T1C.003

DISPLAY COMPATIBLE PMUT ARRAY FOR MID-AIR HAPTIC FEEDBACK

Alexandre Halbach, Pieter Gijsenbergh, Yongbin Jeong, Wouter Devriese,
Hang Gao, Margo Billen, Guilherme B. Torri, Christopher Chare, David Cheyns,
Xavier Rottenberg, and Veronique Rochus
IMEC, Kapeldreef 75, 3001 Leuven, Belgium
alexandre.halbach@imec.be

ABSTRACT

This paper presents a Piezoelectric Micromachined Ultrasonic Transducer (PMUT) array targeting mid-air haptic feedback applications. Compared to existing bulk ultrasound transducer technologies, this array implements polymer-based micromachined ultrasound transducers fabricated in a display-compatible, large area technology. It is, thus, a good candidate for direct integration on top of large displays and allows to fabricate dense PMUT arrays for a fine non-contact haptic experience at interesting price point.

BACKGROUND

Contactless haptic feedback has already been demonstrated [1,2] and commercialized by the company Ultrahaptics [3] using phased arrays of discrete off-the-shelf transducers (about 1 cm diameter, 40 kHz resonance frequency). By focusing the emitted pressure of the transducers to a small spot in space and modulating the pressure at 200 Hz, the nano-receptors of the fingertip can be excited. It was determined by using an Ultrahaptics board that the pressure sensing threshold is 1 kPa [4]. As an alternative to the aforementioned array of discrete transducers, display-compatible polymer-based micromachined PMUTs, based on the technology already described in [5,6], can be used to get a high transducer density and a high resonance frequency, leading to much finer haptic patterns. At the same time, this technology is suited for direct integration on top of large displays.

DESCRIPTION OF THE PMUTS

In a PMUT, an electric field is applied across a piezoelectric layer to induce a membrane vibration and emit acoustic waves. Figure 1 illustrates the cross section of an individual PMUT fabricated with the aforementioned technology [5,6]. The membrane is made of a 15 µm thick polyimide layer on top of which a 500 nm thick piezoelectric PVDF layer is spin-coated. The PVDF layer is sandwiched between two electric traces for actuation. For the fabricated PMUTs, a diameter ranging from 100 µm to 1 mm provides any resonance frequency between 100 kHz and at least 2 MHz as shown with measurements matching simulations on figure 2.

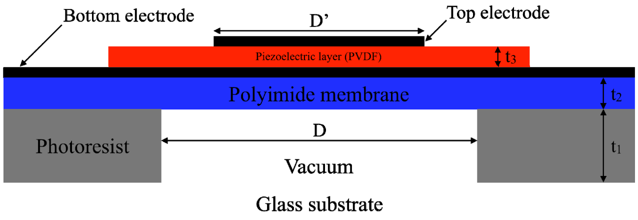

Figure. 1: Illustration of the cross-section of a PMUT.

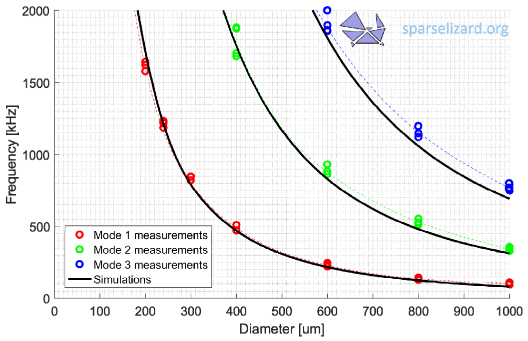

Figure. 2: Resonance frequency vs. cavity diameter for the three first vibration modes (measured and simulated).

For this paper a 4 cm x 4 cm large 64 by 64 array of 480 µm diameter PMUTs was fabricated. A diameter of 480 µm was selected because it provides the highest pressure per PMUT area at 1 cm distance in air. The large 64 by 64 array consists of four 32 by 32 arrays as illustrated on figure 3 (top). The individual 32 by 32 arrays are actuated in a row-column fashion: the top electrodes of all PMUTs in a given row are electrically connected together while the bottom electrodes of all PMUTs in a given column are electrically connected together. This connection can be visualized on the microscope view of a 3 by 3 subarray on figure 3 (bottom). As can be seen, a circular shaped electrode is used to drive the PMUT at its first mode mechanical resonance (390 kHz). A 67% electrode coverage is used to maximize the first mode vibration [5].

978-1-5386-8104-6/19/$31.00 ©2019 IEEE

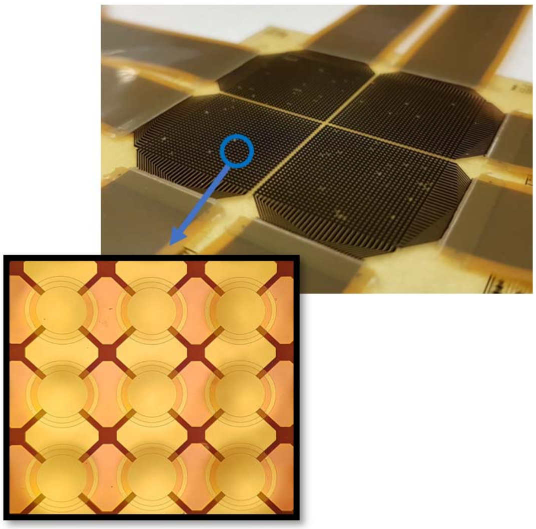

Figure 3: *Fabricated 64x64 PMUT array (top) and zoom on a 3 by 3 subarray (bottom).*

EXPERIMENTAL RESULTS FOR SINGLE PMUTS

The pressure emitted by the PMUTs was measured using the Xarion ETA100 Ultra microphone. The pressure per Volt actuation at resonance versus distance to PMUT was measured for an average 480 µm diameter PMUT (see figure 4). A pressure of about 0.14 Pa/V was measured at 1 cm above the PMUT. For the maximum acceptable actuation of 20 V AC, a 2.8 Pa peak pressure was measured.

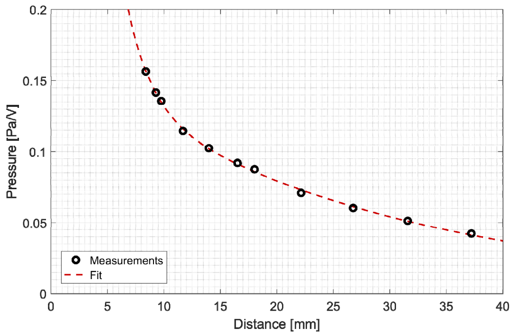

Figure. 4: Pressure versus distance for a 1 V actuated PMUT with a 480 µm diameter.

The Rayleigh integral was used to compute the pressure field generated by a single 480 µm diameter PMUT in air. A 3D piezoelectric-mechanic finite element model was used to provide an accurate first mode membrane velocity profile. In any case all simulations were performed in the open source finite element C++ library *sparselizard* [7]. Figure 5 shows the simulated pressure field around a position at 1 cm above the PMUT center.

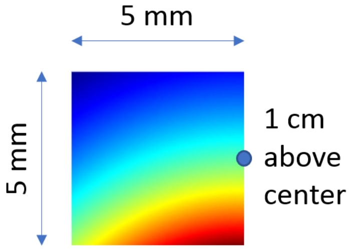

Figure 5: Simulated pressure field 1 cm above a single PMUT. Pressure at 1 cm is 0.14 Pa/V.

EXPERIMENTAL RESULTS FOR PMUT ARRAYS

A good PMUT uniformity across the array, along with a low crosstalk are key for phased array focusing. For that reason, the resonance frequency (f_r) and velocity variation across the array were analyzed using Laser Doppler Vibrometry (LDV) and output pressure measurements.

The 400 kHz target f_r is realized with a mean 2.5% offset. The peak output pressure was measured at 390 kHz. Figure 6 reports the LDV-based f_r offset distribution of 81 equally-spaced devices across the selected 2x2 cm^2 (32x32 PMUTs) array. A non-uniformity of ± 4% is reported. While this number is low for a technology in development, it is large in view of the 7.8 kHz average PMUT bandwidth, i.e. 2% fractional bandwidth (FBW) in air.

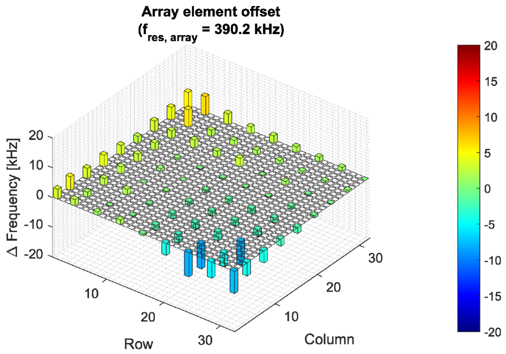

Figure 6: Resonance frequency drift across the array.

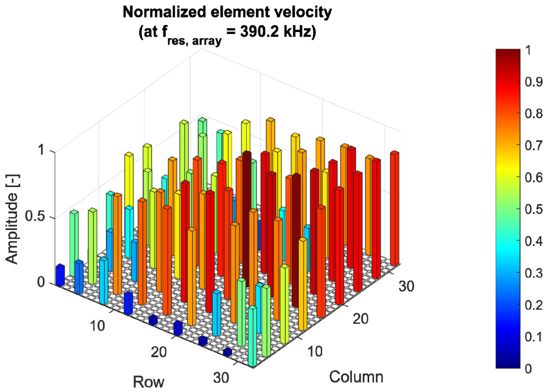

Figure 7:Peak velocity at a 390 kHz driving frequency.

For a fixed 390 kHz driving frequency the peak PMUT velocity in air was also measured on 81 equally spaced PMUTs (figure 7). The drift in resonance frequency seen on figure 6 can be correlated with lower PMUT velocities although other effects (e.g. process variation of the PVDF thickness) also have an influence. The first column in the array has the lowest velocity due to a broken electric trace. Overall some degree of inhomogeneity can be observed in the array. As will be seen later this has an impact on the emitted pressure.

The crosstalk has been analyzed center-to-corner in the 32 x 32 PMUT array (480 µm diameter, 580 µm pitch). In all cases the crosstalk observed between adjacent devices is negligible for the target application. Figure 8 reports the displacement amplitude of a non-stimulated device and its direct neighbor, actuated at 390 kHz. The combined mechanical and acoustic crosstalk lead to a parasitic vibration in quadrature of phase with one order of magnitude lower amplitude, i.e., -20dB$_{\text{power}}$.

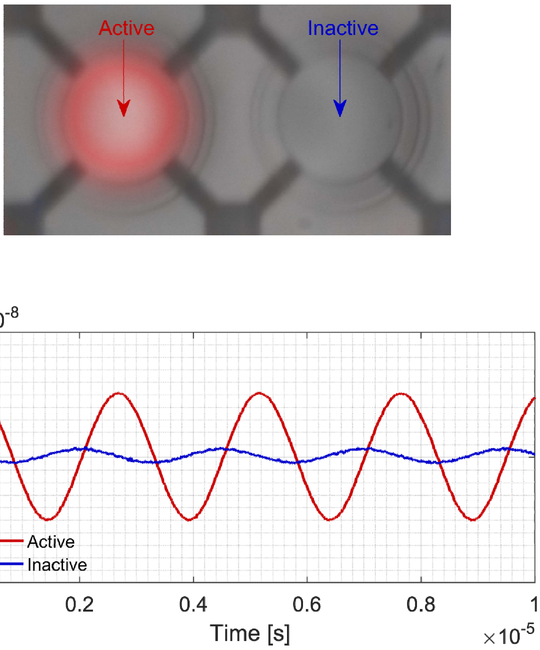

Figure 8: Crosstalk at the center of the PMUT array.

PRESSURE 1D FOCUS OF THE PMUT ARRAY

The array detailed in the previous section (32 x 32 array of 480 µm diameter PMUTs with a 580 µm pitch) is used in this section to create a 1D focused pressure line at 1 cm above the center and top row. The 390 kHz driving frequency mentioned in the previous section is used. A 3D motorized stage shown on figure 9 is used to scan the pressure above the PMUT array. One pressure measurement step is performed every 580 µm (the pitch) in both the row and column dimension of the array. An area larger than the array is covered by the pressure scans (40 pitch side).

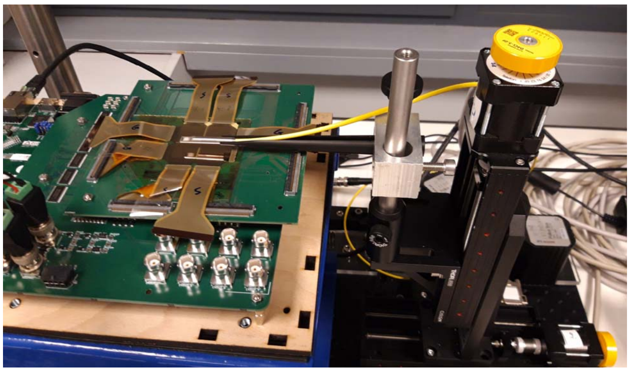

Figure 9: Motorized 3D stage used for the pressure scan. The Xarion ETA 100 Ultra microphone is mounted on it.

When all PMUTs are driven in phase the pressure obtained at 8.5 mm above the array is shown on figure 10. A 3V electric actuation is used. The pressure non-uniformity is correlated to the resonance frequency drift of figure 6.

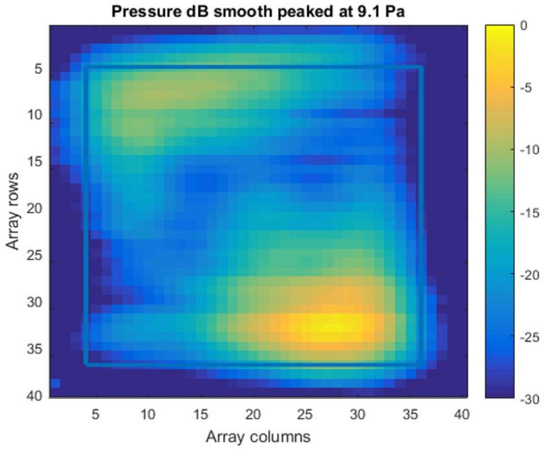

Figure 10: Pressure in dB, 8.5 mm above the uniformly actuated array. The actuation is 3 V peak at 390 kHz. The blue box indicates the edge of the 32 by 32 array.

When the PMUTs are driven with phase delays to focus on a line at 1 cm respectively above the top and central row, the measured pressure scans of figure 11 are obtained. This can be compared with the pressure field simulated at 1 cm above the array center (figure 12). The peak simulated pressure of 19.5 Pa per volt, thus 58.5 Pa for the 3V actuation used in figure 11, is slightly more than double the measured pressure on any 1D focus line. This can be attributed to the fact that not all PMUTs reach their peak resonance velocity (figure 7) as well as to the height misalignment.

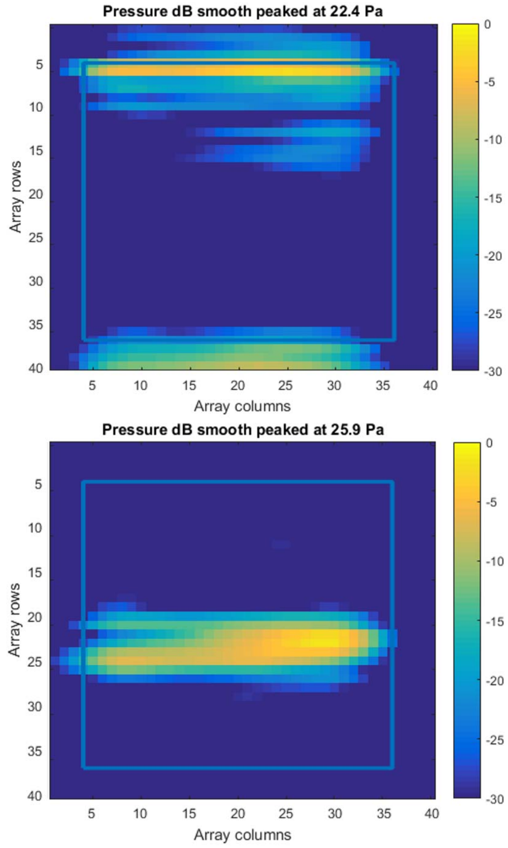

Figure 11: Pressure in dB, 8.5 mm above the 1D-top focused (top) and centrally-focused (bottom) array. The actuation is 3 V peak at 390 kHz.The blue box indicates the edge of the 32 by 32 array.

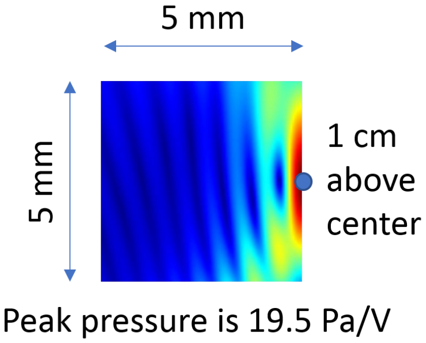

Figure 12: Simulated pressure at the 1D focus point.

A 1D focus simulation was performed to take into account the velocity variation across the array: the velocity was interpolated on the array based on the 81 measurement points of figure 7 but did as such not take into account any undetected, defective row/column. The corresponding 1D focus is shown on figure 13. The decreased pressure at the focus point was observed to be proportional to the decrease in the average velocity in the PMUT array. The focus point size and shape does however not seem to dramatically change compared to the optimal 1D focus.

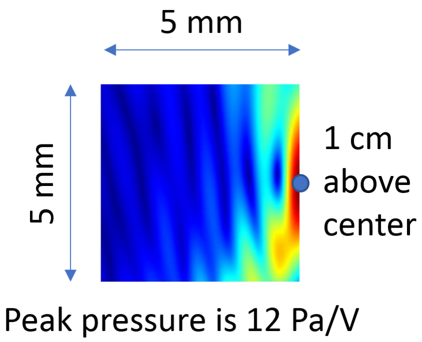

Figure 13: Simulated pressure at the 1D focus point when the PMUT velocity variation across the array is taken into account.

CONCLUSION

This paper reported on the design, fabrication and experimental characterization of a 32x32 array of polymer-based PMUTs. In particular, we assessed important technology metrics to enable the proper definition of tight focus points, required for haptic feedback, i.e., the array uniformity and the inter-device crosstalk. LDV measurements indicate array uniformity and cross-talk respectively better than ±4% and lower than -20dB. These figures are promising but the uniformity, in particular, is large in view of the 2% FBW (in air). Nevertheless, we demonstrated 1D focusing with the sub-optimal array. The single device output pressure of 0.14 Pa/V resulted in an 8.6 Pa/V 1D-focused peak pressure, a factor 3 better than the array subject to a uniform excitation. These findings, compared and confirmed by FEM simulations, support the technology capability for producing mid-air haptic feedback using ~20V excitation amplitude and 2D focusing.

REFERENCES:

[1] Yasutoshi Makino et al., HaptoClone (Haptic-Optical Clone) for Mutual Tele-Environment by Real-time 3D Image Transfer with Midair Force Feedback

[2] Yasuaki Monnai et al., HaptoMime: mid-air haptic interaction with a floating virtual screen

[3] Tom Carter et al., UltraHaptics: Multi-Point Mid-Air Haptic Feedback for Touch Surfaces

[4] Michaël Wiertlewski et al., A High-Fidelity Surface-Haptic Device for Texture Rendering on Bare Finger

[5] Chih Hsien. Huang et al., Design, Modelling, and Characterization of Display Compatible PMUT Device

[6] Yongbin Jeong et al., pMUT device compatible with large-area display technology

[7] Alexandre Halbach, Sparselizard-the user friendly finite element c++ library