Contactless microparticle control via ultrahigh frequency needle type single beam acoustic tweezers

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This paper reports on contactless microparticle manipulation including single-particle controlled trapping, transportation, and patterning via single beam acoustic radiation forces. As the core component of single beam acoustic tweezers, a needle type ultrasonic transducer was designed and fabricated with center frequency higher than 300 MHz and -6 dB fractional bandwidth as large as 64%. The transducer was built for an f -number close to 1.0, and the desired focal depth was achieved by press-focusing technology. Its lateral resolution was measured to be better than $6.7\ \mu\text{m}$ by scanning a $4\ \mu\text{m}$ tungsten wire target. Tightly focused acoustic beam produced by the transducer was shown to be capable of manipulating individual microspheres as small as $3\ \mu\text{m}$. “USC” patterning with $15\ \mu\text{m}$ microspheres was demonstrated without affecting nearby microspheres. These promising results may expand the applications in biomedical and biophysical research of single beam acoustic tweezers. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4966285>]

Contactless particle manipulation devices have found broad applications in biophysical and biomedical research. Optical tweezers are the most well-known of these devices, which provide a method of manipulating particles with sizes in the range from approximately $100\ \mu\text{m}$ down to a few nanometers.^{1–4} However, optical tweezers are limited by high optical power requirements, the high energy of focused lasers can cause local heating and photo-damage of biological samples. On the contrary, acoustic tweezers may overcome these problems, as biological samples are less likely to be damaged by acoustic energy.^{5–8} In addition, acoustic devices are much simpler to setup at a lower cost than their optical counterparts.

The initial research on acoustic tweezers was reported by Wu, who used two opposing sound beams to capture latex spheres and frog eggs.⁵ Since then, the standing wave acoustic tweezers have been investigated in detail and have made significant progress.^{9–11} The standing wave approach mainly works on groups of particles. In contrast, as another type of acoustic tweezers, single beam acoustic tweezers (SBAT) have recently attracted considerable attention because of their capability to trap and manipulate individual particles with a single acoustic beam.^{12–17} The trapping performance of an SBAT is affected by various parameters, such as the medium, frequency, and shape of the acoustic beam, and the acoustic properties of the particle.¹⁸ Generally, in order to trap smaller particles, the SBAT frequency must be increased. A high quality SBAT that can perform more practical biomedical applications at cellular level must meet several criteria, such as high frequency (≥ 200 MHz), low f -number, and cylindrical symmetry of the acoustic beam.

Over the past decade, the performance of acoustic tweezers have significantly improved by continuous adjustment and optimization of the fabrication processes. Transducers able to operate at 200 MHz were developed, and they demonstrated the capability of trapping cells of sizes $15\text{--}20\ \mu\text{m}$,¹⁹ in addition to microspheres of $5\ \mu\text{m}$ and $10\ \mu\text{m}$.²⁰ However, there are still some problems that need to be overcome. First, the frequency of the transducer is still not sufficiently high to conveniently manipulate microparticles with sizes below one micron or even a few microns. Moreover, the -6 dB fractional bandwidth of an SBAT is usually lower than 30%; consequently, the effective excitation frequency range of transducer is narrow, such that the size range of trappable object trapping is limited. Additionally, fabricating a tightly focused transducer for SBAT is very challenging, especially for the ultrahigh frequency range (≥ 200 MHz).

In this study, a focused needle type LiNbO_3 transducer with center frequency higher than 300 MHz and -6 dB bandwidth broader than 60% was developed for SBAT applications. The needle type offers more flexibility in carrying out SBAT experiments given the extremely congested environment in the small area within which the experiments are performed.¹⁶ Owing to its high sensitivity and broad bandwidth, this SBAT could be effectively excited over a wide frequency range (200–350 MHz) and could manipulate microspheres with a wide range of size ($3\text{--}45\ \mu\text{m}$) by controlling the excitation frequency. In addition, the excellent capability of this device to manipulate individual microspheres was experimentally demonstrated by patterning “USC” using $15\ \mu\text{m}$ microspheres without affecting nearby microspheres.

The 36° rotated Y-cut Lithium niobate single crystal (LiNbO_3) was selected to fabricate the ultrahigh frequency needle type transducer because it exhibits good electromechanical

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FIG. 1. (a) Design cross section and photograph of the pressed focused needle transducer; (b) electrical impedance magnitude and phase plots and (c) time-domain pulse/echo response and normalized frequency spectrum for the LiNbO₃ needle transducers.

coupling capability ($k_t = 0.49$), low dielectric permittivity ($\epsilon = 39$), and high longitudinal sound velocity ($v = 7340$ m/s), which makes it an ideal material for designing high sensitivity single element transducers with ultrahigh frequency.²¹ The design cross section and photograph of the press-focused transducer are shown in Fig. 1(a). The fabrication process is described as follows. A Krimholtz, Leedom, and Mattaei (KLM) model-based simulation software PiezoCAD (Sonic Concepts, Woodinville, WA) was utilized to optimize the aperture size and proper thickness of acoustic stacks before fabrication. The 36° rotated Y-cut LiNbO₃ single crystal (Boston Piezo-optics, Bellingham, MA) was first lapped to around 7 μm , after which Cr/Au (50/100 nm) electrodes were sputtered on one side of the LiNbO₃. Then, E-solder 3022 was cast on the other side as the backing material and lapped to 2 mm. The sample was then diced to 0.4×0.4 mm² posts using a dicing saw (Tcar 864-1, Thermocarbon, Casselberry, FL) and housed inside a polyimide tube with an inner diameter of 0.57 mm. A lead wire was connected to the backing layer with an additional amount of conductive epoxy. The polyimide tube provided electrical isolation from the needle housing. Then the transducer was housed in a subminiature version A (SMA) connector. A layer of Cr/Au (50 nm/100 nm) was sputtered across the transducer face to form the ground plane connection. The device was then press focused by highly polished chrome/steel ball bearings (0.8 mm diameter, grade 3, Bal-Tec, Los Angeles, CA) at 90°C to obtain a 0.4 mm focus and an f -number of 1. Finally, a thin layer of parylene (~ 1.5 μm) was vapor-deposited, using a PDS 2010 Labcoator (Specialty Coating Systems, Indianapolis, IN) on the front face of the transducer, this served as an acoustic matching layer and a protection layer.

The frequency dependence of electrical impedance and phase plots as measured with an impedance analyzer (4991A Agilent Technologies, Santa Clara, CA), are displayed in Fig. 1(b). The resonant frequency (f_0) and corresponding impedance (Z) were determined from the plots to be 320 MHz and 28 Ω , respectively. The conventional pulse-echo response measurement was carried out in distilled water, for which the transducer was connected to a pulser/receiver (DPR500, JSR Ultrasonics, NY) and excited by an electrical impulse at a repetition rate of 200 Hz with 50 Ω damping. The energy

involved was 2.3 μJ , and no gain was applied. An X-cut quartz plate was used as a target. The testing distance was at the focal length of the transducer. The measured pulse-echo waveform with normalized frequency spectrum is shown in Fig. 1(c). The center frequency is 285 MHz, which is lower than the resonant frequency determined from the electrical impedance and phase plots. One possible cause of the frequency downshift is the frequency dependent attenuation in water, as the attenuation of ultrasound is proportional to the square of the frequency. The transducer shows broad -6 dB bandwidth of 64%.

High frequency and small f -number make it possible to generate a narrow microbeam. As shown in Fig. 2, the -6 dB beam width was determined to be 6.7 μm by scanning a 4 μm diameter tungsten wire as a pulse-echo target at the focus, where translational scans at the focus of the transducer yield the lateral profile of the beam projections. The measured beam width is in approximate agreement with the theoretically predicted width of 6.1 μm (beam width $\approx f$ -number * wavelength).

The micro particle trapping device was set with the focused transducer in a cell culture dish of distilled water, as shown in Fig. 3(a). A customized LabVIEW program controlled three-axis motorized linear stage (LMG26 T50 MM, OptoSigma, Santa Ana, CA) was used to manipulate the transducer perpendicularly to the beam axis at the focal distance. The trapped motions of the particles were captured using a CMOS camera (ORCA-Flash 2.8, Hamamatsu, Japan) combined with an inverted microscope (IX-71, Olympus, Japan). The images, as well as videos captured by the CMOS camera,

FIG. 2. (a) Image of 4 μm tungsten wire target, and (b) lateral beam profile of the LiNbO₃ needle transducer.

FIG. 3. (a) Schematic diagram of the single beam acoustic tweezer setup; (b) Microsphere manipulation example using the LiNbO₃ needle type transducer. A single 3 μm microsphere was manipulated along the movement of the transducer which was excited at a frequency of 350 MHz. A red circle is a trapped microsphere, while a yellow square is given as a reference point to show the location change of the microsphere; (c) 15 μm microspheres “USC” pattern by the transducer excited at a frequency of 300 MHz.

were recorded with a computer. To perform microspheres manipulation, the transducer was driven in a sinusoidal burst mode by a function generator (AFG3251, Tektronix, Anaheim, CA) and then amplified by a 50 dB power amplifier (525 LA, ENI Rochester, MN) to achieve a desirable peak-to-peak voltage amplitude, duty factor, and pulse repetition frequency. Polystyrene microspheres (Polyscience, Warrington, PA) were used as targeted particles.

Owing to the high sensitivity and broad -6 dB bandwidth, the LiNbO₃ ultrasonic transducers were capable to be excited efficiently at a large range of frequency, and were able to trap and manipulate single microsphere with different sizes. An example of a single 3 μm microsphere manipulation using the LiNbO₃ needle transducer is demonstrated in Fig. 3(b). In this case, the tightly focused needle transducer was driven by a sinusoidal burst under the following conditions: an excitation frequency of 350 MHz, a driving voltage of 1.5 V peak-to-peak, a duty cycle of 1% and a pulse repetition frequency of 1 kHz. The yellow square indicates a reference point to show the motion of the microsphere. As can be seen, a single 3 μm microsphere (a red circle) was stably manipulated along with the movement of the transducer. (The movement is clearly demonstrated in [supplementary material](#), video 1.) As the device manipulated the single microsphere along different paths, the microspheres nearby were slightly affected, which means the microbeam was not sufficiently tight for 3 μm microsphere in this case. When the transducer was excited at 350 MHz, the theoretical beam width was calculated to be 5 μm , which is slightly wider than the microsphere's size.

To manipulate individual microsphere without affecting nearby microspheres, the wavelength and beam width of the transducer should be much smaller than the size of the microspheres. Fig. 3(c) demonstrates a screenshot of “USC” pattern formed by 15 μm microspheres which were manipulated by the tweezer device. In this case, the tightly focused needle-type transducer was driven by a sinusoidal burst under the following conditions: an excitation frequency of 300 MHz, a driving voltage of 3.5 V peak-to-peak, a duty cycle of 1% and a pulse repetition frequency of 1 kHz. The neighbor microspheres were unaffected by the trapped microsphere. (Part of the movement process is clearly demonstrated in [supplementary material](#), video 2.) As the size of

the trapped microsphere is already at the cellular level, such ultrahigh frequency LiNbO₃ transducers have great potential to be a single cell manipulator for wide range of applications in biomedical and biophysical science.

In summary, this study shows that the LiNbO₃ ultrahigh frequency transducers could be used as a microbeam acoustic tweezer for contactless particle manipulation applications. The transducers were found to exhibit center frequency, bandwidth, and beam width comparable to the theoretical values. The single beam acoustic tweezers experiments demonstrate that a single microsphere (as small as 3 μm) can be manipulated by this microbeam device, and 15 μm microspheres can be manipulated without affecting nearby microspheres, as illustrated by the “USC” pattern. The realization of ultrasound microbeams will enable a wide range of biomedical and biophysical applications.

See [supplementary materials](#) for the manipulation of microspheres by the needle type single beam acoustic tweezer.

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