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Evaluating the Influence of PMUT Mechanical Support Properties on Power Conversion Efficiency in Ultrasonically Powered Implants

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***Abstract*— Micromachined Ultrasonic Transducers (MUTs) are being explored as power converters in wirelessly powered biomedical implants. This paper investigates the role of mechanical support properties in piezoelectric MUTs (PMUTs) on their power conversion efficiency. For this purpose, a finite element model (FEM) of a PMUT array was developed and integrated with an equivalent circuit model (ECM). The study considered different mechanical support scenarios, from rigidly clamped to completely free. These were numerically analyzed and validated by impedance measurements and acoustic power transfer experiments on PMUT prototypes. The results show that reducing the mass of the mechanical support increases the Q factor, leading to a significant improvement in power conversion efficiency, with an efficiency increase factor of 5.6x from the clamped to the free case. This approach can potentially enhance overall power conversion efficiency, reduce the need for matching networks, and enable miniaturization in ultrasonically powered implants.**

Keywords—PMUT, Ultrasonic MEMS, PZT, Ultrasonic Powering, Biomedical Implants, Power Transfer.

I. INTRODUCTION

Micromachined ultrasonic transducers (MUTs) have recently gained significant attention as power converters for ultrasonically powered implants in biomedical applications. Compared to traditional piezoelectric transducers, MUTs offer primary advantages in miniaturization and electronic integration, along with reduced or no lead content. Typical MUT designs operating in the frequency range suitable for ultrasonic power transfer (from hundreds of kHz to a few MHz) exhibit significantly low mechanical Q factors in immersion. Combined with the relatively low electro-mechanical coupling factors, this characteristic hampers efficiency. In this context, several MUT technologies, such as Scandium-doped Aluminum Nitride Piezoelectric MUTs (PMUTs) [1] and pre-charged Capacitive MUTs (CMUTs) [2], have been investigated. These investigations highlighted that matching networks, which rely mainly on inductors, are essential to achieve a competitive power conversion efficiency, which poses a challenge for further miniaturization [3]. In this paper, we investigated the impact of the mechanical support properties of PMUTs on the Q factor and explored potential improvements in power conversion efficiency. We numerically analyzed the power conversion performance of a PMUT loaded with a purely resistive matched load, covering a range of mechanical supporting conditions, from rigidly clamped to completely free, and quantified the resulting increase in Q factor and subsequent efficiency improvement. We validated the numerical results through impedance measurements and acoustic power transfer experiments on PMUT prototypes, each provided with a dedicated package to reproduce different simulated mechanical supporting conditions.

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II. MATERIALS AND METHODS

A. Modeling

We implemented a finite element model (FEM) of a spatially periodic, 2D-axisymmetric [4] PMUT cell coupled to an infinite propagation medium, such as water, as schematically shown in Fig. 1. The PMUT FEM included a silicon substrate that is back-etched to define the cavities and mechanically supported by a backing. Using a previously established procedure [5], we extracted the lumped-element parameters from the FEM results to be used in the Equivalent Circuit Model (ECM) of Fig. 2. The ECM is based on Mason's electro-mechanical circuit, which

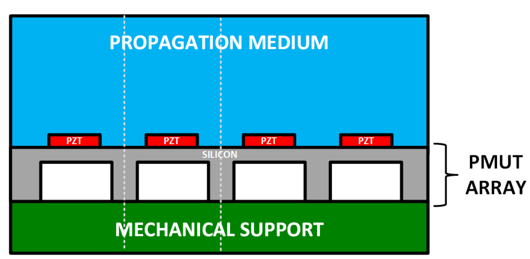


Fig. 1. Schematic cross section of a PZT PMUT array coupled to the propagation medium and mechanically supported by a backing. The PMUT plates are suspended over cavities (white) defined by etching the silicon substrate from the wafer's backside.

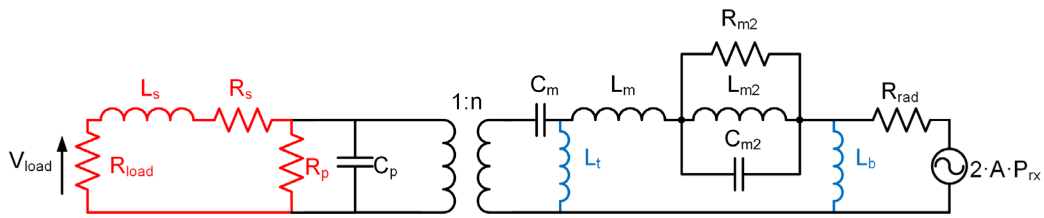


Fig. 2. Equivalent Circuit Model of the PMUT in receive: the elements in black compose the Mason's electro-mechanical circuit; the elements in red represent the electrical load including the parasitic elements; the two shunt inductors included in the mechanical side in blue are mass terms used to account for the mechanical support properties.

comprises C_p, C_m, L_m and the transformer (represented with the turns ratio $1{:}n$). On the mechanical side, the circuit is loaded with the $L_{m2}||R_{m2}||C_{m2}$ tank, representing the second-order vibration mode, in series with the radiation resistance, R_{rad}. On the electrical side, the circuit is connected to a resistive load, R_{load}. L_s, R_s, and R_p account for parasitic effects due to electrical interconnections and losses in the piezoelectric material. The investigated mechanical support properties were accounted for by incorporating two shunt inductors, L_t and L_b. L_t models the effect of the finite mass of the mechanical support [6] on the PMUT plate edge boundary condition, while L_b represents the effective mass of the fluid that loads the PMUT when it is not in a fully-rigid baffle condition. The FEM-ECM integrated model was implemented using ANSYS (Ansys Inc., Canonsburg, PA, USA) and LTSpice (Analog Devices, Norwood, MI, USA).

We applied the described approach to model a sol-gel PZT-based PMUT array designed for power conversion in immersion around 1 MHz. The PMUT array featured 12 hexagonally tiled elements, each comprising 19 circular plates suspended over 190 µm-diameter cavities, for a total active area of 8.54 mm^2. The cavities were created by etching the backside of the silicon microfabrication wafer that had been pre-thinned to a thickness of 200 µm. The PZT and the silicon plate thicknesses were 2 µm and 4 µm, respectively. We compared four supporting conditions to analyze the mechanical support influence on power conversion performance. These included two ideal opposite conditions: clamped and free. Additionally, we studied two intermediate conditions: quasi-rigidly clamped and weakly supported. We implemented these intermediate conditions by modeling the mechanical support as a 200µm-thick backing layer with different densities. We achieved the quasi-rigidly clamped condition by assigning stainless steel's density (7800 kg/m^3) and the weakly supported condition by assigning Mylar's density (1400 kg/m^3) to the material properties of the modeled backing.

For each mechanical support scenario, we first conducted transmit (TX) small-signal simulations to calculate the electrical impedance Z of the immersed PMUT without any parasitic elements. From this, we calculated the optimal resistive load, R_{load}, which, for purely resistive matching, should match the impedance magnitude at the frequency where the phase angle Φ is minimum. Using the computed R_{load}, we performed receive (RX) small-signal simulations by applying a uniform pressure on the immersed PMUT surface. We assessed the RX voltage V_{load} across R_{load}, the electrical power W_{load} dissipated on R_{load}, and the power conversion efficiency η, which we defined as the ratio of W_{load} to $W_{acoustic}$, i.e., the RX acoustic intensity I_{rx} multiplied by the PMUT active area A:

$$W_{load} = \frac{V_{load}^2}{2\,R_{load}} \tag{1}$$

$$W_{acoustic} = I_{rx}\,A = \frac{A\,P_{rx}^2}{2\,Z_a} \tag{2}$$

$$\eta = \frac{W_{load}}{W_{acoustic}} \tag{3}$$

In (1) and (2), V_{load} is the voltage amplitude, P_{rx} is the pressure amplitude at the PMUT surface, and Z_a is the characteristic impedance of the medium.

B. Packaging

To validate the model, we used a 1 MHz, 12-element 2-D PMUT array fabricated using a PZT thin-film-based PMUT technology by STMicroelectronics [5], and packaged [6] as schematically described in Fig. 3(a). The PMUT array was electrically connected to a rigid-flex PCB using wire bonding and glob top encapsulation, as shown in Fig. 3(b). The front of the PMUT die was encapsulated using a 500 µm-thick layer of 1.3 MRayl silicone rubber (Nusil Technologies LLC, Carpinteria, CA). A thin backing was attached to the back of the PMUT die. Fig. 3(c) and (d) show detailed perspectives of both the front and the back of a packaged PMUT array prototype, respectively. We developed and characterized two prototypes to compare with the simulated intermediate mechanical supporting

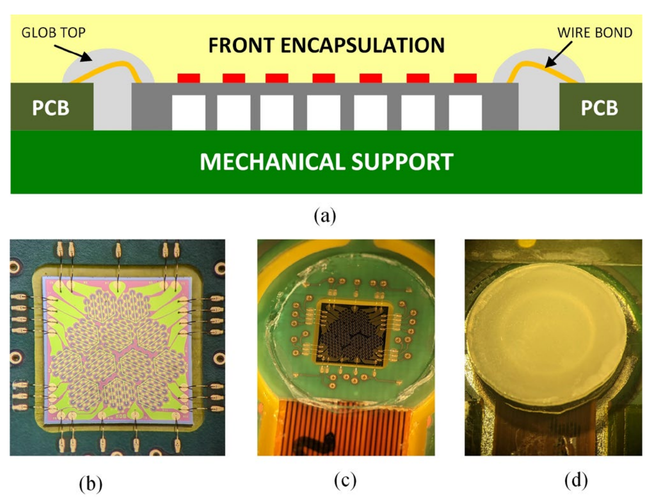


Fig. 3. Packaging of the PMUT arrays: schematic diagram of the package (a); the array elements are electrically connected to a rigid-flex PCB via wire bonding (b); front encapsulation (c) and backing (d).

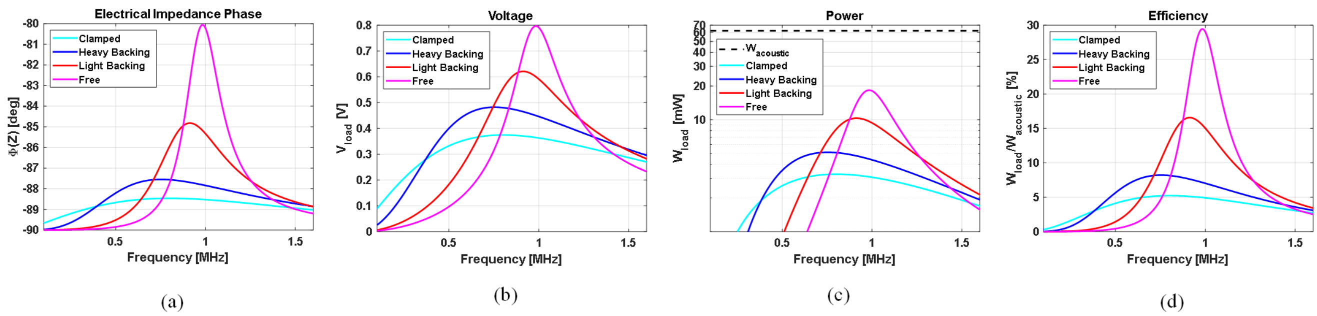


Fig. 4. TX and RX simulated quantities plotted as a function of frequency for the four mechanical supporting scenarios without parasitic elements: electrical impedance phase Φ (a), voltage V_{load} across the optimal load R_{load} (b), electrical power W_{load} dissipated on R_{load} (c), and power conversion efficiency η (d) computed as the ratio of W_{load} to the acoustic power $W_{acoustic}$ at the PMUT surface.

conditions: the first backed with a 200 µm-thick stainless-steel plate and the second with a 200 µm-thick Mylar sheet. The simulations and characterization results below refer to these as "Heavy Backing" and "Light Backing," respectively.

C. Experiments

We characterized the two PMUT arrays by measuring the electrical impedance of all 12 elements connected in parallel using a HP4194A (Hewlett-Packard Inc., Palo Alto, CA, USA) impedance analyzer. Using the resulting data, we fitted the ECM parameters following the approach described in [8], which allowed us to estimate parasitic parameters accurately. We then compared the measured impedance of the two PMUT arrays with the simulated impedance for the Heavy Backing and Light Backing cases, including the parasitic parameters, to assess the Q factor improvement and indirectly estimate the power conversion efficiency improvement. Successively, we computed the optimum R_{load} for the two cases and conducted acoustic power transfer experiments in a water tank setup. We used a 2.25 MHz, 12.5mm-diameter circular piston transducer (V306, Olympus NDT, Waltham, Massachusetts, USA) as a transmitting transducer and the PMUT arrays as receiving transducers. The piston transducer and the PMUT were placed at a distance of 30 mm and accurately aligned. The transmitting transducer was driven using a 10-cycle, 16 V, 830 kHz sine burst using a HP8116A (Hewlett-Packard Inc., Palo Alto, CA, USA) pulse generator. The voltage across the PMUT was acquired using a high input impedance voltage buffer. A 100 Ω precision potentiometer was connected to the PMUT to gradually vary the resistive load in the 4 – 40 Ω range with a 2 Ω step. The RX voltage signals were acquired and used to compute the power dissipated on the load.

III. Results

Fig. 4 shows the simulation results for the four mechanical support scenarios considered. As can be seen from the phase curves in Fig. 4(a), the Q factor increases as the mass of the mechanical support decreases, ranging from infinite (in the clamped case) to the actual mass of the PMUT's silicon microfabrication substrate. This increase in the Q factor corresponds to a decrease in the minimum phase angle and an increase in the voltage amplitude across the optimum resistive load resulting in improved power conversion and, consequently, higher efficiency. Table 1 shows the most relevant parameters. Notably, the efficiency increased by a factor of 5.6x when moving from the ideal Clamped to the ideal Free case, while the efficiency doubled when comparing the Light Backing to the Heavy Backing case.

TABLE I. Simulation Results

PMUT Mechanical Supporting Condition	Parameters[a]				
	f_r [kHz]	$\Phi(f_r)$ [deg]	R_{load} [Ω]	W_{load} [mW]	η [%]
Clamped	799.6	-88.46	21.5	3.26	5.22
Heavy Backing	753.1	-87.54	22.7	5.12	8.22
Light Backing	912.8	-84.84	18.6	10.33	16.56
Free	982.4	-80.0	17.2	18.36	29.44

a. Computed assuming no parasitics and I_{rx}=730 mW/cm^2, Z_a=1.48 MRayl, P_{rx}=147 kPa, A=8.54 mm^2

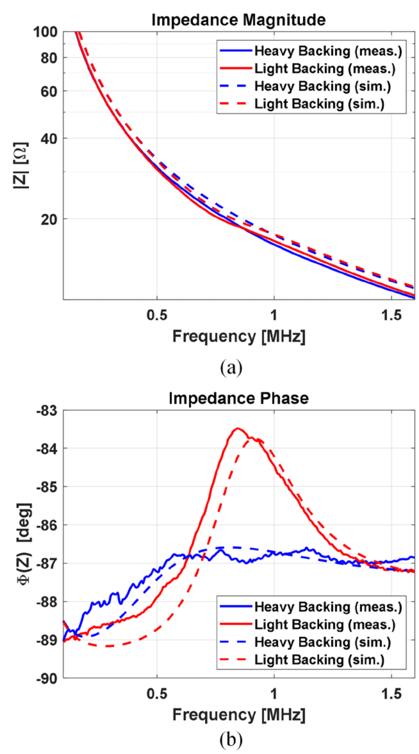
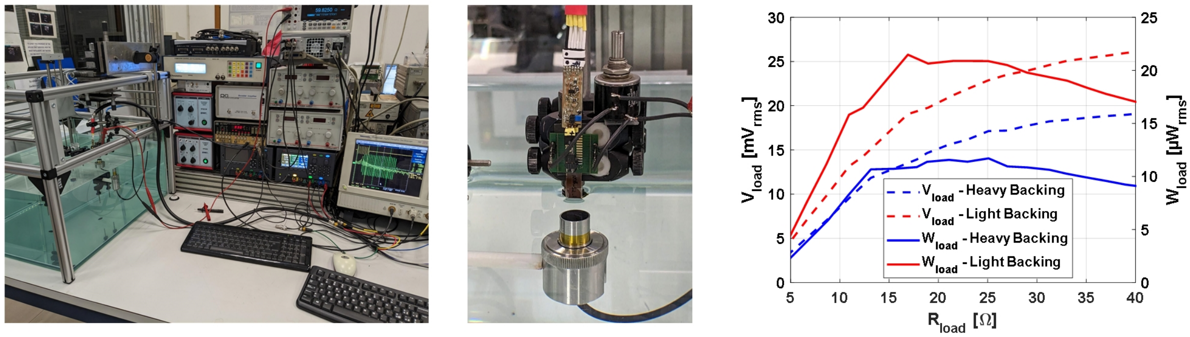


Fig. 5. Measured (solid) and simulated (dashed) impedance magnitude (a) and phase (b) for the Heavy Backing (blue) and Light Backing (red) cases.



(a) (b) (c)

Fig. 6. Acoustic power transfer experimental setup (a) and (b) and results (c): the transmitting transducer is immersed facing upwards towards the PMUT surface (b); a potentiometer (b) is used to vary the resistive load R_{load} connected across the PMUT electrode; rms voltage V_{load} and power W_{load} as a function of R_{load} (c).

Fig. 5 shows the measured electrical impedance results for the two PMUT arrays compared with the simulated impedance for the Heavy Backing and Light Backing cases, including parasitic elements. The simulated and measured data show close agreement. Calculations for these two scenarios, considering the presence of parasitic elements such as a series resistance R_s of 150 mΩ, a series inductance L_s of 5.2 nH, and a parallel resistance R_p of 7 kΩ, resulted in efficiencies of 8.11 % and 16.50 % for the Heavy Backing and Free Backing cases, respectively. This indicates that the influence of the parasitic elements can be considered negligible in this context. Finally, the results of the acoustic power transfer measurements are shown in Fig. 6(c), which shows the RMS voltage V_{load} and the power W_{load} dissipated on R_{load} as a function of R_{load}. The peak in W_{load} corresponds to values of R_{load} that are close to the optimal values listed in Table 1. Furthermore, the maximum W_{load} is double in the Light Backing case compared to the Heavy Backing case, confirming the expected doubling of efficiency derived from the simulations.

IV. Discussion and Conclusion

This work focused on understanding the influence of mechanical support properties on the efficiency of PMUTs for power conversion. The proposed modeling approach using FEM and ECM provided a comprehensive view of the PMUT structure behavior, further validated by experiments. The results suggest a direct correlation between the mechanical supporting condition and the Q factor. Specifically, reducing the mechanical support mass significantly increased the Q factor, improving power conversion efficiency without matching networks. The results showed a significant efficiency increase of 5.6x from the ideal clamped case to the ideal free case, indicating the considerable impact of the mechanical supporting condition. A twofold increase in efficiency was demonstrated and experimentally validated with realistic mechanical supporting configurations implemented through the application of backings with different masses.

Lastly, it should be emphasized that in relation to its mass, the microfabrication substrate also plays a significant role in determining the mechanical support condition. As observed in the case of the PMUT used in this study, the thinning of the substrate to 200 μm and the presence of cavities throughout the entire substrate contributes to a reduction in mass compared to other MUT cavity microfabrication approaches. This subsequently leads to an increase in the Q factor, which is beneficial in terms of power conversion efficiency.

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