MID-AIR HAPTIC FEEDBACK ENABLED BY ALUMINUM NITRIDE PMUTS

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ABSTRACT

This work achieves mid-air haptic feedback, using piezoelectric micromachined ultrasound transducers (PMUTs), with a 6 times higher ultrasound carrier frequency than previously demonstrated [1]. More specifically, a PMUT array, fabricated at the Silterra foundry, reaches 145 dB SPL up to 25 mm above the chip, which is well in the pressure range previously established for tactile sensation [2,3]. The resonance frequency of the 1 cm^2 array is 596 kHz which corresponds to a 575 um acoustic wavelength in air. This enables volumetric shapes with more than 6 times higher resolutions, compared to previously demonstrated haptic feedback, using 100 and 40 kHz transducers [1,2].

KEYWORDS

Haptic feedback, mid-air, tactile, PMUT, pressure, micromachining.

INTRODUCTION

Haptic feedback serves as an interesting modality to add information to a multitude of applications. The evident applications are in the entertainment field, but multiple fields can benefit from adding tactile information to their use-machine interfaces. The medical field, for example, has already implemented haptic feedback in surgical training systems and tele-operated robotic surgery [4].

So far, most existing haptic feedback devices use a contact-based method to transfer force to the user. Some examples are vibrating smart phones and wearable watches, able to generate distinct vibration patterns correlated to a specific cue [5]. A straightforward drawback of these systems is the need for physical contact during operation, hereby limiting usability and introducing hygiene issues. Therefore, during the last decade, multiple modalities were explored to enable mid-air haptic feedback. In this field, air vortices, air jets and ultrasound, received most interest [6]. Firstly, ultrasound outperforms air vortices and air jets when generating accurate and complex volumetric shapes. Secondly, existing ultrasound solutions offer a smaller formfactor compared to their air flow-based counterparts [3,6].

Using ultrasound for generation of sensations in mid-air, has been widely demonstrated with an array of bulk piezoelectric transducers [2,3]. Recently, micromachined devices have shown to be a valid alternative for this application, providing advantages in terms of formfactor, resolution, ease of integration with supporting electronics and robustness [1].

Finally, using a higher ultrasound carried frequency results in an increased achievable resolution for the targeted volumetric shapes. Therefore, in this work we focus on enabling haptic feedback with a transducer working at 596 kHz. This is a 6 times higher carrier frequency than the previously employed 40 kHz and 100 kHz, hereby promising an increased shape resolution and hence more interesting user experience.

This research focusses on the design, fabrication and testing of micromachined devices, aimed at delivering short range mid-air haptic feedback. The sections below first describe the device design and its structure, followed by an in-depth characterization of the mechanical, electrical, and acoustic properties.

DESIGN AND FABRICATION

The devices under investigation are unimorph AlN PMUTs, enabled by a cavity silicon-on-insulator wafer process. From bottom to top, the membranes consist of 5 um of silicon, covered by 200 nm of silicon dioxide, on top of which a 1 um thick AlN layer is located between two electrodes and protected by 200 nm SiO_2. Figure 1 below shows the cross-section of a single device.

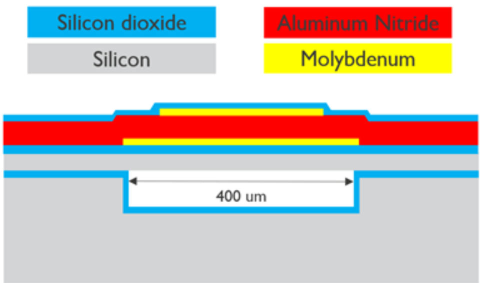

Figure 1: Simplified cross-section of the PMUT stack.

The cavity diameter is designed to 400 um to reach a 600 kHz resonance frequency. To enable a high fill factor, the array pitch is 450 um, which is below the 575 um acoustic wavelength at 600 kHz. The total active area is 9 x 9 mm, occupied by 20 x 20 PMUTs. Figure 2 below shows a sketch of part of the array.

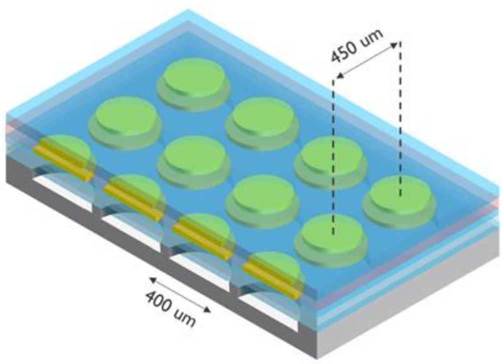

Figure 2: 3D sketch of part of the PMUT array.

When including the bond pads at the side of the array, the total chip size is 1 cm^2. Since this investigation focusses on overall array performance, the array was wirebonded on a PCB such that all PMUTs are actuated simultaneously with one driving signal. The assembly of the chip on the PCB is shown in figure 3 below.

Figure 3: Picture of the PMUT chip, wirebonded to a PCB.

MEASUREMENTS AND RESULTS

This section summarizes the results of a series of measurements performed on the transducer array. First, the individual resonance frequencies of the array membranes are measured with a Laser Doppler Vibrometer (LDV). Secondly, the frequency spectrum of the full array is identified by measuring the pressure output in the frequency domain. Thereafter, the electrical impedance of the array is measured to allow subsequent matching of the impedance to the available driving electronics. This step is crucial to allow efficient driving of the chip. Thereafter, the emitted acoustic field of the PMUT array is registered when driving the chip at its resonance frequency.

Mechanical resonance frequency

A first evaluation of PMUT performance is by measuring the resonance frequency of the membranes. To enable this measurement, the laser light of an LDV is oriented to the middle of a few of the devices in the array. The first measurement aims to register the resonance frequency of some individual PMUTs and therefore, the array is actuated with a with a frequency sweep. Figure 4 below show the frequency dependent velocity of 5 representative devices in the array.

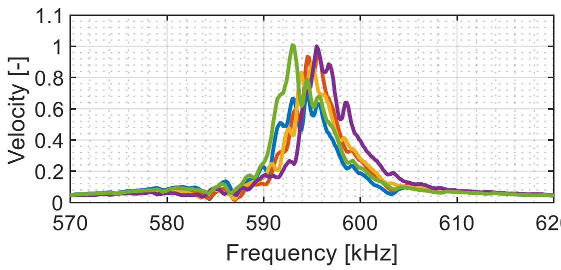

Figure 4: Measured velocities of 5 PMUTs in a 20 x 20 array, when actuating the full array with a frequency sweep.

For these 5 devices, the mean resonance frequency is 595 kHz, which is very close the expected value from Finite Element Modelling, prior to the design. Next, to understand the transducer dynamic behavior, the dynamic response of some PMUT membranes is measured, while actuating with a burst of sinusoidal waves at their natural frequency. A measurement in the center of the membrane for a representative device is show in figure 5. The figure shows that the membrane reaches its maximum velocity after ~350 us. Given that the envisioned application is haptic feedback, the involved actuation signals will be modulated at 200 Hz [7]. This results in a half period time of 2500 us, therefore allowing plenty of time for the PMUT membranes to reach their full maximum speeds.

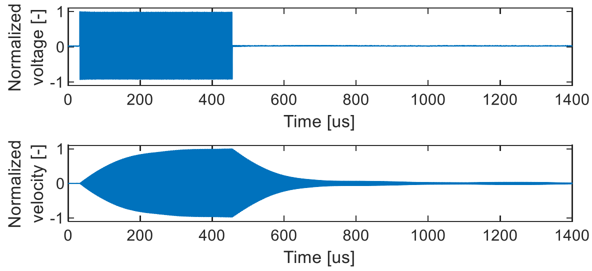

Figure 5: Velocity in the middle of a PMUT membrane in the array (bottom) when actuated with a sinusoidal burst at the resonance frequency (top).

Acoustic resonance frequency

Since the transducer array consists of identical PMUT devices in a 20 x 20 matrix, a distinct resonance frequency peak is expected. From Finite Element Simulations, prior to the fabrication, a resonance frequency of 600 kHz was expected for the 400 um diameter circular PMUT elements. To confirm the optimal working frequency, the pressure was measured at 9 cm distance with a calibrated Xarion ETA 100 microphone, while iteratively actuating with a burst of sinusoidal waves of different frequencies.

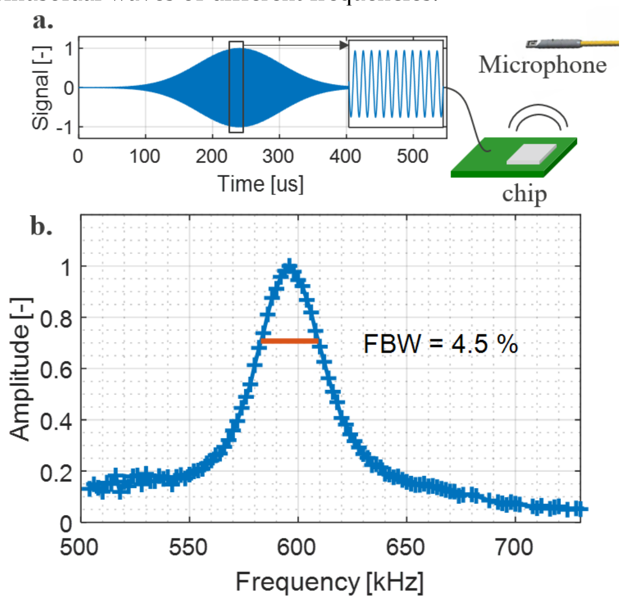

Figure 6: Acoustic frequency spectrum of the transducer array a) Example of an actuation signal with a zoom on the sinusoidal content (left) and a sketch of the setup (right). b) Normalized pressure output in the frequency domain. Showing a resonance frequency of 596 kHz and a -3db fracional bandwidth of 4.5%.

More specifically, the sequential actuation signals consist of a burst of ~200 cycles of a single frequency, overlayed with a gaussian shaped amplitude. Figure 6.a above shows an exemplary actuation signal and figure 6.b summarizes the resulting detected pressure output as a function of frequency. From figure 6, the detected resonance frequency is 596 kHz which is in good agreement with the expected individual resonances of the PMUT devices. Moreover, the -3 dB Fractional Bandwidth (FBW) of the array is 4.5 %. Since haptic feedback mainly requires high output pressures, this narrow bandwidth is not considered as an issue.

Electrical Impedance

To allow efficient driving of the silicon chip, it is important to consider its electrical characteristics and the employed driving equipment. Therefore, the electrical impedance of the full array is measured and thereafter matched, at the resonance frequency, to the 50 Ohm output impedance of the used voltage source. The Agilent 4924A analyzer measured an impedance of 85.8 Ohm and -86.6 degrees phase angle at 596 kHz. After implementing an L-type matching network of a series inductor and parallel capacitor, a new impedance value of 45.4 Ohm and 12 degrees phase angle is established for the entirety of components and chip. This value is close to the targeted 50 Ohm and zero degrees. Figure 7 summarizes the measured values.

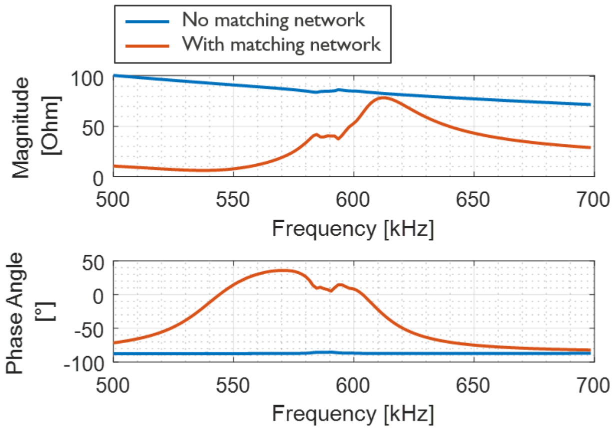

Figure 7: Impedance values of the PMUT chip with and without impedance matching network, targeting 50 Ohm.

Emitted pressure field

To optimize the transducer configuration for haptic feedback, it is important to understand the spatial characteristics of the emitted pressure field. Therefore, the Xarion ETA 100 microphone is attached to a 3D motorized stage, while driving the impedance matched array with a 596 kHz continuous sinusoidal signal of 20 Volt amplitude. Acoustically, this actuation corresponds to plane wave actuation, as all the elements in the 20 x 20 PMUT matrix are excited in phase. By acquiring the output of the microphone at each specified location, the output pressure fields, shown in figure 8, are generated. This figure shows Sound Pressure Levels above 145 dB until ~25 mm above the array surface. Moreover, the contour plot indicates the narrowest beam waist at ~22 mm.

Considering that a higher ultrasound frequency results in higher attenuation in air, it is important to verify the axial decay of the generated pressure. Figure 9 shows the maximum pressure amplitudes achieved above the center of the array, with increasing distance from the

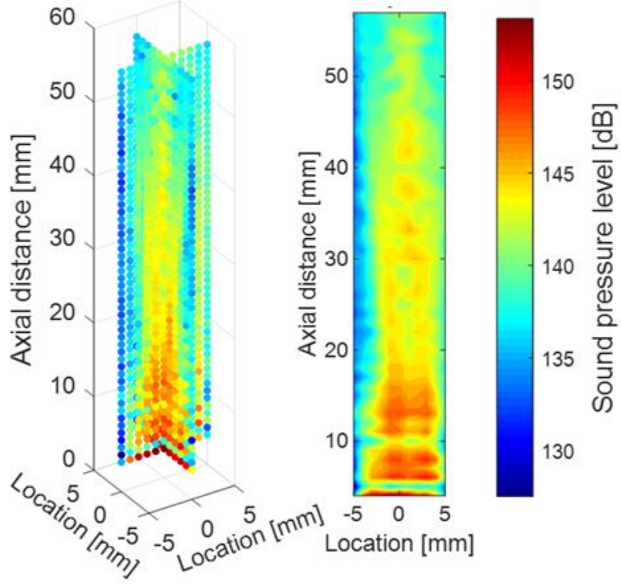

*Figure 8: **Output pressure field amplitudes of a 1 cm^2 silicon PMUT chip, for 20 V amplitude driving at the resonance frequency of 596 kHz.***

array. The graph identifies 40 mm as the boundary from near- to far-field zone, as a clear decay is observed starting from this distance. After 100 mm a pressure of 100 Pascal amplitude is still achieved.

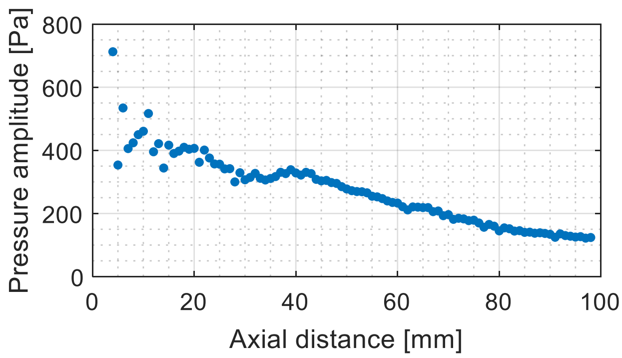

Figure 9: Output pressure above the center of a 1 cm^2 silicon PMUT chip varying with distance from the chip surface, for 20 V amplitude driving at the resonance frequency of 596 kHz.

Perceived haptic feeling

As an addition to the pressure measurements a small user experiment was set up. While actuating the array with a 596 kHz sinusoidal signal of 20V amplitude and amplitude modulation with 200 Hz, 10 lab-users were asked if they could feel a haptic sensation on their fingertips. The 200 Hz modulation was selected in accordance with previous work, establishing this as the right range for mechanoreceptor stimulation [7]. All 10 volunteers claimed to feel a haptic sensation when hovering their fingertips above the silicon chip. This observation, combined with the pressure data above, confirms that a 1 cm^2 PMUT array reaches the necessary pressures for haptic feedback, but an in-depth user experience study should be set up to draw further conclusions on the user experience.

CONCLUSION

This work demonstrates a 1 cm^2 Aluminum Nitride based PMUT array, capable of reaching the required pressures for mid-air haptic feedback at a 6 times higher resonant frequency compared to previous work. The higher ultrasound carrier frequency allows higher resolution patterns and although attenuation in air is increased at elevated frequencies, the array reaches 100 Pascal at a 100 mm distance. This is in the same range as the well-established 40 kHz bulk transducer achieving 20 Pascals at 300 mm [2]. Moreover, compared to the existing bulk-piezo electric solutions, the micromachined approach offers advantages such as smaller formfactors, smaller transducer pitches, easier integration with electronics and a more robust solution.

A next showcase is to leverage the high carrier frequency, small pitch, and individual control of the elements, to generate high resolution tactile shapes. Thereafter, the existing technology can still be improved by doping the AlN layer with Scandium, hereby promising higher output pressures for the next generation chip [8]. Finally, for each envisioned use-case, a PMUT array design can be optimized in terms of frequency, cavity size and configuration, making it a versatile and promising technology platform for mid-air haptic application.

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