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Liquid Mixing using Streaming in Frequency-Modulated Ultrasonic Beams Radiated from SAW Devices
FM 変調による SAW 攪拌の基礎的検討

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1. Introduction

Surface acoustic wave (SAW) is a propagating wave along a sufarce of a semi-infinite elastic solid and its energy more than 90 percent concentrates within a single wavelength from the surface. When liquid is loaded onto the SAW propagating path, a longitudinal wave radiates in an oblique direction into the liquid. As SAW amplitude increases, the liquid shows flowage, vibration, flight and atomization. These phenomena are cold as SAW streaming [1]. SAW streaming has been achieved to mix in a short time dramatically by the sound radiation obliquely [2, 3]. Some SAW devices using plural interdigital transducers (IDTs) have been investigated to additionally advance performance of SAW mixing, which show chaotic flow dynamics to change spatiotemporally [4, 5]. Meanwhile, in order to not only improve the mixing performance, but also miniaturize the device, a control method to excite wave mode (SAW and bulk acoustic wave : BAW) using single IDT has been developed [6]. In this paper, a new control method for SAW mixing to drive IDT in frequency modulation is proposed and reported results of the study.

2. Theory of flow control by FM driving

In this study, a 128°Y-cut X-propagation $LiNbO_3$ substrate as the most popular for SAW devices is used. **Figure 1** shows an IDT configuration. Here, h, a (=h) and $\lambda = 2(a + h)$ are line width, space width and electrode period, respectively. SAW is excited most strongly when its wavelength λ_s equals to λ. Relationship between the center frequency f_s and the propagation velocity υ_s is expressed as follows:

$$f_s = \frac{\upsilon_s}{\lambda} = \frac{\upsilon_s}{2(h+a)} \quad (1)$$

If the wave front is in phase, BAW from the IDT arranged periodically is excited strongly into direction of φ-degree as following formula:

$$\sin\phi = \frac{n\lambda_b}{2l} = \frac{n\upsilon_b}{2lf} \quad (2)$$

Here, υ_b, λ_b, f, l and n are propagation velocity,

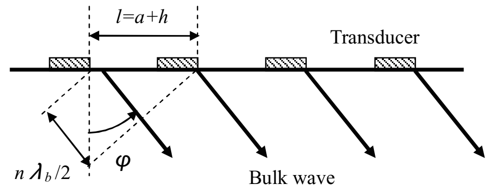

Fig. 1 Radiation of bulk waves generated by IDT when the phase matching condition is satisfied.

wavelength, frequency of BAW, half period of the IDT (=λ/2) and odd number, respectively. The more driving frequency of the IDT increases, the larger the φ-degree of the BAW propagating inside substrate becomes. When liquid such as water is loaded onto a surface of the device, SAW or BAW is converted to longitudinal wave at the interface, propagates consecutively as ultrasound beam into the liquid at an radiation angle of θ_s or θ_b based on Snell's law. The radiation angles are expressed in each ratio of υ_s, υ_b and υ_0, as follows:

$$\theta_s = \sin^{-1}\left(\frac{\upsilon_0}{\upsilon_s}\right) \quad (3)$$

$$\theta_b = \sin^{-1}\left(\sin\phi\frac{\upsilon_0}{\upsilon_b}\right) = \sin^{-1}\left(\frac{\upsilon_0}{\lambda_s f}\right) \quad (4)$$

As a loaded liquid onto the device, water (υ_0 = 1500 m/s) is used in this study. The radiation angle θ_s is almost ±22 degree. The more frequency increses, the smaller θ_b becomes. That is, the angle of oblique sound beam for acoustic streaming can be changed by the driving frequency. It enables flow field to be controlled accordingly.

3. Verification experiment

To confirm the theory as previously noted, sound field and flow field are experimentally investigated using a SAW device with the center frequency of 20 MHz. It can be measured by a hydrophone commercially available. **Figure 2** shows a block diagram of sound field measurement. Longitudinal wave radiates at an angle of θ from the IDT, the device is setup on a θ-stage to adjust direction of IDT. Driving signal whose power is 0.5 W with burst wave of 100 cycles in frequency of 17.6, 19.6 (= f_s) and 21.6 MHz is input to the device. The ultrasound beam is detected by the hydrophone setup on a XYZ-stage, and the data is saved in a

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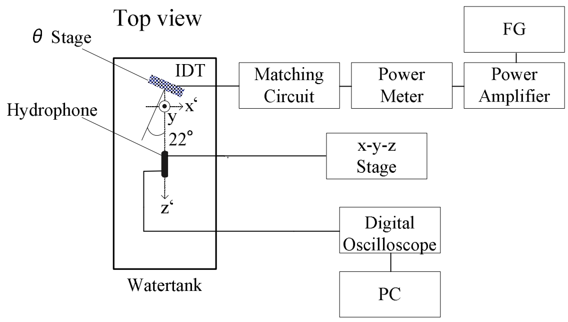

Fig. 2 Experimental setup for measurement of sound field.

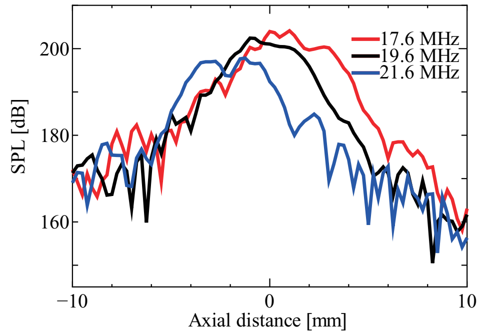

Fig. 3 Beam pattern of 17.6 MHz, 19.6 MHz, and 21.6MHz at 45 mm from the IDT.

personal computer after a FFT signal processing in oscilloscope. The directional characteristics in each driving frequency are shown in **Fig. 3**. The higher the frequency becomes, the more inside the sound peak moves to. Next, acoustic streaming from IDT-side of the device at the driving power of 0.5 W is visualized by particle image velocimetry (PIV) [8]. The results are shown in **Fig. 4**. The higher the driving frequency is, the smaller the radiation angle of the acoustic streaming becomes.

4. SAW mixing in frequency modulation

Relationship between frequency modulated deviation, difference of maximum and minimum in frequency and the mixing performance is investigated. Experimental condition is set to 98 MHz as the center frequency and the modulated frequency deviation of 3 MHz in sine wave. The result is shown in **Fig. 5**. It is cleared that good

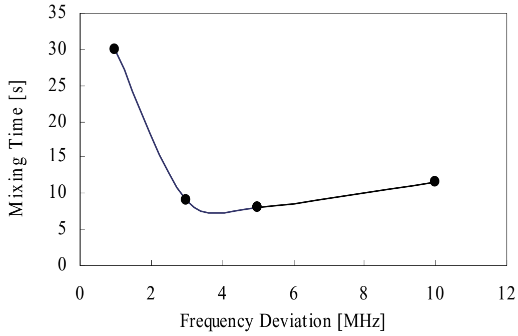

Fig. 5 Mixing time vs. frequency deviation of FM driving signal.

frequency deviation is from 3 to 5 MHz. The mixing performance decreases if the frequency deviation is too smaller or too larger.

5. Conclusions

Driving signal in frequency modulation can control SAW streaming. It is obtained that an optimized frequency deviation can improve the performance of SAW mixing.

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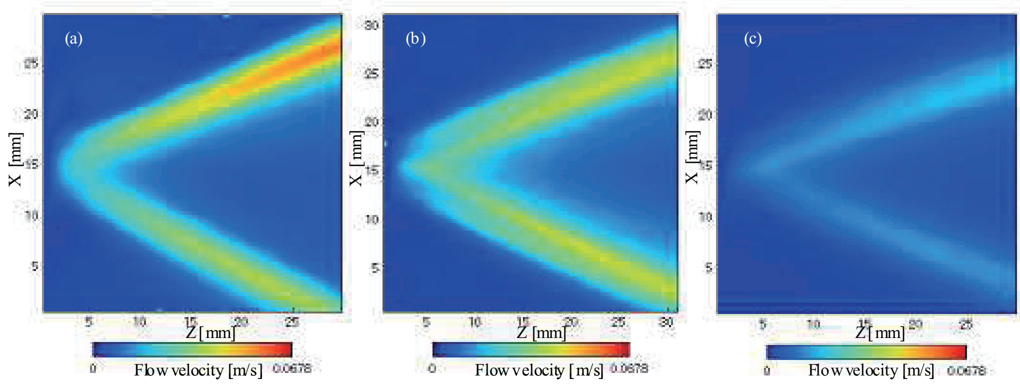

Fig. 4 Flow fields of SAW streaming by driving at 17.6 MHz (a), 19.6 MHz (b), and 21.6 MHz (c).