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The effect of dust particles' electric potential on dusty plasma's absorption characteristic

Chen Yun-yun[a,b,c,*], Gu Fang[a,c], Yang Cui-hong[a,c]

[a] Jiangsu Key Laboratory for Optoelectronic Detection of Atmosphere and Ocean, Nanjing University of Information Science & Technology, Nanjing 210044, China

[b] Jiangsu Collaborative Innovation Center on Atmospheric Environment and Equipment Technology (CICAEET), Nanjing University of Information Science and Technology, Nanjing 210044, China

[c] School of Physics and Optoelectronic Engineering, Nanjing University of Information Science and Technology, Nanjing 210044, China

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ABSTRACT

The absorption coefficient of dusty plasma is deduced on the basis of considering the influence of dust particles electric potential, and its absorption characteristic in the near infrared region is discussed. The involved results manifest that the absorption coefficient of dusty plasma with the dust particles potential is considered is obviously bigger than that of not considered in the given temperature, pressure and frequency ranges, which proves the influence of dust particles potential can not be omitted. Besides, the results also indicate that the maximal absorption ability of the dusty plasma does not occur where the maximal electron number density (plasma resonance frequency) appears. Consequently, two conditions, which determine where the maximal absorption appears, are presented by a series of theoretical deduction.

1. Introduction

The various characteristic of common plasma has been widely studied up to now. But as the rapid development of the aviation, spaceflight, rocket and missile technology, a kind of complex plasma flow field emerged. In general, the special point of the complex plasma is the existence of the dust particles, compared with the common plasma. In other words, from the perspective of species composition, common plasma and the dust particles form a complex system—dusty plasma. In fact, the dust particles are widespread in the universe, they even becomes a form of solid matter in the universe [1–3], such as: interstellar space, the earth's ionosphere and tail and ring, etc. Meanwhile, the dust particles also commonly appear in the fusion reactor [4,5] and the low temperature plasma materials processing device [6].

Since the 1990s, the dusty plasma theory is widely researched [7]. After that, the studies about the scattering [8,9] and absorption characteristics [10,11] are gradually increasing. In essence, the involved researches are quite helpful to the communication technology. As a result, they are mainly discussed in the microwave region. However, it is noted that the studying the scattering and absorption characteristics also can benefit to apply optical methods to diagnose the key parameters (temperature, electron number density) for the dusty plasma flow field. Obviously, to determine whether the

* Corresponding author at: Jiangsu Key Laboratory for Optoelectronic Detection of Atmosphere and Ocean, Nanjing University of Information Science & Technology, Nanjing 210044, China.
E-mail address: yunqq321@sina.cn (C. Yun-yun).

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existing optical methods can be directly applied in the dusty plasma flow field, it needs to study their optical absorption characteristics.

Consequently, the absorption characteristic of the dusty plasma will be studied in this paper, with considering the dust particles potential by introducing a concept named electric potential impact factor.

2. Theory and derivation

2.1. Basic theories

When considering the collisions and charging between electrons, ions and dust particles, especially considering the dust particles potential, the complex conductivity of dusty plasma σ_e is usually described as [12]:

$$\sigma_e = \varepsilon_0 \frac{\omega_p^2 \upsilon_{eff}}{\omega^2 + \upsilon_{eff}^2} + \frac{\left(\eta_{ed} + \eta_{\phi_d}\right)\left(\omega^2 - \upsilon_{eff}\upsilon_{ch}\right)}{\left(\omega^2 + \upsilon_{eff}^2\right)\left(\omega^2 + \upsilon_{ch}^2\right)} \frac{\omega}{k} + i\omega \left[\frac{\left(\eta_{ed} + \eta_{\phi_d}\right)\left(\upsilon_{eff} + \upsilon_{ch}\right)}{\left(\omega^2 + \upsilon_{eff}^2\right)\left(\omega^2 + \upsilon_{ch}^2\right)} \frac{\omega}{k} - \frac{\varepsilon_0 \omega_p^2}{\omega^2 + \upsilon_{eff}^2} \right] \quad (1)$$

where ε_0 is the vacuum electric constant, ω and k represent the detecting wave frequency and wave number respectively, ω_p and υ_{eff} denote the dusty plasma frequency and the effective collision frequency, η_{ed} and η_{ϕ_d} are the charging response factor and electric potential impact factor, $\upsilon_{ch} \approx \frac{\omega_{pi}}{\sqrt{2\pi}} \frac{r_d}{\lambda_D}(1 + \tau + z)$ is the charging frequency (λ_D is Debye radius, ω_{pi} is the ion plasma frequency, $\tau = T_i/T_e$ and $z = Ze^2/r_d T_e$ are the most basic parameters of the dusty plasma [7]).

Therefore, the relative complex dielectric constant should be obtained like:

$$\begin{aligned} \varepsilon_r &= 1 + \frac{\sigma_e}{i\omega\varepsilon_0} = 1 - i\frac{\sigma_e}{\omega\varepsilon_0} \\ &= 1 + \frac{1}{\varepsilon_0}\left[\frac{\left(\eta_{ed} + \eta_{\phi_d}\right)\left(\upsilon_{eff} + \upsilon_{ch}\right)}{\left(\omega^2 + \upsilon_{eff}^2\right)\left(\omega^2 + \upsilon_{ch}^2\right)} \frac{\omega}{k} - \frac{\varepsilon_0 \omega_{pe}^2}{\omega^2 + \upsilon_{eff}^2} \right] \\ &\quad - i \left[\frac{\omega_{pe}^2 \upsilon_{eff}}{\omega\left(\omega^2 + \upsilon_{eff}^2\right)} + \frac{\left(\eta_{ed} + \eta_{\phi_d}\right)\left(\omega^2 - \upsilon_{eff}\upsilon_{ch}\right)}{\varepsilon_0 \omega \left(\omega^2 + \upsilon_{eff}^2\right)\left(\omega^2 + \upsilon_{ch}^2\right)} \frac{\omega}{k} \right] \end{aligned} \quad (2)$$

Under the condition of $\frac{\omega}{k} = c$, relative complex dielectric constant can be represented as:

$$\begin{aligned} \varepsilon_r &= 1 + \frac{1}{\varepsilon_0}\left[\frac{\left(\eta_{ed} + \eta_{\phi_d}\right)\left(\upsilon_{eff} + \upsilon_{ch}\right)c}{\left(\omega^2 + \upsilon_{eff}^2\right)\left(\omega^2 + \upsilon_{ch}^2\right)} - \frac{\varepsilon_0 \omega_{pe}^2}{\omega^2 + \upsilon_{eff}^2} \right] \\ &\quad - i \left[\frac{\omega_{pe}^2 \upsilon_{eff}}{\omega\left(\omega^2 + \upsilon_{eff}^2\right)} + \frac{\left(\eta_{ed} + \eta_{\phi_d}\right)\left(\omega^2 - \upsilon_{eff}\upsilon_{ch}\right)c}{\varepsilon_0 \omega \left(\omega^2 + \upsilon_{eff}^2\right)\left(\omega^2 + \upsilon_{ch}^2\right)} \right] \end{aligned} \quad (3)$$

Finally, the absorption coefficient of dusty plasma can be represented as:

$$\alpha = \frac{\omega}{\sqrt{2}c} \left\{ \left[\left(1 + \frac{\omega_p^2}{\omega^2 + \upsilon_{eff}^2} - A\right)^2 + \left(\frac{\omega_p^2 \upsilon_{eff}}{\omega\left(\omega^2 + \upsilon_{eff}^2\right)} + \frac{B}{\varepsilon_0 \omega} \right)^2 \right]^{\frac{1}{2}} - \left(1 + \frac{\omega_p^2}{\omega^2 + \upsilon_{eff}^2} - A\right) \right\}^{\frac{1}{2}} \quad (4)$$

where $A = \frac{c\left(\eta_{ed} + \eta_{\phi_d}\right)\left(\upsilon_{ch} + \upsilon_{eff}\right)}{\varepsilon_0\left(\omega^2 + \upsilon_{ch}^2\right)\left(\omega^2 + \upsilon_{eff}^2\right)}$, $B = \frac{c\left(\eta_{ed} + \eta_{\phi_d}\right)\left(\omega^2 - \upsilon_{ch}\upsilon_{eff}\right)}{\left(\omega^2 + \upsilon_{ch}^2\right)\left(\omega^2 + \upsilon_{eff}^2\right)}$.

If ignoring the effect of dust particles potential on conductivity, that is $\eta_{\phi_d} = 0$, Eq. (4) returns to the result in Ref. [10], which proves the rationality of the formula that we deduced. At the same time, also based on Eq. (4), if ignoring the collision and charging of electrons and ions on the dust particles, the absorption coefficient can be changed into that of common plasma, which also shows that our model is reasonable.