ICA 2019 AACHEN

PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

Digital micro-laboratory application using surface acoustic wave devices

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ABSTRACT

Droplet manipulation is one of the important applications of surface acoustic wave (SAW) devices. When a sensor is fabricated on the SAW device surface, a digital micro-laboratory for droplet manipulation, mixing, and measurement is realized on a piezoelectric substrate. For optimum droplet manipulation, it is necessary to clarify the acoustic streaming caused by the SAW in droplets. We have discussed droplet manipulation mechanism, experimentally. For optimum control of the droplet, it is necessary to measure the droplet position. When the SAW was generated by the short burst wave, reflected and transmitted signals were observed. The origin of the signals is the longitudinal wave propagation in the droplet. Therefore, it is possible to determine the droplet position with the signals. For the droplet position measurements, the longitudinal wave velocity of the droplet is known. If the droplet position is known and the velocity is unknown, it is possible to measure the velocity of the droplet using the SAW device. This is a unique measurement method of a longitudinal wave velocity of droplets.

Keywords: SAW, digital micro-laboratory, droplet position, estimation of longitudinal wave velocity

1. INTRODUCTION

A surface acoustic wave (SAW) has been widely used duplexers and filters for a mobile communication system, such as a smart phone (1). As the SAW is generated and received using the interdigital transducer (IDT) fabricated on a piezoelectric substrate, the mechanical wave can be electrically controlled. The frequency characteristics are determined by the IDT structure. This is the reason why the SAW device uses filters. Also, sensors and actuators are realized with the SAW device. Particle displacements of the SAW, which is called Rayleigh SAW, are longitudinal and sear vertical components. When a liquid is loaded on the SAW propagating surface, the SAW becomes a leaky-SAW (LSAW) and a longitudinal wave is radiated into the liquid and the SAW attenuates (see Fig. 1). The radiation angle θ_R is called the Rayleigh angle and defined as

$$\theta_R = \sin^{-1}\left(\frac{V_L}{V_{SAW}}\right). \tag{1}$$

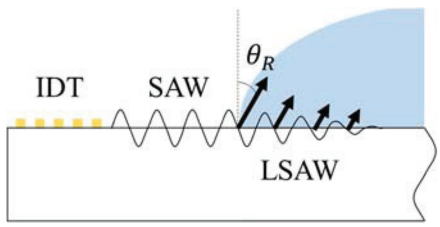

Figure 1 – Schematic illustration of the longitudinal wave radiation from SAW.

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Here, V_L and V_{SAW} are longitudinal wave velocity of liquid and phase velocity of SAW, respectively. Radiation of the longitudinal wave from the SAW is a well-known phenomenon (2). In 1989, Shiokawa and coworkers reported that liquid on the SAW device was manipulated by increasing the amplitude of the SAW. The phenomenon is based on the acoustic streaming caused by the radiated longitudinal wave from the SAW. Shiokawa named the phenomenon SAW streaming.

Many papers have been published about droplet manipulation using the SAW device since 1989 (3-6). We have investigated system called digital microfluidic system or digital micro-laboratory (DML) (7). Droplet manipulation, mixing of droplets, temperature control, and measurements are possible on the DML (8, 9). An electrochemical sensor was fabricated to measure the impedance change (7-9). In this paper, first, we discuss the droplet manipulation mechanism based on the observation results. For the DML application, it is important to know the droplet position for optimum manipulation. When the SAW was generated by a short burst signal, the reflected signal was observed (10, 11). As the transmitted signal was also observed, the droplet position is estimated using the reflected and transmitted signals. To estimate the droplet position, the longitudinal wave velocity must be known. If the droplet position is known, it is possible to estimate the longitudinal wave velocity of a droplet. Measurements of the longitudinal wave velocity is also important. In this paper, results of a feasibility study for estimating the velocity are also described.

2. Experimental setup

The SAW device was fabricated on 128YX-$LiNbO_3$ single crystal. The electrode materials were gold and chromium. Conventional lithography was used to fabricate the IDT. Figure 2 shows the typical measurement system in this study. Tone-burst signal was applied to the IDT. The electrical input power was controlled by an RF-power amplifier. The relationships between the amplitude of the SAW and the applied voltage was reported by Sano and co-workers[3]. The amplitude can be estimated from Ref. 3.

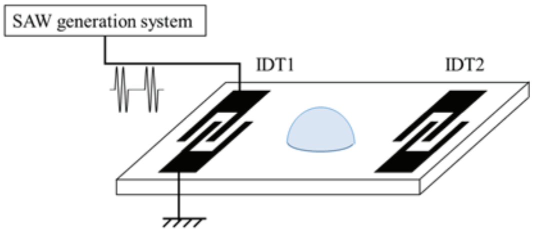


Figure 2 – Experimental setup in this study.

3. Results and discussion

3.1 Droplet manipulation mechanism using SAW device

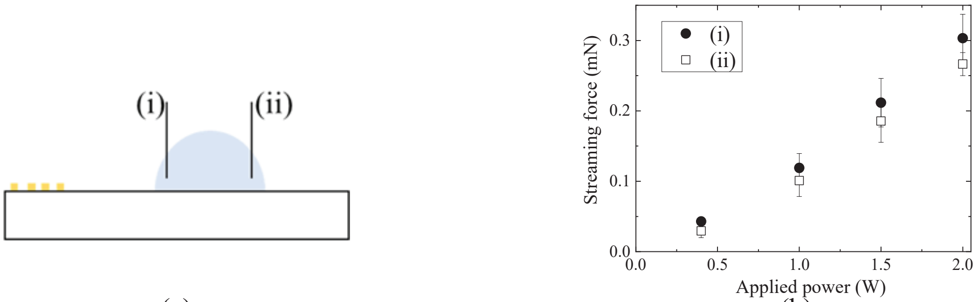
Figure 3 shows the typical results of the droplet manipulation on the SAW device. The operating frequency of the SAW device was 50 MHz. The droplet is manipulated to the SAW propagation direction. From the figure, it is found that the shape of the droplet is the same. However, the observation results using a high speed camera in Fig. 4 shows that the shape of the droplet is changed by the radiated longitudinal wave. The tip of the droplet rolls to the SAW propagation direction. However, the position of the left side, which are the incident side of the SAW, does not change. This means that the streaming force acts only the right side of the droplet. The binding force exists between the droplet and the surface. When the streaming force is above the binding force, the droplet moves to the SAW propagation direction. It is important to measure the streaming force in the droplet. Normally, a hydrophone is used to measure the streaming force in liquid environment. However, the droplet size is smaller than the hydrophone. We developed a flat spring with a strain gage system to measure the streaming force. Figure 5(a) shows the schematic illustration of the measured system. The force at point (i) and (ii) were measured. The results are shown in Fig. 5 (b). The volume of the water droplet was 10 μL. The streaming force at point (i) is larger than it at point (ii). As the radiated longitudinal wave attenuates in the droplet, the reasonable results are obtained. To manipulate the 10 μL water droplet, the applied electrical power above 1.5 W is needed. From the figure, the streaming force at 1.5 W was 0.2 mN. This value is the minimum streaming force to manipulate the 1.5 μL droplet.

(a) (b)

Figure 3 – Observation results of droplet manipulation using a conventional camera.

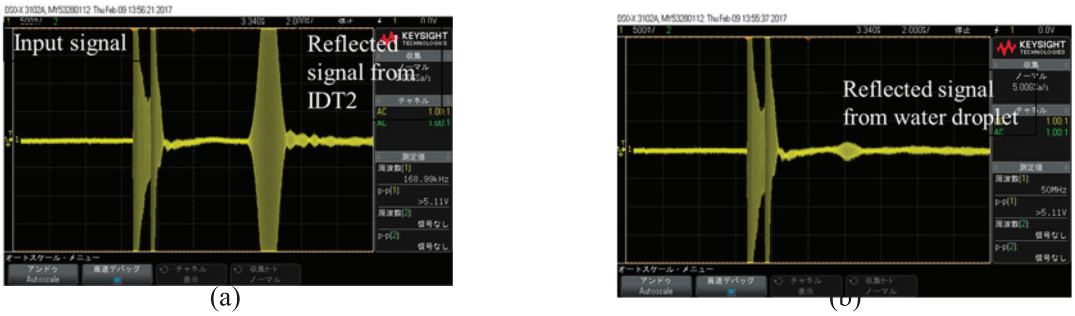
(a) (b)

Figure 4 – Observation results of droplet manipulation using the high speed camera.



(a) (b)

Figure 5 – (a) Measurement positions and (b) results of the streaming force.



(a) (b)

Figure 6 – Observation results of the reflected signal measured by the IDT1. (a) Without and (b) with water droplet between IDT1 and IDT2.

3.2 zDetection of the droplet position

For the DML application, it is important to know the droplet position. Renaudin and coworkers observed the reflected waves from droplets. Based on the results, they proposed the estimation method of the droplet position. We also observed the reflected signals as shown in Fig. 6. When a water droplet was put on the surface between IDT1 and IDT2, the reflected signal from the IDT2 vanishes and new signal appears. The new signal was observed when a short burst signal was applied to the IDT1. We also measured the reflected signals by changing the volume of the water droplet. The results are shown in Fig. 7. The distance of A in Fig. 8 is the SAW propagation path. At the measurements, the distance of A was fixed. From the obtained results, the traveling time of the SAW was deleted and only considered the propagation time in droplets. The time in Fig. 7 depends on the droplet volume. This means that the SAW does not reflect at the interface of air and droplet. The reflected wave propagates in the droplet. We assumed the several propagation paths in the droplet and finally concluded that the propagation path in the droplet is represented by the following equation (see Fig. 8).

$$t_r = \frac{L + \pi r}{V_L} \tag{2}$$

Where, L is shown in Fig. 8 and r is the radius of the droplet. The calculated time using eq. (2) is also plotted in Fig. 7. When the water volume is above 3 μl, the both values agree well. Therefore, the radiated longitudinal wave from the SAW propagates in the droplet. Then, the SAW is excited by the longitudinal wave and propagates to the IDT1.

The transmitted wave is also observed using IDT2. Figure 9(a) shows the observed transmitted wave for the water droplet of 10 μl. The transmitted wave for the 50 wt% glycerol solution droplet of 10 μl are shown in Fig. 9 (b). As the longitudinal wave velocity of 50 wt% glycerol solution is faster than it of the water, the reasonable results are obtained. Figure 10 shows the propagation path of the transmitted signal. The traveling time in the droplet of the transmitted wave is obtained from

$$t_t = \frac{L}{V_L}. \tag{3}$$

In Fig. 11, the measured and calculated results are compared. The both results agree well.

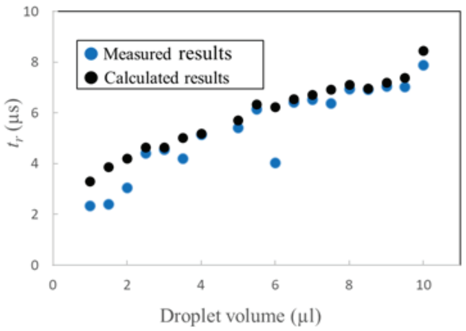


Figure 7 – Measured and calculated results of the traveling time in droplet with changing the water volume.

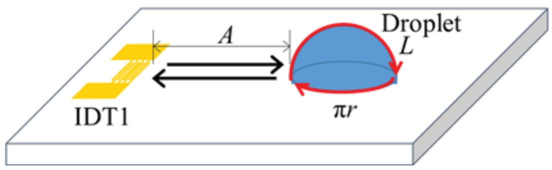
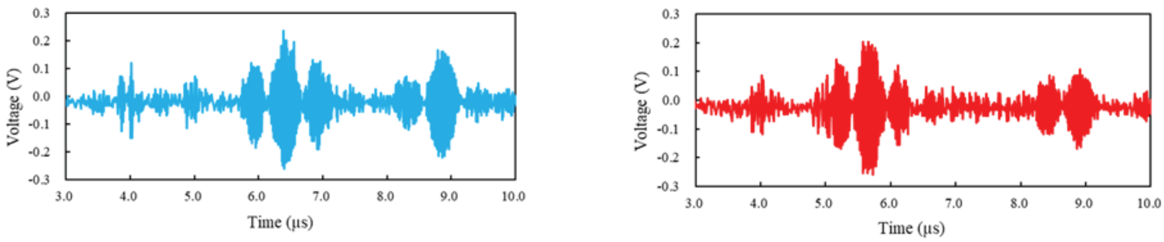


Figure 8 – Propagation path of the SAW on the piezoelectric surface and the longitudinal wave in droplet.



(a) (b)

Figure 9 – Measured results of (a) reflected signal by IDT1 and (b) transmitted signal by IDT2.

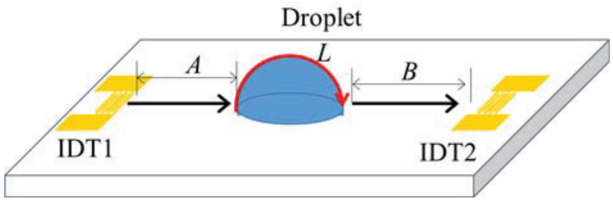


Figure 10 – Propagation path of the SAW on the piezoelectric surface and the longitudinal wave in droplet.

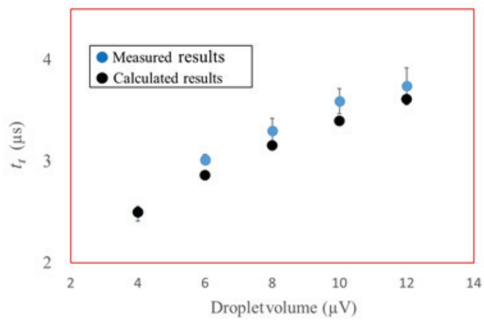


Figure 11 – Propagation path of the SAW on the piezoelectric surface and the longitudinal wave in droplet.

Figure 12 –Schematic illustration of droplet position detection. (a) SAW is generated from IDT1 and reflected and transmitted signals are measured by IDT2. (b) Vice versa.

We tried the detection of the droplet position. Figure 12 shows the estimation method. The SAW was generated from IDT1 or IDT2. The obtained reflected and transmitted times are expressed as the following equations.

$$T_r = \frac{2A}{V_{SAW}} + \frac{L + \pi r}{V_L} \tag{4}$$

$$T_r' = \frac{2B}{V_{SAW}} + \frac{L + \pi r}{V_L} \tag{5}$$

$$T_t = \frac{A + B}{V_{SAW}} + \frac{L}{V_L} \tag{6}$$

Where, T_r and T_r' are the reflected times obtained from IDT1 and IDT2, respectively, T_t is the transmitted time. Using eq. (4), (5), and (6), water droplet positions were calculated. The results are summarized in Table 1. The measurements were carried out eight times. The reasonable results are obtained.

Table 1 – Average and maximum errors and SD.

Droplet volume	Average error, mm	Maximum error, mm	Standard deviation
6	0.52	1.15	0.20
8	0.57	1.28	0.16
10	0.56	1.14	0.21

3.3 Measurements of longitudinal wave velocity

In the previous section, the longitudinal wave velocity is assumed as known. If the longitudinal wave velocity of a droplet is obtained on the DML, it is useful for measuring. In the eqs. (2) - (6), the longitudinal wave velocity of V_L is involved. It is not difficult to determine the velocity from the results. We consider the same configurations as shown in Fig. 10. The propagation time in a droplet, T, is obtained from eqs. (4), (5), and (6).

$$T = \frac{T_r + T_r'}{2} - T_t \quad (7)$$

$$\therefore r = \frac{V_L}{\pi} T \quad (8)$$

The height, h, of the droplet is obtained from the following equation.

$$h = \frac{3v}{2\pi r^2} \quad (9)$$

Where, v is the volume of the droplet. From those equations, the function for the longitudinal wave velocity is derived.

$$f(V_L) = \frac{1}{2}\pi(r+h)(1+a) + \frac{V_L}{V_{SAW}}\left(X - 2T\frac{V_L}{\pi}\right) - T_t V_L \quad (10)$$

Where, X is the distance between IDT1 and IDT2. Also,

$$a = \frac{3b^2}{10+\sqrt{4-3b^2}}, \qquad b = \frac{r-h}{r+h}.$$

From eq. (10), the longitudinal wave velocity, V_L, is obtained using the Newton-Raphson method.

The sample liquids were glycerol solution with different concentrations. In this paper, the droplet volume was fixed at 8 μl. The estimated results were compared with the literature values. The results are shown in Fig. 13. The estimated results almost agree with the literature values.

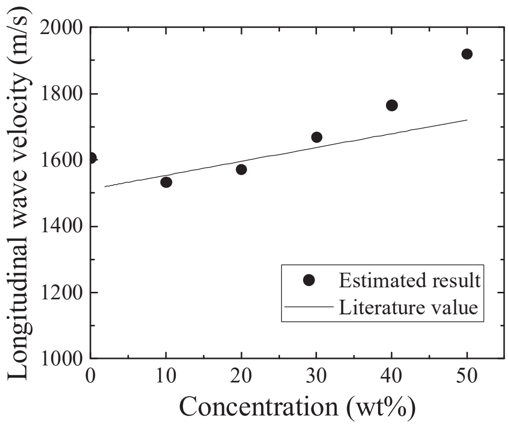


Figure 13 – Comparison the estimated longitudinal wave velocity with the literature value.

4. CONCLUSIONS

The DML using the SAW device is very useful for microfluidic application. For the optimization of the droplet manipulation using the SAW, the streaming force in the droplet was experimentally obtained. The results indicate that the input electrical power of 1.5 W is needed to manipulate a 10 μl water droplet. Then, the detection method of the droplet position is proposed. When a short burst signal is applied to the IDT, the reflected and transmitted signals are observed. As those signals involve the information of a droplet, it is possible to estimate the droplet position from those signals. For droplet position measurements, the longitudinal wave velocity is assumed as known value. Moreover, in this paper, the estimation method of the longitudinal wave velocity is proposed. The improve the accuracy is the future work.

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