MEMS RESONATOR MATCHING NETWORK FOR HIGH-SENSITIVITY SCALN PMUT-BASED ULTRASOUND RECEIVERS

Bernard Herrera Soukup, Pietro Simeoni, Gabriel Giribaldi, Luca Colombo, and Matteo Rinaldi
Northeastern University, USA

ABSTRACT

In this work, we demonstrate the concept of utilizing MEMS Resonator Matching Networks (MRMNs) to increase the sensitivity of an array of piezoelectric micromachined ultrasonic transducers (PMUTs) used in receive mode. The inductive region of the impedance of the MRMNs is set by the center frequency of a MEMS resonator, and it is independent from the resonance frequency of the PMUTs. We use a 20x20 array of 36% doped scandium-aluminum nitride (ScAlN) PMUTs electrically connected in parallel. The array is interfaced with 4 different resonators operating between 400 kHz and 600 kHz, allowing for a significant boost, at arbitrary frequencies, outside of the natural band of the PMUTs in fluid. We report out-of-band gains of up to 10, higher that the quality factor of the PMUTs (Q=3), thus pointing to the possibility of using MRMNs to enable ultrasound receivers with reconfigurable frequency bands.

KEYWORDS

PMUT, Ultrasound, Scandium, MRMN, Reconfigurable

INTRODUCTION

With the unfolding of the vision of the Internet of Things (IoT), the variety of possible computing nodes consistently expands as engineers design them for increasingly specialized functions. A significant subset of these nodes takes advantage of ultrasound for sensing and communication. During the last decade piezoelectric micromachined ultrasound transducers (PMUTs) have drawn significant attention from the research community and have started to see substantial adoption in the commercial realm for applications such as fingerprint authentication, time-of-flight range sensing, imaging, and more [1].

For all these applications, increasing the system sensitivity to incident ultrasound is an important requirement to keep pushing the performance of the computing nodes in terms of size, working range, and power consumption, which will ultimately translate in lower costs and will enable novel applications.

Flexural resonators, such as pMUTs, are characterized by low k_t^2, which means that they have relatively poor conversion capabilities between mechanical and electrical energy. When incident ultrasound bends the pMUT, it generates a voltage across the device electrodes by inducing a charge polarization through the piezoelectric effect. However, the output voltage that can be measured remains limited as most of the incident energy is stored in the transducer's capacitance in the form of reactive power.

The classic approach used to recover the reactive power has been to interface the transducers with inductor-based matching networks (MN). A drawback of this approach is that, at low frequencies, inductors tend to be bulky and are characterized by poor quality factors (Q<10), limiting their efficacy. In recent years, the concept of MEMS Resonator Matching Networks (MRMNs) has been demonstrated in RF wake-up receivers [2], [3]. The inductive region of mechanical resonators is utilized to cancel out the reactance of a capacitive load, while taking advantage of their compact form factor and extremely reduced losses (Q>1000).

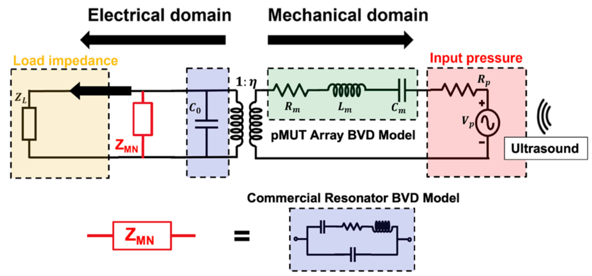

Figure 1: Equivalent circuit of a PMUT-based ultrasound receiver using a mechanical resonator as matching network.

In a first demonstration [4], the same concept was validated with pMUTs, where it was shown that MRMNs can passively amplify the actuation voltage applied on the ultrasound transducers with significantly higher gains than MNs based on inductors. In this work, we propose to use a similar approach in the domain of ultrasound receivers (Fig. 1).

To demonstrate the concept, a 20x20 array of 36% scandium-doped aluminum nitride (ScAlN) pMUTs was fabricated (Fig 2). The PMUTs have a radius of 46 µm, a silicon oxide elastic layer of 1 µm, and a piezoelectric layer of 0.5 µm sandwiched between 200 nm thick electrodes. The array was then interfaced with commercially available resonators to demonstrate their sensitivity-boosting effect.

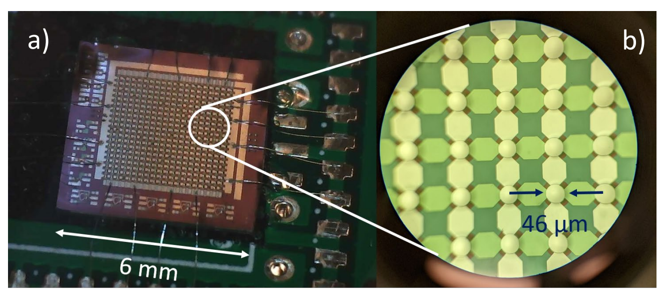

Figure 2. Optical microscope images of the 20x20 $Sc_{0.36}Al_{0.64}N$ PMUT Array. a) Overview of the chip, wire-bonded to a PCB for testing purposes and covered in PDMS for both electrical insulation and mechanical protection. b) Detail of the individual PMUT elements connected in parallel.

METHODOLOGY

The receiving sensitivity of the PMUTs to ultrasound in water was measured by immersing the array in a tank as shown in Fig. 3a. The incident ultrasonic wave was generated through a broadband, commercially available hydrophone (Teledyne TC 4038-4). The actuation frequency was swept over a frequency range between 0 and 2 MHz to extract the standalone array frequency response as shown in Fig. 4. The resonance of the pMUTs was at 700 kHz and showed a peak response of approximately 10 mV with a quality factor (Q) of ~3.

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Next, the array was interfaced with different MRMNs implemented with commercial resonators (Fig. 3b) with frequencies of operation between 400 and 600 kHz. As shown in Fig. 1, the resonator is connected in parallel to the array electrodes. In this way, when the resonator operates in its inductive region, it will cancel out the reactive impedance introduced by the array's electrical capacitance. The frequency sweep is then repeated to observe how the system's response changes with respect to the standalone array case.

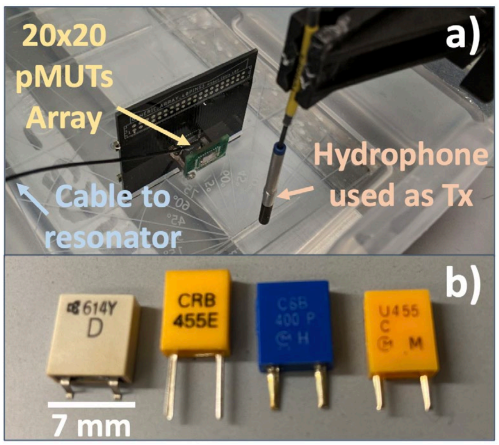

Figure 3. a) Experimental setup used to measure the pMUT array electrical output. b) Commercial resonators used to implement the MRMN.

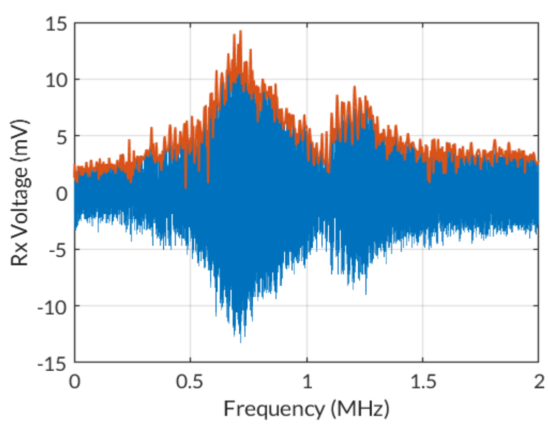

Figure 4. Time-domain frequency sweep pMUT array output voltage and voltage envelope when no MRMN is connected to the transducers.

To verify the voltage gain observed in the frequency sweeps, time-domain, burst measurements were performed for the standalone PMUT array case as well as for each of the PMUT array – MRMN systems. Burst signals, of the same amplitude but with a frequency corresponding to the frequency of maximum gain for each case, were applied to the Tx hydrophone and the Rx voltage on the PMUT array was measured. The number of cycles in the burst was varied in order to allow for the steady state response to be reached, after the particular rise time of each case.

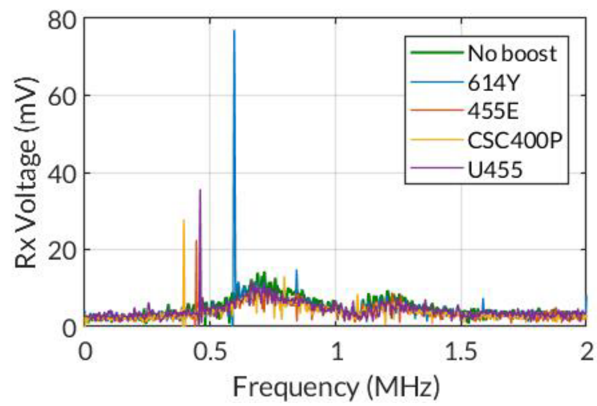

Figure 5. Frequency response of the array when interfaced with the resonators.

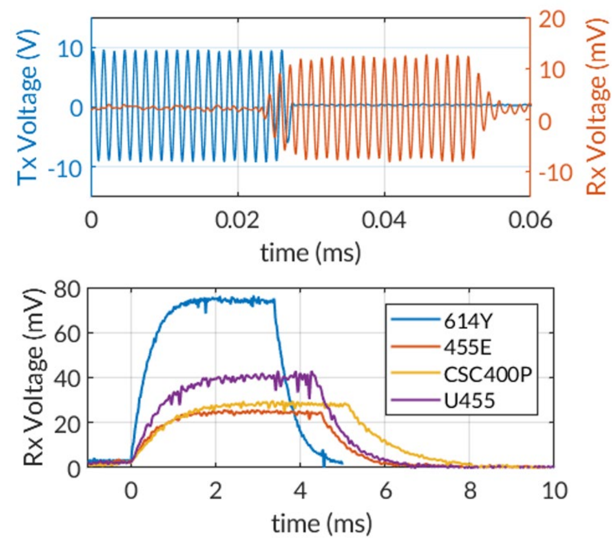

Figure 6. Time-domain, burst response measurements. Top: Standalone PMUT array case. Bottom: Envelope of the PMUT array – MRMN systems' output voltage.

RESULTS

As shown in Fig. 5, each configuration reproduces the response of the standalone PMUTs array, except for a passive sensitivity boost of up to 10 times when the receiver operates in the MRMNs inductive region. The narrow-band, high amplitude peaks are a result of the high quality factor resulting from the addition on the MRMNs.

The time-domain measurements in fig. 6 confirm the measured gains from the frequency sweeps. The different amplitudes of the envelopes in fig. 6 correspond to the different achieved gains, while the varying rise times are a consequence of the different quality factors of each of the resulting PMUT-MRMN systems. The longer rise and fall times observed on the cases with MRMNs, compared to the standalone array, show the trade-off of data rate (bandwidth) for voltage gain from another perspective.

To model the sensitivity boosting mechanism, the admittance response of the mechanical resonators was measured using a Vector Network Analyzer and were then fitted, with modified Butterworth-Van dyke (mBVD) parameters, to reproduce the observed data in circuit simulations performed in Advanced Design System (ADS). The resonators' parameters are shown in Table 1.

The relevant circuit parameters for modeling the PMUT array in the simulation were obtained by using an analytical model that relates the PMUT geometry (radius, thicknesses in the material stack) and material properties (density, piezoelectric coefficient, residual stress) to the equivalent lumped parameters [5]. The static capacitance of the array was obtained from a VNA admittance frequency sweep.

For an individual PMUT the following equivalent circuit parameters in the mechanical domain were extracted: equivalent stiffness of 1560 N/m, equivalent mass of 64×10^{-12} kg, transduction coefficient of 9.4×10^{-6} N/V, and an electrical capacitance of 2 pF. It is important to note that the parameters were calculated including the effect of operation in fluid (mass loading and radiation resistance in water).

Table 1: Equivalent circuit parameters obtained from fitting the mBVD model on VNA Y-parameters measurements taken on the individual resonators.

Model	**C_0 [pF]**	**f_s [kHz]**	**Q**	**k_t^2 [%]**
614Y	190	587	1590	14.5
455E	277	440	1614	10.7
400P	300	391	3387	6.6
U455	302	455	1826	8.2

ADS simulations, implementing the network shown in fig. 1, show that the expected amplification for all resonators is expected to be approximately 9.3 times the electrical output of the standalone PMUTs array. Fig. 7 shows the experimental gain that was observed on each resonator. It must be noted that, for the calculation of the gain, the amplitude at the peak for the boosted case is divided by the amplitude of the standalone response at that frequency. Therefore, even though the peak amplitude for resonator 614Y is larger than for the others, after dividing for the also larger standalone amplitude at the resonant band of the PMUTs, the gain results in a similar value. The only outlier is resonator 455E that does not closely match the simulation. This could be explained by parasitics from the soldering used when connecting the transducer.

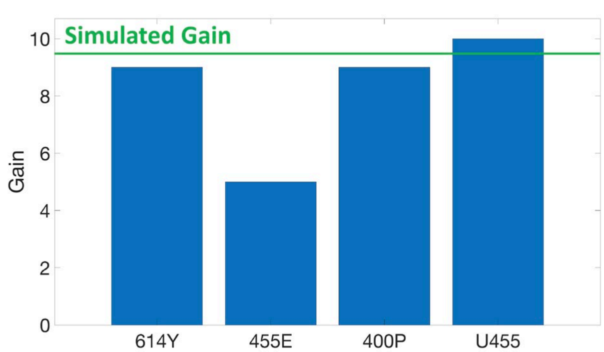

Figure 7. Equivalent circuit simulation gain compared to measured response. All the extracted parameters across different resonators delivered very similar system gain in simulation.

DISCUSSION AND CONCLUSIONS

Based on this analysis, our intuition was confirmed that the high-impedance mechanical branch of the pMUTs plays a negligible role in the matching process, and the optimal matching point between a capacitive load and an MRMN is based on the relative values of the load and resonator capacitances as analytically derived in [3].

This work offers exciting prospects for ultrasonic communication as it shows that the standalone response of the PMUTs does not dominate the receiver sensitivity even when the MRMN is centered out of band. For example, it is theoretically possible to integrate multiple resonators with the PMUT array and design a circuit to multiplex which frequency we desire use to communicate.

The high quality factor of the MRMNs limits the available bandwidth for each frequency. However, in use-cases that involve a large number of sensing nodes that need to transmit small amounts of data, bands of a few kHz are sufficient. We note that a similar switching mechanism could be used to connect a single MRMN to different series resistances to modulate the resonator quality factor. Such mechanism would add an additional degree of freedom to modulate the quality factor of the resonator, thereby trading off sensitivity (range) for bandwidth (data rate). Similarly, if the resonant frequency of the resonator could be tuned, different frequencies of operation could be attained with a single resonator without the need of altering the circuit connections.

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CONTACT

Bernard Herrera: herrerasoukup.b@northeastern.edu