Dual-frequency modes of the dust acoustic surface wave in a semibounded system

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Dual-frequency modes of the dust acoustic surface waves propagating at the interface between a nonmagnetized multicomponent Lorentzian dusty plasma and a vacuum are investigated, including nonthermal and positron effects. The dispersion relation is kinetically derived by employing the specular reflection boundary condition and the dielectric permittivity for dusty plasma containing positrons. We found that there exist two modes of the dust acoustic surface wave; high- and low-frequency modes. We observe that both H and L modes are enhanced by the increase of the pair annihilation rate. However, the effects of positron density are twofold depending on the ratio of annihilated positrons. The effects of nonthermal plasmas are also investigated on the H and L modes of dust acoustic surface waves. We found that the nonthermal plasmas reduce the frequencies of both H and L modes.

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I. INTRODUCTION

In recent years, the physical processes in electron-positron pair plasmas have received considerable attentions in various astrophysical plasmas, such as active galactic nuclei, the atmosphere of neutron stars, pulsar magnetospheres, and supernova environments, and also in laboratory plasmas such as semiconductor plasmas and dense laser-produced plasmas [1–9]. In addition, there has been a considerable interest in the dynamics of gases and plasmas containing dust grains, including strong collective effects and electrostatic interaction between the charged particles [10–19]. The physical characteristics and properties of dusty plasmas have been explored in order to obtain information on plasma parameters in dusty plasmas since charged dust grains are ubiquitous in the Universe. Since the frequency spectra provide useful information on plasma parameters for spatially bounded plasmas, the dispersion properties of various surface waves have drawn much interest in semibounded or bounded plasmas [20–29]. In particular, the wave propagation in semibounded dusty plasmas has been of great interest since the dispersion relations and frequency spectra of the surface dust plasma waves provide useful information on various plasma parameters as well as on applications in nanotechnologies and fusion devices [26–29]. In electron-positron-ion-dust plasmas, the direct positron annihilations with free electrons and the indirect positron annihilations through positronium formation have been investigated since the pair annihilations result in one- and two-photon γ-ray radiation and also provide useful physical and structural information on the plasma system [4–9]. Moreover, it has been shown that nonthermal plasma distributions with depleted velocity distribution tails are frequently found in numerous plasma environments due to the external coupling of the radiation field with the plasma system [30–33]. In addition, it has been shown that the nonthermal plasma distributions deviating from the standard Maxwellian distribution can be fitted very well by a generalized Lorentzian distribution function due to the additional diffusion associated with the external coupling [30]. Recently, the effective screening distance in generalized Lorentzian plasmas has been obtained by considering the effective shielding lengths due to the collective interaction of nonthermal particles, since the effective screening length would not be properly represented by the conventional expression of the Debye length in Lorentzian plasmas [33]. Hence, it would be expected that the propagation of the surface dust acoustic wave in semibounded Lorentzian electron-positron-ion-dust plasmas would be quite different from that in conventional electron-ion-dust plasmas owing to the influence of electron-positron pair annihilation and the nonthermal character of the Lorentzian plasma. However, to the best of our knowledge, it seems that the electron-positron pair annihilation and nonthermal effects on the dispersion properties and propagation of the surface dust acoustic wave in semibounded Lorentzian electron-positron-ion-dust plasmas have not been investigated as yet. Thus, in this paper, we investigate the influence of electron-positron pair annihilation and nonthermal shielding on the propagation of the surface dust acoustic wave along the plasma-vacuum interface in nonmagnetized semibounded Lorentzian electron-positron-ion-dust plasmas.

This paper is composed as follows. In Sec. II, we obtain the dispersion relation and in Sec. III the electron-positron pair annihilation and nonthermal effects on the propagation of the surface dust acoustic wave in semibounded Lorentzian electron-positron-ion-dust plasmas. Finally, the conclusions are given in Sec. IV.

II. DISPERSION RELATIONS IN LORENTZIAN DISTRIBUTIONS

The physical characteristics of waves of bounded plasmas are quite differ from those of bulk plasmas since the boundary conditions have to be taken into account for the plasma-vacuum or the plasma-dielectric interface in the bounded plasmas. If the characteristic length of the plasma is much longer than the scale length of the inhomogeneity, the specular

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reflection condition is extremely useful to investigate the waves propagating along the interface between plasma and vacuum (or dielectric) [20–22]. Under the specular reflection condition, the particles elastically bounce off the interface with a velocity determined by the collision velocity and undergo a mirror reflection such that

$$f_{1\alpha}(v_x,v_y,v_z,\,t,z=0) = f_{1\alpha}(v_x,v_y,-v_z,\,t,z=0), \qquad (1)$$

where $f_{1\alpha}$ is the perturbed plasma distribution function of species α and the plasma occupies the region $z > 0$. For such plasmas, the dispersion relation for surface waves propagating in the z direction at the interface at $z = 0$ is well known in the form [20]

$$\pi\left(\frac{k_x^2c^2}{\omega^2}-1\right)^{1/2} + \frac{\omega}{c}\int_{-\infty}^{\infty}\frac{dk_z}{k^2} \times\left[\frac{k_z^2c^2}{\omega^2\varepsilon_\ell(\omega,k)} - \frac{k_x^2c^2}{k^2c^2-\omega^2\varepsilon_t(\omega,k)}\right] = 0, \qquad (2)$$

where $k = \sqrt{k_x^2 + k_z^2}$ is the wave number, c is the speed of light, ω is the wave frequency, and $\varepsilon_\ell(\omega,k)$ and $\varepsilon_t(\omega,k)$ are the longitudinal and the transverse components of the plasma dielectric permittivity, respectively. In this situation, the y coordinate has a translational invariance and is ignored in our geometry without loss of generality. When the electrostatic limit $\omega^2/c^2 \ll k^2$ is taken, the dispersion relation for the surface wave takes the form [20]

$$\pi + k_x\int_{-\infty}^{\infty}\frac{dk_z}{k^2\varepsilon_\ell(\omega,k)} = 0. \qquad (3)$$

The physical properties of electrostatic waves in plasmas can be resolved by the longitudinal dielectric permittivity $\varepsilon_\ell(\omega,k)$. In electron ($e^-$)—positron ($e^+$)—ion ($i$)—dust ($d$) plasmas, the longitudinal dielectric permittivity can be represented by

$$\varepsilon_\ell(\omega,k) = 1 + \chi_{e^-} + \chi_{e^+} + \chi_i + \chi_d, \qquad (4)$$

where χ_α is the dielectric susceptibility of species $\alpha\ (=e^-,\, e^+,\, i,\, d)$. We consider cold dust particles. Other components in the plasmas are governed by the Lorentzian distribution function [30]

$$f_{\kappa\alpha}(v_\alpha;\kappa) = n_{0\alpha}\left(\frac{m_\alpha}{2\pi\kappa E_{\kappa\alpha}}\right)^{3/2}\frac{\Gamma(\kappa+1)}{\Gamma(\kappa-1/2)} \times\left(1+\frac{m_\alpha v_\alpha^2}{2\kappa E_{\kappa\alpha}}\right)^{-(\kappa+1)}, \qquad (5)$$

where $n_{0\alpha}$, m_α, v_α, and $E_{\kappa\alpha}$ are the density, the mass, the velocity, and the characteristic energy of species α, respectively. In astrophysical and laboratory plasmas, the coupling with an external disturbance often generates the main deviations from the standard Maxwellian distribution since the external radiation field causes non-Columbic diffusion proportional to the square of the particle velocity [30]. The symbol κ is the spectral index of the Lorentzian distribution and Γ is the Gamma function. The characteristic energy is defined by $E_{\kappa\alpha} = (1 - 3/2\kappa)k_BT_\alpha$, where k_B is the Boltzmann constant and T_α is the temperature of species α. If we insert Eq. (5) into the standard form of the susceptibility given by

$$\chi_\alpha = \frac{\omega_{p\alpha}^2}{k^2n_{0\alpha}}\int_{-\infty}^{\infty}\frac{\partial f_{\kappa\alpha}/\partial v}{\omega-\mathbf{k}\cdot\mathbf{v}}d^3v, \qquad (6)$$

we obtain the susceptibility for electrons, positrons, and ions in the form

$$\chi_\alpha = \frac{\omega_{p\alpha}^2}{k^2\lambda_{D\alpha}'^2}\left(\frac{2\kappa}{2\kappa-3}\right) \times\left[\frac{2\kappa-1}{2\kappa}+\zeta_{\kappa\alpha}Z_\kappa(\zeta_{\kappa\alpha})\right] \quad (\alpha = e^-,\, e^+,\, i), \qquad (7)$$

where $\omega_{p\alpha}$ is the plasma frequency, $\lambda'_{D\alpha}$ is the Debye length, and $Z(\zeta_{\kappa\alpha})$ is the modified plasma dispersion function with the argument $\zeta_{\kappa\alpha} = \omega/k\sqrt{(2-3/\kappa)k_BT_\alpha/m_\alpha}$. The Debye lengths of electrons, positrons, and ions are written as, respectively,

$$\lambda'_{De^-} = \lambda_{De^-}\left(1-\frac{n_{e^+}}{n_{e^-}}\beta\right)^{-1/2} \quad \text{(electrons)}, \qquad (8)$$

$$\lambda'_{De^+} = \lambda_{De^+}(1-\beta)^{-1/2} \quad \text{(positrons)}, \qquad (9)$$

and

$$\lambda'_{Di} = \lambda_{Di} \quad \text{(ions)}, \qquad (10)$$

where $\lambda_{De^-} = \sqrt{k_BT_{e^-}/m_{e^-}\omega_{pe^-}^2}$, $\lambda_{De^-} = \sqrt{k_BT_{e^+}/m_{e^+}\omega_{pe^+}^2}$, and $\lambda_{Di} = \sqrt{k_BT_i/m_i\omega_{pi}^2}$ are the conventional Debye lengths of electrons, positrons, and ions, respectively, n_{e^-} and n_{e^+} are the electron and the positron densities before pair annihilations, and $\beta = \Delta n_{e^+}/n_{e^+}$ is the rate of annihilation, with Δn_{e^+} being the amount of pair-annihilated positrons. In dense hot astrophysical plasmas, the ranges of electron density and frequencies are known to be $n_e \approx 10^{18} - 10^{20}\ \text{cm}^{-3}$ and $\omega_{pe} \approx 10^{13} - 10^{14}\ \text{s}^{-1}$ [13]. We consider only direct positron annihilations with free electrons; and the single-photon annihilations of positrons with bound atomic electrons are neglected since their cross section is quite small compared with the cross section of two-photon positron annihilation with a free electron [6]. It is obvious that the positron will affect the electron population in dusty plasmas during the dust charging process due to the influence of electron-positron pair annihilation. Hence, the charge state of the dust grains can be changed by the positron populations in dusty plasmas. However, we neglect the variation of the charge state of the dust grains since we are interested in the physical characteristics and properties of surface waves in dusty plasmas after the dust charging process.

We consider a wave frequency such that $kv_{Td} \ll \omega \ll kv_{Ti},\ kv_{Te^-},\ kv_{Te^+}$, where $v_{T\alpha}$ is the thermal velocity of species α. Then the modified dispersion function can be expanded for small arguments for electrons, positrons, and ions, i.e., $\zeta_{\kappa\alpha} \ll 1$ $(\alpha = e^-,\, e^+,\, i)$. We shall keep the lowest order of the arguments for the investigation of the dust acoustic surface waves. The susceptibilities are finally calculated as

$$\chi_{e^-} = \frac{1}{\mu_\kappa k^2\lambda_{De^-}'^2}, \qquad (11)$$

$$\chi_{e^+} = \frac{1}{\mu_\kappa k^2\lambda_{De^+}'^2}, \qquad (12)$$

$$\chi_i = \frac{1}{\mu_\kappa k^2\lambda_{Di}'^2}, \qquad (13)$$

and

$$\chi_d = -\frac{\omega_{pd}^2}{\omega^2}, \tag{14}$$

where the parameter μ_κ $[=(2\kappa-3)/(2\kappa-1)]$ is a function of the spectral index κ and stands for the measure of the fraction of nonthernal population in Lorentzian plasmas. We note that μ_κ is unity for the Maxwellian plasma ($\kappa \to \infty$). Putting the susceptibilities obtained in Eqs. (11) to (14) into Eq. (4), the dispersion relation can be written as

$$\pi + \frac{k_x}{1-\frac{\omega_{pd}^2}{\omega^2}} \int_{-\infty}^{\infty} \frac{dk_z}{k_z^2 + \frac{k_x^2\left(1-\frac{\omega_{pd}^2}{\omega^2}\right)+\frac{1}{\mu_\kappa \lambda_{\rm Deff}'^2}}{1-\frac{\omega_{pd}^2}{\omega^2}}} = 0, \tag{15}$$

where $\lambda_{\rm Deff}' = (\lambda_{De^-}'^{-2} + \lambda_{De^+}'^{-2} + \lambda_{Di}'^{-2})^{-1/2}$ is the effective Debye length. For typical circumstances of dusty plasmas, it has been shown that the charge of negatively charged dust grains is about $Z \sim -(100\text{–}1000)e$, the size of dust grains is $a \sim 0.01 - 0.1$ μm, and the Debye length of dust grains is $\lambda_{\rm Deff}'/a \sim 5\text{–}100$ [10]. The effects of the electron-positron pair annihilation on the wave appear in the effective Debye length. After some mathematical manipulations using contour integration in the complex k_z plane, one obtains the dispersion relation for the dust acoustic surface wave in a semibounded Lorentzian dusty plasma as follows:

$$\left(1-\frac{\omega_{pd}^2}{\omega^2}\right)\left(1-\frac{\omega_{pd}^2}{\omega^2}+\frac{1}{\mu_\kappa k_x^2 \lambda_{\rm Deff}'^2}\right) = 1. \tag{16}$$

Equation (16) is ready to solve for the wave frequency. There are four solutions for the dust acoustic surface waves which are found as the high-frequency mode (H mode) and the low-frequency mode (L mode):

$$\left(\frac{\omega}{\omega_{pd}}\right)_{\rm H} = \pm\left\{\frac{1}{2}+\mu_\kappa k_x^2\lambda_{\rm Deff}'^2 + \left[\left(\frac{1}{2}+\mu_\kappa k_x^2\lambda_{\rm Deff}'^2\right)^2 - \mu_\kappa k_x^2\lambda_{\rm Deff}'^2\right]^{1/2}\right\}^{1/2} \quad \text{(H mode)} \tag{17}$$

and

$$\left(\frac{\omega}{\omega_{pd}}\right)_{\rm L} = \pm\left\{\frac{1}{2}+\mu_\kappa k_x^2\lambda_{\rm Deff}'^2 - \left[\left(\frac{1}{2}+\mu_\kappa k_x^2\lambda_{\rm Deff}'^2\right)^2 - \mu_\kappa k_x^2\lambda_{\rm Deff}'^2\right]^{1/2}\right\}^{1/2} \quad \text{(L mode)}, \tag{18}$$

where the effective Debye length can now be given as

$$\lambda_{\rm Deff}' = \lambda_{e^-}\left[1-\frac{n_{e^+}}{n_{e^-}}\beta + (1-\beta)\frac{n_{e^+}T_{e^-}}{n_{e^-}T_{e^+}} + \frac{Z_i^2 n_i T_{e^-}}{n_{e^-}T_i}\right]^{-1/2}. \tag{19}$$

If we take a limit of $k_x\lambda_{De^-} \to 0$, i.e., a long-wavelength limit, the positive parts of H- and L-mode waves are reduced to $(\omega/\omega_{pd})_{\rm H} \approx 1$ and $(\omega/\omega_{pd})_{\rm L} \approx 0$, respectively. Therefore, it is interesting to know that both waves are unaffected by the pair annihilation in the long-wavelength limit. If we take a limit of $k_x\lambda_{De^-} \to \infty$, i.e., a short-wavelength limit, the positive part of the frequency of the H mode simply proportional to the wave number,

$$\left(\frac{\omega}{\omega_{pd}}\right)_{\rm H} = \left[\frac{2\mu_\kappa}{1-\frac{n_{e^+}}{n_{e^-}}\beta + (1-\beta)\frac{n_{e^+}T_{e^-}}{n_{e^-}T_{e^+}} + \frac{Z_i^2 n_i T_{e^-}}{n_{e^-}T_i}}\right]^{1/2} k_x\lambda_{e^-}, \tag{20}$$

where the effect of pair annihilation appears only in the coefficient of $k_x\lambda_{De^-}$. Thus, the amount of annihilated positrons, as well as other parameters such as density and temperature, will play an important role in determining the slope in the dispersion curve. The L mode is saturated to $(\omega/\omega_{pd})_{\rm L} \approx 1/\sqrt{2}$ in the short-wavelength limit. It shows that the linearization in Poisson's equation for a Yukawa-type solution with the assumption $|q_\alpha\varphi/k_B T_\alpha| \ll 1$, where φ is the electrostatic potential, is not true in the vicinity of the surface of a highly charged dust grain. It is also shown that the nonlinear correction effects on the standard Debye potential is necessary for describing the screening potential at very short distances around a dust grain [34]. In this work, we neglect the nonlinear corrections since we are interested in the dust acoustic surface in the intermediate- and long-wavelength domains. The nonlinear corrections to the collision and radiation processes in a multicomponent dusty plasma will be then treated elsewhere. It would be expected that the surface wave for large thickness in a plasma slab bounded by two interfaces corresponds to the surface wave in a semibounded plasma. However, the physical properties of the surface wave in a semibounded plasma will be different from those in a bulk plasma due to the spectral reflection condition in the interface of the semibounded plasma. Hence, the direct corresponding relation will not be obtained for the dispersion relations for the surface and bulk plasma waves.

III. NONTHERMAL AND POSITRON EFFECTS

The effects of the electron-positron pair annihilation and the nonthermal effects on the H- and the L-mode waves were investigated for various physical parameters. Figures 1(a) and 1(b) show the scaled H- and L-mode wave frequencies ω/ω_{pd} as a function of the scaled wave number $k_x\lambda_{De^-}$ in the case of $Z_i^2 n_i/n_{e^-} = 1$, $T_{e^-}/T_i = 1$, and $T_{e^-}/T_{e^+} = 1$ for various parameters such as the pair annihilation rate, the electron-positron density ratio, and the spectral index. Figure 1(a) compares the two modes for $\beta = \Delta n_{e^+}/n_{e^+} = 0.1$, 0.5, and 0.9 for $n_{e^+}/n_{e^-} = 1$ and $\kappa = 3$. It is interesting to note that the wave frequency is increased for both H and L modes as the annihilation rate is enhanced. We observe that both the phase and group velocities of the H mode are increased

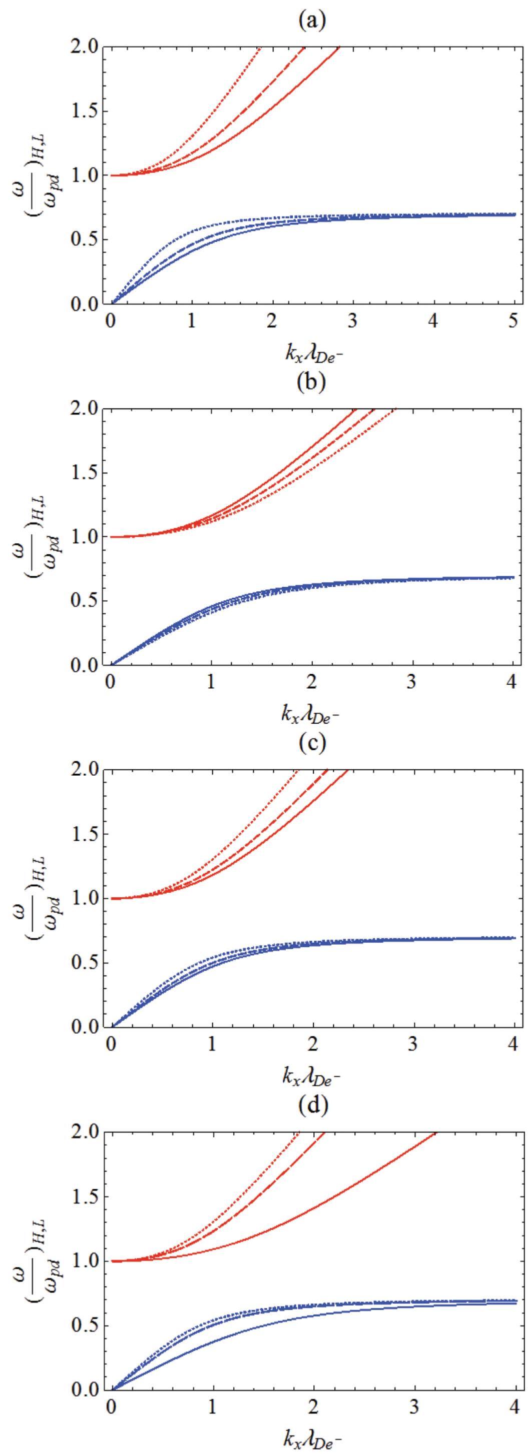

FIG. 1. (Color) The H-mode (upper three red lines) and the L-mode (lower three blue lines) scaled frequencies ω/ω_{pd} as functions of the scaled wave number $k_x\lambda_{De^-}$ for $Z_i^2 n_i/n_{e^-} = 1$, $T_{e^-}/T_{e^+} = 1$, and $T_{e^-}/T_i = 1$. (a) Plots for various pair annihilation rates: $\beta = 0.1$ (solid line), 0.5 (dashed line), and 0.9 (dotted line) in the case of $\kappa = 3$ and $n_{e^+}/n_{e^-} = 1$. (b) Plots for various positron densities: $n_{e^+}/n_{e^-} =$ 0.1 (solid line), 0.5 (dashed line), and 1.0 (dotted line) in the case of $\beta = 0.1$ and $\kappa = 3$. (c) Plots for various positron densities: $n_{e^+}/n_{e^-} =$ 0.1 (solid line), 0.5 (dashed line), and 1.0 (dotted line) in the case of $\beta = 0.9$ and $\kappa = 3$. (d) Plots for various spectral indices: $\kappa = 2$ (solid line), 5 (dotted line), and infinity (dotted line; Maxwellian) in the case of $\beta = 0.5$ and $n_{e^+}/n_{e^-} = 1$.

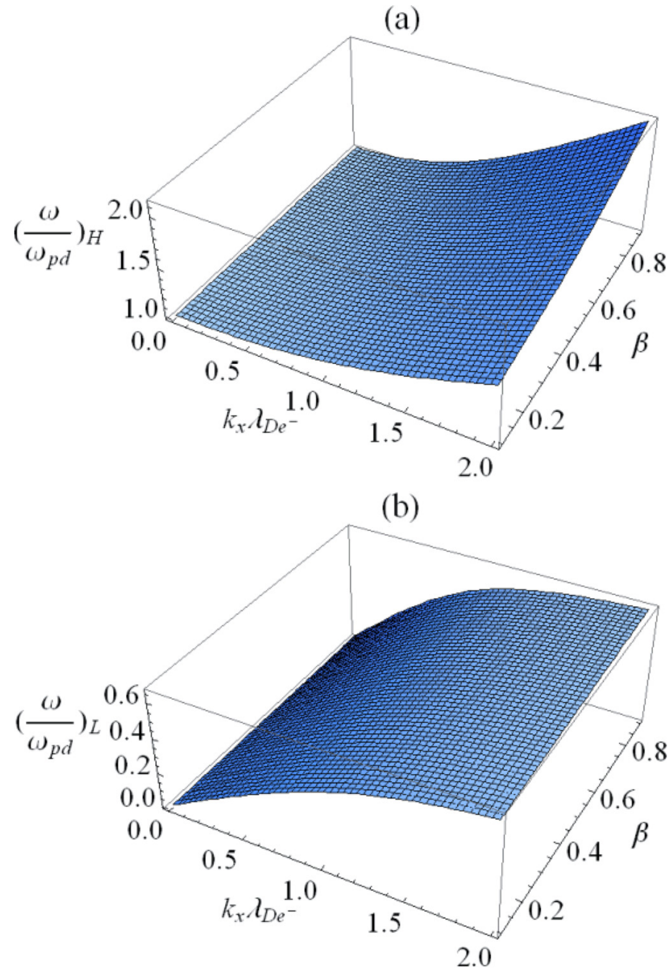

FIG. 2. (Color online) Three-dimensional plots of (a) H-mode and (b) L-mode scaled frequencies ω/ω_{pd} as a function of the scaled wave number $k_x\lambda_{De^-}$ and the annihilated-positron rate β in the case of $\kappa = 3$, $n_{e^+}/n_{e^-} = 1$, $Z_i^2 n_i/n_{e^-} = 1$, $T_{e^-}/T_{e^+} = 1$, and $T_{e^-}/T_i = 1$.

as the annihilation rate is increased. In Fig. 1(b), the effects of positron density on the H and L modes are depicted for $n_{e^+}/n_{e^-} = 0.1$, 0.5, and 1.0 in the case of $\beta = 0.1$ and $\kappa = 3$. We see that the frequencies of both modes are reduced as the positron density is increased in the case of a small value of β. However, we found that this tendency is reversed if we increase the value of β. As can be seen in Fig. 1(c), if we allow a higher β, e.g., $\beta = 0.9$, both the frequencies are enhanced as the positron density is increased. It is then found that the influence of positron annihilation enhances the frequencies for both the H and L modes. Hence, we can expect that the wave frequencies for the dust acoustic surface waves in positron-rare semibounded plasmas are always smaller than those in positron-rich semibounded plasmas. The effects of the nonthermal plasmas on the H and L modes are also investigated. Figure 1(d) compares the cases of $\kappa = 2$, $\kappa = 5$, and the Maxwellian plasma ($\kappa \to \infty$), drawn as the solid, dashed, and dotted curves, respectively. In the figure, we used the parameters $\beta = 0.5$ and $n_{e^+}/n_{e^-} = 1$. We observe that as the nonthermal character of a Lorentzian plasma is increased in the physical system, the frequencies of both modes are reduced. Hence, we have found that the wave frequencies of

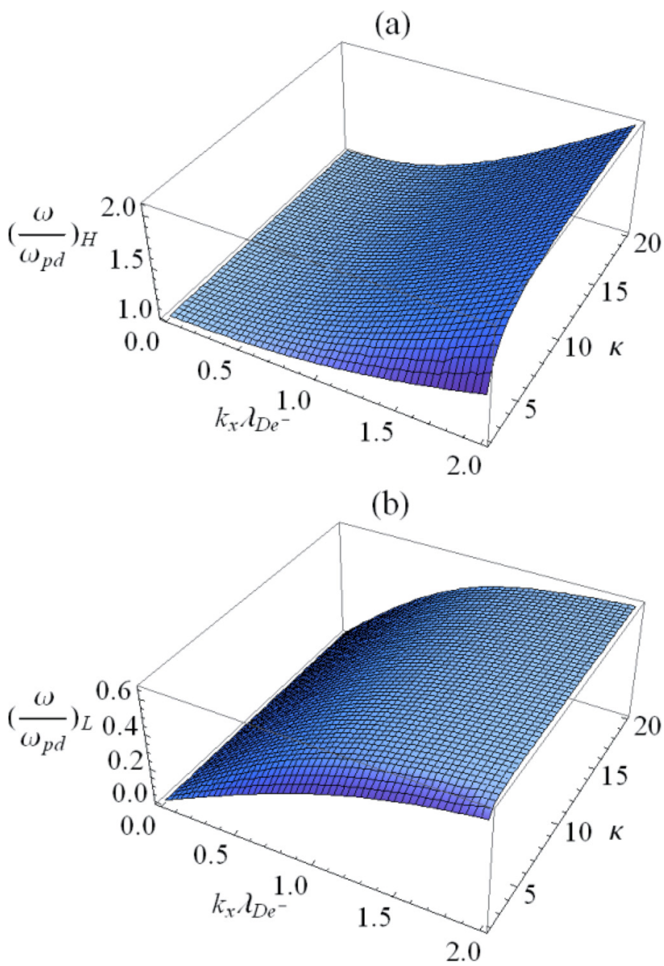

FIG. 3. (Color online) Three-dimensional plots of (a) H-mode and (b) L-mode scaled frequencies ω/ω_{pd} as a function of the scaled wave number $k_x\lambda_{De^-}$ in the case of $\beta = 0.5$, $n_{e^+}/n_{e^-} = 1$, $Z_i^2 n_i/n_{e^-} = 1$, $T_{e^-}/T_{e^+} = 1$, and $T_{e^-}/T_i = 1$.

dust acoustic surface waves in nonthermal plasmas are always smaller than those in thermal plasmas. Figures 2(a) and 2(b) represent three-dimensional plots of the H and the L mode as functions of $k_x\lambda_{De^-}$ and β. Three-dimensional plots of the scaled H- and the scaled L-mode frequencies are drawn in Figs. 3(a) and 3(b), respectively, as functions of the scaled wave number and the spectral index. From those figures, we have found that the nonthermal effects on both the H and L modes of the dust acoustic surface waves increase with increasing wave number k_x. Hence, it would be expected that the investigation of the nonthermal character of the dust acoustic surface waves is more effective in the small-wave-number domain. Recently, the diffusion coefficient [35] in complex dusty plasmas has been obtained using the Green-Kubo [36] relation. In addition, an investigation [37] of the theoretical Green-Kubo relation for viscosity has been obtained using experimentally obtained data. The viscosity was also found to agree with results from an experiment using a hydrodynamical Navier-Stokes equation [37]. Hence, the investigation of the electron-positron pair annihilation effects on the diffusion coefficient in Lorentzian electron-positron-ion-dust plasmas will be treated elsewhere, since the physical characteristics and properties of the diffusion coefficient would be useful in exploring the transport process in complex dusty plasmas. In addition, the investigation of effective interaction potential have been carried out in dense semiclassical plasmas including the quantum diffraction and plasma shielding effects [38,39]. The influence of quantum diffraction and shielding on the propagation of surface waves at the interface between a multicomponent dusty semiclassical plasma and a vacuum will also be treated elsewhere.

IV. CONCLUSIONS

In this work, we have investigated the electron-positron pair annihilation and nonthermal effects on the dust acoustic surface waves propagating at the interface between a plasma and a vacuum. The dispersion relation is kinetically derived by employing the specular reflection boundary condition and the dielectric permittivity for electrons, positrons, ions, and dust particles. The Lorentzian distribution function is used to investigate the effects of nonthermal plasmas. We found that there exist two modes of the dust acoustic surface wave; high- and low-frequency modes. We observe that both H and L modes are enhanced by an increase of the pair annihilation rate. The effects of positron density appear in a twofold result. When the annihilation rate is weak, an increase of positron density reduces the frequency. When the annihilation rate is strong, the property is reversed: an increase of positron density enhances the frequency. The effects of nonthermal plasmas are also investigated. We found that the nonthermal plasmas reduce the frequency of the wave. This result agrees well with previous reports [40,41] on dust acoustic surface waves in various situations. These results will be useful for understanding the physical characteristics and properties of dust acoustic surface waves in various semibounded electron-positron [42–44] dusty plasmas.

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