UNDERWATER ACOUSTIC TWEEZERS CAPABLE OF TRAPPING LARGE AND HEAVY PARTICLES

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ABSTRACT

This paper describes acoustic tweezers capable of trapping large and heavy objects with 523.8 kHz sound waves. The tweezers are fabricated on a 4-mm-thick Lead Zirconate Titanate (PZT) substrate with a Fresnel air-cavity lens placed on its top surface. The fabricated tweezers are operated with continuous or pulsed 523.8 kHz sinusoidal waves, and offer multiple simultaneous trapping zones (up to 40), long range trapping (3-164 mm away from the tweezers), and trapping of large (up to 5mm in diameter) and heavy (up to 5.75 g/cm^3 in density) particles or microspheres. In addition to trapping, electrical control of the vertical position of the trapped particle has been achieved with the tweezers placed horizontally.

KEYWORDS

Acoustic tweezers, acoustic transducer, focused ultrasound, Fresnel lens, air cavity lens, particle trapping, multiple focal points.

INTRODUCTION

Contactless and heatless trapping of microparticles is highly desirable in manipulating particles that are prone to damage by physical contact or heat. Contactless trapping and manipulation of a particle has been achieved with optical tweezers [1], magnetic tweezers [2], etc. However, optical tweezers are not capable of trapping large and heavy objects without generating large amount of heat, and also do not work well where the medium is optically opaque, while magnetic tweezers require a magnetic label, unless the particle is magnetic. Acoustic tweezers, on the other hand, are able to trap large and heavy objects since acoustic waves are mechanical waves that are inherently capable of delivering deep trapping well. Moreover, acoustic tweezers can trap all kinds of particles in all kinds of medium, without generating substantial heat.

In this paper, we demonstrate an acoustic tweezers capable of trapping heavier and larger objects at a record level compared to previous reports over a large volume with multiple simultaneous trappings.

DESIGN

The acoustic tweezers are built on a 4-mm-thick PZT substrate (that has the fundamental thickness resonance at 523.8 kHz, much lower than our previous acoustic tweezers for trapping large and heavy particles) with electrodes on its top and bottom faces patterned into circles so that a voltage applied to the top and bottom electrodes may produce acoustic waves, most effectively at the fundamental resonance frequency. Polydimethylsiloxane (PDMS) film patterned with four Fresnel annular rings (to form Fresnel air cavity rings or lens) is bonded on to the top electrode. The radii of the annular rings R_n are designed into Fresnel half-wavelength bands (FHWB) [3], with annular rings sectored into 18 pie sectors (each occupying a 20^o pie shaped when viewed from the top, as shown at the upper row of Fig. 1, for three different focal lengths with each set of 6 sectors targeting a focal length), according to

$$R_n = \sqrt{n\lambda \times (F_n + \frac{n\lambda}{4})} \quad (1)$$

where λ is the wavelength of acoustic wave in water at 523.8 kHz, while F_n is the focal length associated to the nth circle [4-5]. As illustrated in the lower row of Fig. 1, the air cavities in the PDMS membrane block the acoustic waves that will destructively interfere at the desired focal lengths, due to acoustic impedance mismatch between air (0.4 kRayl) and liquid/solid (more than 1 MRayl). The eighteen symmetric sectors consist of three sets of six sectored Fresnel rings designed for three focal lengths of 9, 10.75, 12.5 mm within which trapping zone is developed due to the interference of the three focused acoustic beams (Fig. 1).

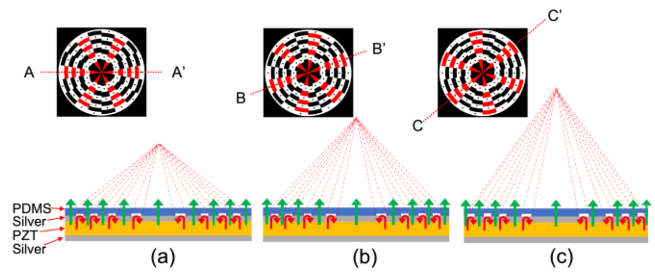

Fig. 1: (a)-(c) top views and cross-sectional views (across A-A', B-B' and C-C') of the acoustic tweezers with three sets of 6 sectors on the top view with the associated focal points in the cross-sectional views. By actuating all the three sets at the same time, a trapping zone is formed within the three focal points.

FABRICATION

The acoustic tweezers are fabricated through the steps illustrated in Fig. 2. To fabricate the air-cavity lens on PDMS membrane, 40 µm thick SU-8 is coated on a 4" x 4" glass substrate and patterned into annular rings (Fig. 2a), which will be air cavity rings in the PDMS membrane. In order to avoid collapse of the PDMS membrane in the air cavity rings, 300-µm-diameter circular holes are added in the SU-8 annular rings, so that those may later be filled with PDMS to function as mechanical support pillars. After treating the SU-8 mold with silane to make it hydrophobic for easy peel-off of PDMS membrane from the SU-8 mold later, PDMS solution is poured onto the glass substrate with SU-8 mold, which then is placed in a mechanical jig with a clamping mechanism (which sandwiches the poured PDMS on the glass substrate containing the SU-8 mold with another glass substrate that is fixed in the mechanical jig, as the distance between the two glasses is controlled by a micromanipulator) for thickness control of the PDMS layer (Fig. 2b). After reaching the desired PDMS thickness (200 µm), the PDMS is heat cured in oven for four hours, followed by peeling off from the mold and trimming to the desired size.

On a 4-mm-thick PZT substrate with pre-deposited 10-µm-thick silver layer on its top and bottom sides, the electrodes are patterned into circles (Fig. 2c). A 10-µm-thick SU-8 layer is then spin-coated on the top surface of the PZT (the surface on top of which PDMS membrane as Fresnel lens will be placed), followed by soft-bake, blank exposure with UV-light, and post exposure-bake (Fig. 2d). The fully cured SU-8 layer provides enough stiction and adhesion for the PDMS membrane (detached from the glass substrate after Fig. 2b) and allows a stable placing of the membrane onto the PZT. The PDMS membrane is then aligned and placed on

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the PZT surface where there is SU-8 adhesion layer (Fig. 2e). After soldering wires on the top and bottom electrodes, we conformally deposit 20-µm-thick Parylene layer for electrical insulation (Fig. 2f). Top-view photo of the fabricated tweezers along with the mask pattern for SU-8 mold and the cross-sectional view of the fabricated tweezers are shown in Fig. 3.

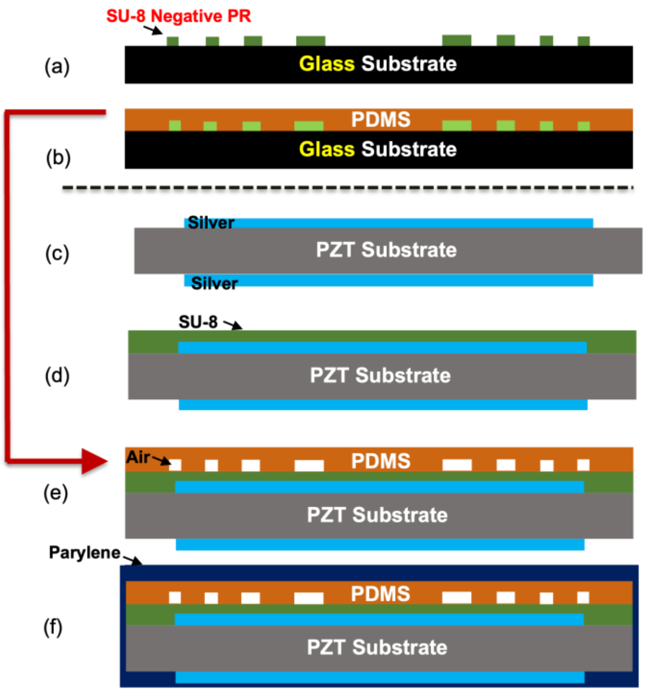


Fig. 2: Brief fabrication steps: (a) pattern SU-8 mold of annular rings on a glass substrate, (b) cast PDMS mix on the SU-8 mold, followed by heat curing and trimming, (c) pattern top and bottom electrodes on a 4 mm thick PZT, (d) spin-coat SU-8 adhesion layer over the PZT, (e) detach the PDMS membrane from the glass substrate, align and place the PDMS membrane on the PZT, and (f) deposit Parylene for electrical insulation.

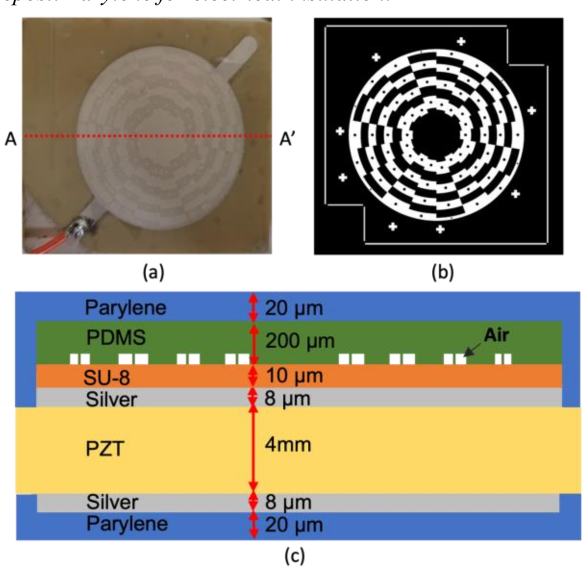


Fig. 3: (a) Top-view photo of the fabricated tweezers, (b) the mask pattern for air-cavity lens, and (c) the cross-sectional view (across A-A') with 300-µm-wide vertical lines in air cavity regions being the support pillars to prevent collapse of the PDMS membrane.

EXPERIMENTAL RESULTS

All the experiments with the fabricated tweezers are done in water with various particles and microspheres in a beaker with the acoustic tweezers placed horizontally or vertically. The tweezers are driven by a continuous sinusoidal wave of 523.8 kHz (equal to fundamental resonance frequency of the PZT substrate in thickness-mode) via a power amplifier capable of delivering the voltage and power, as illustrated in Fig. 7.

Horizontal Placement

With the tweezers placed horizontally, we have obtained trapping of a 4.2 mg Tin particle with density of 5.75 g/cm^3 and diameter of 1.12 mm, a polystyrene polymer sphere with diameter of 2.96 mm and density of 1.05 g/cm^3 (14.2 mg), and a 5 mm in diameter polystyrene polymer sphere (Fig. 4). A list of the trapped particles along with their densities and diameters as well as the minimum peak-to-peak applied voltage for trapping is shown in Table 1.

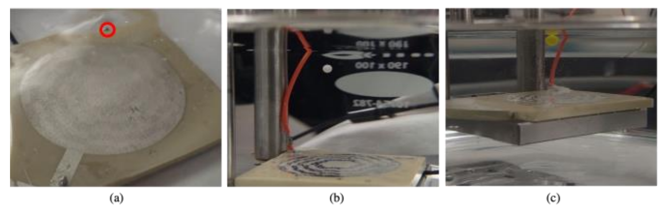
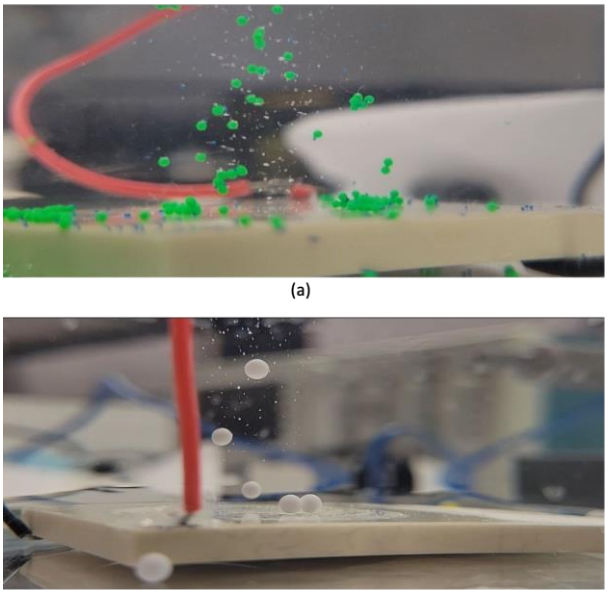


Fig. 4: Photos of trapping (a) a 4.2 mg Tin particle (1.5 mm in its longest direction) with the weight corresponding to a 1.12 mm in diameter, if it was spherical, (b) a white microsphere with diameter of 2.96 mm and density of 1.05 g/cm^3, and (c) a yellow microsphere with diameter of 5 mm and density of 1.03 g/cm^3 when the tweezers is placed horizontally.

Table 1: Various microspheres trapped with the tweezers being driven with a continuous 523.8 kHz sinusoidal wave.

Diameter (mm)	Density (g/cm^3)	Applied Peak-to-Peak Voltage for Trapping (Volts)
0.35	1.13	9.00
0.60	5.75	33.3
0.65	1.10	10.0
0.92	5.75	33.3
1.00	1.03	10.8
1.12	5.75	34.2
2.96	1.05	12.6
5.00	1.03	24.3

In addition to trapping large and heavy particles, simultaneous trapping of multiple microspheres is present (Fig. 5), mainly due to relatively low acoustic-wave loss in water at such a relatively low frequency of 523.8 kHz, leading to more pronounced impacts of wave reflections from water-air and water-beaker interfaces (resulting in more trapping points) than a similarly constructed tweezers operating beyond 1 – 2 MHz [6]. The number of the trapped microspheres is larger for smaller and lighter microspheres. In case of the microspheres with 1 mm in diameter and 1.03 g/cm^3 density, simultaneous trapping of up to 40 microspheres is observed, while only about three 2.97-mm-diameter microspheres of 1.05 g/cm^3 density are trapped simultaneously.



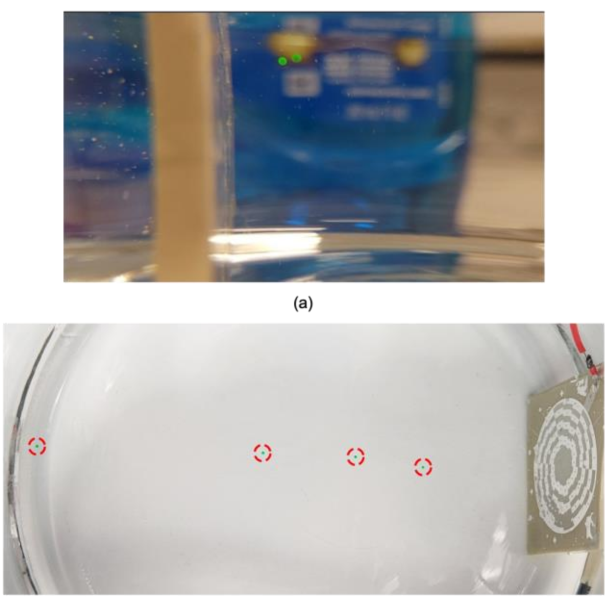
(a)

(b)

Fig. 5: Photos of trapping (a) multiple microspheres with 1.03 g/cm^3 density and 1 mm in diameter and (b) three 2.97-mm-diameter microspheres of 1.05 g/cm^3 density at three different vertical locations.

Vertical Placement

Vertical placement of the tweezers also produces particle trapping, albeit less number of simultaneous trappings and smaller trapped-particle diameter and density (Fig. 6). In one instance, four 1-mm-diameter microspheres of 1.03 g/cm^3 density are simultaneously trapped over 42 – 164 mm from the tweezers placed vertically (Fig. 6b).



(a)

(b)

Fig. 6: Photos of (a) trapping two 1-mm-diameter microspheres of 1.03 g/cm^3 density with the tweezers placed vertically at a distance of about 7mm from the tweezers, and (b) trapping of same microspheres at different horizontal distances (42 – 164 mm) from the tweezers.

Manipulation of Trapped Particle

With a particle (or particles) trapped by a tweezers, the tweezers is moved in a set up shown in Fig. 7, in order to investigate whether and how well the trapped particle(s) follows the tweezers movement. In all our previous acoustic tweezers, the trapped particles followed the movement of the tweezers very reliably and repeatably [7].

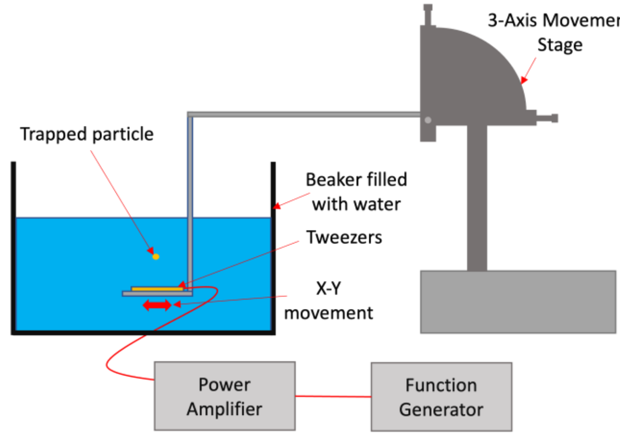


Fig. 7: Experimental setup to move the tweezers in 3-dimentional space, while particles are trapped by the tweezers, with the water-containing beaker remaining stationary.

However, with the tweezers operating at 523.8 kHz, we observe that the trapped particle remains stationary with respect to the beaker and does not follow the tweezers movement. Such behavior can be explained by noting that wave attenuation is relatively small at 523.8 kHz, compared to several MHz, and therefore the effects of the reflected waves from liquid-solid and liquid-air interfaces are quite pronounced, resulting in multiple trapping zones closely placed to each other with each zone having a relatively small energy well. In one experiment, the trapped particle remains stationary with respect to the beaker, even when the tweezers is moved 23 mm in one direction. (Fig. 8)

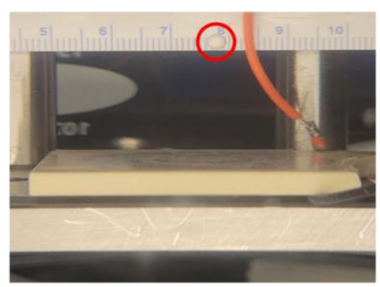


Fig. 8: Photo of a trapped particle remaining stationary, as the stage that holds the tweezers is moved slowly over tens of mm via a 3-axis movement stage.

Electrical Control of Vertical Position of Trapped Particle

We have explored electrical control on the vertical position of the trapped particle with respect to the tweezers placed horizontally, using applied voltage vs time as illustrated in Fig. 9. The idea is to trap a particle with a high voltage (V_H), release the trapped particle by reducing the applied voltage to a low value (V_L) for a brief period (P_w), so that the released particle may fall down due to gravity during P_w, and then increase the voltage back to V_H to trap the particle again, this time at a lower vertical location after the particle having fallen a distance mainly determined by P_w. By trapping a particle and then letting the particle fall followed by trapping it again, a particle can be trapped at various vertical positions, the spacing of which is mainly determined by the duration of low applied voltage (P_w), as shown in Fig. 10. The trajectory of the particle during the falling period P_w is almost vertical, as gravity plays the main role to pull it down, when the particle is initially trapped within a radius of 1 cm from the center of the tweezers and the maximum vertical distance of the trapped particle from the tweezers is 7 cm. For electrical control over the vertical distance beyond 7 cm from the tweezers, the high and low voltage levels need to be modified, since the radius of the trapping region is narrower. In case of trapping a 1-mm-diameter microsphere with 1.03 g/cm^3 density over a vertical distance of 21.5 – 15 cm, the needed V_H and V_L are 22.5 and 13.5 V_{p-p}, respectively, while for vertical distances below 15 cm, the V_H and V_L are 13.5 and 4.5 V_{p-p}, respectively.

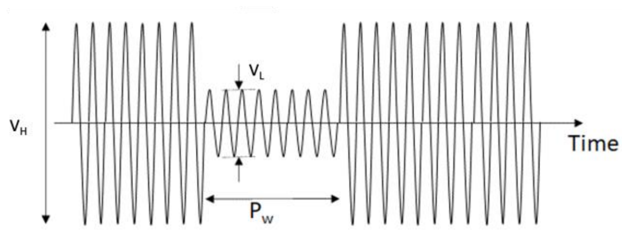


Fig. 9: Applied voltage vs time for electrical control of the vertical position of the trapped particle with the tweezers; particle trapped with a high applied voltage (V_H), particle released with a low applied voltage (V_L) for a brief period P_w during which the particle falls due to gravity, and then particle trapped again with a high voltage at a lower location after falling a short distance.

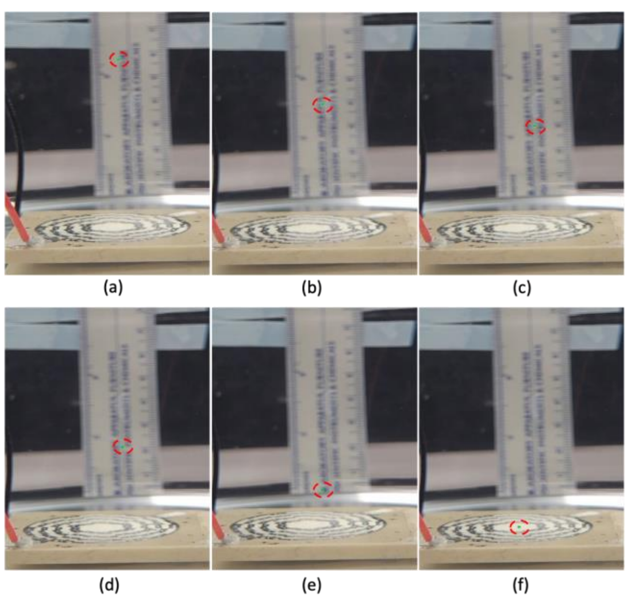


Fig. 10: Photos showing electrical control of the position of a trapped particle along the vertical direction: (a) a trapped particle with 14.4 V_{p-p} (523.8 kHz) applied to the tweezers, (b) the particle trapped at a lower position by decreasing the applied voltage to 5.4 V_{p-p} for ≈ 0.3 sec and increasing it back to 14.4 V_{p-p}, and (c) – (e) the particle trapped at lower positions by repeating the pulsed operation with the duration of the lower applied voltage determining the amount of the distance between two adjacent trapped positions.

DISCUSSION

The acoustic tweezers operating at 523.8 kHz can trap large and heavy particles, many of them simultaneously due to low acoustic loss in the medium (owing to the relatively low frequency) making reflections from liquid-air and liquid-solid interfaces not easily dying out. However, the trapped particle remains stationary, as we move the tweezers, apparently being trapped in different trapping zones. This phenomenon will likely be alleviated or modified with reduced trapping zones, which, though, comes at the cost of reduced effectiveness in trapping large and heavy particles, unless acoustic absorbers are incorporated on the liquid-air and liquid-solid interfaces.

CONCLUSION

The acoustic tweezers presented in this paper offer capability in trapping large and heavy solid particles in liquid medium without damaging the particles due to physical contact or heat. Though the movement of the trapped particle by moving the tweezers does not happen in the current operating mode, electrical control over the vertical position of the trapped particle has been shown to be easily achievable. Other electrical controllability of the trapped particle whether it is rotation or linear translation is likely to be possible, through modification on the tweezers design and applied voltage level and timing.

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