Effects of Droplet Volumes on Acoustothermal Heating in 128° YX $LiNbO_3$ Substrates

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***Abstract*—Surface acoustic wave (SAW) devices can generate significant heat due to acoustic damping when liquid droplets are placed on them, and this heating (acoustothermal heating) can be used for microscale heating purposes. However, SAW devices are often used in biosensing applications where significant acoustothermal temperature rise can damage the proteins or the biomolecules and destroy the sensor performances. In this paper, we have performed thermal camera-based experiments to study the heating phenomena and how they can be controlled by varying droplet sizes. We found that the temperature rise linearly increases with increasing SAW power whereas it decreases with increasing droplet volume. Hence, a larger liquid volume and lower SAW power can be used in biosensors to avoid significant heating.**

Keywords— Acoustothermal heating, Rayleigh surface acoustic wave, Sessile droplets, SAW heating

I. Introduction

Surface acoustic wave (SAW) devices are widely used in wireless communication devices[1], and in biomedical applications[2] such as biosensing[3] or cell sorting[4]. These usages often demand interactions of acoustic waves with fluids which causes the generation of an oscillatory flow (called acoustic fields) and a mean flow (called acoustic streaming)[5]. In some circumstances, the applied SAW power can be high enough to cause a temperature rise in the fluid (called acoustothermal heating)[6-8]. Kondoh et al.[9-11], in a series of studies, reported the SAW-based acoustothermal heating for various SAW powers and duty cycles. Beyssen et al.[12] studied the SAW-based droplet heating and showed how non-uniformity in the temperature rise is associated with the liquid viscosity. Kulkarni et al.[13] and Reboud et al.[14] demonstrated this droplet heating as the energy source for several microscale chemical reactions.

As SAW devices are used in biosensing applications, it deals with biomolecules that are very sensitive to temperature. Several previous studies showed that SAW devices are extremely good candidates for non-specifically bound protein removal and effective mixing of the antigen-antibody which reduces the incubation time and enhances the biosensor performances[15-17]. For such scenarios, excessive acoustothermal heating may damage biomolecules and should be avoided. Based on these studies, it is extremely useful to understand acoustothermal heating and its controlling mechanism so that on-demand regulation of the temperature can be achieved.

In this article, we used 128° YX $LiNbO_3$ piezoelectric substrate to generate Rayleigh SAW and studied the dependence of acoustothermal heating on droplet volumes. We used 2, 5, and 10 microliter droplets of ultrapure water and measure the temperature rise for SAW power ~ 0.01-0.2 W.

II. Materials and Methods

A. Device Design

We used a 128° YX $LiNbO_3$-based SAW device which consists of 120 pairs of IDTs on each side of the piezoelectric substrate. Rayleigh SAW of wavelength 40 microns was generated on the $LiNbO_3$ substrate where the spacing between two adjacent IDTs was kept as 10 microns. The actuation frequency was determined by measuring the insertion loss over an estimated frequency range of 96 to 100 MHz (Fig. 1) and it was estimated to be 98.16 MHz corresponding to the minimum insertion loss of -6.58 dB.

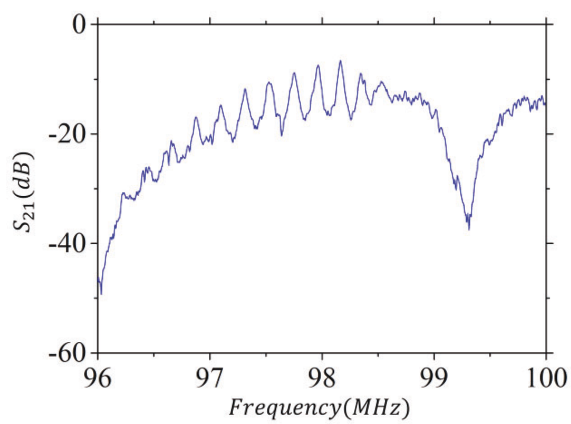

Fig. 1. S21 vs frequency for the SAW device used in the experiments.

B. Experimental Setup

Fig. 2 shows the schematic of the experimental setup used to measure the acoustothermal heating in a sessile droplet. We used a signal generator (Rohde & Schwarz) to generate sinusoidal signals of 98.16 MHz frequency and

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amplified the signal using an RF amplifier (Mini-Circuits). The signal coming from the RF amplifier was split using a 50:50 RF splitter and split signals were connected to the two ports on both the sides of the IDTs. Water droplets of various volumes (2, 5, and 10 microliters) were placed on the delay path and an infrared camera was used to measure the temperature rise in the droplets. We set the time as zero at the start of the SAW on and the droplet temperature was allowed to rise for 90 seconds, and after that, the SAW was off and the temperature was recorded for another 90 seconds to allow the droplet temperature back to room temperature.

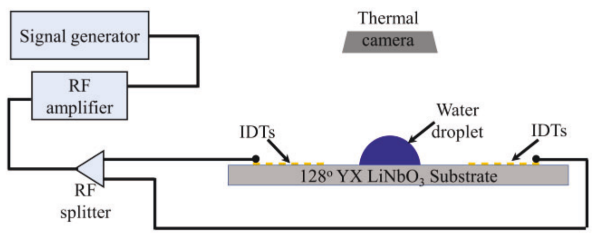

Fig. 2. Schematic of the experimental setup for measuring water droplet temperature in 128° YX $LiNbO_3$ SAW devices using a thermal camera.

III. Results and Discussion

A. Temperature Rise in Water Droplets

Figures 3-4 show the temperature rise (ΔT) as a function of time for 2 and 10 microliter droplets as captured by the thermal camera. For each droplet size and power level, three experiments were performed to understand the repeatability and the standard deviations associated with the measurements. We observed a sharp increase in temperature just after the SAW is on and the rate of increase slows down with time and a steady temperature rise (ΔT_s) is achieved after ~ 40-50 seconds. When the SAW was switched off, the temperature drops very fast initially and thereafter slowly comes back to room temperature.

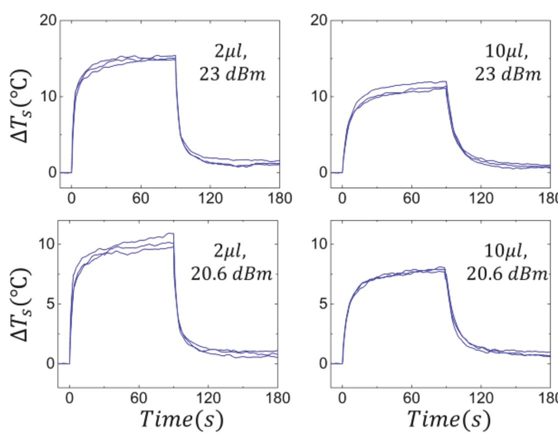

Fig. 3. Temperature rise (ΔT_s) vs. time for 2 and 10 microliter droplets at 23 and 20.6 dBm SAW powers.

Our results indicate that with increasing droplet volume, the temperature rise decreases. At 23 dBm, the maximum temperature rises observed for 2 and 10 microliter droplets are ~15.1 and ~10.6 °C, respectively. At 20.6 dBm power, the temperature rise decreases, and we obtained ~10.4 °C rise for 2 microliter droplet, whereas only ~6.9 °C was observed for 10 microliter droplet.

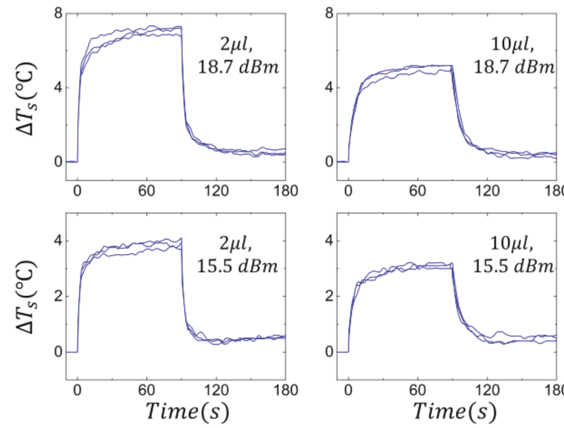

Fig. 4. Temperature rise (ΔT_s) vs. time for 2 and 10 microliter droplets at 18.7 and 15.5 dBm SAW powers.

A similar trend is also observed for 18.7 dBm and 15.5 dBm power levels (Fig. 4). It is obvious that for the same temperature rise, the larger droplet requires more energy than that of a smaller droplet and for the same input energy, the temperature rise should be inversely proportional to the droplet volume. However, in the present study, we have not observed such a relationship. This can be attributed to the complex heating mechanism due to acoustic-fluid interactions. For instance, at 18.7 dBm power level, the temperature rise in a 2 microliter droplet was estimated to be ~ 5.7 °C and for such situations, 10 microliter droplets should have a temperature rise of ~1.1 °C only. Instead, for 10 microliter droplets, a temperature rise of ~3.7 °C is observed.

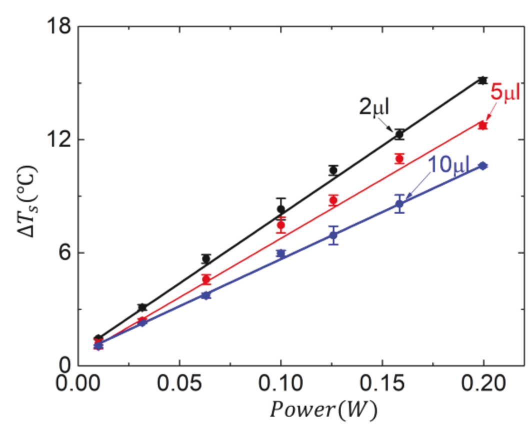

Fig. 5. Steady temperature rise (ΔT_s) vs. SAW power for 2, 5, and 10 microliter droplets.

Figure 5 shows the steady temperature rise (ΔT_s) as a function of SAW power where black, red, and blue symbols represent the temperature rise for 2, 5, and 10 microliters, respectively. The error bars associated with the symbols show the standard deviations of the measurements. We have also plotted a linear fit to show that the temperature rise closely follows a linear relationship with the applied SAW power.

B. *Temperature Rise in $LiNbO_3$ without Water Droplets*

For each power level, we performed three temperature rise measurements in $LiNbO_3$ substrate without water droplets and took an average of these measurements. Fig. 6 shows that average temperature rise (ΔT) as a function of time for 23, 20.6, 18.7, and 15.5 dBm SAW powers. As observed from the figure, the temperature in the substrate is much less than that of the fluids. This is attributed to the fact that the acoustic damping is significantly high in fluids compared to the solid substrate and the damping is essentially causing the acoustic energy to be converted into the internal energy manifesting temperature rise.

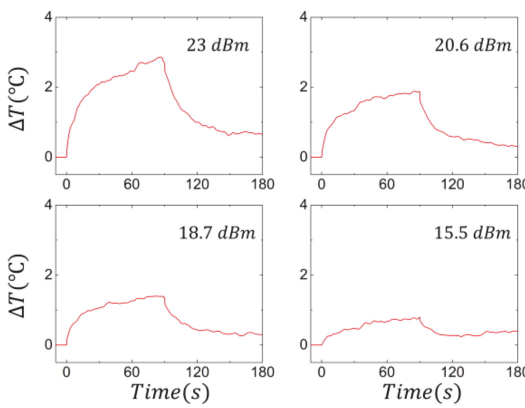

Fig. 6. Temperature rise (ΔT) in $LiNbO_3$ substrate without water droplets as a function of time at 23, 20.6, 18.7, and 15.5 dBm.

IV. Conclusions

In this paper, we have analyzed experimentally the influence of droplet volume on the acoustothermal temperature rise in water droplets placed on the delay path of 128° YX $LiNbO_3$ based SAW device at various power levels. We measured the temperature rise using a thermal camera and capture the heating dynamics for 2, 5, and 10 microliter droplets. Our study shows that the temperature increases linearly with the applied power. However, with increasing droplet volumes, the temperature rise is observed to decrease. These findings will help SAW-based sensor designers to optimize their sample volumes and operating power levels so that significant heating (which may cause denaturing of proteins or biomolecules) can be avoided.

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