The Journal of the Acoustical Society of America

MAY 20 2020

Ferroelectret-based flexible transducers: A strategy for acoustic levitation and manipulation of particles

Yuan Xue; Xiaoqing Zhang ✉; Romol Chadda; Gerhard M. Sessler; Mario Kupnik

J. Acoust. Soc. Am. 147, EL421–EL427 (2020)
https://doi.org/10.1121/10.0001274

ASA
ACOUSTICAL SOCIETY
OF AMERICA

JASA
EXPRESS LETTERS

https://doi.org/10.1121/10.0001274

Ferroelectret-based flexible transducers: A strategy for acoustic levitation and manipulation of particles

Yuan Xue,[1] Xiaoqing Zhang,[1,a)] Romol Chadda,[2] Gerhard M. Sessler,[2] and Mario Kupnik[2]

[1] *Shanghai Key Laboratory of Special Artificial Microstructure Materials and Technology, School of Physics Science and Engineering, Tongji University, 1239 Siping Road, 200092 Shanghai, China*
[2] *Measurement and Sensor Technology Group, Technische Universität Darmstadt, Merckstrasse 25, 64283 Darmstadt, Germany*
yuanxue713@126.com, x.zhang@tongji.edu.cn, chadda@must.tu-darmstadt.de, gerhard.sessler@tu-darmstadt.de, mario.kupnik@tu-darmstadt.de

Abstract: Advanced acoustic levitation devices featuring flexible, lightweight, wide bandwidth, and film-like transducers based on ferroelectrets are designed and fabricated for sophisticated manipulation of particles in a simple way. Owing to the unique properties of ferroelectret films, such as high piezoelectric activity, very small acoustic impedance, a relatively large damping ratio, flexibility, a large area, and small density, the levitator reported features a wider bandwidth compared to ceramic-based levitators. The transportation of levitated particles is achieved by deformation of the film transducer, which represents a different and promising concept for this task. © *2020 Acoustical Society of America*

[Editor: Con Doolan] Pages: EL421–EL427

Received: 21 February 2020 **Accepted:** 27 April 2020 **Published Online:** 20 May 2020

In the past decades, levitation techniques have stimulated considerable research interest. Several different methods have been proposed by researchers to levitate particles, including acoustic, optical, magnetic, aerodynamic, and electrostatic levitation.[1–5] Among all these techniques, acoustic levitation, which uses the acoustic radiation force to counteract gravity and suspend objects in mid-air,[2] has several advantages such as the absence of restrictions on the levitated objects caused by their electric or magnetic properties or problems with heating effects, to name a few. This versatility promises great potential for acoustic levitation in container-less processing, analytical chemistry, material science, biomaterial research, pharmacy, nano-assembly,[6–12] etc.

The fundamental concept of levitation by using acoustic radiation force was first proposed by Bücks and Müller in 1933.[13] King derived the theoretical background of the force that acts on a rigid sphere in a standing wave field.[14] Several decades later, Gor'kov proposed his method to calculate the acoustic radiation potential that acts on a small object in an arbitrary acoustic field (see the supplementary material in Ref. 28).[15] Recent progress in acoustic levitation now allows not only suspending larger and heavier objects but also rotating and translating the levitated object in mid-air.[16] In order to manipulate the levitated object, complicated transducer-array systems are generally needed. This is mainly required due to restrictions with respect to size, shape, and fragility of piezoelectric ceramics. Another drawback of the ceramic-based acoustic elevators is the instability at long working times caused by heating of the piezoelectric materials. In order to simplify the manipulation system and enhance its stability, an effective new approach is implemented in the present paper, which consists of utilizing air-borne and highly sensitive flexible ferroelectret film transducers.

Ferroelectrets, or piezoelectrets, are polymer electret foams with oriented "macro-dipoles," which exhibit a strong piezoelectric effect and a pseudo ferroelectricity.[17] As a new artificial functional material, ferroelectrets have several features, such as a strong piezoelectric effect, flexibility and adaptability to any size and shape, and they have been applied in air-borne transducers. One of these promising materials is irradiated cross-linked polypropylene (IXPP) ferroelectrets, which have a quasi-static d_{33} coefficient of up to ~700 pC/N, and a low acoustic impedance of 0.03 MRayl,[18] close to that of air. These advantages suggest that IXPP ferroelectret films are promising candidates for acoustic levitation, using flexible transducers, which can provide a new approach for manipulating levitated particles. In this work, we report IXPP ferroelectret films as large-area and flexible wide bandwidth acoustic levitators. Such levitators not

---

[a] Author to whom correspondence should be addressed, ORCID: 0000-0001-9498-5709.

only produce stable object traps in a wide working frequency range but also permit controlling the movement of the levitated objects by deforming the film-like transducer.

The preparation process of IXPP ferroelectret films is illustrated in Fig. 1(a). IXPP resin was produced by partly crosslinking linear polypropylene (PP) resin using electron beam irradiation. The sol-gel fraction of the IXPP resin is around 50% to 60%. In the following foaming step, IXPP resin was melted and mixed with a foaming agent and then extruded to form foam sheets. Thereafter, a hot-pressing treatment was carried out to modify the microstructure of the material and enhance its charging capability.[19] In order to render the film piezoelectric, the film sample was exposed to negative corona of -25 kV for 60 s. After polarization, the film is piezoelectric, i.e., it is a ferroelectret. The piezoelectric properties of ferroelectrets are due to space charge accumulation and the cellular structure of the material. When a voltage applied across the film is large enough, tiny Paschen micro-discharges may happen in the air bubbles, which generate positive and negative charges. The charges shift along the electric field and finally are trapped on the surfaces of the top and bottom IXPP walls of the cells, forming oriented "macro-dipoles." The charge distribution and work principle of ferroelectrets are schematically shown in Fig. 1(b). In order to measure the piezoelectric effect in the fabricated films, aluminum electrodes with a thickness of 100 nm were evaporated on both sides of the film samples. In the present study, the IXPP ferroelectret film samples prepared are of a thickness t of about 160 μm and an active area A as large as 100 cm^2 except for the samples specified otherwise. (See the supplementary material for the details of the property measurements of the IXPP films in Ref. 28.)

The dielectric spectrum[20] of a fabricated IXPP ferroelectret film sample with a quasi-static d_{33} coefficient of 600 pC/N and a bulk density of 550 kg/m^3 was measured [Fig. 1(c-1)]. The parameters obtained from the sample are a resonance frequency in thickness direction of 120 kHz, relative permittivity of 1.8, Young's modulus in the thickness direction Y_3 of 1.2 MPa, and an acoustic

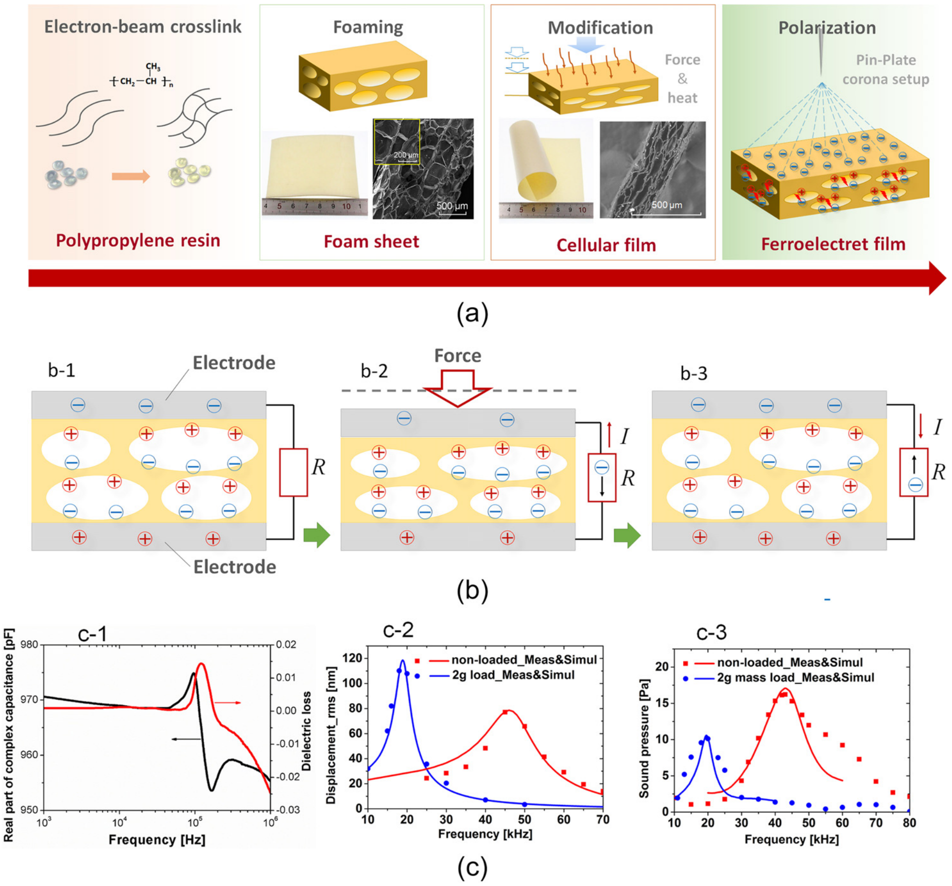

Fig. 1. (Color online) (a) Preparation process of IXPP ferroelectret films. (b) Schematic illustration of the cross-section and working principle of ferroelectrets: (b-1) initial state; (b-2) under compressive deformation; and (b-3) recovery to initial state. (c) Material properties of IXPP ferroelectret films: (c-1) dielectric spectrum of an IXPP film sample under free boundary condition; (c-2) averaged measured (circle and square symbols) and simulated (line) surface displacement of non-loaded (red line) and 2 g loaded (blue line) IXPP films; and (c-3) measured and simulated radiated sound pressure of non-loaded (red line) and 2 g loaded (blue line) IXPP films and at 10 cm distance. The IXPP film samples were driven with a voltage of 100 V$_{\mathrm{rms}}$, and have an active area of 100 cm^2, a quasi-static d_{33} coefficient of 600 pC/N, and a capacitance of 800 pF.

impedance of about 0.03 MRayl. Compared to other piezoelectric materials, such as piezoelectric ceramics and ferroelectric polymer polyvinylidene fluoride (PVDF) with very large acoustic impedances, normally on the order of a few tens of MRayl and a few MRayl, respectively, the IXPP ferroelectrets with their much smaller acoustic impedance are much more suitable for working in air.

In order to evaluate the performance of IXPP ferroelectret films in acoustic levitation, the surface displacement of IXPP film samples and radiated sound pressure generated by them were measured and simulated [Figs. 1(c-2) and 1(c-3)]. The simulations of the samples were conducted by using the commercially available finite element software package COMSOL (Version 5.1, COMSOL Inc., Palo Alto, CA). The simulation model of IXPP ferroelectrets uses the parameters of the experimental samples and a damping ratio of 0.06, which is determined from the experiment. The bottom of the ferroelectret is mechanically fixed on a plastic substrate by using double-sided adhesive tape and is electrically grounded, while the top is mechanically free and loaded with a driving voltage of 100 V_{rms} at a frequency ranging from 10 to 70 kHz.

The resonance frequency of the IXPP sample, clamped on one side (without loading mass) is around 45 kHz [Figs. 1(c-2) and 1(c-3)], and thus smaller than half of the aforementioned resonance of a free-standing IXPP sample. According to the literature,[21,22] the clamped sample has a resonance frequency half that of a free-standing sample. The resonance frequency of such a clamped sample can be further reduced by applying a seismic mass to it, as explained by,[23,24] i.e.,

$$\omega_f = \sqrt{\frac{Y_3 A}{t\left(m_s + \frac{1}{3} m_f\right)}}, \tag{1}$$

where m_s is the seismic mass and $\frac{1}{3}m_f$ represents the effective mass of the ferroelectret film. In these experiments, the clamped films were mass loaded (copper foil, 2 g) to reduce the resonance frequency and enhance the quality factor of the ferroelectret acoustic levitator [Fig. 1(c-2)]. For both tested samples, the surface displacement of the film samples increases with increasing driving frequency until it reaches a maximum value at resonance and then decreases beyond resonance as expected. These results confirm that the application of mass loading not only decreases the resonance but also increases the quality factor of such ferroelectret films.

The measured acoustic pressures, generated by these ferroelectret film samples at a distance of 10 cm, show agreement with the values obtained from numerical simulation below the resonance frequency [Fig. 1(c-3)]. For the non-loaded IXPP film, a maximum ultrasound pressure of 16 Pa was measured at a resonance frequency of 43 kHz, while for the film sample with a 2 g mass loading, a maximum sound pressure of 10.5 Pa was achieved at its resonance frequency of 19 kHz. The resonance frequencies found in this experiment are similar to those determined from displacement measurements, as expected. Different from the displacement measurement, the non-loaded IXPP film sample generates a higher sound pressure than the 2 g loaded film [Fig. 1(c-3)]. This is due to the fact that the radiated acoustic pressure of a ferroelectret actuator increases with the square of the driving frequency.[25] This increase over-compensates the larger displacement of the mass-loaded film [Fig. 1(c-2)]. The broadening of the resonance peaks in Fig. 1(c-3) may be due to a small quality factor of the tested samples.

The agreement between the experimental and simulation results of IXPP ferroelectret samples proves that the simulation model can be employed to estimate the feasibility and performance of acoustic levitation based on ferroelectret films. Here, a schematic of the mechanism of acoustic levitation [Fig. 2(a)] and a 3-dimensional (3D) model [Fig. 2(b)] of a ferroelectret film based acoustic levitator are presented. In the models, the ferroelectret levitator has a curved shape in order to significantly increase the axial and radial forces on the levitated objects.[26,27] Several parameters were taken into consideration when optimizing the model of the IXPP film acoustic levitator, such as the curvature radius R of the IXPP film, the distance d between the IXPP actuator, and the reflector and the working frequency f.

Figure 2(c) shows the Gor'kov acoustic radiation potential in an IXPP acoustic levitator simulated by COMSOL at 30 kHz and 200 V_{rms}. This levitator has two traps to suspend objects and the first node (lower one) is about 3.5 mm above ground. The object traps are well defined since the acoustic radiation of the transducer is uniform with nonuniformities being only on the order of the lateral dimensions of the air bubbles, which amount to a few hundred microns.

The Gor'kov potential allows one to calculate the levitating sound pressure on the object (see supplementary material in Ref. 28). According to this model, we fabricated a ferroelectret film levitator by using a $100 \times 50\,\text{mm}^2$ IXPP film sample with a quasi-static d_{33} of 600 pC/N. The fabricated levitator has a flexible film transducer with a curvature radius of 250 mm and the distance between the reflector and the film transducer is about 14 mm. As a driving voltage,

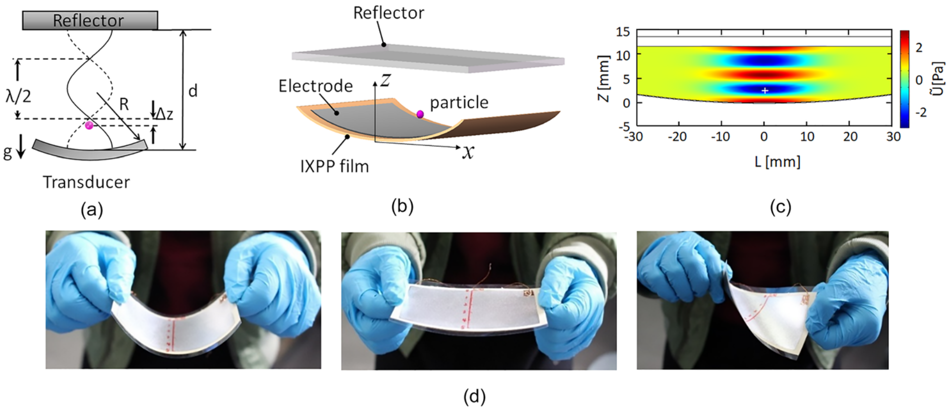

Fig. 2. (Color online) Mechanism, model, simulation, and a prototype of IXPP ferroelectret film-based levitator. (a) Schematic of the mechanism of acoustic levitation for an acoustic levitator with a curved transducer. *R* is the curvature radius. (b) 3D mode of an IXPP ferroelectret film based acoustic levitator. (c) Simulation of Gor'kov relative acoustic radiation potential. *L* is the projection of the length of the IXPP film on the *x* axis See supplementary material in Ref. 28 of an IXPP ferroelectret based levitator at a driving voltage of 200 V_{rms}. (d) Demonstration of flexibility of an IXPP ferroelectret film transducer with a 100 μm thick PET substrate.

240 V_{rms} were applied to the device, a phenylene sulfide (PS) foam particle with a diameter of 2 mm was successfully levitated at the lower node (Mm 1). The PS particle was levitated at the position slightly lower than the node predicted by the simulation. This is because the acoustic radiation force must counteract the gravity of the PS sphere as generally observed in the literature. In this study, the IXPP film was glued onto a 100 μm thick polyethylene terephthalate (PET) substrate, which makes the film transducer very flexible [Fig. 2(d)]. Therefore, levitators with such film transducers allow one to manipulate the levitated particles by adjusting the shape of the film transducer. The various deformations of the film transducer can be performed by a mechanical operation, as will be discussed as follows.

Mm. 1. Levitation of PS foams. This is a file of type "avi" (4873 KB).

The aforementioned experiment and simulation confirm that ferroelectret films do have a place in acoustic levitation applications. For further improving the capability of IXPP ferroelectret based levitators, higher driving voltages are applied and objects with different sizes and different densities are now levitated (Fig. 3). With a driving voltage of 600 V_{rms} and a working frequency of 25 kHz, PS foam particles with diameters ranging from 2 to 4 mm were successfully levitated by the prototype levitator [Fig. 3(a)]. These particles can also be levitated at both nodes of this device [Fig. 3(b)]. Moreover, this ferroelectret based levitator can levitate PS particles with various densities [Fig. 3(c)]. These preliminary experiments prove that the ferroelectret film transducer has an excellent performance in acoustic levitation. In addition, such a ferroelectret film based acoustic levitator has a broad bandwidth. As demonstrated in Fig. 3(d), the device

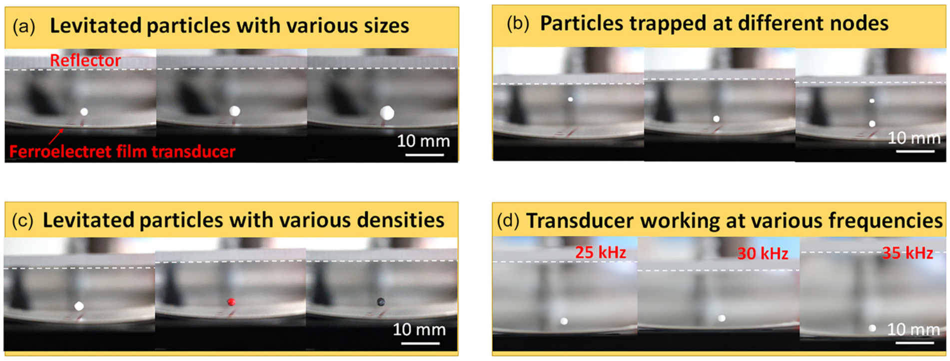

Fig. 3. (Color online) Capability of IXPP acoustic levitator. (a) Acoustic levitation of PS particles with diameters ranging from 2 to 4 mm. (b) Acoustic levitation of PS particles at the lower node, upper node, and both nodes of the IXPP levitator. (c) Acoustic levitation of PS particles with different mass. The diameters of the levitated particles are around 2 to 3 mm. The density of the particle in white is around 200 kg/m^3, and the densities of the red and the black particles were increased by soaking different amount of ink in them. (d) Acoustic levitation of PS particles at 25, 30, and 35 kHz. There are two nodes in the levitator working at 25 and 30 kHz, and 3 nodes in the levitator working at 35 kHz. This IXPP levitator has a driving voltage of 600 V_{rms}, and (a) to (c) are operating with a frequency of 25 kHz.

can successfully levitate PS particles from 25 to 35 kHz at least. Furthermore, the working frequency of such a device could be extended to its resonance frequency of 50 kHz. However, since the size of the levitated objects decreases with increasing frequency, we did not carry out our experiments at higher frequencies. Another very important feature of such an acoustic levitator is the absence of significant heating because of small power consumption as well as excellent heat dissipation performance of the film-like transducer. Therefore, such ferroelectret based devices can operate stably over a long period of time.

According to the literature, the minimum sound pressure $p_{\min}$ for acoustic levitation can be obtained by using[16]

$$p_{\min} = \sqrt{\frac{8\rho_0 \rho_p c_0^2 g}{5k}}, \tag{2}$$

which follows from the radiation potential (see the supplementary material in Ref. 28). In Eq. (2), k equals ω/c_0, ρ_p is the density of levitated PS particles, ρ_0 and c_0 are the density and sound velocity of air, respectively, while g is the gravitational acceleration of earth (9.8 m/s^2). Assuming that the air has a density of 1.2 kg/m^3, and a sound velocity of 343 m/s, $p_{\min}$ for levitating a PS particle with a typical density ρ_{p} of 200 kg/m^3 at 25 kHz (Fig. 3) follows from Eq. (2) as 980 Pa. However, the radiated sound pressure at 25 kHz and a driving voltage of 100 V$_{\mathrm{rms}}$, can be estimated from Fig. 1(c-3) for the case of a transducer, tuned to 25 kHz, to be only about 10 Pa. Considering the fact, however, that the generated sound pressure is proportional to the applied ac-voltage,[25] a sound pressure in excess of about 60 Pa can be reached for an ac voltage of 600 V$_{\mathrm{rms}}$, as applied for the experiments (Fig. 3). This pressure is achieved for non-focused transducers. If curved, focusing transducers are used, as shown in Fig. 2 and used in the levitation experiments, and an additional large increase of the sound pressure is obtained. This increase can amount to 2 or 3 orders of magnitude.[26,27] This indicates that the $p_{\min}$ of 980 Pa required for levitating the PS spheres is readily available when using the IXPP transducers.

Compared with conventional acoustic levitators based on piezoelectric ceramics, the greatest strengths of the ferroelectret acoustic levitators reported in this paper, beside their small thickness, are their flexibility and adaptability to almost any size and shape. As already mentioned above, the flexibility of the ferroelectret levitators makes it possible to manipulate the levitated particles by slightly adjusting the shape of the film transducer (Fig. 4, Mm 2 and Mm 3). Under a driving voltage of 600 V$_{\mathrm{rms}}$ and a frequency of 25 kHz, the movement of a levitated PS foam particle along the central axis of the levitator in a large range can be accomplished by

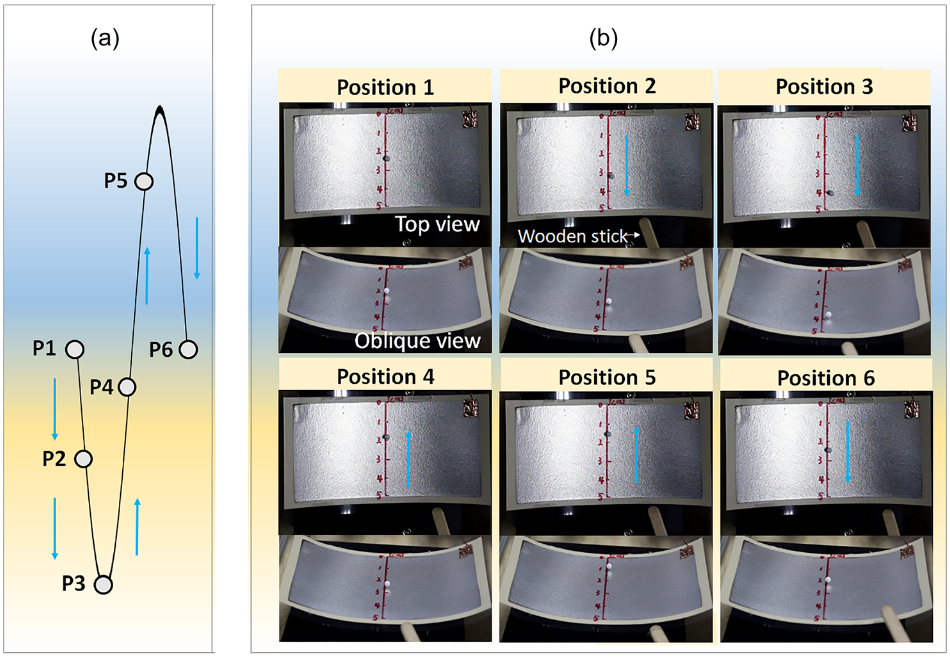

Fig. 4. (Color online) Manipulation of a levitated object of IXPP acoustic levitator. (a) Motion trail and position point of manipulated PS foam particle. (b) Top view (upper) and oblique view (bottom) of manipulation of PS particle by ferroelectret acoustic levitator at the different positions defined in (a). The IXPP levitator has a driving voltage of 600 V$_{\mathrm{rms}}$ and a working frequency of 25 kHz. A wooden stick served as a tool to manipulate the shape of IXPP transducer.

deforming the shape of the film transducer simply with a wooden stick. Here, the wooden stick was used only to make the film transducer deformation. Figure 4(a) shows the motion trail of a PS foam particle manipulated by the levitator. Starting from the center of the levitator, the levitated particle moves back to the bottom edge of the device, and then moves forth to the upper edge. After that, the PS sphere returns back to its initial place. The distance covered by the levitated object is limited by the levitator dimension; the maximum distance is about 4 cm. Figure 4(b) presents the top view and oblique view of manipulation of the particle at different positions. This ferroelectret film based levitator cannot only manipulate the movement of the levitated objects along the main axis but also in transverse direction (Mm 3), showing a new strategy to control the levitated objects. Besides, ferroelectret film transducers with large areas can be made to manipulate levitated objects in a broader range. Corresponding research work, including the control of levitated particles in a complex moving curve and levitation of heavier objects, such as liquid drops and metal spheres, is on the way.

Mm. 2. Manipulation of levitated PS foam along the main axis. This is a file of type “avi” (10124 KB).

Mm. 3. Manipulation of levitated particle along the main axis and in transverse direction. This is a file of type “avi” (8528 KB).

In summary, large-area and flexible acoustic levitators based on IXPP ferroelectret films are reported. Such ferroelectret films with a high piezoelectric d_{33} coefficient and a large active area were made from electron-beam irradiated PP resin. A surface displacement amplitude of 78 nm and an ultrasound pressure of 16 Pa or 118 dB Sound Pressure Level (SPL) (at 10 cm distance) are measured for a non-focused IXPP film sample at a driving voltage of 100 V_{rms} at its resonance frequency. The mechanical properties and performance of film samples can be adjusted by applying mass loading. Numerical simulations are performed not only to confirm the experimental results on surface displacement and ultrasonic operation of IXPP films, but also to estimate the performance of the acoustic levitators based on IXPP ferroelectrets. A flexible ferroelectret acoustic levitator was designed and simulated first and then prepared by using a thin PET substrate to support the IXPP film. For a focusing actuator of this kind, with an active area of 50 cm^2, PS foam particles with 1–4 mm diameter could be levitated and moved under a working frequency ranging from 25 to 35 kHz and a driving voltage up to 600 V_{rms}. Compared with conventional levitators based on piezoelectric ceramics, the greatest advantages of these ferroelectret levitators prepared in this work are their small thickness, lightweight, and their flexibility and adaptability for almost any size and shape. Moreover, the broad bandwidth, simple structure, low cost, and environmental friendliness are further strengths of ferroelectret acoustic levitators. Thus, the ferroelectret levitator has a significant potential for future applications.

Acknowledgment

Financial support from the Natural Science Foundation of China (Grant No. NFSC 61761136004) and the Deutsche Forschungsgemeinschaft (German Research Foundation, Projektnummer Nos. 392020380 and KU3498/1) is gratefully acknowledged.

References and links

[1] M. Barmatz and C. Shipley, “Acoustic levitation in the presence of gravity,” J. Acoust. Soc. Am. **82**, S106 (1987).
[2] E. H. Brandt, “Levitation in physics,” Science **243**, 349–355 (1989).
[3] E. H. Brandt, “Acoustic physics: Suspended by sound,” Nature **413**, 474–475 (2001).
[4] A. El Hajjaji and M. Ouladsine, “Modeling and nonlinear control of magnetic levitation systems,” IEEE Trans. Ind. Electron. **48**, 831–838 (2001).
[5] U. J. Hansen, “Acoustic levitation,” J. Acoust. Soc. Am. **118**, 1946 (2005).
[6] C. Benmore and J. Weber, “Amorphization of molecular liquids of pharmaceutical drugs by acoustic levitation,” Phys. Rev. X **1**, 011004 (2011).
[7] N. Bjelobrk, M. Nabavi, and D. Poulikakos, “Acoustic levitator for contactless transport and mixing of droplets in air,” J. Acoust. Soc. Am. **130**, 2370 (2011).
[8] G. Dumy, M. Hoyos, and J.-L. Aider, “Observation of selective optical manipulation of particles in acoustic levitation,” J. Acoust. Soc. Am. **146**, 4557–4568 (2019).
[9] D. Foresti, M. Nabavi, M. Klingauf, A. Ferrari, and D. Poulikakos, “Acoustophoretic contactless transport and handling of matter in air,” Proc. Natl. Acad. Sci. U.S.A. **110**, 12549–12554 (2013).
[10] Z. Hong, A. Marzo, S. Subramanian, and B. W. Drinkwater, “Manipulation and levitation of particles with acoustic vortices,” J. Acoust. Soc. Am. **138**, 1827 (2015).
[11] A. M. Seddon, S. J. Richardson, K. Rastogi, T. S. Plivelic, A. M. Squires, and C. Pfrang, “Control of nanomaterial self-assembly in ultrasonically levitated droplets,” J. Phys. Chem. Lett. **7**, 1341–1345 (2016).
[12] R. J. Weber, C. J. Benmore, S. K. Tumber, A. N. Tailor, C. A. Rey, L. S. Taylor, and S. R. Byrn, “Acoustic levitation: Recent developments and emerging opportunities in biomaterials research,” Eur. Biophys. J. **41**, 397–403 (2012).
[13] K. Bücks and H. Müller, “Über einige Beobachtungen an schwingenden Piezoquarzen und ihrem Schallfeld” (“Some observations on vibrating piezoelectric quartzes and their sound field”), Z. Phys. **84**, 75–86 (1933).

[14] L. V. King, “On the acoustic radiation pressure on spheres,” Proc. R. Soc. London **147**, 212–240 (1934).

[15] L. P. Gor'kov, “On the forces acting on a small particle in an acoustical field in an ideal fluid,” Sov. Phys. Dokl. **6**, 773–775 (1962).

[16] M. A. Andrade, N. Perez, and J. C. Adamowski, “Review of progress in acoustic levitation,” Braz. J. Phys. **48**, 190–213 (2018).

[17] S. Bauer, R. Gerhard-Multhaupt, and G. M. Sessler, “Ferroelectrets: Soft electroactive foams for transducers,” Phys. Today **57**(2), 37–43 (2004).

[18] Y. Xue, X. Zhang, J. Zheng, T. Liu, and B. Zhu, “Comparative study of transducers for air-borne sound based on normal and irradiation cross-linked polypropylene piezoelectret films,” IEEE Trans. Diele. Electr. Insul. **25**, 228–234 (2018).

[19] X. Zhang, J. Huang, J. Chen, Z. Wan, S. Wang, and Z. Xia, “Piezoelectric properties of irradiation-crosslinked polypropylene ferroelectrets,” Appl. Phys. Lett. **91**, 182901 (2007).

[20] A. Mellinger, “Dielectric resonance spectroscopy: A versatile tool in the quest for better piezoelectric polymers,” IEEE Trans. Diele. Electr. Insul. **10**, 842–861 (2003).

[21] P. Fang, L. Holländer, W. Wirges, and R. Gerhard, “Piezoelectric *d33* coefficients in foamed and layered polymer piezoelectrets from dynamic mechano-electrical experiments, electro-mechanical resonance spectroscopy and acoustic-transducer measurements,” Meas. Sci. Technol. **23**, 035604 (2012).

[22] G. S. Neugschwandtner, R. Schwödiauer, M. Vieytes, S. Bauer-Gogonea, S. Bauer, J. Hillenbrand, R. Kressmann, G. M. Sessler, M. Paajanen, and J. Lekkala, “Large and broadband piezoelectricity in smart polymer-foam space-charge electrets,” Appl. Phys. Lett. **77**, 3827–3829 (2000).

[23] L. E. Kinsler, A. R. Frey, and G. S. Bennett, *Fundamentals of Acoustics* (Wiley, New York, 1982).

[24] P. Pondrom, J. Hillenbrand, G. M. Sessler, J. Bös, and T. Melz, “Vibration-based energy harvesting with stacked piezoelectrets,” Appl. Phys. Lett. **104**, 172901 (2014).

[25] R. Kressmann, “New piezoelectric polymer for air-borne and water-borne sound transducers,” J. Acoust. Soc. Am. **109**, 1412–1416 (2001).

[26] M. A. Andrade, F. Buiochi, and J. C. Adamowski, “Finite element analysis and optimization of a single-axis acoustic levitator,” IEEE Trans. Ultrason. Ferroelectr. Freq. Control **57**, 469–479 (2010).

[27] W. J. Xie and B. Wei, “Dependence of acoustic levitation capabilities on geometric parameters,” Phys. Rev. E **66**, 026605 (2002).

[28] See supplementary material in https://doi.org/10.1121/10.0001274 for the theory of acoustic radiation and potential, measurement of material properties, and measurement of the surface displacement.