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Ring-Focusing Fresnel Acoustic Lens for Long Depth-of-Focus Focused Ultrasound with Multiple Trapping Zones

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Abstract

This paper describes a novel acoustic transducer with dual functionality based on 1-mm-thick lead zirconate titanate (PZT) substrate with a modified air-cavity Fresnel acoustic lens on top. Designed to let ultrasound waves focus over an annular ring region, the lens generates a long depth-of-focus Bessel-like focal beam and multiple trapping zones based on quasi-Airy beams and bottle beams. With 2.32 MHz sinusoidal driving signal at 150 V_{pp}, the transducer produces a focal zone with 9.9 mm depth-of-focus and 0.8 MPa peak pressure at a focal length of 31.33 mm. With 2.32 MHz continuous sinusoidal drive at 30–35 V_{pp}, the transducer is able to trap multiple polyethylene microspheres (350–1,000 μm in diameter and 1.025–1.130 g/cm³ in density) in water either simultaneously (when suspended by mechanical agitation or released from water surface) or sequentially (when placed one after another with a pipette). The largest particles the transducer could trap are two 1-mm-diameter microspheres stuck together (1.07 mg in weight, lifted by buoyance and 0.257 μN acoustic-field-induced force). When the transducer is moved laterally, some firmly trapped microspheres follow along the transducer's movement, while being trapped. When trapped, some microspheres can rotate due to the rotation torque generated by the quasi-Airy beams.

Keywords

Acoustic lens; focused ultrasound; Bessel beam; long depth-of-focus; acoustic trapping; acoustic tweezers; Airy beam; bottle beam; Fresnel lens; ultrasonic transducer

I. INTRODUCTION

NARROWLY focused acoustic beams with long depth-of-focus can be useful for ultrasound imaging [1] and nondestructive testing (NDT) [2], as it enhances the imaging quality with higher signal-to-noise ratio (SNR). It can also increase treatment volume in ultrasound therapeutics [3], while maintaining fine spatial resolution. To achieve this kind of focused acoustic beams, different methods have been explored. A straightforward method is to change the shape of the output wave front through modifying the surface profile of a

transducer [3], [4] or an acoustic lens attached to a flat transducer [5], [6]. However, these devices are usually macro-machined (with limited fabrication accuracy and consistency), or 3D-printed (which is time-consuming and not mass-producible). Another method is to construct thin, planar acoustic meta-surfaces consisting of multilayer periodic stacks of different materials [7] which effectively modulates the transmitted wave front. But the fabrication of these meta-surfaces is nontrivial, since layer thickness control is critical. A third approach is to encode the amplitude/phase distributions of the output waves, such as pulsing each individual elements in a phased array with different time delay and amplitude [1], [2], [8], which requires complicated control with limited acoustic intensity unless extra external power amplifiers are used.

Alternatively, without multiple transducer elements, a single-focusing planar Fresnel acoustic lens which can be mass-produced with high-precision microfabrication offers a simple and effective way of focusing ultrasound through selectively allowing in-phase acoustic waves to interfere constructively at the designed focal point [9], but with limited depth-of-focus. To extend the depth-of-focus of acoustic Fresnel lens, in this paper, we have modified the lens design to focus ultrasounds over a ring (instead of a single point), generating bending quasi-Airy beams to create a limited-diffracting, self-healing Bessel-beam-like focused ultrasound beam with long depth-of-focus.

Moreover, the same lens generates multiple bottle beams and Airy-beam-shaped “acoustical belts” for effective acoustic trapping of multiple relatively large objects (up to 2 mm in length) immersed in water, a useful technology that can be applied to contactless, label-free trapping and manipulation of microspheres [10], cells [11], organisms [10], or embryos [12] in a wide range of media regardless of their optical or electromagnetic properties.

Other types of acoustic trapping transducers (or “acoustic tweezers”) have been reported. The ones based on standing waves trap multiple objects in pressure nodal or antinodal points with good precision and controllability, but rely on acoustic reflectors [11] or additional transducers [13] (bulk-acoustic-wave-based), or have limited trapping volume [10] (surface-acoustic-wave-based). Another type of acoustic tweezers rely on hydrodynamic forces from the acoustic-field-induced streaming, and offers high throughput [14] but has limited repeatability due to the nonlinear nature of the streaming fluid. Other acoustic tweezers are based on travelling-wave trapping beams such as zeroth-order Bessel beams ([12], [15], [16]), vortex beams (with limited trapping size [17], [18]) and twin-trap beams (with weak vertical trapping force [17], [19]). In comparison, our transducer generates bottle beams with stable, fully three-dimensional trapping forces with minimal field disturbance from the trapped object, along with Airy beams with large trapping zones and the capability of rotating the trapped objects [20]. To generate acoustic bottle beams and Airy beams, transducers based on macro-machined corrugated piston transducer (for Airy beam [21]), phased arrays (for both [17] or for bottle beam [22]) and 3D-printed acoustic holographic lens (for bottle beam [23] or Airy beam [24]) have been reported, with limitations mentioned in the first paragraph of this section.

II. DEVICE DESIGN

The transducer (Fig. 1a and 1d) is built on a 1-mm-thick PZT-5A substrate sandwiched by two overlapping circular nickel electrodes. When 2.32 MHz sinusoidal signal is applied across the electrodes, the PZT will vibrate in its fundamental thickness-mode resonance and effectively generate ultrasound waves, which then pass through a modified Fresnel lens consisting of Parylene-sealed annular-ring air cavities (shiny grey circle and rings in Fig. 1d) alternating with non-air-cavity ring areas uniformly coated with Parylene (dark grey rings in Fig. 1d) on the top electrode. The air-cavity rings in the lens almost completely block acoustic waves due to the large acoustic impedance mismatch between air (0.4 kRayl) and solid (over 1 MRayl), whereas the non-air-cavity ring areas allow the waves to pass through. The radii of the ring boundaries of the Fresnel lens are chosen to make the waves arrive in-phase (with a net phase difference less than 180°) at an annular region centered on the central vertical axis with radius F_R and height F_Z . In other words, in any axisymmetric cross section of the lens (Fig. 1b), the path-length (L_n) from “focal point” (point of intersection between the focal ring and the axisymmetric cross-sectional plane) to any ring boundary is longer than F_Z by integer multiples of the half wavelength (λ) so that

$$L_n - F_Z = n \frac{\lambda}{2}, \quad n = 1, 2, \dots, \quad (1)$$

Where $L_n = \sqrt{R_n^2 + F_Z^2}$, $n = 1, 2, \dots$. Through solving (1), we can calculate the ring boundary radii as follows.

For $F_R \leq R_{inner,n} \leq 0$:

$$R_{inner,n} = F_R - \sqrt{n\lambda \times (F_Z + \frac{n\lambda}{4})}, \quad n = 1, 2, \dots; \quad (2)$$

For $R_{max} \geq R_{outer,n} \geq F_R$:

$$R_{outer,n} = F_R + \sqrt{n\lambda \times (F_Z + \frac{n\lambda}{4})}, \quad n = 1, 2, \dots. \quad (3)$$

The R_{max} is set by the transducer's aperture radius. It is worth noting that (2) and (3) are close to the radii equation for a single-focusing Fresnel lens [9], except that for the ring-focusing Fresnel lens, the ring patterns are shifted radially by F_R .

After being focused at the focal ring, the waves then propagate farther, and arrive at a narrow region along the vertical axis with constructive wave interference to create a narrow Bessel-beam-like focal zone with long depth-of-focus. This process also produces bottle beams and quasi-Airy beams where radiation force toward the inner region exists and thus, particles can be trapped (Fig. 1a).

For the ring-focusing Fresnel lens on this transducer working in water ($\lambda = 638 \mu\text{m}$ at 2.32 MHz), we choose $F_R = 8 \text{ mm}$, $F_Z = 12 \text{ mm}$ and $R_{max} = 2F_R = 16 \text{ mm}$. According to

calculation, there are eight sound-passing non-air-cavity Fresnel rings with symmetric ring widths with respect to the focal ring, with the middle two rings merged together to form a wider ring (Fig. 1c and 1d). Interestingly, in any axisymmetric cross section, the passing zones on the ring-focusing Fresnel lens (Fig. 2c) aligns well with the zero-phase zones (Fig. 2b) of a modified Airy function (Fig. 2a). This may be the reason why our modified Fresnel lens can generate Airy-like beams (which are a type of bending, nondiffracting, self-healing acoustic beams [20]–[22]), even without amplitude modification, which has been shown to be less important than phase modulation for maintaining the unique nature of Airy beams [21].

III. SIMULATION

To verify the design, simulations based on finite-element method (FEM) are carried out using COMSOL Multiphysics. The simulations are done in frequency domain at 2.32 MHz with two-dimensional (2D) axisymmetry defined to save computation time and memory.

A. Simulation of Acoustic Pressure

We first simulate the relative acoustic pressure generated by the ring-focusing transducer in water. To demonstrate how the focal zone and trapping zones are generated, we simulate the contributions of the outer (with radii larger than F_R which is 8 mm) and inner (with radii less than 8 mm) Fresnel rings. When only the outer four Fresnel rings are activated, we observe many quasi-Airy beams bending inwards radially towards the central axis, some of which arrive in phase to create a focal zone with long depth-of-focus (Fig. 3a). Similarly, when only the inner four Fresnel rings are activated, we see Airy-like beams generated, but with most beams bending outwards (Fig. 3b).

When all the Fresnel rings on the transducer are actuated, these two aforementioned effects combine (Fig. 3c). First, focused ultrasound is generated in the designed focal ring region and also in the focal zone centered at $Z = 31.33$ mm with depth-of-focus of 9.838 mm and focal diameter of $573\ \mu\text{m}$ (Fig. 3c). From the lateral beam profiles at different axial positions within the focal zone (Fig. 3d), we see Bessel-beamlike pressure distributions. For comparison, we also simulate the acoustic pressure from a single-focusing Fresnel halfwave-band transducer with similar aperture size (31.9 mm) and focal length (31.33 mm), when the vibration amplitude from the PZT surface is the same (Fig. 3e). This transducer generates a single focal zone with depth-of-focus of 5.018 mm and focal diameter of $727\ \mu\text{m}$. From these we see that the ring-focusing transducer produces depth-of-focus almost twice that of a typical Fresnel lens, with thinner beam width, albeit a lower peak pressure (by a factor of 1.73). For low-intensity applications (such as particle trapping and neural stimulation), the lower peak pressure is not a concern, and can be compensated by applying a higher driving voltage. Second, the acoustic beams interfere destructively on some parts of the central axis to create low-pressure zones, while also interfere constructively in their surrounding regions, thus generating multiple bottle beams on the central axis (Fig. 3c and 3f). By simulating the pressure amplitude and phase near a bottle beam at $Z = 14.85$ mm, we clearly see high-pressure regions surrounding low-pressure regions (Fig. 3g and 3i) with a phase singularity at the center of the beam (Fig. 3h and 3j). In a similar fashion, in the off-axis regions, Airy-

beam-shaped “acoustical belts” characterized by high-pressure beams embracing low-pressure beams are also generated (Fig. 3c and 3f). According to analysis in the next subsection, these two acoustic beams can generate acoustic radiation forces towards the beam center, which can effectively trap particles.

In the actual trapping experiments where there is acoustic reflection from the water surface (58 mm above the transducer), the acoustic pressure distribution remains similar, but the pressure amplitude (especially in acoustical belt areas) becomes higher due to half-wavelength resonances (Fig. 3k), which increase the trapping force in these areas.

The interaction between the generated acoustic field and solid objects is also studied. To demonstrate the self-healing property of the quasi-Bessel and quasi-Airy beams, we simulate the acoustic pressure distribution with the presence of two sound-blocking copper rings placed at $Z = 2$ mm and 6 mm (with ring width of 1.5 mm and thickness of 1 mm, whose inner radii are 2 mm and 12 mm, respectively, shown in Fig. 4a). Compared to the case with no obstruction (Fig. 3c), the beam pattern remains similar with less than 20% loss in peak acoustic pressure. To demonstrate the trapping beams’ ability to circumvent obstacles placed at trapping zones, we simulate another scenario where two 1-mm-diameter polyethylene (PE) microspheres are placed in the center of two bottle beams at $Z = 14.85$ mm and 24.80 mm on the central axis, and one PE ring with a square 0.7-mm-side-length cross section and inner radius of 5.35 mm is placed in an Airy acoustical belt region at $Z = 21.95$ mm. The simulated pressure pattern with the obstacles (Fig. 4b) is similar to that for a case with no obstacles (Fig. 3c). Thus, with multiple self-healing and obstacle-circumventing bottle beams and acoustical belts, the transducer is capable of trapping multiple objects simultaneously.

B. Simulation of Acoustic Radiation Force (ARF)

To demonstrate how these acoustic beams can trap particles, we first simulate the acoustic radiation force (ARF) acting on a 70- μ m-diameter PE microsphere (with density of 1.130 g/cm³ and acoustic velocity of 2460 m/s) immersed in water (with reflection from the water surface 58 mm above the transducer), with acoustic pressure values in Fig. 3k normalized (based on measurement data in Fig. 6, with 35 V_{pp} applied on transducer) to have a peak pressure of 0.226 MPa. The acoustic radiation potential is calculated from the simulated acoustic pressure and velocity fields along with the medium and particle properties, and then the ARF is calculated by taking the negative spatial derivatives of the radiation potential (as indicated by Eqs. 27 in [25]). From the simulation results, we clearly see ARF pointing from high-potential (also high-pressure) shells of bottle beams at $Z = 21.2$ mm (Fig. 5a) and 25.3 mm (Fig. 5b), towards their center low-potential (low-pressure) regions. Similarly, in Airy-shaped acoustical belt regions (Fig. 5c), ARF points towards large low-potential zones, and in some regions, forms a vortex pattern which is capable of rotating the trapped object.

For a large microsphere whose diameter is comparable to or larger than the wavelength, ARF needs to be calculated through integrating the second-order momentum fluxes generated by the first-order pressure and velocity fields over the microsphere surface [26]. Using Equations 3–5 in [26], we simulate the vertical ARF exerted on a 1-mm-diameter PE microsphere with density of 1.025 g/cm³ centered on different positions of the vertical axis,

with 35 V_{pp} applied to the transducer. The simulated vertical ARF ranges from 8.7 nN to 2.2 μ N (Fig. 5d). To lift the microspheres, the gravitational force (-5.26μ N) and buoyant force (5.13μ N) need to be balanced, requiring a vertical ARF of 0.13μ N. In Fig. 5d, we identify six positions with such ARF and with a negative spatial force gradient (so that the force is restoring) as potential stable trapping positions.

Comparing the vertical ARF with the pressure amplitude along the central axis, we notice that the vertical ARF is almost proportional to the pressure amplitude (Fig. 5d), and the ARF needed for lifting the microspheres corresponds to the pressure amplitude of 0.03–0.06 MPa. By visualizing only the regions where the pressure amplitude is larger than 0.045 MPa (Fig. 5e), we find many potential trapping positions, most of which in off-axis regions are due to the increased pressure amplitude resulted from the acoustic reflection from the water surface 58 mm above the transducer (Fig. 3k). With reduced reflection from the water surface, the number of the trapping zones will be lower.

IV. EXPERIMENTAL RESULTS

A. Measurement of Acoustic Pressure

The transducer is microfabricated according to steps described in [9]. After fabrication, we measure the acoustic pressure by mechanically scanning a hydrophone (HGL-0085, Onda Corp.) aligned to the center of the transducer along its central vertical axis. Immersed in water, the transducer is driven at 150 V_{pp} with 2.32 MHz sinusoidal pulsed signals, and the measured peak pressure is 0.8 MPa with depth-of-focus of 9.9 mm (15.5λ), in agreement with the simulation (Fig. 6). The minor difference between simulation and measurement is likely due to the slight misalignment between the scanning axis of the hydrophone and the transducer's central axis.

B. Trapping of Polyethylene (PE) Microspheres

As shown in Fig. 7a, the transducer (facing up) is immersed in water in a glass beaker (150 mm in diameter to eliminate reflection from the sidewalls) that is placed on a laser-machined acrylic holder attached to a precision 5-axis manually-movable stage. The PE microspheres are pre-wet in 0.1% Tween-80 solution (a surfactant to overcome their hydrophobicity, purchased from sigma-Aldrich, Inc.) and then slowly released into water from a glass pipette (Fig. 7b) attached to a precision manual syringe pump (VWR International, LLC.). Unless specified otherwise, the microspheres have diameter of 1 mm with density of 1.025 g/cm^3 . During trapping experiments, a function generator (AFG3252, Tektronix, Inc.) generates 2.32 MHz continuous sinusoidal signal, which gets amplified by a power amplifier (75A250, Amplifier Research Corp.) and delivered to the transducer.

We have successfully trapped multiple microspheres in two ways. First, with 35 V_{pp} applied on the transducer, we put microspheres in different trapping zones by picking and releasing them with a pipette in sequence (one microsphere at a time), as shown in Fig. 7b. With the self-healing property of the acoustic trapping beams and strong trapping force, the disturbance during and after the pick-and-release procedure does not affect the trapping efficiency of the previously trapped microspheres. Comparing the third and fourth photo in

Fig. 7b, we see that while falling down, microsphere #2 is pushed laterally towards the center and then get trapped there. second, as shown in Fig. 7c, we release six microspheres into water simultaneously, and five of them get firmly trapped as they fall down due to gravity, when the transducer is driven with $30 V_{pp}$. Two of the five trapped microspheres (1.07 mg in weight) stick together throughout the whole process, lifted by buoyance and a vertical lifting force of $0.257 \mu\text{N}$ from the transducer.

Sometimes, when trapped in the acoustical belts, particles (especially of odd shapes) are found rotating. For example, with $30 V_{pp}$ applied on the transducer, two 1-mm-diameter microspheres glued together are trapped while rotating around the same position at an angular speed of $8.57^\circ/\text{ms}$ (Fig. 7d).

While one microsphere is firmly trapped, we move the transducer (driven with $30 V_{pp}$) at an average speed of $60 \mu\text{m/s}$ for 2.5 mm (Fig. 8a). The trapped microsphere closely follows the transducer's lateral movement throughout the process. However, when we move the transducer vertically by merely tens of micrometers at about the same speed, the trapped microsphere follows the transducer's movement a little, and then falls off the trapping zones. This suggests that in some trapping regions (especially the off-axis regions), the variation in vertical ARF is larger than the lateral one.

In another set of experiments, we first let the microspheres fall on the transducer surface; while the transducer is being actuated ($30 V_{pp}$), we blow with water flow from a pipette to get the microspheres to float above the transducer and move around fast; and then we stop the blow to observe the trapping of microspheres. In this way, we successfully trap many $350\text{-}\mu\text{m}$ -diameter PE microspheres with density of 1.13 g/cm^3 (Fig. 8b) and six 1-mm-diameter PE microspheres (Fig. 8c), despite the initially large fluid disturbance and fast particle movement.

V. SUMMARY

We have designed and microfabricated a novel transducer based on a ring-focusing air-cavity Fresnel acoustic lens, and successfully demonstrated its ability to generate a Bessel-beam-like focal zone with a long focal depth of 9.9 mm which is 15.5 times the wavelength at 2.32 MHz. Furthermore, with the same transducer, we present a brand new way of generating bottle beams and Airy-like “acoustical belts” which firmly trap multiple large (0.35–1.00 mm in diameter) polyethylene microspheres with density larger than that of water, with the capability of rotating the trapped particle. To our knowledge, it is the first demonstration of generating such beams with a single-element, microfabricated acoustic lens.

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Biographies

Yongkui Tang (STM'19) received the B.S. degree from Peking University, Beijing, China in 2014, and the M.S. degree from University of Southern California (USC), Los Angeles, CA, USA in 2016, both in electrical engineering. He is currently a Ph.D. candidate in electrical engineering at USC.

His research mainly focuses on MEMS (microelectromechanical systems), microfabrication, and piezoelectric ultrasonic transducers (especially on self-focusing acoustic transducers (SFATs) and acoustic tweezers).

Eun Sok Kim (M'91–SM'01–F'11) received the B.S., M.S., and Ph.D. degrees in electrical engineering from the University of California at Berkeley, CA, USA, in 1982, 1987, and 1990, respectively.

He was with the IBM Research Laboratory, San Jose, CA, USA, NCR Corporation, San Diego, CA, USA, and Xicor Inc., Milpitas, CA, USA, as a Co-Op Student, Design Engineer, and Summer-Student Engineer, respectively. From Spring 1991 to Fall 1999, he was with the Department of Electrical Engineering, University of Hawaii at Manoa, as a Faculty Member. He joined the University of Southern California (USC) at Los Angeles, in Fall 1999, where he is currently a Professor of the Ming Hsieh Department of Electrical and Computer Engineering. From July 1, 2009 to June 30, 2018, he chaired the Electrophysics division of the department, and oversaw a net tenure-track-faculty growth of 2.5 (from 15.25 to 17.75), 6.5 new tenure-track-faculty hires, 3 new tenure-track-faculty offers and acceptances in the last year as the chair. During his tenure as the chair, US News' ranking raw score on USC EE's Graduate Program rose from 3.9 to 4.2 (out of 5.0).

He is an expert in piezoelectric and acoustic MEMS as well as electromagnetic vibration-energy harvesters (VEHs), having published about 250-refereed papers in the fields. He holds 16 issued US patents in piezoelectric and acoustic MEMS as well as in VEHs.

Dr. Kim is a Fellow of the Institute of Physics. He has received the Research Initiation Award (1991–1993) and the Faculty Early Career Development Award (1995–1999) from the National Science Foundation. He has also received the Outstanding Electrical Engineering Faculty of the Year Award from the University of Hawaii at Manoa in 1996 and the IEEE TRANSACTIONS ON AUTOMATION SCIENCE AND ENGINEERING 2006 Best New

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Fig. 1.

(a) Cross-sectional schematic (across A-A' in (c)) of the transducer, illustrating how the ring-focusing air-cavity Fresnel lens is designed to generate long depth-of-focus focal zone and many trapping zones. (b) Axisymmetric cross-sectional schematic (across A-O in (c)) of the transducer, showing how ring radii are calculated. Top-view diagram (c) and photo (d) of the 2.32-MHz transducer on PZT (brown in (d)) designed for a focal ring with $F_R = 8$ mm (red dashed circle in (c)) and $F_z = 12$ mm, showing sound-blocking air cavities (black in (b) and (c), shiny grey in (d)) and sound-passing non-air-cavity rings (white in (b) and (c), dark grey in (d)).

Fig. 2.

The amplitude (a) and phase (b) of a modified Airy function versus lateral distance. (c) The transmission function of the ring-focusing Fresnel lens, which closely resembles the Airy phase pattern shown in (b).

Fig. 3.

Simulated acoustic pressure amplitude in XZ plane for the ring-focusing transducer (a) with outer four Fresnel rings actuated to create inwards-bending Airy-like beams; (b) with inner four Fresnel rings actuated to create outwards-bending Airy-like beams; (c) with all rings actuated. (d) Bessel-beam-like radial pressure amplitude distributions (red) within the focal zone at $Z = 29.3$ mm (upper) and $Z = 34.2$ mm (lower) compared with scaled Bessel functions of the first kind (black). (e) Simulated acoustic pressure amplitude in XZ plane for a normal Fresnel lens with similar focal length and aperture size. (f) Relative pressure isosurfaces of 0.15 showing multiple bottle beams on the central axis and many “acoustical belts” in off-axis areas; (g)-(j) Acoustic pressure amplitude (in XZ plane (g) and in XY plane (i)) and phase (in XZ plane (h) and in XY plane (j)) distribution for a bottle beam located at $Z = 14.85$ mm on the central axis (highlighted in (f)). (k) Simulated acoustic pressure amplitude in XZ plane for the ring-focusing transducer during trapping experiments with acoustic reflection from water surface (58.0 mm above the transducer surface). The pressure values in all figures are normalized to the values in (c).

Fig. 4. Simulated acoustic pressure amplitude (without reflection, normalized to the values in Fig. 3c) in XZ plane for the ring-focusing transducer (a) with two copper rings blocking some acoustic waves; (b) with two PE microspheres and one PE ring in potential trapping regions (axes rescaled to maintain circular (and square) cross sections of the objects).

Fig. 5.

Simulated acoustic radiation potential (colorbar unit: 10^{-14} Joules) and acoustic radiation force (ARF, white arrows) for 70- μm -diameter PE microspheres, showing fully three-dimensional trapping forces towards the center of bottle beams at $Z = 21.2$ mm (a) and 25.3 mm (b). (c) Same plot for off-axis Airy-shaped acoustical belt regions, showing ARF for particle trapping and rotation (with arrow length logarithmically normalized). (d) Simulated vertical ARF exerted on a 1-mm-diameter PE microsphere centered at different positions of the central axis (red) and the pressure amplitude (black), along with the required vertical lifting force (blue dashed line) and potential stable trapping positions (blue circles). (e) Simulated acoustic pressure amplitude showing regions with pressure amplitude higher than 0.045 MPa for potential trapping capability (colorbar unit: MPa). In all figures, the acoustic pressure distribution is normalized from Fig. 3k with a peak pressure of 0.226 MPa, which corresponds to the case where $35 V_{pp}$ is applied on the transducer (according to measurement data in Fig. 6).

Fig. 6. Measurement (red, with 150 V_{pp} applied on the transducer) and normalized simulation (black) of acoustic pressure along the central axis.

Fig. 7.

(a) Photo of the experimental set-up for all the trapping experiments. Side-view photos showing (b) trapping of three 1-mm-diameter PE microspheres (1.025 g/cm³ density) through picking and releasing them one by one into water with a pipette; (c) trapping process of five out of six 1-mm-diameter PE microspheres released at the same time from water surface, including two sticking with each other; (d) two 1-mm-diameter PE microspheres (glued together) rotating clockwise while being trapped. The transducer is driven with continuous sinusoidal signals of 35 V_{pp} in (b) and 30 V_{pp} in (c) and (d).

Fig. 8.

Side-view photos showing (a) positions of a trapped 1-mm-diameter microsphere (1.025 g/cm^3 density) before and after the transducer is moved to the right for 2.5 mm at an average speed of $60 \text{ } \mu\text{m/s}$. The microsphere (green dash line) remains trapped while following transducers' movement (marked by the left edge of the acrylic holder below it, red dash line). Side-view photos showing (b) trapping process of multiple $350\text{-}\mu\text{m}$ -diameter PE microspheres (1.13 g/cm^3 density) after blowing with a pipette to make them float above transducer surface; (c) trapping of six 1-mm-diameter PE microspheres using the same technique as in (b). The transducer is driven with continuous sinusoidal signals of 30 V_{pp} in all figures.