**Title**

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# HIGH-SPL PMUT ARRAY FOR MID-AIR HAPTIC INTERFACE

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## ABSTRACT

This paper presents a mid-air haptic interface device enabled by a piezoelectric micromachined ultrasonic transducer (pMUT) array achieving an unprecedentedly high transmission pressure of 2900 Pa at a 15 mm distance for the first time. The structure is based on sputtered potassium sodium niobate $(K,Na)NbO_3$ (KNN) thin film with a high piezoelectric coefficient ($e_{31}$ ~ 8-10 C/m$^2$). A prototype KNN pMUT array composed of 15×15 dual-electrode circular-shape diaphragms exhibits a resonant frequency around 92.4 kHz. Testing results show a transmitting sensitivity of 120.8 Pa/cm$^2$ per volt under only 12 $V_{p\text{-}p}$ excitation at the natural focal point of 15 mm away, which is at least 3 times that of previously reported AlN pMUTs at a similar frequency. Furthermore, an instant non-contact haptic stimulation of wind-like sensation on human palms has been realized. As such, this work sheds light on a new class of pMUT array with high acoustic output pressure for human-machine interface applications, such as consumer electronics and AR/VR systems.

## KEYWORDS

Haptic Sensation, PMUT, Ultrasound, KNN, Acoustic Pressure.

## INTRODUCTION

Haptic interfaces can enrich the human-machine interaction experience beyond traditional visual and auditory feedback, by conveying information that can be sensed by mechanoreceptors underneath the skin surface. Mechanoreceptors can respond to various stimulus such as pressure, stretch and dynamic vibration over a wide range of frequencies up to 1 kHz, with the lowest force or displacement threshold around 200 - 300 Hz [1]. Rapidly adapting (RA) receptors, including Pacinian corpuscles and Meissner corpuscles, mainly contribute to the perception of vibration and lateral motion, while slowly adapting (SA) receptors such as Merkel disks and Ruffini endings are more responsive to sustained indentation and skin stretch [2]. On the other hand, the spatial resolution of tactile sensation depends on the densities of mechanoreceptors and their size of receptive fields at specific body sites. For instance, human fingertip can detect a gap close to 2 mm, while the detection threshold for palm is around 10 mm, based on a two-point discrimination method [3].

Current haptic actuators based on the electromagnetic force such as eccentric rotating mass (ERM) or linear resonant actuator (LRA) can induce low frequency vibrations, but suffer from narrow frequency range and large actuation lags [4]. Emerging actuators based on piezoelectric thin film or electrostatic force can achieve wider frequency response, but they often require extremely high excitation voltage. Furthermore, the achievable spatial resolution of contact-mode haptic stimulation is limited by the physical size and shape of the actuators.

Recently, mid-air haptic stimulation has been realized by ultrasonic radiation force and has inspired lots of interests due to their advantages in non-contact mode operation and fine spatiotemporal resolution [5]. By modulating ultrasound carrier signals to lower frequencies for human perception, mid-air haptic actuators can operate over a wide frequency range with fast actuations and diverse stimulation patterns [6]. Moreover, non-contact stimulation is immune from variations of skin surface and hygiene issues. However, current touchless haptic systems based on bulk ultrasonic transducers have very large form-factor in area (tens of centimeters), which is unsuitable for hand-held systems. Piezoelectric micromachined ultrasonic transducers (pMUTs) are promising alternatives with small form-factor, low power consumption, and ease of integration with CMOS electronics. Recently, haptic actuators based on AlN [7-8] and PVDF pMUT arrays [9-10] have been reported, but their acoustic output pressure is limited by the intrinsically low piezoelectric coefficient $e_{31}$ of the active materials even under high driving voltages, resulting in a vague tactile sensation.

Herein, an array of air-coupled pMUTs based on sputtered $(K,Na)NbO_3$ (KNN) thin film with high piezoelectric coefficient has been constructed and its potential as the mid-air haptic interface is experimentally explored. As a result, a high acoustic pressure of 2900 Pa at a 15 mm distance with the corresponding transmitting sensitivity of 120.8 Pa/cm$^2$/V has been attained, enabling instantaneous mid-air haptic stimulation on human palms.

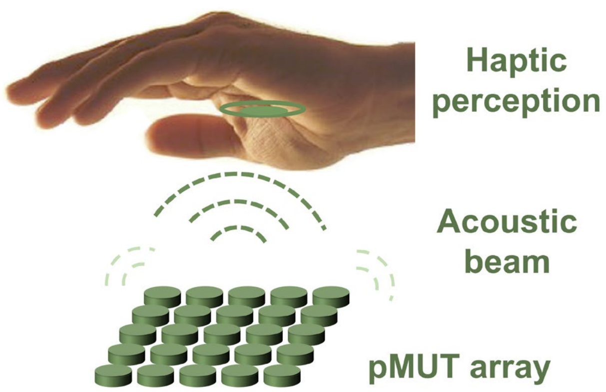


*Figure 1: Illustration of the haptic stimulation on human palms by an array of KNN pMUTs. The transmitted ultrasonic waves propagate through the air and generate an acoustic radiation force over the skin surface.*

# DESIGN AND FABRICATION

## Principle of Design

Mid-air tactile stimulation relies on the phenomenon of acoustic radiation pressure, which is a nonlinear effect of ultrasound on the object within a sound field [11]. This effect allows for application of acoustic radiation force on the skin without requirements of physical contact. The generated ultrasonic waves propagate in the air and get reflected at the air-skin interface due to the large acoustic impedance mismatch (**Figure 1**). As a result, the acoustic radiation pressure exerted on the skin is proportional to the square of the root-mean-square (RMS) sound pressure $p$ [Pa] [12], indicating that high transmitting acoustic pressure from ultrasonic transducers is desired to realize strong stimulation.

PMUTs are capable of converting electrical excitation signals into ultrasonic waves through the converse piezoelectric effect and acoustic radiation impedance. The transmitting performance of pMUT is primarily determined by three factors: 1) the properties of piezoelectric materials, 2) the diaphragm geometry, and 3) the employed driving scheme. Piezoelectric material with high transverse piezoelectric coefficient $e_{31}$ is beneficial for the electromechanical coupling, while smaller acoustic radius (corresponding to higher resonant frequency of pMUT) tends to enhance mechano-acoustic coupling [13]. However, high frequency ultrasound typically experiences greater attenuation during propagation in the air medium, which ultimately leads to a shorter operation distance. Thus, achieving a balance between the transmitting acoustic pressure and operation distance is essential for the design of mid-air haptic actuators based on pMUTs.

In this work, the sputtered potassium sodium niobate $(K,Na)NbO_3$ (KNN) thin film with a high piezoelectric coefficient ($e_{31}$ ~ 8-10 C/m$^2$) is introduced as piezoelectric layer, and an array of 15×15 KNN pMUT elements is utilized as the haptic actuator. The circular KNN pMUT with a diaphragm radius of 500 μm has a unimorph structure consisting of 2-um KNN thin film as the active layer and 5-um Si device layer as the elastic layer. To further boost the vibration amplitude of the diaphragm, dual-electrode design with the differential driving scheme is implemented, where the circular- shaped inner electrode (67% in radius) and the ring-shaped outer electrode are excited by signals with opposite polarity.

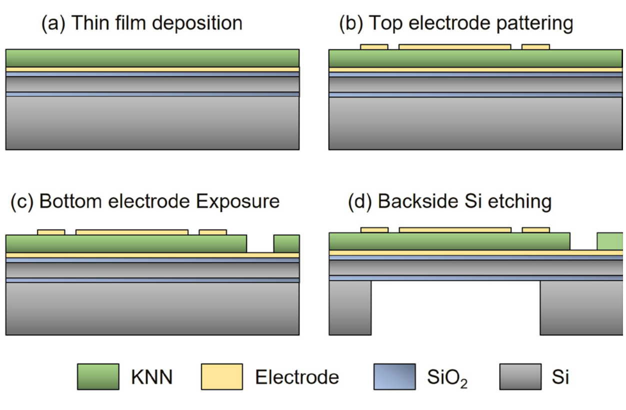


*Figure 2: Fabrication process of the KNN pMUTs. (a) Deposition of bottom electrode and KNN thin film on the SOI wafer, (b) deposition and patterning of top electrode, (c) etching of KNN thin film to expose bottom electrode, (d) DRIE etching of backside Si to define the diaphragm.*

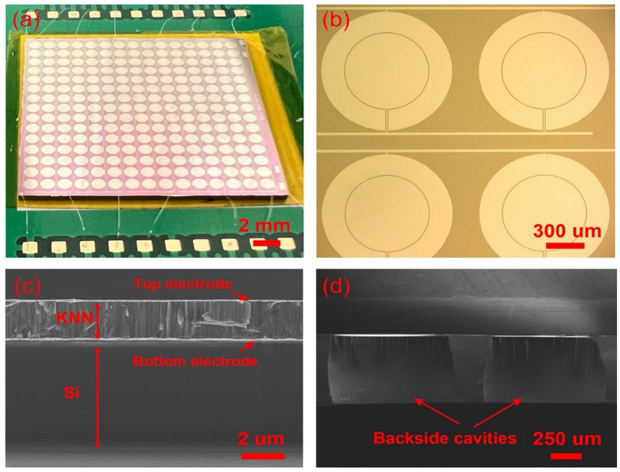


*Figure 3: Characterization results. (a)-(b) optical images of the fabricated KNN pMUT array. The inner electrodes and the outer electrodes in the pMUT array are electrically connected, respectively. (c)-(d) Cross-sectional SEM images, showing the columnar structure of KNN thin film, the tightly stacked layers, and the backside cavity.*

## Fabrication process

The fabrication process of KNN pMUTs is illustrated in **Figure 2**, with the detailed descriptions reported in a previous work [14]. First, the 25 nm-thick ZnO adhesion layer, 200 nm-thick Pt bottom electrode and 2 um-thick KNN thin film [15] are sputtered sequentially on the 6-inch SOI wafer consisting of 5 um-thick Si device layer and 1 um-thick buried silicon oxide. Then 10 nm-thick $RuO_2$ and 100 nm-thick Pt top electrode are sputtered and patterned as the dual-electrode geometry. Afterwards, wet-etching process of KNN thin film is conducted to expose the bottom electrode. Finally, the backside silicon cavity is defined through a deep reactive-ion etching (DRIE) process with the buried oxide layer serving as etching stop.

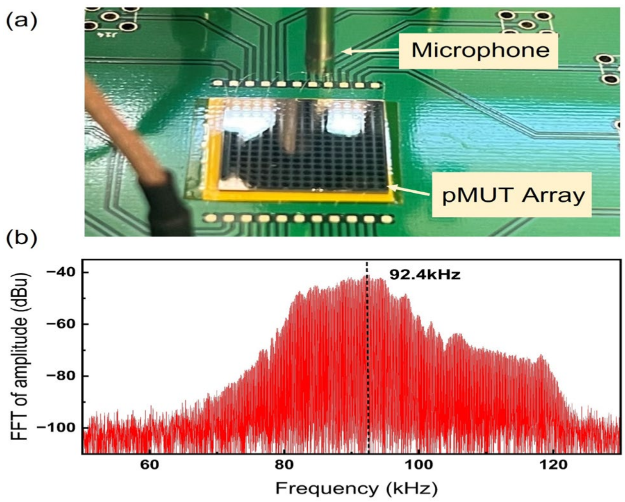


*Figure 4: (a) Pressure measurement setup using a microphone in the ambient air. (b) Frequency response of the KNN pMUT array.*

## RESULTS

### Characterization

Characterization results of the fabricated KNN pMUT array are presented in **Figure 3**. Optical images in **Figure 3a-3b** indicate the smooth surface morphology of the array. The inner electrodes and outer electrodes of each element are electrically connected respectively for ease of the differential driving. In addition, the scanning electron microscope (SEM) is used to examine the microstructure, revealing the columnar structure of KNN thin film, the tight layered structure, and the backside cavities, as shown in **Figure 3c-3d**.

Frequency response of the pMUT array is characterized using a high-sensitivity microphone (Bruel & Kjar, Type 4138) in the ambient environment. A sine-wave chirp signal with frequencies spanning from 50 kHz to 130 kHz is applied to the inner electrode, and the corresponding receiving signal from microphone peaks around 92.4 kHz as shown in the Fast Fourier Transform (FFT) results (**Figure 4**). Furthermore, the pressure field evaluation reveals that the natural focal point of the pMUT array is located approximately 15 mm away from the diaphragm surface. Therefore, all further output pressure evaluations are conducted in the focal area.

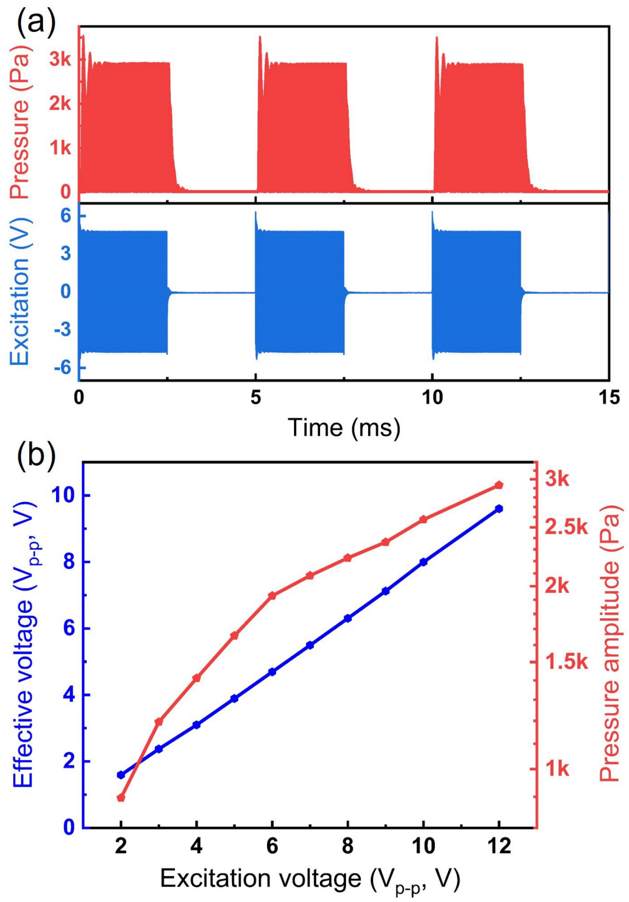


*Figure 5: (a) The excitation signal (12 $V_{p-p}$, blue) and the corresponding output pressure (red) measured by a microphone at the natural focal point of the pMUT array (15 mm away from array surface). (b) Effective input signal and the output pressure amplitude under the differential driving scheme versus the applied excitation voltage.*

### Transmission performance

Ultrasound has the advantage of fast start-up due to its high frequency, but the high frequency signals are not perceptible to mechanoreceptors embedded in the skin. Therefore, the transmitted ultrasound needs to be converted to lower frequencies within the human perception range by means of amplitude modulation (AM). Herein, the pulse width modulation (PWM) scheme is employed, and the details of excitation signal (blue line) and the measured output pressure (red line) are shown in **Figure 5a**. The excitation signal is constituted by a 92.4 kHz carrier frequency, which is the resonant frequency of the pMUT array, and a 200 Hz modulation frequency. Both the carrier and modulation signals are rectangular waves, and the modulation signal has a duty cycle of 50%, corresponding to a pulse width of 2.5 ms within a 5-ms period.

The transmission performance is then analyzed under various excitation voltages. As shown in **Figure 5b**, the output pressure amplitude increases from 896 Pa at 2 $V_{p-p}$ to 2900 Pa at 12 $V_{p-p}$, which corresponds to a RMS sound pressure level around 160.3 dB SPL. This represents the highest output pressure realized using an airborne pMUT array as the mid-air haptic actuators. **Table 1** presents a summary of the transmission performance comparison with other state-of-the-art airborne pMUT arrays, which indicates that the achieved transmitting sensitivity of 120.8 Pa/cm$^2$/V is at least 3 times that of AlN pMUTs at a similar frequency. By applying the beamforming strategy and optimizing the array design to improve the acoustic energy utilization efficiency, the transmission sensitivity of KNN pMUT array can be further enhanced.

*Table 1: Performance comparison with literature*

| Mater. | Freq. (kHz) | Chip area (cm$^2$) | $V_{p-p}$ | Pa @ mm | Pa/cm$^2$/V | Ref. |
|---|---|---|---|---|---|---|
| AlN | 109.4 | 2.25 | 20 | 950@15 | 42.2 | [7] |
| AlN | 596 | 1 | 40 | 410@15 | 20.5 | [8] |
| PVDF | 390 | / | 63 | 1600@20 | / | [9] |
| PVDF | 390 | 4 | 6 | 25.9@8.5 | 2.16 | [10] |
| **KNN** | **92.4** | **4** | **12** | **2900@15** | **120.8** | **This** |

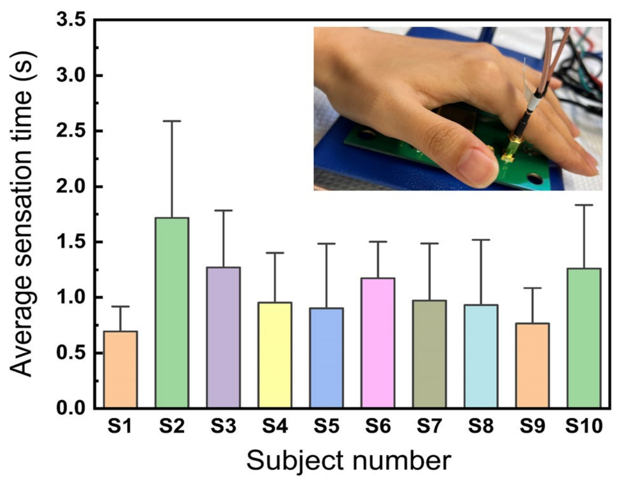


*Figure 6: Average sensation time of ten "switch-on" measurements on volunteers' palm. The inset figure illustrates the haptic stimulation scheme.*

**Volunteer testing results**

The potential of the KNN pMUT array as a mid-air haptic interface is explored via volunteer tests. Ten individuals, including 4 females and 6 males between 20-30 years old, have participated in the experiments. Noise-cancelling earphones are worn by the volunteers throughout the tests to prevent the interference from possible audible sound effects [12]. Ten “switch-on” measurements on the palm have been conducted for each volunteer, and all ten volunteers have reported an instant haptic sensation. **Figure 6** shows the recorded average sensation time with the standard deviation. The haptic sensation experienced by the volunteers is described as a “wind-like pressure”. The air flow felt on the skin accompanying the vibration may be caused by the gradient of pressure localized around the focal point, which can be further reduced by shortening the pulse duration, namely adjusting the duty cycles [16].

# CONCLUSION

This paper has demonstrated a novel mid-air haptic actuator based on the prototype KNN pMUT array. Superior transmission pressure of 2900 Pa at a 15 mm distance has been achieved, which is attributed to the high piezoelectric coefficient ($e_{31}$ ~ 8-10 C/m$^2$) of the sputtered (K,Na)$NbO_3$ thin film and the dual-electrode circular-shape diaphragm geometry with a differential driving scheme for enhanced transmitting efficiency. The resonant frequency of the fabricated pMUT array with 15×15 elements is tested to be 92.4 kHz, and the transmitting sensitivity reaches 120.8 Pa/cm$^2$ per volt under only the 12 $V_{p\text{-}p}$ excitation, which could be further improved by optimizing the array design or applying the beamforming technique. Furthermore, “switch-on” measurements have been performed on human palms, and an instant haptic sensation has been successfully generated. This work highlights the potential of applying pMUT arrays for high-intensity, small form-factor haptic interface.

# ACKNOWLEDGEMENTS

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# REFERENCES

[1] C. Henley, *Foundations of Neuroscience*, United States: Michigan State University, 2021.

[2] S. A. Prescott, and S. Ratté, "Somatosensation and pain", in *Conn's Translational Neuroscience*, pp. 517-539. Academic Press, 2017.

[3] D. R. Kenshalo, "*The skin senses*", Springfield, IL: Charles C Thomas (1968).

[4] C. Basdogan, F. Giraud, V. Levesque, and S. Choi, "A review of surface haptics: Enabling tactile effects on touch surfaces", *IEEE transactions on haptics 13*, no. 3 (2020): 450-470.

[5] G. Wilson, T. Carter, S. Subramanian, and S. A. Brewster, "Perception of ultrasonic haptic feedback on the hand: localization and apparent motion", in *Proceedings of the SIGCHI conference on human factors in computing systems*, pp. 1133-1142. 2014.

[6] S. Inoue, Y. Makino, and H. Shinoda, "Active touch perception produced by airborne ultrasonic haptic hologram", in *2015 IEEE World Haptics Conference (WHC)*, pp. 362-367. IEEE, 2015.

[7] S. Pala, Z. Shao, Y. Peng, and L. Lin, "Ultrasound-induced haptic sensations via PMUTS", in *2021 IEEE 34th International Conference on Micro Electro Mechanical Systems (MEMS)*, pp. 911-914. IEEE, 2021.

[8] M. Billen, P. Gijsenbergh, E. M. Ferrer, M. S. Pandian, X. Rottenberg, and V. Rochus, "PMUT Array Design for mid-air Haptic feedback", in *2022 23rd International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE)*, pp. 1-6. IEEE, 2022.

[9] C. Chare, P. Gijsenbergh, Y. Jeong, P. Heremans, J. Genoe, and D. Cheyns, "High performance large-area polymeric PMUT phased arrays in air", in *2022 IEEE International Ultrasonics Symposium (IUS)*, pp. 1-4. IEEE, 2022.

[10] A. Halbach, P. Gijsenbergh, Y. Jeong, W. Devriese, H. Gao, M. Billen, G. B. Torri et al, "Display compatible PMUT array for mid-air haptic feedback", in *2019 20th International Conference on Solid-State Sensors, Actuators and Microsystems & Eurosensors XXXIII (TRANSDUCERS & EUROSENSORS XXXIII)*, pp. 158-161. IEEE, 2019.

[11] T. Hasegawa, T. Kido, T. Iizuka, and C. Matsuoka, "A general theory of Rayleigh and Langevin radiation pressures." *Acoustical Science and Technology 21*, no. 3 (2000): 145-152.

[12] T. Hoshi, M. Takahashi, T. Iwamoto, and H. Shinoda, "Noncontact tactile display based on radiation pressure of airborne ultrasound", *IEEE Transactions on Haptics 3*, no. 3 (2010): 155-165.

[13] S. Pala, and L. Lin, "An Improved Lumped Element Model for Circular-Shape pMUTs", *IEEE Open Journal of Ultrasonics, Ferroelectrics, and Frequency Control 2* (2022): 83-95.

[14] F. Xia, Y. Peng, S. Pala, R. Arakawa, W. Yue, P. Tsao, C. Chen, H. Liu, M. Teng, J. H. Park, and L. Lin, "High-SPL and Low-Driving-Voltage pMUTs by Sputtered Potassium Sodium Niobate", in *2023 IEEE 36th International Conference on Micro Electro Mechanical Systems (MEMS)*, pp. 135-138. IEEE, 2023.

[15] K. Shibata, K. Watanabe, T. Kuroda, and T. Osada. “KNN lead-free piezoelectric films grown by sputtering”, Appl. Phys. Lett., 121, no. 9 (2022): 092901.

[16] T. Hoshi, D. Abe, and H. Shinoda, "Adding tactile reaction to hologram", *in RO-MAN 2009-The 18th IEEE International Symposium on Robot and Human Interactive Communication*, pp. 7-11. IEEE, 2009.

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