Program Digest, 2019 IEEE International Ultrasonics Symposium (IUS)
Glasgow, Scotland, October 6-9, 2019

Acoustic Tweezers with Electrical Controllability on Rotation of Trapped Particle

Lurui Zhao* and Eun Sok Kim
Ming Hsieh Department of Electrical Engineering
University of Southern California
Los Angeles, CA 90089-0271
luruizha@usc.edu

***Abstract*—This paper describes an electrically controllable acoustic tweezers capable of holding and rotating mm-sized particles through varying the frequency of the electrical voltage applied to the tweezers. The tweezers is composed of a pair of vertically placed acoustic tweezers, in parallel and center aligned, so that the trapping zone of each of the tweezers set overlaps with each other's. Each single transducer is built on a 2.03 mm thick lead zirconate titanate (PZT) substrate with 18 symmetric beamforming sectors (pie shaped when viewed from top) arranged for 3 focal lengths (17.0, 18.5 and 20.0 mm) defined by air-cavity acoustic lens. Acoustic waves generated from the pair of the two tweezers produce Bessel beam zone with acoustic energy well, where a particle gets trapped and held. Once a particle is captured, rotational manipulation is achieved by fine tuning the tweezers' driving frequency, which impacts the trapping zone quite slightly, enabling gravity to provide an asymmetric force that rotates the trapped particle. Our experiments show that a trapping of mm-sized particle is achieved at 1.17 MHz driving frequency for both transducers, and tuning of the frequency by about 100 Hz generates rotation of the trapped particle. The on-demand rotational manipulation is shown to be effective in rotating mm-size polyethylene particles and 24 - 36 hours-post-fertilization zebrafish embryos that are 1.3 - 1.5 mg in weight.**

Keywords*—acoustic tweezers, electrical controllable, rotation, particle manipulation

I. Introduction

Optical tweezers has been a successful tool in scientific instruments over decades, as it offers trapping and tweezing of microparticles without any physical contact by using highly focused laser beams. However, the manipulating force from optical tweezers is on the order of piconewtons and typically only capable of handling particles in micron-size. To handle heavy and/or large particles using optical tweezers usually requires raising the laser intensity, which consequently brings heat effect that possibly damages temperature-sensitive particles such as living cells. To extend the contactless tweezering capability and provide less limitation on heavy particle handling, acoustic tweezers has been developed. Recently reported acoustic tweezers [1-3] is capable of handling heavy and large particles up to the order of mm in size, since it relies on mechanical, instead of optical, waves that carries substantial amount of mechanical pressure or force.

Our previously reported acoustic tweezers [1] had shown to be effective in trapping polyethylene microspheres up to 1 mm in diameter (1.0g/cc in density), as well as late-term zebrafish embryos (24 - 36 hours after fertilization), in both horizontal and vertical operations of the acoustic tweezers [4]. The capturing and holding of a late stage zebrafish embryo (1 mm in diameter and 1.3 - 1.5 mg in weight,) has demonstrated the effectiveness of the acoustic tweezers in handling non-spherical, non-homogeneous living cells in biomedical application.

Electrically controllable manipulation of the particles or cells trapped by the acoustic tweezers is highly desirable in many applications. For example, rotational control is one of the powerful functions that will benefit researchers in cell imaging and/or real-time observation, as it allows the researcher to orient the trapped particle in any desired way.

This paper describes an on-demand rotation control with our recent acoustic tweezers (capable of holding heavy and large particles such as mm-size polyethylene particles and zebrafish embryos at their 24 – 36 hours-post-fertilization) obtained by setting a pair of the tweezers to face each other and fine-tuning the driving frequency (1.07 MHz) by about 100 Hz.

II. Design and Simulations

The tweezers consists of two identical acoustic transducers. The single transducer is designed to deliver multiple focal points along the center line and thus create Bessel beam zone where the energy well develops. The radially-inward radiation force around the zone surrounding the multiple focal points lowers the acoustic potential energy in the zone. Consequently, when a moving particle passes by the zone, it gets trapped if the kinetic energy of the particle is smaller than the depth of the potential energy well.

A. Design of Single Acoustic Transducer

A single acoustic tweezers with multiple focal points is made with Fresnel-zone-plate air-cavity lens over a 2.03 mm thick lead zirconate titanate (PZT) substrate (sandwiched by a pair of patterned electrodes to produce acoustic waves through thickness-mode vibration, most powerfully at 1.07 MHz). Air cavities are used to form the Fresnel lens, since the large acoustic impedance mismatch between air and liquid produces excellent reflection, and consequently, no waves propagate through the regions that are covered by air cavities [5]. Fresnel zone plate is typically consisted of annular rings, as a set of full-ring Fresnel-zone-plate air-cavity lens allows passing of only the acoustic waves that will result in constructive wave interference at a focal point [6]. The focal point of a Fresnel zone-plate is along the line perpendicular to the center of the annular ring (Fig. 1).

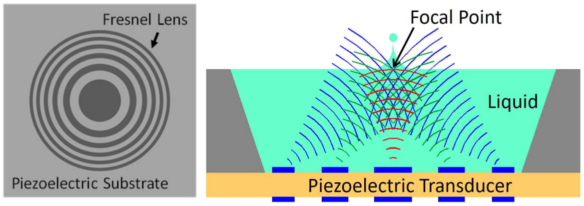

Fig. 1. Full ring Fresnel lens transducer: (Left) Top view of full-ring Fresnel half-wave-band electrodes (dark rings) on piezoelectric substrate (light square) and (Right) Cross-sectional view showing how focusing effect occurs. Acoustic waves from the rings of the patterned electrodes interfere constructively at a focal point leading to an intensified acoustic pressure.

To create multiple focal points along the same central line, annular rings of Fresnel air cavities are sectored into pie shapes with the different sectors designed for different focal lengths (Fig. 2). To preserve the symmetry of the acoustic field, the full ring is sectored and distributed evenly throughout 360º. For 3 focal points, each focal length is covered by the sectors occupying a total of 120º. For this design, 6 sectors with each sector occupying 20º are used for a focal length, and three sets of such sectors are used for 17.0, 18.5 and 20.0mm focal lengths.

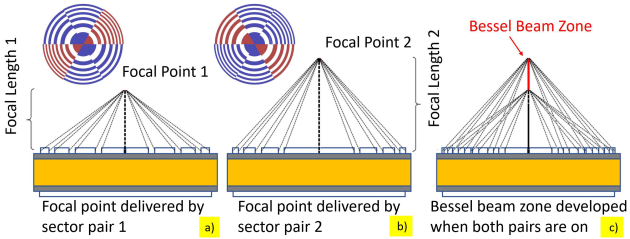

Fig. 2. Top and cross-sectional schematics demonstrating the generation of multi focal points from sectored Fresnel lens (for three different focal lengths): a) and b) when one pair of the sectored Fresnel is actuated; c) when two such pairs are actuated at the same time. Multi focal points and Bessel beam zone are developed due to the interference of the two (or more) focused acoustic beams.

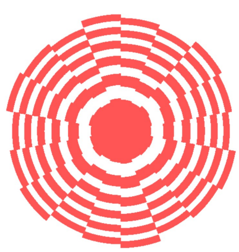

Fig. 3. Pattern of the active ultrasoice source after filtered by Fresnel lens. A total 18 sectors are arranged in 3 sets of 6 pi-shaped sectore: one set of sectored Fresnel lens covers a total of 120º, as each sector occupies 20º angular space. Three sets featuring at 17.0, 18.5 and 20.0 mm focal lengths seperately.

FEM simulation has been carried out with COMSOL to study the pressure distribution in the medium. As shown in Fig. 4, a major high pressured region is developed along the central vertical line near the designed 3 focal points at 17.0, 18.5 and 20.0 mm. Satellite high pressure zones around the major focal zone provide acoustic potential barriers to get particles trapped in the less pressured region.

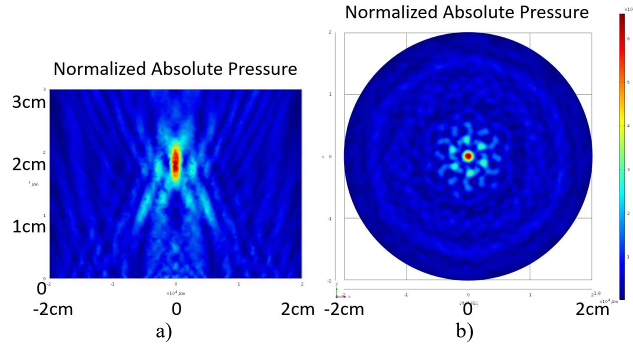

Fig. 4. Simulated normalized absolute pressure proudced by a single transducer shown in Fig. 3. a) on cross-sectional plane along the central verticl line (with the transducer placed at the bottom) and b) on the focal plane at 18.0 mm.

B. Design of the Acoustic Tweezers

A pair of two acoustic transducers (based on the sectored air-cavity Fresnel lens shown in Fig. 3, and fabricated in the steps shown in Fig. 8) is placed in parallel and aligned to the central line, with the air-cavity lenses facing each other (Fig. 5). The distance between two transducers and the rotation angel along the central line is finely tuned for best trapping zone formation. A resonant chamber is formed between the two transducers which can be used to enhance the trapping force. The location and size of the trapping zone is defined by the tweezers' frequency and the resonant chamber. When the two transducers are aligned with a rotational offset on the sector designs (such as illustrated in Fig. 5c), the symmetricity in the resonant chamber breaks, and consequently, the trapping zone moves to a non-central place. A trapping zone is where a lower pressure region is developed within a higher pressure region, as shown in Fig 6. The asymmetricity causes the higher-pressure region (the potential barrier) to appear differently on two sides of the trapping zone, providing the possibility of creating control over the trapping zone.

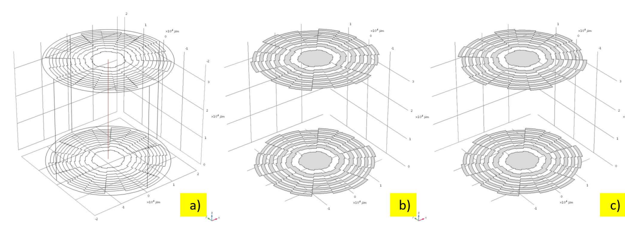

Fig. 5. Schemetics showing the formation of paired transducers as acoustic tweezers, placed in paralle to each other. a) a pair of two sectored transducers aligned at the central line, with Fresnel lens facing each other; b) two transducers with 0º rotation offset on the central line and c) two transducers with 30º rotation offset on the central line.

When a fine tuning of the operating frequency is applied on the tweezers, a minute change of the trapping zone topology is induced, which in turn affects the balanced trapping state. Figures 6 and 7 show the simulated change of the pressure distribution, and thus the trapping zone when the frequency is tuned from 1.070 MHz to 1.072 MHz. Both the location and intensity of the potential barrier respond to the frequency change, as the center of the trapping zone moves up a bit. During the tuning, the trapping zone goes through a dynamic re-stabilization process, generating a force to manipulate the trapped particle to move/situate to the re-established trapping zone. If the trapped particle is not spherical and homogenous, the force is possible to exert a torque to rotate the particle to maintain a minimum potential energy in the newly developed trapping zone, creating a repeatable controllability on the rotation of the particle.

When the tweezers is horizontally placed, the gravity of the particle becomes part of the unbalanced and asymmetric force, creating easier condition to for trapped particle to rotate.

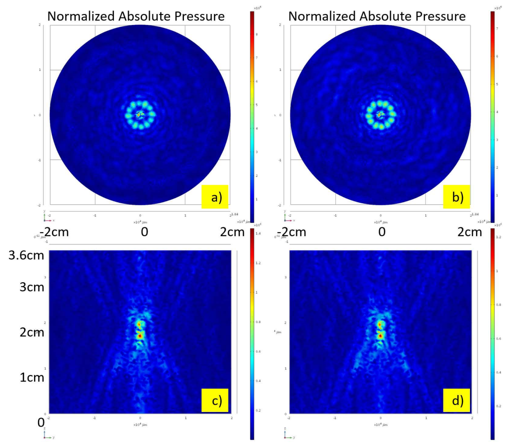

Fig. 6. Simulation result of normalized absolute pressure distribution of the acoustic tweezers formed by the two transducers placed as dipicted in Fig. 5c with a seperation distance of 36 mm and a rotation offset of 30º. a) and b) show the pressure distribution on major trapping zone plane at 18.4 mm above bottom transducer (17.6 mm to the top transducer), when the transducers are diven at 1.070 and 1.072MHz, respectively. c) and d) show the pressure distribution on the cross-sectional plane along the central line, when the transducers are diven at 1.070 and 1.072MHz, respectively

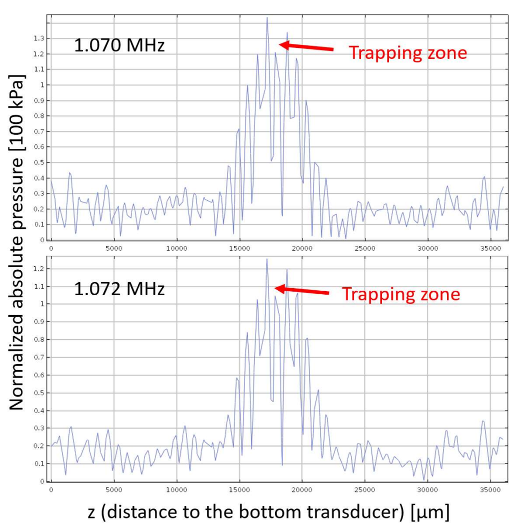

Fig. 7. Simulated normalized pressure along the central line from the one transducer surface to the other. Top figure shows the pressure when both transducers are driven at 1.07 MHz. and bottom figure shows the pressure when driven at 1.072 MHz. The slight change on the trapping zone when frequency shifts leads to the manipulation of the trapped particle.

III. Fabrication

As illustrated in the brief fabrication process shown in Fig 8, we use a 1.03mm thick PZT with nickel layer on its both sides as the substrate to start with. Photoresist is spin-coated for both the front and back sides for the electrode patterning, followed by a wet-etching nickel layer to form the actual electrode. A second layer of photoresist is coated as a sacrificial layer in forming air-cavity reflectors. Then, while protecting the backside electrode, we deposit 5µm thick Parylene film, and define release holes on the front side where air cavities are needed. Oxygen reactive ion etch (RIE) is used to etch through the Parylene to form the releasing holes, and the sacrificial layer is removed by acetone soaking through the holes. Another layer of 5µm thick Parylene film is deposited to seal the releasing holes and provide electrical insulation to the transducer. Figure 9 shows the photo of a packaged single transducer.

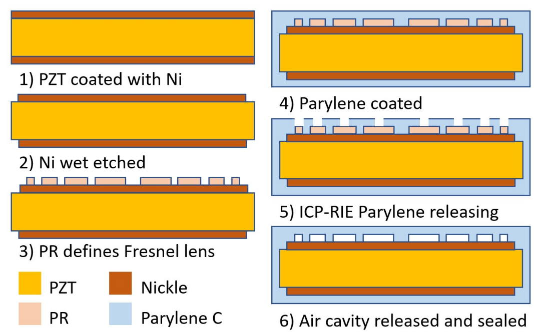

Fig. 8. Brief fabrication flow [1].

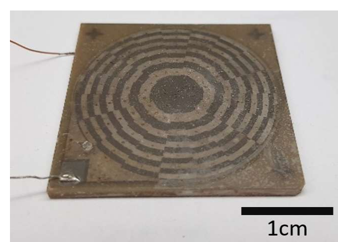

Fig. 9. Photo of the fabricated transducer.

IV. Experiment and Result

A. Experiment Setup

The setup for the rotational control experiment is shown in Fig 10, as the tweezers is composed to two transducers placed vertically. One transducer is fixed while the other one can be positioned manually for precise spacing and central line alignment.

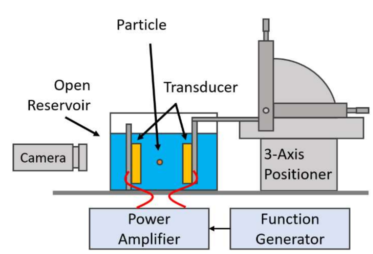

Fig. 10. Experiment setup.

B. *Polyethylene Particles*

A 3.7 cm separation distance and a 30º rotation offset are arranged between two single transducers, and both of the transducers are driven at 1.1689 MHz with 38 V_{pp} continuous sinusoidal wave. A dot-marked (red dot colored on background green as an indicator of rotation) polyethylene sphere of 1 mm in diameter is first injected to the vicinity of the trapping zone by a pipette. After the sphere gets captured firmly, we tune the driving frequency of the tweezers up from 1.1689 to 1.1691 MHz, and observe that the sphere moves slightly downward, starting to rotate. After the dynamic rotation process, where the sphere gains its 90-degree rotation, the sphere moves back upward again, re-captured. When the frequency is increased further to 1.1693 MHz, the sphere is observed to rotate an additional 90 degree (Fig. 11). When the frequency is tuned back to 1.1689 MHz from 1.1693 MHz, backward rotations are observed (Fig. 12).

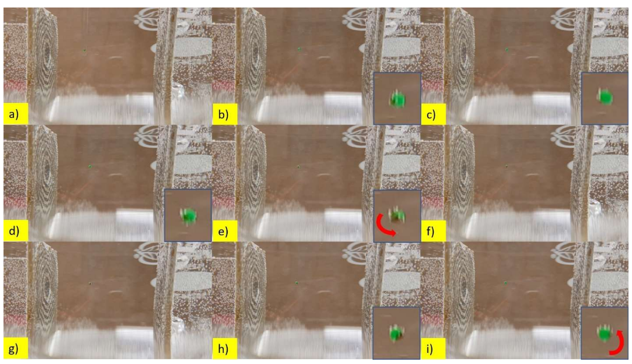

Fig. 11. Photos showing the rotational manipulation on a half-colored (half green and half red) polyethylene sphere of 1 mm in diameter: a) the sphere is released and soon trapped in a trapping zone of the acoustic tweezers; b)-e) by changing the frequency (applied to the tweezers) from 1.1689 MHz to 1.1691 MHz, the trapped sphere rotate around 90 degree, as the red half rotates from left side to down side; f)-i) by changing the frequency from 1.1691 MHz to 1.1693 MHz, the sphere rotate additional 90 degree, as the red half rotates from down side to right side.

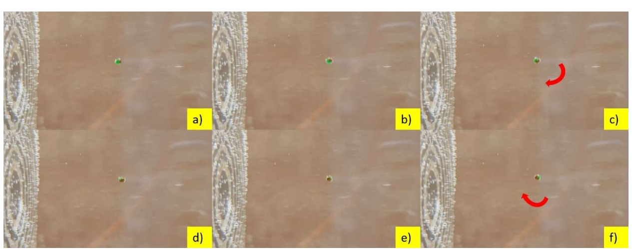

Fig. 12. The trapped half-colored sphere rotates back when frequency is reversed from 1.1693 MHz back to 1.1689 MHz.

C. *Zebrafish Embryo*

For manipulation of a zebrafish embryo which is much heavier than the polyethylene sphere, we increase the driving voltage to 40 V_{pp} and tune the frequency to 1.1730 MHz for a better trapping effect. After the embryo is captured, successful rotational manipulation is observed during a slight lowering of the driving frequency from 1.1730 to 1.1726 MHz (Fig. 13).

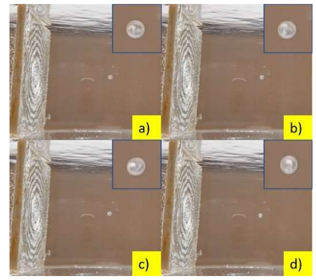

Fig. 13. Rotational manipulation on a 24-36 hours-post-fertilization zebrafish embryo. Rotation is observed when the frequency (applied to the acoustic tweezers) is slightly lowered from 1.1730 to 1.1726 MHz.

V. SUMMARY

We have obtained an electrical control on the rotation of a trapped particle or cell with a pair of two acoustic transducers that can trap particles up to 1 mm in diameter, as well as late-term zebrafish embryos at 24 - 36 hours after fertilization, by tuning the frequency applied to both of the transducers. Each of the transducers consists of three sets of sectored Fresnel lens that individually have focal lengths of 17.0, 18.5 and 20.0 mm. Our experiments show that a trapping of mm-sized particle is achieved at around 1.17 MHz driving frequency, while tuning of the frequency by about 100 Hz generates on-demand rotational manipulation. The angular manipulation has been effective in rotating mm-size polyethylene particles and 24 – 36 hours-post-fertilization zebrafish embryos that are 1.3 – 1.5 mg in weight.

ACKNOWLEDGMENT

This article is based on the work supported by DoD's Congressionally Directed Medical Research Program (CDMRP) under grant number W81XWH-17-1-0538.

REFERENCES

[1] L. Zhao and E.S. Kim, "Acoustic Tweezers for Trapping Late-Stage Zebrafish Embryos," The 32nd IEEE International Conference on Micro Electro Mechanical Systems (MEMS 2019), Seoul, Korea, January 27 - 31, 2019, pp. 57 – 60.

[2] Y. Tang and E.S. Kim, "Acoustic Tweezers Based on Linear Fresnel Lens with Air Cavities for Large Volume Particle Trapping," The 32nd IEEE International Conference on Micro Electro Mechanical Systems (MEMS 2019), Seoul, Korea, January 27 - 31, 2019, pp. 763 - 766.

[3] L. Zhao and E.S. Kim, "Acoustic Tweezers for Sub-mm Microparticle Manipulation," The 31st IEEE International Conference on Micro Electro Mechanical Systems (MEMS 2018), Belfast, UK, January 21 - 25, 2018, pp. 1088 – 1091.

[4] L. Zhao and E.S. Kim, "Acoustic Tweezers for Trapping Late-Stage Zebrafish Embryos," The 32nd IEEE International Conference on Micro Electro Mechanical Systems (MEMS 2019), Seoul, Korea, January 27 - 31, 2019, pp. 57 – 60J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.

[5] C. Lee, H. Yu, and E.S. Kim, "Acoustic Ejector with Novel Lens Employing Air-Reflectors," IEEE International Micro Electro Mechanical Systems Conference, Istanbul, Turkey, January 22 – 26, 2006, pp. 170-173K. Elissa, "Title of paper if known," unpublished.

[6] D. Huang and E.S. Kim, "Micromachined Acoustic-Wave Liquid Ejector," IEEE/ASME Journal of Microelectromechanical Systems, vol. 10, pp. 442-449, September 2001.

[7] L. Zhao and E.S. Kim, "Focused Ultrasonic Transducer with Electrically Controllable Focal-Point Location," IEEE International Ultrasonics Symposium, Kobe, Japan, October 22 - 25, 2018, pp. 1-3