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HIGHLY EFFICIENT PIEZOELECTRIC MICROMACHINED ULTRASOUND TRANSDUCER (PMUT) FOR UNDERWATER SENSOR NETWORKS

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ABSTRACT
A low voltage (<3V) PMUT based ultrasound transducer to perform ultrasonic communication for underwater sensor nodes at distances of 1-2 m is presented. The parasitic components of the PMUT array were minimized to improve its frequency response and power consumption. For the first time, the concept of coupled Piezoelectric Bulk Micromachined Ultrasound Transducer (cPB-MUT) is introduced. In a cPB-MUT, the small PMUT elements are coupled to the bulk silicon substrate through the vibration of water, which produces a strong vibration in the entire substrate. This leads to a 209 Pa/V@1cm transmission sensitivity and above 43dB SNR@20cm, at 33 kHz underwater, using 3 Vp-p.

KEYWORDS
Piezoelectric Micromachined Ultrasound Transducer (PMUT), PZT, ultrasound communication, cPB-MUT.

INTRODUCTION
Following the introduction of Internet of Things (IoT) as a technological revolution of computing and communications to interconnect terrestrial applications, Underwater Sensor Networks (USN) or more recently, Internet of Underwater Things (IoUT) [1], were adopted to tackle many scientific and industrial activities [2]. An USN is defined as a large number of smart underwater sensor nodes, physically distributed near the objects under investigation, and able to communicate wirelessly in a network [3]. USNs are envisioned to enable applications for oceanographic data collection, pollution monitoring, assisted navigation [4], aquarium observation, harbor security, tactical surveillance applications [1], pipeline inspection, etc. To render these applications viable, it is mandatory that the submerged devices are equipped with some form of ultrasonic communication [5], [6].

Recently, PMUTs, because of their small size and excellent performance, have received considerable attention as an alternative transducer technology. However, they are still not fully compatible with USN applications, since their generated output pressure is significantly lower than conventional bulk transducers. This problem is even more pronounced at lower frequencies, which is mainly used in underwater sensor nodes for long distance communication. For instance, Zhou *et al.* presented an in-air range finding PMUT with 2 m range at 1 V drive and at 155 kHz, which has one of the highest generated pressure as <8 Pa/V @ 1cm by consuming about 775 µW power. This value of generated pressure is still far from the conventional transducers in sonar applications.

The two main problems of PMUTs, specially at low frequencies, are, (i) the large parasitic capacitances (C), which in combination with the parasitic resistance (R) forms a low pass filter with a 3dB bandwidth that is lower than the mechanical resonance frequency; and (ii) the small dimensions of PMUTs with respect to the wavelength of the ultrasound wave in the working medium, which leads to a low real acoustic output power [7]. Actually, the RC time constant of a PMUT acts as a low-pass filter and degrades the applied input power significantly. Basically, the parasitic RC consumes most of the input power to charge and discharge the capacitor, so only a small fraction of input electrical power is transferred to the mechanical-acoustical domain.

In this paper, we introduce a novel PMUT based ultrasound transducer for underwater communication at 1-2 m distance range and with < 3.3 V actuation voltage. One approach to reduce the RC value of a PZT based PMUT array was to introduce modifications in the fabrication process. The second approach addressed problem of the small dimension of PMUTs and low acoustic output power, which was alleviated by introducing the concept of coupled piezoelectric bulk-micromachined ultrasound transducers (cPB-MUT). As discussed later, the vibration of the PMUT membranes was coupled to the silicon (Si) substrate by the surrounding water. In this way, the bulk-Si substrate, which was bonded to a PCB, was driven into a strong vibration. Consequently, the dimension of the vibrating transducer was comparable with the wavelength and the output pressure was improved significantly.

MATERIAL AND METHODS
The concept of cPB-MUT

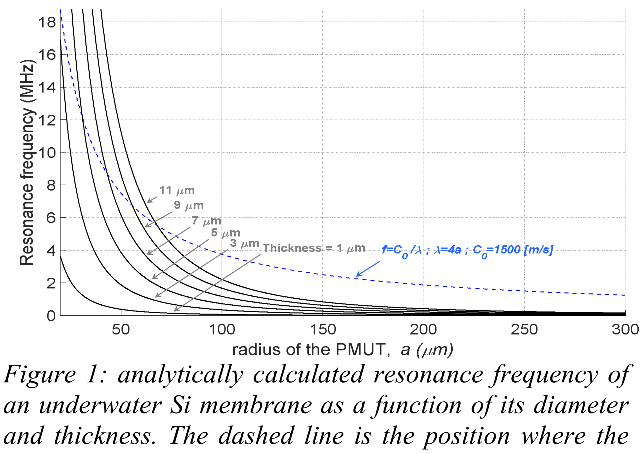

Figure 1: analytically calculated resonance frequency of an underwater Si membrane as a function of its diameter and thickness. The dashed line is the position where the diameter of the membrane is half of the wavelength.

It has already been proven that, in order to reduce the reactive acoustic output power and to increase the real power, the dimension of the PMUT membrane, or any other kind of ultrasound transducer, should be larger than the wavelength [8]. Fig. 1 shows the analytically calculated resonance frequency of an underwater Si membrane as a function of its diameter and thickness. The dashed line is the position where the diameter of the membrane is half of the wavelength. As shown, in order to keep the resonance frequency low and the diameter comparable with the wavelength, the thickness of the membranes should be increased significantly. However, a thick membrane requires a thick piezoelectric layer and a high actuation voltage to induce sufficient bending moment.

The dimension of a transducer with respect to the wavelength can be characterized by ka, where k is the wavenumber and is equal to $2\pi/\lambda$, with λ is being the wavelength, and a the radius of the transducer. If $ka<<1$, then most of the generated power is reactive. Reactive power is consumed to bring the medium in front of the transducer in a back-and-forth vibration. The extra mass of the medium which is brought into vibration by the transducer membrane can be calculated by:

$$m = \rho_m S(8a/3\pi) \quad (1)$$

where ρ_m is the density of the medium and S is the surface area of the membrane. The volume of the medium in vibration can be modeled by a cylinder with cross-section area S and a height of $(8a/3\pi)$.

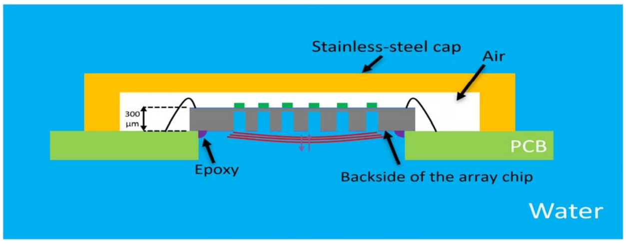

Figure 2: Conceptual schematic of the cPB-MUT.

Fig. 2 shows the concept of the cPB-MUT. As shown, a 12x12 PMUT array is fabricated, in which each PMUT has a diameter of 410 µm and Si thickness of 6 µm. The fabricated array was wire-bonded to the PCB from the front side and bonded to the PCB from the backside. The front side of the chip was encapsulated by a stainless-steel cap to protect it from the water. The back side of the chip was exposed to water through a 11 mm x 11 mm square hole in the PCB. Through the water, the vibrations produced by the PMUT membranes can transmit its mechanical power to the back side of the silicon substrate. In another word, the vibration of the PMUT membranes was coupled to the Si substrate. Accordingly, the resonance frequency is defined as the resonance frequency of the 11 mm x 11 mm bonded substrate, which is 33 kHz in our case. This means that the ka value of each PMUT is much smaller than one. Therefore, there is a strong reactive power, and consequently, a vibration in the water in front of the array. Accordingly, the vibration of water brings the whole substrate into resonance. The vibration of the substrate has a comparable dimension with respect to the wavelength (ka>1), which leads to a significant higher output pressure. Fig. 3 shows the FEM simulation of the first mode of vibration displacement of the proposed cBP-MUT underwater.

FABRICATION PROCESS

The fabrication process of a cPB-MUT is divided into two parts: first, the fabrication of the PMUT array and, second, the wire-bonding, bonding, and encapsulation of the array chip on the PCB to realize the cBP-MUT.

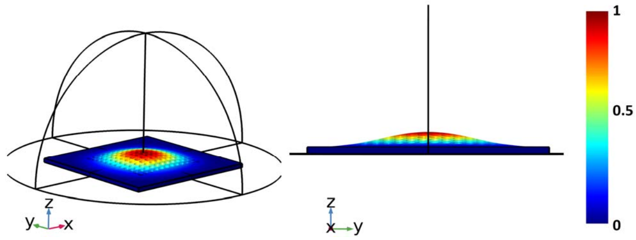

Figure 3: The FEM simulation of the first mode of vibration displacement of the cBP-MUT placed underwater. The displacement is normalized.

Fabrication of the PMUT array

As mentioned earlier, one of the main drawbacks of PZT-PMUTs are the large parasitic capacitance. The parasitic capacitance consumes most of the input electric power, which can be calculated by (2):

$$P_{cap} = ½.f.C.V^2 \quad (2)$$

where f is the mechanical resonance frequency, C the parasitic capacitance, and V the actuation voltage. Accordingly, the mechanical domain receives less power from the front-end electronics. To reduce the parasitic capacitance of the PMUT array, a SiO_2 layer was deposited everywhere except on top of the membranes. The low permittivity of the SiO_2 layer with respect to the PZT results in a significant reduction of the parasitic capacitance. Furthermore, the parasitic resistance was reduced by using a stack of Ti/Ag/Ti/Pt metal layers as the top electrode.

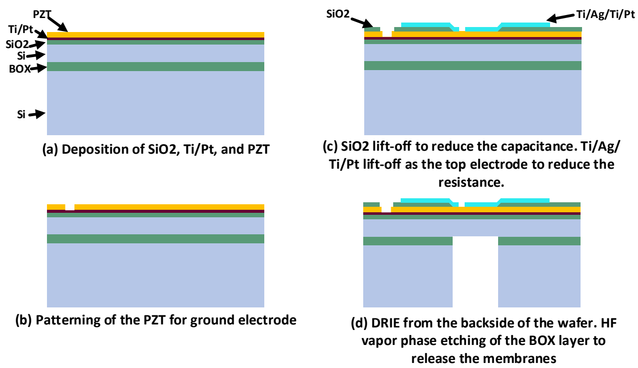

Figure 4: The fabrication process of the PMUT array. (a) SiO_2/Ti/Pt were deposited as the bottom electrode; (b) The PZT layer was patterned to access to the bottom electrode; (c) A SiO_2 layer followed by the top electrode were deposited to minimize the parasitic capacitance; (d) the membranes were released by a DRIE process and removing the BOX layer by HF vapor phase etching.

Fig. 4 shows the fabrication process of the PMUT array. First, SiO_2/Ti/Pt were deposited on top of a SOI wafer as the bottom electrode. Then, a 1 µm PZT layer was deposited by a sol-gel process and patterned to access to the bottom electrode [9]. A 250 nm SiO_2 layer was sputtered on top of the PZT layer as an isolation layer between the top electrode and the PZT. The top electrode layers, which consisted of a stack of Ti/Ag/Ti/ Pt, were deposited and patterned with thicknesses of 20 nm/250 nm/20 nm/150 nm, respectively. Finally, the backside of the wafer was etched by a Deep Reactive Ion Etching (DRIE) process to reach to the Buried Oxide (BOX) layer and the membranes were released by removing the BOX layer by HF vapor phase etching.

To further increase the displacement of each PMUT, a ring electrode was used on top of the membranes, where the induced stress during the deflection has opposite sign with respect the center of the membrane. The ring electrode was actuated with a 180° phase-shifted signal compared to the central electrode. This maximized the applied bending moment to the membrane and leads to a higher displacement. An optical microscopy image of each PMUT is shown in Fig. 5(a).

Fabrication of the cPB-MUT

As shown in Fig. 2, the fabricated and diced PMUT array chip was adhered to a PCB by a two components epoxy. Afterwards, the chip was wire-bonded to the PCB. The front side of the chip was encapsulated by a stainless-steel cap to protect it from water, while the backside of the array chip was exposed to water through a hole in the PCB. This way of packaging ensures underwater ultrasonic wave transmission with minimum risk of damage against water with any degree of salinity. The waterproofness and sufficient high bonding strength between the chip and the PCB were obtained by applying Epotek H54 epoxy at the edges of the PCB and the backside of the array chip, as shown in Fig. 2. The Epotek H54 was applied by a micro-dispenser and was cured on a hot-plate at 150°C for 10 minutes.

Fig. 5 shows the wire-bonded chip on the PCB, the stainless-steel encapsulation, and the backside of the chip through the hole in the PCB.

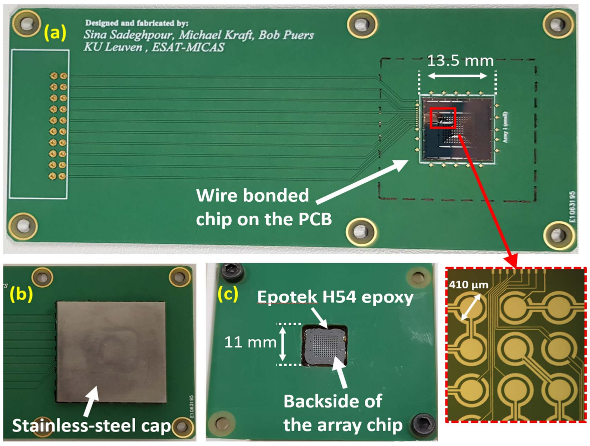

Figure 5: (a) Wire-bonded PMUT array chip on the PCB; (b) stainless-steel cap to encapsulate the front side of the chip; (c) backside of the chip.

RESULTS AND DISCUSSION

In-air measurement of the PMUT array

Each PMUT element in the fabricated array chip was characterized by a Laser Doppler Vibrometer (LDV) (Polytec MSA-500, Waldbronn, Germany). Fig. 6(a) shows the frequency response of the PMUT in-air. The PMUT has a resonance frequency of about 496 kHz. The measured modes of vibration are shown in the insets of Fig. 6(a). The time domain response of each PMUT to the actuation of the center electrode as well as the ring electrode and center/ring electrodes with 0.1 $V_{p\text{-}p}$ are shown in Fig. 6(b). It should be noted that the center/ring electrodes were actuated with 180° phase difference. The obtained displacement by actuating the center electrode, the ring electrode, and the center/ring electrodes was 1.12 µm/V, 0.78 µm/V, and 2.4 µm/V, respectively.

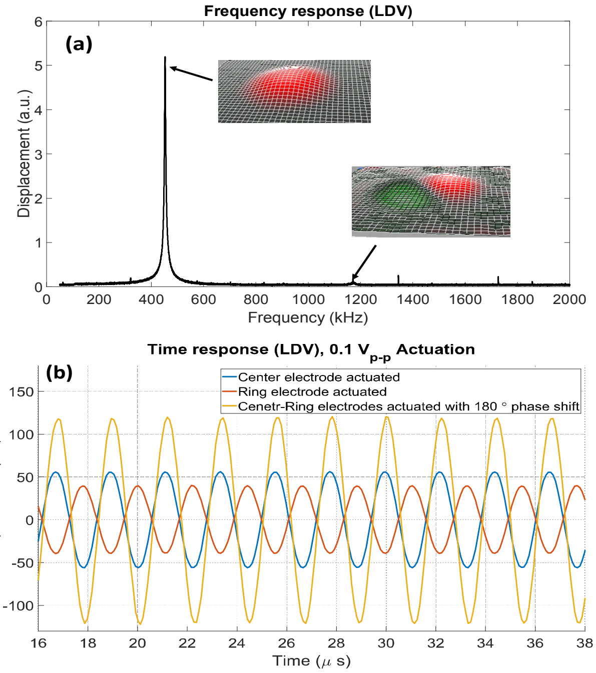

Figure 6: Frequency response (a) and time resonance (b) of the PMUT measured by LDV.

Using the center/ring electrodes with 180° phase shift between them increased the displacement by 215% in comparison to actuating the center electrode alone.

Underwater measurement of the cPB-MUT

The fabricated cPB-MUT was measured underwater in an in-house built 600-liter measurement setup as shown in Fig. 7.

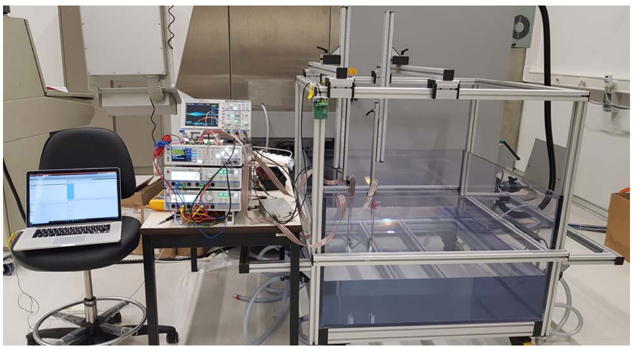

Figure 7: The measurement setup.

The transducer was measured in mutual communication with another cPB-MUT transducer. The interface electronic circuits used as the transmitter and receiver are shown in Fig. 8(b). A voltage amplifier and a charge amplifier were used as the transmitting and receiving circuit, respectively. A charge amplifier at the receive side was mainly used to remove the effect of the PMUT's parasitic capacitance on the amplifier gain. Furthermore, a charge amplifier amplifies the sum of the generated charges from each individual PMUT.

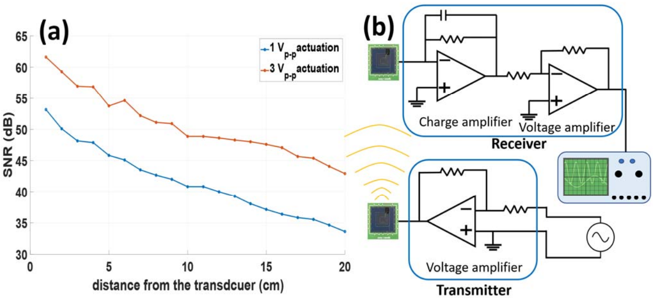

Figure 8: (a) Signal to noise ratio (SNR) with respect to the distance; (b) interface electronic circuits.

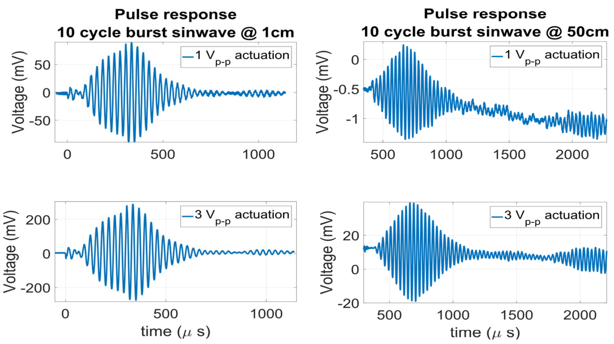

Figure 9: Time response of a mutual communication between two cPB-MUTs at 1 cm and 50 cm.

The peak to peak noise level of the receiving circuit was considered to be 900 µV. Accordingly, Fig. 8(a) shows the Signal to Noise Ratio (SNR) of the communication as a function of the distance from the surface of the transducer. The SNR at 20 cm with 3 $V_{p\text{-}p}$ actuation signal is more than 43 dB. Fig. 9 shows the time response of the cPB-MUT transducer to a 33 kHz, 1 $V_{p\text{-}p}$ and 3 $V_{p\text{-}p}$ sinusoidal burst signal with 10 cycles at 1 cm and 50 cm. According to the results of Fig. 8 and 9, one can conclude that the underwater ultrasound communication between two cPB-MUTs at 1 m is possible by a 3 $V_{p\text{-}p}$ actuation.

Table 1: The underwater pressure response of the cPB-MUT with respect to the other PMUT transducers.

	Transmission sensitivity (Pa/V@1cm)
[10]	1.5 (96 kHz)
[11]	~5 (155 kHz)
[12]	~27 (1.2 MHz)
Our work	**209 (33 kHz)**

The pressure response of the transducer was measured by a 1mm needle hydrophone (Precision Acoustic, UK) at 1 cm. It was found to be around 209 Pa/V @ 1 cm. This is around 2 orders of magnitude higher than the recorded value of the state-of-the-art transducers, as shown in Table 1.

CONCLUSION

A novel PMUT based ultrasound transducer has been designed, fabricated and tested. In the proposed transducer, termed cPB-MUT, the vibration of small PMUT elements was coupled to the silicon (Si) substrate by the surrounding water, which results in vibrations of the entire substrate. The transducer has a remarkable pressure response of 209 Pa/V @ 1 cm and more than 43 dB SNR at 20 cm in mutual communication with another cPB-MUT transducer.

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