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Improved Pulse-Echo Imaging Performance for Flexure-Mode pMUT Arrays

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***Abstract*— Piezoelectric micromachined ultrasound transducers (pMUTs) are potential candidates for catheter-based ultrasound phased arrays. pMUTs consist of lead zirconate titanate (PZT) thin film membranes formed on silicon substrates and are operated in flexure mode by driving the PZT film above its coercive field to induce flextensional motion. The fundamental operation of pMUT devices has been demonstrated; however, pulse-echo imaging has been limited to date. The objective of this work was to optimize transducer design for improved pulse-echo imaging performance. Flexure mode operation was optimized by (1) increasing transmit voltage above the PZT coercive field to induce ferroelectric domain switching, and (2) using partial cycle transmit pulses to increase the polarization in the PZT thin film and increase receive signal. As a result, pulse-echo images of tissue were obtained. 1-D arrays operating at 5 MHz were capable of resolving targets in a commercial tissue phantom as well as human anatomy. Real-time 3-D imaging was also demonstrated using 2-D arrays at 5 and 12.5 MHz. These results suggest that pMUTs have sufficient performance for application in ultrasound imaging with frequency range suitable for catheter-based phased-array transducers.**

Keywords – Acoustic devices; piezoelectric transducers; microelectromechanical systems; medical imaging

I. Introduction

Piezoelectric micromachined ultrasound transducers (pMUTs) have been a topic of research for the production of miniaturized transducers for catheter applications. Specifically, to enable real-time 3-D imaging in a catheter, significant challenges exist such as the complexity, cost of manufacture and limited performance of traditional ceramic-based 2-D transducer arrays. Real-time 3-D imaging catheter probes have not been achieved commercially. One advantage of pMUTs is that they are fabricated using well-established semiconductor batch manufacturing, which provides a more cost-effective approach for large-volume production of high-density 2-D arrays with small form factor. Another pMUT advantage is the high capacitance of the piezoelectric layer which reduces transducer source impedance [1,2].

We have previously reported novel flexure-mode transduction operating above the ferroelectric coercive voltage for pMUT devices [3,4]. This method produces sufficient acoustic output to enable pulse-echo B-mode imaging. To date, several studies have demonstrated the fabrication and modeling of pMUT structures with some limited results [1,2,5,6,7], including a receive-mode only image using a separate piston transducer for transmit [1]. Pulse-echo imaging with pMUT arrays has been demonstrated only by the authors using this unique mode of operation. Operating frequencies, transmit efficiencies, element capacitance and B-mode imaging capability using 2-D pMUT arrays with 25 and 81 elements have been reported [3,4]. This work describes performance optimization of flexure-mode pMUT elements in order to generate pulse-echo B-mode and 3-D images using pMUT 1-D and 2-D arrays.

II. Experimental Procedure

A. Design and Fabrication

pMUT devices were fabricated consisting of piezoelectric membranes that were bulk-micromachined in 100 mm diameter silicon-on-insulator (SOI) wafers with 5 μm device silicon thickness. Specific fabrication details have been described previously [4]. Piezoelectric elements consisting of a lead zirconate titanate (PZT) thin film with 1.2 μm thickness and associated electrodes were formed on the front surface of the SOI wafer. The back side of the wafer was then photolithographically patterned and etched using a deep reactive ion etch (DRIE) process to form the pMUT membrane. One-dimensional arrays with 32 and 64 elements and two-dimensional arrays with 196 and 512 elements were fabricated. The dimensions and operating frequencies for the arrays are summarized in Table 1. All arrays were fabricated with sub-wavelength (λ) element pitch for adequate phased-array operation.

TABLE I. Parameters for 1-D and 2-D pMUT Arrays

Array Type	Membrane Size (μm x μm)	Element Pitch (μm)	# Membranes per Element	Frequency (MHz)
1-D, 32 elements	75 x 100	175 (0.6 λ)	32	5
1-D, 64 elements	75 x 100	175 (0.6 λ)	48	5.5
2-D, 196 elements	40 x 65	90 (0.75 λ)	1	12.5
2-D, 512 elements	80 x 110	200 (0.75 λ)	1	5.6

Electrical leads were routed from the pMUT elements to gold wirebond pads at the edges of the silicon die. Because of the relatively large die size (10 to 18 mm) and tight routing constraints for the 2-D arrays, signal trace resistance and capacitance was optimized to ensure sufficient pulse-echo signal was obtained from the arrays. Table I describes resistance and capacitance parameters used and resulting pulse-

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echo signal obtained. In order to maximize pulse-echo signal, a balance of trace resistance of approximately 10 Ω and capacitance to ground of less than 1 pF per signal trace was required. This was achieved by maximizing thickness of the gold traces to 1.2 µm to reduce resistance and minimizing trace width to reduce parasitic capacitance to ground. pMUT element capacitance was 75 pF for these arrays.

TABLE II. RESISTANCE AND CAPACITANCE OF ROUTED SIGNAL TRACES

	Trace Resistance (Ω)	Capacitance to Ground (pF)	Qualitative Result (pulse-echo signal)
Array 1	73	3.9	No signal detected
Array 2	9	5.1	Poor signal
Array 3	15	2.0	Good signal
Array 4	10	0.5	Best signal

B. *Packaging and Measurement*

pMUT arrays were diced from the silicon wafers and wirebonded into either ceramic pin grid array (PGA) packages or printed circuit boards for testing. The edges of the die and wirebonds were encapsulated in epoxy. Transmit properties were measured by transmitting on the pMUT elements into a pressure-calibrated hydrophone (Onda GL-0200) at 20 mm distance in a de-ionized water tank. Pulse-echo measurements were made by transmitting and receiving with the pMUT elements and reflecting off an aluminum block at 20 mm distance. Ferroelectric polarization hysteresis loops were obtained using a Precision Workstation (Radiant Technologies). Ultrasound images were obtained using the Duke T5 real-time 3-D phased array scanner.

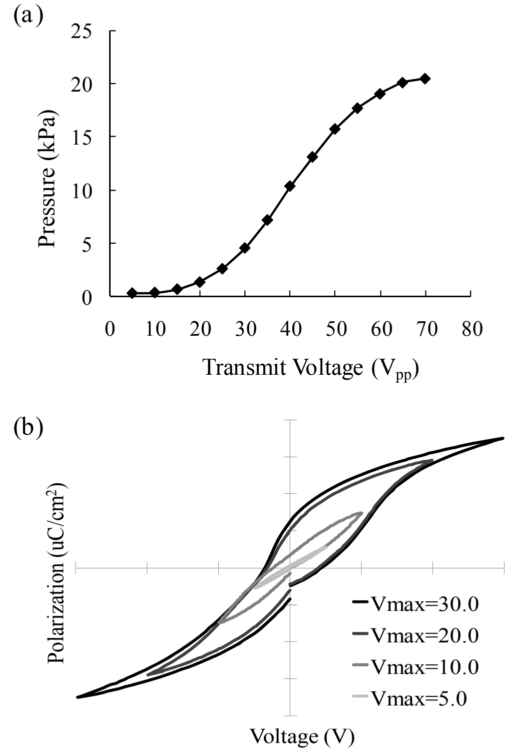

Figure 1. (a) Transmit output pressure at 20 mm distance for a 75 x 100 µm pMUT element. (b) Ferroelectric polarization for a pMUT element with applied voltage levels of ±5, 10, 20 and 30V.

III. RESULTS

A. *Flexure-Mode Operation*

Flexure-mode operation for pMUT devices is a unique transducer method for generating acoustic energy compared to conventional thickness-mode bulk ceramic transducers which are poled and operate below the coercive field (electric field required to induce domain switching) of the PZT material. In our studies [3,4], pMUT devices were driven with a bipolar signal at voltage levels above the coercive field in order to induce ferroelectric domain switching in the PZT film and create sufficient flextensional motion of the membrane to generate acoustic output from the device. Two methods were developed to optimize the drive signal and pulse-echo output of the devices: (1) applied increased drive voltage above the coercive field to induce domain switching, and (2) used transmit biasing to improve receive sensitivity.

The first concept is demonstrated in Figure 1 which shows weak transmit pressure below the coercive voltage threshold of ±6 V or 12 V_{pp}, but rapidly increasing transmit pressure above this threshold. Also shown is the ferroelectric polarization with no hysteresis at ±5 V (no domain switching), minimal hysteresis at ±10 V, and significant hysteresis (full domain switching) at ±20 and 30 V which are voltage levels that produced significant output pressure (i.e., 40 and 60 V_{pp}). Above ±30 V, the domain switching begins to saturate, and transmit pressure increase diminishes.

Transmit biasing is unique to pMUT devices consisting of thin-film PZT. In thin-film form, the ferroelectric domains in PZT are affected by internal film stress, making domain switching less effective than in bulk-ceramic PZT. In particular, PZT films deposited on silicon substrates contain tensile stress which reduces domain switching in the direction of the applied electric field (i.e., through the film thickness) and increases the coercive field [8]. It was also found for pMUTs that domain switching was more effective for positive applied voltage than for negative voltage. A similar effect was observed in bulk-ceramic unimorph actuators containing internal stress in the PZT layer [9]. The ferroelectric polarization switching shown in Figure 2(a) for a pMUT device was more pronounced with greater hysteresis and domain switching for positive voltage. Furthermore, the remanent polarization (polarization at zero voltage) for positive polarity was higher than for negative polarity.

Because pMUT elements undergo full domain switching during each transmit cycle, the final polarity of polarization in the PZT film following the transmit cycle affected the receive signal generated by the pMUT. As shown in Figure 2(b), applying 3 or 4 full sine wave transmit cycles, resulting in negative polarity polarization in the PZT during receive, resulted in lower pulse-echo signal generated. Finishing the transmit cycle with a partial sine wave of positive voltage, resulting in positive polarity polarization in the PZT, significantly increased the pulse-echo signal generated. Applying full or partial transmit cycles did not affect the transmit pressure output; therefore, the improvement in pulse-echo signal was attributed to improved receive signal generated with positive polarization polarity in the PZT film. This effect is referred to as transmit biasing.

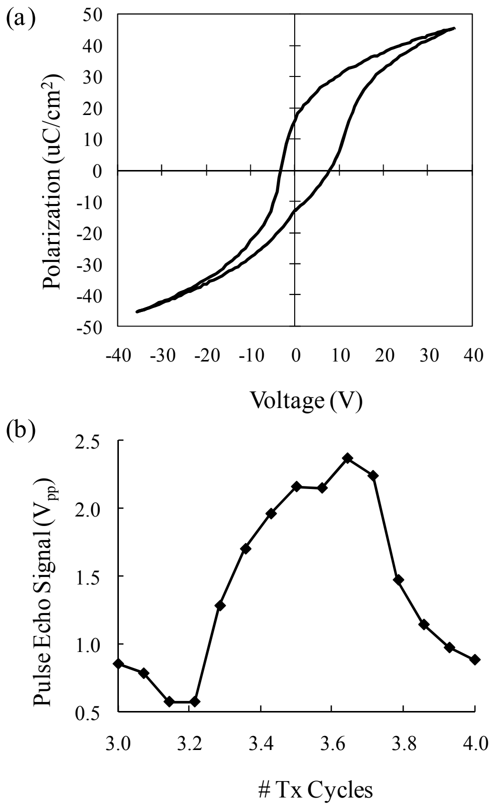

Figure 2. (a) Ferroelectric polarization for a pMUT element showing asymmetric behavior. (b) Pulse echo signal measured from a pMUT element for different number of partial sine wave transmit (Tx) cycles applied.

B. *Imaging with 1-D pMUT Arrays*

One-dimensional pMUT arrays with 32 and 64 elements were capable of producing pulse-echo B-mode ultrasound images with good resolution. The 1-D arrays contained multiple membranes connected in parallel in elevation, as described in Table I. Figure 3 shows an image of resolution strings in a water tank imaged using a 64-element array at 5.5 MHz. Array width in azimuth was 11.1 mm, and theoretical resolution for this array was 0.5 mm at 20 mm depth. Lateral resolution of 0.6 mm was demonstrated at this depth.

Images of tissue targets were also obtained using a 32-element array with 5.5 mm width operating at 5 MHz. Figure 4(a) shows resolution targets in a small parts tissue phantom, exhibiting resolution of less than 2 mm at 25 mm depth. The spacings between the five horizontal and five vertical targets were 2, 1, 0.5 and 0.25 mm, respectively. Four of the five lateral targets and all five vertical targets were resolved. Tissue speckle is also clearly visible. In addition, Figure 4(b) shows resolution of a human jugular vein and carotid artery at a depth of approximately 20 mm. The 1-D pMUT arrays were also capable of penetrating tissue to depth of 60 mm as shown in Figure 5, with images of (a) range targets in the tissue phantom and (b) human liver tissue.

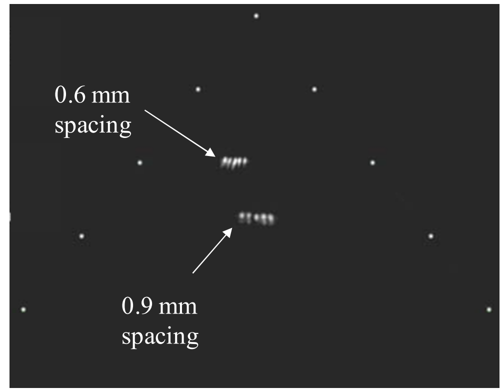

Figure 3. Pulse-echo image of nylon resolution strings in a water tank from a 64-element pMUT 1-D array at 5.5 MHz.

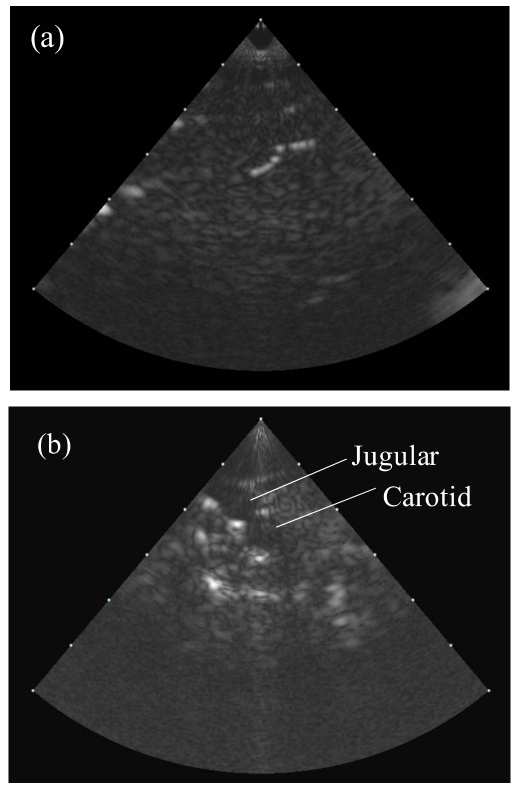

Figure 4. (a) Pulse-echo image of nylon targets in a Gammex/RMI 404 LE tissue phantom from a 32-element pMUT 1-D array at 5 MHz. (b) Image from the same array of a human jugular vein and carotid artery.

C. *Real-Time 3-D Imaging with 2-D pMUT Arrays*

The most significant advancement in this work was the demonstration of real-time 3-D imaging with pMUT 2-D arrays operating at 5.6 and 12.5 MHz with 512 and 196 elements, respectively. The 2-D array elements were individually controlled single membranes. Figure 6(a) shows a 2-D image of resolution strings in a water tank imaged using a 512-element array at 5.6 MHz. Array size was 3.1 mm x 6.3 mm, and theoretical resolution was 1.7 mm at 40 mm depth. Lateral resolution of 2.4 mm was demonstrated at this depth.

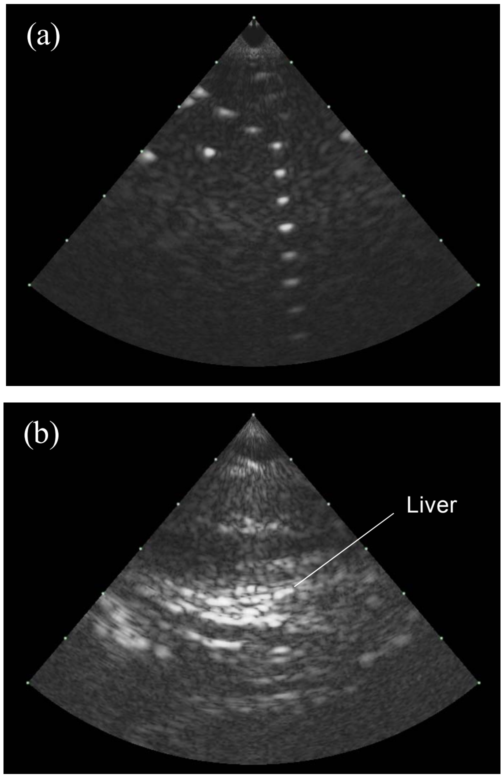

Figure 5. (a) Pulse-echo image of nylon targets in a Gammex/RMI 404 LE tissue phantom from a 32-element pMUT 1-D array at 5 MHz. (b) Image from the same array of human liver tissue.

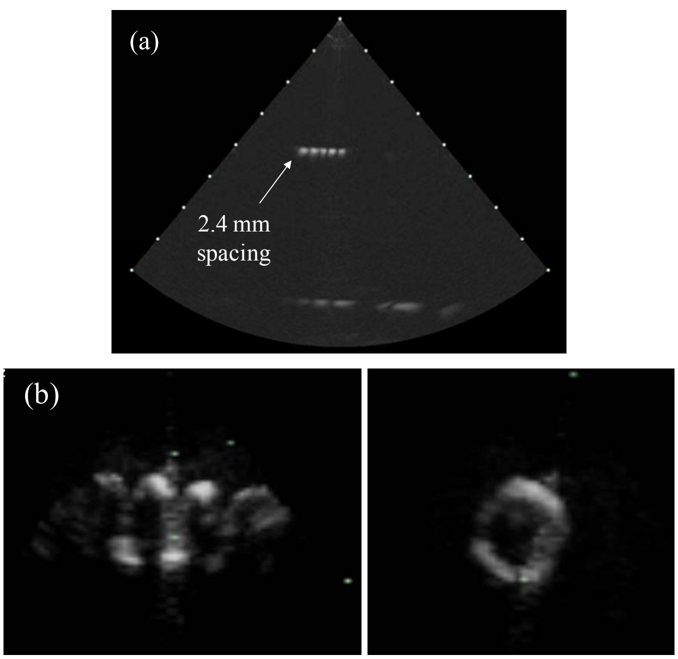

Figure 6. (a) Pulse-echo image of nylon resolution strings in a water tank from a 512-element pMUT 2-D array at 5.6 MHz. (b) Two orthogonal planes extracted from a real-time 3-D image showing side and end views of a metal spring in a water tank using a 196-element pMUT 2-D array at 12.5 MHz.

Figure 6(b) shows still images of a metal spring from an 80° x 80° real-time volume scan acquired at 18 frames per second using a 196-element 2-D pMUT array operating at 12.5 MHz. The volume image was rotated digitally in real time without moving the array or spring target to obtain side and end views of the spring. The pMUT array, which was only 1.2 mm x 1.2 mm and comprised element pitch of 90 µm or 0.75 λ, was capable of imaging the relatively large spring. Spring diameter was 10 mm, and approximately 30 mm of the spring length was imaged. Real-time volume scans of human tissue were also obtained using the 512-element 2-D array.[1]

IV. Conclusion

One- and two-dimensional pMUT phased arrays were fabricated demonstrating improved performance in pulse-echo imaging of resolution and tissue targets. The sensitivity of the arrays was enhanced by operating the pMUT flexure-mode transducers above the coercive field of the PZT film and using transmit biasing to increase the receive signal. For the first time, high-frequency real-time 3-D imaging was demonstrated above 10 MHz (i.e., 12.5 MHz) using a 196-element 2-D phased array with 1.2 mm width and 0.75 λ pitch. In view of these characteristics, two-dimensional pMUT arrays are a promising technology to enable real-time volumetric imaging with medical catheters due to their microfabricated structure, smaller element size and pitch, higher frequency operation and higher element capacitance compared to conventional bulk transducers.

References

[1] J. J. Bernstein et al., "Micromachined high frequency ferroelectric sonar transducers," IEEE Trans. Ultrason. Ferroelec. Freq. Contr., vol. 44 no. 5, pp. 960-969, 1997.

[2] G. Percin, B. Khuri-Yakub, "Piezoelectrically actuated flextensional micromachined ultrasound transducers – II. Fabrication and experiments," IEEE Trans. Ultrason. Ferroelec. Freq. Contr., vol. 49 no. 5, pp. 585-595, 2002.

[3] D. E. Dausch, J. B. Castellucci, D. R. Chou, K. H. Gilchrist, O. T. von Ramm, "Performance of Flexure-Mode pMUT 2D Arrays," Proc. IEEE Ultrasonics Symposium, pp. 1053-1056, 2007.

[4] D. E. Dausch, J. B. Castellucci, D. R. Chou, O. T. von Ramm, "Theory and Operation of 2D Array Piezoelectric Micromachined Ultrasound Transducers," IEEE Trans. Ultrason. Ferroelec. Freq. Contr., vol. 55(11), pp. 2484-2492, 2008.

[5] F. Akasheh, T. Myers, J.D. Fraser, S. Bose, A. Bandyopadhyay, "Development of piezoelectric micromachined ultrasonic transducers," Sens. Act. A, vol. 111, pp. 275-287, 2004.

[6] P. Muralt, et al., "Piezoelectric micromachined ultrasonic transducers based on PZT thin films," IEEE Trans. Ultrason. Ferroelec. Freq. Contr., vol. 52 no. 12, pp. 2276-2288, 2005.

[7] B. Belgacem, F. Calame, P. Muralt, "Design, modeling and fabrication of piezoelectric micromachined ultrasonic transducers," Proc. IEEE Ultrasonics Symp., pp. 483-486, 2005.

[8] D. E. Dausch and G. H. Haertling, "The Domain Switching and Structural Characteristics of PLZT Bulk Ceramics and Thin Films Chemically Prepared from the Same Acetate Precursor Solutions," J. Mater. Sci., vol. 31, pp. 3409-17, 1996.

[9] D. E. Dausch, "Asymmetric 90° Domain switching in Rainbow actuators," Ferroelectrics, vol. 210, pp. 31-45, 1998.

[1] This paper has supplementary downloadable material available at http://ieeeexplore.ieee.org, including two WMV format movie clips (total 2.7 MB) showing real-time 3D scans obtained using 2-D pMUT arrays.