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A 32×32 Integrated CMUT Array for Volumetric Ultrasound Imaging

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Abstract—**Real-time 3D volumetric ultrasound imaging systems require transmit and receive circuitry to generate the ultrasound beam and process the received echo signals. Since a 2D array is required for 3D imaging, the complexity of building such a system is significantly higher, e.g., front-end electronics need to be interfaced to the transducer, a large number of elements need to be interfaced to the backend system and a large dataset needs to be processed. In this work, we present a 3D imaging system using capacitive micromachined ultrasonic transducer (CMUT) technology that addresses many of the challenges in building such a system. The transducer is a 5-MHz CMUT array with an 8 mm × 8 mm aperture size. The aperture consists of 1024 elements (32×32) with an element pitch of 250 µm. An integrated circuit (IC) is integrated very close to the CMUT array. It consists of a transmit beamformer and receive circuitry to improve the noise performance of the overall system. Simultaneous multi-beam transmit is also incorporated in the IC to improve the imaging frame rate. The CMUT is flip-chip bonded to the IC and the final assembly measured 9.2 mm × 9.2 mm. The assembly was then interfaced with an FPGA and a backend system (comprising of a data acquisition system and PC). The FPGA provided the digital I/O signals for the IC and the backend system was used to process the received RF echo data (from the IC) and reconstruct the volume image using a phased array imaging approach. Imaging experiments were performed using wire phantoms. Real-time volumetric images were captured at 5 volumes per second and are presented in this paper.**

Keywords—**3D volumetric imaging; capacitive micromachined ultrasonic transducer (CMUT); 2D array; phased array imaging; ultrasound; real-time; flip-chip bonding; integrated circuits**

I. INTRODUCTION

Real-time volumetric imaging is very important in medicine due to the depth of information it can provide to the physicians [1]. Unlike conventional 2D ultrasound imaging systems, a 3D imaging system can provide 2D images in any orientation with respect to the transducer array and a volume image in real-time.

However, building a 3D imaging system comes with many challenges, such as, integration of the transducer to the electronics and interfacing these to the backend system. Imaging in 3D space also requires a large amount of data to be processed which can severely limit the volume rate. Some of these challenges can be mitigated using advanced assembly techniques, such as flip-chip bonding and appropriate beamforming schemes to improve the imaging frame rate.

Previously, we have demonstrated real-time volumetric imaging with a 16×16 CMUT array [2] and more recently, with a 32×32 tiled CMUT array with front-end electronics integrated with a help of an interposer [3]. However, direct integration of the CMUT array and the IC is always preferable since it helps mitigate additional parasitics and also allows for compact assembly.

This paper describes a new 3D imaging system, which consist of a 32×32 CMUT array as well as front-end electronics that can be directly integrated without use of an interposer board. The new IC has a transmit beamformer and simultaneous multi-beam transmit capability to improve the imaging frame rate by up to four times the conventional phased array imaging approach. Low noise amplifiers are also incorporated to signal condition the received echo. Real-time volumetric images of wire-phantoms have been presented.

II. 32×32 INTEGRATED ARRAY

Fig. 1 illustrates the aperture of our imaging system which is 8 mm × 8 mm in size. The aperture consists of 1024 elements. The diagonal 64 elements are used for receive while the remaining 960 elements are used for transmit of the ultrasound beam. As shown in [4], such a scheme enables us to reduce the number of backend cables required without much degradation in image quality.

We use a 32×32 2D CMUT array as our transducer array. Each element has an operating frequency of 5 MHz (in immersion) and a pitch of 250 µm. The CMUT is fabricated using a process described in [5]. Under the CMUT array is the front-end IC directly integrated using flip-chip bonding technology.

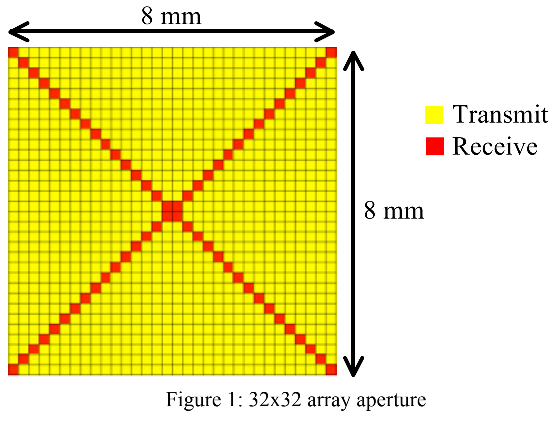

Figure 1: 32x32 array aperture

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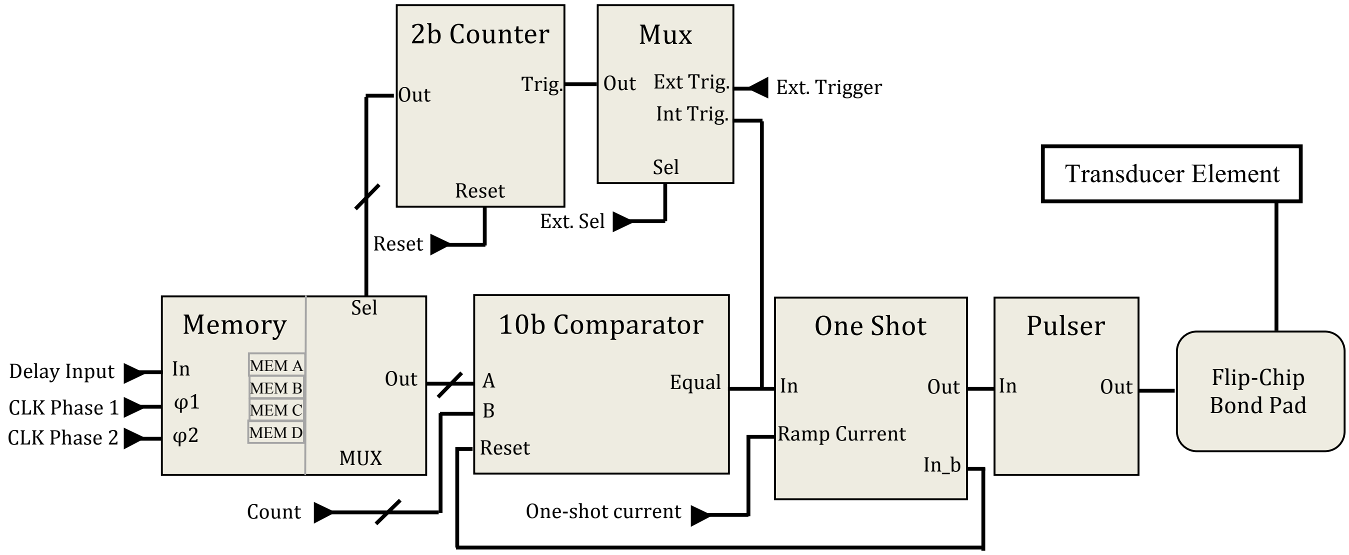

Figure 2a: IC transmit block diagram

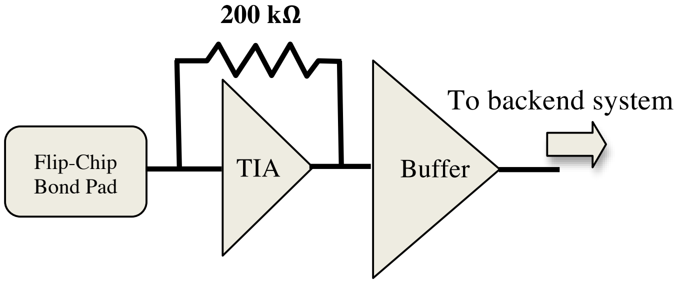

Figure 2b: IC receive block diagram

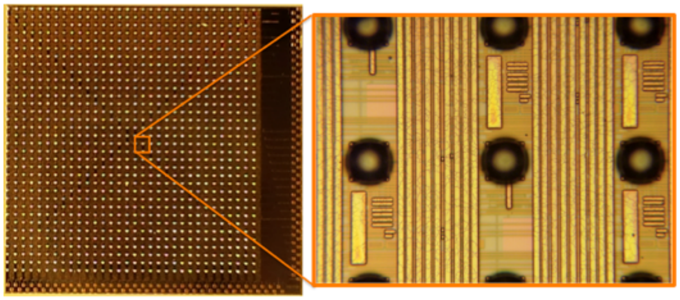

Figure 2c: IC die photo

Integrating front-end electronics to the transducer array is necessary to obtain better noise performance thereby improving the SNR of the overall image [6]. It also allows us to reduce the number of backend cables that would have been otherwise needed to transfer the RF data for image processing. We developed a 32×32 IC that is capable of addressing 1024 CMUT elements. The IC was fabricated in a 0.25-µm high voltage process. On-chip pulsers are incorporated that are capable of providing a unipolar pulse of up to 60 V.

III. CIRCUIT DESIGN & IMPLEMENTATION

Fig. 2 depicts the block diagram of the transmit and receive circuitry for a single element. The transmit element consist of transmit beamformers to enable focusing of an ultrasound wave in space. Each transmit element consist of a 40-bit shift register, a 10-bit comparator, a one-shot circuit and a high voltage pulser. The 40-bit shift register is used to store up to four delay values of 10-bit each. To achieve simpler assembly with the CMUT array, it was necessary to place the transmit and receive circuitry within the 250 µm × 250 µm window (which is the element-to-element pitch of the CMUT array).

The transmit block has two modes of operation—conventional transmit beamforming & simultaneous multi-beam transmit (of up to 4 beams). In the conventional beamforming technique, prior to each transmit beam, the shift registers of each element is loaded with a single delay value. After all the elements are loaded with their respective delays, an external 10-bit counter starts to count. The comparator would then output a high when there is a match between the stored delay value and the external counter. The comparator uses dynamic logic and is self-resetting in nature. The output high of the comparator triggers the one-shot circuitry, which drives the on-chip pulser to fire a unipolar pulse. Therefore, by storing the appropriate delay values to each element, one can steer the ultrasound beam in space. The one-shot circuitry sets the pulse width of the high voltage pulse and consists of a current-starved invertor chain. The pulse width is based on the operating frequency of the CMUT, which is 5 MHz. The on-chip pulser is adapted from the design described in [7]. It is designed to provide a unipolar pulse of up to 60 V and have a rise and fall slew rate of about 1250 MV/sec for a 2.5 pF load (which is roughly the capacitance of the CMUT element).

For simultaneous multi-beam transmit, instead of loading a single delay value, four delays are stored in each element (for a simultaneous transmit of 4 beams). When the first pulse fires, the comparator, in addition to triggering the one-shot circuitry, also triggers the internal 2-bit counter to change the memory location to the next delay value. The next pulse is fired based on the subsequent delay value and so on. As can be

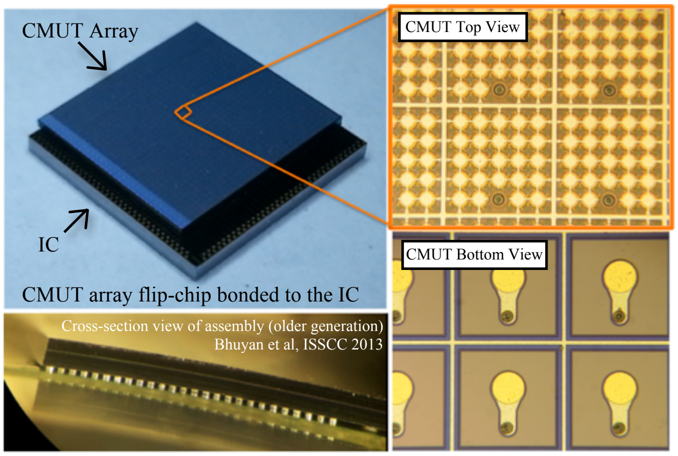

Figure 3: Integrated array (CMUT and IC flip-chip bonded)

seen in the block diagram, the 2-bit counter can also be triggered externally by a global signal, if desired.

Once the IC fires all the transmit beam, it goes into receive phase. In this phase, only the diagonal 64-elements are active. Each receive element consist of a transimpedance amplifier and an output buffer. The transimpedance amplifier is a simple common source configuration design [2]. The amplifier and the buffer combined are designed to have a bandwidth of 20 MHz and a transimpedance gain of 200 kΩ. Since the receive circuitry is incorporated to improve the overall noise performance, it is imperative to design the amplifier with low noise. We achieved a simulated noise figure of 4.5 dB (at 5 MHz). Each receive channel consumes a power of 4.5 mW. Fig. 2c shows the die photo of our IC which measures 9.2 mm × 9.2 mm.

IV. 3D INTEGRATION & ASSEMBLY

The CMUT and IC were integrated together using flip-chip bonding. This allows for compact assembly with minimal parasitics between the CMUT and IC. Flip-chip bonding also allows for tiling of multiple arrays to form a larger array if desired. Often times, the IC size is limited by the reticle size of the wafer. Therefore, if direct integration of the CMUT array and IC, though desirable, is not possible, multiple ICs can be used to interface a larger CMUT array with the help of an interposer board.

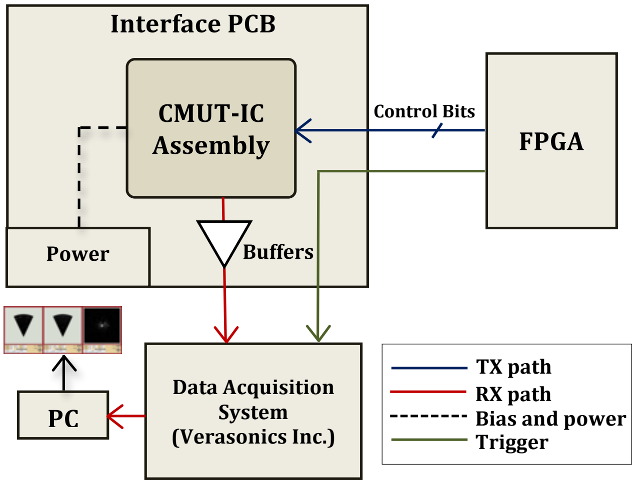

Figure 4: Block diagram of imaging setup

Through wafer vias are incorporated in the CMUT array to enable access of the CMUT element from the backside. The IC was treated with Ni/Au under-bump metallization. Then, a solder jetting process was used to place solder balls on the IC pads. The solder balls are 80 μm in diameter and have a bump height of 50 μm. Finally, using an in-house flip-chip bonder, the IC and the CMUT array were aligned with respect to each other and bonded under high pressure and temperature. Fig. 3 illustrates the assembly.

V. IMAGING RESULTS

Fig. 4 illustrates the experimental setup. It consists of an interface board, FPGA and a data acquisition system from Verasonics (Verasonics, Inc., Redmond, WA). A tank is built on top of the assembly to enable imaging experiments in immersion (oil). The interface board provides the necessary power and bias to the IC as well as the interface to communicate with the data acquisition system and the FPGA.

Multiple data acquisitions were necessary to obtain an image frame. Each data acquisition consists of a delay loading phase, a transmit phase and a receive phase. The FPGA provides all the digital I/Os to the IC during the delay loading and transmit phase. In the receive phase, the RF signal from the IC is buffered in the interface board before it's sent to the backend system (data acquisition system and a host PC) for image reconstruction and display using an in-house imaging software suite.

Nylon wire phantoms with a diameter of 300 μm were used for our imaging experiment (Fig. 5a). Preliminary imaging results of our experiment are shown in Fig. 6. Volume data was captured in real-time and images were displayed in three cross-sections – two B-mode planes

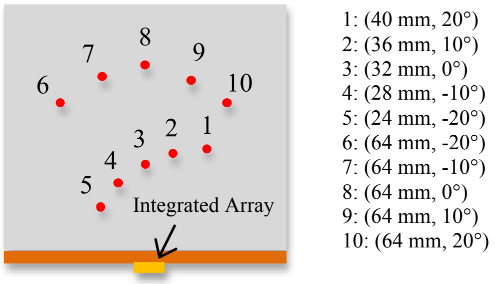

Figure 5a: Wire phantom (location with respect to CMUT array)

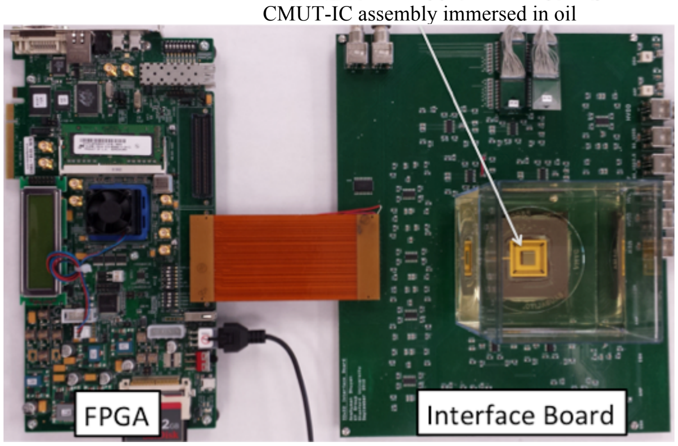

Figure 5b: Illustration of our imaging system

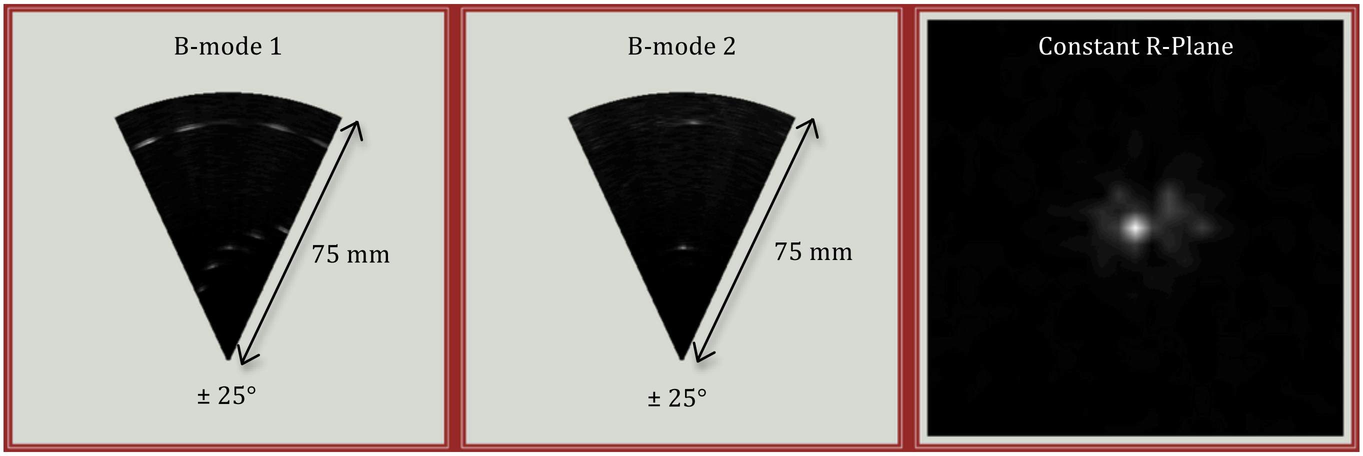

Figure 6: Real-time imaging results in three planes

orthogonal to each other and one constant R-plane. The conventional phase array imaging was used to capture these images. For our imaging experiment, the CMUT was biased at 30 V (75% of collapse voltage) and the IC was set to transmit a unipolar pulse of 25 V. The images were captured at a volume rate of 5 volume frames per second up to a depth of 75 mm. Work is in progress to display 3D rendered images in real-time.

At present, the limitation in volume rate comes from the data-transfer rate between the Verasonics data acquisition system and the PC. We are working on improving the frame rate by using the multi-beam feature of this IC. Though we achieved real-time imaging results, we believe we could get better image quality. With our present IC, we faced an issue of IR drop in the power lines that fed the on-chip pulsers. This was due to the high resistance in the long metal lines. Therefore, when more pulsers were simultaneously pulsing, the large IR drop in the on-chip pulser's supply led to the pulsers pulsing at different pulse widths. This issue affected our transmit beamforming profile leading to a degradation in image quality. We have fixed this issue by making modifications in the IC layout. The new IC has already been fabricated and we are expecting to get better images in our next set of imaging experiments.

VI. CONCLUSIONS

We have developed a 32×32 CMUT based 3D ultrasound system for volumetric imaging. ICs were integrated with CMUTs using flip-chip bonding to achieve better SNR. Real-time images were acquired at a rate of 5 volume frames per second. Successful acquisition of real-time images shows clear feasibility of development of such 3D ultrasound system. More imaging experiments are planned with the new batch of ICs that would eliminate the IR drop in the high voltage power line leading to better image quality. Use of the simultaneous multi-beam transmit feature of the IC will also enable us to improve the achievable volume rate.

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