

Design and Optimization of a Traveling Surface Acoustic Wave (TSAW) Microfluidic Platform for Controlled Liposome Manipulation

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Summary:

We report on the design and optimization of a traveling surface acoustic wave (TSAW)-based microfluidic platform for controlled manipulation of vesicle-sized particles. The study focuses on device geometry, acoustic field distribution, and flow conditions to maximize manipulation efficiency. The optimized structure enables stable and tunable particle deflection, providing a foundation for future integration with sensing and sorting functionalities.

Keywords: acoustofluidics, surface acoustic wave, SAW, TSAW, liposome sorting, fluorescence detection

Background, Motivation and Objective

Surface acoustic wave (SAW)-based microfluidic platforms have been widely explored for contactless manipulation of microparticles and biological samples [1]. In particular, traveling surface acoustic waves (TSAWs) provide flexible actuation for particle deflection and have been successfully applied to high-speed cell handling in microfluidic systems [2, 3]. However, most previous studies have focused on sorting performance in rigid particles or living cells, while the device-level requirements for fragile vesicles like liposomes remain much less understood.

This limitation is especially important for liposomes and other soft vesicle-like objects, which are widely used as model systems for synthetic cells and as carriers in bottom-up synthetic biology [4]. The manipulation of such vesicles is governed not only by acoustic radiation forces but also by their susceptibility to deformation, rupture, and flow-induced instability. Systematic investigation of how channel geometry, transducer configuration, and operating conditions affect stable vesicle deflection is still lacking.

In this work, we focus on the design and optimization of a TSAW-based microfluidic platform for controlled manipulation of liposomes. Our objective is to identify key structural and operational parameters that enable stable and reproducible acoustic deflection, thereby establishing a device architecture suitable for

future integration with fluorescence-assisted liposome sorting.

Method

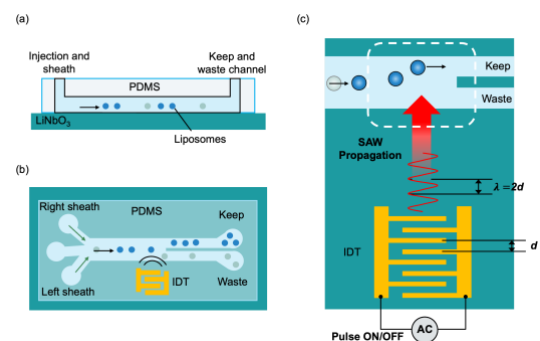


Fig. 1. Schematic of the TSAW-based microfluidic platform for liposome manipulation. (a) Cross-sectional view showing liposome flow within a PDMS channel on a LiNbO₃ substrate. (b) Top view of the microfluidic device with sheath flow focusing and separation into keep and waste outlets. (c) Working principle of TSAW actuation: acoustic waves generated by the IDT induce lateral deflection of selected liposomes toward the target outlet.

The proposed platform consists of a microfluidic channel integrated on a piezoelectric substrate (LiNbO₃) with interdigital transducers (IDTs) for generating TSAWs. Both straight and focused IDT geometries were implemented to investigate their influence on acoustic field distribution and particle manipulation performance.

To systematically analyze device behavior, finite element simulations were performed using COMSOL Multiphysics to model acoustic wave

propagation and the resulting pressure fields within the fluid channel. The simulations were used to compare acoustic energy localization, beam width, and intensity distribution between straight and focused IDT configurations.

Experimentally, microfluidic channels were fabricated and aligned with the IDTs, and vesicle-sized particles were introduced under controlled flow conditions. Liposomes were prepared using electroformation and polyvinyl alcohol (PVA) swelling methods to provide vesicles for manipulation experiments. Key design parameters, including IDT geometry, channel position relative to the acoustic propagation path, RF input power, and flow rate, were varied to evaluate their impact on particle deflection. Particular attention was given to identifying configurations that enhance acoustic energy confinement while maintaining stable flow conditions, which is critical for the manipulation of soft and deformable liposomes.

Results

The results demonstrate controlled lateral deflection of vesicle-sized particles under TSAW actuation in the proposed microfluidic platform. The observed particle trajectories show a clear dependence on both acoustic input power and device geometry, confirming the critical role of structural optimization.

COMSOL simulations reveal distinct differences in acoustic field distribution between straight and focused IDT configurations. The focused IDT generates a more confined acoustic beam with higher localized pressure intensity, whereas the straight IDT produces a broader and less concentrated acoustic field. These trends are consistent with experimental observations, confirming the enhanced deflection efficiency of the focused IDT.

An operational window was identified in which stable and reproducible particle deflection can be achieved without disrupting the flow profile. Within this regime, particles are consistently displaced from their original streamline, while maintaining continuous and stable flow conditions. Outside this range, either insufficient deflection or unstable trajectories were observed, indicating sensitivity to both acoustic and hydrodynamic parameters.

These results provide initial validation of the proposed device architecture and establish key design guidelines for vesicle-scale acoustofluidic manipulation. Ongoing work focuses on extending the optimized conditions to lipid vesicles and integrating fluorescence-based detection for selective liposome sorting.

References

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