Gaining Insight into Piezoelectric Materials for Acoustic Streaming

Numerical simulations are helping researchers understand the interplay between surface acoustic waves and microfluidic flow.

BY GARY DAGASTINE

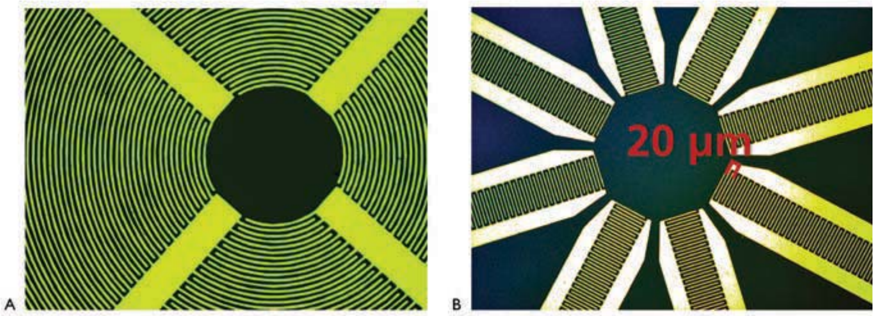


FIGURE 1. A) Optical image of interdigitated transducers or IDTs in a circular pattern on lithium niobate, used to launch surface waves toward a focal point. B) A series of linear IDTs in a two-port configuration. These devices can be used to test the acoustic streaming effect at select orientations over the surface, as well as for experimental validation of simulation results. The 20 µm segment corresponds to the size of the modeled region.

Microfluidic devices are key to many applications such as lab-on-a-chip sensors for medical diagnostics and low-cost flow sensors, but their small size makes effective pumping and fluid mixing challenging.

The mechanical behavior of fluid in geometries a few hundred microns and smaller can differ significantly from behavior at the macroscale. This is because at small scales the ratio of a fluid's surface area to its volume is much larger, and factors such as surface tension, heat transfer, and viscosity play more prominent roles.

Researchers at the SUNY College of Nanoscale Science and Engineering (CNSE) in Albany, NY are exploring the use of surface acoustic waves (SAWs) to induce fluid streaming as a possibility for fluid actuation. Because sound travels at different velocities in substrates and fluids, dispersion results in the wave being launched into the liquid at an angle. The attenuation of this pressure wave causes acoustic streaming (see page 35, at bottom, for more details).

In order to effectively design such devices, an understanding of the acoustic properties of the piezoelectric material used to generate SAWs is a critical first step. In this respect, numerical simulation can be a very powerful tool for helping determine, for example, the effects of various electrode metals and geometries on acoustic wave propagation. The insight gained can be used to inform design decisions.

Graham Potter, a graduate researcher at CNSE, is studying the use of a variety of piezoelectric materials for applications utilizing acoustic streaming. CNSE is part of a unique university-industry partnership with SEMATECH, a worldwide semiconductor industry research consortium aimed at addressing critical challenges in advanced technology manufacturing.

Potter works in Professor James Castracane's laboratory at CNSE; his team designs devices built with piezoelectric substrates such as 128° Y-cut lithium niobate ($LiNbO_3$). "The angle of the cut is determined with reference to the crystallographic axes. This particular orientation has traditionally been used in band-pass filters due to the existence of a Rayleigh wave, a type of SAW, with strong electromechanical coupling propagating in a single direction along the wafer surface," he explained.

"For this reason, many acoustic streaming studies using this material have been limited to linear devices oriented in one direction. We are interested in building circular or focusing device architectures (see Figure 1A). For this reason, and due to the anisotropy of the crystal, we needed to better understand the propagation characteristics of waves over the entire surface," Potter continued.

In his setup, arrays of gold electrodes, known as interdigitated transducers or IDTs, are fabricated on a piezoelectric substrate. Alternating current is applied to the electrodes causing the surface to harmonically vibrate due to the inverse piezoelectric effect, generating a SAW. "By varying the orientation of these test devices over the surface (Figure 1B), the resonant frequency and acoustic streaming response can be determined as a function of propagation direction," Potter explained.

STRONG AGREEMENT BETWEEN SIMULATION AND EXPERIMENT

Simulations were conducted at multiple material orientations using COMSOL Multiphysics® (see Figure 2) and validated against devices fabricated at CNSE. "We observed close agreement between our simulations and the experimental measurements (see Figure 3). This has encouraged the

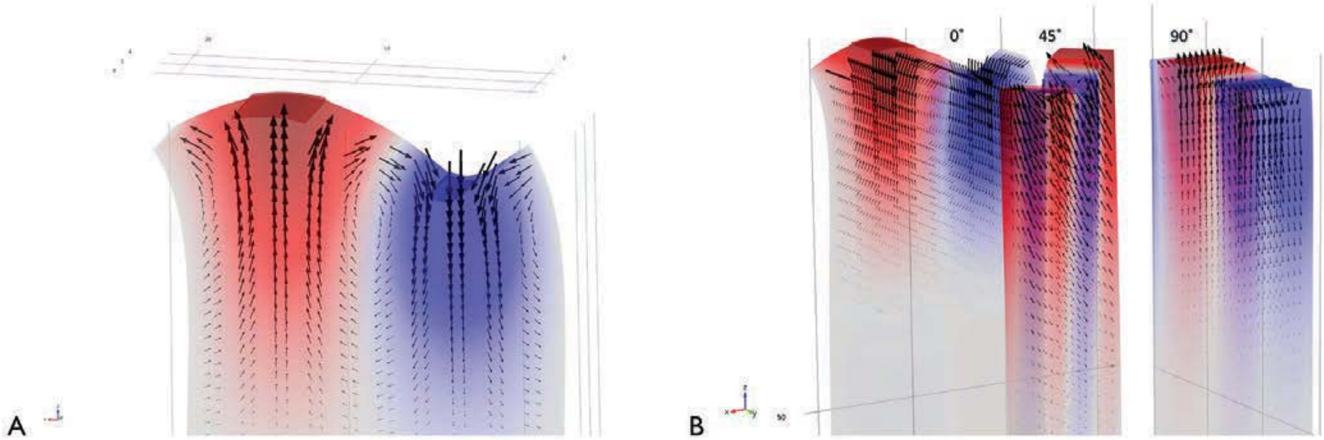


FIGURE 2. A) The vertical displacement and displacement field lines at resonance, obtained from the simulations. For this orientation (0° rotation relative to the crystal X-axis) a Rayleigh wave is observed, with the hallmark displacement in the sagittal plane confined within a few wavelengths of the surface. B) Superimposed images of material displacements for simulations conducted at multiple orientations (0-90 degrees relative to the crystal X-axis), corresponding to orientations of fabricated devices.

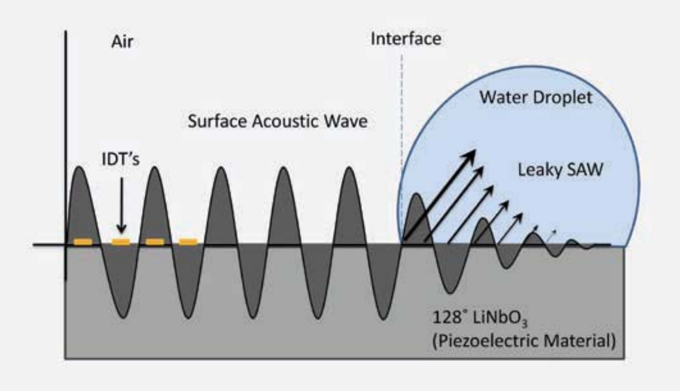
further use of COMSOL Multiphysics in our design process and has really accelerated our understanding of the problem," said Potter.

"For instance, we wanted to confirm that surface waves with greater vertical displacements would have higher streaming velocities. In fact, we were able to correlate the result from simulations to the experimentally measured streaming velocities," he said. "Pieces of information like this are helping to shed light on aspects of the problem and are ultimately leading to tangible design choices."

Potter has used the Piezoelectric Devices interface in COMSOL Multiphysics for frequency domain analysis in this particular study. From his simulations he was able to determine the resonant frequency and phase velocity of the SAWs, important design considerations in optimizing their device geometry for acoustic streaming. "Our group is interested in optimizing the streaming effect through a variety of means, and because this work is multidisciplinary by nature, the multiphysics capabilities of COMSOL are very helpful," he said. "We plan to continue using COMSOL in our research so we can investigate the effects of multiple parameters on our device performance simultaneously, helping to reduce the amount of time we spend prototyping." ■

Rotation from X-Direction (˚)	Experimental Resonance (MHz)	Simulated Resonance (MHz)	Relative Error (%)
0	192.25	190.5	.9
15	187.75	188.2	.24
30	*damaged	182.5	N/A
45	178.75	176.8	1.1
60	174.25	176.0	1.0
75	177.0	177.2	.1
90	178.75	178.7	.03

FIGURE 3. Comparison of simulated and experimentally-determined device responses at select orientations. The experimental resonance is determined by measuring insertion loss for devices (Figure 1B) via a network analyzer. The simulated resonance is determined from peaks in admittance, obtained from frequency domain simulations.



HOW ACOUSTIC STREAMING WORKS

A surface acoustic wave (SAW) can be launched by patterning interdigitated transducers (IDTs) onto the surface of a piezoelectric material. The Rayleigh surface wave will propagate in air with little attenuation; however, upon contacting liquid the wave will begin to "leak" into the fluid. At this point it is referred to as a leaky SAW.

The angle at which it enters the liquid is determined by the SAW's velocity relative to the speed of sound in the liquid. The attenuation of this pressure wave over a long enough time scale results in fluid flow. The process is known as acoustic streaming, first experimentally observed for the case of standing wave modes by Faraday in 1831.