Experimental Study of Mutual Acoustic Coupling in CMUTs with Substrate-Embedded Springs

Byung Chul(B.C.) Lee1,2,*, Amin Nikoozadeh1, Kwan Kyu Park3, and Butrus T. Khuri-Yakub1

1Khuri-Yakub Ultrasonics Group, E. L. Ginzton Laboratory, Stanford University, Stanford, CA, USA
2Center for BioMicrosystems, Korea Institute of Science and Technology, Seoul, Republic of Korea
3School of Mechanical Engineering, Hanyang University, Seoul, Republic of Korea

*Corresponding Email: bchlee@kist.re.kr

Abstract—The inter-cell and inter-element acoustic crosstalk in capacitive micromachined ultrasonic transducer arrays has been continuously investigated in immersion, since their effects cause significant degradation of the transducer performance. In this paper, experimental measurements of the inter-cell and inter-element acoustic couplings in 2-D capacitive micromachined ultrasonic transducers with substrate-embedded springs (PCMUTs) are demonstrated. The measurements are performed on two different PCMUT configurations by means of optical interferometry. First, a single 2-D PCMUT element composed of four unit cells is used to display the inter-cell acoustic coupling. Second, four 2-D PCMUT elements are positioned on 2×2 array formation in order to measure the inter-element acoustic crosstalk. The inter-cell acoustic coupling in a 2-D PCMUT element results in the cancellation of the average pressure at certain lower frequency than the operating frequency. The symmetric and asymmetric inter-element interactions from the 2×2 2-D PCMUT arrays are also analyzed by means of exciting all the elements simultaneously and applying a bipolar voltage pulse to one element, respectively. In order to reduce the inter-cell acoustic coupling in a 2-D PCMUT element, the effect of a viscoelastic polymer on the mutual acoustic coupling of the PCMUT cells are indirectly evaluated by using the hydrophone measurement.

Keywords—CMUT, substrate-embedded springs, PCMUT, mutual acoustic coupling, piston parallel motion.

I. INTRODUCTION

Since the ultrasonic imaging transducer technology has been developed toward the increase of number of elements in 2-D phased arrays such as 32×32 or 64×64 2-D phased arrays, capacitive micromachined ultrasonic transducer (CMUT) technology has been introduced to be one of the most promising transducer technologies. Because many unit cells comprise the element of capacitive micromachined ultrasound transducer (CMUT) arrays, the mechanical coupling between CMUT cells to cells and elements to elements intrinsically exist in CMUT arrays and can lead to significant degradation of the transducer performance, and hence many researches have been identified and intensively examined in order to reduce the effects [1]–[3].

Previously, a capacitive micromachined ultrasonic transducer with substrate-embedded springs, called post-CMUT (PCMUT), has been demonstrated that provides non-flexural parallel-plate piston movement and improves the transducer performance [4]. The 2-D PCMUT element is composed of four unit cells as a result of the finite element analysis (FEA) data (Fig. 1a) [5]. Similar to a conventional CMUT array element, these mutual interactions of the PCMUT element have to be carefully taken into account because these acoustic crosstalk induces significant reduction of sound radiation at certain frequency and increases the ringdown time (Fig. 1b).

In this paper, we report on the experimental measurements of the mutual acoustic coupling between PCMUT cells to cells and 2-D PCMUT elements to elements. The common measurement method for the investigation of the crosstalk, the optical interferometry, is used [2]. After the observation of the mutual interaction in PCMUT, a viscoelastic polymer coating...
is preferred to modify the interaction between PCMUT cells to cells. Because the viscoelastic polymer is opaque and has poor reflection of the laser light, the effect of a viscoelastic polymer on the mutual acoustic coupling of the PCMUT cells is indirectly analyzed by hydrophone measurements.

II. Method

A. PCMUT Device Structure

We fabricated a single 2-D PCMUT element composed of four cells with four truss-patterned piston top plates (Fig. 2a) and a 2×2 2-D PCMUT array with sixteen plane piston top plate cells (Fig. 2b) using our second generation PCMUT fabrication process [4]. The single 2-D PCMUT element is designed for a full 2-D array with a pitch of 280 µm for a center frequency of 1.5 MHz. The truss-patterned piston top plate was chosen to maximize the 3-dB fractional bandwidth. The 2×2 2-D PCMUT array consists of four elements with a pitch of 240 µm for a center frequency of 2 MHz.

Figure 2: (a) A single 2-D PCMUT element composed of four cells with four truss-patterned piston top plates. (b) A 2×2 2-D PCMUT array with plane piston top plates.

B. Experimental Device Characterization

A variety of measurements, an optical interferometry and a hydrophone measurement, have been conducted on the fabricated devices.

The dynamic plate displacement of each PCMUT cell was measured with a laser Doppler vibrometer (LDV, Model OFV-511, Polytec GmbH). To undertake the dynamic displacement measurement at the device surface, the laser from the lens was focused through the medium onto the surface of the transducer. Fig. 3 shows the LDV setup with the water medium on top of the PCMUT device. The displacement decoder from the LDV returned the voltage value to an oscilloscope. The converting factor was 50 nm/V. In addition, the refractive index of the medium was taken into account for the measurement results. In case of oil, the index is 1.47 and for water, the index is 1.33 [2]. As shown in Fig. 3, the motorized x- and y-axis stage was used to move the device for the area scan. This area scan provides time-dependent 3-D surface displacement data of the PCMUT device in order to reconstruct the mutual interaction between cells or elements. We also used an interface PCB board for applying the bias voltage to the PCMUT device and for switching and connecting the elements in the 2×2 2-D PCMUT array. On the AC connection side, we attached a AC function generator (Agilent 33250A, Santa Clara, CA) to excite an AC pulse driving the PCMUT plate.

Figure 3: Experimental setup of a laser Doppler vibrometer used in the measurement of the PCMUT dynamic displacement.

A hydrophone (Model HGL-0200, ONDA Corp.) was used to measure acoustic transient response of the device in vegetable oil. After evaluating the performance of the PCMUT device without any viscoelastic polymer coating, we encapsulated the device with a 500 µm layer of polydimethyldisiloxane (PDMS, Dow Corning Sylgard 160). We performed hydrophone measurements with and without PDMS passivation in the far field and compared the results to evaluate the effect of the viscoelastic polymer over the cell-to-cell interaction.

III. Results and Discussion

A. Inter-cell acoustic coupling in a single 2-D PCMUT element

The dynamic displacement measurement results of the single 2-D PCMUT element are plotted in Fig. 4. The single PCMUT element was excited using an unipolar rectangular pulse of 20 V peak-to-peak and 200 ns duration. The device was initially biased with a DC voltage of 35 V. The unipolar rectangular pulse first pulled down the top plate (Fig. 4a) and then released the top plate to reach the maximum positive peak. During the ring-down time of the device, multiple mutual interaction behaviors were presented. However, note that the amplitude of this mutual interaction
is smaller than the maximum displacement so that the peak-to-peak maximum displacement also demonstrates the non-flexural parallel piston movement of the truss top plate. One period of the oscillated ring-down time of the device is about 0.52 µsec.

Figure 4: Dynamic plate displacement measurement of the single 2-D PCMUT element in immersion. A 3-D perspective view at (a) the moment of the negative maximum peak, (b) the moment of the positive maximum peak, (c) the moment of the mutual interaction after 0.1 µsec passed from the positive maximum peak (Fig. 4b), and (d) the moment of the mutual interaction after 0.4 µsec passed from (c).

B. Mutual acoustic coupling in a 2×2 2-D PCMUT array

Our experiment measurements with the 2×2 2-D PCMUT arrays were performed in water. First, all the four 2×2 2-D PCMUT elements were simultaneously excited using a bipolar sinusoidal pulse of 30 V peak-to-peak and 600 ns duration. The bias DC voltage of 45 V was applied. Similar to the single 2-D PCMUT element, the positive bipolar sinusoidal pulse pulled down all the plates at the same time toward the negative maximum point (Fig. 5a). After the first stroke shows the non-flexural parallel peak-to-peak displacement, the symmetric “flexible-transducer mode”, which the average pressure reaches to minimum value [6], was shown due to the acoustic coupling between these sixteen cells (Fig. 5c and 5d). Next, one element of the 2×2 2-D PCMUT array was excited using the same pulse condition as the previous experiment. The results of inter-element acoustic coupling is shown in Fig. 6. In the initial condition, the maximum non-flexural parallel stroke was demonstrated in Fig. 6a and 6b. After the first stroke from the pulse excitation, the asymmetric boundary condition of the mutual interaction generates a dispersive surface wave which can propagate the energy along the surface.

Figure 5: Dynamic plate displacement measurement of the 2×2 2-D PCMUT array in immersion. A 3-D perspective view at (a) the moment of the negative maximum peak, (b) the moment of the positive maximum peak, (c) the moment of the mutual interaction after 0.2 µsec passed from the positive maximum peak (Fig. 5b), (d) the moment of the mutual interaction after 0.2 µsec passed from (c).

C. An effect of a viscoelastic polymer on PCMUT

The assistance of covering the CMUT device surface with the viscoelastic polymer, as well known as polydimethylsiloxane (PDMS), suppresses the mutual interaction between cells [7]. Thus, the single 2-D PCMUT element was coated with 500 µm thick PDMS to decouple each neighboring cell. A DC bias of 45 V, which was 73.8 % of the pull-in voltage, was applied to the PCMUT device with and without PDMS. A single sine pulse of 70 V peak-to-peak with 650 ns duration was superposed on the DC voltage. The attenuation and diffraction losses were compensated to extract the correct pressure data at the surface of the transducer from the hydrophone measurement. The acoustic transient responses in the far field and their corresponding frequency spectra from the hydrophone measurements with and without PDMS are depicted in Fig. 7. It is seen that the PDMS encapsulation widens the -3dB fractional bandwidth from 81% to 98% by suppressing the mutual interaction without significant degradation on the output pressure of the surface.

IV. Conclusion

In this paper, we present the experimental measurement results of the mutual acoustic coupling in PCMUTs. From the single 2-D PCMUT element, the inter-cell acoustic crosstalk of the single PCMUT element shows similar dynamic response of the flexible-transducer mode. In case of the 2×2 2-D PCMUT array, the inter-cell acoustic crosstalk also demonstrates the flexible-transducer mode which causes the degradation of
the performance, whereas the inter-element acoustic crosstalk generates the dispersive guided modes propagating in the fluid-solid interface. In order to reducing these mutual acoustic couplings in PCMUTs, the PDMS encapsulation can suppress the mutual interaction and reduce the ring-down time so that it enhances 20% of the -3dB fractional bandwidth.

Figure 6: Dynamic plate displacemnt measurement of the 2×2 2-D PCMUT array in immersion. A 3-D perspective view at (a) the moment of the negative maximum peak on one element, (b) the moment of the positive maximum peak on one element. (c) a 3-D perspective view at the moment of the mutual interaction after 0.2 µsec passed from the positive maximum peak (Fig. 5b) and (d) sideview of Fig. 6c. (e) a 3-D perspective view at the moment of the mutual interaction after 0.2 µsec passed from (c) and (f) sideview of Fig. 6e. (g) a 3-D perspective view at the moment of the mutual interaction after 0.2 µsec passed from (e) and (h) sideview of Fig. 6g.

Figure 7: Measured acoustic pressure of the single PCMUT element with and without PDMS. (a) Compensated transient acoustic pressure plot and (b) its frequency spectrum.

ACKNOWLEDGMENT

National Institutes of Health (NIH) and Analog Devices supported this work. All the PCMUT devices was fabricated in the Stanford Nanofabrication Facility (Stanford, CA), a member of National Nanotechnology Infrastructure Network. We would like to thank Timothy Brand for the grinding and polishing process of the wafers.

REFERENCES