TRANSPORTATION OF CHARGED MICROPARTICLES BY A TRAVELLING POTENTIAL OF PLATE WAVES

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Abstract

We report on a method of charge particle transport utilising acoustic waves travelling in a piezoelectric medium. ZnS grains placed onto the surface of X- and Y-cut, *Z*-propagating $LiNbO_3$ plate experience a sequence of hops in the forward and in the backward directions. The jump probability appears to depend on the frequency of the plate wave, the cut of the driving plate and the grain charge. A simple theoretical model is developed explaining the occurrence of the movements by friction-mediated interactions of the particle with a vibrating surface and electrostatic interactions with the travelling piezoelectric potential. A reasonable qualitative agreement between experimental data and the model is found.

Introduction

Microscopic particles subjected to a periodic potential can experience a directional motion. Typically, an asymmetric external potential is used to achieve ratchet behaviour [1]. Extensive studies done over the last decade illustrate that the ratchets can effectively transport μm- and mm-sized particles employing, e.g., optical illumination and electric fields to generate a driving force [2, 3]. Different types of acoustic waves have also been used to pump fluids and particles in suspensions adjacent to the wave-transmitting medium, and the main features of the physics involved are due to acoustic streaming effect [4].

In this work, we have micromachined a piezoelectric-plate device allowing to transport electrically-charged micron-sized particles with a periodic potential of acoustic waves which involves both the elastic displacement of the driving plate and the piezoelectric field influencing the motion of particles.

Experimental

Experiments were performed on two types of ZnS particles that were either positively or negatively charged due to electrophorus. To form a transport device, the particles of a particular type were placed onto either an X- or Y-cut $LiNbO_3$ piezoelectric plate. The travelling Z-propagating acoustic waves were excited in the driving plates with frequencies ranged from 2 to 6 MHz. The device was illuminated with a bright light and placed on the translation stage of an optical microscope equipped with an image capturing technique.

Results and Discussion

Travelling waves produces a pumping of particles across the surface of the driving plate. It is ascertained that the grain movements are single hopping events. Figure 1 illustrates the particle hops (arrows) accomplished in the direction of the travelling wave (a) and in the opposite direction (b).

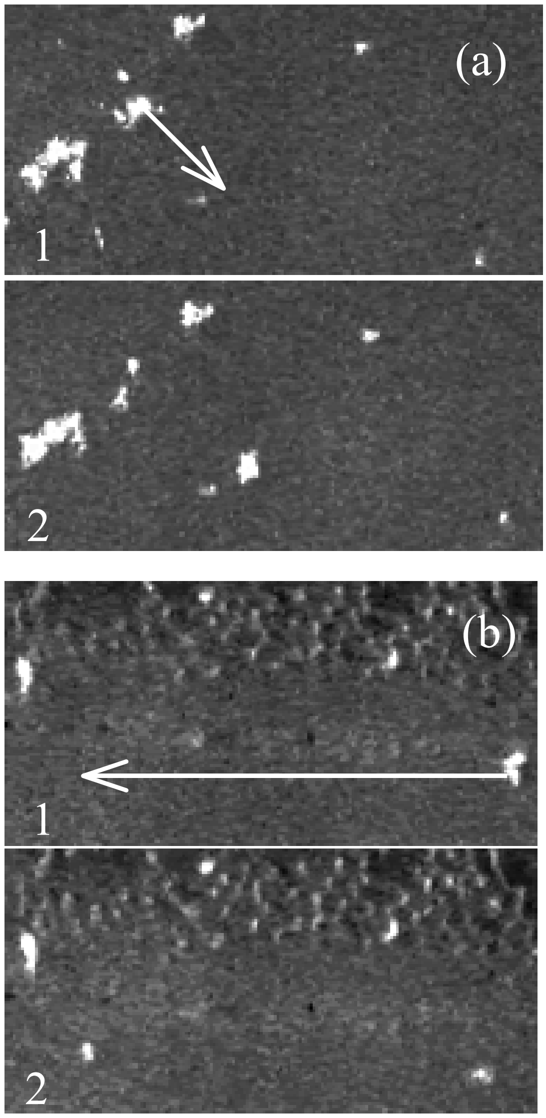

Figure 1: Image of particle positions on the surface of YZ-cut $LiNbO_3$ plate taken before (1) and after (2) excitation of acoustic waves. Image size is 405×190 μm^2

Depending on the frequency of the plate wave, the cut of the driving plate and the grain charge, the probability distributions for hopping forwards (P_f) and backwards (P_b) with respect to the wavevector are changed quite remarkably. These are exemplified in figure 2 showing that the probabilities of the jumps are broadly distributed for the YZ-cut driving plate (a) whereas they are considerably narrower for the XZ-cut $LiNbO_3$ (b). Moreover, by tuning from the second to the first resonant mode of Lamb waves, the length of the backward steps drops (a and c in figure 2). Furthermore, the sign of the particle charge has a profound impact on the probability distribution (b and d in figure 2).

The results are then analysed in the framework of the model describing the occurrence of the movements as being due to friction-mediated interactions of the particle with a vibrating surface, and electrostatic interaction with the travelling piezoelectric potential. In order to attain the displacement and electric fields at the surface of the driving plate, we computed the standard piezoelectric equations of state for the $LiNbO_3$ symmetry and the stress equations of motion satisfying the mechanical and electrical boundary conditions at the plate surfaces [5, 6]. Thus, for YZ-cut $LiNbO_3$ they are of the form

$$\rho \frac{\partial^2 u_i}{\partial t^2} = \frac{\partial T_{ij}}{\partial x_j} ,$$

$$\frac{\partial D_i}{\partial x_i} = 0 ,$$

$$T_{ij} = c_{ij\,kl} \frac{\partial u_k}{\partial x_l} + e_{m\,ij} \frac{\partial \varphi}{\partial x_m} ,$$

$$D_i = e_{i\,kl} \frac{\partial u_k}{\partial x_l} - \varepsilon_{ij} \frac{\partial \varphi}{\partial x_j} ,$$

$$T_{23}(\pm h) = T_{22}(\pm h) = T_{21}(\pm h) = 0 ,$$

$$D_2(+h) = -\varepsilon_0 \frac{\partial \varphi}{\partial y}, \quad \varphi(-h) = 0 ,$$

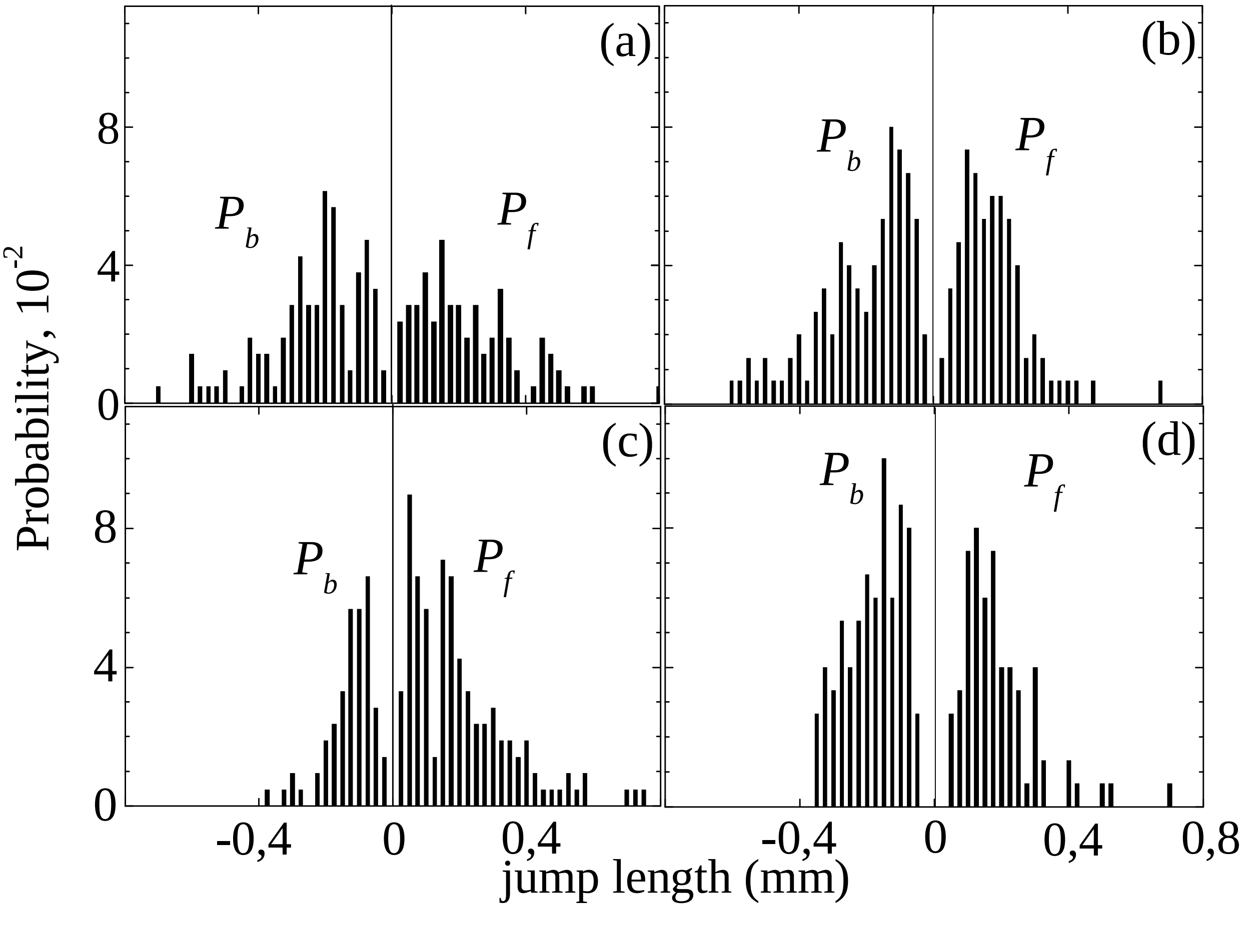

Figure 2: Probabilities P_f and P_b for a positively (a, b and d) and a negatively (b) charged ZnS grain to jump forwards and backwards vs jump length for the first (b, c and d) and second (a) resonant mode of Lamb waves. The driving $LiNbO_3$ plate is YZ- (a and c) and XZ- (b and d) cut

where u_i is the displacement components, φ is the electrostatic potential, **T** is the stress tensor, **D** is the electric displacement vector, $c_{ij\,kl}$ are the elastic moduli of the medium, $e_{m\,ij}$ are its piezoelectric coupling coefficients, ε_{ij} is the tensor of the dielectric constants, ρ is the mass density and repeated indices are summed. We arrived at the components of the displacement and electric field strength exhibited in figures 3 and 4.

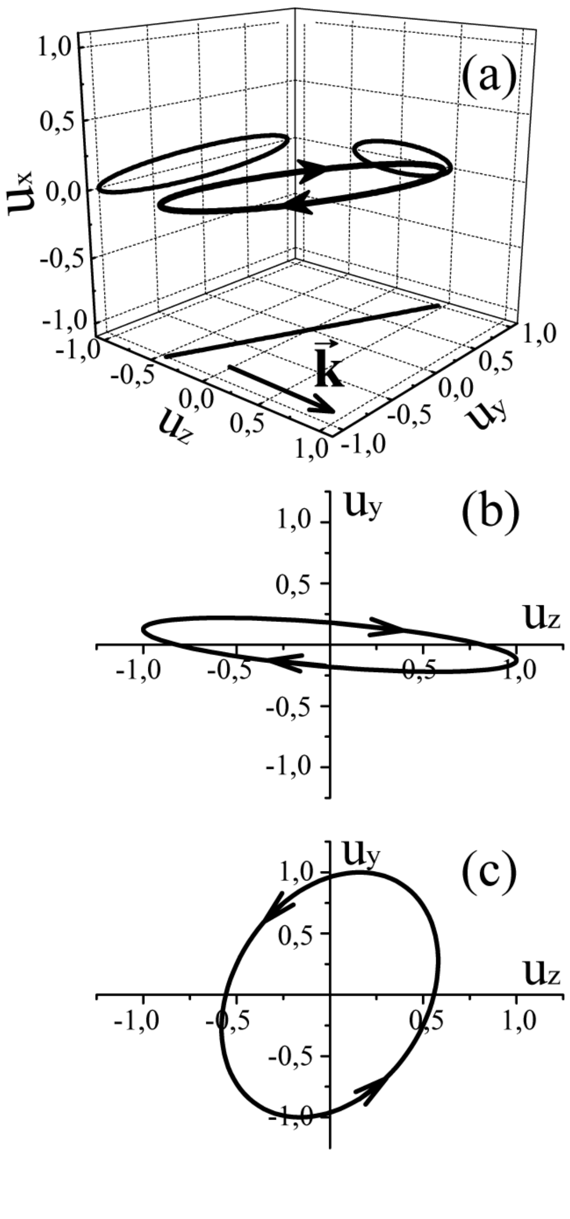

Figure 3: Computed elliptical displacements at the surface of XZ- (a) and YZ- (b and c) cut $LiNbO_3$ plate for the first (a and b) and second (c) resonant mode of Lamb waves

The simplified explanation of the experimental findings is then based on the assumption that the motion of grains is characteristic of the mechanical and electrical forces deduced from the above theoretical treatment.

Thus, it has been found that, contrary to the XZ-plate geometry, the second resonant mode of Lamb waves in YZ-cut $LiNbO_3$ is of a backward origin. This indicates that the electrostatic potential travels in the direction opposite to that of the acoustic power flow. As a consequence, the number of backward steps is enhanced in figure 2(a) at the expense of the forward jumps compared with the ones displaced in figure 2(b). Similar transformation of P_f vs P_b is observed by going down to the first resonant mode in the YZ-cut plate; compare (a) and (c) in figure 2. Note moreover that the movements in the wave are clockwise at the first resonant mode (b in figure 3) whereas they are counter-clockwise at the second mode (c in figure 3) leading to additional enhancement of lengthy hops in the backward direction in figure 2(a). Finally, the decrease in the P_b

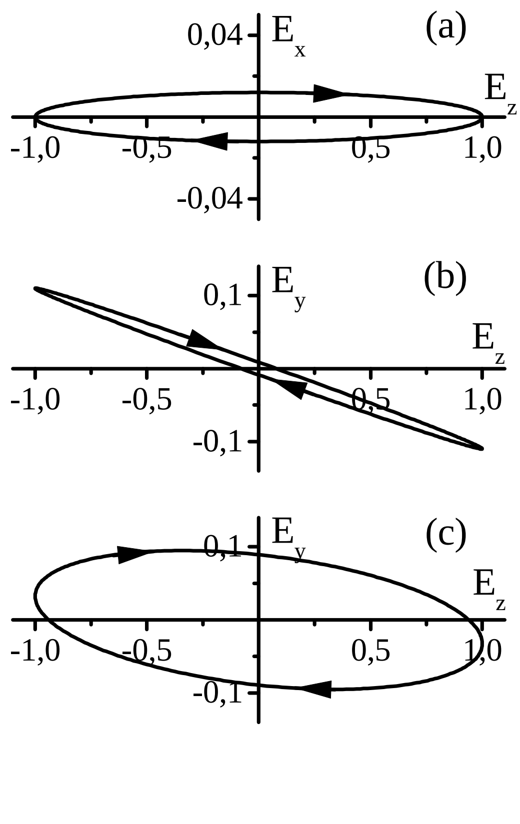

Figure 4: Computed piezoelectric fields for the same conditions as in figure 3

probability in figure 2(d) compared with that in figure 2(b) could be explained by the relative phase shifts of the displacement and electric fields; see figures 3(a) and 4(a). Indeed, the fluctuating friction force acting to the particle due to mechanical displacement of the surface does not depend on the particle charge and forces the grain to move back and forth. The other periodic force is of electrical origin. Therefore, it forces the grains with the opposite charge to move in the opposite directions. Significantly, the phases of the surface displacement and the electric field strength are shown to be the same in figures 3(a) and 4(a). Hence, for positively charged grains, the forward and backward motions maintained due to the friction force are accompanied by the electrical force acting in the same directions. This is no longer valid for negatively charged grains as the electric and mechanical forces are in the opposite directions. As a consequence, the movement probability is enhanced in figure 2(d) compared with figure 2 (b).

Conclusion

Summarising, by employing the waves in a piezoelectric plate, the pumping function can be performed which is sensitive to the wave mode, plate symmetry and the charge of pumped species. The device can be profitable in different fields, notably in nanotechnology and biology.

References

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