Published in final edited form as:

IEEE Trans Ultrason Ferroelectr Freq Control. 2008 October ; 55(10): 2336–2344. doi:10.1109/TUFFC.933.

Characterization of Dual-Electrode CMUTs: Demonstration of Improved Receive Performance and Pulse Echo Operation with Dynamic Membrane Shaping

Rasim O. Guldiken, Mujdat Balantekin, Jaime Zahorian, and F. Levent Degertekin

G. W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA

Abstract

A 1-D dual-electrode CMUT array for intracardiac echocardiography (ICE) with a center frequency of 8 MHz has been designed, fabricated, and used to demonstrate the potential of dual-electrode CMUTs. Using a dual-electrode CMUT, 9 dB higher receive signal level is obtained over the 6 dB fractional bandwidth as compared with a conventional CMUT with an identical center electrode biased close to its collapse voltage. Because the same device shows a 7.4 dB increase in maximum pressure output, 16.4 dB overall improvement in transduction performance has been achieved as compared with conventional CMUT. A net peak output pressure of 1.6 MPa on the dual-electrode CMUT membrane with tone burst excitation at 12 MHz is also reported. The frequency response of the dual-electrode CMUT is similar to that of a conventional CMUT with the same membrane geometry with about 15% increase in the center frequency. Monostatic operation of dual-electrode CMUTs shows that the high performance of the transducer is applicable in typical pulse-echo imaging mode of operation. With dynamic shaping of the CMUT membrane to optimize the transmit-and-receive modes of operation separately during each pulse-echo cycle, dual-electrode CMUT is a highly competitive alternative to its piezoelectric counterparts.

I. Introduction

CAPACITIVE micromachined ultrasonic transducers (CMUTs) were introduced as an alternative to piezoelectric transducers over a decade ago [1]–[4]. These transducers are micromachined electrostatic sensors and actuators with a parallel-plate structure with a single movable top electrode (membrane) and a rigid electrode on the substrate. It is well known that electrostatic parallel plate devices have a limited actuation range due to the collapse (pull-in) phenomenon [5]. The electrostatic collapse of this parallel-plate structure occurs when the movable membrane travels 1/3 of the gap, leaving 2/3 of the gap region unusable. Although the electrode size can be optimized, this phenomenon ultimately limits receive sensitivity, which requires smaller gaps. Membrane collapse also limits the maximum output pressure of the CMUT as one needs to use larger gaps to improve displacement range of the device. Consequently, this single electrode structure creates a conflict in gap optimization; in receive mode, small gap is advantageous because it results in higher capacitance change for small displacements—higher sensitivity, while in the transmit mode large gaps are needed for higher output pressure. Therefore, one needs to explore either other operation modes for the CMUT that goes beyond the membrane collapse or CMUT designs with other membrane and electrode configurations. This is a necessity to close the perceived performance gap

between CMUTs and piezoelectric transducers. For example, a 10 dB overall sensitivity gap between CMUT and piezoelectric transducers has been reported [6]. This study was conducted on 1-D medical imaging arrays, and the CMUT output pressure limited by the available gap thickness was noted as the main reason for this performance gap.

As mentioned above, collapsed mode or collapse snap-back operation of CMUTs have been proposed that demonstrates overall transduction performance increase (both transmit and receive) of 11 dB when compared with conventional operation [7]–[10]. However, the frequent substrate-membrane contact may prevent reliable and stable operation in this mode. CMUTs with non-uniform membrane thickness were also proposed by several groups, and versions of these devices have been demonstrated to achieve up to 6 dB gain in transduction performance [11]–[15].

As another alternative solution, a dual-electrode structure for CMUTs that offers higher net output pressure in the transmit mode and higher sensitivity in the receive mode was also recently introduced [14], [16], [17]. The dual-electrode CMUT has 2 side electrodes and a center electrode. Side electrodes are connected together to be used for generating acoustic waves during the transmit cycle and membrane shaping to reduce the gap in the receive cycle. The center electrode is essentially used for detecting small echo signals in the receive cycle. A micrograph of a fabricated dual-electrode CMUT is shown in Fig. 1. The dual-electrode CMUT enables use of the leveraged bending concept to improve device performance [18]. By using the side electrode excitation, the stable displacement range without collapsing the membrane can be increased from 1/3 of the gap to nearly the full gap. An increased volume displacement results in a higher maximum transmit pressure; a 6.8 dB increase over conventional CMUT was predicted and experimentally shown [16]. Moreover, by applying moderate DC bias to the side electrodes during the receive mode, the membrane is brought closer to the substrate. Hence, a higher electromechanical transformer ratio is achieved with a lower center (receive) electrode bias. Therefore, the dual-electrode CMUT has an effectively larger gap as compared with the conventional CMUT during transmission phase, and it has an effectively smaller gap during receive phase. Previously reported proof-of-principle experiments demonstrated some of these benefits by statically biasing the electrodes. A significant improvement in maximum transmit pressure was shown, but the measured improvement in the receive mode was well below the achievable figures due to sub-optimal design of the particular devices used [16].

For realistic imaging applications with dual-electrode CMUTs, it is important to have dynamic biasing between transmit and receive cycles and operate the transducer in the monostatic (pulse-echo) mode. This approach also uses the available array area efficiently. In this paper, implementation of a 1-D dual-electrode CMUT array for intracardiac echocardiography (ICE) is described, and the design improvements are discussed. The array element performance in terms of received signal level, maximum transmit pressure, and frequency response are measured and compared with a conventional CMUT with the same geometry—essentially the same device. Finally, pulse-echo operation of the dual-electrode CMUT with dynamic membrane shaping is demonstrated. These results show that in addition to significant improvements in device performance, the dual-electrode CMUT can use simpler electronics due to its electrically isolated transmit and receive terminals.

II. Dual-Electrode CMUT Design and Fabrication

To design the dual-electrode CMUTs for 1-D ICE array, the coupled field electrostatic analysis capability of commercial finite element analysis (FEA) program Ansys 11.0 (ANSYS Inc., Canonsburg, PA) is used. A flexible simulation code is developed that can be used to predict both transmit and receive mode performance and to study comparative

improvements with conventional CMUT designs. Previously, the static membrane profile with side and center electrode activation just before the collapse was evaluated to estimate the relative transmit pressure improvements with the dual-electrode structure [16]. Because that analysis does not provide the net pressure output information, in this study, the output pressure on the fluid structure interface (FSI) node is obtained directly from the coupled AC simulation. To evaluate the receive mode sensitivity improvements, the transformer ratio “ n ” as a function of side and center electrode biases is evaluated [16].

Using the same basic FEA program, a 64-element 1-D dual-electrode CMUT array for ICE applications was designed and fabricated for 8 MHz center frequency. The array elements have 105 μm pitch and element length of 2.4 mm. As shown in Fig. 1, each array element has 2 columns of 50 μm $\times$ 100 μm rectangular membranes that are made of a 3.5 μm thick silicon nitride layer with buried aluminum electrodes. Forty-eight of these membranes are electrically connected in parallel to form a single element of the array. The physical array parameters are summarized in Table I. The electrodes and their lateral location and depth in the dielectric membrane affect the performance of the dual-electrode CMUT. An earlier analysis called for thin dielectric layers and gap thickness beneath the electrodes, limited by practical fabrication concerns, to reduce the effective gap in receive mode, optimize the device performance [16]. As a result, in this case, the 15 μm wide center and 10 μm wide side electrodes were placed over the last 250 nm of the 3.5 μm thick membrane (Fig. 1).

The dual-electrode CMUTs were fabricated using the same low temperature process described earlier [19]. This surface micromachining process uses plasma enhanced chemical vapor deposition (PECVD) nitride deposition at 250°C for membrane formation and cavity sealing and chromium as the sacrificial layer. The surface micromachining process allowed the size and position of the top electrode to be defined lithographically. It should be emphasized that dual-electrode CMUTs are implemented without additional steps in the conventional CMUT fabrication process.

III. Characterization of Dual-Electrode CMUTs

Several relevant characterization experiments are conducted to verify the simulations and to quantify the performance improvements of dual-electrode CMUTs. First, the collapse voltage values corresponding to center and side electrode are obtained. DC bias is swept several times to observe the charging effect on the device. No significant charging effect is observed. The collapse voltages for the center electrode (with no side electrode bias) and the side electrode (with no center electrode bias) are found to be 120 V and 240 V, respectively. A receive-only experiment is performed to measure the receiver performance improvement and determine the optimal operating points for dual-electrode vs. conventional CMUT device comparison. Furthermore, pulsed excitation experiment is conducted to observe the effect of side electrode biasing on the frequency response. In addition, absolute net output pressure generated by the CMUTs is measured using a calibrated hydrophone as a receiver, and relative transmit performance increase estimates are verified [16].

A. Receive Sensitivity Measurement

For characterization of the receive mode operation of the dual-electrode CMUT, the setup shown in Fig. 2 is used. The CMUT array is placed 3 mm away from a piezoelectric transmitter (IS2002HR, Valpey Fischer Corporation, Hopkinton, MA), which is excited with a 10-cycle tone burst at 10 MHz, in the design bandwidth of the ICE array element. The center electrode of the CMUT is the receive terminal, and it is connected to the input of a low noise transimpedance amplifier (TIA) (AD8015, Analog Devices, Norwood, MA), which electrically terminates the device with a virtual short circuit, removing the effects of termination impedance from the measured characteristics [20]. TIA configuration is

commonly used for CMUT receiver electronics [21], [22]. The received signal amplitude is then measured while varying center and side electrode DC bias levels. The results are plotted in Fig. 3(a). Conventionally, CMUTs with no side electrode are operated close to the collapse voltage to maximize the receive signal, indicated by the point A ($V_{\text{center}} = 115$ V, $V_{\text{side}} = 0$ V) in Fig. 3(a). On the other hand, the dual-electrode CMUT is biased to the point B ($V_{\text{center}} = 80$ V, $V_{\text{side}} = 160$ V) to achieve maximum sensitivity during receive. One can see that the received signal amplitude is increased from 1.7 V (point A) to 5.3 V (point B). This corresponds to a gain of 10 dB achievable with dual electrode structure when compared with conventional CMUT. The important operation points that will be used throughout the paper and in the discussion section are summarized in Table II. Finite element simulation that was used in designing the array element is illustrated in Fig. 3(b), and it shows good agreement with the measured data.

B. Pulsed Excitation Measurement

To compare the effect of membrane shaping by the side electrode on the frequency response of the CMUT, pulsed excitation experiments are performed. The setup used in the pulsed excitation measurements is illustrated in Fig. 4. In this experiment, 2 neighboring elements of a dual electrode array shown in Fig. 1 are used. One dual-electrode CMUT array element is used for the transmission operation. This element is excited with a short transmit pulse using the side electrodes. The neighboring array element is used for receive mode of operation. The center electrode receives the echo (transmitted by the side electrode of neighboring array element) from a flat aluminum reflector in oil at 7 mm away. The received echo waveforms and corresponding frequency spectra are shown in Fig. 5(a) and (b), respectively. The bottom blue traces, which are dashed in Fig. 5(b), correspond to the time and frequency response at operation point A in Fig. 3(a), while the top red traces correspond to the response at point B, respectively. Both time signals in Fig. 5(a) show similar characteristics, including the long tail due to ringing in the unbacked silicon substrate, which can be eliminated by placing matched and lossy backing material in contact with the silicon substrate [23]. This resonance causes a dip around 7.5 MHz in the frequency response, which is centered around 8 MHz as designed. The received echo signal amplitude is increased by 2.8 times (9 dB) with membrane shaping by the side electrode showing the effect of having a smaller gap.

C. Transmission Measurements

The output pressure generated by the dual-electrode CMUT array element is measured in a water tank using both the center and side electrodes in the transmit electrode. A broadband calibrated hydrophone (GL series hydrophone, ONDA Corporation, Sunnyvale, CA) was used as the receiver. The same dual-electrode CMUT used in receive mode experiments is coated with 3 μm thick parylene-C layer for electrical isolation and used as the transmitter. Fig. 6 shows the setup used in the transmit mode characterization experiments. The operation frequency of the CMUT is shifted to 12 MHz from 9 MHz due to the parylene layer, as predicted by FEA simulations. The DC bias was set to half of the collapse voltage for either the center or side electrode so that the maximum AC voltage could be applied without collapse. Therefore, the bias was set to 60 V for the center electrode (side electrode 0 V) and 120 V for the side electrodes (center electrode 0 V). A 10-cycle tone burst signal at 12 MHz was applied to each set of electrodes with varying voltage levels. The output pressure is measured by the hydrophone located 7 mm away from the dual-electrode CMUT. The signal is then compensated for diffraction in water and pressure output on the membrane is obtained. For fair comparison, the output pressure values are equated by normalizing to the width of the electrodes, i.e., the center electrode actuation values are scaled by a factor 20/15. The pressure output on the membrane surface as a function of AC amplitude is illustrated in the Fig. 7 as discrete points (circle for center electrode, rectangle

for side electrode). Conventional CMUT operation generates a maximum of 0.66 MPa of peak pressure on the membrane while the dual-electrode can generate 1.6 MPa of peak pressure. The simulated output pressure on the membrane is illustrated in the same figure by solid line for the side electrode and by the dashed line for the center electrode. The output pressure on fluid structure interface (FSI) node is directly obtained from the FEA simulation.

IV. Pulse Echo Experiments

To demonstrate the potential of dual-electrode CMUTs for imaging applications where the array elements are mostly monostatically operated, experiments are performed by dynamically biasing the side electrodes between the transmit and receive cycles of a single pulse-echo event. A moderate bias voltage is needed during the transmit mode for a large transmit swing, which increases the output pressure such as point C in Fig. 3(a) [10]. After the transmit pulse is emitted, the operating point is shifted so that during the receive mode of the same cycle the gap is reduced, which in turn increases the sensitivity while keeping the center electrode bias constant; see point B in Fig. 3(a). As illustrated by the experimental schematic of Fig. 8, the output of 2 signal generators are added to obtain the desired dynamic bias waveform as well as the tone burst transmit signal. The output of the adder is connected to a high-voltage, high-speed amplifier (TDA9535, ST Microelectronic, Geneva, Switzerland) that drives the side electrode. The center electrode is connected to the TIA mentioned earlier. A DC voltage is applied to the bottom electrode to provide required bias levels avoiding the bias voltage limitation of the particular high-voltage amplifier used. The oil-air interface 9.5 mm away from the transducer is used as the reflection surface.

Fig. 9(a) shows the 3 different voltage waveforms applied to the side electrode to demonstrate the effect of dynamic membrane shaping during a single pulse-echo cycle. During the transmit phase, a 120 V bias and a 15-cycle, 10 V peak-to-peak tone burst at 10 MHz is applied to the side electrode during the transmit cycle. Then the receive biases are set after a 3 μ s long transition phase. For the bottom trace, the center electrode bias is set to 115 V, while the side electrode bias is reduced from 120 V to 30 V during the receive phase; see point D in Fig. 3(a). For the middle trace, the center electrode bias is set to 80 V and the side electrode bias is kept at 120 V; see point C in Fig. 3(a). For the top trace, the center electrode bias is kept constant at 80 V while the side electrode bias is dynamically increased to 160 V; see point B in Fig. 3(a). Note that identical transmit DC bias of 120 V and tone burst amplitude of 10 V is applied to the side electrodes for all 3 cases. The first case, marked by point D in Fig. 3(a), approximately simulates the conventional operation (no side electrode bias) during the receive phase. Due to the limitation in the electronics, the 30 V bias is applied to the side electrode during the receive phase. The maximum receive signal obtained with 30 V side bias is only 1.5 percent more as compared with the one obtained with no side electrode bias, showing that this case is indeed close to the no bias case as predicted by the simulations; see point A in Fig. 3(a).

The corresponding echo waveforms received by the center electrode are shown in Fig 9(b). These waveforms are filtered by a high pass filter with 4 MHz cutoff frequency to remove the effects of the slowly varying bias transition region. From Fig 9(b) one can observe that the received signal amplitude is increased by 2.1 times (6.5 dB) with 120 V side electrode bias and 80 V center electrode bias (middle trace) as compared with the bottom trace, which corresponds to the conventional CMUT operation with bias level close to collapse voltage. With the optimal receive phase, parameters for this particular device (160 V side electrode and 80 V center electrode bias) result in the top trace showing a 10 dB (3.2 times) increase in the center electrode receive sensitivity. The pulse-echo results with dynamic biasing are summarized in Table III.

V. Discussion

The results presented in sections III and IV demonstrate significant improvements in CMUT performance due to dual-electrode structure. In the receive mode (Fig. 3), the membrane shaping by using the side electrode increases the receive sensitivity by 3.2 times (10 dB) at 10 MHz for this particular dual-electrode CMUT device. as shown from Fig. 3(b), the finite element simulation of the transformer ratio agrees well with the measured results, confirming that this ratio is a valid figure of merit for evaluating the performance of CMUT in the receive mode of operation. It can be observed both from Fig. 3(a) and (b) that the data are divided into 2 distinct regimes, namely, the collapse and contact regions. In the collapse region (side electrode voltage: $V_{\text{side}} \leq 160$ V), there is a certain center electrode voltage (V_{center}) that causes pull-in instability and collapse, whereas in the contact region ($V_{\text{side}} \geq 160$ V), there is no such V_{center} value. The membrane simply touches the bottom dielectric layer without going through an unstable collapse. Even though spurious effects such as charging and fabrication nonuniformities were not taken into account, occurrence of collapse-contact region, the relative variation of transformer ratio, and hence the sensitivity gain and optimum operation points with conventional and dual-electrode CMUTS are very well captured by the FEA results of Fig. 3(b).

Because dual electrode structure is obtained by simply changing the top electrode pattern, the dynamics of the device is not changed significantly. In the pulse excitation experiment results (Fig. 5), the frequency response comparison shows that side electrode biasing shifts the center frequency to a higher value, about 15%, and this is well predicted for the transmit case by a finite element model [16]. consequently, the improvement with dual-electrode CMUT as compared with conventional CMUT is not constant as a function of frequency: The average improvement within the 6 dB bandwidth is 9 dB, while the gain at 10 MHz is 10 dB, which matches the results shown in Fig. 3.

Dual-electrode CMUTs improve the maximum pressure output without going into collapse region or applying large pulses, which reduces one's control on the frequency spectrum of the generated pressure signals. This can be significant for applications such as harmonic imaging. Transmission measurements of dual electrode CMUTs of Fig. 7 are performed using tone burst signals and indicate 1.6 MPa maximum output pressure while its conventional counterpart achieves 0.66 MPa. as can be observed from the same figure, the Pa/V efficiency is not increased with the dual-electrode CMUT. However, the dual-electrode configuration enables higher net output pressure values (in pascals) by allowing increased transmit swing via higher AC voltages applied without collapse. Transmission performance increase comes at a cost of increased voltage values both for AC and DC values. The results show that the dual-electrode CMUT increases the maximum transmit pressure by 7.4 dB. These results are also predicted well by the finite element simulations (Fig. 7). Therefore, the use of these analysis techniques for further design and optimization studies is well justified. These results indicate an overall transduction improvement of 16.4 dB over a conventional CMUT with the same geometry, a significant advance in CMUT performance. Note that dynamic biasing with conventional CMUTs is also possible, and the comparisons made here already takes this possibility into account by biasing the center electrode at half the collapse voltage in transmit and close to collapse in receive for conventional operation.

The demonstrated performance improvements with dual-electrode CMUTs are obtained by implementing simple design changes—reducing the isolation layer between the top and bottom electrodes. The silicon nitride isolation layer thickness is limited by the breakdown voltage of the nitride and fabrication nonuniformities.

The advantages of dual-electrode CMUTs are also valid when they are used pulse-echo mode. The dynamic biasing experiments (Fig. 9) show that the optimal receive phase parameters for this particular device results in a 10 dB (3.2 times) increase in the center electrode receive sensitivity over a conventional CMUT. This gain is in agreement with receive sensitivity measurements (Fig. 3) and pulsed excitation measurements (Fig. 5). It can be observed from Fig. 9 that the direct coupling from the transmit burst dies out in less than 2 μ s for this particular case. Also note that the initial coupling with 30 V side electrode bias case is longer because of the 5 MHz ringing in the electronics. This transition region can be further reduced with electronics specifically designed for this application. In these experiments, the transition region was set to be linear in shape with 3 μ s in duration. This section can be shaped differently to achieve time gain compensation and reduced in duration to minimize the dead zone. Finally, it needs to be noted that the pulse-echo experiments are performed without a T/R switch or protection circuitry.

VI. Conclusions

Dual-electrode CMUTs extend the design space for CMUTs by taking better advantage of available microfabrication capabilities. In this study, a total performance improvement of 16.4 dB has been shown with dual-electrode CMUTs when compared with conventional CMUTs with the same overall membrane dimensions. This gain makes the CMUTs more competitive with piezoelectric transducers [6]. In addition, 1.6 MPa peak pressure levels on the CMUT membrane has been obtained with tone burst excitation in agreement with simulations. Pulse-echo operation of dual-electrode CMUTs with improved transducer performance is also demonstrated. This is achieved by dynamically adjusting the CMUT membrane geometry during the transmit-and-receive phases of a single pulse-echo cycle by varying the side electrode bias voltage. Further improvements should be possible by fabricating dual-electrode CMUTs with nonuniform membrane structures such as notches and thicker center sections [11]–[13], [15].

Acknowledgments

This project was supported by Grant Number R01HL082811 from the National Heart, Lung, and Blood Institute. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Heart, Lung, and Blood Institute or the National Institutes of Health.

Biographies

Rasim O. Guldiken received the B.S. degree in 2002 from Middle East Technical University (M.E.T.U), Ankara, Turkey; the M.S degree in 2004 from Northeastern University, Boston, MA; and the Ph.D. degree in 2008 from the Georgia Institute of Technology, Atlanta, GA, all in mechanical engineering. He is currently an assistant professor in the mechanical engineering department at the University of South Florida, Tampa, FL. His research interests include micromachined transducers for medical ultrasound imaging applications, acoustics, bio-MEMs sensor design and fabrication,

biotechnology, and thermo-fluidics. Dr. Guldiken received student paper awards in transducers and transducer materials at the IEEE Ultrasonic Symposium in 2005 and 2007 for his research on CMUTs.

Mujdat Balantekin was born in Turkey in 1978. He received the B.S. degree in 1999 from the University of Gaziantep and the M.S. and Ph.D. degrees in 2001 and 2005 from the Bilkent University, all in electrical and electronics engineering. From 1999 to 2005, he was a teaching and research assistant at the Bilkent University. He has been working as a research engineer at the Georgia Institute of Technology since 2005. His current research

interests include atomic force microscopy, nanoscale material characterization, and micromachined ultrasonic transducers.

Jaime S. Zahorian was born in Norfolk, VA, in 1981. He received B.S. degrees in mechanical and electrical engineering from Old Dominion University, Norfolk, VA, in 2005. He is currently pursuing a Ph.D. degree at Georgia Institute of Technology. His research focuses on modeling, designing, fabricating, and experimentally characterizing micromachined ultrasound transducer arrays for medical imaging.

F. Levent Degertekin was born in diyarbakir, Turkey. He received the B.S. degree in 1989 from the Middle East Technical University, Turkey; the M.S. degree in 1991 from Bilkent University, Turkey; and the Ph.D. degree in 1997 from Stanford University, CA, all in electrical engineering. He worked at the E. L. Ginzton Laboratory of Stanford University first as a Visiting Scholar during the 1992–1993 academic year and then as an Engineering Research Associate from 1997 to 2000. Currently he is a professor and Woodruff Faculty Fellow in the G. W. Woodruff School of Mechanical Engineering with a joint appointment in the School of Electrical and Computer Engineering, at Georgia Institute of Technology. His research interests are in micromachined acoustic and opto-acoustic devices, intravascular ultrasound imaging, MEMS metrology, and atomic force microscopy.

Dr. degertekin was an associate editor for the *IEEE Sensors Journal*. He serves on the Technical Program Committee of the IEEE Ultrasonics Symposium. Dr. degertekin has received an NSF CAREER award for his work on ultrasonic atomic force microscopy, and, with his students, the IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society Outstanding Paper Award in 2004. He holds 20 U. S. patents and has authored more than 150 scientific publications.

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Fig. 1. Micrographs of dual electrode CMUTs: (a) overall view of 8 elements of a 64-element dual electrode CMUT array; (b) close-up view of two dual-electrode 50 μm CMUT membranes with 15 μm side and 10 μm center electrodes used in experiments. The membrane is seen as the light green layer under the thick line on the lower right edge.

Fig. 2.
Experimental setup used for dual electrode CMUT receive mode experiments.

Fig. 3.

(a) Experimental received signal amplitude versus center electrode bias voltage for different side bias voltages. (b) simulated transformer ratio as a function of center and side electrode DC bias values.

Fig. 4.
Experimental setup used for dual electrode CMUT pulsed excitation experiments.

Fig. 5.

(a) Experimental received waveforms with the center electrode of the dual-electrode CMUT for different bias voltages; (b) frequency response of the signals in (a). The dips in the frequency spectra around 7.5 MHz are due to standing wave resonances in the silicon substrate.

Fig. 6.
Experimental setup used for dual electrode CMUT pressure output experiments.

Fig. 7. Experimental and simulated output pressure on the surface of the CMUT membrane as a function of AC input swing voltage for center and side excitation of the dual-electrode CMUT.

Fig. 8.
Experimental setup used in the pulse-echo experiments.

Fig. 9.

(a) The dynamic bias plus the tone burst signal applied to the side electrodes during pulse-echo experiment; (b) echo signals received by the center electrode corresponding to the side electrode voltages in (a). The bottom trace corresponds to the point C, the middle trace corresponds to the point D, and the top trace corresponds to the point B in Fig. 3(a).

Table I

Physical Array Parameters Used in Design and Fabrication.

Number of Array Elements	64
Element Size	100 μm $\times$ 2.4 mm
Cell Size	50 μm $\times$ 100 μm
CMUT Cells per Element	48
Gap/Isolation Thickness	0.1 μm /0.25 μm
Total Membrane Thickness	3.5 μm
Center/Side Electrode sizes	15 μm /10 μm

Table II

Summary of Important Operation Points for Conventional and Dual-Electrode CMUTs [obtained from Fig. 3(a)].

	Center Electrode Bias (V)	Side Electrode Bias (V)	Signal Amplitude (V)
Point A	116	0	1.66
Point B	80	160	5.3
Point C	115	30	1.72
Point D	80	120	2.4

Table III

Summary of Pulse-Echo Operation Points for Conventional and Dual-Electrode CMUTs with Dynamic Biasing.

Curve	Transmit Side Electrode Bias (V)	Receive Side Electrode Bias (V)	Receive Center Electrode Bias (V)	Pulse-echo Amplitude (V)
Top	120	160	80	0.815
Middle	120	120	80	0.55
Bottom	120	30	115	0.258