An Endoscopic Imaging System Based on a Two-Dimensional CMUT Array: Real-Time Imaging Results

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Abstract— **Real-time catheter-based ultrasound imaging tools are needed for diagnosis and image-guided procedures. The continued development of these tools is partially limited by the difficulty of fabricating two-dimensional array geometries of piezoelectric transducers. Using capacitive micromachined ultrasonic transducer (CMUT) technology, transducer arrays with widely varying geometries, high frequencies, and wide bandwidths can be fabricated. A volumetric ultrasound imaging system based on a two-dimensional, 16×16-element, CMUT array is presented. Transducer arrays with operating frequencies ranging from 3 MHz to 7.5 MHz were fabricated for this system. The transducer array including DC bias pads measures 4 mm by 4.7 mm. The transducer elements are connected to flip-chip bond pads on the array back side with 400-μm long through-wafer interconnects. The array is flip-chip bonded to a custom-designed integrated circuit (IC) that comprises the front-end electronics. Integrating the front-end electronics with the transducer array reduces the effects of cable capacitance on the transducer's performance and provides a compact means of connecting to the transducer elements. The front-end IC provides a 27-V pulser and 10-MHz bandwidth amplifier for each element of the array. An FPGA-based data acquisition system is used for control and data acquisition. Output pressure of 230 kPa was measured for the integrated device. A receive sensitivity of 125 mV/kPa was measured at the output of the amplifier. Amplifier output noise at 5 Mhz is 112 nV/√Hz. Volumetric images of a wire phantom and vessel phantom are presented. Volumetric data for a wire phantom was acquired in real-time at 30 frames per second.**

Keywords-*ultrasound imaging, catheter, capacitive micromachined ultrasonic transducer, CMUT, integrated electronics, volumetric, real-time*

I. Introduction

Better catheter-based ultrasound imaging tools are desired for diagnosis and image-guide procedures. The development of these tools is challenging because of the small space available for the imaging probe and the long connection between the probe and an external system. With capacitive micromachined ultrasonic transducer (CMUT) technology, transducer arrays with geometries well-suited to catheter-based imaging can be fabricated. Examples of such arrays are shown in Fig. 1 [1,2]. Integration of electronics with the transducer can mitigate the effect of the long cables connecting the device to an external system. Integrated amplifiers isolate the transducer from the significant parasitic line capacitance. By providing some type of multiplexing with the integrated electronics, the number of cables connecting the array to the system can be reduced.

This paper presents results from a real-time volumetric imaging system designed for catheter-based imaging. The system is based on a two-dimensional (16×16-element) CMUT array. The array is flip-chip bonded to a custom-designed integrated circuit that comprises the front-end electronics. The device is connected to an FPGA-based system for data acquisition and image processing.

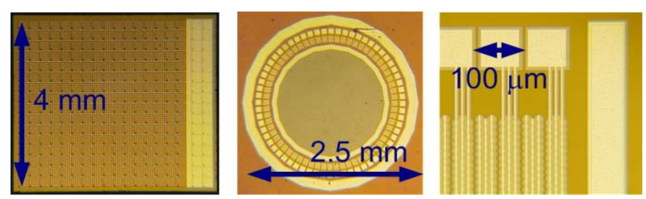


Figure 1. Examples of CMUT arrays advantageous for catheter-based ultrasound imaging: a fully populated two-dimensional array, a ring array, and a high frequency 1-D array.

II. System Description

An illustration of the imaging system is shown in Fig. 2.

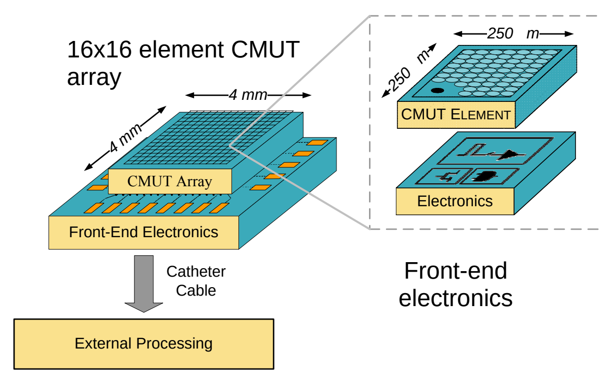


Figure 2. Illustration of a catheter-based real-time volumetric ultrasound imaging system.

Each element of the transducer array is connected to a flip-chip bond pad on the back side of the array via a 400-μm long through-wafer interconnect. The array is flip-chip bonded to an integrated circuit that provides a pulser and amplifier for each element of the array. The system is connected to a data acquisition system (Lyrech Signal Processing, Quebec City, Quebec Canada) that samples the output at 75 MHz.

Pictures of CMUT arrays fabricated for this system are shown in Fig. 3. Arrays with center frequencies between 4 MHz and 7.5 MHz were fabricated. Further information about these arrays can be found in [3].

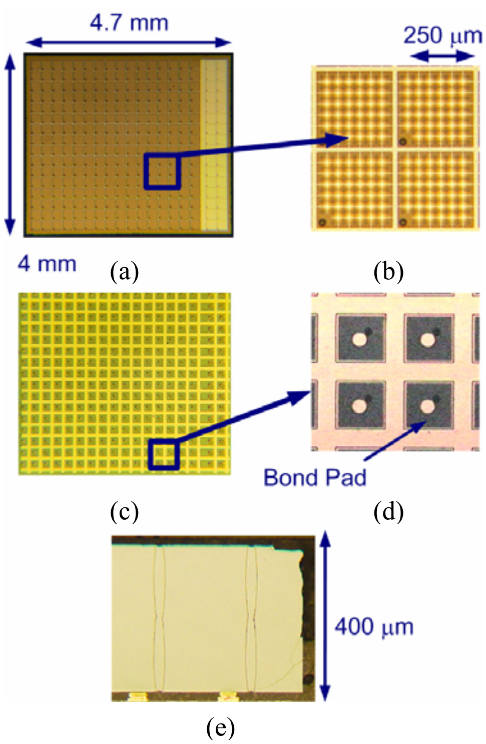


Figure 3. Photographs of the fabricated arrays. (a) Top side. (b) Close-up of 4 elements. (c) Back side. (d) Back side of 4 elements. (e) Cross section showing the through-wafer vias.

Each transducer element is connected to its own copy of a pulser/amplifier circuit on the IC. The circuit is shown in Fig. 4. The pulser provides a unipolar pulse with a peak amplitude of up to 27 V. The width of the pulse depends on the width of the controlling signals, IN_N and IN_P. For a 5-MHz transducer array, a 110-ns pulse is used. Signal TX_EN_b controls a high voltage switch that protects the amplifier's low voltage electronics during transmit. The switch is closed when receiving to connect the transducer to a transimpedance amplifier.

The amplifier has a transimpedance gain of approximately 500-kΩ and bandwidth of 10 MHz. A transimpedance amplifier is used because of its low input impedance. A low input impedance is appropriate for the high output impedance of the CMUT transducer. A single pulser/amplifier circuit can be selected at a time. Only the selected amplifier and accompanying output buffer are turned on. When receiving, the consumed power is 8.5 mW. A sample oscilloscope trace showing the control signals and amplifier output is shown in Fig. 5.

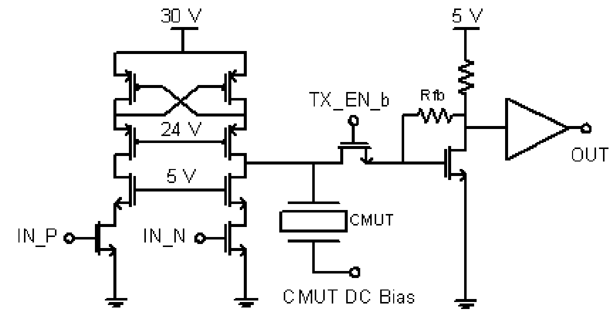


Figure 4. The front-end IC contains a copy of the circuit shown for each element of the transducer array.

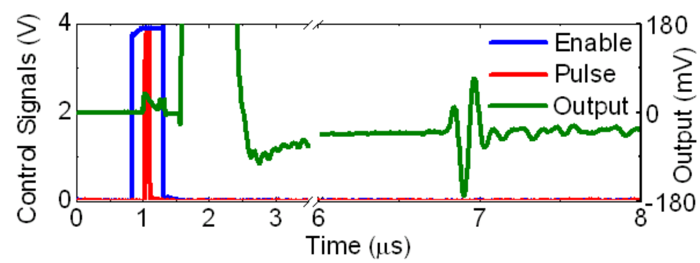


Figure 5. Oscilloscope trace illustrating the functionality of the front-end electronics. The Enable signal controls the switch protecting the amplifier. The Pulse signal dictates the width of the applied pulse. The amplifier is turned on when enable goes low.

A photograph of a CMUT array flip-chip bonded to an integrated circuit is shown in Fig. 6(a).

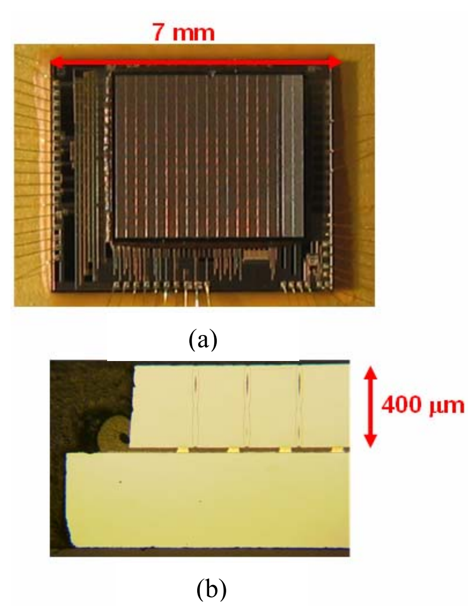
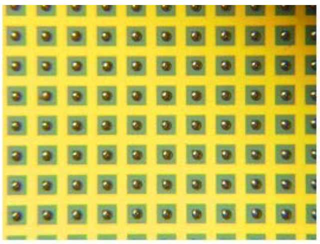
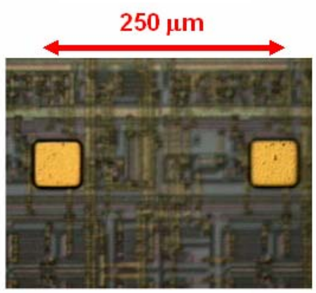


Figure 6. (a) The transducer array flip-chip bonded to the front-end IC. (b) A cross-section of the device. Some of the anisotropic conducting film (ACF) can be seen sticking out on the left side.

Two flip-chip bonding techniques have yielded functioning devices. The first is based on anisotropic conducting film (ACF). For this technique, gold bumps are applied to the pads on the IC using a wire bonder. ACF is then applied on either the IC or CMUT array. A flip-chip bonder is used to align and bond the two parts. In the bonded device, the ACF film conducts at the points where it is squeezed between the CMUT-side pads and the gold bumps on the IC. A cross-section of a device bonded using ACF is shown in Fig. 6(b). For the second flip-chip bonding technique, solder bumps are deposited on the CMUT pads. The pads on the IC are plated with Ni and Au to provide the correct metallurgy for the solder bumps. Pictures illustrating the solder-based bonding technique are shown in Fig. 7.



(a)



(b)

Figure 7. (a) Solder bumps applied to the back side of the CMUT array. (b) Ni-Au plated pads on the electronics die.

III. OUTPUT PRESSURE AND RECEIVER CHARACTERIZATION

A 5-MHz transducer array and accompanying IC were characterized. For each element of the device, the received echo from a plane reflector was recorded. The normalized energy of the received echoes is shown in Fig. 8. The two nonfunctioning elements are attributed to open flip-chip bond connections.

The output pressure of 5 elements was measured at 5 mm using a hydrophone. The measured pressures normalized to the transducer face are shown in Fig. 9.

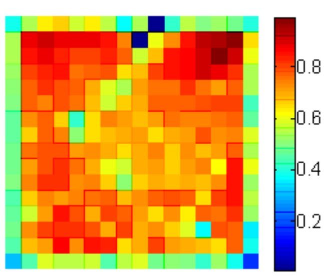


Figure 8. Normalized energy of received echo from a plane reflector for each element of the array. The CMUTs were biased with 17 V DC. The mean of the normalized energies is 0.7. The standard deviation is 0.14.

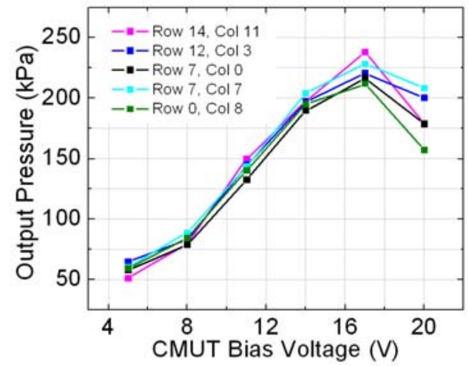


Figure 9. Output pressure for 5 transducer elements.

The receive sensitivity for the same 5 elements is shown in Fig. 10. The measured sensitivity includes the gain of the amplifier.

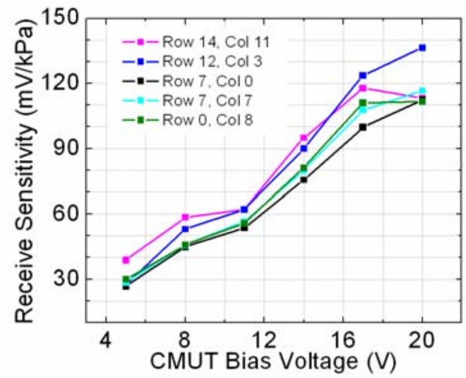


Figure 10. Receive sensitivity at the amplifier output for 5 elements.

The amplifier output noise at 5 MHz was measured as 112 nV/√Hz.

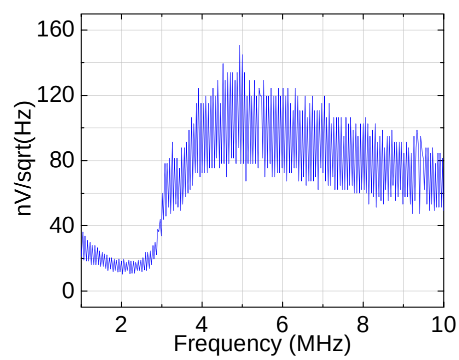


Figure 11. Amplifier output noise.

Using the receive sensitivity measurements, the output noise voltage can be expressed as a noise pressure of approximately 1 mPa/√Hz. In [4], Rhyne describes reception noise figure for an ultrasound transducer and receiver. Reception noise figure is defined as the loss in SNR due to the noise of the amplifier and transducer. It can be calculated as the ratio of the total measured noise to the noise due to the acoustic medium. The acoustic medium noise is $\sqrt{\dfrac{4kTR_{med}\Delta f}{S}}$ where R_{med} is the medium impedance in Rayls, S is the area of the transducer, and Δf the bandwidth. For 250-µm elements, the medium noise is calculated as 0.6 mPa/√Hz, resulting in a reception noise figure of 4.4 dB.

IV. IMAGING RESULTS

Images of a wire phantom obtained with the characterized array are shown in Fig. 12. Although all elements have their dedicated pulsers and amplifiers, only a single element is selected at a time to simplify the initial implementation of the IC. Thus, classic synthetic aperture image reconstruction is used. For a 3-cm penetration depth, 10 ms are needed to acquire a single frame with no averaging. The images shown in Fig. 12 and Fig. 13 were obtained by averaging 16 acquisitions. Images of liquid filled polyethylene tubes in a tissue mimicking material are shown in Fig. 13. Corresponding photoacoustic images are also shown [5].

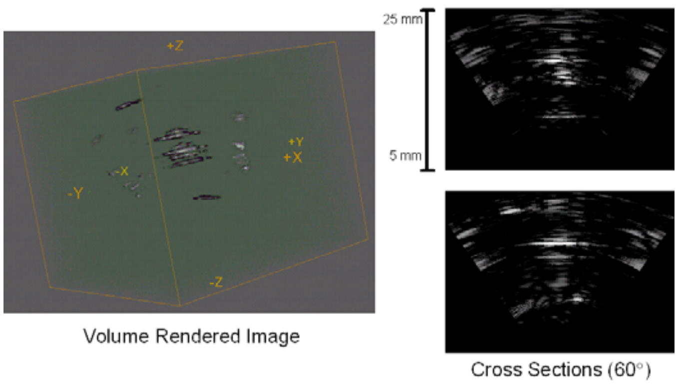


Figure 12. Volume rendered and cross-secional views of wire target. Wires in the Y direction are between 0.8 mm and 1.5 mm apart. Cross sections are shown with 30-dB dynamic range.

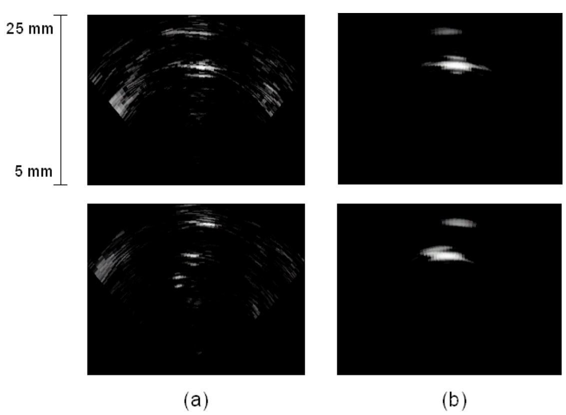


Figure 13. Pulse-echo (a) and photoacoustic (b) images of a vessel-like phantom. The phantom consist of 3 polyethylene tubes (1.3-mm outer diameter, 3.6 mm apart) in tissue mimicking material.

The first frame of a two-second movie of a metal ball moving within a wire phantom is shown in Fig. 14. The imaging data is acquired in real-time using an FPGA-based acquisition system. Real-time transfer of the data and image reconstruction is being developed.

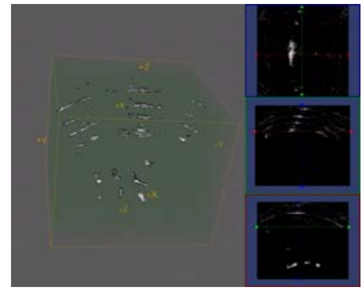


Figure 14. First frame of a two-second movie acquired in real-time.

V. CONCLUSION

Volumetric ultrasound images were acquired in real-time using a fully-populated two-dimensional transducer array with integrated electronics. The system described here meets the challenges of catheter-based imaging. Future work will focus on the development of an IC that uses multiple transducer elements on transmit and receive, and on the development of real-time image reconstruction.

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REFERENCES

[1] D. T. Yeh, O. Oralkan, I. O. Wygant, M. O'Donnell, B. T. Khuri-Yakub, "3-D ultrasound imaging using forward viewing CMUT ring arrays for intravascular and intracardiac applications," presented at the 2005 IEEE International Ultrasonics Symposium, Rotterdam, The Netherlands, Sep. 18-21, 2005.

[2] D. T. Yeh, O. Oralkan, I. O. Wygant, A. S. Ergun, J. Wong, and B. T. Khuri-Yakub, "High-resolution imaging with high-frequency 1-D linear CMUT arrays," presented at the 2005 IEEE International Ultrasonics Symposium, Rotterdam, The Netherlands, Sep. 18-21, 2005.

[3] X. Zhuang, I. O. Wygant, D. T. Yeh, A. Nikoozadeh, O. Oralkan, A. S. Ergun, C.-H. Cheng, Y. Huang, G. G. Yaralioglu, and B. T. Khuri-Yakub, "Two-dimensional capacitive micromachined ultrasonic transducer (CMUT) arrays for a miniature integrated volumetric ultrasonic imaging system," in *Proceedings of SPIE Medical Imaging,* 2005, pp. 37-46.

[4] T. L. Rhyne, "Characterizing Ultrasonic Transducers Using Radiation Efficiency and Reception Noise Figure," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 45, pp. 559-566, 1998.

[5] I. O. Wygant, X. Zhuang, P. S. Kuo, D. T. Yeh, O. Oralkan, B. T. Khuri-Yakub, "Photoacoustic imaging using a two-dimensional CMUT array," presented at the 2005 IEEE International Ultrasonics Symposium, Rotterdam, The Netherlands, Sep. 18-21, 2005.

[6] I. O. Wygant, D. T. Yeh, X. Zhuang, A. Nikoozadeh, O. Oralkan, A. S. Ergun, M. Karaman, B. T. Khuri-Yakub, "A miniature real-time volumetric ultrasound imaging system," in *Proceedings of SPIE Medical Imaging,* 2005, pp. 26-36.