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Reverberation reduction in capacitive micromachined ultrasonic transducers (CMUTs) by front-face reflectivity minimization

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Abstract

Front-face acoustic reflectivity of ultrasonic imaging transducers, due to acoustic impedance mismatch with the propagation medium, may cause reverberation phenomena during wideband pulse-echo operation. Front-face reflectivity may be reduced by promoting the transmission of the echoes, received from the medium, to the transducer backing, and by maximizing the mechanical-to-electrical energy conversion and dissipation by tuning the electrical load impedance connected to the transducer. In Capacitive Micromachined Ultrasonic Transducers (CMUTs), the energy transfer from the medium to the backing is very low due to the large impedance mismatch between the medium and the transducer substrate, typically made of silicon. Reverse Fabrication Process (RFP) makes it possible providing CMUTs with custom substrate materials, thus eliminating the original silicon microfabrication support. In this paper, we propose two methods for the front-face reflectivity reduction in RFP-CMUTs: the first one is based on the use of low-impedance, highly attenuating backing materials, and the second one is based on the maximization of the mechanoelectrical energy conversion and dissipation. We analyze the methods by finite element simulations and experimentally validate the obtained results by fabricating and characterizing single-element RFP-CMUTs provided with different backing materials and electrical loads.

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Keywords: Reverberation; Transducer reflectivity; Capacitive Micromachined Ultrasonic Transducer (CMUT); MEMS

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1. Introduction

During pulse-echo ultrasound imaging operation, the echoes generated by the investigated medium are partially reflected by the transducer surface, thus resulting in a second propagation of ultrasonic waves, which in turns generate a set of unwanted echoes. Such effect, often referred to as “multiple reflection reverberation”, may cause noise and, in some cases, significantly compromise the quality of ultrasound images; Scanalan (1991).

In piezoelectric transducers, the energy transfer from the medium to the backing is favored by the presence of typically employed matching layers between the piezoelectric material and the propagating medium; Nickel and Angelsen (1996). On the other hand, in Capacitive Micromachined Ultrasonic Transducers (CMUT), the same energy transfer is very low due to the large impedance mismatch between the medium and the transducer substrate, typically made of silicon. Ultrasound imaging with CMUT linear arrays has been extensively investigated, and transducer performance has been compared with equivalent state-of-the-art piezoelectric arrays; Mills and Smith (2003), Savoia et al. (2005), Legros et al. (2008), Savoia et al. (2011). Although the typical performance indexes, i.e., sensitivity, bandwidth, and element directivity, achievable with the two transducer technologies were shown to be comparable, most of the B-mode images obtained with CMUT arrays are in general characterized by a lower contrast. Reverse Fabrication Process (RFP) makes it possible to provide CMUTs with custom backing materials, thus eliminating the original silicon microfabrication support; Caliano et al. (2005), Bagolini et al. (2015).

In this paper, we analyze two methods for the front-face reflectivity reduction in RFP-CMUTs. The first method is based on the improvement of the energy transfer from the medium to the backing, by using low-impedance and highly attenuating backing materials. The second method is based on the maximization of the electromechanical energy conversion and dissipation using a high biasing voltage and a conveniently chosen resistive electrical load.

2. Methods

2.1. Modeling

In order to evaluate the effectiveness of the proposed methods for the reduction of reflectivity, we made a finite element simulation of a CMUT using the software Ansys (Ansys Inc., Canonsburg, PA). The behavior of an infinite periodic circular cell layout supported by a backing and coupled to a propagation medium, was modeled using an axisymmetric 2-D model, widely used in the literature. We carried out time-domain pulse-echo simulations in order to evaluate the effect of the front-face reflectivity. By exciting the biased transducer with a broadband raised cosine pulse, we observed the voltage between the electrodes and isolated the first two echo signals (v_1 and v_2). We then defined and computed the Reverberation Level Coefficient (RL), i.e, the ratio between the spectra of the second and first echo signals, in order to quantify the effect of the front-face reflectivity on the transduced voltage, actually used for image formation: $RL = V_2/V_1$. We performed a first set of simulations in order to study the effect of different backing materials on the CMUT front-face reflectivity. In the simulations, the electrical port of the CMUT was set to open circuit, thus simulating high-impedance voltage readout condition, and the specific acoustic impedance of the backing material was varied from 20 MRayl (crystalline silicon) to 1.48 MRayl (water) including different intermediate cases. We then carried out a second set of simulations by clamping the CMUT base, thus simulating an infinite backing impedance, and by varying the bias voltage and the electrical load resistance. The bias voltage, normalized to the collapse voltage, was increased from 0.6 to 0.98, while the load resistance was varied from 200 kΩ/cell to 1.6 MΩ/cell.

2.2. Experiments

We experimentally investigate the reflectivity reduction methods by performing water coupled pulse-echo measurements using single-element RFP-CMUTs specifically provided with different backings and electrical loads. The single-element CMUT transducers were originally fabricated as test devices using the same process parameters of a CMUT array for biometric ultrasound imaging: Caliano et al. (2010), Lamberti et al. (2011). In this paper, we used three different composite materials, each characterized by its specific acoustic impedance, for the fabrication of the backings. The three composite materials share the same matrix (epoxy resin) and their specific acoustic impedance is increased by filling the matrix with tungsten and/or alumina powders. Fig. 1(a) summarizes the characteristics of the backing materials used. We assembled three single-element RFP CMUTs featuring a circular active area with a 3.5-mm diameter composed by 11244 circular cells and designed to operate at a centre frequency of 12 MHz with a 100% -6-dB two-way fractional bandwidth [Fig. 1(b)].

(a) Backing characteristics.

Backing Compound	Specific Acoustic Impedance [MRayl]
1) Epoxy + Al_2O_3 + W	7.3
2) Epoxy + Al_2O_3	4.9
3) Epoxy	3.3

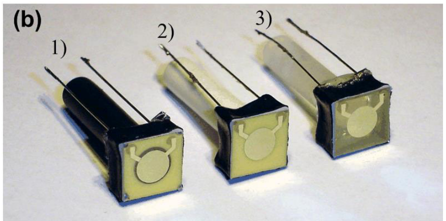

Fig. 1. (a) characteristics of the backing materials; (b) assembled single-element CMUT prototypes.

3. Results

Fig. 2 shows the simulated and measured RL for different backing configurations. As the backing impedance is decreased, a reduction of the front-face reflectivity is observed, more significantly far from the resonance frequency. In fact, near the resonance frequency, the mechanical impedance at the front-face is dominated by the very low mechanical impedance of the CMUT. A very good agreement between the experimental results and the subset of simulations corresponding to the values of the backing impedance closest to those of the fabricated prototypes, i.e., 8 MRayl, 5 MRayl, and 3 MRayl, is evident.

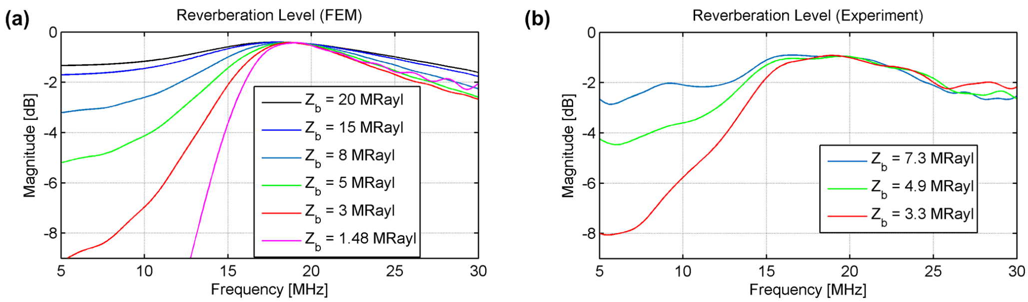

Fig. 2. (a) Simulated and (b) measured RL for different values of the backing specific acoustic impedance.

Fig 3 reports the simulated and measured RL for different bias voltages using the optimal resistance value of 800 kΩ/cell. The experiments were carried out using the 7.3 MRayl backing. Both the simulations and experiments show that the maximum reduction of the front-face reflectivity is achieved near the resonance frequency, where the mechanical impedance at the front-face is in this case dominated by the contribution of the resistive load. The simulation results show that a RL of -10 dB is obtainable with a normalized bias voltage of 0.98. However, since in the experiments the maximum stable normalized bias voltage applicable to the CMUT prototype was 0.94, the experimentally observed RL was -4.8 dB. Furthermore, this value resulted to be less than the simulated value of -6.2 dB, possibly due to the presence of electrical parasitic components in the measurement set-up that were not included in the simulations.

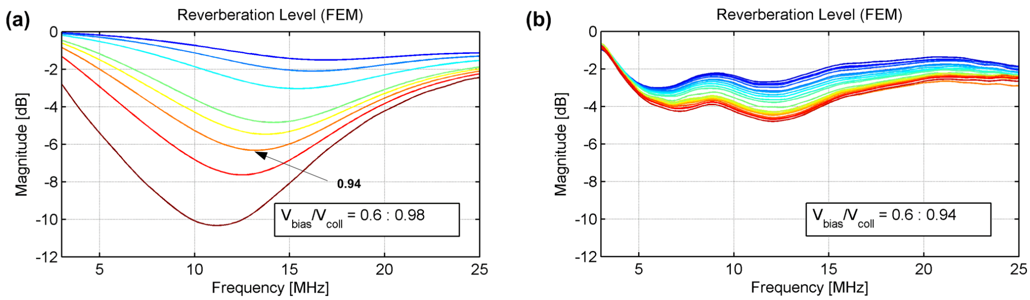

Fig. 3. (a) Simulated and (b) measured RL for different values of the bias voltage and fixed load resistance.

4. Discussion and conclusion

In this paper, we have carried out a preliminary investigation of the CMUT front-face reflectivity, which is potentially responsible of reverberation artifacts in medical imaging applications. We propose and analyze two methods for the minimization of the front-face reflectivity. The first method consists in the improvement of the energy transfer into the backing, by lowering the backing material specific acoustic impedance. The second method relies on the maximization of the mechanoelectrical conversion by operating at high bias voltages and on the dissipation of the converted energy on a resistive electrical load. The two methods were analysed using FEM; experimental validation was carried out using single-element RFP-CMUTs. The first method resulted to be efficiently implementable by using composite materials compatible with the fabrication of RFP-CMUTs. Although in theory more efficient, the second method resulted to be more difficult to practically implement, due to the difficulty of stably biasing the CMUT very close to the collapse. Future work will focus on the evaluation of the proposed methods combined with the use of lossy materials, typically employed on the transducer front-face for fixed beam focusing, and on the assessment of the ultrasound imaging quality improvement.

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