Progress in Development of HIFU CMUTs for use under MR-guidance

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Abstract. High intensity focused ultrasound (HIFU) guided by magnetic resonance imaging (MRI) is a noninvasive treatment that potentially reduces patient morbidity, lowers costs, and increases treatment accessibility. Traditionally, piezoelectric transducers are used for HIFU, but capacitive micromachined ultrasonic transducers (CMUTs) have many advantages, including fabrication flexibility, low loss, and efficient transmission. We designed, fabricated, and tested HIFU CMUTs for use under MRI guidance and have demonstrated continuous wave (CW) focusing. In this paper, we demonstrate that CMUTs can be designed for therapeutic ultrasound. First, we demonstrate successful unfocused heating of a HIFU phantom to 18.6°C, which was successfully monitored under MR guidance. Second, we demonstrated a focused CMUT array whose beam profile matched with simulation. In the future, we will expand the array and system for upper abdominal cancer therapy.

Keywords: MR-guided HIFU, CMUT.

INTRODUCTION

Minimally invasive, therapeutic ultrasound treatments of cancers have become popular in recent years because they reduce morbidity, mortality, and recovery time. Traditionally, piezoelectric transducers have been used for medical applications, but recently CMUTs have shown competitive advantages including the ease and flexibility in fabrication, integration with electronics, and competitive performance [1,2]. CMUTs are fabricated using silicon micro-machining methods that provide uniformity and sub-micron accuracy, so shapes and geometries can be optimized for performance.

In previous years, we presented finite element models (FEM) and optimization of the transducer array and CMUT membrane designs for external HIFU ablation of upper abdominal cancers [3]. Transducers were designed for low frequency operation from 1-4 MHz and surface output pressure of 1-2 MPa peak to peak. Based on FEM, we fabricated single-element test transducers and sub-costal annular arrays for ablation of liver cancers. These transducers were tested with special regard to high power CW operation. This year, we successfully demonstrated MR-temperature maps of the heating produced by an unfocused CMUT. With this successful demonstration, we continued to design, fabricate, and test a focused 8-element annular array for noninvasive HIFU therapy.

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CMUT MEMBRANE FABRICATION

Circular CMUTs cells with center frequency of 3 MHz and 1 MPa peak to peak output pressure, were patterned into 2.5 mm by 2.5 mm test transducers and 3 cm, 8-element, concentric ring arrays (Fig. 1). Cells were fabricated using the silicon wafer bonding process [4] that utilizes a low resistivity silicon membrane, which acts as the top electrode. The low resistivity silicon improves electrical contact resistance [5], series parasitic capacitance, and problems associated with electromigration [6].

CMUT designs for HIFU

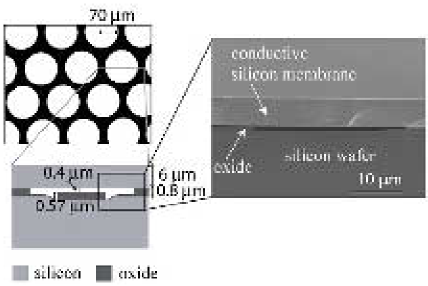

FIGURE 1. Simplified schematics and SEM images of the cross-section of part of a single CMUT cell.

EXPERIMENTAL SETUP

We measured the static and dynamic responses of the design before testing in noncontact heating situations. We mounted the test transducers on a printed circuit board (PCB) using silver epoxy and connected the pads with gold wire bonds. For dynamic response, such as frequency response as well as CW and tone-burst pressure measurements, the CMUTs were immersed in soybean oil, which provides electrical insulation and has acoustic properties like liver tissue [1]. A hydrophone (Onda Corporation, Sunnyvale, CA) was positioned 2 cm from the surface to measure the output pressure. The data was corrected for the hydrophone's frequency response [7] and sound attenuation and diffraction [8] to calculate the surface pressure. For dynamic response, DC biases were swept from 50-90% of the collapse voltage and a 2.5 MHz, 30-cycle burst with amplitudes from 0-300 Vpp was applied. Based on the pressures measured from these voltage sweeps, we chose to operate at a DC voltage that was 70% of the collapse voltage and an AC voltage of 250 Vpp.

We monitored heating from CW operation of a test transducer using a 3.0 T GE MRI scanner (Wakesha, WI). We placed the test CMUT on the bench top and isolated it electrically from a gel phantom by covering it with soybean oil and a sheet of polyethylene. An ultrasonic gel (MediChoice, Mechanicsville, VA) coupled sound into the HIFU phantom (Insightec, Haifu, Israel). The CMUT, which was matched to 50 Ω with an air-core inductor, was operated in CW mode for five minutes. The temperature in the phantom was measured in the sagittal plane using a fast gradient echo sequence with TR/TE (Repetition Time/Echo Time) of 28.7/19.1 seconds; one hundred images were captured over 12 minutes. Temperature change was detected by a shift in the proton resonance frequency and the change in phase. We calculated this phase changes by subtracting the phase images of successive frames [9].

Temperature Measurement Setup

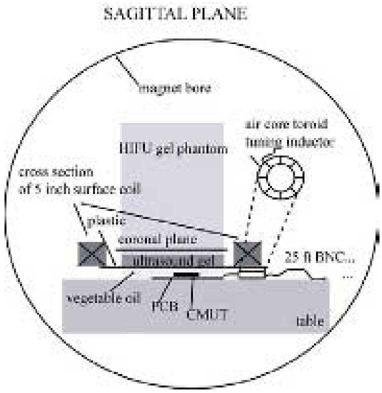

FIGURE 2. Schematic of the setup used to measure unfocused heating in a HIFU phantom.

Finally, the equal-area, concentric ring array was fabricated from the CMUT cells and driven by the focusing electronics. The electronics consisted of digital synthesizers and amplifiers with variable gain and phase. Only four channels were used to reduce the complexity of the electronics and also because of the yield of the array, as we will explain later. The phase was calculated for a focus at 35 mm from the transducer's surface. A hydrophone was then scanned in this plane to measure the beam profile and the results were compared to a simulation [10].

RESULTS AND DISCUSSION

We first measured the artefacts of the HIFU CMUT using the same MR sequence used to collect the temperature information. This artefact extended less than 1 mm into the phantom, which indicates that temperature measurements should be accurate and unaffected by the transducer even at distances very close to the transducer. An unfocused HIFU CMUT was then used to heat a HIFU phantom and monitored the temperature rise in the 3.0 T MRI scanner. We found that the transducer was 68% efficient and the phantom reached a maximum temperature change of 18.6°C over 5 min. (Fig. 3), which is adequate for HIFU applications [11].

With this success, we tested a larger focused transducer. The beam profile matches the expected profile calculated using Huygen's principle. The beam width is comparable, but the side lobe energy is increased because of the dispersive guided wave (Fig. 4). The agreement with the model is promising for further HIFU transducer development. However, the array design needs to be changed to improve the yield; because each ring was near 1 cm^2 in size, it was difficult to achieve a perfectly defect free area. To improve this, we will use a segmented 2-D array design, with switches in the backside electronics that remove the elements with defects.

HIFU heating by unfocused transducer

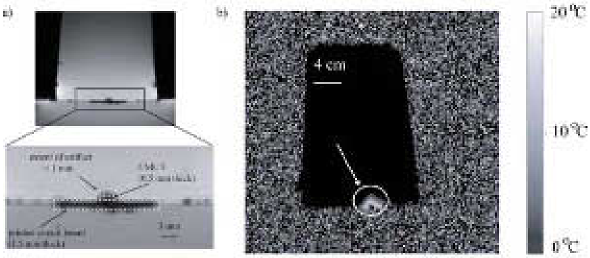

FIGURE 3. An unfocused CMUT demonstrated minimal artifact (a) in the MR scanner. MR temperature maps were able to monitor the unfocused heating a HIFU phantom (b).

Annular array beam profile

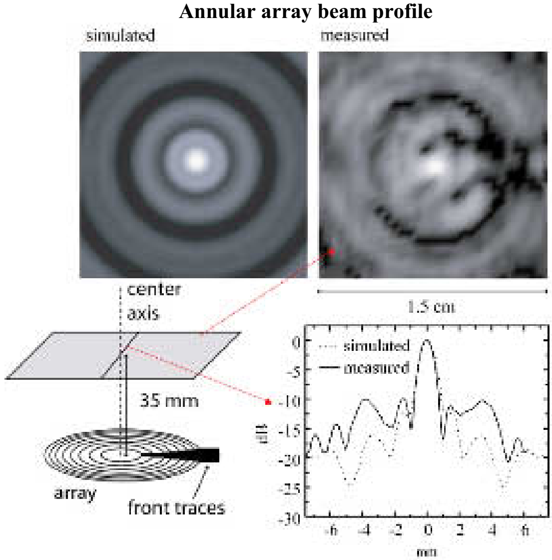

FIGURE 4. Comparison of simulated and measured beam profile.

CONCLUSION

CMUT membranes designed for non-invasive HIFU have been fabricated and tested. We have demonstrated MR temperature mapping of the therapy applied by an unfocused HIFU CMUT. Even an unfocused transducer was efficient enough to heat the phantom by 18.6°C in 5 min. With focusing, the heating will be faster and the treated region will be greater. We have also demonstrated focusing of 4-elements concentric ring array. In the future, we plan to build full-scale ring arrays that are more robust to small fabrication defects and demonstrate liver cancer ablation.

ACKNOWLEDGMENTS

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