Electrode Optimization for Multi-Channel Piezoelectric Micromachined Ultrasonic Transducers

Teng Zhang, Ashwin A. Seshia
Department of Engineering, University of Cambridge, Cambridge, UK

***Abstract*—This paper reports on a piezoelectric micromachined ultrasonic transducer (PMUT) featuring a multi-electrode design optimized for multi-channel acoustic data and power telemetry. Building on insights from a prototype PMUT designed in prior research, this study systematically reevaluates the mode selection and electrode configuration to minimize intermodal interference encountered when multiple modes are simultaneously activated. The redesigned PMUT integrates simultaneous interrogation of an axisymmetric mode at 950 kHz with an asymmetric mode at 4.28 MHz, enabling efficient 2-channel operation suitable for applications in wireless power transfer and data telemetry. Experimental results validated that the optimized electrode configuration offers improvements in data rate, data quality, and power output, demonstrating the efficacy of the design approach for suitable multi-channel applications.**

Keywords— Piezoelectric micromachined ultrasonic transducer (PMUT), multi-frequency operation, wireless power transfer, data telemetry, electrode optimization.

I. Introduction

Recent advancements in miniaturization of ultrasound transducers, particularly Piezoelectric Micromachined Ultrasound Transducers (PMUTs), have led to significant innovations across a broad spectrum of applications including ultrasonic ranging, haptic interfaces, medical imaging, and fingerprint sensing [1, 2]. Despite widespread research into materials, fabrication processes, design innovations, and system integration, PMUTs have primarily been explored within the confines of fixed-frequency operation, typically at a specific resonance mode (generally the fundamental mode). The choice of materials, device topology, and operating frequencies for PMUTs are largely dictated by specific application requirements.

However, current literature reveals a gap in exploring PMUT capabilities to operate across multiple frequencies and broad frequency ranges, which could enhance their utility. For example, existing research includes studies on PMUT arrays designed with elements that operate at diverse frequencies for enhanced imaging applications. Notably, Wang et al. and Cai et al. have developed PMUT arrays integrating transducers of varying dimensions, thereby achieving different operating frequencies [3, 4]. These designs are however limited by the number of transducers operating at a particular frequency due to the trade-off between the number of devices of a particular design that can accommodated in a limited chip area [5]. Expanding beyond single-mode operations, multi-mode functionality has been explored in other MEMS devices, presenting opportunities to operate at several frequencies within a single device [6, 7]. This approach is particularly promising for PMUTs, where tailored electrode designs can enable selective access to multiple operational modes. Our prior research has successfully demonstrated the multi-mode operation of PMUTs, where both fundamental and higher-order modes were activated simultaneously in a design adapted for biomedical applications [8]. In this context, an integrated PMUT array was operated in a multi-channel configuration; a low-frequency carrier provided WPT (wireless power transfer) for deep-tissue biomedical implants, while high-frequency channels facilitated acoustic COM (communication). This dual-capability approach does not necessitate sacrificing array element density.

In this study, it is noted that the strategic selection and combination of different operational modes, along with targeted electrode design, are crucial for balancing the sensitivity across different channels or modes. Although integrating multiple modes simultaneously typically involves a trade-off regarding mode sensitivity, certain combinations have shown reduced mechanical response overlap, thus yielding better signal quality. Based on these observations, the performance of multi-channel PMUTs can be further enhanced by focusing on two primary objectives: increasing the carrier frequency to accelerate data transmission speeds and reducing intermodal interference to improve channel resolution. These goals are pursued through the development of innovative electrode designs that facilitate the excitation of higher-harmonic modes and the strategic selection of mode combinations that demonstrate minimal strain overlap.

II. Device Design

The previous circular and square dual-channel PMUT prototypes are shown in the Figure 1. Experimental validations have demonstrated that while PMUT prototype exhibit faster data transmission capabilities due to the higher carrier frequency of the COM (0,3) mode, the quality of data transmission requires careful calibration of the drive amplitude ratio between the axisymmetric WPT (0,1) and the COM (0,3) modes. This attributes to the great overlap in stress distribution when combining two axisymmetric modes (m=0 and n≠0) at the same time, which may cause intermodal interference. Here, m is the number of nodal diameters and n is the number of nodal circles. In contrast, square PMUTs, despite a reduced data rate attributed to the lower carrier frequency of the asymmetric COM (1,2) mode, provide superior data quality without the prerequisite of drive amplitude adjustments when combing with an axisymmetric (0,1) mode for WPT. This advantage is attributed to the distinct mechanical strain patterns that are generated by high-order asymmetric modes (m≠0 and n≠0), which feature multiple radial nodes and disparate mechanical strain distribution across various regions of the vibrating membrane. These distinctive strain patterns differ markedly from those generated by the axisymmetric modes, effectively reducing mode interference.

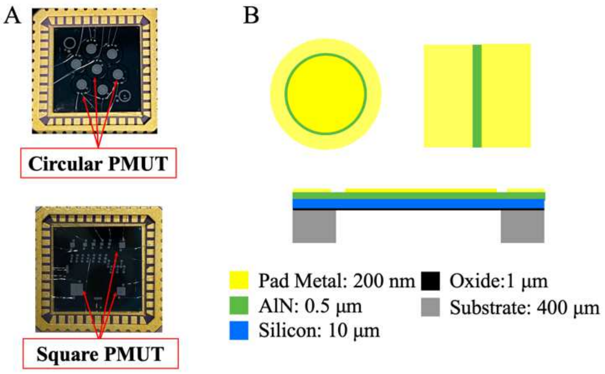

Figure 1. A: Circular and square dual-channel PMUT prototypes. B: Cross sectional view of PMUT structure.

To maximize electromechanical coupling efficiency and enhance the performance of single-mode operations within a multi-mode scheme, the mechanical responses of first three axisymmetric and two asymmetric modes are studied with their deflection profile plotted in Figure 2. Their mechanical stress profiles, along with zero-crossing radial coordinates, are essential for guiding our electrode optimization efforts and are listed in the following table:

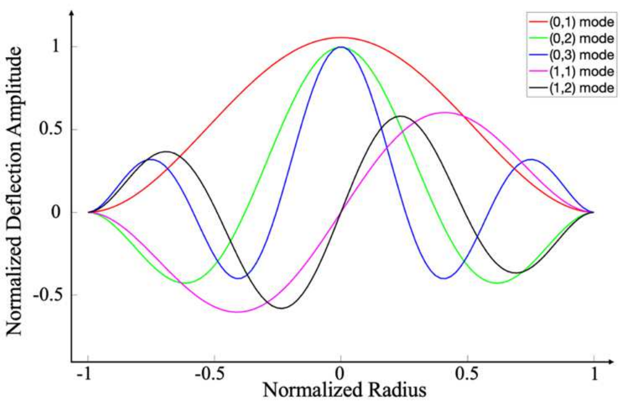

Figure 2: Normalized deflection profile of first 3 axisymmetric and 2 asymmetric modes.

Table 1. Zero-crossing mechanical stress radius and resonant frequency ratio for first 3 axisymmetric and 2 asymmetric modes of circular PMUTs

Mode	(0,1)	(1,1)	(0,2)	(1,2)	(0,3)
r_0	0.66	0.74	0.39 0.84	0.47 0.86	0.26 0.59 0.89
f/f_0	1	2.09	3.89	5.98	8.3

The electrode design aims to efficiently cover areas within the same stress polarity as indicated by the stress nodal circle in the table, where r_0 represents the normalized radius of the stress nodal circle for symmetric modes, at which location the mechanical stress flips the polarity. This strategic placement is critical for reducing inter-mode interference. Although the fundamental mode exhibits maximum deflection amplitude at the center, its broad deflection pattern frequently overlaps with those of other modes, resulting in significant intermodal interference. For example, the asymmetric modes exhibit peak deflections around the center at diametrically opposite points, which mostly overlap with the fundamental (0,1) mode. In contrast, the high-order axisymmetric modes, specifically the (0,2) and (0,3) modes, display peak deflection regions at both the center and an annular ring at the periphery of the circular PMUT. This configuration is ideally suited for multi-channel operation and is implemented with uniform ring electrodes that are distinctly separated from the central peak deflections of the asymmetric modes. Furthermore, due to their higher operating frequencies—3.89 and 8.3 times that of the fundamental (0,1) mode—the axisymmetric (0,2) and (0,3) modes are selected for COM applications. Their uniform electrode layout is essential for facilitating high-speed data communication. On the other hand, the first asymmetric (1,1) mode, with its distinctive mode shape and unique deflection patterns, is adapted for Wireless Power Transfer (WPT) applications due to its minimal strain overlap and reduced mechanical interference with the axisymmetric modes.

As a result, the chosen electrode pattern includes a pair of splitting electrodes E_1 for targeting the asymmetric (1,1) mode used for WPT, due to its distinctive mode shape and minimal overlap with the axisymmetric modes utilized for COM. Additionally, two annular ring electrodes (E_2 and E_3 are designed to focus on the higher-order axisymmetric modes (0,2) and (0,3), thereby enhancing their functionality in COM applications. This tailored electrode pattern ensures that each mode operates with optimal efficiency and minimal interference under multi-channel operation, supporting the dual functionality of the PMUT in both WPT and COM applications.

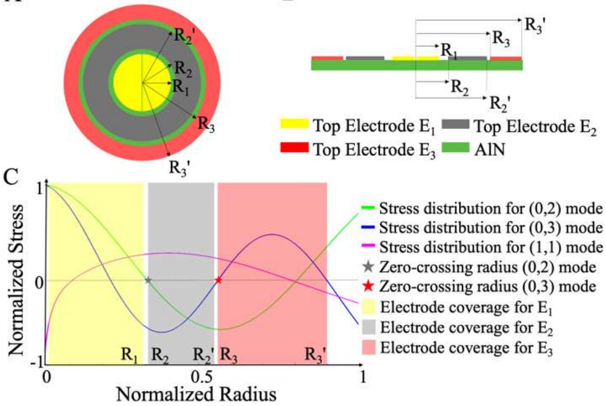

Figure 3 A: Top electrode pattern with splitting electrode E_1 (yellow), and two annular ring electrode E_2 (gray) and E_3 (red). B: Cross-section view of proposed electrode-optimized PMUT. C: Normalized stress distribution of two targeting axisymmetric modes and one asymmetric mode.

Shown in Figure 3 C, the normalized radial stresses are plotted of a circular membrane across normalized radius for the 3 targeted modes. In this case, the marked zero-crossing radial locations are critical in balancing the channel sensitivity for these modes and also reducing the inter-mode interference when PMUT is driven in multiple modes simultaneously. The individual electrode dimension is first individually studied, then combined together to determine the optimal dimension for a sensitivity-balanced multi-mode PMUT. In practical terms, the (0,3) mode, with its highest operating frequency and limited overlap with the asymmetric (1,1) mode, is prioritized for COM applications where high-quality data transmission is critical. The electrode pattern for this mode is designed to ensure minimal interference from lower-frequency modes. This is achieved by carefully positioning the annular electrode E_3 to cover the maximum stress area towards the edge of the PMUT, setting its inner radius precisely at a zero-crossing point of the stress distribution. Further electrode optimization focuses on the splitting electrode E_1 and the annular electrode E_2, which are optimized for operations involving the (1,1) and (0,2) modes, respectively. Aligning these electrodes within the positive stress regions of the (1,1) mode profile allows for connecting and driving E_1 and E_2 in parallel, significantly enhancing the sensitivity of the (1,1) mode. Alternatively, when targeting just the (0,2) mode, E_2 is driven individually. This flexibility in electrode configuration enhances the ability to select and switch specific channels or operating frequencies effectively, providing robust multi-channel operation capabilities. The finalized PMUT and electrode dimensions are determined through this comprehensive analysis. The PMUT features a radius of 280 µm and includes a central splitting electrode E_1 with a radius of 109 µm. The annular electrode E_2 spans from 110 µm to 155 µm, and the annular electrode E_3 extends from 165 µm to 252 µm. Fabrication of the PMUTs utilized an Aluminum Nitride (AlN) on Silicon-on-Insulator (SOI) platform, with each device featuring a 0.5 µm-thick AlN layer atop a 10 µm-thick SOI device layer. The fabricated PMUTs are shown in Figure 4 below.

Figure 4. Optical micrographs of optimized multi-channel PMUT A: TX; and B: RX.

III. PMUT CHARACTERIZATION

Digital Holographic Microscopy (DHM) is utilized to record the vibration responses and resonant frequencies of the optimized PMUTs, capturing the first five modes at 464 kHz, 950 kHz, 1.78 MHz, 2.31 MHz, and 4.28 MHz. Subsequently, the deflection sensitivity of both the traditional single-electrode PMUT and the newly optimized multi-channel PMUT were studied and compared. Both PMUTs, having identical dimensions, were driven at the appropriate electrodes with a 4 V_{pk} AC signal, and the deflection sensitivity of its first five modes was recorded. The results of these analyses are displayed in Figure 5. For the newly designed PMUT, the axisymmetric modes (0,1), (0,2), and (0,3) were driven using annular ring electrode E_3, while the asymmetric modes (1,1) and (1,2) were driven using central splitting electrode E_1.

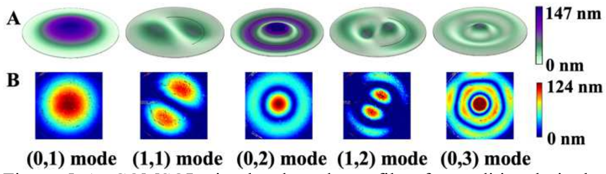

Figure 5 A: COMSOL simulated mode profile of a traditional single-electrode PMUT. B: Experimentally measured vibration profiles of an electrode optimized multi-channel PMUT for first 5 modes.

Figure 5 shows that despite a reduced driving sensitivity at the fundamental mode—attributable to the electrode placement—the electrode optimized multi-channel PMUT exhibited superior driving sensitivity across all higher-order resonant modes. Notably, the asymmetric modes (1,1) and (1,2) demonstrated 28.2 nm/V and 20.7 nm/V deflection sensitivity, corresponding to 71.7% and 56.5% compared to traditional single electrode PMUT from FEA simulation. Meanwhile the axisymmetric (0,3) mode showed a 46.4% increasing comparing to dual-channel PMUT prototype from 17.9 nm/V to 26.2 nm/V. These findings underscore the effectiveness of electrode optimization in enhancing the PMUT's mechanical sensitivity for higher modes. To verify the improvement of electrode optimization on the actual performance of the PMUT in multi-channel operation, we defined a figure of merit to evaluate the PMUT sensitivity-bandwidth (SBW) product:

$$SBW = S_{Max} \times BW_F,$$

where S_{Max} represents the transmitting-receiving sensitivity in V/V at the resonant peak of each mode, and BW_F is the -6dB fractional bandwidth for the designated mode. The SBW for the first five modes from the previous dual-channel PMUT prototype and the optimized multi-channel PMUT are measured and summarized in the table below. Specifically, improvements in the (1,1) and (0,3) modes' transmitting-receiving sensitivity, and the balance between them, demonstrate the design benefits and prove the effectiveness of electrode optimization.

Table 2. SBW comparison between dual-channel PMUT prototype and electrode optimized PMUT

SBW	(0,1)	(1,1)	(0,2)	(1,2)	(0,3)
Dual-Channel Prototype (dB)	-73.3	-119.9	-88.7	-120.3	-85.6
Optimized PMUT (dB)	-87.8	-95.5	-79.1	-101.4	-70.3

IV. WIRELESS POWER TRANSFER AND COMMUNICATION

The Wireless Power Transfer (WPT) and Communication (COM) dual-channel applications were tested on the optimized multi-channel PMUTs, using the (1,1) mode for WPT and the (0,3) mode for COM. A pair of PMUTs—one as a transmitter and the other as a receiver—were positioned across the same 17.2 mm-thick bio-mimicking phantom. This phantom, composed of gelatine and water, was designed to mimic the acoustic properties of human tissue. The transmitter was driven with a summed signal fed to the splitting electrodes. The transmitter was driven by a combined signal, incorporating a continuous 10V sinusoidal AC signal for the WPT channel at the (1,1) mode frequency and a 10 V Amplitude Shift Keying (ASK)-modulated signal for the COM channel at the (0,3) mode frequency. On the receiving end, the inner splitting electrode of the receiver PMUT was targeted to pick up the WPT signal, while the annular ring electrode was used to capture the COM signal. The responses from each channel were recorded with an oscilloscope (setup depicted in Figure 5).

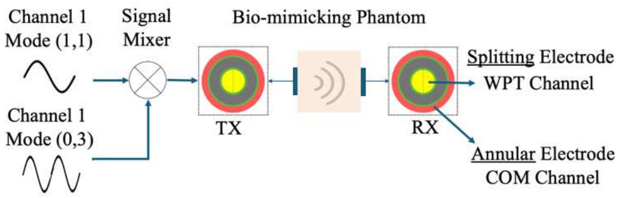

Figure 5. Experimental Setup for dual-function WPT and COM experiments on optimized multi-channel PMUT utilizing asymmetric (1,1) mode for WPT and axisymmetric (0,3) mode for COM.

Because of the higher carrier frequency, the data transfer rate significantly increased from 50 kbps to 945 kbps comparing to previous dual-channel PMUT prototype with COM channel frequency at 828 kHz. By integrating both axisymmetric and asymmetric modes, the new electrode layout reduced overlapping areas of mechanical stress compared to the original multi-channel PMUT design. This enhancement led to improved data quality with reduced Signal-to-Noise Ratio (SNR) on the COM channel, even without adjusting the drive amplitude ratio between the WPT and COM channels. The previous dual-channel PMUT prototype was driven and tested with an amplitude ratio ($V_{COM}/V_{WPT=}3.5$) between COM and WPT channel. As a result, the Bit Error Rate (BER) decreased from 1.7×10^{-2} to 8.8×10^{-3} , when driving the two channels at a 1:1 amplitude ratio for this electrode optimized PMUT. For WPT, the static capacitance was measured at 1.8 pF for either side of electrode E_1. The tailored electrode design, based on the asymmetric mode deflection profile, resulted in a reduced electrode area and static capacitance, thereby enhancing the PMUT's receiving sensitivity and leading to a higher output voltage. Consequently, while the COM channel exhibited a faster transfer rate and improved data quality, the electric voltage and received power from the WPT channel at the asymmetric (1,1) mode increased by 4.3% and 22.7% respectively.

V. Conclusion

In summary, this research has demonstrated the effectiveness of multi-channel Piezoelectric Micromachined Ultrasonic Transducers (PMUTs) through innovative electrode designs that facilitate the concurrent operation of multiple modes. The optimized PMUT design integrates both axisymmetric and asymmetric modes, specifically tailored for wireless power transfer and communication applications.

The strategic electrode design, characterized by distinct separation of ring and splitting electrodes, effectively minimizes mechanical stress overlap and intermodal interference, a critical factor in multi-channel operation. This approach not only preserves the integrity of data transmission and power delivery but also optimizes the acoustic performance of each mode. The experimental validation confirms improvements in data rate, data quality, and power levels, outperforming previous dual-channel PMUT prototype. Furthermore, the dual-functionality of the optimized PMUT array is tested within a biomedical application framework using a bio-mimicking phantom, which simulates the operational environment of biomedical implants. In this setup, a low-frequency carrier supports wireless power transfer, while high-frequency channels enable acoustic communication.

In conclusion, this study underscores the potential of electrode optimization on a multi-channel PMUTs to overcome traditional limitations of fixed-frequency ultrasonic devices, paving the way for broader application and more sophisticated ultrasonic systems. Future research will focus on further refining electrode configurations and exploring additional mode combinations to enhance the operational bandwidth and adaptability of PMUT arrays in various complex applications.

References

1. Pop, F., B. Herrera, and M. Rinaldi, *Lithium Niobate Piezoelectric Micromachined Ultrasonic Transducers for high data-rate intrabody communication.* Nature communications, 2022. **13**(1): p. 1-12.
2. Pala, S., et al. *Ultrasond-induced haptic sensations via PMUTS*. in *2021 IEEE 34th International Conference on Micro Electro Mechanical Systems (MEMS)*. 2021. IEEE.
3. Wang, H., et al. *A multi-frequency PMUT array based on ceramic PZT for endoscopic photoacoustic imaging*. in *2021 21st International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers)*. 2021. IEEE.
4. Cai, J., et al., *Beyond fundamental resonance mode: high-order multi-band ALN PMUT for in vivo photoacoustic imaging.* Microsystems & Nanoengineering, 2022. **8**(1): p. 116.
5. Balasingam, J.A., S. Swaminathan, and A. Emadi. *A Low-Frequency Piezoelectric Micromachined Ultrasonic Transducer based on Multi-User MEMS Process with Enhanced Output Pressure*. in *2020 IEEE International Ultrasonics Symposium (IUS)*. 2020. IEEE.
6. Ganesan, A. and A. Seshia. *A Proposal for Absolute Inertial Imaging using Two Mechanical Modes*. in *2018 IEEE International Frequency Control Symposium (IFCS)*. 2018. IEEE.
7. Zhang, H., et al., *A low-noise high-order mode-localized MEMS accelerometer.* Journal of Microelectromechanical Systems, 2021. **30**(2): p. 178-180.
8. Zhang, T. and A.A. Seshia. *Multi-mode piezoelectric micromachined tranducers for multi-channel acoustic power transfer and data telemetry*. in *2023 22nd International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers)*. 2023. IEEE.