ACOUSTIC HEATING AND THERMOMETRY IN MICROFLUIDIC CHANNELS

H. Jagannathan, G.G. Yaralioglu, A.S. Ergun, and B.T. Khuri-Yakub

Edward L. Ginzton Laboratory, Stanford University, Stanford, CA 94305-4088

Tel: 1-650-725-2990, Fax: 1-650-725-7509

ABSTRACT

This paper presents the results of the work performed in establishing closed loop temperature control of fluids in microfluidic channels. Acoustic energy is used to introduce heat into localized regions of the channel. The temperature of the fluid in these regions is determined by using the relationship between the attenuation and speed of sound propagating in the fluid with temperature. The above two operations of heating and temperature measurement when used in unison serve as a very powerful tool in microfluidics. The system requires milli-watts of power for heating and has a temperature measurement accuracy of 0.1 degrees.

INTRODUCTION

The growth in the field of micro-fluidics has underscored the need for improved measurement and actuation techniques of fluids in micro-channels. Current techniques of sensing fluids in micro-channels include the use of lasers, fluorescence microscopy, and image processing with cameras. These techniques involve bulky instruments which complicate the system integration. The actuation of fluids is performed by mechanical pumping or by the moving of micro-machined components, such as switches or valves. Heating is commonly done by using polysilicon resistors that are fabricated inside the channel [1].

While ultrasound theory is generally used to study fluid flow in large pipes and tubes, it is rarely applied in the field of micro-fluidics. Our work emphasizes the use of ultrasound to achieve useful operations in micro-channels [2], using both piezoelectric transducers and Capacitive Micromachined Ultrasonic Transducers (CMUTs). The piezoelectric devices operate at a center frequency of 400 MHz in air and have been used in our experiments. CMUTs have also been fabricated to operate at a center frequency of 50 MHz. The channels are composed of either PDMS (polymethylsiloxane) or glass.

Precisely controlling and monitoring temperature in micro-channels is crucial to monitor the reaction rates between two or more chemicals. Many bio-medical procedures such as the Polymerase Chain Reaction (PCR) among others, involve the cycling of temperatures. Therefore, gaining the ability to control and monitor the temperature in micro-channels will enable the same procedures to be carried out in small and portable devices.

THE ULTRASONIC TRANSDUCER

Piezoelectric Transducers

The piezoelectric transducers used in our experiments are made by depositing a thin layer of zinc oxide in between two thin layers of gold. The zinc oxide is deposited by magnetron sputtering [3] while the patterning of the electrodes is performed by standard lithography techniques.

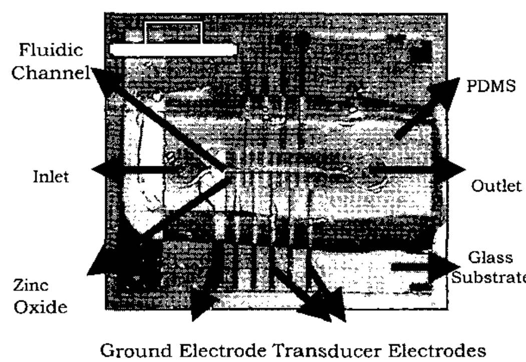

Figure 1. A picture of a piezoelectric transducer

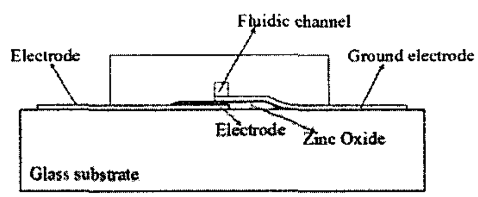

Figure 2. The cross-section of a piezoelectric transducer

Figure 1 shows a picture of a fabricated transducer while Figure 2 shows a cross-sectional diagram of the piezoelectric transducer. The transducers that were fabricated, operate with a center frequency of 400 MHz.

0-7803-7744-3/03/$17.00 ©2003 IEEE.

Capacitive Micromachined Ultrasonic Transducer (CMUT)

The need for better performing transducers and the availability of advanced fabrication facilities enabled the evolution of conventional ultrasonic devices to the modern micromachined ultrasonic transducers. The CMUT resulted from such a development [4]. Figure 3 shows the membranes of a fabricated CMUT while Figure 4 shows the picture of a CMUT integrated with the channels.

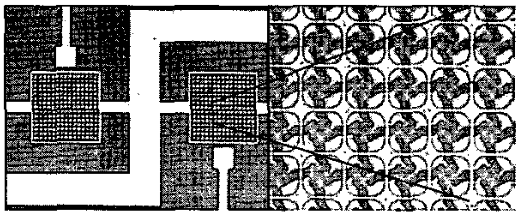

Figure 3. A picture of a CMUT

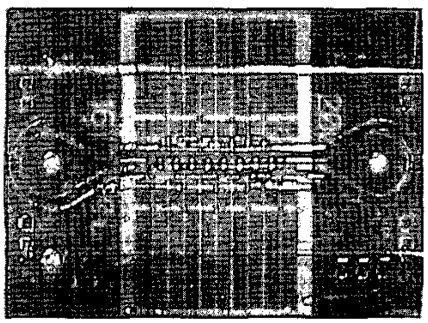

Figure 4. CMUT integrated with a micro-channel

It can be seen from Figure 3 that the CMUT consists of an array of thin membranes suspended over posts. Many membranes are electrically connected in parallel to make a transducer. The membranes of the CMUT are fabricated using silicon nitride and the electrodes required for the actuating and receiving the signals are made by depositing aluminum. The frequency of operation of the CMUT is determined by the thickness and the dimension of the membrane. The height of the cavity determines the DC voltage required to operate it.

CMUTs possess a number of advantages compared to piezoelectric transducers. Firstly, CMUTs have over 100% factional bandwidth. In practice the CMUTs still have broader bands of operation than their piezoelectric counterpart which are known to be narrow band. Secondly, CMUTs are relatively insensitive to temperature. Piezoelectric materials on the other hand are known for depolarizing high temperatures making them useless at those conditions. The ability to fabricate CMUTs in dense and compact arrays makes it a more attractive substitute to piezoelectric transducers for mobile ultrasonic devices.

THE FLUIDIC CHANNEL

With the field of microfluidics gaining popularity on a daily basis, a number of methods now exist for fabricating micro-channels. We investigated three such methods during our experimentation. The first method involved the fabrication of PDMS channels. Here, a blank silicon wafer was etched to the dimensions required for the micro channel. Using the patterned wafer as a mould, silicone rubber was cast on the wafer and then subsequently used after solidification. The second method was to spin and pattern SU8 walls over a glass wafer using standard lithography techniques, and the desired wall height was obtained by successive spinning of SU8. The final method used glass made by machining it to the required dimensions. These glass channels fabricated in the final method were used in our experiments.

THE EXPERIMENTAL SETUP

The acoustic transducer was aligned with the microfluidic channel under the microscope and was bonded in place. The chip consisting of the transducer and the micro-channel were then mounted on a printed circuit board and were connected to the electronics by means of wire bonds. The printed circuit board contained the surface mounted components that made up the pulse generator, protection and amplification circuitry, and the switching circuitry. The same transducer was used for both heating and pulse echo measurements. The pulse generator made by operating the transistor in the avalanche mode, was used to feed in pulses 2.5 ns in width and 60 V in amplitude for the pulse echo measurements. The protection and amplifying circuitry were used to clip the high voltage signals and increase the amplitude of the pulses in interest for better signal processing. A mechanical relay was utilized in the switching circuitry. The circuit performed the switching operation between the pulser electronics and the circuitry for ultrasonic heating. Due to the inherent delay of the mechanical switch, an 8 ms delay was present between the application of the heating signal and the application of the pulse for pulse echo measurements. Work is currently under progress to replace the mechanical switch with a solid state switch intended to reduce the delay from 8 ms to a few hundred microseconds.

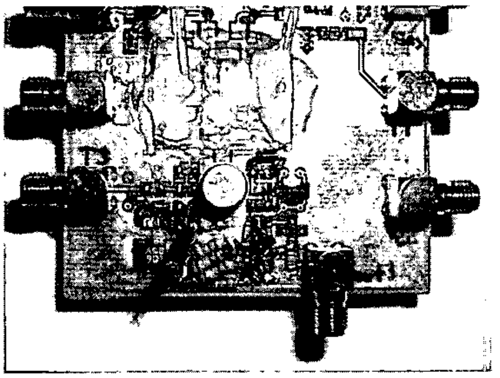

Figure 5. Photograph of a printed circuit showing the assembled fluidic chip along with the electronics

Figure 5 shows one such printed circuit board housing the ultrasonic transducer, the micro-fluidic channel and the necessary electronics.

PULSE ECHO MEASUREMENTS IN MICROFLUIDIC CHANNELS

Figure 6 shows the pulse echo measurement done in a fluidic channel filled with air using the mentioned setup. The pulses on the upper left hand side of the figure correspond to the multiple reflections at the bottom of the fluidic channel with the channel filled with air. The amplitude of these pulses reduces due to repetitive transmission and attenuation losses of the sound wave.

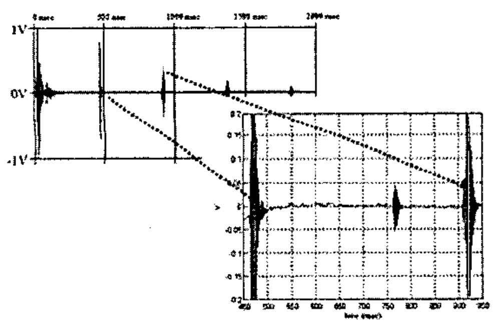

Figure 6. Pulse echo measurements in the micro-channel

The pulses seen on the bottom right hand side of the figure shows the pulse echo measurements done with water inside the fluidic channel. As indicated the first pulse that is seen corresponds to the bottom of the fluidic channel and the second pulse corresponds to the top of the fluidic channel. The position of the second pulse relative to the first is used to calculate the temperature of the fluid in the channel.

ULTRASONIC HEATING

Ultrasonic heating has been used for quite some time in physiotherapy for treating injuries, pain and inflammation. This method of treatment is termed as ultrasonic diathermy which involves the application of a strong beam of ultrasound on the skin surface to obtain internal heating of tissues. Modern nebulizers and humidifiers too make use of high intensity ultrasonic transducers for breaking up water and other liquids into fine droplets.

The heating of fluids in the micro-channels was done by the same method. To obtain heating using ultrasound, a tone burst of a single frequency was applied to the transducer. It was observed that maximum heating was obtained when the frequency of the tone bursts matched one of the multiples in the central resonant frequency of the transducer-electronics system. This result is expected because when the frequency of the applied tone bursts and that of the system match, maximum electrical energy applied to the transducer is converted into mechanical energy. This mechanical energy in turn results in maximum heating of the fluid in the channel. Acoustic heating is done by sending an acoustic wave through the fluid to be heated. The heating is obtained due to the frictional damping of the fluid.

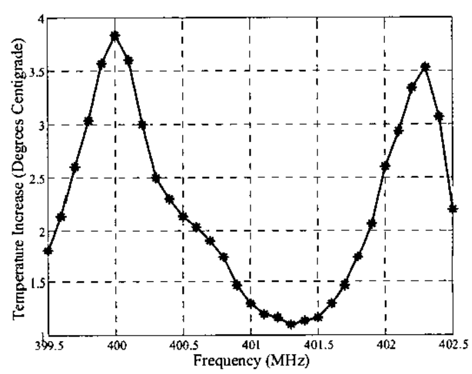

Figure 7. Variation of heating with frequency of applied tone bursts

Fig 7 shows the heating obtained when a tone burst signal maintained at constant amplitude of 20 dBm is applied to the transducer while sweeping its frequency. As can be seen, maximum heating is obtained at 400 MHz and 402.3 MHz. Thus, these values of frequency were chosen when operating the transducer as a heater. Our experiments typically needed around 100 mW of power to increase the heat of the water by 4 degrees.

ULTRASONIC TEMPERATURE MEASUREMENT

Determining temperature in micro-channels is essential in order to understand the rate of certain reactions. Current methods of temperature measurement use thermocouples placed inside or in thermal contact with the channel; however, these methods pose significant problems for packaging and integration. Due to the small volumes of the fluids used in micro-channels, the need to make measurements without disturbing the temperature is imperative.

The ultrasonic measurement of temperature in micro channels was performed by measuring the velocity of sound propagating in a liquid [5,6]. This was done by measuring the time of flight of sound waves along the height of the channel. A well defined relationship between the velocity of sound in a fluid and the temperature of that fluid was used to find the temperature at that instant. It should be noted that the attenuation of sound could also be used as a secondary reference for the temperature measurement.

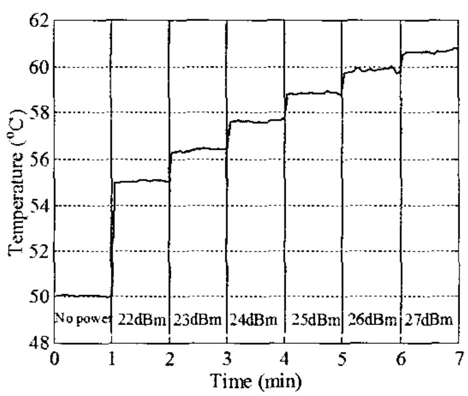

Figure 8. Temperature measurements by varying power applied for heating

The pulse echo measurements were made using the automated Labview program. A one point calibration was done initially knowing the room temperature of the liquid which was water in our case. Upon this calibration the consecutive data was run through a data extraction routine to obtain the temperature for each data point. Figure 8 shows the temperature plot obtained using the above mentioned procedure. The tone burst was maintained at a constant length of 100 ms and the frequency at 400 MHz. The temperature measurements were carried out by varying the amount of power applied at the transducer. It was observed that increased heating was obtained for increased applied power to the transducer, achieving a temperature resolution of 0.1 degrees.

CONCLUSION

In our experiments, ultrasonic transducers have been integrated with micro-channels successfully to obtain the temperature control and measurement of fluids in channels. The heating is performed using a few hundred milli-watts of power and the temperature is measured with an accuracy of 0.1 degrees. Work in progress uses the system to measure fluid flows in micro-channels. These results show promise for the application of ultrasound in micro-fluidics. Future work will include improving the switching speeds of the switching circuitry, replacing piezoelectric transducers with CMUTs and performing flow measurement in channels.

ACKNOWLEDGEMENT

This work was made possible by support from the Defense Advanced Research Program Agency (DARPA) under the BIOFLIPS program.

REFERENCES

1. C. Liu, J. Huang, Z. Zhu, F. Jiang, S. Tung, Y. Tai, C. Ho, "A Micomachined Flow Shear-Stress Sensor Based on Thermal Transfer Principles," J. Micromechanical Systems, Vol. 8, 1999, pp 90-99.

2. H. Jagannathan, G.G. Yaralioglu, A.S. Ergun, F.L. Degertekin, and B.T. Khuri-Yakub, "Micro-Fluidic Channels with Integrated Ultrasonic Transducers," in Proc. IEEE Ultrason. Symp., pp.859-862, Atlanta, USA, 2001

3. B.T. Khuri-Yakub, J. G. Smits, and T. Barbee, "Reactive Magnetron Sputtering of ZnO," J. Appl. Phys. 52, pp. 4772-4774, July 1981.

4. M. I. Haller, and B. T. Khuri-Yakub, "A surface micromachined electrostatic air transducer," in Proc. IEEE Ultrason. Symp., pp.1241-1244, Cannes, France, 1994

5. V.A. Del Grosso and C.W. Mader, "Speed of sound in pure water," J. Acoust. Soc. Am., 52(2), pp 1442-1446, 1972.

6. W. Marczak, "Water as a standard in the measurements of speed of sound in liquids," J. Acoust. Soc. Am., 102(5), pp 2776-2779, 1997.