PLASMA PHYSICS

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SPECIFIC FEATURES OF MICROWAVE METHODS FOR DUSTY PLASMA DIAGNOSTICS. I. DIELECTRIC PERMITTIVITY, REFRACTIVE AND ABSORPTION INDICES

Two widely used approaches for the determination of the refractive, n, and absorption, $\varkappa$, indices of a dusty plasma have been analyzed. In one of them, the expressions for n and $\varkappa$ obtained for a dust-free plasma are used, but the collisions of plasma ions with dust particles are taken into account by means of the collision frequency parameter. In the other approach, the characteristic charging frequency for dust particles is additionally introduced.

K e y w o r d s: dusty plasma, refractive index, absorption index, microwave diagnostic methods, dielectric permittivity.

1. Introduction

The progress and development of researches in physics of plasma, including a high-temperature plasma of controlled fusion reactions, are governed, to a large extent, by the innovations implemented in the methods for measuring plasma parameters. Among the methods of plasma diagnostics, microwave methods [1–4] are widely used nowadays. Their advantage consists in their contactless character and the absence of restrictions on the plasma temperature.

Both active and passive methods are used in the plasma diagnostics. When using the passive method, the own microwave radiation emitted by a plasma is measured. On the other hand, the interaction of electromagnetic waves with a plasma and the measurement of the results of this interaction form the basis of active methods.

Among the active methods that are most often used in the plasma diagnostics, there are methods that are based on the measurement of the phase shift or ab-

sorption index for an electromagnetic wave that propagates through a plasma; e.g., this is the method of plasma interferometry. In this method, the measurement results are used to determine the refractive index n and the absorption index $\varkappa$ [1–4]:

$$\varphi_p = \frac{\omega}{c} \int_0^{S_p} n(s)ds, \tag{1}$$

$$\mu_p = \frac{\omega}{c} \int_0^{S_p} \varkappa(s)ds, \tag{2}$$

where ω is the probing frequency, c the light speed, $n(s)$ and $\varkappa(s)$ are the refractive and absorption, respectively, indices at the given point s in the plasma, and S_p is the path of a microwave beam in the plasma.

The active methods are used to measure some parameters in both weakly and strongly ionized plasma (the electron concentration, the collision frequency, and others), as well as in a high-temperature plasma in experiments dealing with controlled thermonuclear

fusion. Recently, the application scope of active microwave methods was somewhat extended owing to their usage in the diagnostics of a dusty plasma [5–8].

The dusty plasma (complex, colloidal plasma) is an ionized gas that contains macroscopic (micron- and submicron-sized) charged particles [9–15]. The interest in a dusty plasma is associated with its wide spread in the nature (atmosphere, outer space, and so forth) and in technological plasma installations (etching, sputtering, thermonuclear, and others). The research of the processes running in a dusty plasma and the determination of its properties can be useful for the solution of many physical and applied problems. The study of the dusty plasma properties showed that dust particles can form plasma clusters and crystals. As a rule, plasma particles (macroscopic particles) are charged negatively, and their charge can reach a value of up to 10^5 times the electron charge. The presence of charged dust particles not only changes the balance between the electron and ion concentrations, thus affecting the propagation of plasma oscillations, but also results in the emergence of new low-frequency waves [9–15].

One of the specific features of a dusty plasma is the influence of dust particles on the scattering of electromagnetic waves in the plasma. In works [16–20], it was shown that the scattering of electromagnetic waves depends on the following parameters: the concentration, size, and charge of dust particles. In works [21, 22], the influence of dust particles on the scattering of electromagnetic waves under ionospheric conditions was considered.

As was already mentioned, the development of microwave methods for the dusty plasma diagnostics has received an impetus in recent years [5–8]. There are several approaches aimed at the consideration of the interaction between electromagnetic waves and a dusty plasma [23, 24]. Rather often, this consideration includes issues that go beyond the scope of the microwave application for the dusty plasma diagnostics. The literature on this issue is scarce and occasional.

The aim of this work is to analyze the method used, while considering the interaction of microwaves with a dusty plasma, namely, to summarize the corresponding literature data, and to consider the scope of applications and the specific features of active microwave methods used for the dusty plasma diagnostics.

2. Propagation of Electromagnetic Waves Through a Plasma

2.1. Dielectric permittivity of a plasma

In the general case, the complex dielectric permittivity of a medium can be written in the form [25, 26]

$$\varepsilon'_{ij}(\omega, k) = \delta_{ij} + \sum_a \chi^{(a)}_{ij}(\omega, k), \qquad (3)$$

where δ_{ij} is the identity tensor,

$$\chi^{(a)}_{ij}(\omega, k) = i \frac{\sigma^{(a)}_{ij}(\omega, k)}{\omega \epsilon_0}$$

is the tensor of high-frequency dielectric susceptibility (polarizability) of the a-th plasma component, $\sigma^{(a)}_{ij}(\omega, k)$ the complex conductivity tensor, ω the frequency, k the wave vector, and ϵ_0 the electric constant. The dependences of the indicated tensors on the frequency ω and on the wave vector k are responsible, respectively, for the frequency dispersion and the spatial dispersion of the electromagnetic field in the medium. If the velocity distribution of plasma particles is isotropic, the tensor $\chi^{(a)}_{ij}(\omega, k)$ can be expressed only in terms of the identity tensor δ_{ij} and the tensor $k_i k_j$. Accordingly, for an isotropic medium, the tensor $\chi^{(a)}_{ij}(\omega, k)$ can be expressed in the form

$$\varepsilon'_{ij}(\omega, k) = \left(\delta_{ij} - \frac{k_i k_j}{k^2}\right) \varepsilon^{tr}(\omega, k) + \frac{k_i k_j}{k^2} \varepsilon^l(\omega, k), \quad (4)$$

where $\varepsilon^{tr}(\omega, k)$ and $\varepsilon^l(\omega, k)$ are the transverse and longitudinal, respectively, dielectric permittivities. In the case of a cold plasma, an insignificant influence of the particle thermal motion on the wave propagation and the spatial dispersion can be neglected. Accordingly, we obtain the following equations:

$$\varepsilon^{tr}(\omega, k) = \varepsilon^l(\omega, k) = \varepsilon'(\omega), \varepsilon'_{ij} = \varepsilon'(\omega)\delta_{ij}.$$

In the absence of an external magnetic field, a cold plasma is isotropic. In this case, the complex dielectric permittivity is determined as follows [27]:

$$\varepsilon' = \varepsilon - i \frac{\sigma}{\omega \epsilon_0}, \qquad (5)$$

where ε is the dielectric permittivity, and σ the high-frequency plasma conductivity. In the general case, the parameters ε', ε, and σ depend on the frequency and the coordinates.

For a two-component plasma containing electrons and ions, the quasineutrality condition looks like

$$N_e = Z_i N_i, \tag{6}$$

where N_e is the electron concentration in a plasma, N_i the ion concentration, and Z_i the charge number of ions. Accordingly, the dielectric permittivity ε and the conductivity σ of a plasma are determined by the formulas [27]

$$\varepsilon = 1 - \frac{N_e e^2}{\epsilon_0 m_e (\omega^2 + \nu_{(e),\text{eff}}^2)} - \frac{N_i Z_i^2 e^2}{\epsilon_0 m_i (\omega^2 + \nu_{(i),\text{eff}}^2)}, \tag{7}$$

$$\sigma = \frac{N_e e^2 \nu_{(e),\text{eff}}}{m_e (\omega^2 + \nu_{(e),\text{eff}}^2)} + \frac{N_i Z_i^2 e^2 \nu_{(i),\text{eff}}}{m_i (\omega^2 + \nu_{(i),\text{eff}}^2)}, \tag{8}$$

where $\nu_{(e),\text{eff}}$ and $\nu_{(i),\text{eff}}$ are the effective collision frequencies of electrons and ions, respectively, with dust particles; and m_e and m_i are the electron and ion, respectively, masses. Since the mass ratio $m_e/m_i \ll \ll 1$ – e.g., for the hydrogen atom (proton), we have $m_e/m_i = 5.446 \times 10^{-4}$ – the influence of ions is very small, as a rule, and it is not taken into consideration, as usual. The account for ions is required, if the concentration of negative ions in a plasma is high or the concentration of electrons is very low. If the ionic contribution is neglected, Eqs. (7) and (8) take the form

$$\varepsilon = 1 - \frac{N_e e^2}{\epsilon_0 m_e (\omega^2 + \nu_{\text{eff}}^2)}, \tag{9}$$

$$\sigma = \frac{N_e e^2 \nu_{\text{eff}}}{m_e (\omega^2 + \nu_{\text{eff}}^2)}, \tag{10}$$

where

$$\nu_{\text{eff}} = \nu_{ei} + \nu_{en} \tag{11}$$

is the effective collision frequency of electrons with ions and neutral particles,

$$\nu_{ei} = \frac{\sqrt{2} N_i Z_i^2 e^4 \Lambda_{ei}}{12 T_e^{3/2} m_e^{1/2} \pi^{3/2} \epsilon_0^2}$$

is the frequency of electron-ion collisions, Λ_{ei} the Coulomb logarithm,

$$\nu_{en} = N_n K_{el}$$

is the frequency of electron-neutral collisions, and K_{el} is the rate constant for electron-neutral collisions. Collisions between electrons in isotropic plasma are insignificant, when $\omega^2 \gg \nu_{\text{eff}}^2$, so that they can be neglected [27].

2.2. Refractive and absorption indices

In the microwave plasma diagnostics, the dielectric permittivity and conductivity parameters play rather an auxiliary role. It is the refractive index n and the absorption index $\varkappa$ that are directly determined. A relation of the complex dielectric constant with the indices n and $\varkappa$ is given by the formula

$$\varepsilon' = (n - i\varkappa)^2. \tag{12}$$

With regard for Eqs. (5) and (12) for n and $\varkappa$, respectively, we obtain

$$\varepsilon = n^2 - \varkappa^2, \tag{13}$$

$$\frac{\sigma}{\omega \epsilon_0} = 2n\varkappa. \tag{14}$$

From whence, in view of Eqs. (9) and (10), the refractive index n and the absorption index $\varkappa$ can be written in the form [27]

$$n^2 = \frac{1}{2} \left(1 - \frac{\omega_{pe}^2}{\omega^2 + \nu_{\text{eff}}^2} \right) + $$
$$+ \frac{1}{2} \sqrt{ \left(1 - \frac{\omega_{pe}^2}{\omega^2 + \nu_{\text{eff}}^2} \right)^2 + \left(\frac{\omega_{pe}^2}{\omega^2 + \nu_{\text{eff}}^2} \frac{\nu_{\text{eff}}}{\omega} \right)^2 }, \tag{15}$$

$$\varkappa^2 = -\frac{1}{2} \left(1 - \frac{\omega_{pe}^2}{\omega^2 + \nu_{\text{eff}}^2} \right) + $$
$$+ \frac{1}{2} \sqrt{ \left(1 - \frac{\omega_{pe}^2}{\omega^2 + \nu_{\text{eff}}^2} \right)^2 + \left(\frac{\omega_{pe}^2}{\omega^2 + \nu_{\text{eff}}^2} \frac{\nu_{\text{eff}}}{\omega} \right)^2 }, \tag{16}$$

where

$$\omega_{pe} = \left(\frac{N_e e^2}{\epsilon_0 m_e} \right)^{1/2}.$$

is the electron plasma frequency. In the limiting case of high frequencies, i.e. if $\omega^2 \gg \nu_{\text{eff}}^2$, Eqs. (9), (10), (15), and (16) can be somewhat simplified [27]:

$$\varepsilon = 1 - \frac{N_e e^2}{\epsilon_0 m_e \omega^2}, \tag{17}$$

$$\sigma \approx \frac{N_e e^2 \nu_{\text{eff}}}{m_e \omega^2}, \tag{18}$$

$$n^2 = \frac{1}{2} \left(1 - \frac{\omega_{pe}^2}{\omega^2} \right) + $$
$$+ \frac{1}{2} \sqrt{ \left(1 - \frac{\omega_{pe}^2}{\omega^2} \right)^2 + \left(\frac{\omega_{pe}^2}{\omega^2} \frac{\nu_{\text{eff}}}{\omega} \right)^2 }, \tag{19}$$

$$\varkappa^2 = -\frac{1}{2}\left(1 - \frac{\omega_{pe}^2}{\omega^2}\right) +$$

$$+ \frac{1}{2}\sqrt{\left(1 - \frac{\omega_{pe}^2}{\omega^2}\right)^2 + \left(\frac{\omega_{pe}^2}{\omega^2}\frac{\nu_{\text{eff}}}{\omega}\right)^2}. \tag{20}$$

In the particular case where $\omega^2 \gg \nu_{\text{eff}}^2$ and $\varepsilon \gg$ $\gg \sigma/(\omega\epsilon_0)$ $(\varepsilon > 0)$, Eqs. (19) and (20) for the refractive index n and the absorption index $\varkappa$ can also be strongly simplified to the form [27]

$$n \approx \sqrt{\varepsilon} = \left(1 - \frac{\omega_{pe}^2}{\omega^2}\right)^{1/2}, \tag{21}$$

$$\varkappa \approx \frac{1}{2}\frac{\sigma}{\omega\epsilon_0\sqrt{\varepsilon}} = \frac{1}{2}\frac{\omega_{pe}^2}{\omega^2}\frac{\nu_{\text{eff}}}{\omega}\left(1 - \frac{\omega_{pe}^2}{\omega^2}\right)^{-1/2}. \tag{22}$$

Most often, expressions (21) and (22) are used, when the methods of microwave plasma diagnostics are considered and applied [1–4]. In the case where $\omega^2 \gg \nu_{\text{eff}}^2$ and $\omega_{pe} \geq \omega$, the electromagnetic wave rapidly decays in plasma. If the penetration depth of the alternating field into a plasma is smaller than the thickness of a plasma with $\omega_{pe} \geq \omega$, then the electromagnetic wave becomes reflected from the plasma boundary. Figure 1 illustrates the dependences of the refractive (panel a) and absorption (panel b) indices on the ratio ω_{pe}/ω, which were calculated according to formulas (15) and (16).

3. Propagation of Electromagnetic Waves in a Dusty Plasma

3.1. Dusty plasma

The dusty plasma contains macroscopically small charged particles. In a gas-discharge plasma, provided that the emission processes are absent, a dust particle captures electrons and ions, so that it becomes electrically charged. Since the mobility of electrons is higher, the dust particle acquires a negative charge [9–15]. Owing to the processes of electron emission (thermionic, photoelectron, secondary electron emission) from the surface of a dust particle, its total charge decreases by magnitude and, under certain conditions, it may became positive. In this case, the coexistence of particles and electrons emitted by them in the framework of a common two-component system is possible. The account for dust
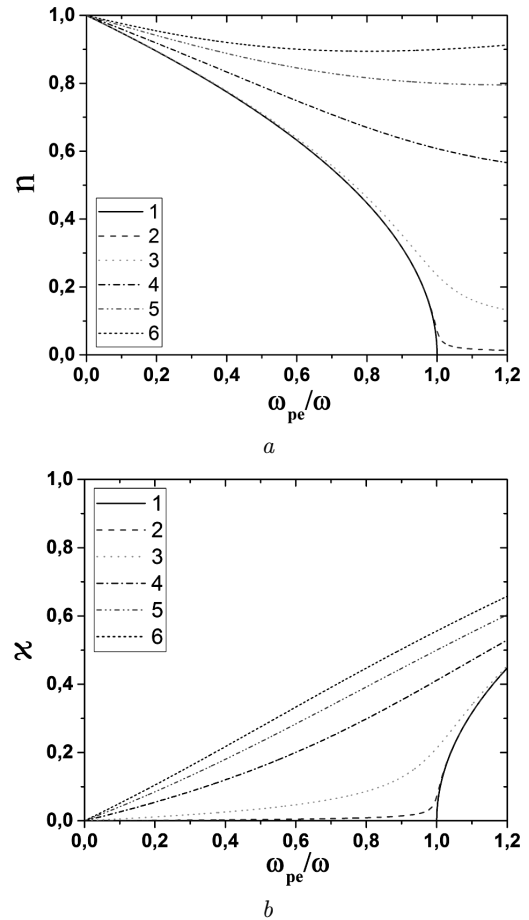
Fig. 1. Dependences of the refractive (a) and absorption (b) indices in a dusty plasma on the ratio ω_{pe}/ω for various values of the ratio $\nu_{\text{eff}}^2/\omega^2 = 10^{-5}$ (1), 10^{-2} (2), 0.1 (3), 0.5 (4), 0.8 (5), and 1 (6)

particles leads to the following condition of plasma quasineutrality:

$$N_e + Z_d N_d = Z_i N_i, \tag{23}$$

where N_d is the concentration of dust particles, and Z_d their charge number.

In the orbital-motion-limited (OML) approximation, the cross-sections of the electron and single-charged ion capture by a dust particle are determined by the following expressions [11]:

• for the electron capture,

$$\sigma_e(v_e) = \begin{cases} 0 & \text{if } \dfrac{2e\phi_s}{m_e v_e^2} \leq -1, \\ \pi r_d^2\left(1 + \dfrac{2e\phi_s}{m_e v_e^2}\right) & \text{if } \dfrac{2e\phi_s}{m_e v_e^2} > -1; \end{cases} \tag{24}$$

• for the ion capture,

$$\sigma_i(v_i) = \pi r_d^2 \left(1 - \frac{2e\phi_s}{m_i v_i^2}\right), \tag{25}$$

where r_d is the dust particle radius (most often, the dust particle is assumed to be spherical); v_e and v_i are the electron and ion, respectively, velocities with respect to the particle; and ϕ_s is the surface potential of the particle with respect to the plasma (it is adopted to be negative, $\phi_s < 0$).

The stationary charge of a particle, Z_d, corresponds to the equality between the electron and ion fluxes absorbed by the particle. In the dimensionless form, it can be determined from the relation [11]

$$\exp(-z) = \frac{N_i}{N_e}\left(\frac{\mu}{\tau}\right)^{1/2}(1 + z\tau)(1 + P), \tag{26}$$

where $\tau = T_e/T_i$ is the ratio between the electron and ion temperatures, $\mu = m_e/m_i$ is the ratio between the electron and ion masses,

$$z = \frac{|Z_d|e^2}{r_d T_e}$$

is the normalized absolute value of the dust particle charge, and

$$P = |Z_d|\frac{N_d}{N_e}$$

is the Havnes parameter determining the ratio between the product of the concentration and charge of dust particles, on the one hand, and the concentration of the electron component, on the other hand.

The charging frequency of a dust particle is defined as the relaxation frequency of small charge perturbations to the stationary value [11],

$$v_{\text{ch}} = \frac{1+z}{\sqrt{2\pi}}\frac{r_d}{\lambda_{di}}\omega_{pi}, \tag{27}$$

where

$$\lambda_{di} = \left(\frac{\epsilon_0 T_i}{N_i Z_i^2 e^2}\right)^{1/2}$$

is the ion Debye radius, and

$$\omega_{pi} = \left(\frac{N_i Z_i^2 e^2}{\epsilon_0 m_i}\right)^{1/2}$$

is the ion-plasma frequency.

In a dusty plasma, besides the electron-ion, ν_{ei}, electron-neutral, ν_{en}, ion-ion, ν_{ii}, and ion-neutral, ν_{in}, collision frequencies, the frequencies of collisions between dust particles and electrons, ν_{ed}, ions, ν_{id}, and neutral atoms (molecules), ν_{nd}, as well as between the particles themselves, ν_{dd}, have to be taken into consideration [11]. The frequency of collisions between electrons and dust particles can be determined from the relation [28]

$$\nu_{ed} = \frac{8\sqrt{2\pi}}{3}r_d^2 N_d v_e \Phi_e(z, L), \tag{28}$$

where the multiplier $\Phi_e(z, L)$ makes allowance for the electrostatic interaction between an electron and a dust particle. For an uncharged particle, $\Phi_e(z, L) = 1$. More specifically, this quantity involves the absorption and scattering of electrons by the dust particle:

$$\Phi_e(z, L) = \Phi_e^{coll}(z) + \Phi_e^{orb}(z, L),$$

where

$$\Phi_e^{\text{coll}}(z) = \left(1 + \frac{z}{2}\right)\exp(-z)$$

and

$$\Phi_e^{\text{orb}}(z, L) = \frac{1}{4}z^2\Lambda_{ed}.$$

For the electron-particle collisions, the Coulomb logarithm Λ_{ed} is determined by the formula [28]:

$$\Lambda_{ed} = \int_0^\infty e^{-x}\ln\left(1 + 4L^2\frac{x^2}{z^2}\right)dx - $$
$$- 2\int_z^\infty e^{-x}\ln\left(\frac{2x}{z} - 1\right)dx, \tag{29}$$

where $L = \lambda_d/r_d$ is the ratio between the screening length (the Debye radius) and the particle radius. For the first parameter, we have

$$\lambda_d = \frac{\lambda_{de}\lambda_{di}}{\left(\lambda_{de}^2 + \lambda_{di}^2\right)^{1/2}},$$

where

$$\lambda_{de} = \left(\frac{\epsilon_0 T_e}{N_e e^2}\right)^{1/2}$$

is the electron Debye radius.

With regard for the collisions between electrons and dust particles, Eq. (11) for the effective collision frequency of electrons looks like

$$\nu_{\text{eff}} = \nu_{ed} + \nu_{ei} + \nu_{en}. \tag{30}$$

3.2. Dielectric permittivity

In a dusty plasma, the tensor of complex dielectric permittivity is determined by Eq. (3), in which the dielectric susceptibilities of the electron and ion plasma components, as well as dust particles, are taken into account [9, 11, 29]. In a number of works [30–33], their authors considered the transverse, $\varepsilon^{tr}(\omega, k)$, and longitudinal, $\varepsilon^l(\omega, k)$, components of the dielectric permittivity of a dusty plasma. In work [30], the following expressions were obtained for $\varepsilon^l(\omega, k)$ and $\varepsilon^{tr}(\omega, k)$:

$$\varepsilon^l(\omega, k) = 1 + \frac{4\pi}{k^2} \sum_\alpha \frac{e_\alpha^2}{m_\alpha} \int dv \frac{1}{\omega - k \cdot v + i\nu_{\alpha d}} \times$$
$$\times \left(1 + \frac{i\nu_{\alpha d}}{\omega + i\nu_{ch}} \frac{1 + \Gamma_{k\omega}^{(l)}}{1 + G_{k\omega}}\right) \left(k \cdot \frac{df_\alpha^0}{dv}\right), \tag{31}$$

$$\varepsilon^{tr}(\omega, k) = 1 + \frac{2\pi}{\omega} \sum_\alpha \frac{e_\alpha^2}{m_\alpha} \int dv \frac{1}{\omega - k \cdot v + i\nu_{\alpha d}} \times$$
$$\times \left(v_i + \frac{i\nu_{\alpha d}}{\omega + i\nu_{ch}} \frac{\Gamma_{k\omega, i}^{(t)}}{1 + G_{k\omega}}\right) \left(\delta_{ij} - \frac{k_i k_j}{k^2}\right) \frac{df_\alpha^0}{dv_j}, \tag{32}$$

where the quantities $\Gamma_{k\omega}^{(l)}$, $\Gamma_{k\omega, i}^{(t)}$, and $G_{k\omega}$ are determined by the expressions

$$\Gamma_{k\omega}^{(l)} = \sum_\alpha \int dv \frac{-ie_\alpha \sigma_\alpha v f_\alpha^0}{\omega - k \cdot v + i\nu_{\alpha d}}, \tag{33}$$

$$\Gamma_{k\omega, i}^{(t)} = \sum_\alpha \int dv \frac{-ie_\alpha \sigma_\alpha v v_i f_\alpha^0}{\omega - k \cdot v + i\nu_{\alpha d}}, \tag{34}$$

$$G_{k\omega} = \frac{-1}{\omega + i\nu_{ch}} \sum_\alpha \int dv \frac{\nu_{\alpha d} e_\alpha \sigma_\alpha v f_\alpha^0}{\omega - k \cdot v + i\nu_{\alpha d}}. \tag{35}$$

For the Maxwell velocity distribution and at high frequencies $\omega \sim \omega_{pe} \gg \max(kv_e, \nu_{ch}, \nu_{\alpha d})$, expressions (31) and (32) for the longitudinal and transverse, respectively, dielectric permittivities coincide: $\varepsilon^{tr}(\omega, k) = \varepsilon^l(\omega, k) = \varepsilon'(\omega)$, where $\varepsilon'(\omega)$ is given by the expression

$$\varepsilon' = 1 - \frac{\omega_{pe}^2}{\omega^2} \left[1 - i\frac{2}{3}(2 + z)\frac{\nu_{ed}}{\omega} - \sqrt{\pi}zA\left(\frac{\nu_{ed}}{\omega}\right)^2 \exp(z)\right]. \tag{36}$$

Here, $\tau_T = T_i/T_e$, and

$$A(z) = \frac{5}{4} - \frac{z}{6} + \left(\frac{5}{4} - z + \frac{z^2}{3}\right) K(z), \tag{37}$$

where

$$K(z) \equiv \int_1^\infty d\tau_T \exp\left[-(\tau_T^2 - 1)z\right] \tag{38}$$

In the case $\omega \gg k\nu_e \gg k\nu_i$, the authors of work [31] obtained the following expression for the complex dielectric permittivity:

$$\varepsilon' = 1 - \sum_\alpha \frac{\omega_{p\alpha}^2}{\omega^2} + \frac{i}{\omega^3} \sum_\alpha \omega_{p\alpha}^2 v_{ad}. \tag{39}$$

In works [33–35], analytic expressions were derived for the dielectric permittivity and the conductivity of a dusty plasma. The corresponding longitudinal and transverse dielectric permittivities of a dusty plasma are described by the expressions [33]:

$$\varepsilon^l(\omega, k) = 1 + \left(1 - \frac{i\omega N_d}{\omega + i\nu_{ch}} \frac{\sigma_\alpha(v_\alpha)}{k}\right) \times$$
$$\times \frac{\omega_{pa}^2}{k^2 v_a^2} \frac{W(\xi)}{1 - \frac{i\nu_{\alpha n}}{\omega + i\nu_{\alpha n}}(1 - W(\xi))}, \tag{40}$$

$$\varepsilon^{tr}(\omega, k) = 1 - \left(1 - \frac{i\omega N_d}{\omega + i\nu_{ch}} \frac{\sigma_\alpha(v_\alpha)}{k}\right) \times$$
$$\times \frac{\omega_{pa}^2}{\omega + i\nu_{an}^2} \frac{1 - W(\xi)}{1 - \frac{i\nu_{\alpha n}}{\omega + i\nu_{\alpha n}}(1 - W(\xi))}, \tag{41}$$

where $\xi = (\omega + i\nu_{\alpha n})/(kv_\alpha)$. For a cold plasma, $|\xi| \gg \gg 1$, and the dependence $W(\xi)$ looks like

$$W(\xi) = -\frac{k^2 v_\alpha^2}{(\omega + i\nu_{an})^2}. \tag{42}$$

In the case $|W(\xi)| \ll 1$, formulas (40) and (41) for the longitudinal and transverse dielectric permittivities coincide: $\varepsilon^{tr}(\omega, k) = \varepsilon^l(\omega, k) = \varepsilon'(\omega)$, where $\varepsilon'(\omega)$ is given by the expression

$$\varepsilon' = 1 - \frac{\omega_{pa}^2}{\omega(\omega + i\nu_{an})} + \frac{i\omega_{pa}^2 N_d \sigma_\alpha(v_\alpha)}{k(\omega + i\nu_{an})(\omega + i\nu_{ch})}. \tag{43}$$

From expression (43), taking Eq. (5) for the complex dielectric permittivity into account, and neglecting the ionic component, we obtain the following formulas for the dielectric permittivity and the high-frequency conductivity in a dusty plasma:

$$\varepsilon = 1 - \frac{N_e e^2}{\epsilon_0 m_e(\omega^2 + \nu_{\text{eff}}^2)} +$$

$$+ \frac{\omega}{k} \eta_d \frac{N_e e^2}{\epsilon_0 m_e} \frac{(\nu_{\rm eff} + \nu_{\rm ch})}{(\omega^2 + \nu_{\rm eff}^2)(\omega^2 + \nu_{\rm ch}^2)}, \quad (44)$$

$$\sigma = \frac{N_e e^2 \nu_{\rm eff}}{m_e (\omega^2 + \nu_{\rm eff}^2)} +$$

$$+ \frac{\omega}{k} \eta_d \frac{N_e e^2}{m_e} \frac{\omega^2 - \nu_{\rm eff} \nu_{\rm ch}}{(\omega^2 + \nu_{\rm eff}^2)(\omega^2 + \nu_{\rm ch}^2)}, \quad (45)$$

where $\nu_{\rm eff}$ is the effective electron collision frequency, which is determined by Eq. (30), and the parameter $\eta_d = N_d \sigma_e(v_e)$.

3.3. Refractive and absorption indices

When considering the refractive, n, and absorption, $\varkappa$, indices in a dusty plasma, two approaches are
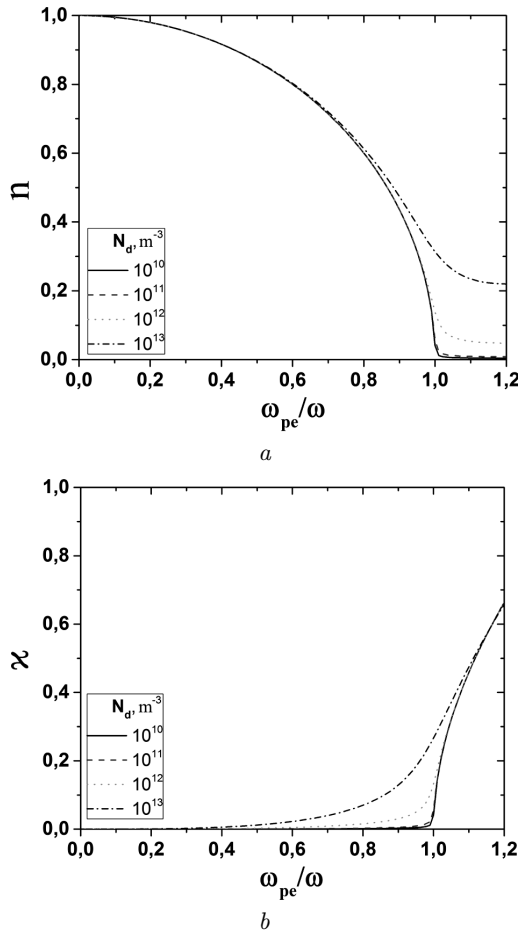

Fig. 2. Dependences of the refractive (a) and absorption (b) indices in a dusty plasma on the ratio ω_{pe}/ω for various concentrations of dust particles. The calculation parameters are $r_d = 1 \times 10^{-6}$ m, $N_i = 1 \times 10^{16}$ m^{-3}, $N_n = 1 \times 10^{20}$ m^{-3}, $T_e = 1$ eV, and $T_i = 0.1\,T_e$

used. In one of them, expressions for n and $\varkappa$ obtained for a particle-free plasma – see formulas (15), (16), (19), and (20) – are used [12, 23, 36–38]. In this case, the transition to a dusty plasma is performed, by considering the additional frequencies of particle collisions with dust particles (see Section 2.1). This approach is rather justified and can be used in the case of high frequencies, which follows from Eq. (39) and a small number of particles in plasma.

The results of calculations of the refractive, n, and absorption, $\varkappa$, indices obtained according to formulas (15) and (16) for weakly ionized and strongly ionized dusty plasmas are exhibited in Figs. 2 to 4. The effective collision frequency was determined from Eq. (30). The calculations were carried out with regard for the following conditions:

• Ar ions were assumed to be single-charged;

• the rate constant for electron-neutral collisions was calculated, by supposing the Maxwell distribution of electrons over their velocities and taking the cross-sections of elastic collisions into account [39];

• the Cu$_2$O dust particles were assumed to be perfect spheres of the same radius;

• the charge of dust particles was determined by equality (26);

• the quasineutrality condition (23) for a dusty plasma was supposed to be obeyed.

As one can see from Figs. 2 and 4, an increase of the dust particle concentration induces the growth of both the refractive, n, and absorption, $\varkappa$, indices. This is a result of an increase of the parameter $\nu_{\rm eff}$. In essence, the observed scenario is similar to that discussed in Section 2.2 (see Fig. 1). However, in this case, an important factor is the collision frequency of electrons with dust particles. An increase of the dust particle size changes the values of both n and $\varkappa$, as is shown in Fig. 3. Thus, the concentration and the size of dust particles substantially affect the refractive and absorption indices, especially if $\omega^2 \to \omega_{pe}^2$. In the high-frequency limit, when $\omega^2 \gg \omega_{pe}^2$ and $\omega^2 \gg \nu_{\rm eff}^2$, the influence of dust particles on n and $\varkappa$ can be neglected in some cases.

In the other approach, besides the frequency of collisions between particles and dust particles, the characteristic frequency of the dust particle charging is also taken into account. In this case, expression (44) for the dielectric permittivity and expression (45) for the high-frequency conductivity of a dusty plasma are
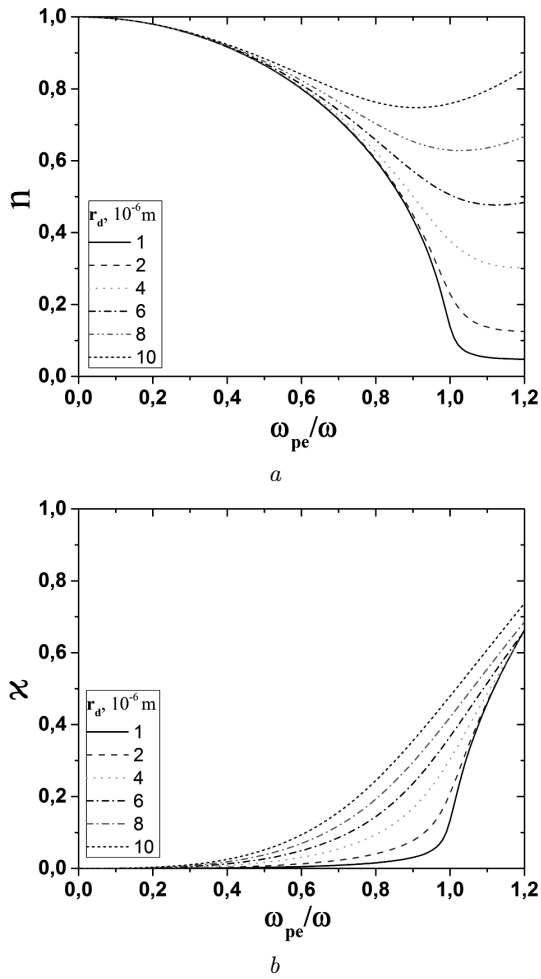
Fig. 3. Dependences of the refractive (*a*) and absorption (*b*) indices in a dusty plasma on the ratio ω_{pe}/ω for various values of the dusty particle radius. The calculation parameters are $N_d = 10^{12}$ m^{-3}, $N_i = 1 \times 10^{16}$ m^{-3}, $N_n = 1 \times 10^{20}$ m^{-3}, $T_e = 1$ eV, and $T_i = 0.1\,T_e$

used. The formulas for the refractive index n and the absorption index $\varkappa$ can be written as follows [33]:

$$n = \left(\frac{1}{2}\varepsilon + \frac{1}{2}\sqrt{\varepsilon^2 + \left(\frac{\sigma}{\omega\epsilon_0}\right)^2} \right)^{1/2}, \qquad (46)$$

$$\varkappa = \left(-\frac{1}{2}\varepsilon + \frac{1}{2}\sqrt{\varepsilon^2 + \left(\frac{\sigma}{\omega\epsilon_0}\right)^2} \right)^{1/2}, \qquad (47)$$

where ε is determined by expression (44) and σ by expression (45). This approach [33–35] was applied in
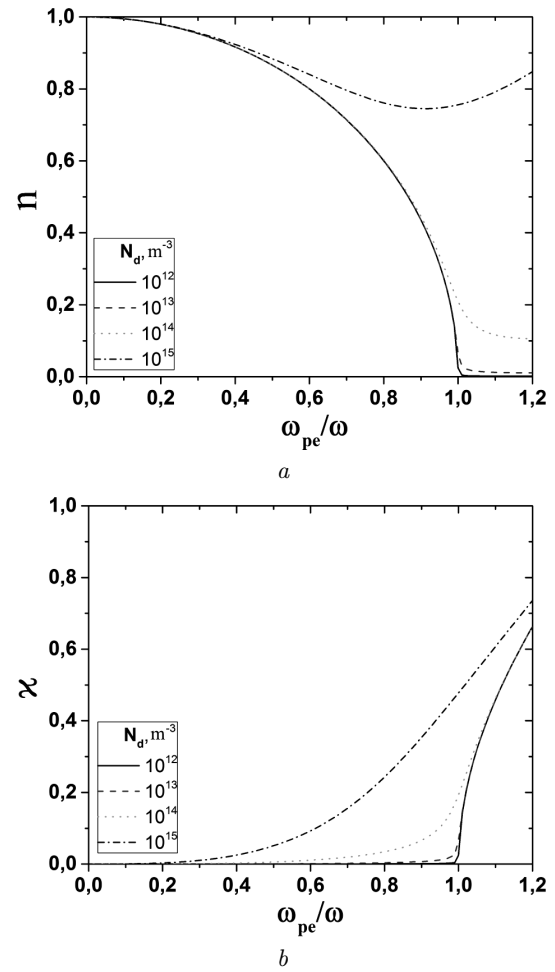

Fig. 4. Dependences of the refractive (*a*) and absorption (*b*) indices in a dusty plasma on the ratio ω_{pe}/ω for various concentrations of dust particles. The calculation parameters are $r_d = 1 \times 10^{-6}$ m, $N_i = 1 \times 10^{19}$ m^{-3}, $N_n = 1 \times 10^{19}$ m^{-3}, $T_e = 10$ eV and $T_i = 0.1\,T_e$

a number of works [24, 40–51]. In so doing, a number of simplifications and assumptions in Eqs. (43)–(46) are often made [24, 33–35, 40–51].

First – see, e.g., works [33–35, 40–43, 45–50]) – when calculating the parameter η_d, it is assumed that the absorption cross-section $\sigma_e(v_e) \approx \pi r_d^2$, so that this quantity depends only on the dust particle size. In works [24, 44], expression (24) was used, where the potential of the dust particle surface is determined by the formula $\phi_s = \frac{Z_d e}{4\pi\epsilon_0 r_d}$. Accordingly, Eq. (24) takes the form

$$\sigma_e(\nu_e) = \pi r_d^2 \left(1 + \frac{Z_d e^2}{6\pi\epsilon_0 r_d T_e} \right). \qquad (48)$$
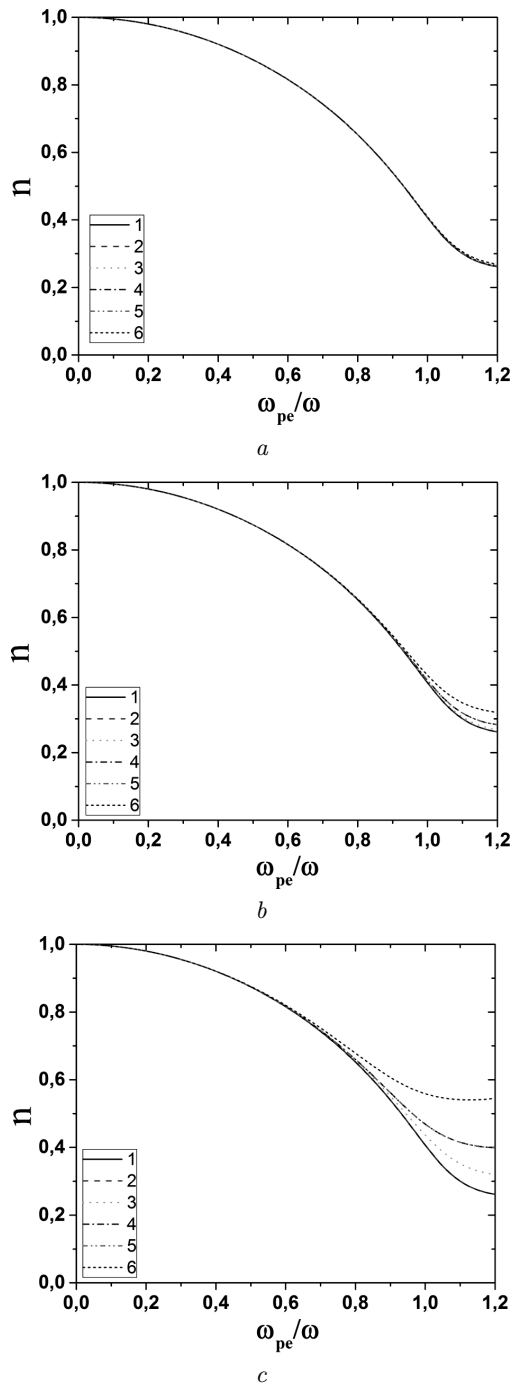
Fig. 5. Dependences of the refractive index n in a dusty plasma on the ratio ω_{pe}/ω in various approximations (on the curve labeling from *1* to *6*, see the text). The parameter $N_d = 10^{11}$ (*a*), 10^{12} (*b*), and 10^{13} m^{-3} (*c*). The other calculation parameters are $r_d = 1 \times 10^{-6}$ m, $N_i = 1 \times 10^{19}$ m^{-3}, $N_n = 10^{24}$ m^{-3}, $T_e = 3000$ K, and $T_i = 0.1 \times T_e$
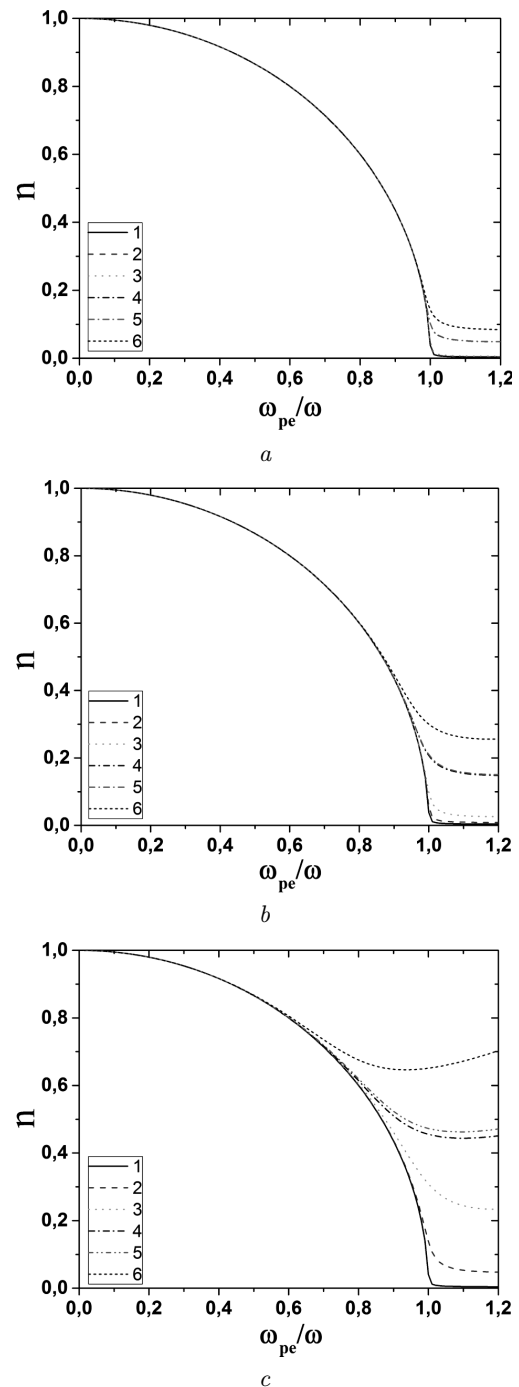
Fig. 6. Dependences of the refractive index n in a dusty plasma on the ratio ω_{pe}/ω in various approximations (on the curve labeling from *1* to *6*, see the text). The parameter $N_d = 10^{10}$ (*a*), 10^{11} (*b*), and 10^{12} m^{-3} (*c*). The other calculation parameters are $r_d = 1 \times 10^{-6}$ m, $N_i = 1 \times 10^{16}$ m^{-3}, $N_n = 10^{20}$ m^{-3}, $T_e = 1$ eV, and $T_i = 0.1 \times T_e$

It allows the dependence of the absorption cross-section on the electron temperature, as well as the size and charge of dust particles, to be taken into account more accurately.

Second, the quantity ω/k in Eqs. (44) and (45), which is actually the parameter $\nu_{ph} = \omega/k$ in the medium, is put equal to the light velocity in vacuum, $\nu_{ph} = c$ (see, e.g., works [33–35, 40, 41, 43–51]). This substitution is quite allowable, if the refractive index $n \approx 1$. But, in the case $n \neq 1$, the refractive index has to be taken into account: $\omega/k = c/n$. Then Eqs. (44)–(47) can be solved numerically, while determining n and $\varkappa$.

Since different approximations are used in calculations, it is of interest to compare the refractive index values obtained from Eqs. (44)–(47) and from Eqs. (15), (16), (19), and (20). The conditions already described above were chosen as initial ones: Ar ions, Cu$_2$O particles, and so forth. The plasma parameters were taken according to the data of work [46] and to the parameters of weakly ionized plasma, which were also described above (see the caption of Fig. 2). The calculation results obtained for the refractive index are presented in Figs. 5 and 6. The labeling of the curves in those figures are as follows. Curves *1* and *2* were calculated by formula (15): curves *1* not taking ν_{ed} into account and curves *2* taking ν_{ed} into account. Curves *3* to *6* were calculated according to formulas (44)–(46): curve *3* for $\omega/k = c$, $\sigma_e(v_e) \approx \pi r_d^2$, and not taking ν_{ed} into account; curve *4* for $\omega/k = c/n$, $\sigma_e(v_e) \approx \pi r_d^2$, and not taking ν_{ed} into account; curve *5* for $\omega/k = c/n$, $\sigma_e(v_e) \approx \pi r_d^2$, and taking ν_{ed} into account; and curve *6* for $\omega/k = c/n$, $\sigma_e(v_e)$ calculated by formula (48), and not taking ν_{ed} into account.

As one can see from Figs. 5, *a* and 6, *a*, at $\omega^2 \gtrsim \omega_{pe}^2$ and a relatively low concentration of particles, the calculated values of n are almost identical for all approximations and approaches. With the increase of the dust particle concentration (Figs. 5, *b*, 5, *c*, 6, *b*, and 6, *c*), the calculation results begin to differ from one another in different approaches and approximations starting from $\omega_{pe}/\omega \gtrsim 0.5 \div 0.6$. The calculated values of n are maximum in the case where Eqs. (44)–(47) were used. The minimum values were obtained, when no allowance was made for dust particles – Eqs. (11), (15), and (16) – which is quite reasonable. A similar situation also takes place, when the size of dust particles is varied. The analysis testifies that, in the

high-frequency limit, i.e. at $\omega^2 \gg \omega_{pe}^2$ and $\omega^2 \gg \nu_{\text{eff}}^2$, the influence of dust particles on n and $\varkappa$ can be neglected sometimes. In those cases, Eqs. (19)–(22) can be used for calculations. Hence, the density, size, and charge of dust particles substantially affect the refractive and absorption indices of a dusty plasma.

Besides those dust particle parameters, the refractive and absorption indices also depend on the probing frequency (see Figs. 3 to 6). Therefore, the measurements of the phase shift and the absorption coefficient at various frequencies can be used to evaluate or determine such dusty plasma parameters as the average density, dust particle size, and frequency of collisions between electrons and dust particles.

For the picture to be complete, it is also worth noting the following two specific features of a dusty plasma. First, the charge of dust particles can be rather large. Accordingly, the concentration of ions can substantially exceed the concentration of electrons. In this case, the ionic component in the dielectric permittivity has to be taken into account (see, e.g., Eqs. (7) and (8)). Second, in the general case, dust particles are different by their size and are described by a certain distribution function [9, 12]. In works [34, 35, 43, 45], for this size distribution to be taken into consideration, expressions (44) and (45) were proposed to be used in the form of the sums

$$\varepsilon = \sum_{j=1}^{N_d} \varepsilon_j \text{ and } \sigma = \sum_{j=1}^{N_d} \sigma_j$$

over dust particle groups with identical sizes, or this summation should be carried out only over the parameter η_d [43, 45]:

$$\eta_d = \sum_{j=1}^{N_d} N_{dj} \pi r_{dj}^2.$$

The analysis of the high-frequency conductivity in a dusty plasma with various model distributions of dust particles over their size showed [43] that this parameter can increase or decrease, depending on the distribution itself and on the difference between the maximum and minimum particle sizes.

4. Conclusions

The refractive, n, and absorption, $\varkappa$, indices in weakly and strongly ionized dusty plasmas are calculated and compared in the framework of various

approaches and approximations. If the concentration of dust particles is low, and if the frequency is high, $\omega^2 \geq \omega_{pe}^2$, the calculated values of n practically coincide in all approximations and approaches. At higher concentrations of dust particles, the calculation results obtained in different approaches and approximations begin to deviate from one another at $\omega_{pe}/\omega \geq 0.5 \div 0.6$. A similar situation also takes place for the varied dust particle size. Hence, the concentration and size of dust particles significantly affect the refractive and absorption indices for microwaves, especially if $\omega^2 \to \omega_{pe}^2$. In the high-frequency limit, i.e. when $\omega^2 \gg \omega_{pe}^2$ and $\omega^2 \gg \nu_{\text{eff}}^2$, the influence of dust particles on n and $\varkappa$ can be neglected in some cases, so that methods developed for a dust-free plasma can be applied. The measurements of the phase shift and the absorption coefficient at various frequencies can provide some information about such parameters of a dusty plasma as the average density, dust particle size, and frequency of collisions between electrons and dust particles.

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ОСОБЛИВОСТІ ВИКОРИСТАННЯ
МІКРОХВИЛЬОВИХ МЕТОДІВ ДЛЯ ДІАГНОСТИКИ
ЗАПОРОШЕНОЇ ПЛАЗМИ. І. ДІЕЛЕКТРИЧНА
ПРОНИКНІСТЬ, ПОКАЗНИКИ
ЗАЛОМЛЕННЯ ТА ПОГЛИНАННЯ

Р е з ю м е

Проаналізовано два підходи, які зазвичай використовуються для визначення показників заломлення n і поглинання $\varkappa$ запорошеної плазми. У першому використовують вирази для n і $\varkappa$, отримані для плазми без порошинок з урахуванням додаткових частот зіткнень частинок з порошинками. У другому враховуються не тільки частоти зіткнень частинок з порошинками, а і характерна частота зарядки порошинок.