Miniaturized, Wearable, Ultrasound Probe for On-Demand Ultrasound Screening

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***Abstract*—There are several applications in the medical field that require periodic monitoring of blood vessels or organ functions. Ultrasound, being one of the preferred imaging modalities, is often used for such applications. However, present day ultrasound probes are bulky and inconvenient. We present a low profile, wearable ultrasound probe that can be taped onto the patient's body for periodic or constant monitoring of organ functions. The small form factor is key for such applications. Therefore, CMUT technology is ideal for development of such probes. The probe consists of a 64-element 1D linear array CMUT operating at 5 MHz. Front-end electronics were integrated with the CMUT to improve the SNR of the acquired image. The final assembly measures 6 cm x 3.5 cm x 0.35 cm. A PDMS lens lay on top of the assembly to allow focusing in the elevation plane. The probe is interfaced to a backend system (Verasonics data acquisition system, Verasonics, Inc., Redmond, WA). Verasonics provides the high voltage pulses and also digitizes the received RF echo data for image reconstruction. Field characterization of the probe was performed using a calibrated hydrophone and was compared to Field II simulations. Finally, imaging experiments were performed on a commercially available phantom as well as the human neck. Images were also acquired with a commercially available probe for the sake of comparison. The CMUT probe provided with comparable image quality to that of the commercial probe. Real time images were also acquired by the CMUT probe at 30 frames per second.**

***Index Terms*—low profile, wearable, portable, CMUT, ultrasound, capacitive micromachined ultrasonic transducer, real-time**

I. INTRODUCTION

Ultrasound imaging has been one of the most preferred mode of imaging in the medical field due to its low cost and non-ionizing radiation. Several medical conditions, e.g., renal transplants, require constant or periodic monitoring of organ functions. Blood vessels of the transplanted kidney need to be monitored periodically to detect any early complications. For such applications, a portable monitoring system is desired to perform periodic monitoring, possibly even remotely.

Present day ultrasound probes are bulky and unsuitable for such applications. Therefore, we present a miniaturized, wearable ultrasound probe that would allow feasibility of such a portable monitoring system. The small form factor of the probe is crucial for success of its intended application. We believe CMUT technology would be ideal for development of such a probe. CMUTs have various advantages such as wide bandwidth, easy integration with electronics, and ability to make large arrays [1]. The wideband nature of CMUT helps achieve a better image resolution, whereas seamless integration with electronics helps preserve the overall image SNR. Also, if sufficient demand ever exists, CMUT technology would help deliver batch-fabricated arrays in large quantities at a low cost.

II. SYSTEM INTEGRATION

A. Overall Setup

Figure 1 illustrates the overall setup. The small form factor of the probe allows it to be conveniently taped on the human body. The probe is then connected to a flexible cable that carries the RF channels and the power signals to and from the backend system. The present assembly has the flexible cable attached to the probe but one can also have a detachable cable that can be plugged in to the probe when desired.

The backend consist of an interface box that provides the necessary power to the electronics and also acts as a medium for the RF signals to pass to the image acquisition system (Verasonics data acquisition system, Verasonics, Inc., Redmond, WA).

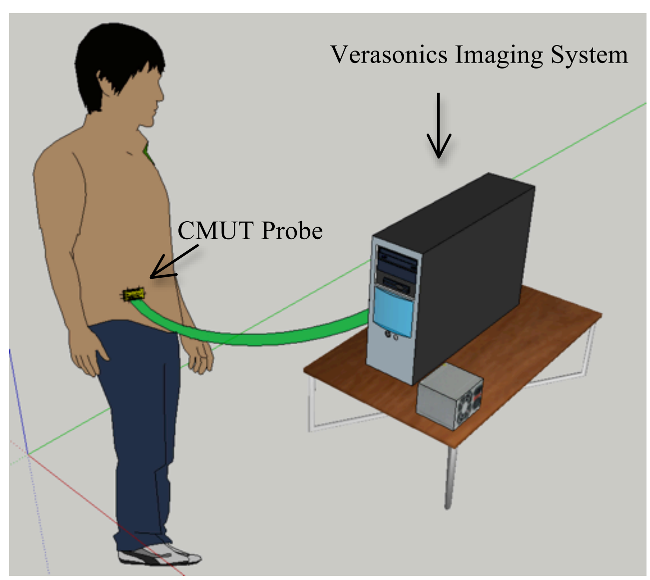

Figure 1. Pictorial illustration of setup

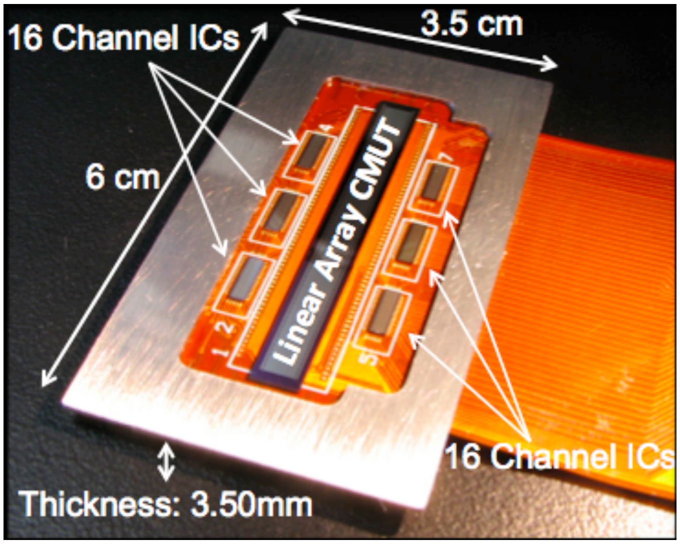

Figure 2. Integration of CMUT and ICs on flexible PCB

Such a setup is ideal for applications that require constant monitoring of body organs at a bedside. However, in the future, we do envision scaling down of the backend system to the size of a smart phone making the entire setup portable.

B. CMUT Probe Assembly

One of the main objectives of this paper is to make this probe very small and portable. The probe consists of frontend ICs and the CMUT integrated on a flexible PCB. Placement of these different components and assembly is key to achieving the small factor size. Figure 2 shows the probe along with the different components.

The CMUT was fabricated in-house using the standard wafer bonding process and consists of a 132-element linear array operating at 5 MHz [2]. Out of the 132 elements, only 64 elements are used in this prototype implementation. The CMUT array measured 5 mm x 43 mm with an element-to-element pitch of 0.3 mm. Each element measures 3 mm x 0.290 mm with an equivalent capacitance of 40 pF. The electronics are integrated with the CMUTs to provide signal conditioning of the received echo from the CMUT. Each IC consists of 16 channels and therefore 4 ICs were required to integrate with one CMUT array. The CMUT and ICs were wire bonded onto the flexible PCB. The two extra ICs shown in Figure 2 were used for debug purposes. The probe measured 60 mm x 35 mm x 3.5 mm. The assembly could be made even smaller and thinner by modifying the stiffener design that was used to provide mechanical strength of the probe.

The whole assembly (Figure 4) was then encapsulated with a PDMS lens to provide insulation & focusing with a focal depth of 11 mm in the elevation direction. Finally, the flexible cable, which is 1 meter long, was electrically insulated with copper tape to shield the traces from external interferences.

C. Frontend Electronics

The IC was designed to improve the performance of the overall system. Direct connection of the CMUT array to the imaging system would lead to degradation of SNR due to large capacitances in the flexible cable (on the order of few hundreds of pF). Therefore, integration of the IC close to the CMUT was essential to condition the received signal and to improve the SNR. The block diagram of the IC is shown in Figure 3a [3]. This kind of architecture enables seamless integration with the backend imaging as it uses only one cable per TX/RX channel and system pulsers for transmit.

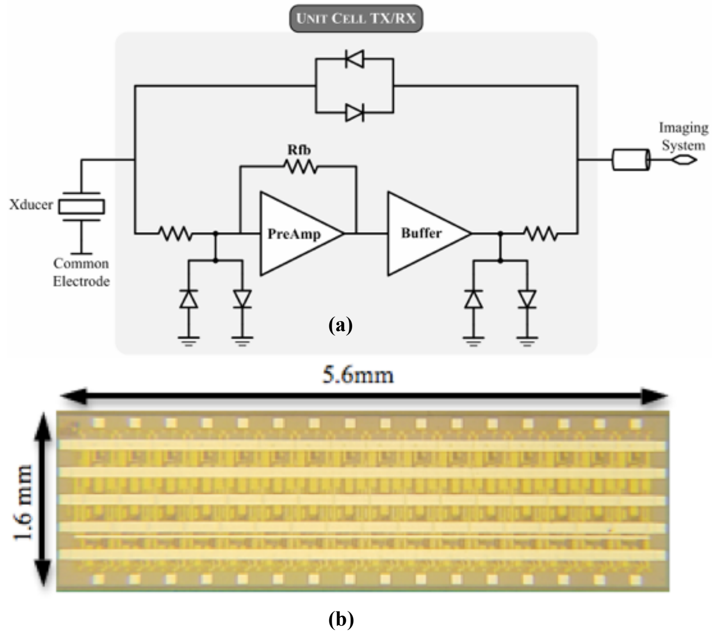

Figure 3. (a) Block diagram of a single channel, **(b)** Die photo of a single IC (16 channels)

The circuit is divided into two paths: transmit and receive. The high-voltage transmit pulse (up to ±50V) from the imaging system passes through the circuit through the diode expander circuitry. The diodes at the input and output of the amplifier serve as protection from the high voltage pulses during transmit. During receive cycle, the diode expander circuit acts as an open-circuit and the small signal from the CMUT passes through the amplifier and buffer. We designed the amplifiers and buffers to have a bandwidth of 10 MHz. The simulated noise figure is 12.5 dB. The power consumption is 6.72 mW per channel. The IC measures 5.6 mm x 1.6 mm and has 16 channels. Figure 3b shows the die photo of a single IC.

D. Backend System

The backend consists of the interface board and the imaging system. As mentioned earlier, the interface board provides the necessary bias and power supplies to the CMUT and ICs and also acts as a medium for the RF signals to traverse between the probe and the imaging system.

We used the Verasonics system and a host PC (Mac Pro, Apple Inc., Cupertino, CA) for image acquisition and for providing the high voltage pulses. In-house imaging code was developed for image reconstruction and was used for display of the acquired images [4]. We used the classical phased array algorithm for image reconstruction.

Figure 4. Assembly photos of CMUT probe

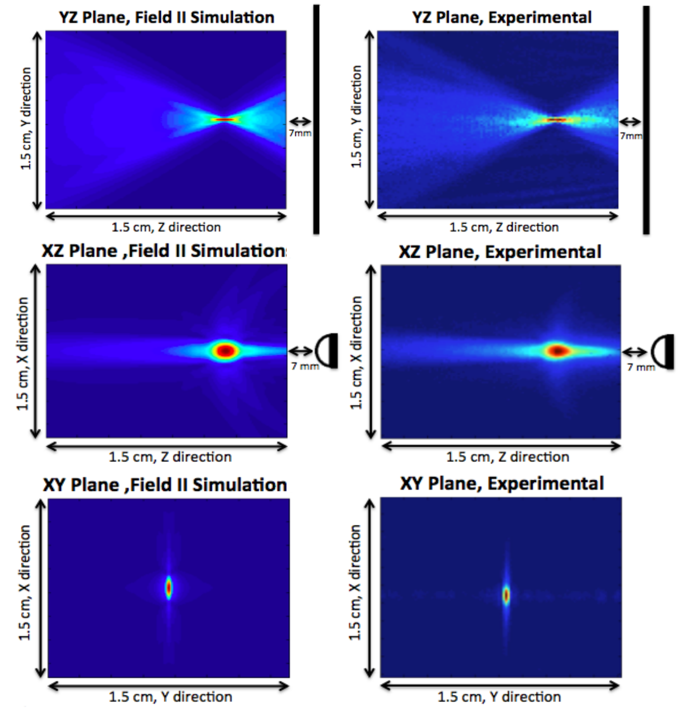

Figure 5. Field plots, simulations versus experiments

III. CHARACTERIZATION

After assembly of the probe, we performed field characterization using a calibrated hydrophone (Onda HNP-0400, Onda Corporation, Sunnyvale, CA). The field was characterized in all three planes crossing the on-axis focal spot. Field II simulations were also performed and were compared with experimental data [5]. The probe was placed in a water tank and the hydrophone was mechanically scanned using an XYZ scanner. Field plots can be seen in Figure 5. The XY plane was measured at a distance of 11 mm away from the probe. The experiment was performed with the probe electronically focused at its elevation focal point of 11 mm. The CMUTs were biased at 50 V (40% of the collapse voltage) and excited with a 40-Vpp, single cycle sinusoidal signal at 5 MHz.

At its focal point, the output pressure is measured as 750 kPa. The experimental results match well with the Field II simulations. The 3-dB beam width was experimentally measured to be 1.19 mm in the axial direction and 0.23 mm in the elevation direction.

IV. IMAGING RESULTS

We use the classical phased array algorithm for image reconstruction. An in-house imaging code was developed to acquire, reconstruct and display the images of a commercially available phantom (Gammex 406 LE, Gammex, Inc., Middleton, WI) in real time up to a depth of 5 cm. The phantom comprises 0.1 mm diameter nylon wires surrounded by tissue mimicking gel. Finally, we present images of the human neck, more specifically, the jugular vein.

We also acquired the same images using a commercially available piezoelectric transducer array (Philips L7-4) for the sake of comparison of image quality. The L7-4 consists of 128 elements. However, to make the comparison fair, we activated only 64 elements. The commercial probe had a very similar pitch and center frequency as compared to the CMUT probe. We also used same imaging code for acquisition of the image.

Figure 6 illustrates the phantom images as acquired by both the CMUT probe as well as the commercial probe. The CMUT was biased at 50 V (40% of the collapse voltage) and a 40-V_{pp} pulse was applied to both probes for image acquisition. The images obtained from the CMUT probe (which is much smaller and more portable) are comparable to those obtained from the commercial probe. The resolutions in both images are similar. It is important to note that the pulse provided by the Verasonics system has a limited fractional bandwidth varying between 50-70% depending on the settings of the system. Therefore, the presented image resolution does not fully reflect the wide bandwidth of the CMUT probe. Figure 7 shows the neck images obtained using the CMUT probe acquired in real-time. At 30 frames per second, the pulsation of the vein was clearly observable.

V. CONCLUSIONS

We have developed a wearable ultrasound probe using CMUT technology. ICs were integrated with CMUTs on a flexible PCB to achieve better SNR. Real time images were acquired and showed comparable resolution to a commercially available piezoelectric transducer array, equivalent to the CMUT array in size and number of elements. Successful acquisition of real time images shows clear feasibility of development of such wearable probes for applications that require constant monitoring of organs or blood vessels.

Some of the future work includes replacing the long flexible cable with a coaxial cable bundle for better shielding. Improvement of the transmit pulse is also important to take

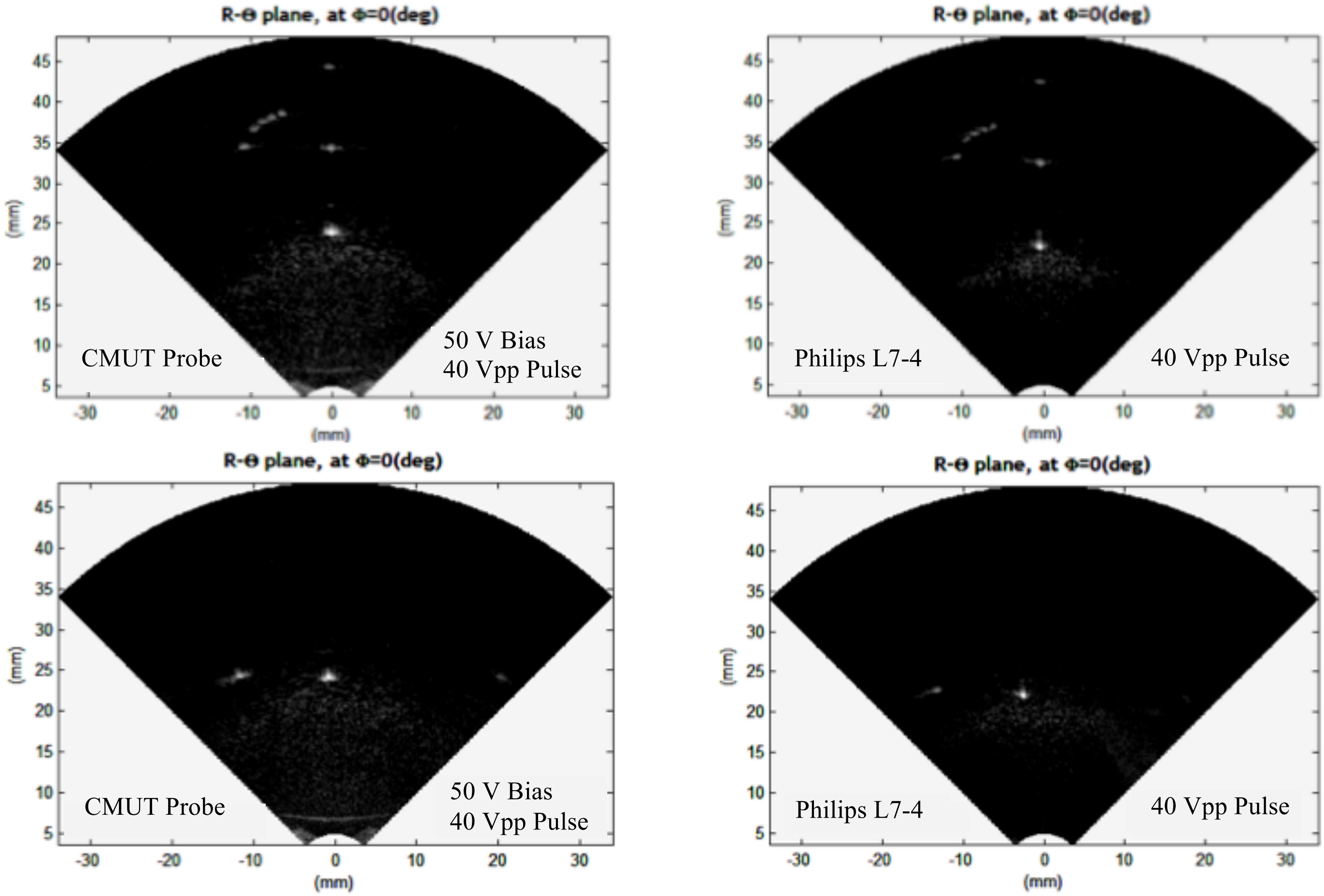

Figure 6. Images of nylon wires (Gammex 406LE) acquired by the CMUT probe (left) & a commercially available probe (right). Dynamic range: 40 dB.

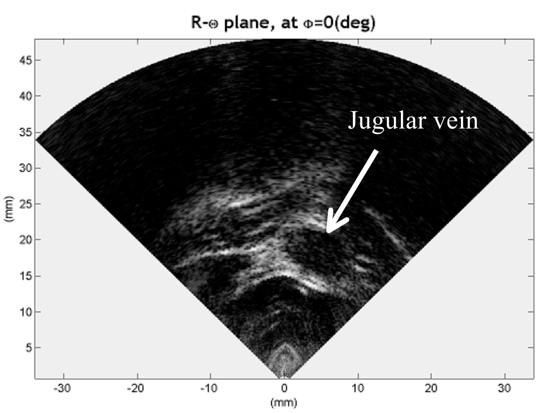

Figure 7. Neck images depicting the jugular vein

advantage of the wide bandwidth of the CMUT. Finally, miniaturization of the backend system would enable us to get a step closer towards making the entire system portable.

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