Experimental Observation of Vertically Polarized Transverse Dust-Lattice Wave Propagating in a One-Dimensional Strongly Coupled Dust Chain

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Externally driven, vertically polarized transverse dust-lattice waves were observed in a one-dimensional strongly coupled dust chain levitated in the plasma-sheath boundary of a dc argon plasma at low gas pressure around 5 mtorr. Real and imaginary parts of the complex wave number were measured in the experiments. The experimental result clearly shows that the observed transverse dust-lattice wave propagates as a backward wave, which is in good agreement with the theoretical prediction.

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It has been widely observed that negatively charged dust particles form strongly coupled dust crystals in laboratory plasmas [1–6]. One of the most interesting features of the physics in the strongly coupled dust crystals is the possibility of propagation of dust-lattice waves (DLW) on them. It has been theoretically predicted that longitudinal DLW (L-DLW) and vertically polarized transverse DLW (T-DLW) can propagate in a one-dimensional strongly coupled dust chain [7–13]. Melandsø [7] has derived the dispersion relation for L-DLW propagating in a 1D dust chain. Experimentally, the propagation of the L-DLW has been clearly demonstrated in an rf discharge by Homann *et al.* [14], by chopping a laser light to drive the waves. On the other hand, dispersion characteristics of the T-DLW have been obtained theoretically by Vladimirov *et al.* [8]. The dispersion relation indicates that the T-DLW propagates as a backward wave. To the best of our knowledge, however, there has been no experimental verification of the T-DLW in a laboratory plasma except our preliminary observations of spontaneously excited T-DLW with vertical dust particle oscillation [15]. It should be emphasized that the recent observations [16] of horizontally polarized transverse dust-lattice waves in the crystal plane can exist only in a two-dimensional dust crystal and are not the subject of the present paper.

In this paper, we present the first experimental observation of the externally excited T-DLW propagating in a 1D strongly coupled dust chain in a dc argon plasma with low gas pressure. The complex wave numbers measured in the experiments match quite well with the theoretical dispersion relation except for frequency dependence of the imaginary part.

The experiment was carried out in a large unmagnetized plasma device as shown in Fig. 1(a). Argon plasmas were generated by a dc discharge between hot filaments and tungsten anode enclosing permanent magnets at low gas pressure around 5 mtorr. Typical plasma parameters measured with a Langmuir probe are electron temperature $T_e \sim 0.7$ eV and plasma density $n_e \sim 5 \times 10^{13}$–$5 \times 10^{15}$ m^{-3}, which can be controlled by changing the discharge current. Plasma potential is almost zero. The diameter of the employed dust particle is 4.4 ± 0.1 μm and its mass density is 1.5×10^3 kg/m^3. Dust particles can be levitated above a negatively biased (-40 V) mesh electrode and confined horizontally by a negatively biased ring electrode. The diameters of the mesh and ring electrode

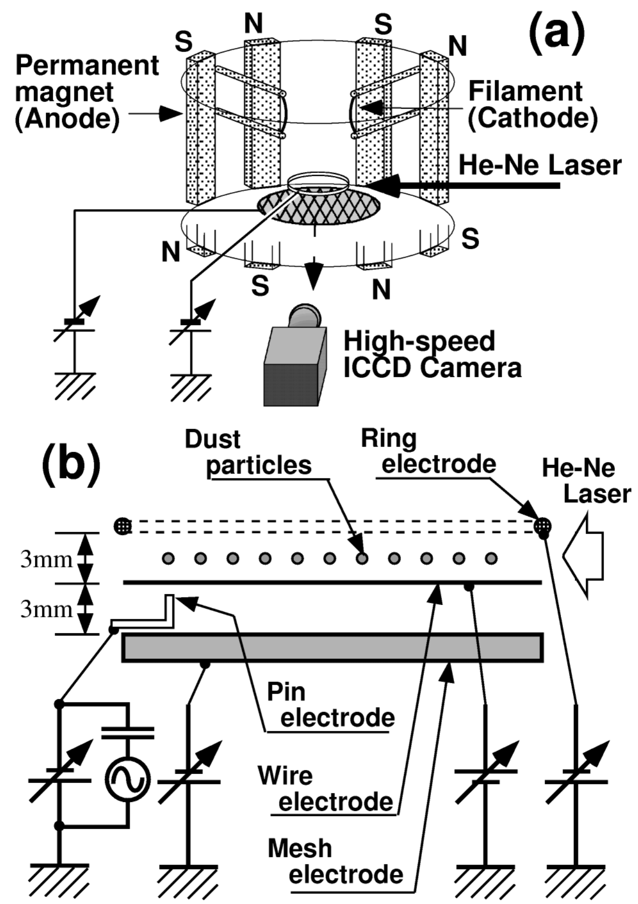

FIG. 1. Experimental apparatus. (a) Schematic drawing of the experimental setup showing the discharge and measurement configurations. (b) Detailed description of the electrodes to arrange the dust particles and to excite the DLW.

are both 80 mm. Figure 1(b) shows the detailed description of electrodes to arrange the confined dust particles and drive the T-DLW. The dust particles were arranged in a straight line by using a thin wire electrode, 0.4 mm in diameter and 80 mm in length, which was biased positively less than 1 V. To drive the T-DLW, a sinusoidal voltage was applied to the pin electrode, which was located at the edge of the dust particle array on the left-hand side. The amplitude was $0.2V_{p-p}$ and the driven frequency was changed from 21 Hz through 27 Hz every 0.2 Hz. In order to measure the T-DLW, the dust particles were illuminated with a vertical sheet of He-Ne laser light and detected by a high-speed intensified charge coupled device (ICCD) camera, which has a very good temporal resolution with up to 125 image frames per second.

Figure 2(a) shows a snapshot of the levitated dust particle chain taken by the ICCD camera. The total length of the dust particle chain was about 12 mm. The figure was the image obtained at the middle of the dust particle chain and the length of this figure is corresponding to about one-third of the total length. The waves were found to propagate only from left to right because of strong wave damping, which prevented them from reaching the right edge and generating significant reflected wave energy. Then, there were no reflected waves. Figure 2(b) shows the time evolution of the vertical displacement from the equilibrium position for each dust particle in Fig. 2(a). The waveforms were interpolated in time. It is clearly found that the transverse wave was excited on the left-hand side to propagate toward the right-hand side with some damping. On the other hand, the constant-phase timing advances as the wave propagating from the left to the right hand [see dashed line in Fig. 2(b)], which means that the phase velocity of the wave has the opposite direction to that of the group velocity. The result indicates that the observed transverse wave propagates as a so-called backward wave.

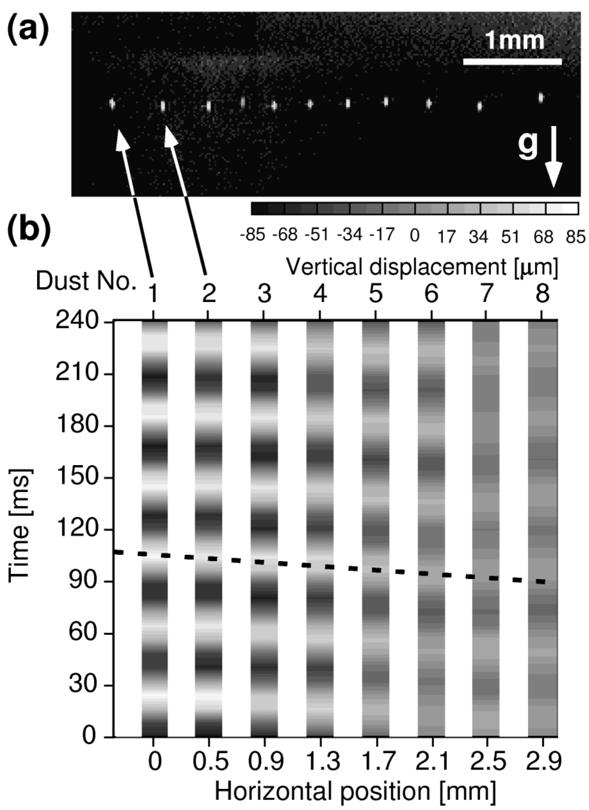

FIG. 2. Experimental data for the T-DLW taken by the ICCD camera. (a) Snapshot of a part of dust particle chain. (b) Time evolution of the vertical displacement of each dust particle in (a). The waveforms are interpolated in time. The driven frequency is 24.4 Hz.

In order to obtain the dispersion relation from the experimental results as shown in Fig. 2(b), we found the real and imaginary parts k_r, k_i of the complex wave number $k = k_r + ik_i$ by measuring the amplitude and phase of the observed transverse wave for every driven frequency.

The dispersion relation for T-DLW propagation can be calculated based on Ref. [8] by using a simplified model of 1D dust particle chain. In our analysis, we consider the delayed charging effect of dust particles, because the charging process of dust particles is known to have a profound effect on the dynamic behavior of dust particles [17]. The possibility of dust particle instability due to the delayed charging effect was pointed out first by Nitter *et al.* [18]. Our recent experiment [17,19] has clearly demonstrated the instability of vertical oscillations of dust particles due to the effect of the delayed charging in an inhomogeneous sheath plasma. The charging process can also directly influence the collective modes in the dusty plasma. In a recent work, Morfill *et al.* [10] have investigated the effect of a stochastic charging process on the dispersion relation of L-DLW and shown that this leads to instabilities. Similarly, using a generalized viscoelastic formalism to describe the strongly coupled dust component, Mishra *et al.* [20] have recently shown that the transverse shear modes in the strongly coupled dust plasma can be driven unstable through the delayed charging mechanism described above. It is therefore of great interest to analyze the effects of delayed charging associated with vertical dust oscillations on the dispersion characteristics of T-DLW, which was recently done in detail by Ivlev *et al.* [21], just after the submission of this paper, independently of our present work.

Consider the dust particles in equilibrium along a straight line at a regular interval d; when the nth dust particle is vertically disturbed from its equilibrium position, it experiences forces by interaction with its nearest neighbors through a Debye screened Coulomb force and through direct interaction with vertically varying background electric field E. If z_n denotes the vertical displacement of the nth particle, we get the linearized equation of motion:

$$M_d\left(\frac{d^2 z_n}{dt^2} + \beta\frac{dz_n}{dt}\right) = -\gamma z_n + \alpha(d) \times (2z_n - z_{n+1} - z_{n-1}) + \delta Q_n E, \quad (1)$$

where

$$\alpha(d) = \frac{Q^2}{4\pi\epsilon_0 d^3}\left(1 + \frac{d}{\lambda_D}\right)\exp\left(-\frac{d}{\lambda_D}\right), \quad (2)$$

is the quantity related to the screened interparticle potential. M_d is the mass of the dust particle, λ_D is the Debye length, and γ is the restoring force coefficient for a single particle oscillating in an electrostatic potential well. E is the sheath electric field. β is the coefficient related to the friction force between a dust particle and neutral gas molecules. Q is the equilibrium charge of the dust particle levitated at the equilibrium position z_0, and δQ_n is the charge deviation from Q associated with the inhomogeneous Q variation in the vertical direction and the delayed charging due to the finite charging time when the dust particle oscillates through the sheath. The last term on the right-hand side of Eq. (1) represents the effective force acting on dust particles due to the charge variation. The force becomes either positive or negative depending on the signs of δQ_n and E around the equilibrium position, which leads to damping (or growth) of the T-DLW. The time variation of δQ_n is described by the equation

$$\frac{\partial \delta Q_n}{\partial t} = -\frac{\delta Q_n}{\tau_c} + \frac{\partial Q}{\partial z}\frac{z_n}{\tau_c}, \quad (3)$$

where τ_c is the typical charging time for the dust particle. Equation (3) is a Lagrange coordinate version of the fluid charging equation used in Ref. [20]. It shows that for instantaneous charging (τ_c tending to zero), $\delta Q_n = \frac{\partial Q}{\partial z} z_n$, i.e., the charge takes on a value determined by the instantaneous vertical position, as expected; on the other hand, if τ_c tends to infinity, δQ_n tends to zero and the charge retains its original value. For a typical T-DLW with finite $\omega\tau_c \ll 1$, we assume that z_n and δQ_n oscillate as $\exp(-i\omega t + iknd)$, substitute them into Eqs. (1) and (3), and obtain the modified T-DLW dispersion relation as

$$M_d\omega^2 + iM_d\beta^*\omega = \gamma^* - \alpha(d)(2 - e^{ikd} - e^{-ikd}), \quad (4)$$

where $\gamma^* = \gamma - \frac{\partial Q}{\partial z}E$, $\beta^* = \beta - 2\omega_i$, $\omega_i = -\frac{\tau_c}{2M_d}\frac{\partial Q}{\partial z}E$.

Figure 3 shows a comparison between the experimental dispersion relation and the theoretical one based on Eq. (4) by using the experimental parameters, given in Table I. In the real part as shown in Fig. 3(a), k_r decreases dramatically as the driver frequency increases. The experimental dispersion relation clearly shows the backward wave property, which is in good agreement with the theoretical prediction. The transverse waves are found to be observed in a very narrow frequency range compared to the theoretical dispersion curve, although the driven frequency was changed from 21 Hz through 27 Hz every 0.2 Hz to obtain the waveforms in the experiment. Even below the driver frequency of 23.6 Hz, the vertical dust oscillations were distinctly obtained above noise levels; however, it is quite difficult to determine k_r because the phase difference

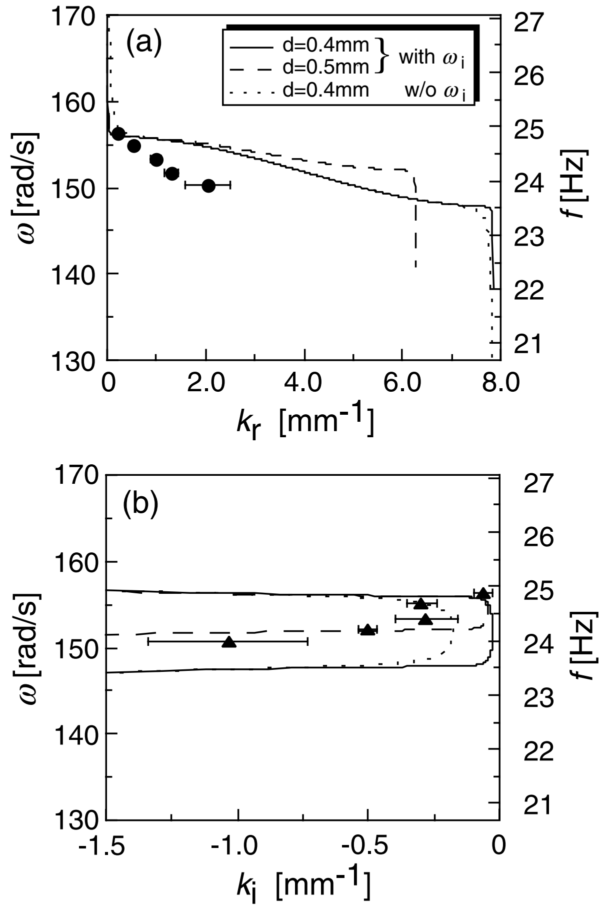

FIG. 3. Dispersion relation. (a) Closed circles represent experimentally obtained k_r and (b) closed triangles k_i of the T-DLW. Solid and dashed lines are numerically calculated theoretical curves based on Eq. (4). Employed parameters are listed in Table I. The dotted line means the theoretical dispersion curves without the delayed charging effects.

TABLE I. Parameters used in calculation of Eq. (4). E and $\partial Q/\partial z$ in γ^* and β^* are numerically calculated by using the Child-Langmuir collisionless ion sheath model. Q is determined by the product of capacitance of a dust particle and the floating potential at the equilibrium position z_0. $\lambda_D(z_0)$ is the Debye length at z_0 by taking account of electron density drop.

Parameters	Value
n_e	7.5×10^{13} m^{-3}
T_e	0.7 eV
$\lambda_D(z_0)$	8.12×10^{-4} m
M_d	6.69×10^{-14} kg
τ_c	5.97×10^{-5} s
γ^*	1.63×10^{-9} N m^{-1}
β^*	2.39×10^{-1} s^{-1}

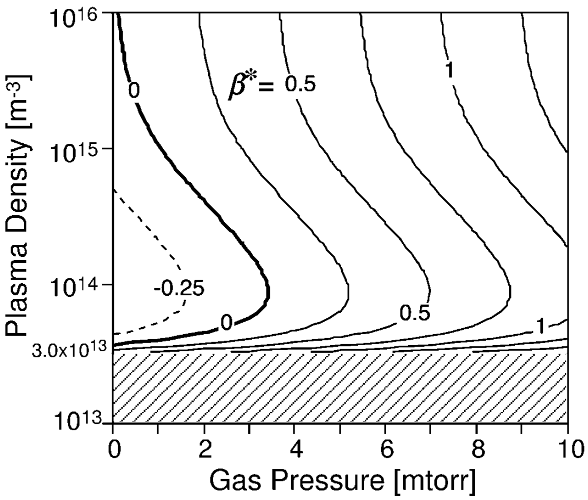

FIG. 4. Contour plots of β^* in parameter spaces of the plasma density and neutral gas pressure. The hatched region means the condition that dust particles cannot levitate.

between the dust particles becomes incoherent rapidly with a decrease in the driver frequency. On the other hand, although the value of the imaginary part k_i obtained in the experiments agrees with the theoretical value, its ω dependence does not match the theoretical one. These need further work.

β^* in Eq. (4) says the imaginary part k_i arises from not only neutral gas drag force corresponding to β but also the delayed charging effects ω_i. In Fig. 3, the dispersion curves without the delayed charging effects are plotted as dotted lines. The effects of ω_i have little affect on the real part of dispersion relation. However, the imaginary part is found to be influenced by the delayed charging effect. If ω_i becomes a large positive value to yield the condition $\beta^* < 0$, a T-DLW instability will occur. Figure 4 shows the calculated β^* as functions of plasma density and neutral pressure. The hatched region means that dust particles cannot levitate below the critical plasma density $n_{cr} \sim 3.0 \times 10^{13}$ m^{-3}. For neutral pressure less than 3 mtorr, the T-DLW becomes unstable at lower plasma density except near n_{cr}. We can achieve the condition $\beta^* < 0$ by decreasing plasma density and gas pressure in our experiments. The self-excited T-DLW associated with the T-DLW instability has been observed in our experiments as mentioned previously [15].

In summary, we have demonstrated the existence of T-DLW propagating in a one-dimensional strongly coupled dust chain levitated in dc argon plasma at low gas pressure. Both parts of the complex wave number were measured in the experiments. The real part clearly shows that the observed T-DLW propagate as a backward wave, which was theoretically predicted.

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