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Concentration and mixing of particles in microdrops driven by focused surface acoustic waves

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***Abstract*—The concentration and indeed mixing of particle suspensions are important procedures in microfluidic processes. Relying on diffusion for mixing leads to unreasonably long mixing times, and enhancing or avoiding it by promoting chaotic mixing typically relies on complex geometries. Concentric circular and elliptical single-phase unidirectional transducers (SPUDTs) were used to focus the SAW, with a straight SPUDT as a benchmark for comparison. Due to the increased wave intensity and asymmetry of the wave, we found both circular and elliptical SPUDTs concentrate particles in under one second, one order of magnitude faster than the straight SPUDT and several orders of magnitude faster than conventional microscale devices. The concentric circular SPUDT was found to be most effective at a given input power since it generated the largest azimuthal velocity gradient within the fluid to drive particle shear migration. On the other hand, the concentric elliptical SPUDT generated the highest micromixing intensity due to the more narrowly focused SAW radiation that substantially enhances acoustic streaming in the fluid.**

I. Introduction

The concentration of particle suspensions is an important procedure in microfluidic processes. For example, the separation of red blood cells from plasma is an important and necessary pre-treatment step in blood diagnostics [1]–[3]. Due to the low Reynolds numbers at these scales, the generation of turbulence to effect mixing is equally difficult. However, there has been some progress in micromixing, with two main categories: (i) passive mixers which rely on diffusion or chaotic advection in the absence of any external energy input, and (ii) active mixers using external energy to drive the mixing process [4]. Relying on diffusion for passive mixing, in particular, leads to unreasonably long mixing times when working on the microscale as the diffusion time scales as $T \sim L^2/D$, where L is the characteristic length scale of the system, and $D \sim 10^{-9}$ is the diffusion coefficient. Enhancing diffusivity or avoiding it by promoting chaotic mixing in passive mixers typically relies on complex, and therefore inconvenient geometries in mixing channels. Many active mixer designs have been investigated to avoid such problems, exploiting pressure [5], dielectrophoresis [6], thermal [7], [8], and other forcing mechanisms [4]. The same liquid recirculation generated using electrohydrodynamics and SAWs for particle concentration can be used to drive dispersion *instead of* concentration to achieve effective micromixing [1], [3]. The focus of this paper will be on using focused SAWs to drive microfluidic bulk liquid recirculation for rapid particle concentration and micromixing using an 128° rotated Y-cut X-propagating Lithium Niobate ($LiNbO_3$, LN) wafer to generate a Rayleigh SAW on the piezoelectric substrate.

Tan *et al.* [9] showed that SAW may be exploited to pump liquids in microchannels at velocities up to several centimeters per second, typically one or more orders of magnitude higher than currently available micropump technology [10]. In particular he showed that using electrokinetics — which is the current method of choice in microfluidics [11] — similar translation speeds [12] are also possible with discrete drops in open microfluidic platforms, far exceeding that possible with electrowetting [13]. On the other hand, Li *et al.* [3] demonstrated that it is possible to generate a net *azimuthal* component to the acoustic streaming by breaking the symmetry in the distribution of SAW radiation along the width of a drop and transverse to the radiation propagation direction.

Microparticles in an aqueous suspension within a droplet may be concentrated out and deposited at the droplet's bottom centre in around 15 seconds [3]. Such rapid concentration effects is in part due to particle migration under shear gradients [1], [14] between regions of high shear at the periphery of the drop due to the convection driven by streaming phenomenon and regions of low shear at the centre of the drop where the linear velocities become negligible. Here we investigate the effect of focusing the SAW radiation on the substrate to a narrow region far smaller than the IDT aperture to increase the amount of radiation passing into the fluid drop. This is accomplished using an electrode-width-controlled (EWC) single-phase unidirectional transducer (SPUDT), originally proposed by Hartmann, et al. over twenty-five years ago for telecommunications [15]. In doing so, the time required to perform concentration will be shown to decrease by one order of magnitude while using lower input powers than reported previously [3], representing concentration times one to two orders of magnitude faster than electrohydrodynamics [1], [2], [16] commonly used in active microfluidics devices.

II. Interdigital transducers

White and Voltmer [17] first reported the direct generation of SAW on a piezoelectric substrate using an *interdigital* *transducer* (IDT), dramatically simplifying the process of generating useful low-loss, MHz-order acoustic waves. The transducers used in this study combine the unidirectional propagation characteristics of the SPUDT configuration with curved electrodes to deliver the acoustic radiation to a smaller area near the focus of the IDT. A comparison of the effects of focusing is provided by using a straight EWC-SPUDT (Fig. 1(a)) along with two focusing elliptical EWC-SPUDTs with eccentricities of approximately 0.831 (E1) and 0.616 (E2), respectively (Fig. 1(b) and (c)), and a circular EWC-SPUDT (Fig. 1(d)). Each of these transducers had 30 pairs of electrodes and were fabricated on 0.5-mm thick, 127.68° Y-X LN single crystal substrates using standard photolithography processes. Figure 2 shows the SAW propagation

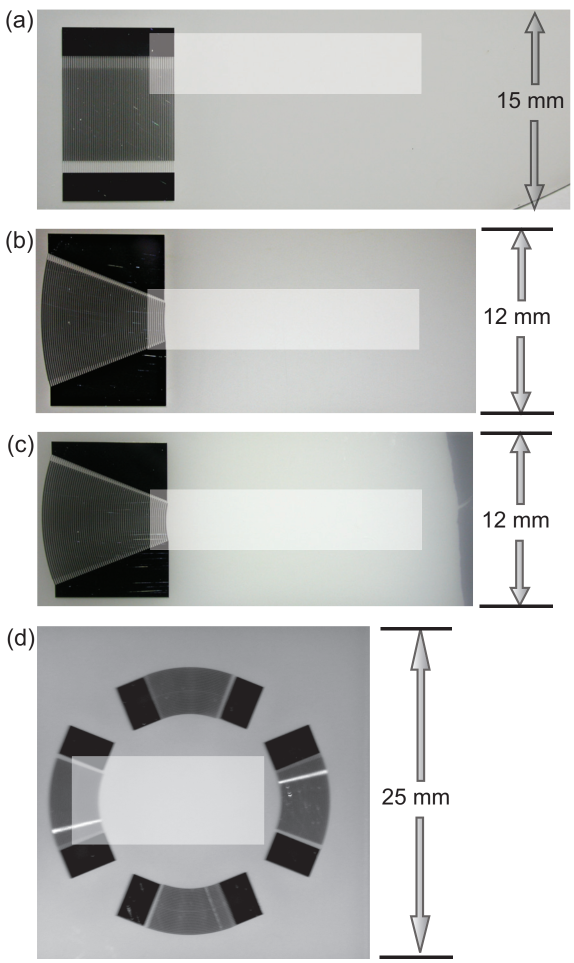

Fig. 1. The SPUDTs fabricated and used in this work, including a (a) 30 MHz straight SPUDT, a (b) 30 MHz focusing elliptical SPUDT (E1) with an approximate eccentricity of 0.616, a (c) 30 MHz focusing elliptical SPUDT (E2) with an approximate eccentricity of 0.831 and a (d) 30 MHz focusing circular SPUDT. The vibration displacement perpendicular to the substrate surface was measured using a scanning laser vibrometer across the area highlighted in each image; the results of the vibrometer scans are shown in Fig. 2.

patterns obtained using scanning Laser Doppler Vibrometry (LDV; Polytec PI MSA-400, Waldbrunn, Germany) for the straight SPUDT, the elliptical (E1 and E2) SPUDTs, and the circular SPUDT. A comparison between Figs. 2(a) and 2(b) clearly show that focusing of the SAW into a high intensity beam along the focal line of the transducer is achieved with the use of the elliptical SPUDT. By further reducing the eccentricity of the elliptical geometry, the focused beam becomes more narrow and intense.

Figure 2(c) shows a highly intensified SAW at a distance of approximately 7 mm from the SPUDT aperture with a smaller eccentricity of 0.616. The SAW eventually focuses to a spot when the eccentricity decreases to zero, in which case the ellipse becomes a circle, as seen in Fig. 2(c) and (d). The cross in each figure panel indicates the approximate location where a droplet was dispensed and irradiated with SAW to perform micromixing or particle concentration and dispersion. The locations were selected along the edges of the SAW radiation field in the substrate in order to generate an asymmetric radiation field across the width of the droplet; in each case the distance of the drop from the IDT's output aperture was fixed at 5 mm.

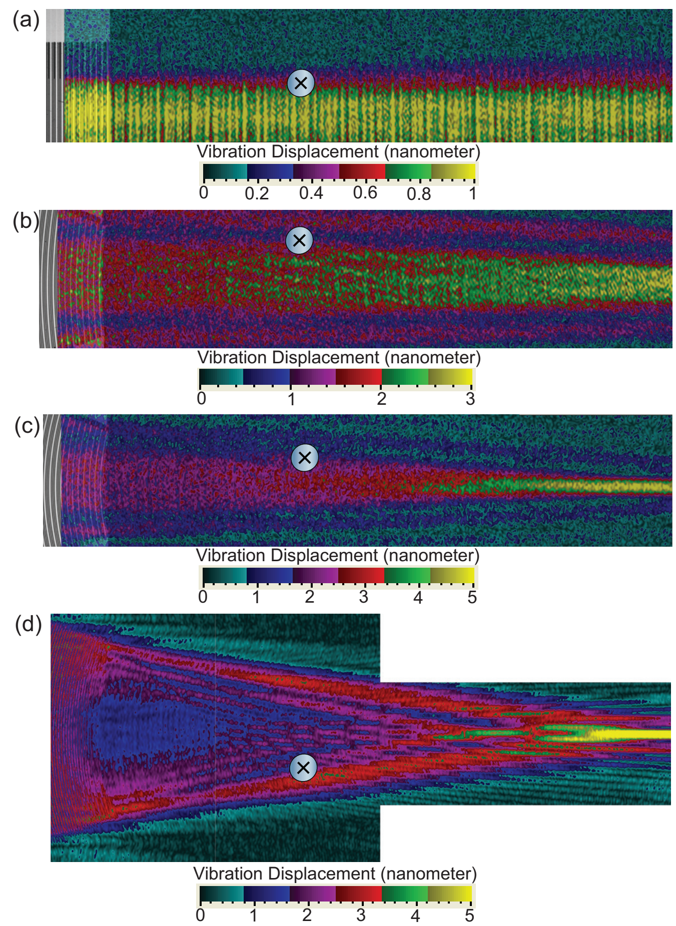

Fig. 2. The amplitude of surface displacement perpendicular to the lithium niobate substrate surface as SAW propagates from (a) a straight SPUDT, (b) a concentric elliptical SPUDT with eccentricity 0.831(E1), (c) a concentric elliptical SPUDT with eccentricity 0.616 (E2) and, (d) a concentric circular SPUDT. The scanned area for each transducer corresponds to the highlighted area shown in Fig. 1. Each cross indicates the position at which a drop will be placed to study SAW-induced mixing and particle concentration and dispersion.

III. EXPERIMENTS

The time required to concentrate microparticles out of a homogeneous aqueous suspension for a variety of input powers was measured with each of the different 30 MHz SPUDT designs. Fluorescent polystyrene particles 0.5 μm in diameter (Duke Scientific, Victoria, Australia) were diluted in deionised water to a concentration of approximately 0.1 % of solid particles. The 0.5 μl drops of these particle suspensions were then placed 5 mm from the SPUDT aperture at the periphery of the focused region of the propagating wave, as illustrated in Fig. 2.

The same set of SPUDT designs were used to compare micromixing efficacy. A 0.5 μl deionized water drop dyed blue with food dye was carefully pipetted onto a 2 μl drop of glycerine dyed green and placed directly on the Teflon-coated surface. The water drop was slowly pipetted onto the glycerin free surface to avoid mixing due to inertial currents arising from the impact of the drop; the relatively high viscosity of glycerine was beneficial in this regard.

IV. RESULTS AND DISCUSSION

Figure 3 shows sequential images of the induced drop rotation which acts to rapidly concentrate the suspended particles towards the centre of the drop on the substrate for a concentric circular SPUDT. Similar concentration patterns were observed for the concentric elliptical (E2) and straight SPUDTs. Figure 4 shows the normalised standard deviation of the pixel intensity against time for three different input powers for the concentric circular SPUDT, indicating the concentration time is decreased as the input power (and therefore the SAW amplitude) is increased. Qualitatively, the concentration behavior is similar for all the SPUDT devices, though the speeds at which the concentration occurs for each SPUDT design differs.

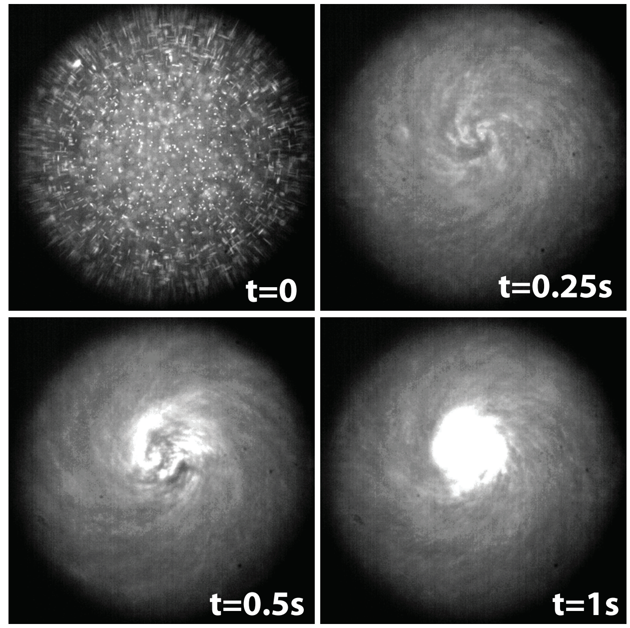

Fig. 3. Concentration of particles in the 0.5 μl drop via drop rotation induced by acoustic radiation from the focused elliptical SAW. Similar patterns were observed for the concentration driven by the circular and straight SPUDTs.

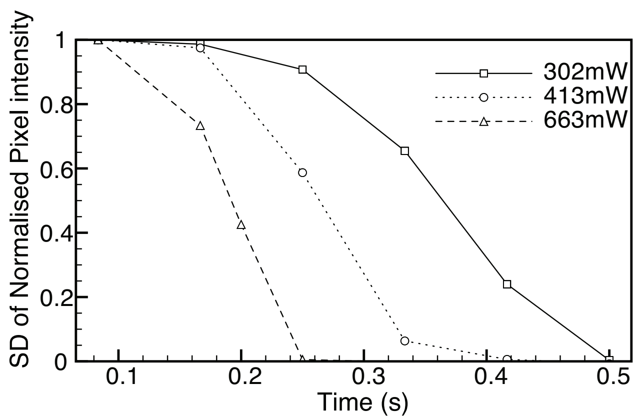

Fig. 4. The normalized pixel intensity is a measure of the particle concentration; plotted here against time using the concentric circular SPUDT at different power levels it shows an increase in input power reduces the time required to concentrate the particles out of suspension.

The time to achieve particle concentration versus a range of powers for each SPUDT design is provided in Fig. 5, again demonstrating the superior performance of the focusing SPUDTs over the straight SPUDT. In both of the focusing SPUDT designs, we note that the particle concentration time is extremely rapid, occurring in just under one second. The difference in the concentration times can be explained by recalling the mechanism by which the particles concentrate: shear-induced migration arising due to the shear gradients across the radial axis of the drop from SAW-driven streaming. The larger the shear gradient, the faster the particles are transported into the centre of the droplet.

The progression of mixing of water and glycerin may be quantified using the ratio of effective diffusivity D_{eff} versus the molecular diffusion without convection $D_0 \sim 10^{-9}$ m^2/s for a droplet size on the order of $L \sim 10^{-3}$m; D_{eff}/D_0 provides a measure of the mixing enhancement. Figure 6 compares this mixing enhancement for each SPUDT design. By using a log-log plot and determining the slope of the mixing enhancement versus time data for each SPUDT design, it is possible to compare the effectiveness of mixing in each design with a single parameter: the exponent n at which the mixing enhancement scales with power, i.e., $(D_{\text{eff}}/D_0) \sim P^n$. Generally, the scaling occurs with values of n greater than or equal to 2. Specifically, it scales as $n = 2$ for the straight SPUDT, $n = 2.14$ for the elliptical (E1) SPUDT, and $n = 2.3$ for the circular SPUDT.

V. CONCLUSIONS

Rapid concentration of suspensions of particles and mixing of fluids in microdrops was demonstrated by producing acoustic streaming in drops via focused SAWs using straight, concentric circular, and elliptical SPUDTs. We show that the focused SPUDTs increase the concentration speed over a straight SPUDT by at least one order in magnitude. Since the shear-induced migration mechanism requiring a radial gradient

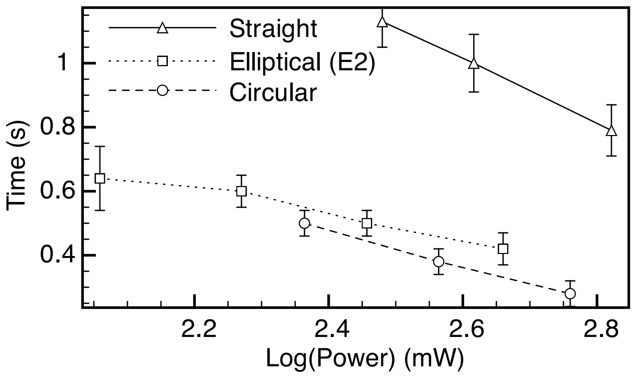

Fig. 5. Particle concentration times as a function of the applied power for the concentric circular, elliptical (E2), and straight SPUDTs.

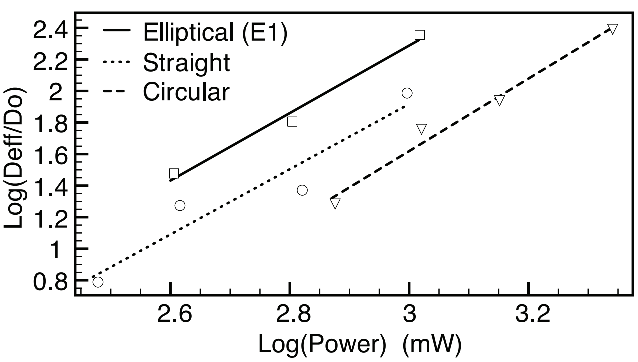

Fig. 6. Effect of the input power on the mixing enhancement, measured by the ratio of the effective diffusivity D_{eff} to the diffusivity due to pure diffusional mixing D_0 in the absence of SAW-driven convection when no power is applied.

in the azimuthal velocities appears to govern the particle concentration, the SPUDT that produces the largest secondary azimuthal recirculation for a given power is the most effective for concentrating the particles. As such, the concentric circular SPUDT was observed to be more efficient for particle concentration than the elliptical SPUDT. Nevertheless, we observe that both of these SPUDTs are able to concentrate the particles very rapidly in under one second. On the other hand, micromixing relies to a large extent on the primary acoustic streaming flow to transport the dye to the other regions of the drop of greater depth, especially in the present case when the dye is placed at the apex of the drop. With this arrangement, the elliptical SPUDT was observed to be the most effective for micromixing, increasing the effective diffusivity well beyond the results of the straight SPUDT. This is because the elliptical SPUDT provides the highest intensity of SAW radiation into the drop. In any case, these focusing SAWs provide a very rapid and effective mechanism for microfluidic manipulation, in particular, particle concentration and micromixing, which is one order of magnitude, if not several orders of magnitudes, faster than current microfluidic technology.

VI. Acknowledgements

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