.[1–3] During the reentry of high-speed targets, dust particles are mainly produced by the ablation effect of thermal protective materials on the surface of the targets. This results from the high temperature and pressure caused by the friction between the target body and the surrounding atmosphere. Then, the dusty plasma sheath coated on the surface of the target is formed.[2,4–6] Meanwhile, dust particles can accumulate higher charges, which have larger mass and volume. Specifically, the charge amount of these particles generally varies. The ratio of charge to mass is many orders of magnitude smaller than that of the average ion. Due to the existence of dust particles, the physical phenomena in plasma become more complex, such as the collision, adsorption and shielding of electrons and ions on them, which will make the interaction between dust plasma and external EM waves more complex. Therefore, dusty plasma is also called complex plasma. Dusty plasma widely exists in interstellar space, near-Earth space, and all types of gas discharge in laboratories,[7–12] having potential application in industrial and military fields. Therefore, the studies of dusty plasma are becoming more and more extensive. Tsintsadze *et al.*[13] and Shukla *et al.*[14] studied the instabilities of EM waves in dusty plasmas. Khrapak *et al.*[15] investigated the dynamics of dust particles in plasmas. Shi *et al.*[16] deduced the complex dielectric constant of weakly ionized dusty plasmas. Tsytovich *et al.*[17] analyzed experimental phenomena and theories of dust particles.

Due to the existence of dusty plasma sheath, the monitoring and communication between the high-speed aircraft and the ground are greatly affected, and the plasma sheath is usually regarded as weakly ionized dusty plasma. Therefore, in order to explore the interaction mechanism between EM waves and dusty plasma, scholars have carried out research on the propagation and attenuation characteristics of EM wave in weakly ionized dusty plasma. Wang *et al.*[18,19] investigated the propagation properties of terahertz waves in a weakly ionized dusty plasma sheath by the auxiliary differential equation of the finite-difference time-domain (FDTD) and propagation matrix methods. Juli *et al.*[20] studied the propagation characteristics of EM waves in the dusty plasma. Li *et al.*[21] researched the attenuation properties of the weakly ionized dusty plasma and found that the dust density and radius

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†Corresponding author. E-mail: lxguo@xidian.edu.cn

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affected the attenuation constant. Jia *et al.*[22] derived dielectric relation and investigated the propagation of EM waves in weakly ionized dusty plasma. Prudskikh *et al.*[23] discussed the properties of low-frequency EM waves in a polydisperse dusty plasma environment. Hong *et al.*[24] analyzed the reflection, transmission, and absorption coefficient of microwaves in weakly ionized dusty plasma with multi-collisions. Our group has derived the modified complex dielectric constant in weakly ionized dusty plasma based on the BGK model, calculated the propagation characteristics of EM wave, and discussed the influence of dust parameters on reflection, as well as the transmission coefficient of EM wave.[25,26] Liu *et al.*[27] derived the BGK collision model in non-uniform magnetized dusty plasma and analyzed the influence of the external magnetic field on the propagation properties of THz circularly polarized waves. In this paper, the attenuation characteristics of obliquely incident EM waves in weakly ionized dusty plasma are discussed.

The collision between electrons and other particles in plasma is the main reason for EM wave propagation and attenuation. The dielectric constant is modified based on the BGK collision model in weakly ionized plasma, considering that the minimum electron velocity is not zero and the second part of the collision cross-section is not ignored. The attenuation characteristics of obliquely incident EM wave propagating in the L-Ka frequency band in the weakly ionized dusty plasma are calculated by the WKB method. The structure of the paper is as follows: Section 2 is the theoretical deduction of EM wave attenuation based on the modified dielectric constant in the weakly ionized dusty plasma. Section 3 compares the attenuation results with different dielectric constants in traditional and modified models. Section 4 discusses the influence of dust density, dust radius, plasma thickness, electron density, electron temperature, and incident angle on the attenuation of EM wave. Section 5 analyzes the attenuation change of EM wave at different reentry heights of hypersonic vehicle. Finally, Section 6 gives a brief conclusion.

2. Physical model

In weakly ionized dusty plasma, collisions occur mainly between neutral molecules and electrons. Assuming that the weakly ionized dusty plasma is non-magnetized, the kinetic equation within the BGK collision model can be written as

$$\frac{\partial f^{(\mathrm{e})}}{\partial t}+\frac{e}{m_{\mathrm{e}}}\boldsymbol{E}\cdot\frac{\partial f^{(\mathrm{e})}}{\partial \boldsymbol{\upsilon}}=\left(\frac{\partial f^{(\mathrm{e})}}{\partial t}\right)_{\mathrm{B-G-K}}, \tag{1}$$

where $\boldsymbol{E}$ is the electric field, $f^{(\mathrm{e})}$ is the electron distribution function, m_{e}, e, $\boldsymbol{\upsilon}$ are the mass, charge, and velocity of the electron. The last term in Eq. (1) is the BGK collision term[28]

$$\left(\frac{\partial f^{(\mathrm{e})}}{\partial t}\right)_{\mathrm{B-G-K}}=-\nu_{\mathrm{en}}\left(f^{(\mathrm{e})}-f_0\right), \tag{2}$$

where ν_{en} is the collision frequency.

The electron distribution function $f^{(\mathrm{e})}$ under small perturbations can be written as

$$f^{(\mathrm{e})}(\boldsymbol{\upsilon})=f_0(v)+f_1(\boldsymbol{\upsilon}), \tag{3}$$

where

$$f_0=n_{\mathrm{e}}\left(\frac{m_{\mathrm{e}}}{2\pi k_{\mathrm{B}}T_{\mathrm{e}}}\right)^{3/2}\exp\left(-\frac{m_{\mathrm{e}}v^2}{2\pi k_{\mathrm{B}}T_{\mathrm{e}}}\right)$$

is the Maxwell distribution function at equilibrium. f_1 is a perturbation term caused by the external EM field. n_{e} is the electron density, T_{e} is the electron temperature, and k_{B} is the Boltzmann constant.

From Eqs. (1)–(3) the perturbation term can be obtained as[29]

$$f_1(\boldsymbol{\upsilon})=\frac{e\boldsymbol{E}n_{\mathrm{e}}v\exp\left(-\dfrac{m_{\mathrm{e}}v^2}{2k_{\mathrm{B}}T_{\mathrm{e}}}\right)}{2\sqrt{2}m_{\mathrm{e}}(\pi)^{3/2}(\mathrm{j}\omega+\nu_{\mathrm{en}}(v))}\left(\frac{m_{\mathrm{e}}}{k_{\mathrm{B}}T_{\mathrm{e}}}\right)^{5/2}. \tag{4}$$

The $\nu_{\mathrm{en}}(v)$ can be substituted with the collision frequency formula $\nu_{\mathrm{en}}=V_{\mathrm{Te}}\sigma_{\mathrm{n}}n_{\mathrm{n}}$,[30] where V_{Te} is the velocity of electron thermal motion, $V_{\mathrm{Te}}=(k_{\mathrm{B}}T_{\mathrm{e}}/m_{\mathrm{e}})^{0.5}$, σ_{n} is the effective cross-section of the molecules,[23] usually $\sigma_{\mathrm{n}}=4.4\times10^{-20}$ m^2, n_{n} is the density of neutral molecules.

The charge current caused by the perturbation function can be written as

$$I_{\mathrm{e1}}=-e\int_{\upsilon_{\min}}^{\infty}\boldsymbol{\upsilon}\cdot\sigma_{\mathrm{e}}^{\mathrm{d}}f_1(\boldsymbol{\upsilon})\,\mathrm{d}v, \tag{5}$$

where $\upsilon_{\min}$ is the minimum electron velocity. $\sigma_{\mathrm{e}}^{\mathrm{d}}$ is the collision cross-section of electron and dust particles.

According to the orbit-limited motion theory, the collision cross-section of electron and dust particle can be expressed as[16]

$$\sigma_{\mathrm{e}}^{\mathrm{d}}=\pi r_{\mathrm{d}}^2\left(1+\frac{2e\varphi_{\mathrm{d0}}}{m_{\mathrm{e}}v^2}\right), \tag{6}$$

where r_{d} is the radius of dust particles, $\varphi_{\mathrm{d0}}=-eZ_{\mathrm{d}}/(4\pi\varepsilon_0 r_{\mathrm{d}})$ is the difference in the electric potential between the dust particle surface and the background particle without perturbation, and Z_{d} is the charge number of dust particles.

The Shukla charging equation can be written as

$$\frac{\partial q_{\mathrm{d1}}}{\partial t}+\nu_{\mathrm{ch}}q_{\mathrm{d1}}=I_{\mathrm{e1}}+I_{\mathrm{il}}, \tag{7}$$

where I_{el} and I_{il} are the charge current of electrons and ions under perturbation, respectively. q_{d1} and ν_{ch} are the charge and charge frequency of the dust particle,[30] respectively.

Considering the law of electric charge conservation[22]

$$\nabla\cdot\boldsymbol{J}_{\mathrm{d}}+\mathrm{i}\omega\rho_{\mathrm{d}}=0, \tag{8}$$

where $\rho_{\rm d} = n_{\rm d} q_{\rm d1}$ is the charge density.

According to Ohm's law, $\boldsymbol{J}_{\rm d} = \sigma_{\rm dcomplex} \boldsymbol{E}$. Considering the collision effect and charging effect, the solution of the total complex dielectric constant for non-magnetic weakly ionized dusty plasma within the modified BGK collision model can be obtained.

In the previous literatures,[18,22] the minimum electron velocity $\upsilon_{\rm min} = 0$ and the collision cross-section $\sigma_{\rm e}^{\rm d} = \pi r_{\rm d}^2$ were used. Then the traditional model of the complex dielectric constant is given by

$$\varepsilon_{\rm r1}(\omega) = 1 - \frac{\omega_{\rm p}^2}{\omega^2 + \nu_{\rm en}^2} + \frac{\omega_{\rm p}^2 \nu_{\rm en}}{{\rm j}\omega(\omega^2+\nu_{\rm en}^2)} + \frac{{\rm j}\omega\eta_{\rm ed} c(\nu_{\rm en}+\nu_{\rm ch}) + \eta_{\rm ed} c(\omega^2 - \nu_{\rm ch}\nu_{\rm en})}{{\rm j}\omega\varepsilon_0(\omega^2+\nu_{\rm en}^2)(\omega^2+\nu_{\rm ch}^2)}, \quad (9)$$

where $\eta_{\rm ed} = \frac{\pi r_{\rm d}^2 n_{\rm e} n_{\rm d} e^2}{m_{\rm e}}$, $\omega_{\rm p} = \sqrt{\frac{n_{\rm e} e^2}{m_{\rm e}\varepsilon_0}}$ is the plasma frequency.

To improve the dielectric constant model in weakly ionized dusty plasma, three modifications were made. Case 1: the minimum electron velocity was set to $\upsilon_{\rm min} = (-2e\varphi_{\rm d0}/m_{\rm e})^{1/2}$. Case 2: the contribution of the electrical potential part in the second term of the collision cross-section to the charge current was considered. Case 3: both these two factors were modified simultaneously.

Case 1:

$$\varepsilon_{\rm r2}(\omega) = 1 - \frac{\omega_{\rm p}^2}{\omega^2 + \nu_{\rm en}^2} + \frac{\omega_{\rm p}^2 \nu_{\rm en}}{{\rm j}\omega(\omega^2+\nu_{\rm en}^2)} + \frac{{\rm j}\omega a(\nu_{\rm en}+\nu_{\rm ch}) + a(\omega^2 - \nu_{\rm ch}\nu_{\rm en})}{{\rm j}\omega\varepsilon_0(\omega^2+\nu_{\rm en}^2)(\omega^2+\nu_{\rm ch}^2)}, \quad (10)$$

where

$$a = \frac{8}{3\sqrt{\pi}} \frac{c n_{\rm d} n_{\rm e} \pi r_{\rm d}^2 e^2}{m_{\rm e}} \Phi_1(u_{\rm min}),$$

$$\Phi_1(u_{\rm min}) = \int_{u_{\rm min}}^{\infty} u^4 {\rm e}^{-u^2} {\rm d}u, \quad u_{\rm min} = \left(-\frac{e\varphi_{\rm d0}}{k_{\rm B} T_{\rm e}}\right)^{1/2}.$$

Case 2:

$$\varepsilon_{\rm r3}(\omega) = 1 - \frac{\omega_{\rm p}^2}{\omega^2 + \nu_{\rm en}^2} + \frac{\omega_{\rm p}^2 \nu_{\rm en}}{{\rm j}\omega(\omega^2+\nu_{\rm en}^2)} + \frac{{\rm j}\omega b(\nu_{\rm en}+\nu_{\rm ch}) + b(\omega^2 - \nu_{\rm ch}\nu_{\rm en})}{{\rm j}\omega\varepsilon_0(\omega^2+\nu_{\rm en}^2)(\omega^2+\nu_{\rm ch}^2)}, \quad (11)$$

where

$$b = \frac{5 c n_{\rm d} n_{\rm e} \pi r_{\rm d}^2 e^2}{3 m_{\rm e}}.$$

Case 3:

$$\varepsilon_{\rm r4}(\omega) = 1 - \frac{\omega_{\rm p}^2}{\omega^2 + \nu_{\rm en}^2} + \frac{\omega_{\rm p}^2 \nu_{\rm en}}{{\rm j}\omega(\omega^2+\nu_{\rm en}^2)} + \frac{{\rm j}\omega c_1(\nu_{\rm en}+\nu_{\rm ch}) + c_1(\omega^2 - \nu_{\rm ch}\nu_{\rm en})}{{\rm j}\omega\varepsilon_0(\omega^2+\nu_{\rm en}^2)(\omega^2+\nu_{\rm ch}^2)}, \quad (12)$$

where

$$c_1 = \frac{8 c n_{\rm d} n_{\rm e} \pi r_{\rm d}^2 e^2}{3\sqrt{\pi} m_{\rm e}} \left(\Phi_1(u_{\rm min}) + \frac{e\varphi_{\rm d0}}{k_{\rm B} T_{\rm e}} \Phi_2(u_{\rm min})\right),$$

$$\Phi_2(u_{\rm min}) = \int_{u_{\rm min}}^{\infty} u^2 {\rm e}^{-u^2} {\rm d}u.$$

According to Maxwell's equations, the wave equation in the weakly ionized dusty plasma can be written as[31]

$$\nabla^2 \boldsymbol{E} + [k^2(z) - k_0^2 \sin^2\theta_n]\boldsymbol{E} = 0, \quad (13)$$

where $k(z)$ is the wave number that varies depending on the spatial position z in the weakly ionized dusty plasma, k_0 is the wave number in the vacuum, and $\theta_{\rm n}$ is the refraction angle in the weakly ionized dusty plasma. According to the law of refraction, the relationship between incident angle and refraction angle at the interface is satisfied: $\sin(\theta) = n' \sin(\theta_{\rm n})$. Here n' is the refractive index of weakly ionized dusty plasma, θ is the incident angle.

The electric field equation in the weakly ionized dusty plasma can be obtained by solving Eq. (13) with the WKB method

$$E_{\rm t} = E_0 \exp\left[{\rm j}\int_0^L \sqrt{k^2(z) - k_0^2 \sin^2\theta_{\rm n}}\,{\rm d}z\right], \quad (14)$$

where E_0 is the initial electric field intensity of the incident EM wave. $E_{\rm t}$ is the electric field intensity after the EM wave passed through the weakly ionized dusty plasma. L is the dusty plasma thickness.

Then the propagation function of the EM wave energy is

$$P(z) = P_0 \exp\left[-2\,{\rm Im}\left(\int_0^L \sqrt{k^2(z) - k_0^2 \sin^2\theta_{\rm n}}\,{\rm d}z\right)\right], \quad (15)$$

where P_0 is the power of the EM wave before entering the weakly ionized dusty plasma.

Therefore, the attenuation (Att) of EM wave can be obtained as follows:

$${\rm Att} = \left|10 \times \lg\frac{P(L)}{P_0}\right| = \left|8.686\,{\rm Im}\left(\int_0^L \sqrt{k^2(z) - k_0^2 \sin^2\theta_{\rm n}}\,{\rm d}z\right)\right|. \quad (16)$$

3. Comparison of the attenuation results of the traditional and the three modified dielectric constant models

Figure 1 shows a comparison of the attenuation changes of obliquely incident EM waves in L-Ka frequency band through the dusty plasma based on traditional and three modified models. The calculation parameters are as follows: $n_{\rm e} = 5.0 \times 10^{17}$ m^{-3}, $r_{\rm d} = 1$ μm, $n_{\rm d} = 1 \times 10^{13}$ m^{-3}, $T_{\rm e} = 3000$ K, $\theta = 30°$. We can observe that the attenuation changes obtained with $\varepsilon_{\rm r1}$ and $\varepsilon_{\rm r3}$ show a similar trend and are smaller than that with $\varepsilon_{\rm r4}$. Considering the modification of the second term of the collision cross-section alone, it has little effect on the attenuation ($\varepsilon_{\rm r3}$). However, only considering the modification of

the minimum electron rate (ε_{r2}) changes obviously compared with the attenuation of the traditional model ε_{r1}, and the ε_{r4} model of the two modified has a greater change. This conclusion is consistent with the previous study.[25] Therefore, it is necessary to consider the influence of the minimum electron velocity and the second term of the collision cross-section on the dielectric constant, which will affect the attenuation characteristics of EM waves in the weakly ionized dusty plasma.

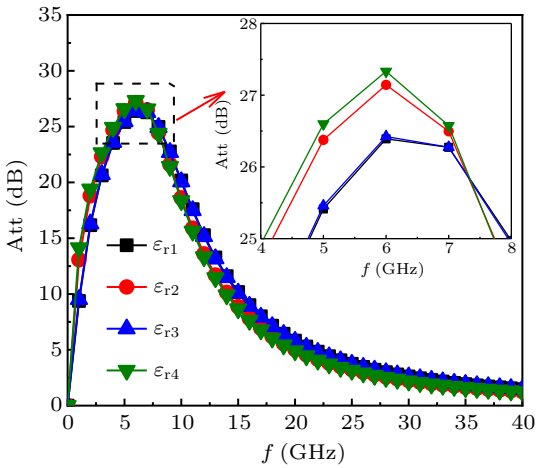


Fig. 1. Comparison of attenuation between traditional and three modified models.

4. The influence of different parameters on the attenuation of obliquely incident EM wave

Further analysis will be discussed with the modified model ε_{r4}, and the calculated parameters are shown in Table 1.

Table 1. Calculation conditions for the following figures. The units of n_d, r_d, L, n_e, T_e, θ are 10^{13} m^{-3}, μm, cm, 10^{17} m^{-3}, 10^3 K, and degree, respectively.

Fig.	n_d	r_d	L	n_e	T_e	θ
2	1,3,5,7	1	5	5	3	30
3	1	1,3,5,7	5	5	3	30
4	1	1	3,5,7,10	5	3	30
5	1	1	5	1,3,5,7	3	30
6	1	1	5	5	2,3,4,5	30
7	1	1	5	5	3	0,30,45,60

Figure 2 shows the effect of different dust densities on the attenuation of obliquely incident EM wave in L-Ka frequency band. We can see that the change of overall dust density has little effect on the attenuation of EM waves. The significant energy attenuation can be observed for the incident EM wave frequency near the plasma frequency, which results from the resonance absorption of EM waves when the incident wave frequency is close to the plasma frequency. The attenuation of EM waves causes some interesting changes about 7.5 GHz (near the collision frequency). The incident wave frequency is lower than 7.5 GHz, the attenuation of EM waves decreases gradually with increasing dust density. On the contrary, the attenuation of EM waves increases with the dust density for the incident frequency above 7.5 GHz. This is because the collision between charged and neutral particles hinders the Debye shielding of charged particles in the low frequency region and enhances the collision absorption and attenuation of EM waves in the high frequency region. In addition, the possibility of charge adsorption between electrons and dust particles increases with the dust density, and the inelastic collision of dust particles causes a greater loss of electron energy. The shielding effect of weakly ionized dusty plasma in the low frequency region is further weakened, and the absorption loss ability in the high frequency region is enhanced.

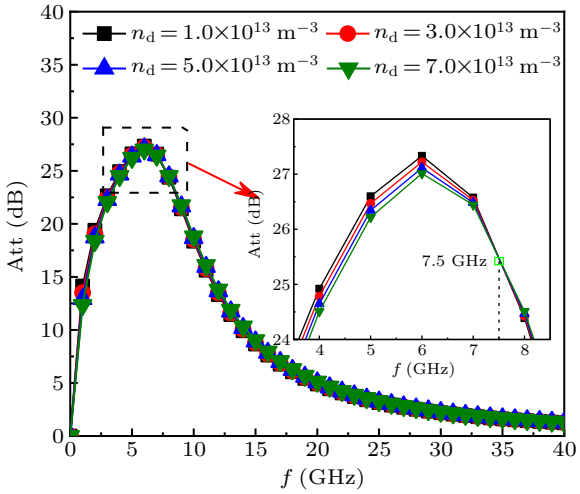


Fig. 2. Effect of dust density on attenuation under modified models.

Figure 3 presents the effect of different dust radius in weakly ionized dusty plasma on the attenuation of EM wave in L-Ka frequency band under the modified BGK collision model. It can be seen from Fig. 3 that the attenuation of EM wave first decreases and then increases with the dust radius. The attenuation of EM wave decreases with the increase of dust radius for the incident frequency smaller than 7.5 GHz. For a constant collision frequency, the increase of dust particle radius leads to more absorption of charged particles, the increase of the charging frequency, and the increase of the inelastic collision probability between electrons and dust particles. However, severe collisions occur before electrons being accelerated by the electric field results in a decrease in the attenuation of EM wave. When the incident frequency larger than 7.5 GHz, the energy of the external EM wave is absorbed by charged particles and converted into the internal energy of dusty plasma through inelastic channels, indicating the enhanced attenuation of EM wave with the increase of dust radius. The attenuation will gradually approach zero for a very high incident frequency, which results from the fact that the electric field changes too fast and the electrons cannot keep up with the rapidly changing. Consequently, the absorbed energy of EM wave decreases, which leads to a decrease in the attenuation of EM wave. Compared with Fig. 2, the effect of dust

radius on attenuation is obviously significant than that of dust density, which is the reason for the restriction of orbit-limited motion theory.

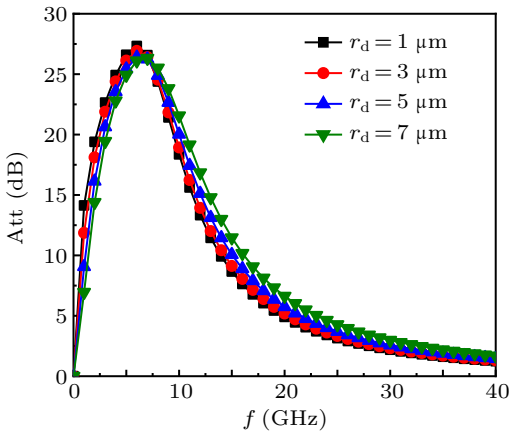


Fig. 3. Effect of dust radius on attenuation under modified models.

Figure 4 shows the influence of different dusty plasma thicknesses on the attenuation of obliquely incident EM wave in L-Ka frequency band under the modified model. The thickness was set to 3 cm, 5 cm, 7 cm, and 10 cm, respectively. From Fig. 4, we can see that the larger the thickness of dusty plasma, the greater the attenuation of EM wave. A larger thickness of dusty plasma increases the interaction distance and leads to a significant influence on the EM wave, which makes it more difficult for the EM wave to pass through the dusty plasma. Therefore, the attenuation of EM wave caused by dusty plasma is larger. In addition, it is interesting that the incident frequency corresponding to the peak attenuation kept in a constant for the increase of thickness, indicating that the plasma frequency is an important factor to determine the corresponding incident frequency of peak attenuation value of EM wave.

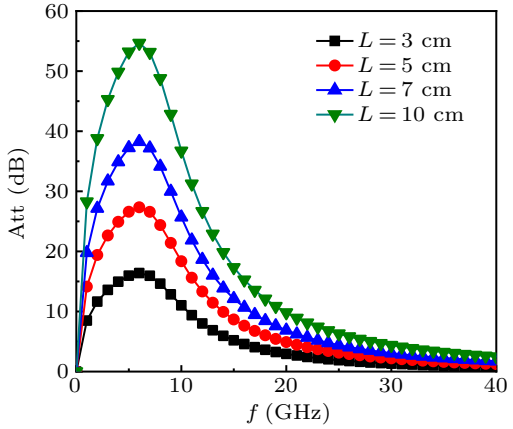


Fig. 4. Effect of dusty plasma thickness on attenuation under modified models.

Figure 5 shows the effect of different electron densities on the attenuation of EM waves in L-Ka frequency band under the modified model. It can be seen from Fig. 5 that the incident frequency value corresponding to the attenuation peak gradually shifts to a higher frequency with the increase of electron density. It has proved that the peak frequency is plasma frequency. This is because when the incident wave frequency is lower than the plasma frequency, it is difficult for the EM wave to penetrate the plasma, and most of the EM waves are attenuated. When the plasma frequency is reached, the resonance absorption phenomenon occurs inside the dusty plasma, and the attenuation value reaches the maximum. Then, the transmission energy of EM wave increases gradually, and the attenuation will decrease continuously with the increase of incident wave frequency. The increase of electron density increases the collision probability between free electrons and neutral molecules, which intensifies the energy conversion of EM wave and increases the attenuation. In addition, we also find that the incident frequency corresponding to the attenuation peak gradually shifts to the high frequency with the increase of electron density. Because of the relationship between electron density and plasma frequency, it is proved again that plasma frequency is an important factor in determining the peak attenuation.

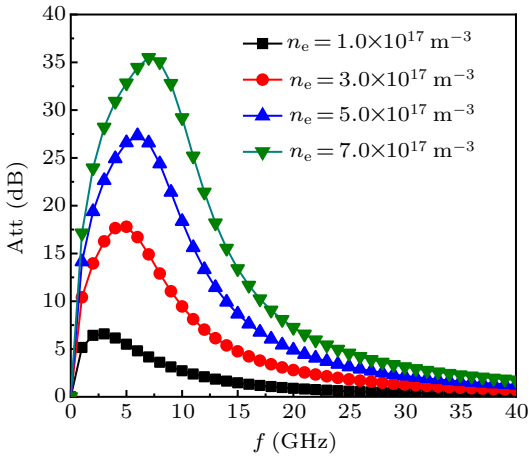


Fig. 5. Effect of electron density on attenuation under modified models.

Figure 6 shows the influence of different electron temperatures on the attenuation of obliquely incident EM wave in L-Ka frequency band. It can be seen from Fig. 6 that the attenuation of EM wave decreases with the increase of electron temperature at low frequency and increases with the increase of frequency above plasma frequency. This is due to the fact that when the EM wave frequency is lower than the plasma frequency, the oscillation absorption of EM wave is dominated by free electrons in the dusty plasma, and the collision between free electrons and neutral particles weakens the oscillation absorption of free electrons. Thus, the higher the electron temperature, the more severe the collisions between free electrons and neutral particles, and the smaller the attenuation of EM wave. The collision attenuation of free electrons

and neutral particles in plasma is dominant for the incident frequency higher than the plasma frequency. The higher electron temperature leads to a larger collision frequency and enhances the attenuation of EM wave.

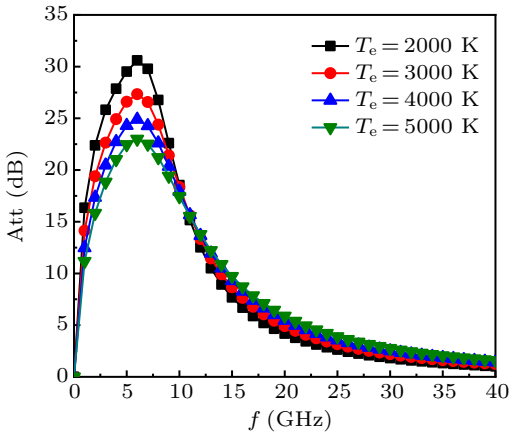


Fig. 6. Effect of electron temperature on attenuation under modified models.

Figure 7 shows the effect of different incident angles on the attenuation of EM wave in L-Ka frequency band under the modified model. It can be seen from Fig. 7 that the variation of the incident angle is not evident to the attenuation of the EM wave in the very low frequency region (< 2.5 GHz). As the frequency of the incident wave increases, the attenuation amplitude increases with the incident angle. This is because when the incident angle of EM wave increases, the reflection effect of dusty plasma on EM wave will be enhanced, and the transmission of EM wave will decrease, which will lead to the increase of attenuation of EM wave. In addition, we found that the incident frequency corresponding to the peak attenuation gradually shifts to the high frequency with the increase of incident angle, and the peak value shows an increasing trend. This indicates that the incident angle is also an important factor affecting the peak value of attenuation. We can control the attenuation intensity by controlling the incident angle of EM wave to fulfill the requirement of target stealth and monitoring.

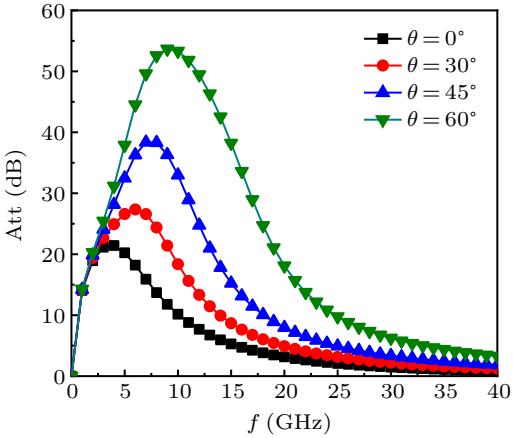


Fig. 7. Effect of incidence angle on attenuation under modified models.

5. The influence of different reentry heights of high-speed aircraft on the attenuation of EM wave

The spatial distributions of electron density at different reentry heights in NASA experiments[4,32] are adopted to investigate the influence of different electron density distributions on the attenuation of EM wave. Parameters $n_d = 1.0 \times 10^{13}$ m^{-3}, $r_d = 1$ μm, $\theta = 30°$, and $T_e = 3000$ K are adopted in simulation. The maximum electron density, mean electron density, and dusty plasma thickness at different heights[4] are shown in Table 2.

Table 2. Average electron density and dusty plasma thickness at different reentry heights.

Altitude (km)	Average electron density (m^{-3})	Plasma thickness (cm)
21	2.78×10^{16}	5.30
25	5.53×10^{17}	7.21
30	3.37×10^{18}	7.09
47	4.39×10^{17}	6.73
53	3.42×10^{17}	7.09
61	2.17×10^{17}	7.76
71	7.51×10^{16}	12.09
76	2.07×10^{16}	14.0

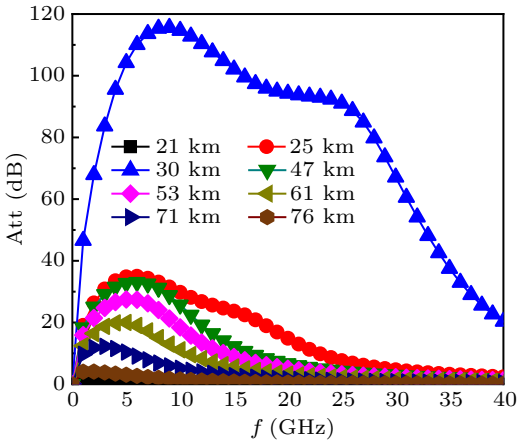


Fig. 8. Effect of different reentry heights on the attenuation of EM wave under modified models.

Figure 8 shows the effect of dusty plasma on the attenuation of EM wave in L-Ka frequency band when high-speed aircraft is located at different reentry heights. We can see from Fig. 8 that the attenuation of EM wave varies with different reentry heights and its attenuation intensity increases from 21 km to 30 km and decreases from 30 km to 76 km. This result is related to the spatial distribution of electron density. The conclusion drawn from Fig. 5 shows that the greater the electron density, the greater the attenuation of EM waves. Nevertheless, there is a different change at the height of 76 km and 21 km. It can be seen from Table 2 that although the average electron density at 76 km is greater than that at 21 km, they remain in the same order of magnitude, and the difference is very small. Moreover, the plasma thickness at the height of 76 km

is much larger than that at 21 km. Combined with the influence of thickness and electron density on the attenuation of EM wave, it can be concluded that the attenuation is minimal at the height of 21 km. The thickness of dusty plasma at other reentry heights is basically maintained at a similar level, which can be explained by the average electron density. Therefore, the dusty plasma thickness and electron density synergistically affect the attenuation of EM wave.

6. Conclusion and perspectives

The attenuation characteristics of obliquely incident EM wave in weakly ionized dusty plasma in L-Ka frequency band were studied by using the modified dielectric constant under the BGK collision model with the minimum electron velocity and the second term of collision cross-section considered. The simulation results indicate that the dust density and dust radius have the same variation trend on the attenuation of obliquely incident EM wave and the maximum attenuation should appear around the plasma frequency. The EM wave attenuation decreases with the increase of dust radius (or dust density) for incident frequency smaller than the collision frequency (about 7.5 GHz) and increases with the increase of dust radius (or dust density) for incident frequency higher than the collision frequency. However, the effect of dust density on attenuation is weaker than that of dust radius due to orbit-limited motion theory. The attenuation of EM wave is proportional to dusty plasma thickness, electron density, and incident angle. The higher electron temperature in weakly ionized dusty plasma leads to more severe collisions between particles. The collisions will hinder the Debye shielding of charged particles in the low frequency region and enhance the loss ability of EM waves in the high frequency region due to collision absorption. Consequently, the attenuation of EM wave first decreases and then increases with the increase of electron temperature. Using the experimental spatial distribution data of electron density at different reentry heights, we find that attenuation change is related to electron density and plasma thickness. This work theoretically analyzes the influence of weakly ionized dusty plasma on obliquely EM wave attenuation characteristics and gives a further understanding of the influence of different plasma parameters on EM wave amplitude.

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