MIXING, TRAPPING, AND EJECTION OF SINGLE MICROPARTICLE WITH SIZE AND MATERIAL SELECTIVITY USING ACOUSTIC TWEEZERS

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ABSTRACT

This paper presents the mixing, trapping, and ejection of a single microparticle based on an acoustic tweezers. Finite Element Model (FEM) simulation, along with analytical modeling, is used to study the selectivity of particles based on size and material properties. The acoustic tweezers is optimized to have a single trapping zone, where particles are trapped due to acoustic radiation force (which is calculated for particle sizes exceeding the Rayleigh approximation). The tweezers is experimentally shown to lift microparticles from the tweezers surface, selectively trap a single particle based on size and material acoustic properties, and then eject it upwards for collection. All these are obtained with negligible heat generation.

KEYWORDS

Acoustic Tweezers, Contactless Microparticle Trapping, Acoustic Radiation Force, Particle Delivery

INTRODUCTION

Contactless and label-free manipulation of microparticles with negligible heat is highly desirable for handling biomolecules in microfluidic platforms [1]. Acoustics waves are ideally suited for a contactless, bio-friendly, and reliable manipulation method without generating substantial heat [2]. Acoustic tweezers [3] uses focused mechanical waves to trap and manipulate the targeted particles based on acoustic radiation force and acoustic streaming. If a tweezers relies on standing waves for particle trapping [4], multiple particles are trapped in the nodal points, and there is no precise control of the location of the trapping. Further, the trapped particles do not necessarily follow the tweezers as the tweezers is moved.

Acoustic tweezers using multiple focal points to generate a quasi-Bessel beam has been demonstrated for trapping particles within the focal zones [5]. These tweezers work on the principle of constructive interference of acoustic waves to create the desired pressure pattern by selectively blocking out the waves that cause destructive interference. This allows having precise control over the position of a single trapped particle, which can be manipulated by moving the tweezers.

This paper describes an acoustic tweezers designed with three focal points after optimizing the inter-focal distances using FEM simulations to create a zone of low pressure surrounded by high-pressure zones on all its sides. A particle (or particles) inside the low-pressure zone cannot escape, and follows as the tweezers is moved. For observation of the particle manipulation, two long-range microscopes are placed perpendicular to each other for getting both the front and side view of the tweezers. This imaging setup allows accurate localization of the trapped particle position with respect to the tweezers in the 3D space. By changing the actuation parameters, the tweezers can also be used as a micromixer or lifter.

DEVICE DESIGN AND FABRICATION

A multi-foci-Fresnel acoustic transducer with three focal points has been shown to trap particles in liquid [6]. We have studied a design with seven Fresnel rings to maximize the trapping capability by optimizing the design parameters. The center circle and the first inner ring (Fig. 1) are designed to constructively interfere at the first focal point, f_1, while the next two rings and the three outmost rings are designed for the second focal point, f_2, and the third focal point, f_3, respectively to generate a well of pressure within them.

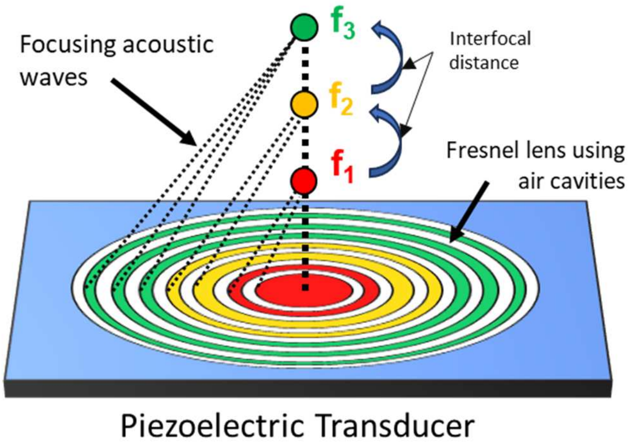

Figure 1: Schematic of the Multi-Foci-Fresnel Transducers design using 3 focal points.

Keeping the tweezers' operational frequency at 9.28MHz, corresponding to a wavelength of around 160µm in water, we have simulated acoustic pressure patterns with Finite Element Model (FEM) using COMSOL. At this frequency and with the first focal length (f_1) of 2mm, which is around 12.5 times the wavelength, the simulation results suggest a formation of a low-pressure region surrounded by high-pressure zones on all sides when the inter-focal distance (i.e., $f_2 - f_1$ and $f_3 - f_2$, as illustrated in Fig. 1) is kept at 2.5 times the wavelength, as shown in Fig. 2. The optimized pressure well has a radial dimension of 220µm and a height of 190µm at -3dB compared to peak acoustic pressure value. Similar studies have been conducted over various frequencies to make sure that the conclusions drawn are valid.

To have a better understanding of particle trapping, an analytical model using a piston-like acoustic potential [7] is developed to validate the results obtained from the FEM simulations (Fig. 3).

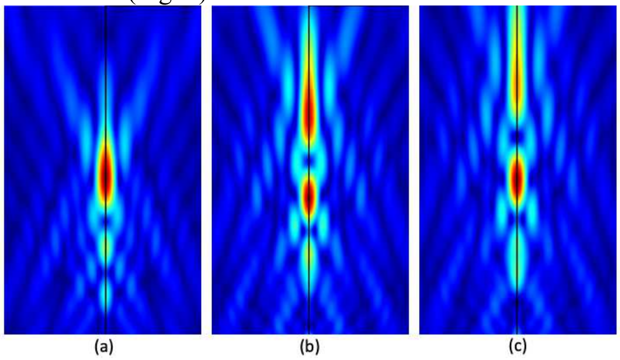

Figure 2: Pressure distribution above the 9.28MHz transducer with a fixed first focal distance for optimizing the inter-focal distance at (a) 2.25 times the wavelength, (b) 2.5 times the wavelength, (c) 3.15 times the wavelength.

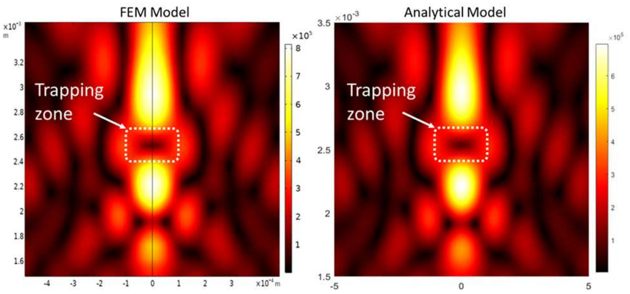

Figure 3: Acoustic pressure patterns above the transducer obtained by FEM simulation and analytical model.

We have fabricated the tweezers on a 270µm-thick Lead Zirconate Titanate (PZT-5A) substrate with a fundamental thickness resonance frequency of 9.28MHz. Fresnel Half Wavelength Bands are formed with annular air cavities formed with patterned photoresist as a sacrificial layer (Fig. 4). The patterned photoresist is coated with Parylene, and removed with acetone through etch holes in the Parylene [8]. The large impedance mismatch between the water and air makes the acoustic waves (produced by the PZT) get completely reflected at the air-water interface, leading to selective blocking of the waves, which would have resulted in destructive interference at the focal points. Seven Fresnel rings are used for three focal points at 2, 2.39, and 2.78mm, based on the optimized focal length to inter-focal distance obtained in the simulations. The cross-sectional schematic and the top-view photo of the fabricated device are shown in Fig. 4.

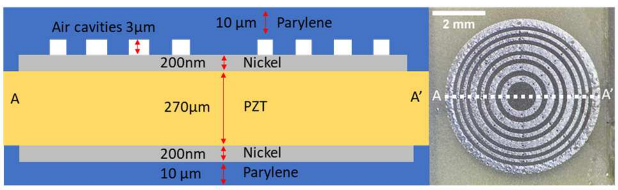

Figure 4: Cross-sectional schematic (left) and top-view photo (right) of the fabricated 9.28MHz acoustic transducer.

EXPERIMENTAL TRAPPING

The acoustic tweezers is placed inside a transparent acrylic chamber, and the trappings are recorded with two long-range Dino-Lite digital microscopes (AM7915MZTL and AM73915MZTL) placed perpendicular to each other for simultaneous recording of the front and side views, as shown in Fig. 5.

To avoid any influence of reflection on the desired acoustic pattern (or to avoid standing waves), acoustic absorbers are placed above the tweezers, blocking reflections from the water surface [9]. Trapping experiments performed with and without acoustic absorbers demonstrate the need to prevent reflections for achieving single-particle trapping (Fig. 6).

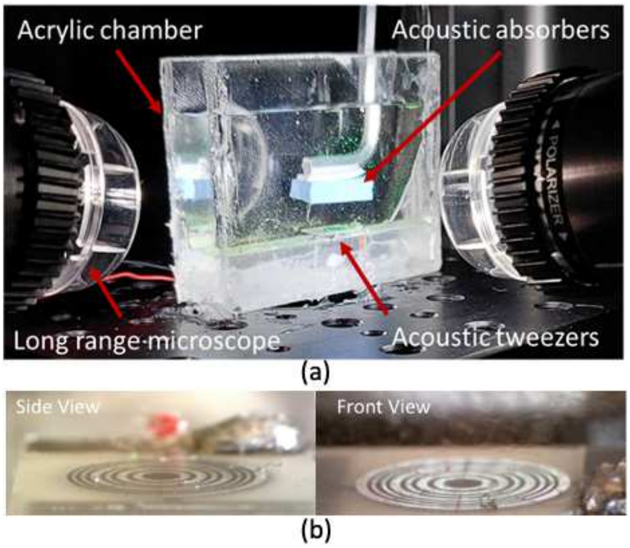

Figure 5: Photos of the (a) experimental setup, (b) side-view and front-view from the two Dino microscopes placed as shown in (a).

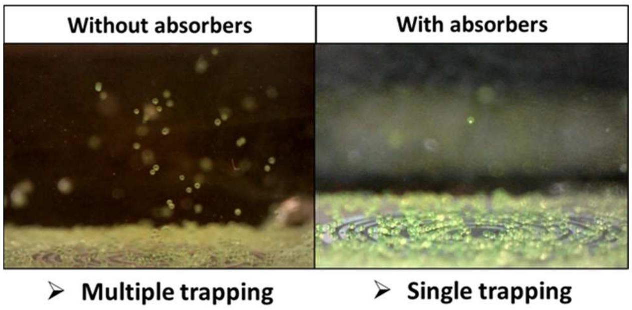

Figure 6: Comparison of 100µm polystyrene microspheres trapping: (left) without acoustic absorbers and (right) with acoustic absorbers.

TRAPPING AND DELIVERY SEQUENCE

After introducing enough particles to cover the tweezers surface fully, first without operating the tweezers, we operate the tweezers in a mixing mode with a low duty cycle of 1.6% and for a pulse repetition frequency of 100Hz (Fig. 7) to lift all the particles that are initially on the active surface of the acoustic tweezers.

While the particles are in suspension, due to the mixing mode, in the liquid, the acoustic transducer can trap 100µm polystyrene and polyethylene microspheres when actuated by continuous sinusoidal waves at low voltages of $1.2V_{pp}$ and $0.85V_{pp}$, respectively (Fig. 7).

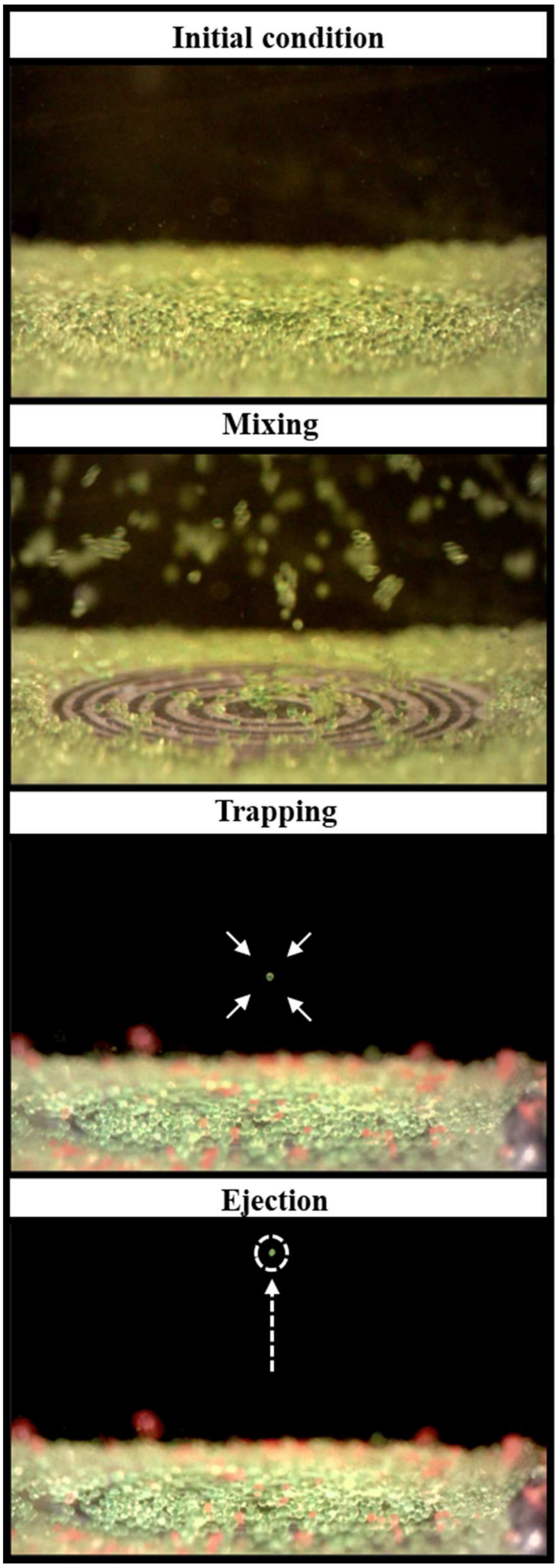

Figure 7: Sequence of images showing the device's mixing, trapping, and vertically moving capabilities on 100µm polystyrene microspheres.

Experimental observation revealed that particles of 200µm in diameter are pushed away from the acoustic tweezers due to acoustic radiation force and acoustic streaming, while particles of 50µm in diameter appear trapped for a few seconds and slowly drift away from the trapping zone.

FEM Multiphysics simulations coupling acoustic and elastic domains are performed to compute the acoustic radiation force, outside of the Rayleigh approximation when the particle size is similar to the wavelength, applied to the particle via the surface integration of the time average of the second order of the acoustic pressure and the momentum flux transfer [10]. Results reveal the presence of a low-pressure zone at the corners of the trapping zone (which is in the shape of a ring in 3D), as shown in Fig. 8. This small opening in the pressure-well borders explains the size limit of the trapped particles.

While a single particle is trapped, if the voltage applied to the transducer is increased, the trapped particle is pushed upward almost vertically due to the dominant effect of acoustic streaming at higher voltages (> $4V_{pp}$).

Switching through the three modes of mixing, trapping, and ejection, an automated selective particle delivery system can be established, as shown in Fig. 7.

Using a mixture of 100µm polystyrene and polyethylene microspheres, we observe the capability of selective trapping by tuning the applied voltage. Polyethylene microspheres (1.09g/cc) can only be trapped with an applied voltage of 750-950mV$_{pp}$. In contrast, polystyrene ones (1.05g/cc) can be trapped with a larger range of 750mV$_{pp}$-1.5V$_{pp}$ (Table 1).

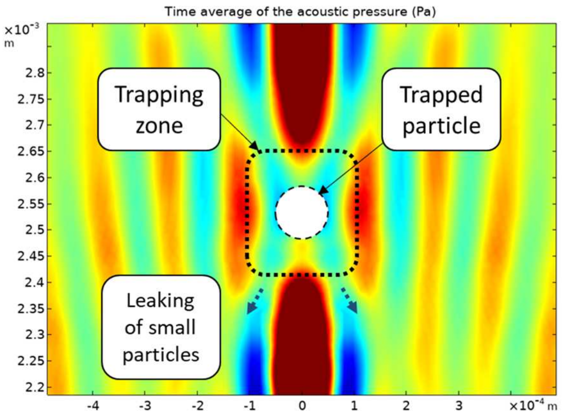

Figure 8: Time average of the second order of the pressure that induces acoustic radiation force in the presence of a microsphere inside the trapping zone.

Table 1. Properties of the 100µm diameter trapped particles.

Material	Density	Trapping voltage
Polyethylene (red)	1.09g/cc	0.75 – 0.95V$_{pp}$
Polystyrene (green)	1.05g/cc	0.75 – 1.5V$_{pp}$

The difference in the trapping voltages for different particles is due to the difference in the acoustic impedances of the particles, as the acoustic impedance is directly related to the density of the particle and its acoustic properties. The bulk modulus of these polymers corresponds to the inverse of their compressibility coefficient. The stiffer the particle is, the lower the compressibility is, thus, resulting in larger impedance mismatch between the particle and the liquid medium, which generates distinct scattered pressure, changing the trapping force for a given voltage.

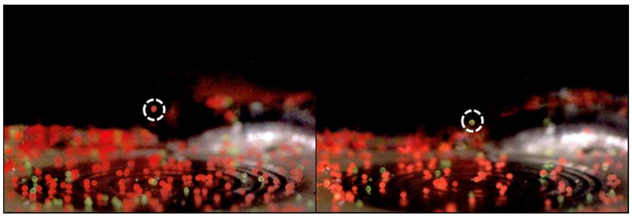

Figure 9: Images of selective trapping of a single 100µm microsphere: (left) polyethylene and (right) polystyrene in a mixture of different particles by adjusting the trapping voltage.

CONCLUSION

An acoustic tweezers capable of mixing, trapping, and ejecting a single particle is presented. The device is designed to produce the desired pressure pattern, enabling control over the particle size that can be trapped. The frequency and the focal lengths of the acoustic tweezers determine the trapping-zone size. For single-particle trapping, acoustic absorbers are necessary to avoid any disturbance in the pressure pattern due to reflection from the water-air interface. The fabricated acoustic tweezers operating at 9.28MHz are designed to be able to trap microparticles with a size between 50 and 200µm in diameter.

The mixing effect is generated by applying a higher voltage (than the voltage used for trapping) at a low duty cycle of 1.6% and for a pulse repetition frequency of 100Hz. While the particles are suspended after operating the transducer in the mixing mode, the trapping of a single particle is achieved. The trapping exhibits a size selectivity as well as a material selectivity, which is evident from the actuation voltage of the tweezers for trapping a specific particle. After trapping, the single particle can be easily collected by slowly increasing the voltage to induce more acoustic streaming, which will dominate the acoustic radiation force and will result in the particle being pushed upwards vertically.

All these manipulation steps are performed using very low power to actuate the transducer, generating negligible heat, making this technique viable for cell treatment. The automated lifting, trapping, and ejection sequence of a single particle could be useful for automated single-particle delivery.

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