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Vibration characterization of Elliptical Reflector Focusing Transducer for High-power Bulk-Wave Acoustophoresis

Zhirui Chen[1†], Chikahiro Imashiro[1], Weiquan Wang[1], Wei Qiu[2] and Takeshi Morita[1*]
([1]The Univ. of Tokyo; [2]Lund Univ.)

1. Introduction

Acoustophoresis, recognized for its non-contact nature and low energy consumption, has emerged as a promising tool for manipulating various biological samples, with significant potential in modern biotechnology. However, its primary limitation lies in the relatively low throughput, which restricts its broader clinical application [1)]. To achieve higher throughput, a strong acoustic field is required to generate sufficient acoustic radiation force for effective microparticle manipulation. This typically requires high input power to PZT elements, leading to substantial heat generation. While reducing PZT size has improved efficiency [2)], it limited the induced acoustic energy in the fluid channel. In this study, we proposed an elliptical reflector focusing transducer which can efficiently transfer energy from the PZT to the channel.

2. Principle of the Proposed Transducer

The cross-section of the proposed transducer is shown in Fig. 1(a). The PZT element generates longitudinal plane wavefront. When these waves reach the reflector's outer surface, they partially transform into transverse waves under mode conversion. To focus the transverse wave, the reflector was designed as an ellipse [3)], with its shape determined by the velocities of the longitudinal (c_d) and transverse waves (c_t). This design excites strong vertical vibrations at the focal point (0, $\sqrt{C} \cdot c_t$), which can be used to drive the chip via its sidewall [Fig. 1(b)]. At specific frequencies, a half standing-wave field can be generated in the channel along y-direction [Fig. 1(c)]. It should be noted that the design only utilized a portion of the ellipse where y≥d [Fig. 1(a)], to minimize propagation loss by shortening the acoustic path while enabling observation of the channel using the microscope [Fig. 1(c)].

3. FEM Simulation

Numerical simulations for the acoustophoretic devices were performed using 2D models with a sandwiched chip [Fig. 2(a)]. To verify the focusing mechanism of the proposed transducer, we compared the average vertical displacement amplitude, d_y, along the chip mounting line between a single PZT element [Fig. 2(b)] and the proposed transducer [Fig. 2(c)] under the same input power. The performance of the device driven by the elliptical transducer [Fig. 2(f)] was then compared with two common setups of conventional devices driven by a single PZT, actuation from the chip's bottom using a PZT (*bap*) [Fig. 2(d)] and actuation from the chip's side using a PZT (*sap*) [Fig. 2(e)]. A dimensionless efficiency parameter, $\eta = \omega E_{ac} V_I / P_{in}$ [2)], was used to quantify energy conversion efficiency from the PZT to the channel. The simulation result showed that the transducer produced a displacement 5.5 times higher than that of a single PZT under the same input power. The vibration mode at 2.06 MHz validated a strong focusing mechanism at the focal point [Fig. 3(c)]. Vibration modes of different devices at their resonance frequencies showed perfect half standing wavefields inside the channel with a large acoustic pressure [Fig. 4(a)-(c)]. In terms of efficiency, the transducer-driven device (*sae*) reveals a better performance to the device driven by a single PZT (*bap* and *sap*) [Fig. 4(d)], with 2 times than the bottom actuation and 1.6 times than the side actuation. Furthermore, *sae* model surpassed common models at their efficiency peaks.

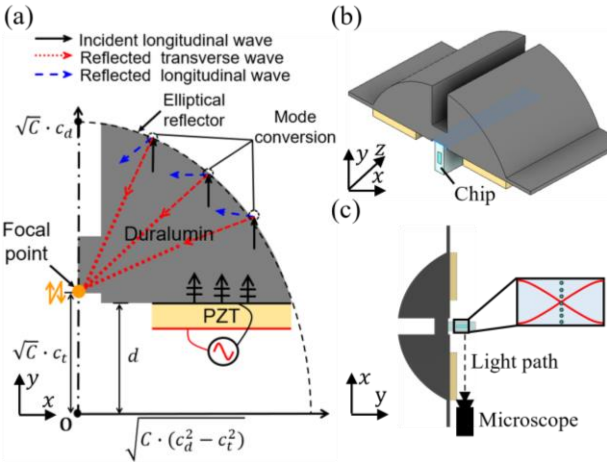


Fig. 1 Scheme of the proposed device: (a) Principle of the proposed transducer. (b) 3D sketch of the proposed acoustophoresis device. (c) The optical access to the channel where microparticles are focused by pressure half standing wave.

E-mail: †chen-zhirui@g.ecc.u-tokyo.ac.jp,
* morita@pe.t.u-tokyo.ac.jp

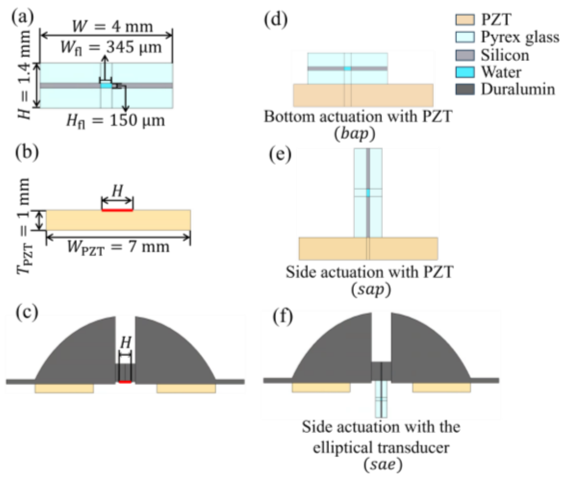


Fig. 2 Illustration of the 2D models in simulations.

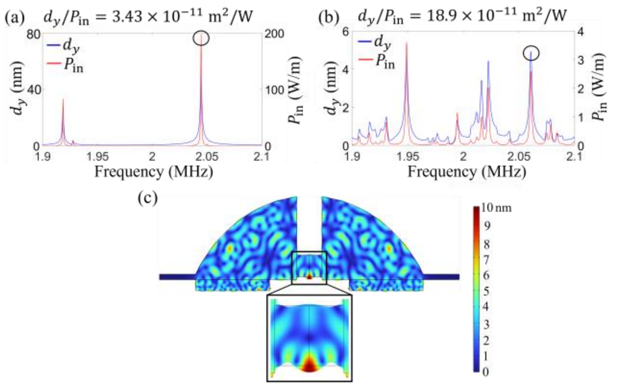


Fig. 3 (a-b) Frequency analysis results of models without chips. (c) The vibration mode of the transducer at 2.06 MHz.

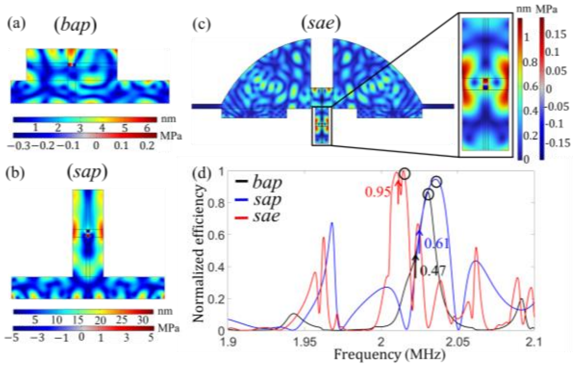
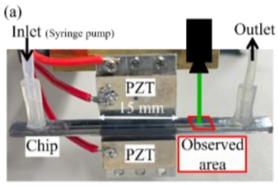


Fig. 4 Vibration modes and induced sound fields using (a) *bap*, (b) *sap*, and (c) *sae*. (d) Normalized efficiency parameter

4. Experimental result

After confirming performances of the transducer in simulations, a prototype was fabricated. In Fig. 5, particle focusing experiments demonstrated that the transducer could focus 5-μm-diameter particles well with a narrow fluorescent bandwidth at the resonance frequency (1.8375 MHz), compared to the off-resonance case (1.830 MHz). The optimal frequency with minimal particle bandwidth was 1.8375 MHz [Fig. 5(d)]. Admittance and velocity spectrums showed four velocity peaks with corresponding admittance peaks from 1.5 MHz to 2.5 MHz [Fig. 6]. In Fig. 7, at the first peak near the chip's optimal frequency, velocity measurement showed a 1.5 times amplification from the PZT to the vibrating block, with a peak-peak velocity of 0.7 m/s. At the maximum velocity peak, a 2.1 times amplification with a velocity of 1 m/s was achieved. In conclusion, the device's working frequency is determined by the chip's channel width, so higher efficiency can be expected at the transducer's largest resonance peak (2.257 MHz) when using a chip with matched channel width in the future.



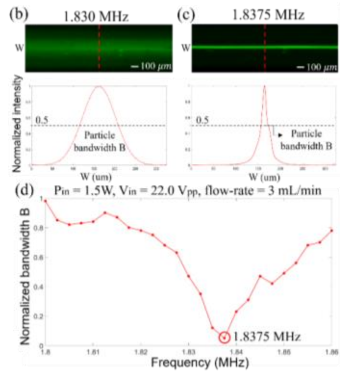


Fig. 5 Particle focusing experiment. (a) Experimental setup. (b) Particle focusing results.

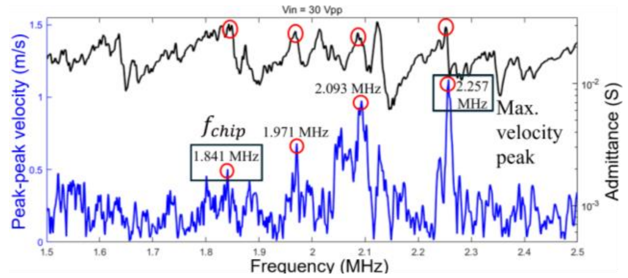


Fig. 6 Admittance and velocity spectrums of the fabricated transducer at an input voltage of 30V_{pp}.

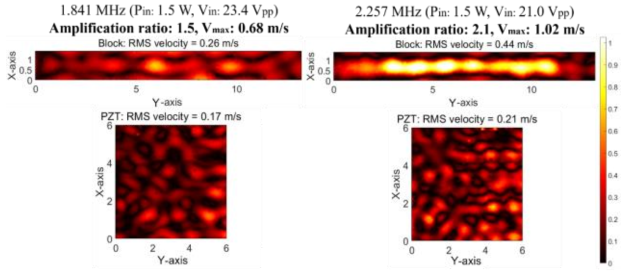


Fig. 7 Vibration velocity distribution on the surfaces of the PZT and the vibrating block.

4. Conclusion

In this study, we proposed elliptical reflector focusing transducer for high-power bulk-wave acoustophoresis. Numerical simulations confirmed its focusing mechanism and high efficiency of the acoustophoresis device compared to the common one. The particle focusing experiment demonstrated the transducer can effectively focus microparticles. Vibration characterization showed large vibration amplification of the transducer, indicating potential for even higher efficiency at the largest resonance peak with a well-matched chip in the future.

References

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