

Ultrasound-Driven Electronically Programmable Microbubbles

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Abstract:

We present an on-chip bubble customization platform that enables active bubble writing, erasing, and reconfiguration via electrolysis on electrode arrays. The bubbles, when actuated by an external ultrasound input, create a variety of programmed flows ranging from streaming due to volumetric oscillation of a single bubble, to diverse symmetry-broken directional flows when multiple bubbles interact. Interestingly, we generate a novel bubble shooting flow pattern whose flow direction depends on the incident ultrasound frequency. The active bubble reconfiguration ability unlocks a range of new acoustofluidic functions in a single device with unprecedented controllability.

Research Summary:

Ultrasound resonant microbubbles have emerged as a powerful driver for numerous technologies. At the microscale, microbubbles have been used to achieve propulsion, steering, and deformation of actuators, swimmers, and end-effectors (1–3). While current ultrasound-microbubble systems have demonstrated advanced functionality, scalability, and rapid response, their lifetime, programmability, and controllability remain limited. For example, under continuous oscillation, microbubbles are prone to rectified diffusion, leading to device failure in the long run (4, 5). Unwanted excitation coupling among bubbles also compromises frequency selectivity and independent control (6, 7). Many of these limitations arise because microbubbles utilized in most acoustofluidic systems are passively captured, which does not allow for altering their configurations and rejuvenating devices. One way forward is to change the passive capture paradigm and introduce active, real-time, and in situ microbubble generation and modulation in next-generation ultrasound-microbubble systems.

We unite electrolysis-driven bubble generation with ultrasound actuation to create an active microbubble customization platform. In our approach, a single electrode switches the microbubble states between bubble generation and bubble detachment by tuning the voltage of the localized electrolysis. At low voltages, electrolysis will lead to a low gas-generation rate and a slow increase in bubble volume over time. Upon turning off the electrolysis, the bubble will stop growing and be trapped on the electrode surface due to the surface tension and pinning force (Fig. 1, panel i). Once the bubble reaches the desired size, externally incident ultrasound waves will excite oscillations that induce flows (Fig. 1, panel ii). To clear a bubble, we would simply increase the electrode voltage to generate sufficient hydrogen to detach the bubble (Fig. 1, panel iii). Interestingly, if the bubbling was maintained and coupled to acoustic oscillations, we observed bubbles being actively ejected and transported in the x - y plane, which we termed “bubble shooting” (Fig. 1, panel iv).

This microbubble reprogramming approach embodies a universal framework that can be adapted to multiple electrodes in arrays. Toward this end, we fabricated electrode arrays where each electrode was individually wired and controlled. Because the bubble state on each electrode could be individually tuned, the generated bubbles could be used alone or in combination by controlling a series of time-staggered DC voltage pulses for each electrode along with the globally applied ultrasound amplitude and frequency. To highlight the platform’s potential capabilities, we demonstrated four acoustofluidic operations, including modulating bubble size, inducing bubble interactions, programming modular bubbles, and generating shooting bubbles (Fig. 2).

We show that the platform is capable of real-time bubble generation and modulation and provides multi-degree-of-freedom flow programming for microscale actuation

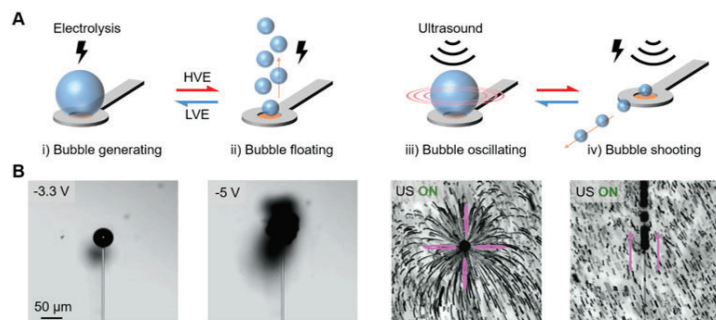


Figure 1: Ultrasound-driven electronically programmable microbubbles. (A) Schematic illustration of bubble state switching on a single electrode, including: i) bubble generating; ii) bubble floating; iii) bubble oscillating; iv) bubble shooting. HVE and LVE denote high-voltage and low-voltage electrolysis, respectively. US denotes ultrasound. (B) Representative images corresponding to the four bubble states in (A) with ultrasound at 74 kHz and 10 VPP. Flow fields were visualized using 5 μm -diameter tracer particles and superimposed frames, with magenta arrows indicating flow directions. Yellow arrows indicate bubble moving directions.

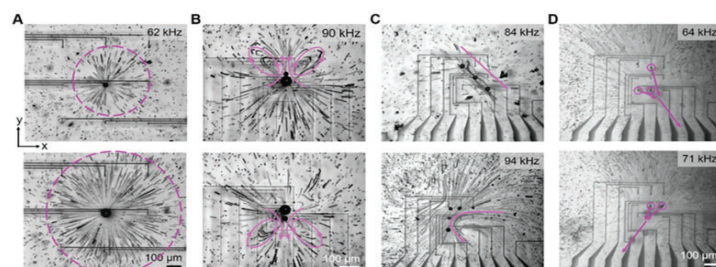


Figure 2: Active bubble configuration and flow programming. (A) Bubble-size modulation and flow scaling. (B) Controlled bubble-pair interaction and flow polarization. (C) Dynamic bubble patterning and flow programming. (D) Frequency-selective directional bubble shooting. Flow fields were visualized using 5 μm -diameter tracer particles and superimposed frames, with magenta arrows indicating flow directions.

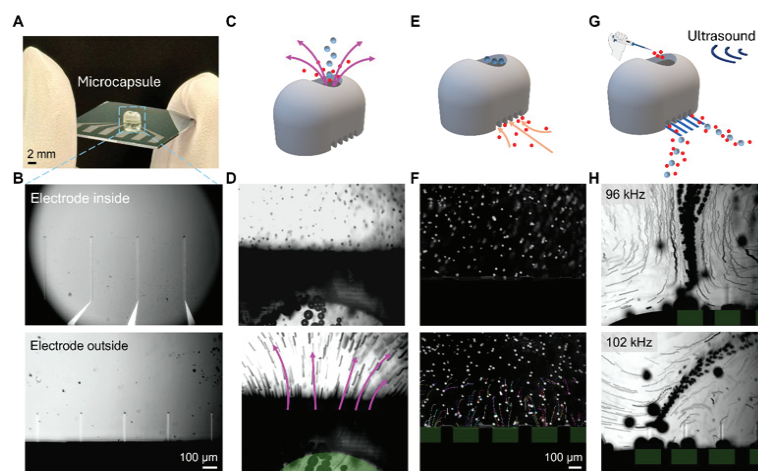


Figure 3: A multifunctional microcapsule enabled by programmable bubble shooting. (A) Optical image of a microcapsule printed by two-photon polymerization on a Si substrate with electrode arrays. It contains a circular top opening and five bottom semicircular openings, each aligned with a microelectrode. (B) Electrodes positioned inside (top panel) and outside (bottom panel) the capsule for different operating modes. (C) Schematic of preloaded cargo released from the top opening driven by bubbling from internal electrodes. (D) An image before bubbling and the superimposed image of particle release during bubbling at -5 V using five electrodes. (E) Schematic of particle collection through the bottom openings driven by bubbling from internal electrodes. (F) Images before bubbling and particle trajectories during bubbling at -8 V using five electrodes. (G) Schematic of selective directional release of preloaded contents through programmable bubble shooting by switching the ultrasound excitation frequencies. (H) Superimposed images showing directional bubble shooting at 96 and 102 kHz, respectively. The ultrasound excitation voltage was 5 VPP, and the electrolysis voltage was -4 V. Magenta arrows denote flow directions. Green rectangles denote the positions of openings.

and manipulation. In lab-on-chip systems, the platform may be assembled into higher-level workflows for particle/cell routing, sorting, and localized sample processing. For microscopic robotics, electronically selected bubble pairs could generate reconfigurable thrust and steering under external ultrasound excitation. To further advance the functional scope, by integrating the electrode array with a two-photon-polymerized microcapsule, controllable bubble generation and shooting enabled directional drug release and on-demand chemical reactions (Fig. 3).

References:

- [1] Z. Miao, et al., Acoustically powered micro-clampbot for single-particle transportation. *Science Advances* 11 (39), eady3213 (2025).
- [2] N. Mahkam, et al., Multifunctional acoustic microrobot for boundary-free multimodal 3D swimming. *Proceedings of the National Academy of Sciences* 122 (4), e2417111122 (2025).
- [3] X. Liu, et al., Sonic-hand: Biomedical micromanipulation driven by acoustic gas-liquid-solid interactions. *Science advances* 11 (13), eads8167 (2025).
- [4] D. Ahmed, et al., Rotational manipulation of single cells and organisms using acoustic waves. *Nature communications* 7 (1), 11085 (2016).
- [5] Z. Shi, et al., Ultrasound-driven programmable artificial muscles. *Nature* 646 (8087), 1096–1104 (2025).
- [6] L. Ren, et al., 3D steerable, acoustically powered microswimmers for single-particle manipulation. *Science advances* 5 (10), eaax3084 (2019).
- [7] H. Han, et al., Imaging-guided bioresorbable acoustic hydrogel microrobots. *Science Robotics* 9 (97), eadp3593 (2024).