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Research Article

Study of the Propagation Characteristics of Terahertz Waves in a Collisional and Inhomogeneous Dusty Plasma with a Ceramic Substrate and Oblique Angle of Incidence

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In this paper, the propagation properties of a terahertz (THz) wave in a collisional and inhomogeneous dusty plasma with a ceramic substrate and oblique angle of incidence are studied using the scattering matrix method. The influence of the various corresponding parameters, such as the frequency of the THz wave, angle of incidence, electron density, radius and density of the dust particles, and the collision frequency, on the absorbance and transmittance is calculated. The results of the simulation indicate that an increase in the wave frequency increases the transmittance and decreases the absorbance. Moreover, the absorbance of a THz wave in a dusty plasma with a ceramic substrate increases with an increase in the incident angle, maximum electron density, coefficient of steepness, density and radius of the dust particles, and collision frequency. These results provide an important theoretical basis for the problem of communication blackout between ground and spacecraft.

1. Introduction

During the reentry process, the intense friction between the surface of an aircraft and the atmosphere results in the ionization of the air molecules around the aircraft, producing dust particles. A plasma sheath, therefore, covers the surface of the aircraft [1], and this plasma, which contains electrons, ions, neutral particles, and dust particles, is referred to as dusty plasma [2]. During this period, the electromagnetic (EM) wave passing between the aircraft and the earth station will be absorbed by the dusty plasma [3], meaning that communication will be degraded and may even be interrupted, which is known as the "blackout problem" [4, 5]. Studying the propagation properties of EM waves in dusty plasma during the reentry process has become an important research issue following increases in the number of space missions.

Numerous studies have been carried out to investigate the characteristics of EM wave propagation in a plasma slab, and these have achieved fruitful results [6, 7]. In [8], the reflectance, transmittance, and absorbance of an EM wave propagating through an inhomogeneous, collisional, magnetized plasma were extensively studied. The differences between the effects of three electron density profiles, with uniform, parabolic, and double exponential distributions, on the propagation properties were also compared. The angular spectrum expansion and the 4×4 transfer matrix method were applied by Li et al. to investigate the reflection, transmission, and absorption of the vortex in an inhomogeneous and magnetized plasma slab [9]. The results proved that the parameters of the plasma have a significant impact on the magnitudes of the reflected and transmitted intensities and the distortion of orbital angular momentum states. Based on these studies, Chen et al. proposed an improved

scattering matrix method for studying the reflection of EM waves from the plasma sheath [10]. However, these research studies have mainly focused on a typical plasma and may be unrealistic for real applications [11]. The dust particles in the plasma can absorb the energy of the EM waves via charging effects and collisions, meaning that the influence of the dust particles in the plasma on the propagation characteristics of the EM wave cannot be ignored.

Many prior researchers have focused on the propagation of an EM wave in plasma. Since THz technology has become increasingly mature, many scholars have studied the propagation characteristics of a THz wave in dusty plasma [12]. To analyse the impact of dusty plasma on wave propagation, Cao et al. used the propagation matrix method to study the propagation characteristics of THz waves in an inhomogeneous dusty plasma. In addition, the effects of the angle of incidence and the density and radius of the dust particles have been discussed [13]. The time variability of dusty plasma was used in [14] to study the propagation characteristics of the THz wave in a space-time inhomogeneous and fully ionized weakly dusty plasma sheath, using the FDTD method. The results showed that the ability of EM waves to penetrate the dusty plasma layer could be effectively improved by increasing the frequency of the incident wave, meaning that the use of THz technology to penetrate spatially inhomogeneous and time-varying dusty plasma is feasible. Later, Chen et al. analysed the transmittance and reflectance of THz waves in a spatially inhomogeneous time-varying and weakly ionized dusty plasma [15]. Although THz wave's properties in both plasma and dusty plasma have been investigated, as described above, the angle of incidence of the THz wave on the plasma and dusty plasma is usually assumed to be vertical. This is an idealized simplification since the THz wave is usually incident on the dusty plasma at an oblique angle under real conditions [16]. The angle of incidence of the THz wave on the dusty plasma will influence both the propagation distance and the THz wave's energy in the dusty plasma, which will, in turn, affect the propagation characteristics of the THz wave in the dusty plasma. It is, therefore, vital to study the propagation characteristics of a THz wave that is obliquely incident on a dusty plasma in order to ensure communication between the ground and the aircraft.

Since THz technology has a large number of potential applications in the field of reentry communication, the propagation characteristics of a THz wave in a dusty plasma are considered in this paper, and a model of a THz wave that obliquely penetrates a dusty plasma with a ceramic substrate is established. In addition, the influence of various parameters, such as the wave frequency, incident angle, electron density, density and radius of the dust particles, and collision frequency, on the absorbance and transmittance is calculated using the scattering matrix method (SMM). The rest of this paper is organized as follows: in Section 2, we present a propagation model of a THz wave in an inhomogeneous and collisional dusty plasma with an oblique angle of incidence, which to the best of our knowledge has seldom been studied before. The SMM used for the physical model is also described in detail. In Section 3, we present an expression for the electron density and a diagram of the model. The variation in the absorbance and transmittance of dusty plasma versus the frequency of the incident wave is discussed, for different values of the incident angle, maximum electron density, coefficient of steepness, density of dust particles, radii of dust particles, and collision frequency. Finally, conclusions are presented in Section 4.

2. Propagation Model and Theoretical Formulations

Figure 1 shows a model of the propagation of the THz wave into an inhomogeneous and collisional dusty plasma at an oblique incident angle. It can be seen from Figure 1 that the EM wave incident into the dusty plasma at θ_0 and refracted out of the dust plasma at θ_p after attenuation and refraction. The region marked 0 is the incident region, which is assumed to be a vacuum. Region p is the transmission region, which is filled with ceramic. The dusty plasma is distributed between regions 0 and p and is stratified into n sublayers for convenience of calculation. Note that the electron density of each sublayer can be regarded as having a uniform distribution when n is sufficiently large. The thickness of the dusty plasma layer is L, and the interfaces between adjacent sublayers are denoted by d_m $(m = 1, 2, \ldots, n, p)$. In addition, the relative dielectric constant and thickness of ceramic substrate are set as $\varepsilon_p = 9.3$ and 10 mm, respectively.

Since the electron density in each sublayer is uniform, the propagation constant for the sublayers can be written as [17]

$$k_m = k_0 \sqrt{\varepsilon_r^m}, \tag{1}$$

where k_0 is the propagation constant in a vacuum and $k_0 = \omega/c$, where c is the speed of light in free space and ω is the angular frequency of an incident wave. In addition, ε_r^m is the complex permittivity of the m-th sublayer in dusty plasma, and an expression for this can be obtained by solving the Boltzmann and Shukla equations [18]:

$$\varepsilon_r^m(\omega) = 1 - \frac{\omega_{p,m}^2}{\omega^2 + \nu_{en}^2} + \frac{c\eta_{ed,m}(\nu_{ch} + \nu_{en})}{\varepsilon_0(\omega^2 + \nu_{en}^2)(\omega^2 + \nu_{ch}^2)} + i\frac{1}{\omega}\left[\frac{\omega_{p,m}^2 \nu_{en}}{\omega^2 + \nu_{en}^2} + \frac{c\eta_{ed,m}(\omega^2 - \nu_{ch}\nu_{en})}{\varepsilon_0(\omega^2 + \nu_{ch}^2)(\omega^2 + \nu_{en}^2)}\right], \tag{2}$$

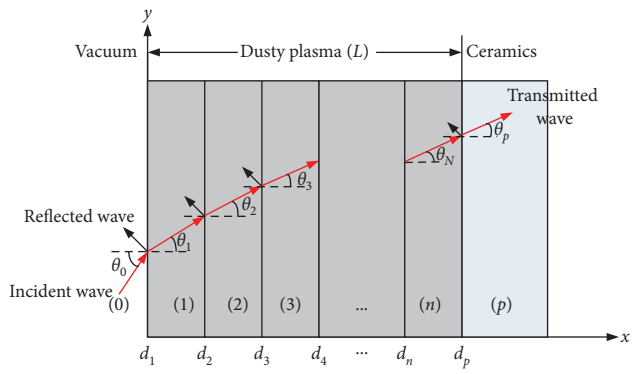

FIGURE 1: Schematic diagram of the propagation of a THz wave with the oblique incidence in dusty layered plasma.

where ε_0 is the dielectric constant in a vacuum ($\varepsilon_0 \approx 8.854 \times 10^{-12}$ F/m), ν_{en} is the collisional frequency, and ν_{ch} is the electron relaxation rate of the dust particles. In addition, $\eta_{ed,m}$ and $\omega_{p,m}$ are the charge response coefficients of the dust particles and the plasma angular frequency in the m-th sublayer, and their expressions are $\omega_{p,m} = \sqrt{N_{e,m}e^2/(m_e\varepsilon_0)}$ and $\eta_{ed,m} = (e^2\pi r_d^2 N_{e,m}N_d)/(m_e)$, respectively. The charge on an electron is $e = 1.602 \times 10^{-19}$ C, the mass of an electron is $m_e = 9.11 \times 10^{-13}$ kg, and r_d is the radius of the dust particles. $N_{e,m}$ and N_d are the densities of the electrons and dust particles in the dusty plasma, respectively.

As shown in Figure 1, the electric field of the incident region can be obtained as

$$E_z^0 = E_0\left(e^{-jk_0(x\cos\theta_0 + y\sin\theta_0)} + re^{jk_0(x\cos\theta_0 - y\sin\theta_0)}\right), \quad (3)$$

where r is the total reflection coefficient and k_0 is the propagation constant in the incident region.

Similarly, the electric field in the m-th sublayer can be expressed as

$$E_z^m = E_0\left(b_m e^{-jk_m(x\cos\theta_m + y\sin\theta_m)} + c_m e^{jk_m(x\cos\theta_m - y\sin\theta_m)}\right), \quad (4)$$

where k_m is the propagation constant in the m-th sublayer, and b_m and c_m are the partial transmission coefficient and the partial reflection coefficient, respectively.

Finally, the electric field can be written as

$$E_z^p = E_0 t e^{-jk_p(x\cos\theta_p + y\sin\theta_p)}, \quad (5)$$

where t is the total transmission coefficient of the dusty plasma and k_p is the propagation constant in the transmission region.

In addition, the relation between the refraction angles of adjacent sublayers can be obtained from Snell's law [19]:

$$\sin\theta_0 = \sin\theta_1\sqrt{\varepsilon_r^1} = \cdots = \sin\theta_m\sqrt{\varepsilon_r^m} = \cdots = \sin\theta_n\sqrt{\varepsilon_r^n}. \quad (6)$$

At the boundary, the tangential components of the electric and magnetic fields at the reflection surface must be continuous. In conjunction with Snell's law, the boundary equation for the incident region can be obtained:

$$\begin{cases} e^{-jk_0x\cos\theta_0} + Ae^{jk_0x\cos\theta_0} = B_1e^{-jk_1x\cos\theta_1} + C_1e^{-jk_1x\cos\theta_1}, \\ k_0\cos\theta_0 e^{-jk_0x\cos\theta_0} - Ak_0\cos\theta_0 e^{jk_0x\cos\theta_0} = B_1k_1\cos\theta_1 e^{-jk_1x\cos\theta_1} - C_1k_1\cos\theta_1 e^{jk_1x\cos\theta_1}. \end{cases} \quad (7)$$

In addition, equation (7) can be reduced to the following matrix form:

$$\begin{pmatrix} b_1 \\ c_1 \end{pmatrix} = S_1\begin{pmatrix} r \\ 1 \end{pmatrix}, \quad (8)$$

where S_1 denotes the transfer matrix. We then have

$$S_1 = \begin{pmatrix} 1 & 1 \\ k_1\cos\theta_1 & -k_1\cos\theta_1 \end{pmatrix}^{-1}\begin{pmatrix} 1 & 1 \\ -k_0\cos\theta_0 & k_0\cos\theta_0 \end{pmatrix}. \quad (9)$$

The transfer equations for each sublayer and transmission region can be obtained in a similar way, and the corresponding transfer matrix also can be derived. We then have

$$\begin{pmatrix} b_m \\ c_m \end{pmatrix} = S_m\begin{pmatrix} b_{m-1} \\ c_{m-1} \end{pmatrix}, \quad (10)$$

where

$$S_m = \begin{pmatrix} e^{-jk_md_m\cos\theta_m} & e^{jk_md_m\cos\theta_m} \\ k_m\cos\theta_m e^{-jk_md_m\cos\theta_m} & -k_m\cos\theta_m e^{jk_md_m\cos\theta_m} \end{pmatrix}^{-1} \times \begin{pmatrix} e^{-jk_{m-1}d_m\cos\theta_{m-1}} & e^{jk_{m-1}d_m\cos\theta_{m-1}} \\ k_{m-1}\cos\theta_{m-1}e^{-jk_{m-1}d_m\cos\theta_{m-1}} & -k_{m-1}\cos\theta_{m-1}e^{jk_{m-1}d_m\cos\theta_{m-1}} \end{pmatrix},$$
$$\begin{pmatrix} b_n \\ c_n \end{pmatrix} = S_p t, \quad (11)$$

where

$$S_p = \begin{pmatrix} e^{-jk_n d_p \cos\theta_n} & e^{jk_n d_p \cos\theta_n} \\ k_n \cos\theta_n e^{-jk_n d_p \cos\theta_n} & -k_n \cos\theta_n e^{jk_n d_p \cos\theta_n} \end{pmatrix}^{-1} \begin{pmatrix} e^{-jk_p d_p \cos\theta_p} \\ k_p \cos\theta_p e^{-jk_p d_p \cos\theta_p} \end{pmatrix}. \quad (12)$$

Combining equations (8), (10), and (11), we have

$$S_g \begin{pmatrix} r \\ 1 \end{pmatrix} = S_p t, \quad (13)$$

where r and t are the reflection and transmission coefficients, respectively. S_g denotes the global transfer matrix, and $S_g = (\prod_{m=n}^{2} S_m) S_1$. Simplifying equation (13) gives

$$\begin{pmatrix} r \\ t \end{pmatrix} = -\left(S_{g1}, S_p\right)^{-1} S_{g2}, \quad (14)$$

where S_{g1} and S_{g2} are the first and second columns of S_g, respectively. The reflectance and transmittance can be expressed as $R = |r|^2$ and $T = |t|^2$, respectively. Finally, the absorbance can easily be obtained as [20, 21]

$$A = 1 - T - R. \quad (15)$$

3. Numerical Simulation and Analysis

As mentioned previously, the plasma results from the friction between the air and the aircraft's surface during the reentry process. The results reported by Cui et al. show that the electron density of the flow field is relatively small outside and inside. In contrast, the electron density in the middle is relatively large [22]. A model based on a double exponential distribution is therefore used here to calculate the propagation properties of dusty plasma. This distribution model is shown in Figure 2. The curve of the electron density can be expressed as

$$N_e = \begin{cases} N_0 e^{x_1 (x - x_0)}, & 0 < x < x_0, \\ N_0 e^{x_2 (x_0 - x)}, & x_0 < x < L, \end{cases} \quad (16)$$

where N_0 denotes the maximum electron density, and the value of x is x_0 when N_e equals N_0. In addition, x_1 and x_2 are the coefficients of steepness on the outside and inside of the curve, respectively.

3.1. Effect of Incident Angle. The absorbance and transmittance of the THz wave in a dusty plasma with different incident angles are shown in Figure 3. The parameters of the dusty plasma are set as follows: the incident angles are $\theta = 0, (\pi/6), (\pi/4), (\pi/3)$, $x_1 = 2 \times 10^3$, $x_2 = 8 \times 10^3$, $N_d = 1 \times 10^{14}\,\mathrm{m}^{-3}$, $r_d = 1 \times 10^{-6}\,\mathrm{m}$, $\nu_{en} = 0.1\,\mathrm{THz}$, $L = 10\,\mathrm{cm}$, and $N = 500$. It can be seen from Figure 3 that increasing the frequency of the incident wave increases the transmittance and decreases the absorbance. It can also be observed that increasing the frequency of the incident wave increases the transmission capability of the THz wave in a dusty plasma. Similar results also have been reported in the literature [11]. Moreover, increasing the incident angle decreases the transmittance and increases the absorbance and the propagation distance of the THz wave in a dusty plasma. Hence, more of the energy of the THz wave is absorbed in collisions between electrons and dust particles, resulting in an increase in the absorbance. From Figures 1 and 3, it can be seen that the horizontal component of the THz wave is decreased by increasing the incident angle. Consequently, the transmittance decreases with an increase in the incident angle. Finally, when the collision frequency is equal to the incident wave frequency, a peak in absorbance will appear.

3.2. Effect of Electron Density. Note that both the maximum and the steepness coefficient of the electron density distribution have significant impacts on the absorbance and transmittance, according to equation (15). The absorbance and transmittance of the THz wave in dusty plasma for different values of the maximum electron density and different coefficients of steepness are shown in Figures 4 and 5, respectively. The maximum electron density and the coefficient of steepness were set to $N_0 = 1 \times 10^{19}, 5 \times 10^{19}, 1 \times 10^{20}\,\mathrm{m}^{-3}$ and $x_2 = 2 \times 10^3, 5 \times 10^3, 8 \times 10^3$, respectively. Other parameters were set as follows: $\theta = \pi/6$, $N_d = 1 \times 10^{14}\,\mathrm{m}^{-3}$, $r_d = 1 \times 10^{-6}\,\mathrm{m}$, and $\nu_{en} = 0.1\,\mathrm{THz}$. From Figures 4 and 5, we can see that increasing the frequency of the incident wave increases the transmittance and decreases the absorbance, confirming the results in Figure 3. In addition, increases in the maximum electron density and the steepness coefficient increase the absorbance and decrease the transmittance. This can be explained by the fact that the electron density increases with increasing the maximum electron density and coefficient of steepness, and the possible of collision between charging particles increases, which results more energy of THz wave is absorbed and transfers to neutral particles. Therefore, the absorbance increases and the transmittance decreases [23]. There is also an interesting phenomenon in which the absorbance peak moves to a higher frequency with increases in the maximum electron density and coefficient of steepness.

3.3. Effect of Dust Particles. As mentioned above, the dust particles in the plasma have a significant impact on the propagation characteristics of the THz wave. We, therefore, calculate the absorbance and transmittance of the THz wave in a dusty plasma for different densities and radii of the dust particles, as shown in Figures 6 and 7. In addition, the

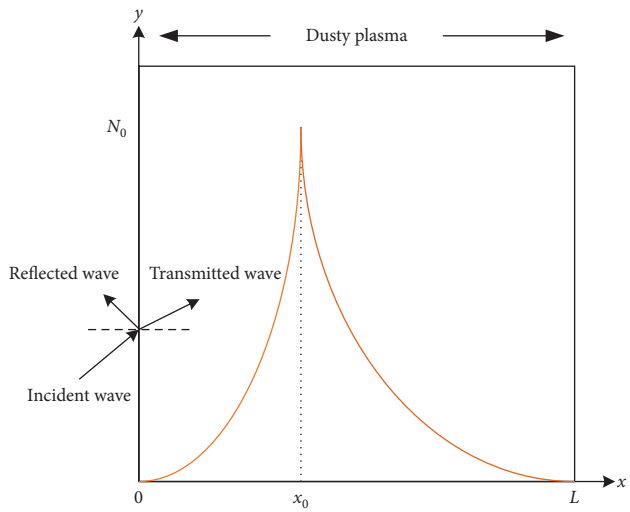

Figure 2: Distribution model for electron density in a dusty plasma.

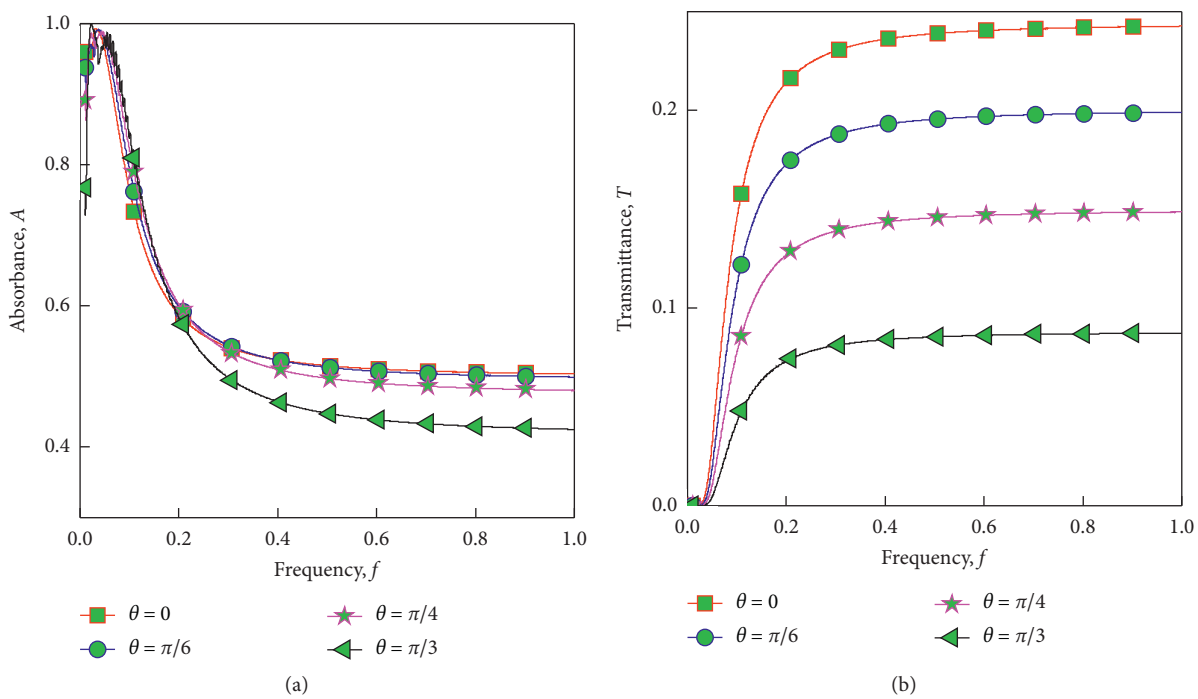

Figure 3: Absorbance and transmittance versus wave frequency for different incident angles in a dusty plasma environment.

distribution of dust particles is uniform in this paper. Moreover, the densities and radii are set to $N_d = 1 \times 10^{13}, 5 \times 10^{13}, 1 \times 10^{14}\,\mathrm{m}^{-3}$ and $r_d = 1 \times 10^{-6}, 5 \times 10^{-6}, 8 \times 10^{-6}\,\mathrm{m}$, respectively. The other parameters are set as follows: $\theta = \pi/6$, $N_0 = 1 \times 10^{19}\,\mathrm{m}^{-3}$, $x_2 = 8 \times 10^{-3}$, and $\nu_{en} = 0.1\,\mathrm{THz}$. As shown in Figures 6 and 7, increasing the frequency of the incident wave increases the transmittance and decreases the absorbance. In addition, increasing the density and radius of the dust particles decreases the transmittance and increases the absorbance. This can be attributed to the fact that increasing the density and radii of the dust particles increases the number of collisions in the dusty plasma, meaning that more of the energy of the THz wave is absorbed, and the transmittance is reduced [24]. Moreover, due to the charging effect of the dust particles in the plasma, increasing the density and radius of the dust particles also means that the energy of the THz wave is absorbed. It can be observed from the simulation results that the dust particles in the plasma will result in attenuation of communication between the ground and the aircraft [25].

3.4. Effect of Dust Particles. Figure 8 shows the influence of collision frequency on the transmittance and absorbance of the THz wave. The parameters of the dusty plasma are set as follows: $\nu_{en} = 0.1, 0.5, 0.8\,\mathrm{THz}$, $\theta = \pi/6$, $N_0 = 1 \times 10^{19}\,\mathrm{m}^{-3}$,

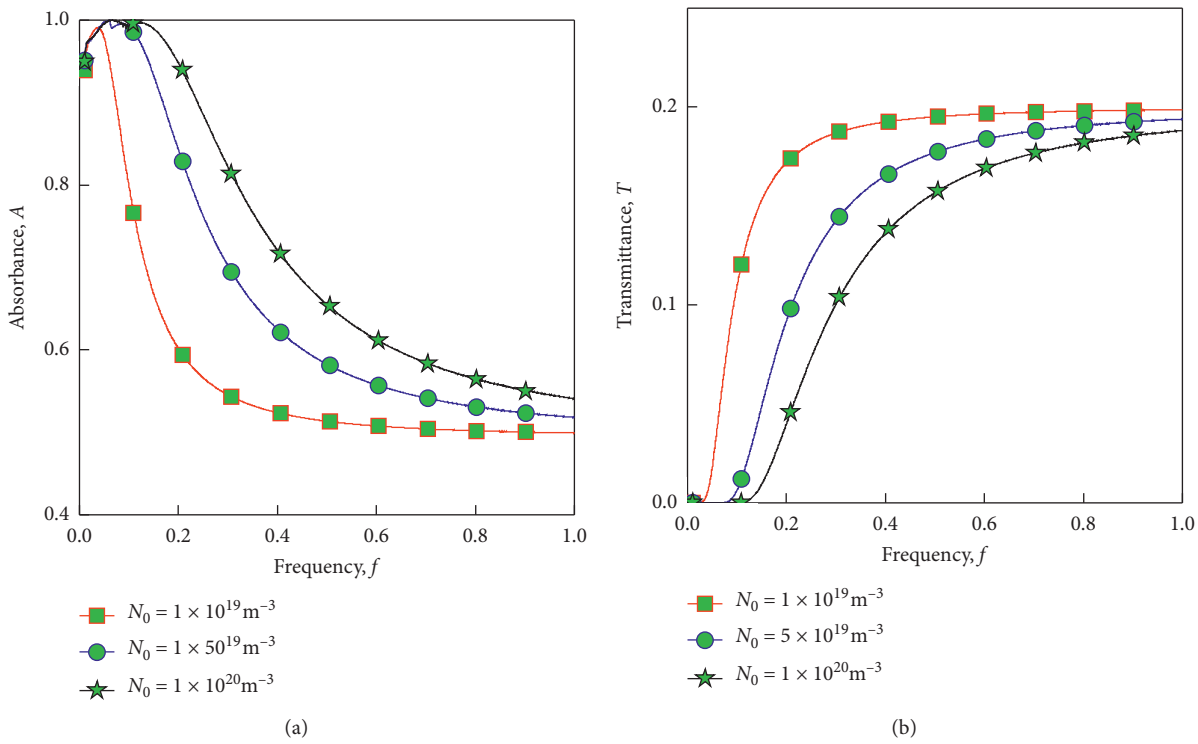

Figure 4: Absorbance and transmittance versus wave frequency for different maxima in the electron density in a dusty plasma environment.

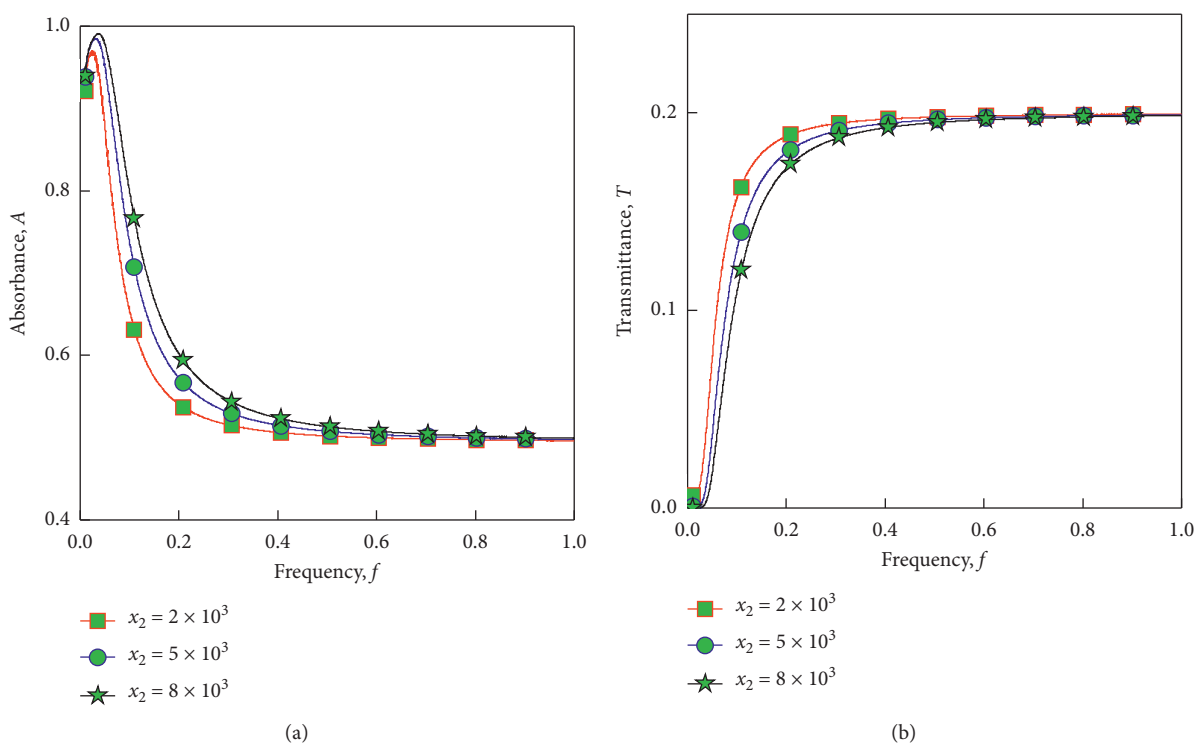

Figure 5: Absorbance and transmittance versus wave frequency for different steepness coefficients of the electron density in a dusty plasma environment.

$x_2 = 8 \times 10^3$, $N_d = 1 \times 10^{14}\,\mathrm{m}^{-3}$, and $r_d = 1 \times 10^{-6}\,\mathrm{m}$. As can be seen from Figure 8, increasing the frequency of the incident wave increases the transmittance and decreases the absorbance. In addition, the transmittance decreases and the absorbance increases when the collision frequency is increased. This can be explained by the fact that when the

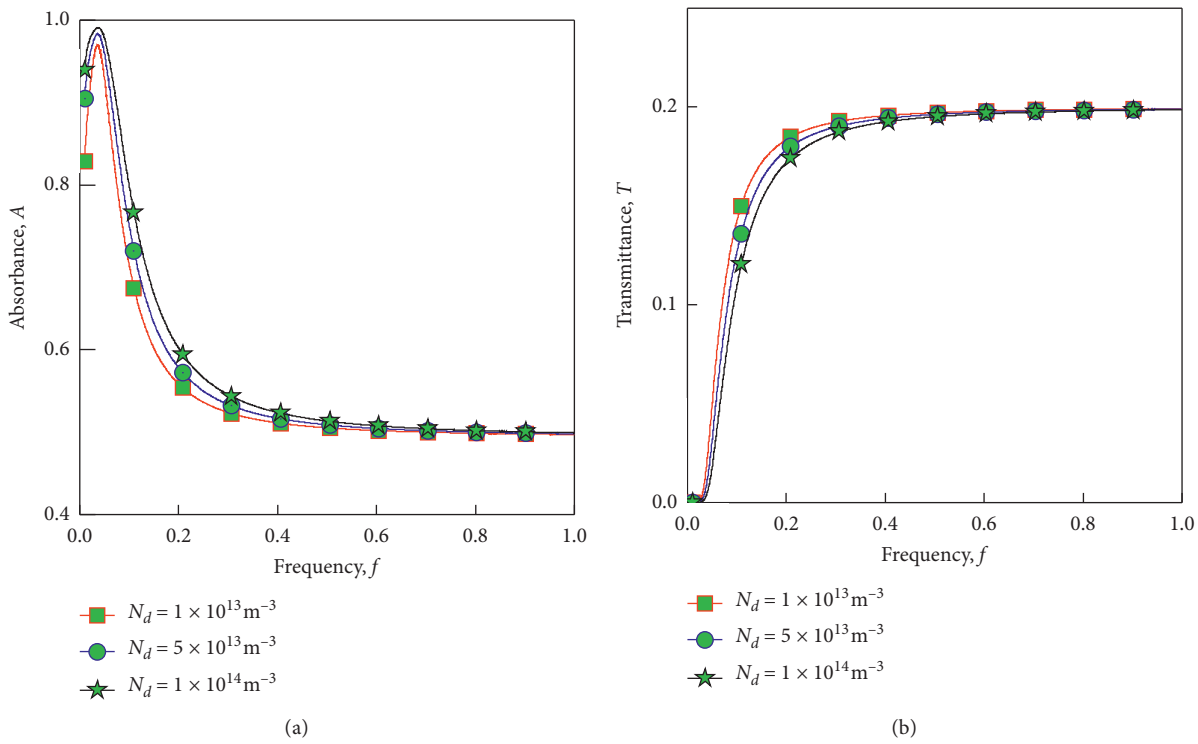

Figure 6: Absorbance and transmittance versus wave frequency for different densities of dust particles in a dusty plasma environment.

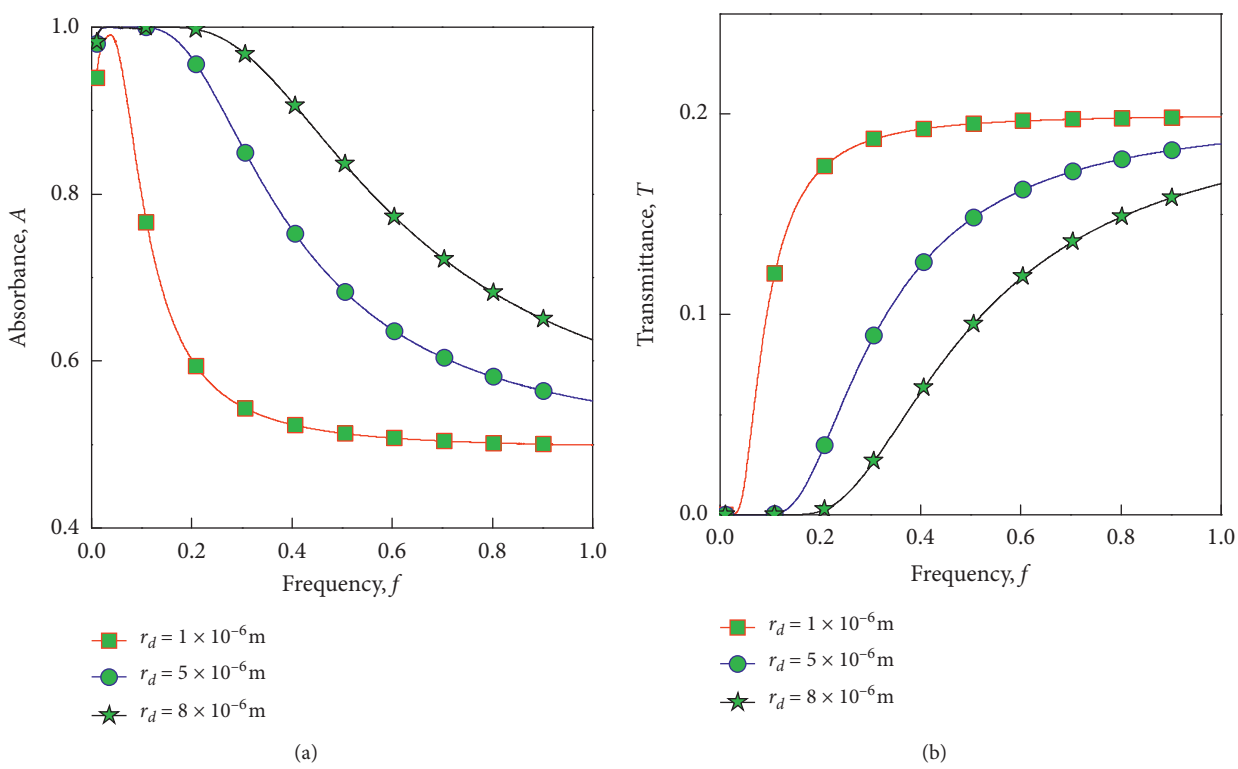

Figure 7: Absorbance and transmittance versus wave frequency for different radii of dust particles in a dusty plasma environment.

collision frequency is increased, more of the energy of the THz wave is absorbed by collisions among the various particles and is transferred to neutral particles [26]. Consequently, a lower collision frequency contributes to a higher transmittance, which is advantageous in terms of the blackout problem.

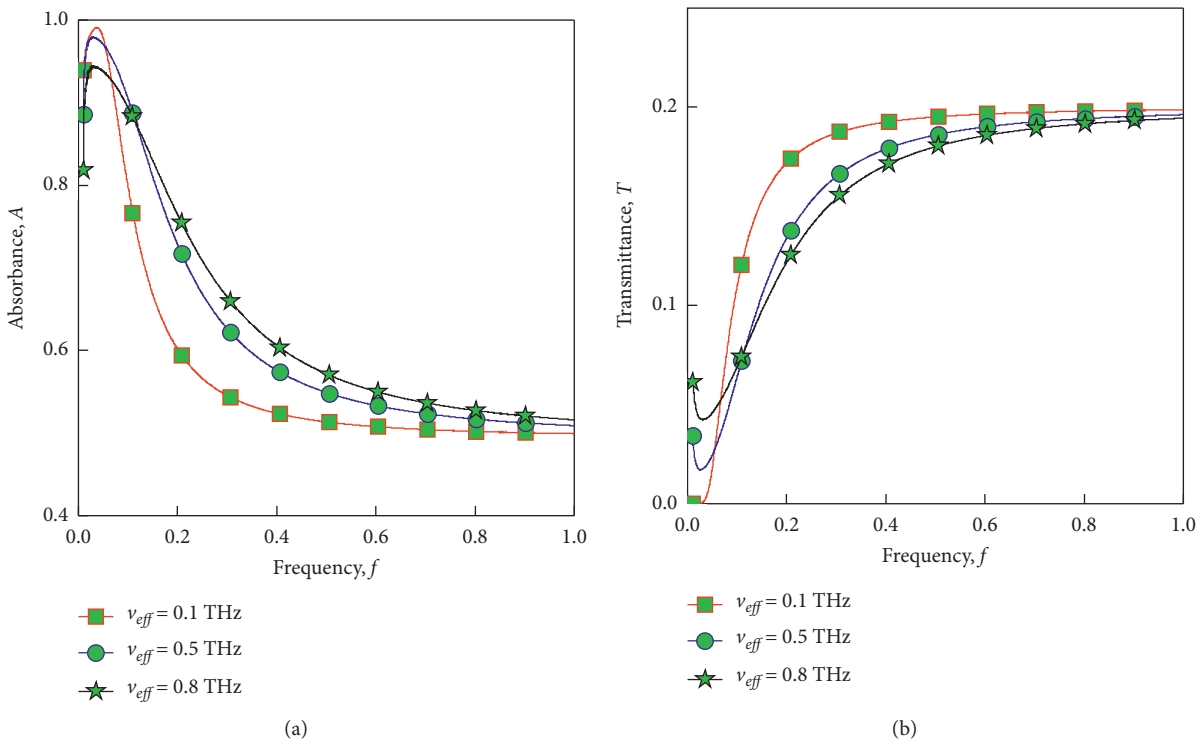

Figure 8: Absorbance and transmittance versus wave frequency for different collision frequencies in a dusty plasma environment.

4. Conclusions

The transmittance and absorbance of a THz wave propagating obliquely in a dusty plasma with a ceramic substrate are calculated using the SMM. In addition, the impacts of the frequency of the THz wave and the parameters of the dusty plasma, such as the angle of incidence of the wave, the electron density, the density and radius of the dust particles, and the frequency of collisions on the transmittance and absorbance of the THz wave in the dusty plasma, are analysed. The results of simulations demonstrate that the absorbance increases and the transmittance decreases with an increase in the angle of incidence, the maximum value of the electron density, the coefficient of steepness, the density and radius of the dust particles, and the collision frequency. In addition, the peak in the absorbance shifts to a higher frequency with increases in the maximum electron density, the coefficient of steepness, and the radius of the dust particles. Consequently, these simulation results provide a theoretical basis for determining the mechanism of EM wave propagation in a dusty plasma and offer some potential ways to solve the blackout problem.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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