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2015

Kishor, R., Seah, Y. P., Zheng, Y. J., Xia, H. M., Wang, Z. F., Lu, H. J., et al. (2015). Characterization of an acoustically coupled multilayered microfluidic platform on SAW substrate using mixing phenomena. *Sensors and Actuators A: Physical*, 233, 360-367.

<https://hdl.handle.net/10356/85054>

<https://doi.org/10.1016/j.sna.2015.07.017>

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Characterization of an acoustically coupled multilayered microfluidic platform on SAW substrate using mixing phenomena

Rahul Kishor¹², Y P Seah⁴, Y J Zheng^{3*}, H M Xia⁴, Z F Wang⁴, H J Lu⁴, T T Lim¹⁵

Abstract Optimization of the reusable microfluidic platform on surface acoustic wave (SAW) requires a clear understanding of the various factors that affects the acoustic energy transmission to the fluid in the microchannel. This article reports the characterization and analysis of the reusable SAW microfluidic platform. The acoustic energy transfer through various layers was characterized by the microfluidic mixing phenomenon. During this work, mixing efficiency was considered to evaluate the acoustic energy transmission. The three different parameters taken into consideration are the input voltage, SAW frequency and the coupling layer thickness. The effect of the factors on the output response is examined by conducting experimental studies and developing new analytical models. The acoustic wave was coupled through a liquid layer to a disposable superstrate. The anti-symmetric higher order lamb waves generated on thin glass plate generates compressional waves in the liquid to induce fluid motion. The acoustic energy delivered to the fluid increased as the square of the applied voltage and saturated at 50 V. The frequency response demonstrated a higher acoustic energy transmission for the 100MHz compared to the 50MHz, which was validated by numerical studies. Power transmitted through the coupling layer displayed a sinusoidal dependence on the normalized thickness of the layer. Finally, the effect of temperature is also considered to confirm the validity of the developed models.

Keywords Surface acoustic wave; Disposable; Reusable; Micromixers;

*Corresponding author

¹Environmental Chemistry and Materials Group, Nanyang Environment & Water Research Institute (NEWRI), Nanyang Technological University, 1 Cleantech Loop, Singapore 637141

²Interdisciplinary graduate school (IGS), 50 Nanyang Avenue, Nanyang Technological University, Singapore 639798

³Division of Circuits and Systems, School of Electrical and Electronic Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798 E-mail address: YJZHENG@ntu.edu.sg; Tel: +65 65927764

⁴Singapore Institute of Manufacturing Technology, 71 Nanyang Drive, Singapore 638075.

⁵Division of Environmental and Water Resources Engineering, School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

1. Introduction

Microfluidics allows manipulation of small volume of liquid that is vital in various analytical steps on a Lab-on-a-Chip (LOC) device, such as sample preparation, mixing, pumping and detection [1]. Various technologies including optics [2], magnetism [3], electrowetting [4], acoustics [5] and others allow microfluidic manipulations. Recently, there is increasing focus on surface acoustic wave (SAW) devices for microfluidic actuations[6] owing to its useful and unique features[7]. The SAW device is compact and inexpensive; SAW field is biocompatible and generates large force for fast fluidic actuation. Further, it provides contact free manipulation avoiding any potential contamination of fluids. SAW can also perform sensitive detection and allows integration with integrated circuits [8] .

SAW has enabled various microfluidic technologies in open and closed channels including fluid mixing [9], fluid translation [10, 11], particle concentration [12] and sorting [13], jetting and atomization [14]. The above applications are the results of interaction of the SAW with fluids. A recent review discussed the growing interest

for using the disposable superstrates on the expensive piezoelectric substrates [7]. SAW coupling to a glass superstrate using water as a couplant was reported previously [15]. Disposable glass superstrate was also used to demonstrate droplet actuation using slanted finger interdigital transducer (IDT)[16]. Fluid couplant in SAW is further discussed in our paper.

Mixing is an essential element on a LOC device, with applications in biochemical processes, drug-delivery and nucleic acid synthesis. However, in these instances, the flow in the micro-channels is laminar and mixing occurs only due to diffusion, which takes significantly longer time. Various passive and active micromixers have been reviewed [17]. Rapid mixing on liquid droplets using SAW as the primary force was demonstrated earlier by various groups [18-20]. The quantitative study relating the efficiency of the chaotic mixing process due to SAW for variations in the fluid viscosity and input power was also performed in a microfluidic well[21]. The effect of SAW was used as a mixer in polydimethylsiloxane (PDMS) microchannel bonded to the lithium niobate (LiNbO₃) substrate [22]. Mixing of water and beads in a Y shaped channel by SAW was also demonstrated at low Reynolds number [23]. The mixing behaviour is varied at different SAW frequencies [24]. When the channel length was larger than the wavelength of the sound at a particular frequency, transition from a uniform flow to mixing occurs. The recent work on SAW-based mixing is concentrated on liquid confined in a PDMS channel and bonded to the substrate using oxygen plasma [9]. Johansson et.al [25] used polydimethylsiloxane (PDMS) channels as superstrate for particle manipulations in continuous-flow microfluidic operation, and performed a detailed evaluation of the acoustic wave coupling mechanisms and distribution of acoustic nodes in the fluid relative to the channel walls for effective particle manipulations. A qualitative visualization of the effects of PDMS microchannel in the acoustic waves within the fluid is performed using finite element methods (FEM). Potentially, these studies will be leveraged for our future works. In our paper, we use mixing phenomenon to characterize the acoustic energy transfer through the various layers.

The reusable platform consists of microchannel created on a polydimethylsiloxane (PDMS) bonded to a disposable superstrate (glass), and acoustically coupled to the piezoelectric substrate made the device reusable in different tests. The fluid motion in the microchannel is caused due to the higher order antisymmetric lamb wave modes generated on the glass superstrate, which acts a thin plate[15]. The antisymmetric mode with prominent transverse vibrations is coupled to the fluid in the microchannel causing fluid motion. A layer of water acting as an acoustic couplant and act as a matching layer between the glass and the SAW substrate. Mixing of water and beads in a Y shaped channel by SAW coupled to a disposable glass superstrate was also demonstrated at low Reynolds number [23] However, dependence of the mixing efficiency on the SAW frequency and coupling layers thickness has not been discussed in this study. Our paper focuses to characterize SAW transmission in liquid channel in a direct manner, which is through mixing. We established a novel mechanism for characterizing the SAW energy transmission in fluidic channels, which is essential for all the SAW microfluidics design, using a mixing structure. The main contribution of the paper comes from the discussion of the effect of thickness of coupling layer and frequency on the mixing efficiency in a Y-shaped microchannel and development of analytical models. The analytical models that are developed in this paper can be used to optimize the power transmission coefficient and hence increase mixing efficiency, which will be done in our subsequent works. The platform can be extended to other SAW based microfluidic applications. The decoupling of the expensive piezoelectric substrate with the microfluidic device enables lower cost and disposability. This makes the platform an ideal fit for the development of point of care clinical diagnostics[26], screening or analytical tests[27]. In future, we plan to demonstrate all microfluidics functions, e.g. mixing, sample preparation, pumping, and also replace PDMS with thermoplastics, to make the platform more economical.

2. SAW design and fabrication

2.1. SAW device design

The anisotropic piezoelectric substrate used was a LiNbO₃ wafer with the crystal cut rotated 128° around the Y-axis. A double-electrode transducer was used to reduce the inter-finger reflection and improve its performance

[28]. ANSYS transient simulation was used to determine the design specifications of the IDT for the frequencies of 50 MHz and 100 MHz as shown in Table 1.

Table 1: SAW design parameters

Parameter	Value	
	50 MHz	100 MHz
IDT pitch ($\lambda/8$)- μm	9.7	4.765
Number of IDT pairs	50	50
IDT thickness- μm	0.15	0.15
Aperture-mm	4	3

A 2-dimensional model shown in Fig. 1 was generated from the simulation results. Several assumptions reported in a previous work [29] were made.

The IDT widths were designed by observing the amplitude waveforms across the length of the device. For the exact IDT width, the transient signal waveform increased periodically in amplitude corresponding to the number of IDT pairs before stabilising to constant amplitude as shown in Fig. 2.

Fig. 1 2D finite element model, used to simulate the SAW and determine the IDT width for a particular frequency. The blue and the green colours denote the dampers used to cancel the reflections of the acoustic wave from the edges. The red region represents the piezoelectric substrate. The magnified view from the surface shows the IDT. The surface of the substrate has higher meshing density as compared to the bulk.

In order to reduce the computation time, only ten pairs of IDTs were used in this model. Simulation was also done to study the effect of increasing pairs of IDT, only an increase in the magnitude of the SAW amplitude was observed, validating our reduced model for finding the IDT width.

Fig. 2 Transient simulation waveform for a SAW model with ten pairs of IDT (the reduced number of IDT pairs only affected the magnitude of the wave). The amplitude increased until a period of ten corresponding to the number of IDTs before stabilising at constant amplitude.

2.2. SAW device fabrication

The fabrication process of the SAW device begins with a layer of aluminium patterned (thickness of 300 nm) on the 128° rotated Y cut LiNbO₃ substrate using a positive photoresist to form the IDT. After patterning and stripping of the photoresist, the gold of thickness 1.5 μm was then sputtered to create the metal pads for the contacts. To protect the IDT from oxidation, an additional layer of AZ-4620 photoresist was deposited by evaporation, for a thickness of 0.8 μm, except in the SAW propagation area. The final fabricated device is shown in Fig. 3.

Fig. 3 Fabricated SAW devices at frequency of 50 MHz. The yellow regions show the gold pads and the fine lines show the IDTs.

2.3. SAW device characterization

The centre frequency of the fabricated device was characterized using the network analyser. Maximum acoustic power was generated from the SAW device at this frequency.

Fig. 4 Measured S11 using the network analyser for the two devices at frequencies (a) 50.5 MHz and (b) 103 MHz. The devices were designed for 50 MHz and 100 MHz respectively.

The tolerance of the IDT width was 2% and 4% for the devices working at frequencies of 50 MHz and 100 MHz respectively. This could be induced by the photomask fabrication and photolithographic process, which in turn caused variance to the centre frequency. Fig. 4 shows the S11 (reflection coefficient) for the fabricated devices, which achieved -20dB at ~50 MHz and -8dB at ~100 MHz.

2.4. Micromixer design

Fig. 5 shows the schematic of the reusable micromixing platform. The SAW was transmitted from the piezoelectric substrate through a coupling layer of water and a glass superstrate into the fluid flowing through

the microchannel. A Y shaped microchannel made of PDMS enclosed the fluid. A reservoir was specially designed to hold the water couplant.

Fig. 5 Reusable SAW mixing schematic. The acoustic wave generated on lithium niobate (LiNbO_3) was transmitted through a coupling layer of water into the microchannel made of PDMS bonded to glass. The mixing channel has a width of 1.15mm and a height of 200µm.

3. Experimental setup

The electrical signal was generated from a pulsed RF power amplifier, as a high voltage ($>30 \text{ V}$) was required for mixing to take place. The pulsed RF input was generated using the Tektronix AFG3252 arbitrary function generator. A pulsed RF signal with a period of T_p of 5 ms and T_{ON} (duration for which the signal is turned on) of 1 ms was generated. The output signal from the function generator has amplitude in the range of 100-200 mV. This was channelled to a pulsed power amplifier (TOMCO) which has a power gain of 60 dB. The output from the pulsed power amplifier provided the input to the SAW device.

The mixing effect due to the SAW disturbance was visualized using CMOS video camera (INFINITY1). Two dyes of red and green colours were introduced into the microchannel at a flow rate of $1 \mu\text{L}/\text{min}$. The flow rate was controlled by syringe pumps (NE-1600, New Era, USA).

(a)

(b)

(c)

Fig. 6 Images of the SAW mixing experiment (a) unmixed liquids at the beginning of the experiment, (b) liquids mixed using SAW (c) Homogenously mixed liquids where the two dyes were mixed externally to form the homogenously mixed solution.

By virtue of the laminar nature of the flow, the two liquids initially flowed separately without significant mixing as seen in Fig. 6(a). Upon initializing the SAW, mixing occurred between the two streams of liquid, as shown in Fig. 6(b). The two dyes were then homogenously mixed laterally. It was then flowed through the microchannel as shown in Fig 6(c). This was representative of the completely mixed state. The region of interest (ROI) was selected to be within the SAW aperture region, shown in Fig. 6(a).

The mixing efficiency(σ) was calculated by extracting the pixel intensities I_{unmix} before mixing, I_i obtained with the acoustic wave induced mixing and I_{mix} after complete mixing [30] as follows:

$$\sigma = 1 - \sqrt{\frac{1}{N} \sum_{i=1}^N \sigma_i^2} \quad (1)$$

Where $\sigma_i = \frac{I_i - I_{mix}}{I_{unmix} - I_{mix}}$ and N is the total number of pixels.

The value of σ varies from zero for non-mixing to one for complete mixing. Please note that during the mixing test, the experimental setup (mixing platform and the channel placement) remain unchanged.

4. Results and discussions

To calculate the efficiency using Eq. 1, the pixel values (corresponding to the intensity) was extracted using the ImageJ software [31]. An average of 20,000 pixels (N in Eq. 1) in the ROI was used to calculate the efficiency.

4.1. Transient behaviour of mixing

Fig. 7 shows the transient response of the mixing phenomena. The increase in mixing efficiency can be observed immediately before saturating at a value, dependent on the voltage level.

Fig. 7 Transient mixing phenomena. The mixing achieved saturation within 1.5 s.

The experimental result demonstrated that the mixing behaviour saturated within a time of 1.5 seconds. 70% efficiency at a voltage input of 45 V was obtained in 1.5 s. Hence, in this study, a time of 1.5 s was considered for the SAW based mixed state.

4.2. Effect of voltage on mixing

To examine further the influence of voltage on mixing, the voltage was varied from 20 V to 60 V. The mixing efficiency was calculated at each voltage step. Fig. 8 shows the mixing efficiency with different voltage for the device working at 50 MHz. Maximum efficiency of 80% was attained with an input voltage of 50 V. The mixing efficiency graph demonstrated two trends with increasing voltages. At lower voltages, the mixing efficiency increased with voltage rapidly following a second order polynomial response. At higher voltages (around 50 V), the mixing efficiency became saturated.

The interaction of the acoustic wave with fluid generates acoustic streaming [32]. As the wave is applied in a direction perpendicular to the liquid flow direction, acoustic streaming forces a mass movement in an orthogonal direction of flow and thus rapidly induces mixing. Acoustic streaming is a nonlinear second order phenomenon. As reported by Nguyen and White [33], the acoustic streaming velocity is proportional to the square of the applied voltage. Mixing efficiency, which is proportional to the acoustic streaming velocity, thus increases with the square of the voltage. The experiment observation obtained is in line with this trend. At higher voltages, the nonlinearity of the acoustic field in the fluid causes the saturation of the acoustic streaming velocity [34, 35]. In this study, the mixing efficiency saturated beyond a certain applied voltage (50 V) which follows prior research findings closely.

Due to saturation in the level of mixing, the input power need not be increased beyond 50 V. Any further increase would reduce the power conversion efficiency.

Fig. 8 Mixing efficiency as a function of voltage. The error bars show the mixing efficiency variation from the mean value. The solid lines shows a second order polynomial fit for voltages less than 50 V and thereafter saturating for higher voltages.

4.3. Effect of coupling layer thickness on mixing efficiency

The acoustic mixing efficiency is dependent on the thickness of the coupling layer. The effect of varying thickness on the efficiency was examined experimentally. Fig. 10 shows the experimental observation that indicates, a larger coupling layer thickness gives rise to a higher mixing efficiency.

Fig. 9 Wave transmission through the various layers. A_i and B_i represents the transmitted wave and reflected wave amplitude at each layers. The terms in red denotes the incident (A_1) and transmitted waves (A_2, A_3). The reflected waves (B_1, B_2) are represented in green. The exponential part shows the phase dependence of the wave on the acoustic wave frequency (ω) and wavenumber (K).

The acoustic impedance of the coupling layer prevents total reflection of the incoming wave from the LiNbO_3 substrate. The wave diffracts into the water coupling layer from the SAW device at an angle of 22.1° . However, on passing through the coupling layer of certain thickness (L), the wave gets attenuated [36]. Fig. 9 shows the wave amplitude through the various layers to determine the power transmission coefficient (T_r). The power transmission coefficient can be calculated from [37] :

$$T_r = 4 r_{13} / (r_{13} + 1)^2 \left[1 - (r_{23}^2 - 1)(r_{12}^2 - 1) (\sin k_2 L)^2 / (r_{13} + 1)^2 \right] \quad (2)$$

With $r_{ij} = \rho_j c_j / \rho_i c_i$, where ρc represents the characteristic acoustic impedance with c and ρ denoting the wave velocity and the density respectively in the medium.

L in Eq. 2 denotes the coupling layer thickness. The parameter of Eq. 2, other than the sinusoidal function remains unchanged for the experiment. The power transmission coefficient (T_r) is directly proportional to the

square of the sinusoidal function. For the operating frequency of 50 MHz, the square of sine function gives values of 8.6×10^{-8} , 0.71 and 0.75 for the coupling layers of thicknesses 0.6 mm, 0.7 mm and 0.8 mm respectively. Thus, T_r increases for thicknesses in the order of 0.8 mm, 0.7 mm and 0.6 mm.

Fig. 10 Mixing efficiency as a function of coupling layer thickness

The experimental results shown in Fig. 10 thus confirm the theoretical model. An optimum coupling layer thickness can be designed to reduce the attenuation.

4.4. Effect of frequency on mixing

The SAW devices designed for frequencies of 50 MHz and 100 MHz were used to study the effect of frequency on the mixing efficiency. A coupling layer thickness of 1 mm was used for the experiment.

Fig. 11 Mixing efficiency obtained for SAW devices at 50 MHz and 100 MHz.

As observed experimentally and shown in Fig. 11, the SAW device working at 100 MHz has a higher mixing efficiency than 50 MHz at lower voltages. However, at higher voltages, the mixing efficiency reaches a maximum as mentioned in the effect of voltage, and both the devices deliver quite similar mixing efficiency.

The analysis for the effect of frequency is twofold: SAW power (P_s) is generated on the substrate at different frequencies and delivered into the fluid through the various transmission layers. The power generated by the transducer is given by [38]:

$$P_s = G_a |V|^2 / 2 \quad (3)$$

where, G_a is the IDT conductance and V is the applied electrical potential. As the IDT is bidirectional, only half of the wave power is delivered into the microfluidic chip. G_a is proportional to the frequency and the aperture of the IDT. The power generated by the transducer for the two frequencies is:

$$P_s(50\text{ MHz}) = 0.533P_s(100\text{ MHz}) \quad (4)$$

The acoustic wave generated passes through the various layers before it reaches the microchannel as shown in Fig 12. As the wave passes through the thin water layer, it undergoes an attenuation of 0.55 dB and 2.3 dB for the 50 MHz and 100 MHz devices respectively. The longitudinal wave generated in the fluid reaches the water-glass (bottom) interface at an incident angle (θ_w) of 22.1° . The compressional waves from water generate lamb waves in the thin glass plate of thickness 0.15mm. As discussed previously by Hodgson et al[15], higher order antisymmetric waves are generated on the glass plate. The dispersion curve for glass [39, 40] shows that at a frequency of 50MHz A1 mode is excited. The 100 MHz incident acoustic wave excites the A1, S1 and A2 lamb wave modes. For the excited modes, the phase velocity of the normal wave is less than the velocity of the longitudinal waves c (5960 m/s) and close to the transverse velocity b (3200 m/s) in the plates. The displacements for mode A_n in this case are[41]:

$$\begin{aligned} u_1 &\cong \left(n + \frac{1}{2}\right) \frac{\pi}{h} A \left\{ -\sin \left[(2n+1)\pi \frac{x_2}{2h} \right] + 2(-1)^n \frac{\sinh(\chi k x_2)}{\sinh(\chi k h)} \right\} \\ u_2 &\cong ikA \left\{ \cos \left[(2n+1)\pi \frac{x_2}{2h} \right] + (2n+1)(-1)^n \frac{\pi \chi}{kh} \frac{\cosh(\chi k x_2)}{\sinh(\chi k h)} \right\} \end{aligned} \quad (5)$$

where u_1 and u_2 are the longitudinal and vertical (transverse) components of the mechanical displacements. The plate thickness along the x_2 direction is equal to $2h$ and n represents the mode number. Computation of the transverse component of displacement (u_2) on the surface of the plate ($x_2=h$) shows that the magnitude of second order mode (A_2) is about three times the magnitude of the first order mode (A_1). The second order mode excited in the 100MHz excitation generates larger displacement, consequently improves mixing efficiency. The sound wave transmitted through the glass plate placed between two liquid media, can also be analysed quantitatively by the Eq 6 obtained from Brekhovskikh[42]:

$$\begin{aligned} W &= 2N / [2M + i(M^2 - N^2 - 1)] \\ M &= (Z_2/Z_1) \cos^2 2\gamma_2 \cot P + (Z_{2t}/Z_1) \sin^2 2\gamma_2 \cot Q \\ N &= Z_2 \cos^2 2\gamma_2 / Z_1 \sin P + Z_{2t} \sin^2 2\gamma_2 / Z_1 \sin Q \\ P &= k_2 (h/2) \cos \theta_2 \\ Q &= \kappa_2 (h/2) \cos \gamma_2 \end{aligned} \quad (6)$$

where κ_2, κ_2 are the wavenumbers of the acoustic wave for the longitudinal and transverse component respectively in glass; Z_2, Z_{2t}, Z_1 denotes the acoustic impedance for the longitudinal, transverse wave in glass, and the compressional wave in water respectively; θ_2, γ_2 are the angle of incidence for the longitudinal and transverse wave in glass. The longitudinal wave in glass undergoes total internal reflection and the wave only resides on the surface. The angle of incidence of the longitudinal wave is represented in the complex form. We set $\theta_2 = \pi/2 + i\zeta$, with $\zeta = 0.9579$, using this $\sin \theta = \cosh \zeta$, $\cos \theta = -i \sinh \zeta$. The transmission coefficient (power- $|w|^2$) for the 50MHz and 100MHz acoustic wave is 0.155 (-8dB) and 0.2916 (-5.35dB) respectively.

The quantitative results align with the qualitative results obtained above, with the 100MHz excitation conveying larger power to the fluid above compared to the 50MHz acoustic wave excitation. From the reflection coefficient of the device shown in Fig. 4, the 50 MHz and 100 MHz devices have a reflection coefficient of 0.794% and 15% respectively, Thus, the transmission coefficient for the two devices are -0.034 dB and -0.71 dB. There is an additional reduction of power by -3.01 dB due to the bidirectional nature of the IDTs. Hence, summing up the various losses, the total coupling attenuation of power was 11.594dB and 11.37dB for the 50 MHz and 100 MHz device respectively. The transmitted power is equal to the generated power by the SAW

device minus the attenuated power through various layers. Thus, the numerical computation shows that the power transmitted by the 100 MHz device was higher than the 50 MHz device.

Fig. 12 Acoustic Wave transmission through the various layers, showing the waves and its refracting angles at each layer. Medium 1, 2, 3 and 4 are the piezoelectric lithium niobate substrate, water coupling layer, glass and fluid within the microchannel respectively. $P_{l\text{-water}}$ represents the longitudinal wave in water, at an incident angle of 22.1° ; $P_{t\text{-glass}}$ is the transverse wave in glass with a transmission angle of 53.4° , the longitudinal component undergoes total internal reflection and will have the character of surface waves.

4.5. Acoustic heating

Temperature rise changes the acoustic impedance of various layers and can hinder the model presented in Sec 4.3 for calculating the power transmission coefficient. To justify the validity of the model, we performed the following experiment to measure the temperature. Temperature was recorded at the LiNbO_3 surface for a time-period of 20 seconds using a Fluke DT-610B thermometer.

Fig. 13 Positions along the SAW device for measuring the temperature. Three points were chosen along the centre line of the SAW aperture at distance of 1 mm (P1), 5 mm (P2) and 13 mm (P3) from the IDT.

The observation points (P1, P2 and P3) were chosen along the centre line of the SAW aperture as shown in Fig 13. Different Voltages (25V, 35V and 45V) were also applied for the experiment.

Fig. 14 Temperature measured for a time period of 20 sec with different voltages (25V, 55V and 45V) at various positions as indicated on Fig 14. The inset shows the magnified view of the graph for a time-period of 2 sec

Fig. 14 shows the experimental results for a period of 20 s. It indicates that for a time period of 20 s, the temperature rises only from 24.35⁰ C to 39.05⁰ C (corresponding to 45V and position P1). The mixing efficiency in our experiment was calculated at 1.5 s. The temperature rises by a maximum of 0.8⁰C (24.35⁰C to 25.15⁰C) for the period of 1.5 s, as shown in Fig. 14. Considering the dependence of the velocity of sound in water [43] and density [44] as a function of temperature, a 0.16% change in the acoustic impedance is obtained. This temperature rise is considered negligible and is unlikely to cause a substantial amount of shift in the acoustic impedance. Hence, the Kinsler approximation model discussed in Sec 4.3 is appropriate. The temperature increase is also not substantial to cause any heating of the liquid.

5. Conclusion

This article reports the design, fabrication and characterization of a reusable microfluidic platform using SAW device. The Y-shaped microchannel was made from PDMS and bonded to a glass superstrate. It was then coupled to the SAW generated on the LiNbO₃ substrate using water as an acoustic coupling layer. The platform was characterized using microfluidic mixing phenomenon. Two dye solutions were introduced into the microchannel and mixing efficiency was calculated. Mixing efficiency of 80% was obtained within 1.5 s for an input signal of 50 V. Experiment was conducted with varying coupling layer thickness to find the optimal thickness for maximum acoustic energy transmission. An analytical model formulated to predict the behaviour for different thicknesses substantiates the experimental findings. Two devices working at frequencies of 50 MHz and 100 MHz were used to study the acoustic energy transmissions at different frequencies. The experimental result shows that the power transmission was higher for the 100 MHz as compared to the 50 MHz. The numerical value obtained from the analytical model confirms this behaviour. The results obtained provide useful design guidance for the selection of voltages, frequencies and the thickness of couplant layers for improving the acoustic energy transfer for various microfluidic manipulations.

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