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Front-End Electronics for Cable Reduction in Intracardiac Echocardiography (ICE) Catheters

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***Abstract*—3-D imaging ICE catheters with large element counts present design challenges in achieving simultaneous data readout from all elements while significantly reducing cable count for a small catheter diameter. Current approaches such as micro-beamformer techniques tend to rely on area and power hungry circuits, making them undesirable for ICE catheters. In this paper, a system which uses are an efficient real-time programmable on-chip transmit (TX) beamformer circuitry to reduce the cable count on the TX side and analog 8:1Time Division Multiplexing (TDM) with Direct Digital Demodulation (DDD) to reduce the cable count on the receive (RX) side is presented.**

***Index Terms*—Intracardiac Echocardiography (ICE), TDM, TX Beamformer, CMUT**

I. Introduction

Catheter based ultrasound imaging has a broad range of surgical applications. Many surgical procedures of the heart are now being performed using minimally invasive methods with the help of catheter based ultrasound imaging guidance such as Intracardiac Echocardiography (ICE). ICE catheters provide a unique method to image the inner workings of the heart [1]. But current ICE can only provide 2D and limited-volume 3D real time volumetric images of the heart structure. 3D ICE imaging systems requires the generation of ultrasound transmit beams and collection of receive signal data from a large element count 2D ultrasound arrays. Furthermore, in order to limit the effect of motion artifacts, the data from the transducer elements needs to be captured within a short time window so as close to simultaneously as possible. In order to obtain real-time 3D images from ICE catheters, as many transducer elements as possible need to be connected in parallel to the back-end image processing system for both transmit and receive operations.

Direct connection of large numbers of elements is extremely challenging due to the requirement of large numbers cables to be placed inside a small size catheter [2]. Furthermore, by placing many tens to hundreds of cables inside the catheter increases the catheter size and reduces the mechanical flexibility of imaging system, making the surgical procedures difficult. One way to resolve this issue is to design and place transmit beamformer integrated circuitry (ICs) with high voltage transducer pulsers along with receiver multiplexing circuity directly underneath the ultrasound transducer at the tip of the catheter thus reducing the required number of external cables. Capacitive Micromachined Ultrasound Transducers directly built on top of CMOS ICs (CMUT-on-CMOS)[3] can be a viable solution to integrate ultrasound arrays with electronics to reduce the number of external cables required. This approach opens up the possibility to include complex transmit beamforming and receiver analog front end (AFE) circuitry along with cable reduction circuitry in order to eliminate a significant number of electrical connections and make possible higher transducer element counts that would otherwise be impractical.

In this paper we first introduce an area efficient transmit beamformer circuit design which can be programmed via a single micro-coax cable to produced focused and steered ultrasound beams. Then we describe briefly receiver electronics using an LNA based AFE coupled with TGC and cable reduction using Time Division Multiplexing (TDM) [4][5] to reduce the receiver side cable count by a factor of 8:1. We also present some experimental results of both the transmit beamformer and receiver circuity working in tandem to generate ultrasound pulses and capture echo responses from a CMUT transducer to demonstrate the viability of the approach in drastically reducing the cable counts for ICE applications.

II. Transmitter Beamformer

Modern ICE systems require hundreds of transmit elements. Connecting to each element in the ultrasound arrays to generate focused transmit beams from outside is extremely challenging especially for small diameter catheter probes. One solution to resolve the problem is to place transmit beamformer electronics directly underneath the ultrasound array on the tip of the catheter [6]. An area efficient on-chip transmitter beamformer with low cable count was designed so that overall system can be implemented in a catheter based ultrasound system. Using the beamformer the transmitted beams can be steered and focused with each element capable of having individually programmable delays. 1 shows the basic block diagram of the designed beamformer circuit.

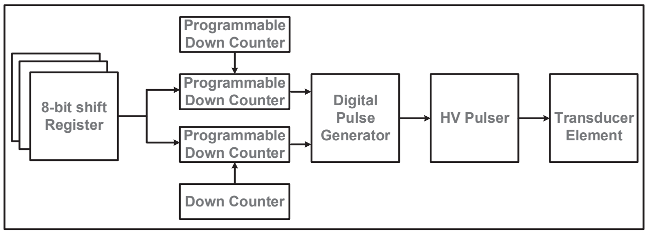

Fig. 1. Diagram of Transmit Beamformer

The transmit beamformer consists of an 8-bit shift register, two comparators, a digital pulse shape generator and a 25V pulser for each element. The beamformer can be programmed via single micro-coaxial cable by loading data using a serial protocol into the shift register, clocked in using the receiver TDM clock to save cables. There are two on-chip down counters in the beamformer which time both the delays and pulse width. To control the pulse width, the start value of one of the counters can be programmed to start at a lower value than the other down counter which always starts at the maximum value.

Before each firing the start value of the programmable counter and the 8-bit registers of each transmit elements are programmed from an FPGA with the required element delays and global pulse width. After the beamformer is programmed both the counters start counting. The values of the stored registers for each transmitter are compared with the programmable counter value. When the value stored in a register matches the value of the programmable counter then the comparator sends a start pulse to the corresponding pulse generator to start the transmit pulse. When the value in a register matches the value of the other counter, its comparator sends a stop pulse to the pulse generator which ends the transmit pulse. The difference between the start value of the programmable counter and the non-programmable counter thus determines the pulse width, and difference between the stored value of shift registers and programmable counter determines the delay of the pulse.

A 16 channel transmit beamformer IC with 25 V pulsers was fabricated in a 0.18 μm TowerJazz 4M1T high voltage process occupying a 3.22 mm 0.9 mm area as shown in 2. Each of the pulsers has individual 8-bit registers to set delays up to 1.27 μs in 5 ns increments. The transmit registers can be reconfigured using a single additional micro-coax cable in 0.7 μs allowing rapid phased array imaging.

III. Receiver Electronics

The receiver (RX) side of the design consists of a 32 channel IC as pictured in Fig. 3, which was fabricated using the same technology process as the TX IC. The receiver IC design implements a Low Noise Amplifier (LNA) based Analogue Front End (AFE) with integrated Time-Gain Compensation (TGC) coupled with analog Time Division Multiplexing (TDM) circuitry to achieve an 8:1 cable reduction. The RX IC operates from the same 1.8 V supply as the TX IC and consumes approximately 9 mW average power (assuming a 10% duty cycle). The RX design requires 3.25 mm 0.55 mm of IC area for the full 32 channel AFE and four 8:1 TDM multiplexers.

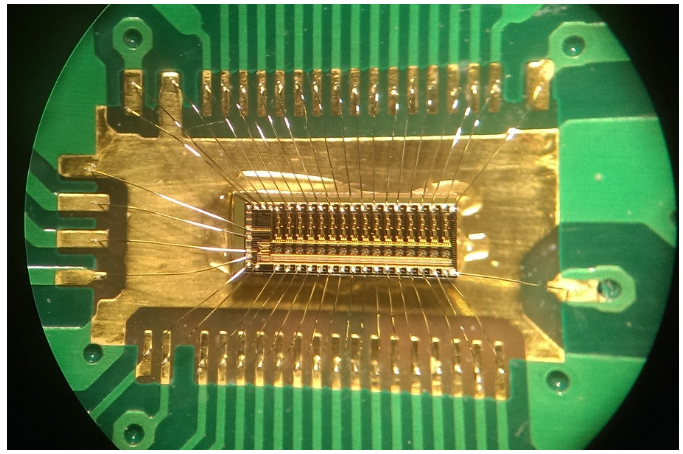

Fig. 2. Micrograph of Wire-bonded Transmitter IC

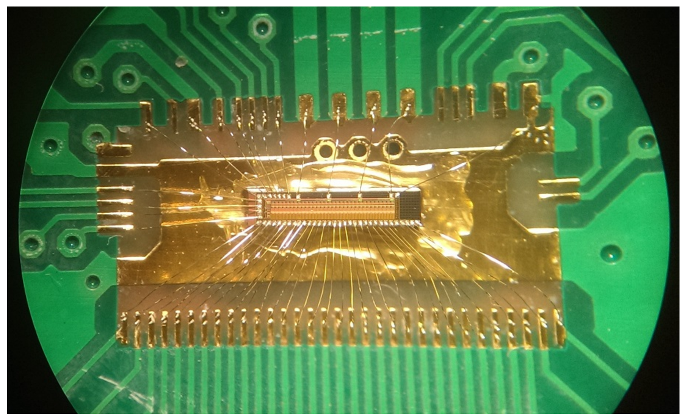

Fig. 3. Micrograph of Wire-bonded Receiver IC

The AFE was designed for 1D element CMUT transducers with 7 MHz center frequency and 80% fractional bandwidth, and has been designed to have a 3 dB bandwidth of around 11 to 12MHz. The amplified signals from the AFE are each sampled at 25 MSPS by the TDM front end, and then multiplexed into a TDM channel running at 200 MSPS utilizing the same clock as the TX IC.

The TDM output signals from the IC are fed through a 48 AWG micro-coaxial cable and further external LNA stage (Texas Instruments LMH5401) which drives the input of a high speed ADC (TI ADC16DX370) with 800MHz analogue bandwidth. The ADC is synchronized with a phase adjusted version of the 200MHz clock fed to the TX/RX ICs so that it can perform the direct digital multiplexing using the technique described in [4]. Once digitized, the demultiplexed data is then interpolated, phase corrected, and filtered in real time using a Stratix V FPGA (5SGSMD5K2F40C2N) from Altera before being transferred over a PCI Express link to a computer

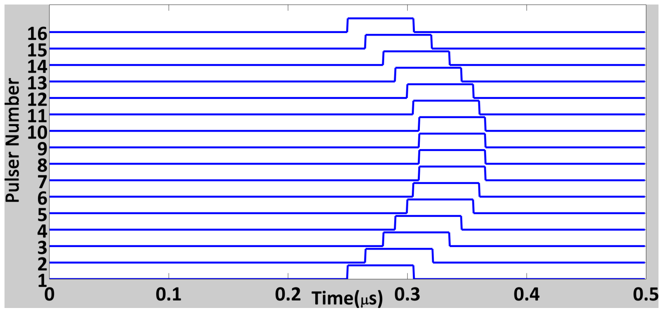

Fig. 4. Low voltage pulses for focussed beam from transmit IC test points

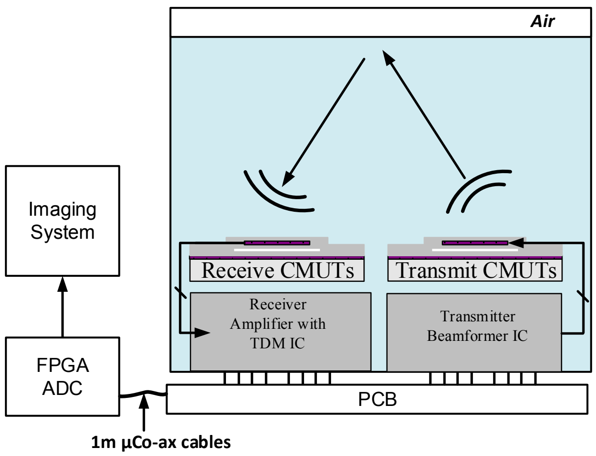

Fig. 5. Diagram of the test setup

IV. Experimental Results

The transmit beamformer and receiver ICs have been wire-bonded to a test PCB along with a 1D CMUT transducer array. The pulse generator outputs which feed to the high voltage pulsers are buffered and fed out as low voltage test points from the IC for observation purposes to verify that the correct beam pattern is being generated. The beamformer was programmed to generate a focused beam pattern as demonstrated in 4 which shows the signals at the IC test points.

The CMUT array used for the test setup was designed for 7MHz center frequency and 80% fractional bandwidth when immersed in water and coated in Parylene. 5 shows the experimental setup. Using the beamformer, the programmed focused beam with a 65 ns pulse width was sent through the integrated high voltage pulsers connected to the CMUT transducer to generate a focused transmit beam. The receiver electronics connected to a further set of CMUT transducer elements were then used to capture echo signals from an air-water interface approximately 17mm away from the transducer and then multiplex the signals using the TDM circuity. 6 shows the resulting demultiplexed echo signal from 4 of the 32 receive channels.

The Signal to Noise Ratio (SNR) was calculated for each channel to measure the uniformity of the receive channels by comparing the RMS power of the received echo pulse with the RMS noise power from a quiet part of the received signal. 7 shows the results of the SNR calculations for 16 of the receive channels. Some non-uniformity is observed in the SNR measurement which is mainly due non-linearity of the CMUT array.

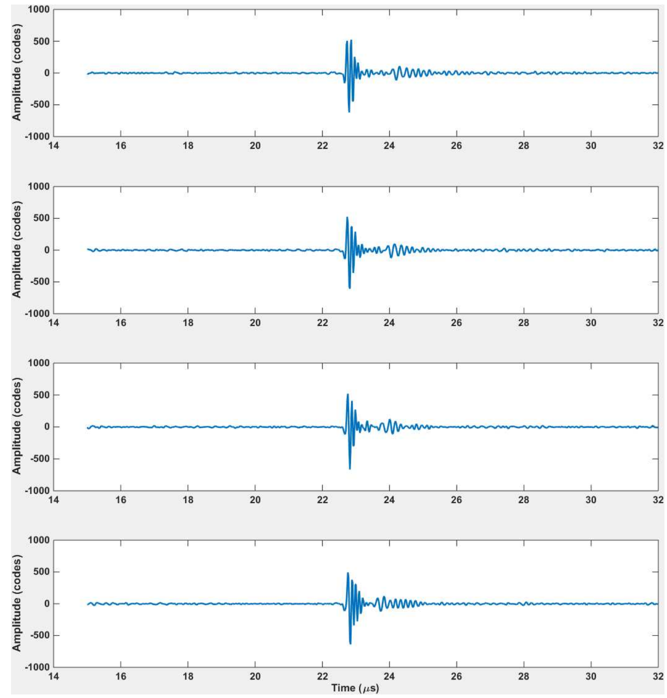

Fig. 6. Pulse echo response from four receive channels from an air-water interface at 17 mm distance

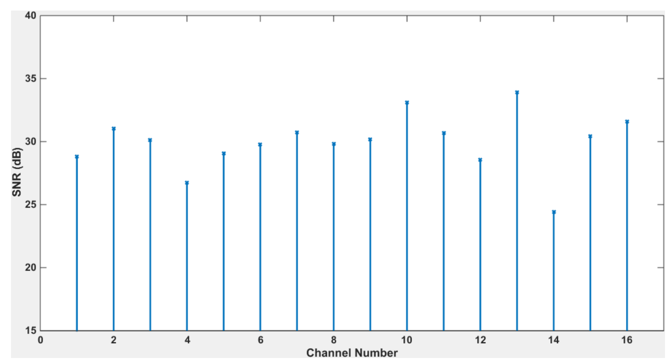

Fig. 7. Calculated SNR for 16 receive channels

V. Conclusions & Future Work

In this article we have successfully demonstrated the feasibility for wire reduction by wirebonding a CMUT array to custom made CMOS chips. Initial results are showing promising. An area efficient programmable transmit beamformer coupled with time-division multiplexing for the receive channels provides an alternative strategy to reduce cable count for whole ultrasound system, which is well suited to the requirements of CMUT on CMOS based ultrasound ICE catheters. Detailed experiments of the entire imaging system are underway.

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