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Radiation dominated acoustophoresis driven by surface acoustic waves

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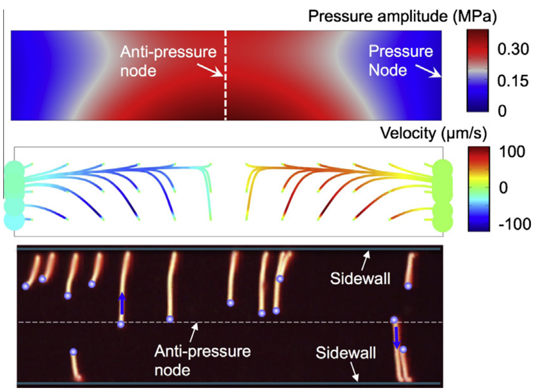
GRAPHICAL ABSTRACT



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ABSTRACT

Acoustophoresis-based particle manipulation in microfluidics has gained increasing attention in recent years. Despite the fact that experimental studies have been extensively performed to demonstrate this technique for various microfluidic applications, numerical simulation of acoustophoresis driven by surface acoustic waves (SAWs) has still been largely unexplored. In this work, a numerical model taking into account the acoustic–piezoelectric interaction was developed to simulate the generation of a standing surface acoustic wave (SSAW) field and predict the acoustic pressure field in the liquid. Acoustic radiation dominated particle tracing was performed to simulate acoustophoresis of particles with different sizes undergoing a SSAW field. A microfluidic device composed of two interdigital transducers (IDTs) for SAW generation and a microfluidic channel was fabricated for experimental validation. Numerical simulations could well capture the focusing phenomenon of particles to the pressure nodes in the experimental observation. Further comparison of particle trajectories demonstrated considerably quantitative agreement between numerical simulations and experimental results with fitting in the applied voltage. Particle switching was also demonstrated using the fabricated device that could be further developed as an active particle sorting device.

1. Introduction

In recent years, there has been a growing interest in applying acoustic fields for non-invasive manipulation of micron-sized particles in microfluidics [1,2]. In particular, acoustic manipulation approach exhibits no or minor negative impact on the viability

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and functionality of biological cells [3], which makes it more preferred in cell analysis applications compared to other cell manipulation techniques. Acoustically induced particle motion, referring to acoustophoresis, is typically implemented by generating a standing acoustic field across a microfluidic channel. Suspended particles exposed to the standing field are subjected to two acoustic effects, which are acoustic radiation force and Stokes drag force from acoustic streaming flow. The acoustic radiation force strongly depends on the particle's physical property, which enables selective manipulation of synthetic particles or biological cells based on their intrinsic physical properties.

Earlier studies typically attached bulk acoustic transducers onto silicon microfluidic channels to construct acoustophoresis-based microfluidic devices [3–10]. Constructive interference of incident acoustic waves and reflected waves can generate a standing acoustic wave field across the channel for acoustophoresis-based particle manipulation. Bulk acoustic transducers are incompatible with soft polymer materials due to their poor acoustic reflection property. However, these polymer materials have been widely used in the fabrication of microfluidic devices since the development of soft lithography technique [11]. Therefore, surface acoustic wave (SAW) transducers have gained significant attention due to its easy integration with soft polymer-based microfluidic devices [12,13]. SAW-based particle manipulation has been successfully applied for focusing [14,15], separation [16–22], patterning [23–25], and enrichment [26] of particles or biological cells for various microfluidic applications. In these applications, acoustic streaming effect is typically minimized to implement acoustic radiation dominated particle manipulation. Instead, acoustic streaming usually generated by a single travelling SAW has been demonstrated as one of the most promising techniques for non-invasive manipulation of fluids or droplets in microfluidics [27–36].

Parallel to the rapidly increasing experimental demonstration on acoustophoresis in microfluidics, further efforts are also required on the numerical simulations to gain an insightful understanding of the acoustophoresis-based particle manipulation and to optimize the design of acoustic-based microfluidic devices. Previous numerical studies mainly focused on acoustophoresis driven by bulk acoustic waves [37–41]. Most recently, Tan et al. performed a comprehensive numerical investigation on SAW-induced capillary wave motion arising from the acoustic streaming effect [42]. Johansson et al. developed a numerical model to simulate the acoustic field generated by SAW transducers in liquids [43]. However, numerical modeling of acoustophoresis driven by SAWs has still been largely unexplored.

In this work, we present a numerical study of acoustic radiation dominated acoustophoresis driven by a standing surface acoustic wave (SSAW) field. The other acoustic effect, acoustic streaming, is a fluid motion arising from the acoustic attenuation along the wave travelling path. In our SAW-based microfluidic device, the channel height is much smaller than the SAW wavelength, resulting in very limited acoustic attenuation along the fluid, and acoustic streaming is thus negligible in this study. This acoustic radiation dominated region has also been observed in other experimental studies [44,45]. The developed numerical model is able to simulate the piezoelectric effect in the solid substrate and the SSAW field in the fluid. The acoustic radiation force acting on suspended particles can be calculated from the distribution of acoustic pressure in the fluid, based on which the trajectories of individual particles can be predicted to evaluate the acoustophoresis response to SAW excitation. The simulated SAW-induced acoustophoresis was compared to experimental observation obtained from fabricated SAW-based microfluidic devices, which has demonstrated both qualitative and quantitative agreement. This numerical model is generally applicable for the design of SAW-based microfluidic devices in the application of acoustic radiation dominated particle manipulation.

2. Theory and design

2.1. Acoustic radiation

Fig. 1a and b show a typical configuration of SAW-based microfluidic device including a microfluidic channel located between two interdigital transducers (IDTs) patterned on a piezoelectric substrate. When excited by an AC signal, the IDT can convert an electrical field into an acoustic wave. In this design, two identical travelling SAWs propagate toward the channel in opposite directions. As a result, constructive interference of the two SAWs gives rise to a standing acoustic field across the channel. Particles exposed to the standing field are subjected to a time-averaged acoustic radiation force, given as the gradient of a radiation force potential [46]

$$\langle \mathbf{F}_{ac} \rangle = -\nabla U_{ac}, \tag{1}$$

where the radiation force potential is written as

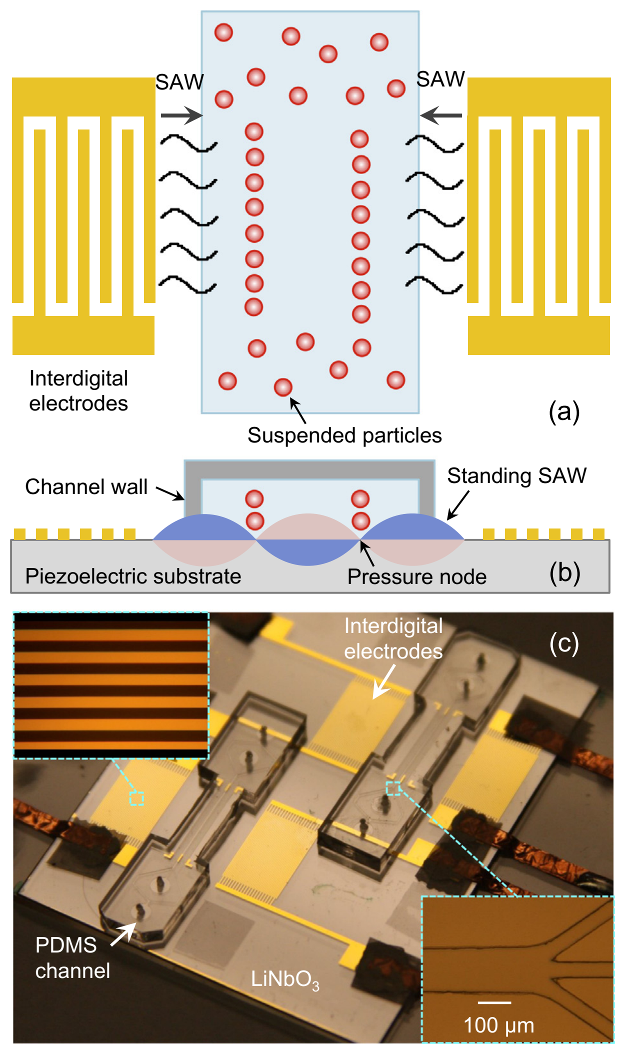

Fig. 1. (a) Schematic illustration of particle focusing into two parallel lines using a SSAW field generated by two IDTs on both sides of the channel. (b) Cross-section of the SSAW-induced particle focusing. Two pressure nodes are located across the channel where suspended particles are aligned. (c) Photograph of two SAW-based microfluidic devices fabricated on a piezoelectric substrate. The upper-left inset shows the interdigital electrodes and the lower-right inset shows the trifurcation channel.