Unique flow transitions and particle collection switching phenomena in a microchannel induced by surface acoustic waves

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We present an experimental approach for controlled switching between uniform flow for pumping and vortical flow for mixing in a microchannel fabricated onto a piezoelectric substrate. For particle laden fluids, this arrangement permits a choice between transport and alignment of microparticles. Using surface acoustic waves with amplitudes beyond 1 nm, the transition from uniform to mixing flows occurs when the acoustic wavelength in the fluid is reduced to a dimension smaller than the channel width, i.e., $\lambda_f \geq \mathcal{W}_{ch}$ for uniform flow and $\lambda_f < \mathcal{W}_{ch}$ for mixing flow. On the other hand, using relatively weak surface acoustic waves with amplitudes below 1 nm, particles in an initially homogeneous suspension agglomerate into equally spaced lines with a separation of $\lambda_f/2$. Switching the transducer between its fundamental resonant frequency f_0 and its first harmonic frequency $f_1^+ \sim 2f_0$ causes a switch between uniform and mixing flow, while switching between large and small amplitude excitation allows one to choose whether to collect the particles in the flow along nodal lines parallel to the channel. These results are uniquely achieved without requiring the microfabrication of complex microchannel architectures and control schemes; the switching is simply achieved by adjusting two parameters: the acoustic excitation frequency and amplitude. © *2010 American Institute of Physics*. [doi:10.1063/1.3524511]

The ability to transport fluid and particulate matter in microchannels without syringe pumps remain a challenge. An added complexity, but one that is often necessary in many microfluidic operations, is the incorporation of schemes to mix fluids and manipulate particles within microchannels, the former often requiring the fabrication of complex three-dimensional architectures such as baffles or flow-splitters, and the latter requiring either large lasers for optical trapping or external electric fields for dielectrophoresis. Recently, we and others[1] have demonstrated the possibility for exploiting acoustic streaming[2] generated in a liquid due to surface acoustic wave (SAW) excitation for a host of microfluidic operations[3] that include not only the ability to drive microchannel fluid flow,[4,5] particle alignment,[6,7] and cell sorting,[8] but also to heat,[9] vibrate,[10,11] mix,[12] jet,[13] and even atomize fluids,[14] not to mention manipulating particles within drops.[11,12] In our recent work on SAW microchannel transport[5] in which grooved microchannels were fabricated in the piezoelectric (128° Y-cut X-propagating lithium niobate) substrate along that the SAW propagates, we showed that under strong acoustic excitation, i.e., substrate displacement $\xi > 1$ nm, it is possible to drive both uniform and oscillatory microchannel flows depending on the channel width $\mathcal{W}_{ch}$ relative to the acoustic wavelength in the fluid λ_f (see Fig. 1). Unidirectional flow with typical speeds of around 10 mm/s was observed when $\mathcal{W}_{ch} \leq \lambda_f$, whereas oscillatory mixing flows occur when $\mathcal{W}_{ch} > \lambda_f$. In addition, an initially homogeneous suspension of microparticles seeded within the flow field were observed to agglomerate along a central line when the width of the channel was comparable to the acoustic wavelength ($\mathcal{W}_{ch} < \lambda_f$) due to the presence of a pressure node at this location, even when the SAW is being driven along the channel, itself along the *X*-axis. This concentration behavior was found to weaken as the width of the channel was reduced to less than the acoustic wavelength: the narrower the channel, the more uniform the flow. On the other hand, under a weak acoustic excitation $\xi \leq 1$ nm, the microparticles were seen to agglomerate into equally spaced lines (with a separation of $\lambda_f/2$) due to the presence of an acoustic standing wave across the channel and to slowly move in opposition to the SAW propagation direction due to slow streaming. In this paper, we show that it is possible to switch back and forth between the phenomena described above, i.e., between unidirectional flow and oscillatory mixing flow, or

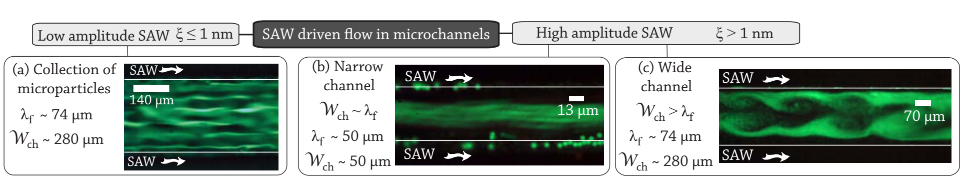

FIG. 1. (Color online) Schematic summarizing the phenomena observed in this study. (a) Application of low amplitude SAW $\xi \leq 1$ nm results in the collection of microparticles along pressure nodal lines across the channel whereas high amplitude SAW $\xi > 1$ nm drives either (b) uniform flow when $\mathcal{W}_{ch} < \lambda_f$ (not shown) or both collection and unidirectional throughflow in narrow channels when $\mathcal{W}_{ch} \approx \lambda_f$, or (c) an oscillatory mixing flow when $\mathcal{W}_{ch} > \lambda_f$.

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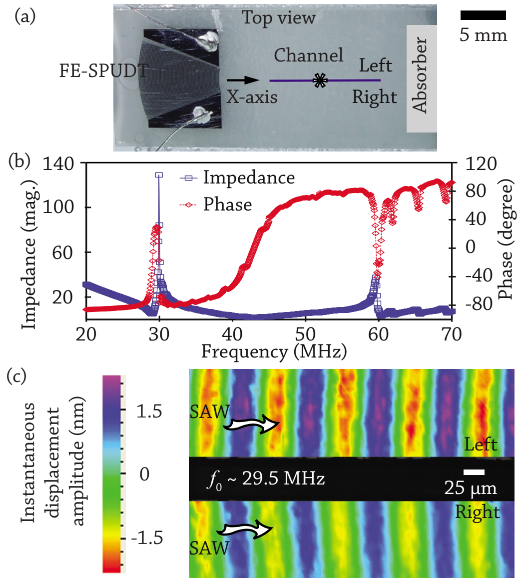

FIG. 2. (Color online) (a) An FE-SPUDT fabricated on the lithium niobate substrate in which a grooved microchannel is cut along the focused region of the transducer. (b) The measured impedance and phase spectra of the transducer, showing the fundamental SAW resonant frequency $f_0 \approx 29.5$ MHz and the first harmonic frequency $f_1^+ \approx 59$ MHz. (c) Amplitude of the instantaneous surface displacement perpendicular to the substrate surface when the transducer is excited by a sinusoidal signal at $f_0 \approx 29.5$ MHz.

between unidirectional flow and multiple collection lines, in a single microchannel of *fixed dimension* simply by driving the focusing elliptical single-phase unidirectional transducer[15] (FE-SPUDT) used to generate the SAW on the piezoelectric substrate at its fundamental resonant frequency f_0 and first harmonic frequency f_1^+. Essentially, this proposed approach eliminates the need in our previous work to use multiple channels of different widths to traverse across the $\mathcal{W}_{ch} \leq \lambda_f$ and $\mathcal{W}_{ch} > \lambda_f$ conditions required to achieve the switching.

Figure 2(a) shows the FE-SPUDT that combines the unidirectional propagation characteristics of a single-phase unidirectional transducer with the ability to deliver focused SAW using curved electrodes.[12,15] We then fabricated a rectangular microchannel $\mathcal{L}_{ch} = 10$ mm long, $\mathcal{D}_{ch} = 180$ μm deep, and $\mathcal{W}_{ch} = 50$ μm wide, into the SAW device using a KrF 248 nm exciplex laser (Extech Ltd., Oxford, England), as shown in Fig. 2(a). In all the experiments, the damping material (α-gel, Geltec Ltd., Yokohama, Japan) was used to minimize wave reflection from the substrate ends. Figure 2(b) shows the impedance and phase angle of the transducer measured using a precision impedance analyzer (4294A, Agilent Technologies, USA). The fundamental resonant frequency was $f_0 \approx 29.5$ MHz and the first harmonic frequency was $f_1^+ \approx 59$ MHz. For a 29.5 MHz SAW, $\lambda_{SAW} \approx 67$ μm and $\lambda_f \approx 50$ μm, whereas for a 59 MHz SAW, $\lambda_{SAW} \approx 135$ μm and $\lambda_f \approx 25$ μm. Figure 2(c) shows the propagation pattern of the SAW in the area indicated with an asterisk in Fig. 2(a), generated with the $f_0 \approx 29.5$ MHz FE-SPUDT along both sides of the microchannel and measured using the scanning laser Doppler vibrometer (Polytec PI MSA-400, Waldbrunn, Germany). Due to a slight misalignment of the channel, the amplitude of SAW is slightly higher on the left side of the channel, although this can be compensated by using a double aperture FE-SPUDT.[16] In the experiment,

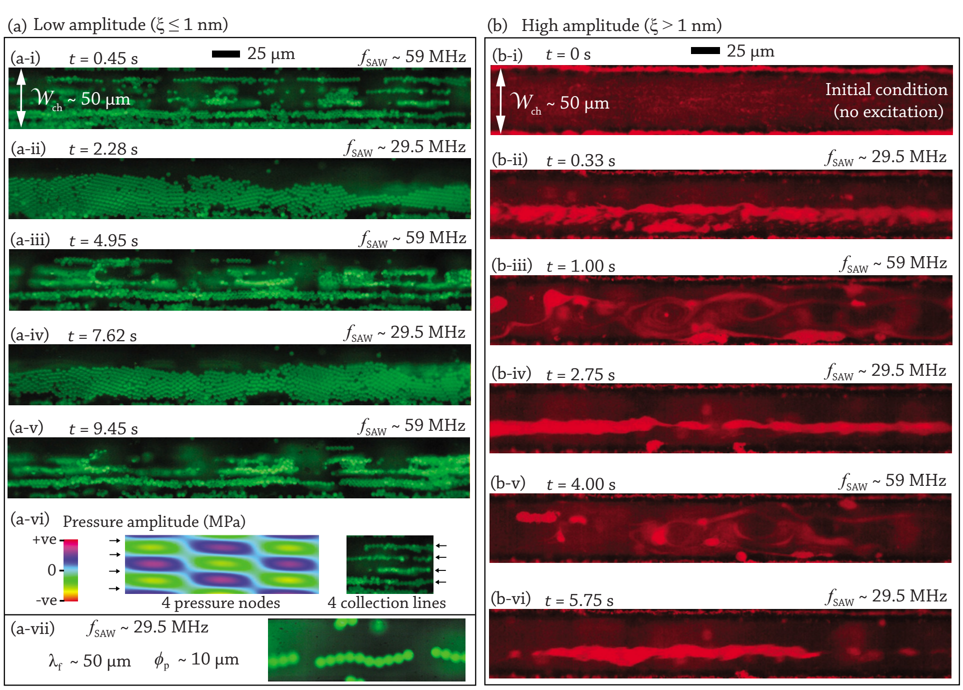

FIG. 3. (Color online) (a) Switching between particle transport and agglomeration in a 50 μm wide channel with low excitation amplitudes: (aii) and (aiv) particle transport under unidirectional flow when the SAW is driven at f_0, and, (ai), (aiii), and (av) particle agglomeration into four collection lines when the SAW is driven at f_1^+. Image (avi) shows a comparison between the numerical and experimental results, showing that particles collect at along the nodes of the pressure field and why four nodal lines are generated when the SAW is driven using $f_1^+ \approx 59$ MHz excitation. (avii) Using 10 μm particles, we demonstrated the formation of a single collection line under f_0 excitation. (b) Switching between uniform and unidirectional throughflow and oscillatory mixing flow in a 50 μm wide channel with high excitation amplitudes: (bi) no excitation and no flow, (bii), (biv), and (bvi) unidirectional flow when the SAW is driven at f_0, and, (biii) and (bv) mixing, transverse oscillatory flow when the SAW is driven at f_1^+. The estimated longest transition time for the fluid to change from one state to the next state is approximately 0.2 s. The area of the channel where all images were captured is indicated with an asterisk in Fig. 2(a) (enhanced online). [URL: http://dx.doi.org/10.1063/1.3524511.1] [URL: http://dx.doi.org/10.1063/1.3524511.2]

$\phi_p = 1$, 5, and 10 μm diameter spherical fluorescent polystyrene particles suspended in an aqueous solution (BioScientific, Gymea, NSW) were dispensed into the channel using a syringe. Particles of 1 μm facilitate the observation of the flow field since these particles are below the critical size at which acoustic forces on the particles themselves dominate the drag force induced by the fluid's acoustic streaming.[17] Likewise, particles of 5 and 10 μm facilitate the observation of particle collection due to the stronger acoustic radiation force exerted on these particles.[15,16] The motion of the particles was subsequently recorded via high speed video (Olympus iSpeed) at a speed of 60 fps through a stereomicroscope (Olympus BXFM, Tokyo, Japan) under fluorescent illumination supplied by an EXFO X-Cite 120 mercury light source (Olympus, Tokyo, Japan).

Figure 3(a) shows the results for low amplitude SAW where the microparticle collection can be switched from (ai) particle agglomeration into four collection lines to (aii) particle transport along a single line under unidirectional flow, (aiii) to four collection lines, (aiv) to a single collection line, and subsequently back to four collection lines again. The number of collection lines C_ℓ is always an integer number of nodal lines with separation $\delta_{st} \approx \lambda_f/2$ that fit within a channel width. Therefore, under f_1^+ excitation, four collection lines were observed in the 50 μm wide channel, i.e., $C_\ell \sim \mathcal{W}_{ch}/\delta_{st} \approx 4$, consistent with the numerical result [Fig. 3 (avi)] obtained using the previously developed model.[5] However, under f_0 excitation, the results show a single collection line instead of the two collection lines, suggesting the width of the channel is not the same as the acoustic wavelength. Figure 3(b), on the other hand, shows the ability to switch back and forth between unidirectional throughflow [Fig. 3 (bii), (biv), and (bvi)] and oscillatory throughflow [Fig. 3 (biii) and (bv)], thus demonstrating the possibility of pumping a fluid and subsequently mixing it within the same microchannel without the need for complex microfluidic mixing schemes or the application of additional external forces. Note here that the slightly higher intensity of SAW on the left side of the channel [see Fig. 2(c)] generates an unbalanced acoustic pressure force on the particles across the width of the channel, and therefore we observed that particles in Fig. 2 were not concentrated at the central line but slightly closer toward the right side of the channel wall. Nonetheless, the results taken together clearly demonstrate the possibility for switching between different flows in a single microchannel simply by toggling between the fundamental resonant and first harmonic frequencies and the ability to selectively drive particle collection by manipulating the vibration amplitude.

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