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PMUT Array for Mid-Air Thermal Display

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***Abstract*—This paper presents a mid-air thermal interface enabled by a piezoelectric micromachined ultrasonic transducer (pMUT) array. The two-stage thermal actuating process consists of an ultrasound-transmission process via a pMUT array and an ultrasound-absorption process via porous fabric. The pMUT design employs sputtered potassium sodium niobate (K,Na)NbO$_3$ (KNN) thin film with a high piezoelectric coefficient (e_{31} ~ 8-10 C/m^2) as piezoelectric layer for enhanced acoustic pressure. Testing results show that the prototype pMUT array has a resonant frequency around 97.6 kHz, and it can generate 1970 Pa of focal pressure at 15 mm away under the 10.6 V$_{p\text{-}p}$ excitation. As a result, fabric temperature in the central focal area can rise from 24.2℃ to 31.7℃ after 320 seconds with an average temperature variation rate of 0.023℃/s. Moreover, thermal sensations on the human palms have been realized by the heat conduction through the fabric-skin contact. As such, this work highlights the promising application of pMUT array with high acoustic pressure for human-machine interface, particularly mid-air thermal display.**

***Keywords*— Thermal sensation, PMUT, ultrasound, KNN**

I. INTRODUCTION

Thermal display enriches the interactive experiences by simulating temperature changes while interacting with virtual objects in addition to vibrotactile feedbacks. Haptic actuators using focused ultrasound have the advantages of fine spatiotemporal resolution, remote operation, and multimodal stimulations [1]. Specifically, thermal stimuli can be created by converting acoustic energy to heat through sound absorption or by transporting air via acoustic streaming [2-3]. However, bulk ultrasonic transducers have large form factors for wearable consumer electronic products.

Piezoelectric micromachined ultrasonic transducers (pMUTs) are promising alternatives due to their small form-factor, low power consumption and ease of integration. However, their potential to generate thermal stimuli is yet to be explored due to low transmitting pressure limited by the low piezoelectric coefficient of active materials such as AlN [4]. This study reports an array of air-coupled pMUTs with the sputtered potassium sodium niobate (K,Na)NbO$_3$ (KNN) thin film of high piezoelectric coefficient (e_{31} ~ 8-10 C/m^2) as the thermal haptic actuators for the first time.

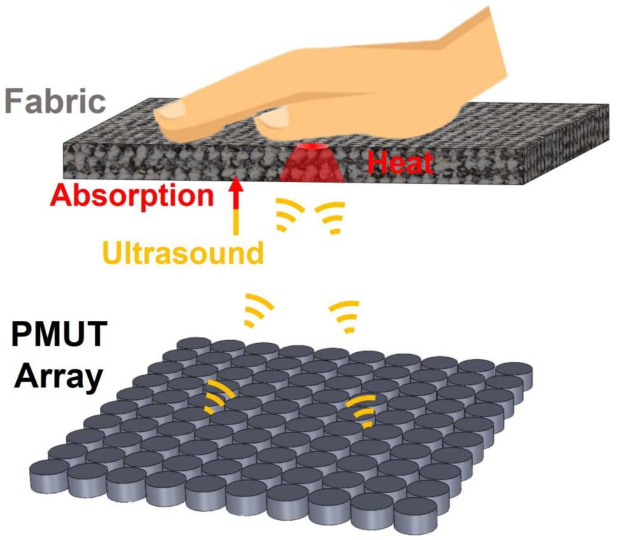

Fig. 1. Illustration of thermal stimulation on the human palm using a KNN pMUT array and fabric. Ultrasonic waves emitted from the pMUT array travel through the air and are absorbed by the porous fabric. The sound absorption increases the temperature of fabric, creating a thermal sensation on the palm.

II. DESIGN AND FABRICATION

A. Principle of Design

The thermal haptic actuating process consists of a pMUT array to transmit ultrasound and porous fabric to absorb ultrasound (Fig. 1). For the first stage, a KNN pMUT array, composed of 15×15 circular unimorph diaphragms with a 2 µm-thick KNN piezoelectric layer and a 5 µm-thick Si elastic layer, is utilized as the thermal actuator. The transmitted ultrasonic waves propagate through the air before being absorbed, thus the pMUT geometry is optimized to balance the acoustic pressure and propagation attenuation. Besides, a dual electrode design with the differential driving scheme is applied to actuate individual pMUT in order to enhance the output acoustic power.

For the second stage, porous cotton & nylon fabric is used as the sound absorption medium to convert ultrasound energy to heat energy. The increased fabric temperature due to heat generation renders the thermal sensation on human palm via heat conduction through the fabric-skin contact. In order to maximize the absorbed ultrasound, the fabric is placed at the focal plane of the pMUT array.

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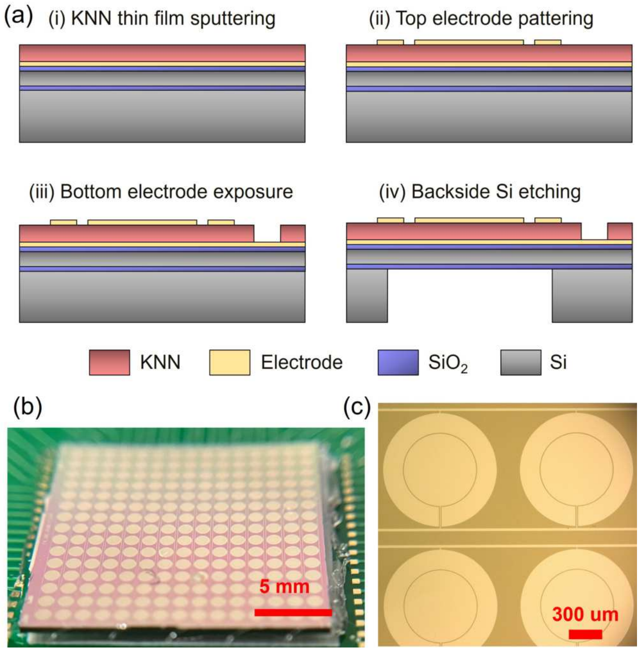

Fig. 2. Fabrication process and characterization results. (a) Fabrication process: (i) bottom electrode and KNN thin film deposition on SOI wafer, (ii) top electrode deposition and etching, (iii) etching of KNN thin film to reveal bottom electrode, (iv) backside silicon DRIE etching. (b-c) The fabricated pMUT array with inner and outer electrodes interconnected, respectively.

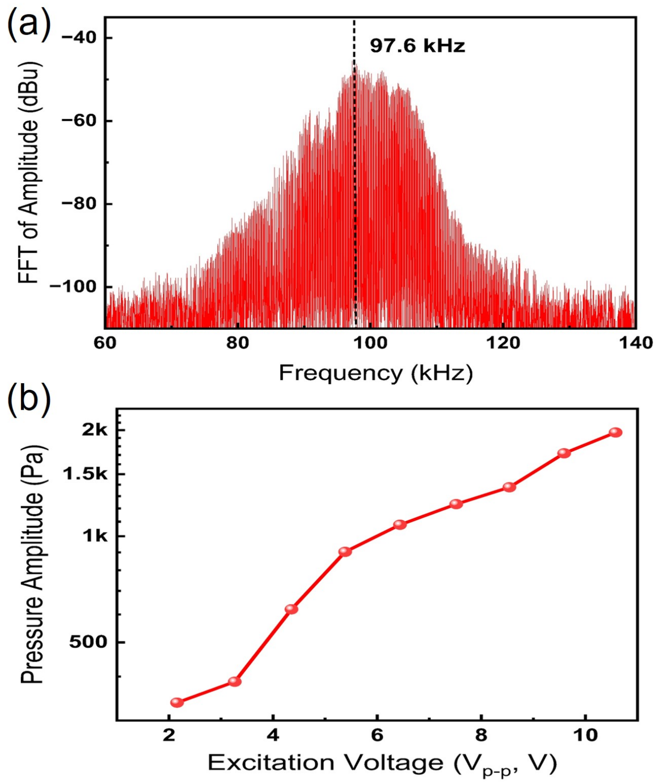

Fig. 3. Pressure measurement results using a microphone in the ambient air environment. (a) Frequency response of the KNN pMUT array, with resonant frequency around 97.6 kHz. (b) Pressure amplitude around focal area versus the effective excitation voltage applied across inner and outer electrodes using the differential driving method.

B. Fabrication and device characterization

The fabrication process of KNN pMUT array is illustrated in Fig. 2a. Detailed descriptions are available in previous work [5]. First, ZnO adhesion layer, bottom electrode, and KNN thin film [6] are successively sputtered onto SOI wafer, which includes a 5 μm-thick Si device layer and a 1 μm-thick buried silicon oxide. Then, RuO_2/Pt top electrode is sputtered and shaped into a dual-electrode design. Afterwards, KNN thin film is wet-etched to reveal the bottom electrode. Finally, a backside silicon cavity is formed using a deep reactive-ion etching (DRIE) method, and the buried oxide layer acts as the etching stop during the process.

The characterization results of the fabricated pMUT array are shown in Fig. 2b-2c. The radius of each pMUT element is 500 μm and the size of the array is around 2 cm by 2 cm. The images clearly show that inner electrodes and outer electrodes are electrically interconnected for applying differential driving signals to all elements at the same time.

III. RESULTS

The pMUT array with a resonant frequency of 97.6 kHz (Fig. 3a) can transmit 1970 Pa of focal pressure at 15 mm away under the 10.6 V_{p-p} excitation (Fig. 3b). Therefore, the fabric is fixed at 15 mm away from the surface of the pMUT array using a XYZ-stage (Fig. 4a). Thermal camera (FLIR A320) is utilized to track the fabric temperature during the heating process. The thermal emissivity is set as 0.88 for the cotton & nylon fabric [7]. Starting from a room temperature of 24.2℃, fabric temperature in the central focal area can rise to 31.7℃ after 320 seconds with an average temperature variation rate of 0.023℃/s, which is faster than that of the peripheral area due to higher ultrasound intensity in the focal region (Fig. 4b-4c). Moreover, thermal sensations on the palms of 5 volunteers are successfully tested by the heat conduction through the fabric-skin contact (Fig. 5).

IV. CONCLUSION

This work introduces a novel mid-air thermal interface based on pMUT array for the first time. Piezoelectric material, KNN, with high piezoelectric coefficient is utilized as piezoelectric layer for improved acoustic pressure transmission at the first stage. Porous fabric is placed around focal plane of pMUT array to maximize acoustic energy conversion at the second stage. As a result, the prototype KNN pMUT array generates 1970 Pa focal pressure at 15 mm away, which turns out to heat up the fabric by 7.5 ℃ over 320 seconds. Furthermore, through heat conduction via fabric-skin contact, thermal sensations on human palms have been successfully realized. These results underscore the air-coupled pMUT array with high acoustic pressure and small form factor as a promising candidate for thermal display.

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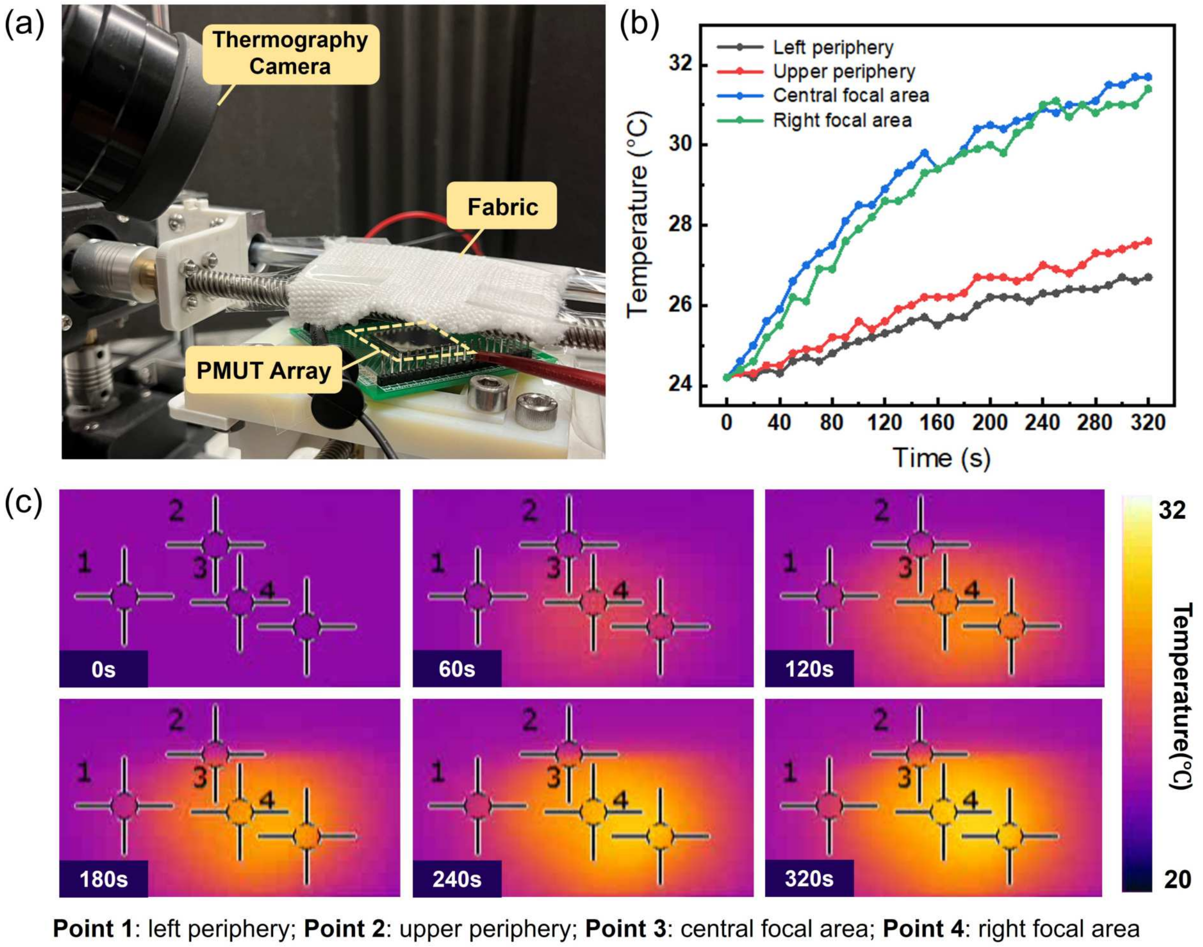

Fig. 4. Thermal experiment setup and results. (a) Setup consists of 1) a XYZ-stage for pMUT array and fabric positioning; 2) a FLIR thermal camera for fabric temperature tracking. (b) Temperature trends at four representative positions of fabric. (c) Thermal images showing accelerated heating process around focal area.

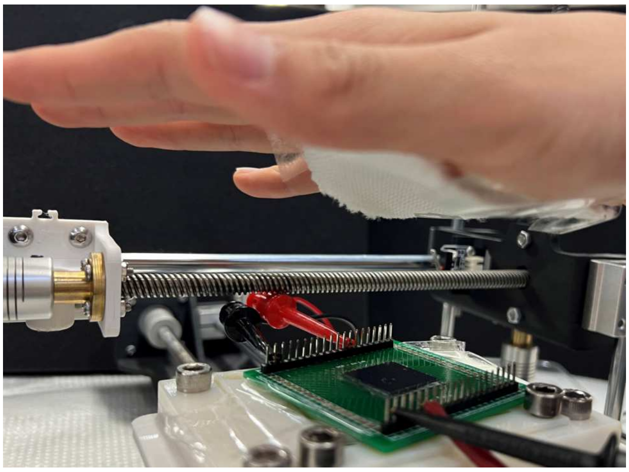

Fig. 5. Volunteer tests. Thermal sensations on the human palms are rendered by the heat conduction through the fabric-skin contact.

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