An Integrated Circuit with Transmit Beamforming and Parallel Receive Channels for 3D Ultrasound Imaging: Testing and Characterization

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***Abstract*—The cost and complexity of medical ultrasound imaging systems can be reduced by integrating the transducer array with an integrated circuit (IC). By incorporating some of the system's front-end electronics into an IC, bulky cables and costly system electronics can be eliminated. Here we present an IC for 3D intracavital imaging that requires few electrical connections but uses a large fraction of a 16x16-element 2D transducer array to transmit focused ultrasound. To simplify the receive and data acquisition electronics, only the 32 elements along the array diagonals are used as receivers. The IC provides a preamplifier for each receiving element. Each of the 224 transmitting elements is provided an 8-bit shift register, a comparator, and a 25-V pulser. To transmit, a global counter is incremented from 1 to 224; each pulser fires when its stored register value is equal to the global count value. Electrical testing of the fabricated IC shows that it works as designed. The IC was flip-chip bonded to a two-dimensional capacitive micromachined ultrasonic transducer (CMUT) array. A two-dimensional image of a wire target phantom was acquired.**

I. Introduction

Modern real-time three-dimensional (3D) ultrasound imaging systems utilize fully-populated two-dimensional (2D) transducer arrays; these arrays can have thousands of elements. It is too bulky and complex to use cables to connect each of the array's elements to the image processing and display hardware. Electronics closely coupled with the transducer array can simplify this connection; they can be used to implement some of the system's front-end functionality such that fewer cables are needed to connect the handheld probe to the main system hardware. These electronics can be incorporated into the probe [1] with specialized connectors or, as is done for this work, the transducer array can be flip-chip bonded to an IC.

In additional to simplifying the connection between the probe and main system, receive sensitivity benefits from preamplifiers closely coupled with the transducer elements. Preamplifiers are particularly important for 2D arrays since the elements are small in size and thus their device capacitance is small. Preferably, parasitic capacitance in parallel with the device should be reduced as much as possible relative to the device capacitance. Typical 5 MHz array elements are 150-μm by 150-uμm and have on the order of picofarads of capacitance.

In [2], we presented a 16-by-16-element 5-MHz capacitive micromachined ultrasonic transducer (CMUT) array flip-chip bonded to a custom-designed IC. With that device, we demonstrated 100% element yield, excellent sensitivity, and 3D imaging of a nylon-wire phantom. The IC presented there provided a 25-V pulser and preamplifier to every element of the array, but only a single element at a time could be selected for transmit or receive. That IC was useful for characterization and could be used to acquire 3D images. However, for imaging, it is preferred that every element of the array be used in parallel for both transmit and receive.

In this paper, we present an IC that uses nearly every element of the array to transmit focused ultrasound. To simplify the receive and data acquisition electronics, only those elements along the diagonals of the array are used to receive. A previous study [3] showed that this use of the array provides similar imaging performance to using the entire array for both transmit and receive, except for increased side lobe levels. In future work, the IC could be extended to include receive beamforming electronics to utilize more receive elements.

II. Circuit Design and Implementation

Fig. 1 illustrates the top-level design of the IC. The design is the same as described in [4], except that the receiving elements are not also used to transmit and are fixed to those elements along the array diagonals. The separation of the transmit and receive elements has a small impact on the point spread function [3] and simplifies the layout of the IC.

The 32 elements along the array diagonals are used to receive. A control signal selects between the two array diagonals such that their outputs can be acquired 16 at a time. A transimpedance amplifier is provided to each receiving element. The amplifier is the same as described in [2], except that the feedback resistor was slightly reduced to increase the bandwidth beyond 10 MHz at the expense of increased noise. The 32 receiving elements share 16 source-follower buffers.

The elements not used for receive are used to transmit. The circuitry provided to each transmitting element is shown in Fig. 2. Prior to each transmission, the 224 8-bit shift registers are loaded with delay count values using 16 parallel inputs.

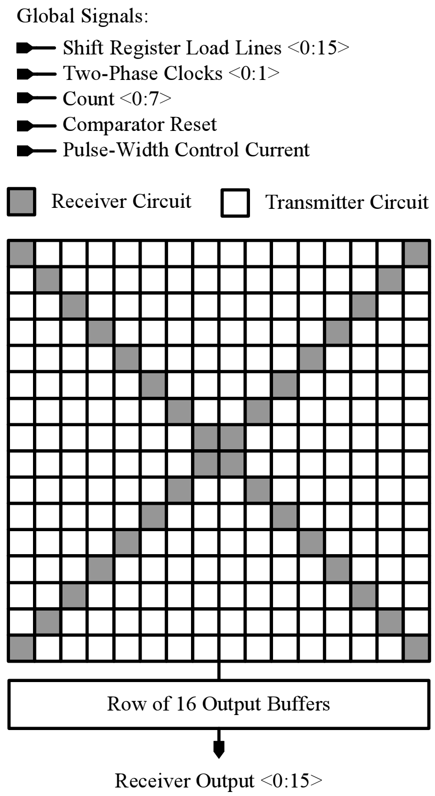

Fig. 1. The IC uses the 32 elements along the array diagonals to receive. A preamplifier is provided to each of the receiving elements. The remaining elements are used to transmit. The transmit circuitry includes shift registers that store delay information so that all of the transmitting elements can be used in parallel to transmit focused ultrasound.

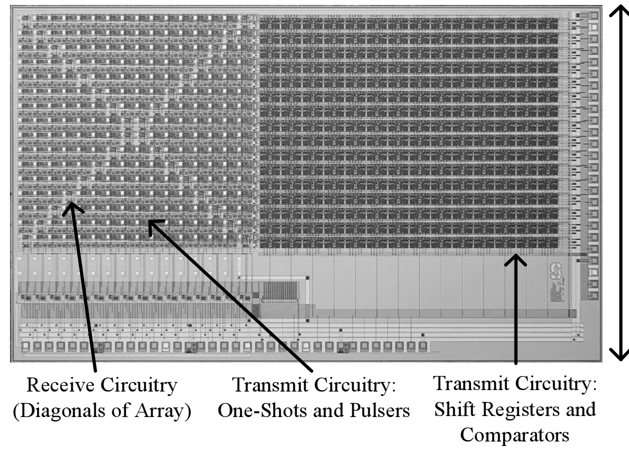

Fig. 3. A photo of the fabricated integrated circuit.

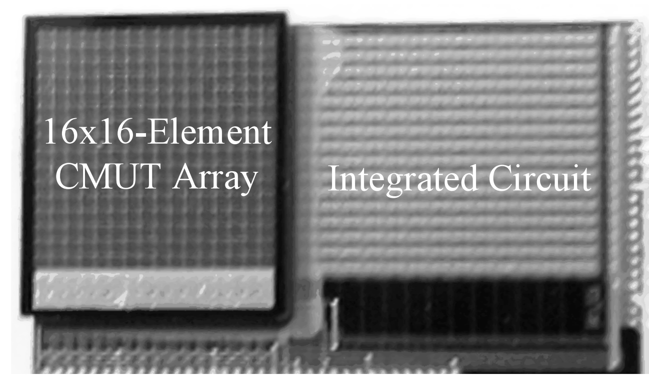

Fig. 4. A photo of a CMUT array flip-chip bonded to the integrated circuit.

The shift registers are simple 8-bit transmission gate registers. To transmit, a global 8-bit Gray code counter is incremented from 1 to 224. A comparator circuit triggers a one-shot which in turn triggers the pulser when the stored 8-bit delay count value is equal to the global counter. With this method of generating delayed pulses, every pulser can be triggered at an arbitrary time. The IC can thus be used to steer beams in any direction; the beams can be tightly focused for high signal-to-noise ratio or defocused for high frame rates.

The comparator circuit determines when the pulser is fired. A one-shot circuit determines the pulse width. A current, which is common to all of the elements, can be adjusted to obtain a pulse width suitable for a particular transducer's frequency response.

The IC was implemented in a high-voltage BiCMOS process (National Semiconductor, Santa Clara, CA). The process provides standard and high-voltage CMOS, bipolar, and DMOS devices. The minimum feature size of the process is 1.5 μm. Fig. 3 is a photo of the fabricated IC. The preamplifiers are located directly adjacent to the flip-chip bond pads for the receiving elements. Because the transmit circuitry occupies a large area, it was separated into two regions on the IC. The shift registers and comparators are arrayed on the right side of the IC. The one-shot and pulser circuits are located adjacent to the flip-chip bond pads for the transmitting elements.

The IC was flip-chip bonded to a 16x16 element CMUT array (Fig. 4) using the solder-bumping method described in [2].

III. Measurements

An FPGA-based data acquisition system (VHS-ADC, Lyrtech Signal Processing, Quebec City, Canada) hosted by a PC is used to operate the IC for testing. Values to be loaded into the IC's shift registers and information about the count rate of the global counter are transferred from the PC to the FPGA using the PC's cPCI bus. The FPGA generates a two-phase clock and the input signals for the IC's shift registers. Using a 100 MHz FPGA clock, the IC's shift registers are loaded in about 5 μs. When transmitting, the FPGA provides the 8-bit Gray-code counter for the IC. The Gray code counter is not incremented at a constant rate; it is only incremented at times when a pulser on the IC needs to be fired. The number of clock cycles between each count value is transferred from the PC to the FPGA for each transmission.

The IC was first tested without a CMUT array. The IC was packaged in a 121-pin PGA package. The flip-chip bond pads for 14 of the transmitters and 2 of the receivers were wire bonded to pins of the package. Fig. 5 shows the measured

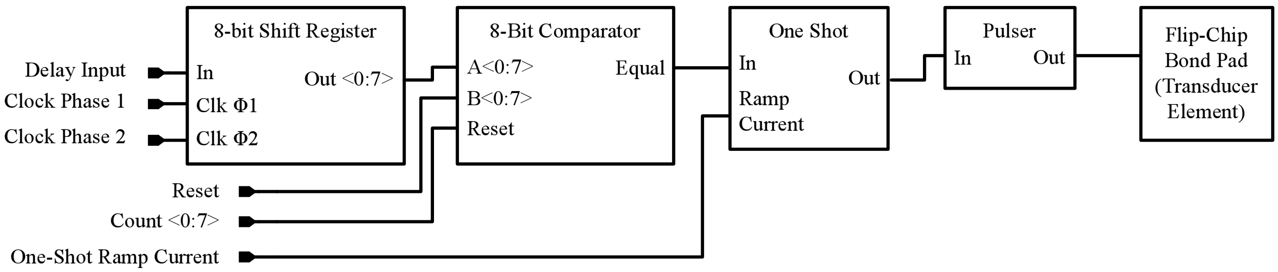

Fig. 2. Transmit circuitry is provided to each of the 224 transmitting elements. Prior to transmit, a delay value is loaded into the 8-bit shift register. The pulser is triggered when the stored value is equal to a global counter. A one-shot determines the width of the pulse.

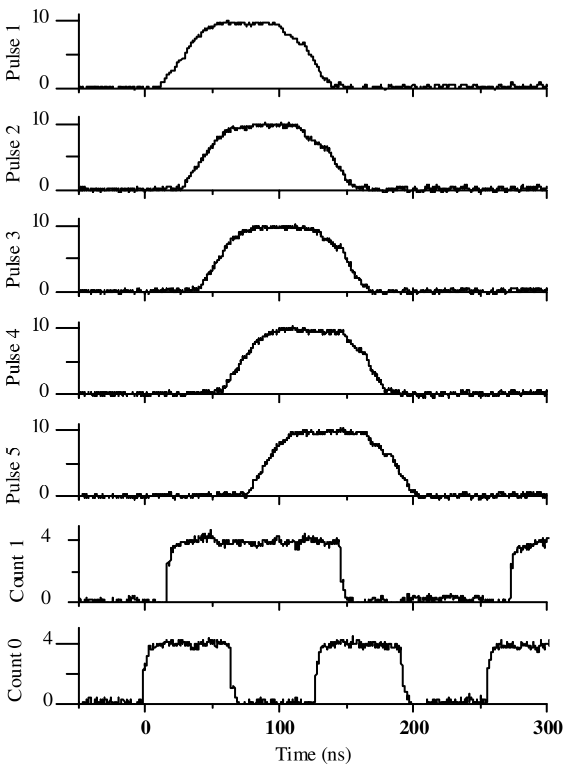

Fig. 5. The output of 5 pulsers along with two bits of the global Gray code counter are shown. In this case, the pulsers' shift registers are loaded with values such that the pulsers fire in succession as the Gray code counter is incremented. Each transition of Count 0 corresponds to 4 increments of the total Gray code counter value.

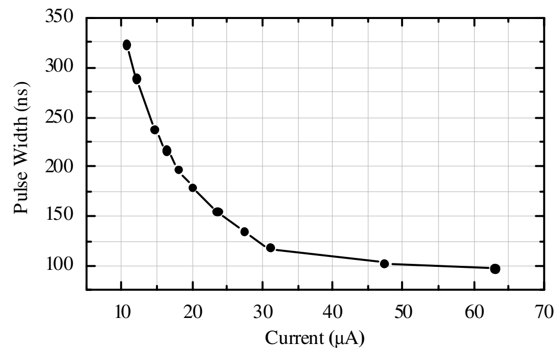

Fig. 6. A control-current for the one-shot is used to adjust the pulse width.

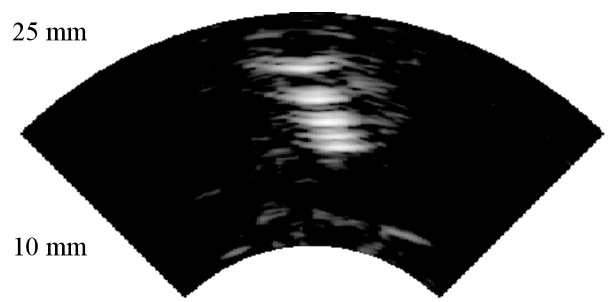

Fig. 7. A two-dimensional image of a nylon-wire phantom was acquired. The image is shown with 25-dB dynamic range.

output of 5 pulsers along with two bits of the global counter. In this case, the transmitters were loaded with values one count apart so that as the Gray code counter is incremented, the pulsers fire in succession. The pulsers can generate up to 25-V pulses. For this test, the pulsers were limited to 10-V so that their output could be measured with an active oscilloscope probe. The active probe has less capacitance than a conventional oscilloscope probe and thus better indicates the shape of the pulse that would be provided to a transducer element.

Fig. 6 shows the pulse width as a function of the one-shot control current. For this test, pulse widths as short as 100 ns were measured, which is sufficient for the 2.5 MHz transducer array initially used. However, larger control currents can be used to provide shorter pulses.

The IC was flip-chip bonded to a CMUT array with a center frequency of 2.5 MHz. Each element of the array was used to transmit and receive, confirming that every element of the array was working. The device was used to acquire a 2D image of a nylon-wire phantom (Fig. 7). Forty transmit beams spanning 90° focused at 17 mm were used for the image.

IV. Conclusion

Testing of the IC on its own and flip-chip bonded to a 2D CMUT array shows that the IC works as designed. We are currently working on the supporting electronics so that the IC can be incorporated into a complete imaging system. The IC's output will be connected to a 16-channel data acquisition system which will include an FPGA-implemented beamformer.

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