Supplementary Material (ESI) for Lab on a Chip

A Millisecond Micromixer via Single-Bubble-Based Acoustic Streaming

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1. Device Fabrication

The Polydimethylsiloxane (PDMS) microchannel was fabricated using standard lithography and mold replica technique (Fig. S1). The silicon mold for the microchannel was patterned by photoresist (Shipley 1827, MicroChem, Newton, MA) and etched by a Deep Reactive Ion Etching (DRIE, Adixen, Hingham, MA) process to a depth of 155 µm. In order to reduce surface energy and damage to the PDMS channel during the demolding process, the silicon mold was coated with 1H,1H,2H,2H-perfluorooctyl-trichlorosilane (Sigma Aldrich, St. Louis, MO) in a vacuum chamber after DRIE. Sylgard™ 184 Silicone Elastomer Base and Sylgard™ 184 Silicone Elastomer Curing Agent (Dow Corning, Midland, MI) were mixed at a 10:1 weight ratio and cast onto the silicon mold. The uncured PDMS on the silicon mold was then left in a -20 °C freezer for 30 min to remove bubbles and later stored in a 65 °C oven for 2 h to cure. After peeling the PDMS from the silicon mold, inlets and outlets were drilled into the PDMS using a silicon carbide drill bit. Finally, the PDMS was bonded to the plastic substrate by activating oxygen plasma.

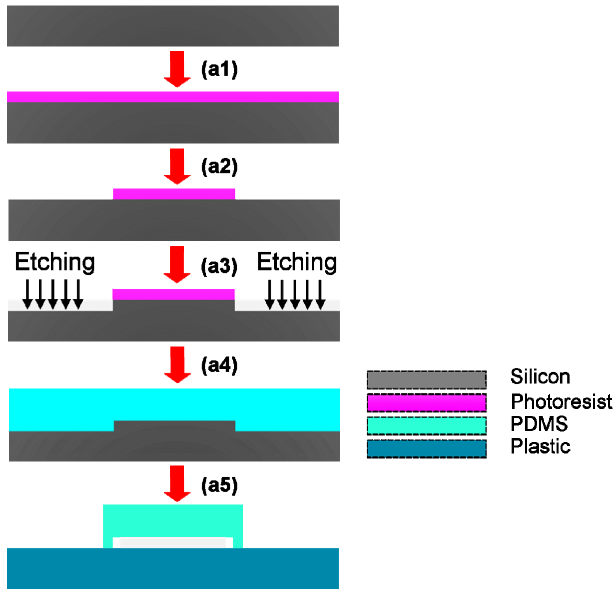

Fig. S1. Fabrication process of the microchannel.

2. Detailed Calculation of Bubble Resonance Frequency

The resonance frequency, f, of an air bubble trapped within the horse-shoe structure in stationary fluid was estimated by the small-amplitude behavior of the Rayleigh-Plesset equation,[1]

$$f^2 = \frac{1}{4\rho\pi^2 a^2}\left\{3\kappa\left(p + \frac{2\sigma}{a}\right) - \frac{2\sigma}{a}\right\}, \qquad (1)$$

where ρ is the density of the water (1000 kg·m^{-3}), σ is the surface tension of water (0.0728 N·m^{-1}), κ is the polytropic exponent for a bubble containing air (1.4),[2] and p is atmospheric pressure (101.325 kPa). From the curvature of the trapped air bubble, we have extrapolated the radius of the bubble, a = 41 µm. Using these parameters, the resonance frequency was calculated to be 81.63 kHz. Experimentally, the resonance frequency was measured to be 70.1 kHz. The discrepancy between the experimental and theoretical resonance frequencies can be attributed to the oblate shape of the trapped air-bubble since a spherical shape was assumed for theoretical calculations.

3. **Verification of Homogeneous Mixing**

Acoustic pressure is proportional to the applied voltage. Ideally, higher voltages may result in stronger acoustic streaming; however, as pressure is increased, the bubble becomes unstable, giving rise to transient cavitation (i.e. bubble growth and subsequent collapse). The chosen voltage (8 V_{PP}) allowed the bubble to remain steady while providing sufficient stress for rapid, homogenous mixing.

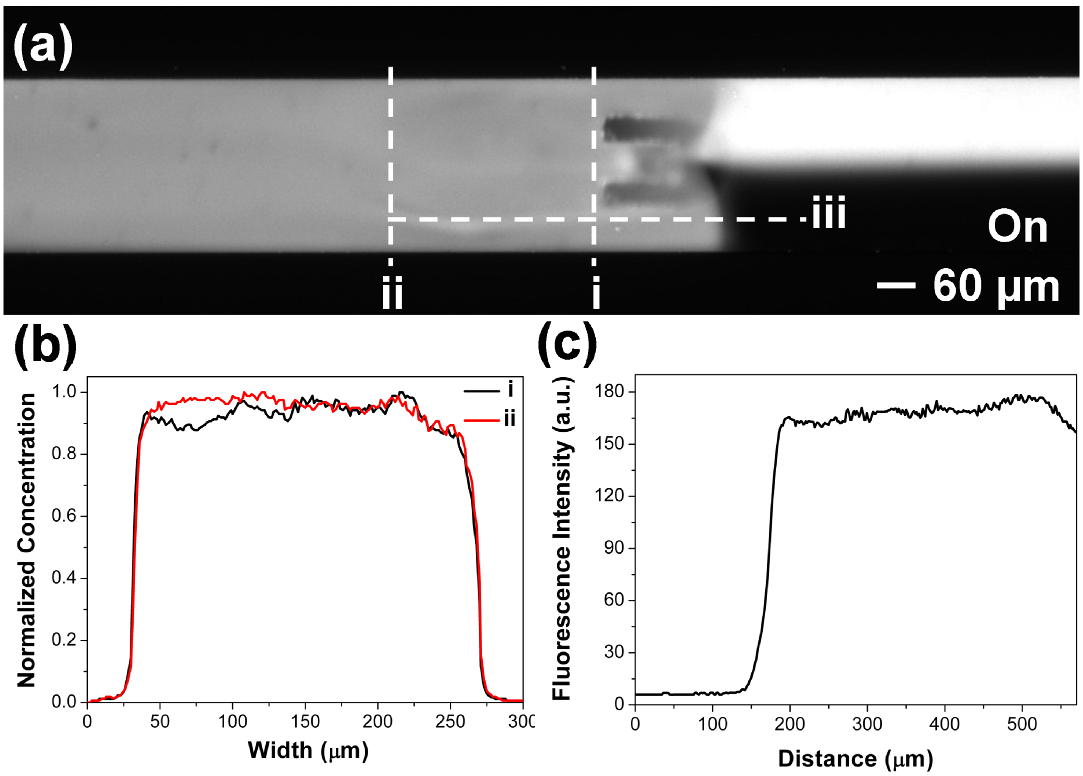

Fig. S2 Characterization of the mixing performance. (a) Homogenized mixing of DI water and fluorescent dye in presence of acoustic waves. (b) Plot of normalized fluorescent concentration across the channel width in positions i and ii shown in (a). (c) Plot of fluorescent intensity along the dashed line in figure (a) marked as iii.

To verify that uniform mixing of the two fluids is achieved just after the fluids pass the horse-shoe structure, we measured the gray-scale value of the images obtained. The cross-sectional dye concentration profile (vertical dashed lines in Fig. S2a) was measured and normalized against its own peak intensity (Fig. S2b). A uniform gray-scale distribution was observed once the fluids passed the horse-shoe structure. To verify that the intensity was homogenous near the bubble, the fluorescent intensity as a function of location (Fig. S2c) was plotted along the horitontally dashed line (the unmixed to mixed region) in Fig. S2a. The plot suggests that fluorescent intensity was constant once the fluids pass the horse-shoe structure, suggesting fast and homogenous mixing.

3. Video Captios

Video 1. The video shows the single bubble trapping process when deionized (DI) water was injected into each inlet at a flow rate of 5μl•min^{-1}. As the fluid passed through the PDMS horse-shoe structure, an air bubble was trapped due to surface tension.

Video 2. Microparticle (diameter: 1.9 μm) solution was injected into the microfluidic channel. Due to surface tension a single air bubble was trapped. The resonance frequency of the single bubble was experimentally determined to be 70.1 kHz. Pressure and velocity fluctuation due to bubble oscillation resulted in a vigorous microstreaming phenomenon around the bubble as shown in the video.

Video 3. The video shows the mixing effect of fluorescein and DI water as the fluids pass the horse-shoe structure at a combined flow rate of 16 μl•min^{-1}. Trasition from the non-mixing laminar flows and the fully mixed homogizied solution was obvious.

References

1. T. G. Leighton, *The Acoustic Bubble*, Academic Press, London, 1994.

2. L. A. Crum, J. Acoust. Soc. Am., 1983, **73**, 116-120.