Polymer-based piezoelectric ultrasound transducer arrays on glass demonstrating mid-air applications

Christopher Chare*†, Pieter Gijsenbergh†, Yongbin Jeong*†, Jan Genoe*†,
Paul Heremans*†, David Cheyns†, and Kris Myny*†
*Department of Electrical Engineering, K.U. Leuven, Leuven, Belgium 3001
†Sensor and Actuator Technologies, imec, Leuven, Belgium 3001
Email: christopher.chare@imec.be

***Abstract*—Glass backed ultrasound transducer arrays enable the possibility of exciting new ultrasound applications that require larger surface areas and scaling beyond traditional CMOS fabricated devices. In this work, we describe the modeling and design of our fabricated large area polymer-based P(VDF-TrFE) piezoelectric micromachined ultrasound transducers (PMUTs). In addition, we demonstrate the capabilities of the technology using a fabricated large area annular array driven with phased input signals yielding focused acoustic waves in mid-air. Theoretical electromechanical modeling and simulations of individual PMUTs were conducted and the nominated PMUT design was incorporated into an annular array for use in mid-air ultrasound focusing. Array performance was characterized using a Polytec laser Doppler vibrometer and a Xarion optical microphone and was subsequently compared with expected results. The PMUTs were driven at 256 kHz and the input phase delay was configured to produce a focal point at 10 mm above the center of the annular array. The pressure at the focal point was found to have a pressure exceeding 300 Pa and good linearity w.r.t. input voltage. Reasonable agreement is observed between the expected and measured fields demonstrating the future capability of using large-area PMUTs for ultrasonic applications in air.**

***Index Terms*—piezoelectric transducers, ultrasonic transducer arrays, microelectromechanical devices**

I. Introduction

The use of ultrasound in airborne applications such as mid-air haptic feedback and gesture recognition has become of considerable interest with the advent of micromachined ultrasonic transducers (MUTs). Advantages of using MUTs over conventional ultrasonic transducers include the ease of miniaturization, superior impedance matching, and the possibility of monolithic integration with electronics [1]. Typical applications of MUTs within the scope of contemporary applications include medical imaging and fingerprint detection [2], [3]. However, the utilization of large area fabrication techniques, such as those used in the thin-film display industry, allows for the fabrication of MUTs targeted towards applications that are considered unfeasible using MUTs based on traditional CMOS based technology. This allows for the possibility of implementing MUT based applications such as mid-air haptics and gesture recognition due to the scalability and cost effectiveness of large-area fabricated MUTs [4].

In this work, we consider a large-area polymeric piezoelectric micromachined ultrasonic transducer (PMUT) array for the purpose of generating an acoustic focus with an appreciable focal pressure in mid-air, in order to demonstrate the potential of the technology for airborne applications. A systematic array design approach based on a PMUT electromechanical model was conducted and the array was subsequently fabricated and measured.

II. Materials and Methods

A. Transducer Description

PMUTs with varying diameters from 400 µm to 1 mm as shown in Fig. 1 were fabricated on a glass substrate upon which a 35 µm layer of photoresist is spin-coated and patterned to create the circular micro-cavities. A 15 µm polyimide membrane layer was then bonded to the cavity layer, on which an aluminum layer was evaporated and patterned as the bottom electrode. A 450 nm active layer of P(VDF-TrFE) was subsequently spin-coated and etched, followed by a top electrode layer consisting of 300 nm of sputtered aluminum [5].

B. PMUT Modeling and Characterization

Individual PMUTs of differing radii were driven with a 1 V sine wave swept between a 1 Hz to 2 MHz input frequency applied to the inner top electrode with respect to a grounded bottom electrode. The PMUTs were then measured using a Polytec MSA-500 laser doppler vibrometer (LDV) and Agilent E4980A impedance analyzer.

The measurements of individual PMUTs were used in determining the material parameters through an electromechanical equivalent circuit model based on the Mason model [6]. The electromechanical model was specifically adapted for use with the polymeric PMUTs, by incorporating considerations for the elastic boundary conditions due to the low elastic moduli of the materials used in the stack. To this end, the model has assumed that the flexural axisymmetric modal shape function (of the fundamental mode) to be based on the vibrational mode for clamped circular disks given as,

$$u(w_0) = J_0(\gamma_0 w_0) - \frac{J_0(\gamma_0 a)}{I_0(\gamma_0 a)} I_0(\gamma_0 w_0) \qquad (1)$$

where J_n, I_n are the n'th order Bessel and modified-Bessel functions of the first kind, and γ_0, w_0, a are the fundamental eigenvalue solutions for the clamped circular plate, radial

978-1-7281-5448-0/20/$31.00 ©2020 IEEE

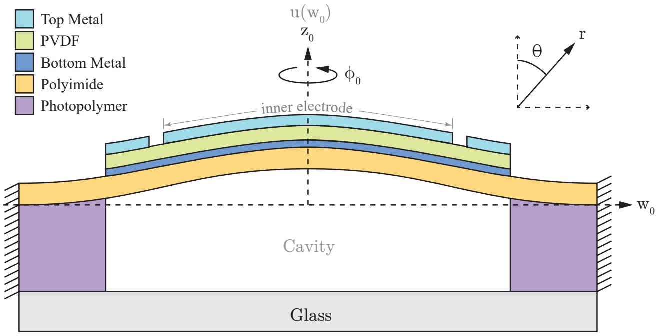
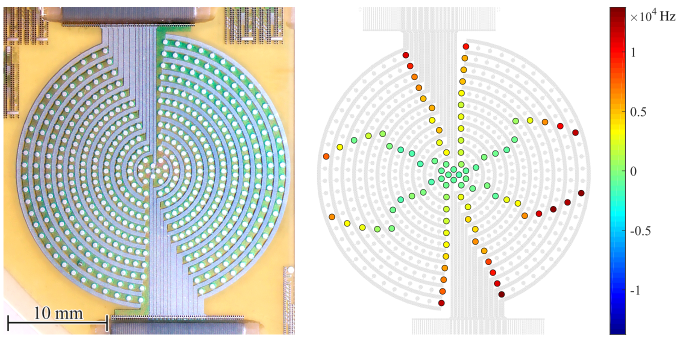


Fig. 1. Cross-sectional axisymmetric illustration of the PMUT stack.



(a) (b)

Fig. 2. (a) Top-down image of the annular PMUT array. (b) Measured frequency offset of individual PMUTs within the array from the nominal system resonant frequency of 256.6 kHz.

coordinate within the plane of the PMUT, and nominal PMUT radius respectively [7].

The simulated responses of the PMUTs were then validated using the measurement data around the fundamental resonant frequency, and an optimally sized PMUT with appropriate electrode design was selected for use in a PMUT array. Here, the optimal PMUT design to be used was determined to be a 300 μm radius PMUT, with an inner electrode radius covering 75% of the PMUT radius operating at 260 kHz, the results of which will be further elaborated within the discussion.

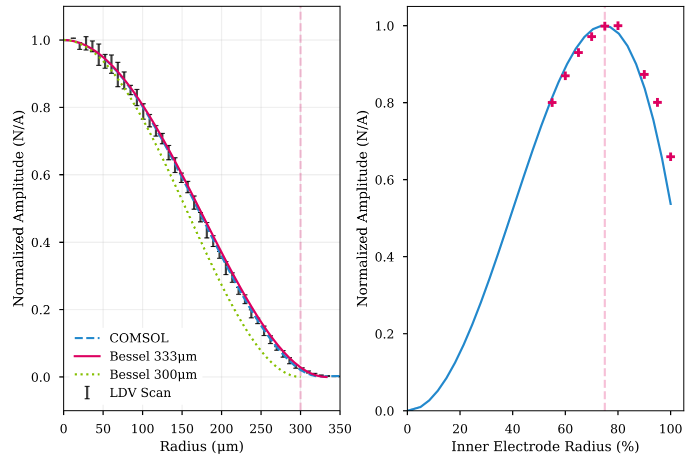
C. Array Design and Measurement

Given the parameters of the electromechanical model and vibrational modal shape of the selected 300 μm PMUT diaphragm, the acoustic far field pressure for an individual PMUT was obtained through the monopole contribution from the Kirchoff-Helmholtz boundary integral for vibrating resilient disks in an infinite baffle [8]. The far field pressure equation used was,

$$p(r,\theta) = 2\int_0^{2\pi}\int_0^{a} g(r,\theta|w_0,\phi_0)\frac{\partial}{\partial z_0}p\left(w_0,z_0\right)w_0\,dw_0\,d\phi_0 \tag{2}$$

where,

$$\frac{\partial}{\partial z_0}p(w_0,z_0) = -ik\rho c u(w_0), \quad w_0 \in [0,a] \tag{3}$$



(a) (b)

Fig. 3. (a) Fundamental axisymmetric modal shapes of a 600 μm diameter PMUT. Theoretical clamped vibrational modal shapes are denoted 'Bessel'. Good agreement is observed between the electromechanically predicted clamped modal shape with extended radius and COMSOL multiphysics simulation, with respect to the LDV measurement. (b) LDV measurements of peak vibrational velocity amplitude for varying inner electrode radii (red) and electromechanical model prediction (blue) for a 600 μm diameter PMUT. The predicted and measured values are in good agreement, and peak output is shown to be at approx. 0.75 the nominal PMUT diameter.

and r is the radius, θ is the zenith angle, ϕ_0 and z_0 are the polar angle and height coordinate with respect to the plane of the PMUT, k is the angular wavenumber, and ρ and c are the density and speed of sound in air respectively. Here we use the far-field version of the Green's function in spherical-cylindrical coordinates given as,

$$g(r,\theta|w_0,\phi_0) = \frac{e^{-ikr}}{4\pi r}e^{iz\sin\phi_0} \tag{4}$$

It follows that when using the identity,

$$J_n(z) = \frac{1}{2\pi}\int_0^{2\pi} e^{i(z\sin\phi - n\phi)}d\phi \tag{5}$$

we obtain (6) as the far field pressure for an individual PMUT where U is the maximum vibrational velocity amplitude of the diaphragm. This expression was used in calculating the total pressure field from an array by taking the complex sum of all contributing PMUTs while also considering the attenuation loss due to high frequencies in air.

The target pressure at the focal point of the PMUT array was selected to be greater than 1 kPa at a distance of 10 mm above the center of the array, when driven with a 15 V square wave. To achieve this target pressure, an annular PMUT array as shown in Fig. 2a was designed such that there would be a total of 12 rings, with identical opposing signal lines to mitigate loss and delay from parasitic resistances of the metal layers. The kerning between adjacent PMUTs was set to be at a minimum of 150 μm to minimize the possibility of mechanical cross-talk.

$$p(r,\theta) = -ik\rho c U \frac{e^{-ikr}}{r} \frac{1}{I_0(\gamma_0 a)} \frac{1}{(k\sin\theta)^4 - \gamma_0^4} \Big(-\gamma_0 a J_0(ka\sin\theta) \left[J_0(\gamma_0 a) I_1(\gamma_0 a) \left((k\sin\theta)^2 - \gamma_0^2 \right) + J_1(\gamma_0 a) I_0(\gamma_0 a) \left((k\sin\theta)^2 + \gamma_0^2 \right) \right] + 2\gamma_0^2 J_0(\gamma_0 a) I_0(\gamma_0 a) ka \sin\theta J_1(ka\sin\theta) \Big) \quad (6)$$

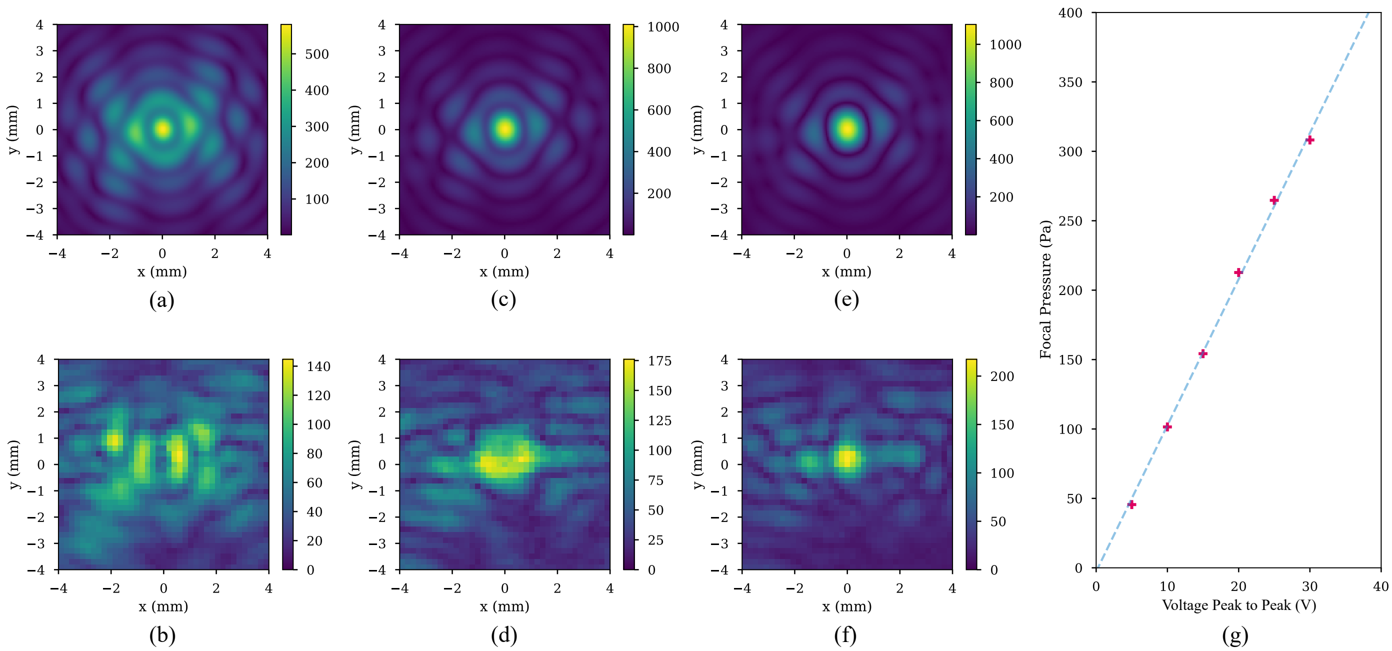


Fig. 4. Simulated (top) and measured (bottom) pressure fields at plane offsets/heights of 8 mm (a-b), 9 mm (c-d), and 10 mm (e-f) above the center of the annular array. The adjacent colorbars represent the pressure in Pa. (g) Measured (red) peak pressures at the focal point located 10 mm above the center of the array with increasing peak to peak driving voltage. The blue line represents a linear fit.

Once fabricated, the annular array was poled with a DC voltage source. Performance and uniformity was then investigated using the Polytec MSA-500 laser doppler vibrometer.

After characterization the annular arrays were then driven using a custom high-voltage ultrasound driver board, which was controlled by programming the individual driving phases through an FPGA. Each channel of the driver was connected to a specific ring of the array, and was supplied with a square wave signal with a phase delay equivalent to the theoretical phase required to create a focal point at 10 mm above the array. The input voltage amplitude of the square wave was varied from 5 to 30 V.

The acoustic field of the annular array was then measured using a Xarion ETA-100 Ultra optical microphone mounted on a 3-axis micro-positioning stage. Three high-resolution measurements of plane sections at a height of 8, 9, and 10 mm above the surface of the annular array were conducted.

III. Results and Discussion

A. Single PMUT Element

The nominal radius of the PMUT was selected to be 300 µm based on measurements from previous experiments indicating optimal process variability and performance. The electromechanical model simulation for the current PMUTs suggested that the effective radius of the fundamental mode extended beyond the nominal radius by approximately 33 µm using pre-existing material parameters. The simulation results were validated using LDV scans over the entire area for 300 µm PMUTs at the fundamental resonant frequency. As shown in Fig. 3a, the measured fundamental vibrational mode conformed to the mode shape described by (1) with the predicted extended radius when driven at the resonant frequency of 260 kHz. The effective radius of 333 µm was thus hereby defined to replace the nominal PMUT radius a.

Using these results in the electromechanical model, an optimal inner electrode design was investigated. Fig. 3b shows the result of the simulated optimal inner electrode radius given a PMUT device radius of 300 µm. The maximum velocity amplitude of PMUTs with increasing inner electrode coverage were measured via the LDV in response to a 1 V sine input signal at the resonant frequency. Both simulated and measured results indicated a maximum response when the inner electrode coverage was approximately 75% of the nominal PMUT radius.

B. Annular PMUT Array

Each ring of the annular array, consisting of 300 µm PMUTs with 75% inner electrode coverage connected in series, was characterized using the LDV subject a 1 V sine input and a frequency sweep around resonance. The uniformity of the array is plotted on Fig. 2b. It is evident from the plot that the individual resonant frequencies were not entirely uniform over the whole array, resulting in more than 10 kHz of deviation from the average frequency in some areas. Due to this spread, it was determined that the array would be driven at a frequency of 256.6 kHz which resulted in the maximal peak total output pressure of all the measured PMUTs in the array.

The array was connected to the driver board and the resultant acoustic field was measured with the optical microphone. The measurement along with the predicted acoustic field are shown in Fig. 4 for plane sections at heights of 8, 9, and 10 mm. The measured acoustic field distributions are in reasonable agreement with the simulated fields, with a clear demonstration of an acoustic focus at 10 mm above the center of the array. We also observe a linear increase of acoustic pressure at the focal point with respect to increased driving voltage as shown in Fig. 4g.

There are however some notable discrepancies between the measured and simulated acoustic outputs. The acoustic fields of the planes at 8 and 9 mm, although similar, contain slight differences with respect to each other. Moreover, the observed acoustic pressure at the focal point is almost an order of magnitude lower than the expected target pressure of ≥ 1 kPa.

The discrepancies can be attributed to multiple factors that have not been taken into account in the theoretical results, the first of which are related to the non-idealities in regards to driving the array. The driver board was not able to produce accurate phase delays due an inappropriate FPGA system clock, resulting in poor phase resolution with deviations up to 20° from the set-point. Secondly, the non-uniformity of the array was not considered in the simulation, as not all the PMUTs would have been operating optimally. Given that the average bandwidth of the selected PMUTs was measured to be approximately 7 kHz, the PMUTs with larger natural resonant frequency offsets as those seen in Fig. 2 would exhibit a diminished contribution to the output pressure. Finally, both mechanical and acoustical cross-talk between PMUTs within an array was not investigated prior to this work. It is currently assumed that the majority of cross-talk or interference is mechanically based due to the poor rigidity of the polymer materials.

The array was nevertheless able to produce a concentrated acoustical focal point with an appreciable focal pressure, thus demonstrates the feasibility of using this technology for airborne ultrasound applications. We are confident that with further optimizations of the system, that pressure outputs even suitable for haptic feedback will be realized.

IV. Conclusion

In this work, a polymeric annular PMUT array was fabricated for the purposes of demonstrating the capability to perform high pressure acoustic focusing in mid-air for potential airborne ultrasound applications. An electromechanical model based on the polymeric PMUTs was used to understand and design the annular array for an appreciable focal pressure of ≥ 1 kPa at 10 mm above the array. The annular array was successful in producing an acoustic focal point at the target location. The maximum pressure attained at the focal point was approximately 300 Pa. Further investigations of the discrepancy between the simulated and measured focal pressure are on-going, along with optimization of the system to increase the effective pressure output. The results of this work present a promising result for the feasibility of using large-area polymeric PMUTs for airborne ultrasound applications subject to improved performance and fabrication.

Acknowledgment

This work was supported by the FWO project HAPPY: haptic feedback the next step in smart interfacing (ID S004418N).

References

[1] Y. Qiu, J. Gigliotti, M. Wallace, F. Griggio, C. Demore, S. Cochran, and S. Trolier-Mckinstry, "Piezoelectric micromachined ultrasound transducer (pmut) arrays for integrated sensing, actuation and imaging," *Sensors*, vol. 15, no. 4, p. 8020–8041, 2015.

[2] K. M. Smyth, C. G. Sodini, and S. . Kim, "High electromechanical coupling piezoelectric micro-machined ultrasonic transducer (pmut) elements for medical imaging," in *2017 19th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS)*, 2017, pp. 966–969.

[3] X. Jiang, H. Tang, Y. Lu, E. J. Ng, J. M. Tsai, B. E. Boser, and D. A. Horsley, "Ultrasonic fingerprint sensor with transmit beamforming based on a pmut array bonded to cmos circuitry," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 64, no. 9, pp. 1401–1408, 2017.

[4] L. C. J. M. Peters, R. Ollearo, R. G. F. A. Verbeek, J. L. P. J. van der Steen, H. B. Akkerman, A. W. F. Volker, P. L. M. J. van Neer, and G. H. Gelinck, "Low-cost monolithic processing of large-area ultrasound transducer arrays," in *2019 IEEE International Ultrasonics Symposium (IUS)*, 2019, pp. 60–63.

[5] P. Gijsenbergh, A. Halbach, Y. Jeong, G. B. Torri, M. Billen, L. Demi, C.-H. Huang, D. Cheyns, X. Rottenberg, and V. Rochus, "Characterization of polymer-based piezoelectric micromachined ultrasound transducers for short-range gesture recognition applications," *Journal of Micromechanics and Microengineering*, vol. 29, no. 7, p. 074001, May 2019. [Online]. Available: https://doi.org/10.1088/1361-6439/ab1f41

[6] C. Chare, P. Gijsenbergh, V. Rochus, P. Heremans, D. Cheyns, and J. Genoe, "Electromechanical equivalent circuit modeling for axisymmetric pmuts with elastic boundary conditions," unpublished.

[7] A. W. Leissa, *Vibration of plates*. Published for the Acoustical Society of America through the American Institute of Physics, 1993.

[8] L. L. Beranek and T. J. Mellow, *Acoustics: sound fields and transducers*. Academic, 2012.