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# Vertical jetting induced by shear horizontal leaky surface acoustic wave on 36°Y-X $LiTaO_3$

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Shear horizontal surface acoustic waves (SH-SAWs) have been regarded as a good candidate for liquid sensing applications, but being inefficient in fluid manipulation due to a minimal fluid coupling between the fluid and acoustic waves. However, in this letter, a vertical jetting function was realized using the SH-SAW generated from a 36°Y-X $LiTaO_3$ SAW device. The jetting of the droplet induced by the SH-SAWs was observed nearly along vertical direction, and the aspect ratio of the liquid beam is proportional to the applied power before breaking up, which is dramatically different from those generated from the conventional Rayleigh SAWs. By conducting theoretical simulation and experimental investigation on the SH-SAWs systematically, we concluded that the wave/energy pressure dissipated into the sessile droplets causes this vertical ejection on the device surface.

**Keywords:** Vertical jetting, shear horizontal leaky surface acoustic wave, 36°Y-X $LiTaO_3$, energy coupling.

Surface acoustic wave (SAW) technology has received considerable interest in microfluidics and lab-on-chip community due to its advantages of low cost, fast fluidic actuation, good miniaturability and compatibility with other sensing/microfluidic components.[1] SAW based sensors and microfluidics have recently been intensively reported for a variety of applications in biological, chemical, and medical engineering.[2–5]So far, Rayleigh SAWs are the most commonly used wave mode in SAW based microfluidics, which are composed of longitudinal and vertically polarized displacement components, thus they are strongly coupled into the liquid media located on their propagation paths. Therefore, they have been extensively applied to generate microfluidic functions, including mixing, pumping, ejection, nebulization and jetting. [6–11] Although it has been extensively utilized in SAW based biosensors, shear horizontal SAWs (SH-SAWs) have rarely been used in fluid manipulation because it is generally accepted that there is a minimal fluid coupling between the SH-SAW and fluid.[12] Theoretically energy from a pure shear wave is difficult to be strongly dissipated into an ideal Newtonian liquid, however, most of the shear waves generated on the piezoelectric materials (such as 36° Y-X $LiTaO_3$) are quasi-shear waves which are accompanied with small longitudinal or compression components, and might lead to acoustic energy dissipation into liquid. Previously, there are some reports that the SH-SAW or Love mode SAWs generated on 36° Y-X $LiTaO_3$ device could be used to manipulate droplets for acoustic streaming/pumping[13] and nebulization. [14] However, SH-SAWs showed poor efficiency of droplet later movement and then were less interesting in comparison to Rayleigh waves.

[13] In addition, the mechanisms of these SH-SAW based microfluidic functions have not been well explained.

Rayleigh wave based jetting has been intensively investigated using 128° Y-cut $LiNbO_3$[15] and ZnO thin film SAW devices,[16] as well as phononic horn structure .[17] Both an inclined angle jetting along the Rayleigh angle using one-side interdigitated transducers (IDTs) [18] and a nearly vertical jetting based on a standing Rayleigh SAW generated from two opposite focusing IDTs [19] have been reported. However, as far as we know, there are no reports on the jetting phenomena induced from the SH-SAW devices. In this paper, we report the vertical jetting phenomena generated from a SH-SAW device, which is dramatically different from those generated from the conventional Rayleigh SAWs. Theoretical simulation based on finite element analysis is conducted to explain this mechanism.

Fig. 1 illustrates the schematic diagram of the jetting phenomena induced by a leaky SH-SAW on a 36° Y-X $LiTaO_3$ substrate. The SAW devices were fabricated on a 36° Y-X $LiTaO_3$ wafer using the standard lithography and lift-off technique. Nakamura et al. reported that the SAW on the 36° rotated Y-X $LiTaO_3$ is the leaky SH-SAW,[20] in which the predominant component of surface displacement is shear horizontal. Electrode-width-controlled single phase unidirectional interdigital transducer (EWC-SPUDT)[21] was designed and fabricated on the 36° Y-X $LiTaO_3$ to generate unidirectional SAWs toward a de-ionized droplet. The droplet was placed 2 mm in front of the interdigital transducers (IDTs) on a hydrophobically-treated surface, e.g., coating with a 500 nm thick CYTOP layer (Asahi Glass Co.)[21]. The aluminum IDT of 150 nm thick consisted of 30 pairs of fingers with a wavelength of 100 μm and an aperture size of 2.5 mm. The central frequency characterized using an HP8752A network analyzer was 41.17 MHz, corresponding to an SH-SAW velocity of 4117 m/s.[20]

For a comparison, a Rayleigh-type SAW device (with the same IDT pattern as above) was fabricated on a 128° Y-X black $LiNbO_3$ substrate. The central frequency of the Rayleigh wave devices was measured to be 39.9 MHz, corresponding to a Rayleigh velocity of 3990 m/s. The SAWs were generated on the surface by applying an RF signal to the IDTs using a signal generator (Marconi Instruments 2019A). The signal was then amplified using an RF power amplifier (MI TF2175) prior to being applied to the IDTs. The output power to the SAW device was measured using an RF power meter (RACAL Instruments 9104). The streaming and jetting phenomena were recorded using a high speed video camera (VISION Research Phantom MIRO 4)).

Finite element method (FEM)/boundary element method (BEM) has been considered as a well-known accurate method to simulate surface acoustic wave devices, which can obtain the surface vibration amplitude and second effects such as backscattering and bulk-wave interaction. [22–25] The actuation of the droplet strongly depends on the surface vibration, therefore, in order to investigate the vibration characteristics of the SH-SAW on the 36° Y-X $LiTaO_3$ surface, an FEM/BEM analysis was conducted to simulate the surface vibration of the SH-SAW device. The aforementioned structural parameters were adopted in the simulation in the absence of droplet and CYTOP thin layer. The material property parameters of the $LiTaO_3$ and aluminum were cited from the literature.[26] The surface vibration distribution along its propagation direction up to 19 wavelengths away from the IDT edge was obtained.

Based on the FEM/BEM analysis, when a sinusoidal excitation voltage with an amplitude of 1 V is applied on the IDT, the SH-SAW displacement distributions along X, Y and Z axes are shown in Fig. 2, denoted using $U_x$, $U_y$ and $U_z$, respectively. It is observed that besides the main displacement component in the Y direction, there are also weak displacement components in both X and Z directions, indicating that the SH-SAW is quasi-shear horizontal SAW. The amplitude of the displacement component $U_y$ is two orders of magnitude higher than those of the other two components, $U_x$ and $U_z$, indicating that longitudinal components are insignificant. This is different from typical Rayleigh wave modes, which are mainly composed of a longitudinal and a vertical shear (out of plane) component.[26]

In order to understand the coupled fluid-acoustic wave interactions and dissipation of SAW energy into the droplet, 3D FEM analysis based on COMSOL Multiphysics software was carried out for both the SH-SAW and Rayleigh SAW. The water droplet with a viscosity of $1.4\times10^{-3}$ kg/m$^3$ and a surface tension of $7.2\times10^{-3}$ N/m with substrate was built as a hemi-spherical shape with a radius of 600 μm. The substrate was set as 200 μm thick. The stress-free and slip boundary condition was applied between the model droplet and the surrounding ambient. The boundary between the solid and the water droplet was set with the continuity of the normal stresses and displacements.

The SAW induced liquid deformation and jetting are critically dependent on the radiation of SAW energy into the liquid.[15] The aim of the simulation was to identify the distribution of the energy and acoustic pressure into the liquid for explanation of the mechanism, thus the simulation was only limited within the initial stages of the wave interaction with the droplet. When the SH-SAW propagates beneath the droplet, the pressure distributions inside the droplet were calculated and the results were compared with those from the Rayleigh wave.

From the COMSOL FEM analysis, Fig. 3 shows the pressure field inside the water droplet induced by a continuous excitation at the corresponding central frequencies of the SAW devices. Fig. 3(a) shows the simulation results of the interaction of SH-SAW and liquid droplet. Results show that the SH-SAWs do not dissipate its energy quickly into droplet at their initial interaction point (i.e., at the edge of the droplet). This is reasonable as the SH-SAWs generally do not leak significantly into the liquid droplet. The SH-SAWs quickly propagate along the bottom of the droplet and further into the central part of the droplet. Simultaneously the wave energy is gradually transferred into the droplet through the viscous effects of the liquid, and then the wave pressure moves up from the bottom of the liquid. This eventually generates an approximately vertical pressure gradient in the droplet.

To compare with, Fig. 3 (b) shows the simulated droplet pressure distribution induced by the Rayleigh wave. As the Rayleigh wave arrives at the edge of the droplet, the SAW energy strongly dissipates and then attenuates quickly along the propagation direction as shown in Fig. 3(b). The pressure gradient generated by the Rayleigh wave energy dissipation inside the droplet clearly follows the Rayleigh angle, which has been well-documented. [18,24]

The attenuation of the leaky SAW due to viscous liquid loading transfers an acoustic pressure into the droplet, creating thereby a significant acoustic streaming in the liquid that facilitates mixing, stirring, vibrating, pumping, ejection, and atomization. [8,16,27,28] Therefore, exploiting the acoustic streaming inside the droplet will help to better understand the energy distribution inside the droplet and the different jetting phenomena induced by SH-SAW and Rayleigh wave. Firstly, laminar flow physics was applied to analyze the acoustic streaming fields which were induced by SH-SAW and Rayleigh wave respectively. Fig. 4(a) and 4(b) show the simulated cross section view of acoustic streaming field and the energy and pressure distribution induced by SH-SAW and Rayleigh wave, respectively. As can be seen from Fig. 4(a), the SH-SAW propagates with relatively shallow energy penetration into the droplet and the energy and pressure distributed randomly in the whole contact area between the droplet and the surface. There is no other obvious motion expect for the upward movement from the bottom, indicating a vertical upward pressure in the droplet. In contrast, for Rayleigh wave device, the Rayleigh wave penetrates into the droplet and attenuates as soon as it comes across at the edge of the droplet, which drives the edge fluid with a Rayleigh angle. When the moving liquid reaches the droplet boundary, the interaction between the liquid and solid boundary induces a reverse flow and goes back toward the IDTs.

To verify the simulation results of pressure and energy distribution and coupling of the SH-SAW with the liquid, a droplet with sub-micron polystyrene particles was put in front of the IDTs and the flow pattern was taken from top-view. As is shown in Fig. 4(c), when the SH-SAW is applied, the particles within the droplet start to be agitated and an irregular streaming pattern has been generated. The streaming patterns changes with lots of parameters, such as applied power, durations with the applied power, and also the positon of the droplet on the SAW path. This is probably due to the energy and pressure generated from the SH-SAW distributed randomly and irregularly in the whole contact area between the droplet and the surface. This is different from the Rayleigh wave generated flow pattern, in which the streaming always starts from the front edge and SAW driving flow interacts with the reverse flow, which produces a double vortex (butterfly) flow pattern (see Fig. 4 (b) as a comparison).[11,29] The phenomenon verifies that energy from the SH-SAWs was truly dissipated into droplets, and causes the internal streaming. We also used large size of polystyrene particles in the droplet and took the side-view movies of acoustic streaming induced by SH-SAW and Rayleigh wave (as shown in Supporting Videos), which successfully demonstrates the different pressure and energy distributions between SH-SAW and Rayleigh wave.

When a large RF power (7.5 W) is applied to the SH-SAW wave device, the droplet is observed ejected from the hydrophobic surface, as shown in Fig. 5(a). The maximum jetting height was obtained from the high speed videos recorded in the jetting process, which can be used to compare the amplitude of acoustic energy dissipated into the droplet. From the high speed video images, at the initial stage, the droplet is agitated and twisted, then deformed into an elongated and vertical liquid beam as the SAW energy/pressure has been dissipated into the liquid. This vertical jetting can be explained based on the vertical pressure distribution into droplet due to the SH-SAW demonstrated from the FEA simulation (see Fig. 3(a) and Fig. 4(a)), in which the wave energy/pressure is mostly concentrated at the center of the droplet and vertically dissipated. This results in an upward acoustic pressure within the droplet to overcome its surface tension and gravity, thus generating the jetting of a liquid beam. Finally, the liquid beam will break up and pinch-off of the tiny droplet is observed, which falls on the side wall.

To be compared with, jetting generated from the Rayleigh SAW wave device is presented in Fig. 5(b). It shows a typical Rayleigh angle of 23° towards the SAW propagation direction. The acoustic energy of Rayleigh wave leaks into the droplet efficiently and then the induced coherent jetting takes place continuously until the whole droplet has been ejected. This is totally different from those generated from the SH-SAW devices.

The jetting height is usually determined by both droplet size/volume and input power. In the case of small droplet size/volume and sufficient input power, the jetting height varies proportionally with its droplet size/volume. The jetting phenomenon is determined by the interaction between acoustically driven inertia and the force due to the surface tension and gravity. If the input power is fixed, the jetting height increases with droplet volume until it reaches a maximum. This is because the increase of radiated acoustic energy is lower than that of surface tension and gravity, when the droplet volume and the contact surface increase. On the other hand, jetting performance dependent on input power is critical for practical application. The higher power applied on the IDT can excite stronger shear horizontal SAWs and ultimately induce a stronger pressure radiation. To investigate the effects of the RF power, various RF power levels up to 7.5 W have been applied to the SH-SAW devices while the droplet volume is fixed 2 μL, and the obtained maximum jetting heights are shown in Fig. 6 (a). With an RF power below 0.91 W, the droplet mainly shows a deformation rather than obvious jetting beam. When the RF power is gradually increased, the large acoustic pressure inside the droplet induced by the SAW overcomes the surface tension force, resulting in jetting of a coherent liquid beam. At an RF power of 7.3 W, the droplet is found to be elongated with a maximum height of 14.3 mm before breaking up [30]. The jetting was estimated by measuring the aspect ratio of the liquid jet, defined as the ratio between the jet beam length and the radius of the droplet. The aspect ratio was found to be proportional to the applied RF power before pinching off of small drops as shown in Fig. 6 (b). Therefore, a simple linear equation can be obtained to describe the relationship between power ($P$) and aspect ratio ($A$), i.e., $A = 3.46 \times P - 1.95$.

In conclusion, we demonstrated a SH-SAW driven microfluidic jetting on the 36 °Y-X $LiTaO_3$ substrate and the phenomenon was dramatically different from the conventional Rayleigh wave mode jetting. The jetting of the droplet driven by the SH-SAWs was vertical on the substrate surface. Theoretical analysis was carried out to simulate the vibration of the substrate surface and pressure/energy radiation into the droplet, which explained the unique jetting behavior generated by the SH-SAW. This unique jetting phenomenon observed presents promising potential for the applications, such as ink-jet, soft biological printing and directional non-contact droplet dispensing.

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**Figure Captions:**

Fig. 1. Schematic illustration of droplet jetting generated from an SH-SAW device on 36°Y-X $LiTaO_3$ substrate.

Fig. 2. Simulated vibration displacements along *x*, *y*, and *z* direction as a function of the normalized distance *x*/*λ* away from IDTs.

Fig. 3. Finite element analysis of pressure/energy radiation in droplets during (a) SH-SAW; (b) Rayleigh SAWs propagating across the droplet bottom.

Fig. 4. Finite element analysis of streaming fields (m/s) induced by (a) Rayleigh SAWs; (b) SH-SAW, and the experimental particle streaming top-view snapshots driven by (c) SH-SAW (d) Rayleigh wave

Fig. 5. (a) SH-SAW induced jetting process of the droplet of 2 μL, with an applied RF power of 7.5 W; (b) Rayleigh SAW induced jetting processes of 2 μL, with an applied RF power of 7.5 W. The wave propagates from right to left.

Fig. 6. (a) Snapshots of droplet jetting at highest points with various RF power levels (1) 0.9 W (2) 1.4 W (3) 2.2 W (4) 3.5 W; (5) 7.5W. (b) Jetting height of droplet aspect ratio as a function of the applied power on the SH-SAW device.