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Coupled Piezoelectric Bulk-Micromachined Ultrasound Trasndcuer (cPB-MUT): An Ultrasound Transducer with Enhanced Pressure Response in Liquid and Dense Medium

Sina Sadeghpour
Dep. of electrical engineering (ESAT)
KU Leuven
Leuven, Blegium
sina.sadeghpour@esat.kuleuven.be

Michael Kraft
Dep. of electrical engineering (ESAT)
KU Leuven
Leuven, Blegium
michael.kraft@kuleuven.be

Robert Puers
Dep. of electrical engineering (ESAT)
KU Leuven
Leuven, Blegium
puers@esat.kuleuven.be

***Abstract*—A new type of ultrasound transducer based on piezoelectric micromachined ultrasound transducer (pMUT) technology was developed, which is called coupled piezoelectric bulk-micromachined ultrasound transducer (cPB-MUT). In this transducer technology the vibration of small pMUTs are coupled to the bulk silicon substrate through the vibration of water or any other dense medium; this produces a strong vibration in the entire substrate. CPB-MUT was designed for underwater applications such as underwater sensor networks and underwater communication in the range of 1-2 meters. A cPB-MUT with a resonance frequency of 33 kHz was fabricated. It is capable of producing about 210 Pa/V at 1cm underwater.**

Keywords—piezoelectric micromachined ultrasound transducer (pMUT), piezoelectric, coupling, underwater communication

I. Introduction

Since the introduction of microelectromechanical system (MEMS) technology, many new micro-devices in the field of sensors and actuators have been developed. Moreover, many conventional devices were substituted by a MEMS solution. MEMS device are miniaturized, more power efficient, and much cheaper to produce specially for mass production purposes. Recently, micromachined ultrasound transducers (MUTs) have been tried as an alternative to conventional and large ultrasound transducers in many application, such as non-destructive testing and evaluation [1], finger-print sensors [2], in-air range finding and gesture recognition [3], haptic feedback, and medical imaging [4]. However, reaching the required performance of transducers for underwater sensor network (USN) applications by MUT technology is still a challenge [5].

Recently, piezoelectric MUTs (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 PZT transducers. This problem is even more pronounced at lower frequencies, which are 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 (<8 Pa/V @ 1cm), while consuming about 775 μW power [6]. This value of generated pressure is still far from the conventional transducers in sonar applications. Moreover, the pMUT was fabricated by a very efficient, but hard to process, piezoelectric material (PMnN-PZT).

It is well known that in order to produce high output acoustic power, the lateral dimension of the transducer should be bigger than half of the transmitted wavelength [7]. The lateral dimension of pMUTs, due to their thin membrane thickness, is usually smaller than the wavelength. This problem is more pronounced for low frequency applications (<1 MHz). Therefore, current pMUT technology is not capable of transmitting a high amount of pressure in underwater low frequency applications.

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. This transducer is called coupled piezoelectric bulk-micromachined ultrasound transducers (cPB-MUT). As discussed later, the vibration of the PMUT membranes was coupled to the bulk 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.

II. Materials and Methods

In general, the output acoustic pressure of micromachined ultrasound transducers (MUTs) are low compare to bulk PZT disk technology. The reason is that in most cases MUT resonators are much smaller than the wavelength of the transmitted wave [7,8]. This phenomenon is amplified when the pMUT is used underwater, or in general in dense medium applications, since for a constant frequency the wave length is larger with respect to in-air applications. The dimension of the pMUT membrane with respect to the wavelength can be characterized by ka, where k is the wavenumber and is equal to

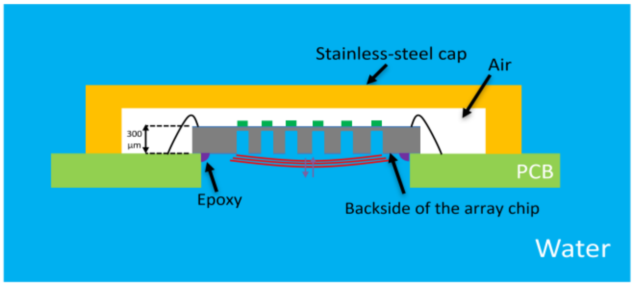

Fig. 1. Conceptual illustration of the cPB-MUT

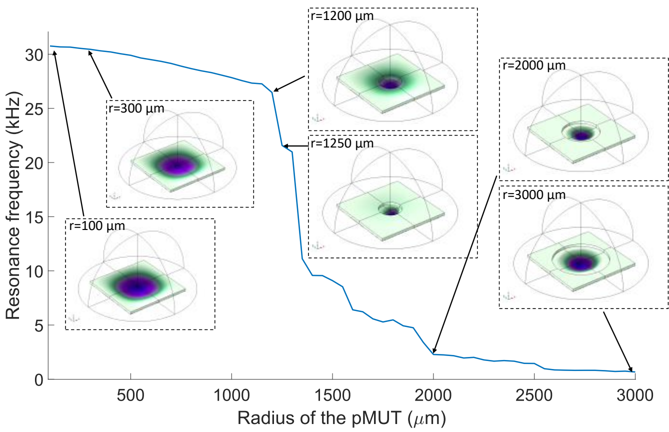

Fig. 2. FEM eigenfrequency simulation of a bulk Si plate as a function of the radius of a singular pMUT

$2\pi/\lambda$, 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 (water in this case) in front of the transducer in a back-and-forth vibration [7,9]. Therefore, for an underwater pMUT with a frequency range of less than 2 MHz, typically the diameter of the membrane is much smaller than the wavelength. In other words, ka is much smaller than one and most of the acoustic power is reactive.

In our work, the reactive power (the vibration of the medium) is transferred to an active power by coupling it to the vibration of the bulk silicon substrate. The conceptual illustration of the cPB-MUT is shown in Fig. 1, in which a conventional pMUT array is bonded to a PCB. By exciting the pMUT elements at the resonance frequency of the bulk silicon substrate, water in front of each pMUT becomes into resonance. The vibration of the water is coupled to the bulk Si and brings it into a strong resonance. Therefore, the total vibrating area is comparable to the wavelength and results in a higher output active acoustic power.

Fig. 2 shows the FEM eigenfrequency simulation of bulk Si as a function of the radius of a singular pMUT. The bulk Si plate had a thickness of 300 μm and a dimension of 8x8 mm, whereas the pMUTs had a thickness of 6 μm with 1 μm PZT layer, with varying diameter. The maximum dimension of the pMUT in a cPB-MUT configuration is the one which results in a resonance frequency near or equal to the resonance frequency of the bulk Si. This is a critical dimension, since a larger lateral dimension results in a lower resonance of the pMUT than that of the bulk

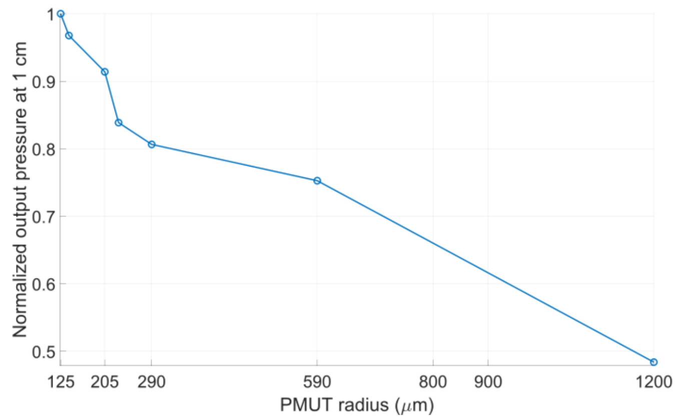

Fig. 3. FEM simulation of the output pressure of several pMUT arrays with different lateral dimensions. The total size of the pMUT arrays was kept constant and equal to the area of the single pMUT with radius of 1200 μm.

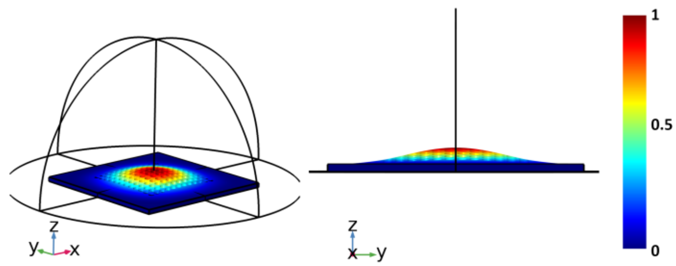

Fig. 4. FEM simulation of the first mode of vibration displacement of the cBP-MUT with 12x12 pMUT array placed underwater. The displacement is normalized.

Si. This means that the bulk Si does not vibrate anymore and this is only the pMUT that vibrates. Bulk Si is stationary and works as an anchor for the pMUT, as shown in Fig. 2 for r>1200 μm. By trespassing the radius of 1200 μm in the pMUT membrane, the resonance frequency dropped suddenly and the bulk silicon became stationary. This will reduce the effective area with respect to the wavelength and decrease the output acoustic power. Consequently, the maximum radius of the pMUTs in cPB-MUT is limited to a value with an equivalent resonance frequency of the bulk Si.

Fig. 3 shows the FEM simulation of the output pressure of several pMUT arrays with different lateral dimensions, while the total size occupied by pMUTs was kept constant and equal to the area of a single pMUT with the radius of 1200 μm. This is chosen, since a pMUT with the radius of 1200 μm is the maximum size that can be used in the cPB-MUT. Unquestionably, by choosing a smaller pMUT radius, more pMUTs should be considered in the array. As show in Fig. 3, by reducing the dimension of pMUTs, the output pressure tends to increase. This may have two reasons. (i) By increasing the pMUT radius, the bulk Si becomes more rigid and takes the role of anchor for the pMUT. This reduces the vibration amplitude of the bulk Si and thus the output acoustic power. (ii) Furthermore, by increasing the pMUT radius, the generated reactive power reduces as well, which results in less coupling between the water and bulk Si.

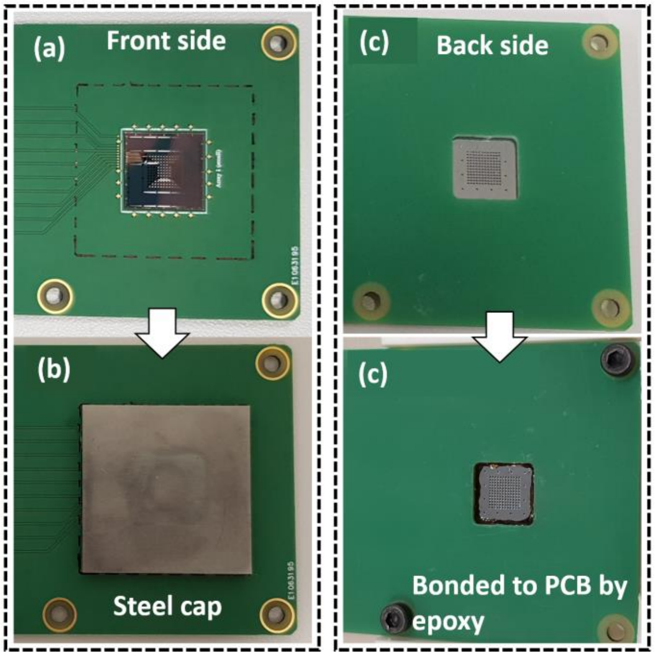

Fig. 5. Fabrication steps of the cPB-MUT. (a) the pMUT array chip was placed in a PCB with a window, and wire bonded; (b) the chip is protected against water by a stainless-steel cap; (c) backside of the chip through the window in the PCB; (d) the chip was bonded to the PCB by Epotek H54 epoxy.

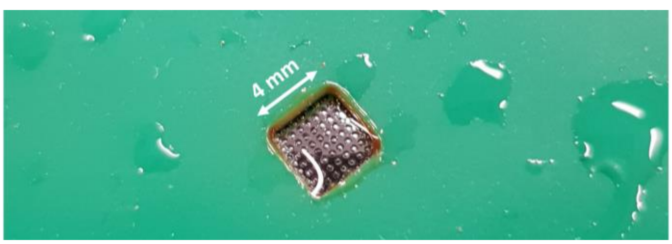

Fig. 6. CPB-MUT with a smaller PCB window and, therefore, a higher resonance frequency.

On the other hand, a small pMUT in the array has also some practical issues. For instance, water cannot easily penetrate into the trench of pMUTs. Moreover, a small pMUT does not vibrate very efficient in a very low frequency. Therefore, we have chosen a 12x12 pMUT array, in which each pMUT has a radius of 205 μm and a thickness of 6 μm. Fig. 4 shows the FEM simulation of the normalized first mode of vibration displacement of the cBP-MUT with 12x12 pMUT array placed underwater.

III. Fabrication

The pMUT array of the proposed cPB-MUT was fabricated by the process explained in [10-12]. A 1 μm PZT layer was used as the piezoelectric material. The fabrication process of the cPB-MUT is compatible with any pMUT array chip. As illustrated in Fig. 1, the cPB-MUT was fabricated by first putting the array chip on a PCB with an opening (window) with the desired dimension, which defined the resonance frequency; second, wire bonding the chip to the PCB in order to access to the bond pads of the different pMUT elements in the array; third, encapsulating the pMUT array by a stainless-steel cap; and forth

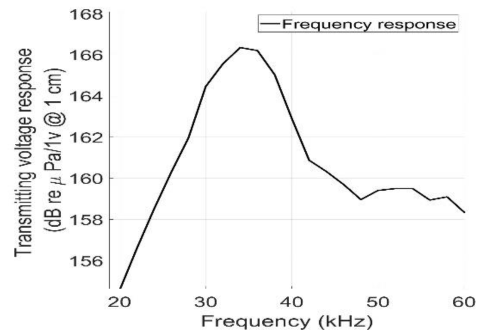

Fig. 7. Frequency response of the cPB-MUT meausred underwater by a needle hydrophone.

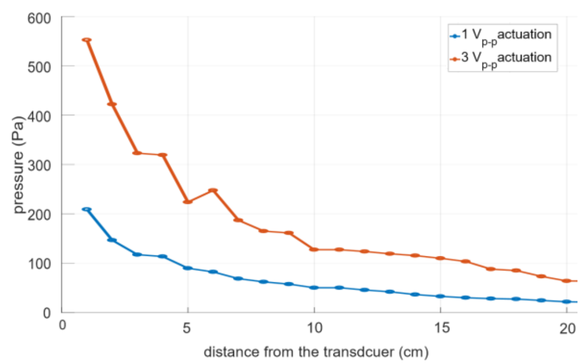

Fig. 8. Output axial pressure as a function of the distance from the transduce

applying a thin layer of Epotek H54 epoxy at the backside of the chip to bond it to the PCB. The Epotek H54 was applied by a micro-dispenser, avoiding contact with the membranes, and was cured on a hot-plate at 150°C for 10 minutes.

Fig. 5 shows the assembly steps of the cPB-MUT. A 11x11 mm PCB rectangular window was realized, while the effective dimension of the transducer, due to the applied epoxy, was around 8x8 mm. Fig. 6 shows a cPB-MUT with a smaller window, which increases the resonance frequency. The pMUT array chip in this device is the same as the one shown in Fig. 5.

IV. Results and Discussions

The transducer with the resonance frequency of 33 kHz was characterized underwater by a hydrophone as well as mutual communication with another cPB-MUT transducer. Fig. 7 shows the frequency response of the transducer measured by a 1 mm needle hydrophone (Precision acoustics, UK). A transmitting voltage response (TVR) of 166 dB at 1cm was obtained. The output axial pressure as a function of the distance from the transducer is shown in Fig. 8 for to two different actuation voltages, 1 V_{p-p} and 3 V_{p-p}. In this measurement, the entire array was actuated with one amplifier. However, since an array of pMUTs was used, every single pMUT can be actuated with a separate amplifier to overcome the problem of driving a high capacitance. As such, more current than voltage is delivered to the transducer. As a guideline, the front-end architecture shown in Fig. 9 is recommended.

Fig. 10 shows the time domain response of the cPB-MUT in mutual communication at two different distances, 1cm and

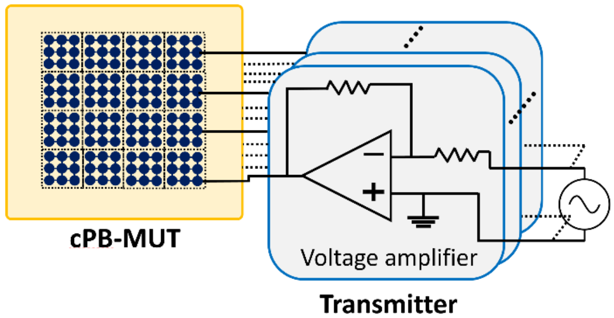

Fig. 9. Recommended transmitter front-end architecture to be used for the cPB-MUT.

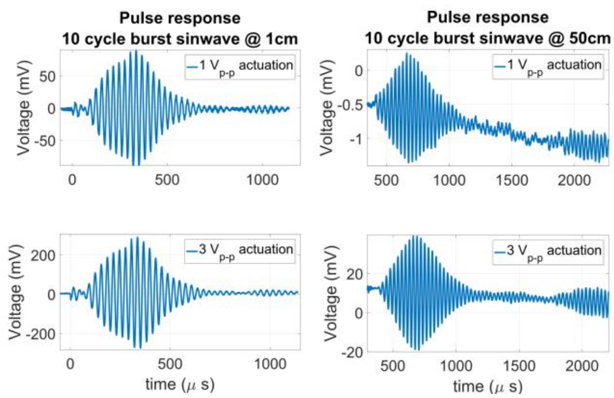

Fig. 10. Time domain response of the cPB-MUT in mutual communication at two different distances, 1 cm and 50 cm.

TABLE I. THE UNDERWTAER PRESSURE RESPONSE OF THE CPB-MUT WITH RESPECT TO THE STATE-OF-THE-ART.

Transducer	*Transmission sensitivity (Pa/V@1 cm)*	*Frequency*
[13]	1.5	96 kHz
[14]	5	155 kHz
[15]	27	1.2 MHz
cPB-MUT	**210**	**33 kHz**

50 cm. The transmitter was actuated with two 1$V_{p\text{-}p}$ and 3 $V_{p\text{-}p}$ sinusoidal 10 cycles burst signals. As shown, the mutual communication at 50 cm is clearly possible with even a 1 $V_{p\text{-}p}$ actuation signal. The obtained pressure response corresponding to 166 dB TVR, was about 210 Pa/V at 1 cm. This value is about two orders of magnitude higher than reported values in the state-of-the-art, as shown in Table I.

V. CONCLUSION

A novel ultrasound transducer based on pMUT technology has been developed and characterized underwater. The proposed transducer was termed coupled piezoelectric bulk-micromachined ultrasound transducer (cPB-MUT) and is capable of underwater communication in the range of 1 meter with actuation voltages of less than 3 $V_{p\text{-}p}$. In the proposed transducer, a pMUT array chip was bonded to a PCB containing a window. The array chip is clamped by the edge of the window. The chip was exposed to water on its backside, while the front side was protected by a stainless-steel cap. The vibration of the individual pMUT elements was coupled to the bulk silicon substrate through the surrounding water. Basically, the reactive generated output power of each pMUT brings the water into vibration, which results in the vibration of entire substrate. Consequently, the vibrating area was enlarged significantly, which resulted in a higher acoustic output power.

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