Acoustic Coupling and Remote Excitation in an Array of Multi-Mode Piezoelectric Micromachined Ultrasonic Transducers

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Summary- **This paper investigates acoustic cross-coupling and remote excitation in an array of PMUTs (piezoelectric micromachined ultrasound transducers). Though undesired cross-talk can impact on PMUT array performance, the same can be also employed for remote excitation. The device array under study comprises of 7 PMUTs with constant pitch which is designed and characterized at the fundamental and higher order modes. The insights are employed to demonstrate a remote frequency filter and dual-channel excitation employing acoustic coupling.**

Keywords- PMUT, Multi-mode, Harmonics, Acoustic coupling, Crosstalk.

I. INTRODUCTION

Piezoelectric micromachined ultrasound transducers (PMUTs) are considered a promising solution for various applications, including ultrasound imaging, fingerprint sensing, mid-air haptics, and range finding in air. Researchers have extensively studied PMUTs to optimize electro-mechanical transduction efficiencies, reduce power consumption, enhance integration with electronics, ensure compatibility with flexible substrates, and accommodate compact form factor applications. With the intention of designing more powerful ultrasound transducers, many researchers have developed high-density PMUT arrays to improve acoustic sound pressure level response, bandwidth, directivity, and transmission distance. However, as transducer density increases and inter-element pitch decreases, adjacent PMUTs often become undesirably coupled through electrical feedthrough and acoustic coupling of PMUT elements through the chip substrate and solid-air interface [1-3]. This phenomenon, known as cross-coupling or crosstalk, can degrade overall performance by increasing total ring-down time, reducing receiver resolution, and distorting ultrasound beams in transmitter configurations. Consequently, most existing research in the field focuses on mitigating undesirable crosstalk and inter-element coupling through structural modifications, such as inserting resonant cavities and grooves between transducers [4-6]. In contrast, this study analyzes and investigates crosstalk in the electrical, mechanical, and acoustic domains. Based on these observations, innovative applications are explored that utilize cross-coupling, in contrast to previous research. This approach demonstrates the potential for remote filtering and remote excitation within a low-frequency PMUT array, validating the viability of harnessing cross-coupling for beneficial purposes.

II. MATERIALS AND METHOD

In this study, several transducer chips, each comprising seven identically designed PMUTs, are fabricated. As shown in Fig. 1B, a central PMUT is situated in the center of the die and surrounded by six peripheral elements with the same pitch spacing. The PMUT array employs an AlN-on-SOI (Silicon-On-Insulator) fabrication scheme with each circular PMUT cell having a radius of 660 μm designed for a fundamental mode operating frequency of 100 kHz. The device leverages a piezoelectric MEMS process involving the deposition of a 0.5 μm aluminum nitride (AlN) thin film on a 10 μm doped silicon device layer. A cross-sectional view of the device, presented in Figure 1(A), reveals that the 10 μm doped silicon device layer functions as the bottom electrode, while the top electrode consists of a metal layer comprising 20 nm of Cr and 1000 nm of Al. To minimize on-chip acoustic coupling and reduce electrical crosstalk, each PMUT is isolated by a 5 μm-thick annular ring etched all the way through the device layer. The substrate is electrically grounded in order to mitigate the impact of electrical feedthrough on the measured response.

The proposed materials and fabrication process enable efficient PMUT operation while minimizing undesirable effects on the device performance. The PMUT response is studied using a digital holographic microscope (DHM) under frequency sweep, and the observed mode shapes are shown in Fig. 2. The first four modes of the PMUTs have resonances occurring approximately at frequencies of 101 kHz, 369 kHz, 560 kHz, and 828 kHz respectively. These modes are measured by electrically driving the PMUTs and recording the vibration profiles using the DHM. The sources of cross-coupling are examined first, followed by an investigation of a remote on-chip frequency filter and dual-channel excitation features for different coupling levels across each mode. This approach aims to harness the coupling, typically considered undesirable in practical applications, for potential benefits.

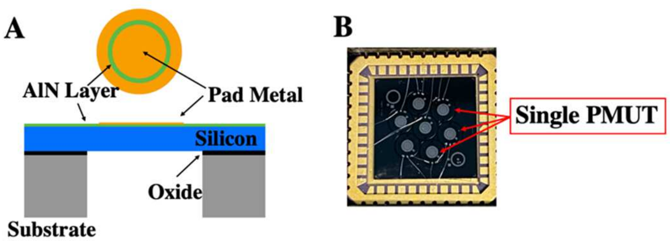

Fig. 1. A. Cross-sectional view of the device and top view of the pad metal and AlN layer. B. Optical image of the packaged chip consisting of an array of PMUTs.

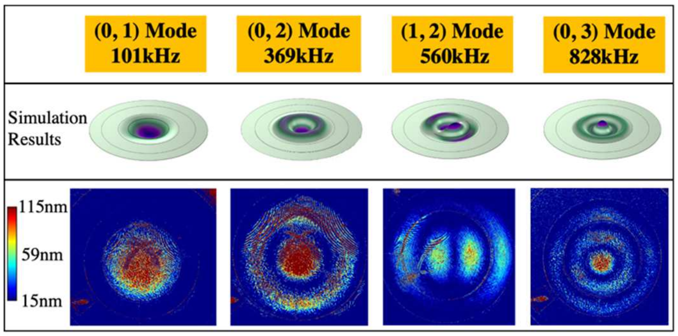

Fig. 2. Frequencies and mode shapes of the first 4 modes under 1 MHz measured using a digital holographic microscope. The deflection amplitudes are measured for a 10 Vpk-to-pk AC drive.

III. CROSS-COUPLING CHARACTERIZATION

In the designed array, inter-element coupling arises from three primary sources: electrical coupling, acoustic coupling through air, and acoustic coupling through the Si substrate [6, 7]. To gain a comprehensive understanding and effectively control the cross-coupling in a high-density PMUT array, each coupling source is individually investigated.

Electrical coupling primarily stems from capacitive coupling between electrodes on adjacent PMUTs with minimal pitch [8, 9]. To analyze its impact on the overall coupling between PMUTs, we conducted an experiment where we drove a particular PMUT (referred to as PMUT 2) at various frequencies and monitored the electrical output from the electrodes of the adjacent PMUT (referred to as PMUT 1). In Fig. 3A, adjacent PMUTs 1 and 2 exhibited fundamental modes at 97.98 kHz and 96.69 kHz, with 3 dB bandwidths of 1.04 kHz and 0.76 kHz respectively. Initially, we drove PMUT 2 at an off-resonant frequency (f_1) for both PMUT 1 and PMUT 2. We noticed a near-linear increase in the output voltage on PMUT 1 corresponding to the increase in voltage on PMUT 2. This observation confirmed the presence of electrical coupling through capacitive coupling, as the acoustic intensity from PMUT 2 is lower off-resonance thereby reducing the level of mechanical coupling. Next, we increased the driving frequency of PMUT 2 to match its resonant frequency (f_2). This change led to a substantial increase in the vibration amplitude and acoustic intensity of PMUT 2. Consequently, the voltage output on PMUT 1 exhibited an exponential increase, reaching 0.99 V when PMUT 2 was driven at 10 Vpk-to-pk. Comparing this outcome with the previous off-resonant frequency scenario (f_1), it became evident that acoustic coupling played a more substantial role in the overall coupling effect across transducers. Finally, we drove PMUT 2 at the resonant frequency (f_3) of PMUT1. In this case, the voltage output on PMUT1 increased but not as significantly as when driving PMUT2 at its resonant frequency (f_2). This observation suggests that, despite the existence of capacitive coupling, its impact on overall cross-coupling effects during array operation is limited.

Our findings confirmed the existence of electrical coupling through capacitive feedthrough, but its impact on the overall cross-coupling is limited. Acoustic coupling proved to be a more significant factor, particularly when driving PMUT 2 at its own resonant frequency. By comparing the results across different driving frequencies, the relative contribution of capacitive and acoustic coupling to the overall cross-coupling during array operation can thus be deduced.

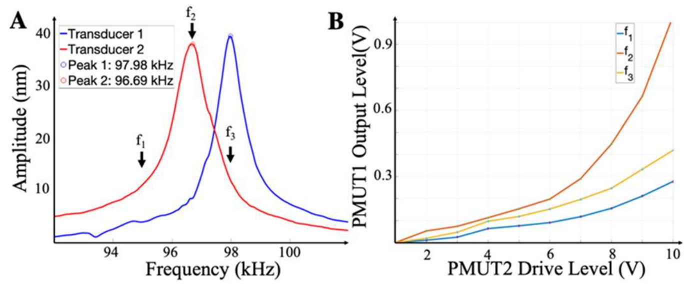

Fig. 3A: Frequency mismatch of two adjacent PMUTs under 3Vpk-to-pk drive. B: Electrical response from coupled PMUT 1 when increasing drive voltage on PMUT 2 under frequencies f_1, f_2 and f_3.

Concurrently, acoustic coupling through air and the Si substrate is investigated. Two adjacent PMUTs were selected for electrical driving at the same frequency, with comparable mechanical response amplitudes but with a calculated phase shift based on theoretical calculations. The mechanical and acoustic responses of one of the transducers was measured as impacted by the driving of the other PMUT. PMUT 1 and PMUT 2, from the electrical coupling test, were used for these tests. In contrast to the electrical coupling case, the drive signal was specified at a frequency of 97.3 kHz where the two PMUT frequency response curves intersect, ensuring both transducers had comparable amplitudes during operation. The phase shift is calculated based on the ultrasound wavelength and pitch between the two PMUTs to induce destructive interference on the response of the PMUT of interest. The material properties, wavelength, and phase delay were calculated and listed in Table 1. The distinct phase shifts for each medium enable the cross-coupling effects through air and the SOI wafer to be individually compared and understood.

Table 1. Calculated phase delay for vibration inhibition.

	Speed of Sound (m/s)	Wavelength (mm)	Phase Delay (°)
Air	340	3.54	34.39
SOI Wafer	8443	87.22	185.98

In the experiment, PMUT 1 is selected for monitoring its vibration and acoustic responses under a 2 Vpk-to-pk drive with phase delay, while PMUT 2 is driven at different amplitudes ranging from 2 V to 20 Vpk-to-pk to assess the inhibition effect on PMUT 1. As illustrated in Fig. 4A, when increasing the drive level of PMUT 2 from 2 V to 10 V and further to 20 V, the vibration amplitude on PMUT 1 decreased by 6% and 19.2% from the solid-air interface, respectively. On the other hand, when considering only the acoustic propagation through the SOI substrate, the PMUT 1 peak amplitude response is significantly reduced, having its peak amplitude less than 10 nm, when the adjacent PMUT 2 is driven under a 20 V signal. This finding suggests that acoustic coupling through the Si substrate dominates the overall crosstalk effect.

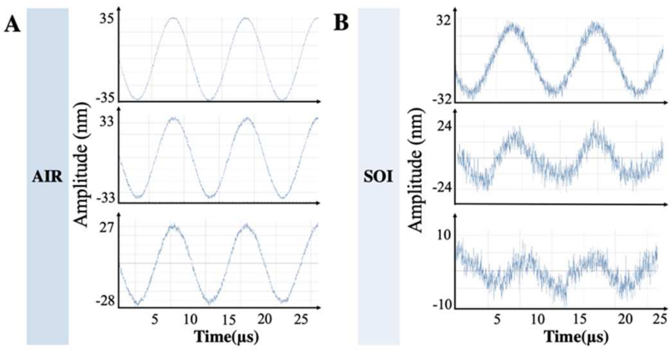

Fig. 4: Comparative analysis of optically recorded deflection amplitudes on PMUT 1 with phased driving on PMUT 2. (A) The deflection amplitude reduction correlates with acoustic coupling designed for propagation through a solid-air interface. (B) The same phenomenon is observed when acoustic coupling is designed for propagation through an SOI wafer, demonstrating more pronounced coupling. In both scenarios, the drive voltage (V pk-to-pk) on PMUT 2 increases incrementally from 2 V (top), to 10 V (middle), and finally to 20 V (bottom), illustrating the effect coupling levels on PMUT 1.

IV. DEVICE APPLICATIONS

Building upon the identification and characterization of coupling sources summarized in the previous section, an exploratory study of potential applications is undertaken that leverage this coupling between PMUTs. Although crosstalk is often considered an undesirable effect in ultrasound imaging and other applications, the research presented here demonstrates how this effect may be leveraged to enable new and useful functionality. In this section, we analyze the behavior of higher modes across different frequencies and coupling levels, and discuss two practical applications derived from the observed coupling phenomena.

First, the acoustic coupling is utilized to excite a single PMUT with a complex signal comprising two frequencies by driving two PMUTs on the same chip operating at different modes. Such a dual-channel configuration is often of interest in applications where PMUTs are utilized as transducers for simultaneous acoustic power transfer and data telemetry or in acoustic data telemetry applications allowing for an increase in the number of channels for data transmission within a single device. Second, a PMUT is employed as an acoustically coupled filter to process such complex signals for on-chip filtering. The coupling level is quantified by comparing the optically recorded deflection amplitudes of an electrically driven PMUT and its adjacent acoustically coupled counterpart. Representative results are shown in Fig. 5, where the vibration amplitudes and coupling levels are measured for a 10 Vpk-to-pk drive. Coupling levels are found to be 16.3%, 9.2%, 6.8% for the (0,1), (0,2), and (0,3) modes, and less than 3% for the (1,2) mode. This observation supports the conclusion that acoustic crosstalk is more significant at lower operating frequencies [3].

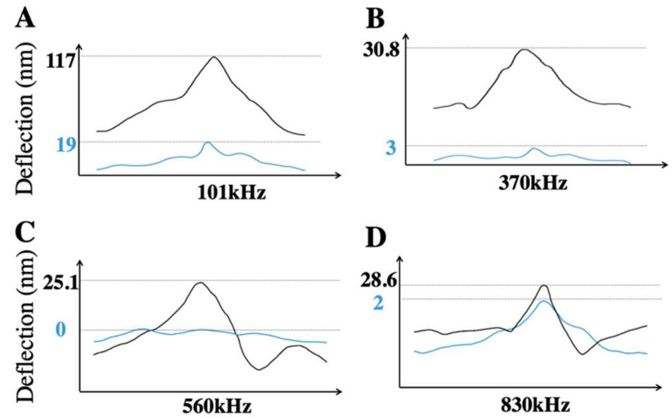

Fig. 5. A-D: Measured frequency response and coupling level of direct-excited (black) and acoustically coupled (blue) PMUTs at (0,1), (0,2), (1,2) and (0,3) modes. Maximal deflection amplitude measured at center of PMUT using a DHM.

Based on the asymmetric coupling levels, an acoustically coupled PMUT was tested as a channel select filter. First, the central PMUT was driven in both (0,1) and (0,3) modes simultaneously with a hybrid signal combining both frequencies, and electrical signals from an adjacent PMUT were collected to verify the filtering effect. Since the deflection amplitude at the (0,3) mode is relatively weaker and its coupling level is less than half of the fundamental mode, the acoustically coupled PMUT exhibits a filtering effect, predominantly responding at the (0,1) mode. Fig. 6A shows the deflection profile of a PMUT filter coupled only through the acoustic domain, and only the (0,1) mode pattern is observed. In contrast, the vibration signals from a directly driven PMUT in Fig. 6C contain both frequencies at (0,1) and (0,3) modes; the electrical signals from the filtering transducer mainly comprise of the fundamental mode signal.

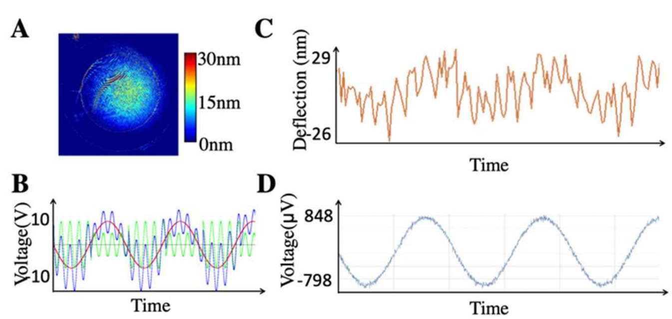

Fig. 6 A: Deflection profile of the coupled PMUT. B: Waveform used to directly drive the actuated PMUT; Red channel 1 at 101 kHz; Green: channel 2 at 828 kHz; Blue: combined driving signal. C: Vibration amplitude of directly driven PMUT. D: Electric response of acoustically coupled PMUT shows the filtering effect with a signal at 101 kHz only.

In an alternative approach, the central PMUT can also be remotely excited into a hybrid dual-channel mode. In this experiment, all six outer PMUTs were electrically driven, and the central PMUT was remotely acoustically driven into a hybrid combination of the (0, 1) and (0, 2) modes. Since the acoustic coupling is much weaker in the higher mode, only one annular PMUT is employed for exciting the (0,1) mode, while the remaining five PMUTs were driven concurrently in the (0,2) mode to compensate for the reduced coupling in this mode. As shown in Fig. 7, the deflection profile displays a combined operating mode profile with the electrical signal extracted from the central PMUT exhibiting components at the two frequencies, with the amplitude in the (0,2) mode being significantly lower. In summary, these observations demonstrate the potential for further optimization of designs and acoustic cross-coupling for mode selection, filtering, and remote hybrid multi-mode excitation.

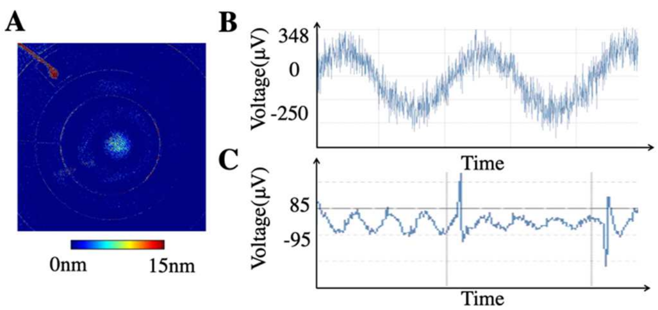

Fig. 7. A: Deflection profile of coupled secondary PMUT shows coupling of both (0,1) and (0,2) modes. B: Measured time-domain electrical response for the (0,1) mode. C: Measured time-domain electrical response for the (0,2) mode.

VI. CONCLUSION

This study delved into a comprehensive investigation of cross-coupling effects in piezoelectric micromachined ultrasound transducers (PMUTs) and demonstrated innovative applications by harnessing these effects for beneficial purposes. By individually characterizing the primary sources of inter-element coupling, including both electrical and acoustic sources, the research determined that while electrical coupling through capacitive feedthrough is present, its impact on overall cross-coupling is limited. The dominant factor affecting the overall crosstalk effect is found to be acoustic coupling, particularly through the silicon substrate.

By capitalizing on the asymmetric coupling levels across different modes, we proposed two practical applications. The first application involved remotely exciting a single PMUT with a complex signal comprising two frequencies by driving two PMUTs on the same chip operating at different modes. The second application employed a PMUT as an acoustically coupled filter to process complex signals for on-chip filtering. These applications demonstrate the potential for utilizing acoustic cross-coupling in mode selection, filtering, and remote hybrid multi-mode excitation.

The findings of this study offer a novel perspective on the useful adaptation of cross-coupling effects in PMUT arrays, which have generally been considered undesirable in ultrasound applications. Future research could explore further optimization of PMUT designs to enhance the beneficial aspects of cross-coupling, as well as investigate other potential applications that capitalize on these effects in high-density PMUT arrays. In summary, this study outlines the approaches to both characterize the crosstalk in PMUT arrays as well as explore the potential to extend the capabilities of PMUT devices by leveraging crosstalk in a beneficial manner.

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