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Novel Phased-Array Platform based on Directly Modulated Ultrasonic Transducers

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***Abstract*—This work proposes, for the first time, the use of Directly Modulated Ultrasonic Transducer (DMUT) array as an efficient way to drive individual sub-sections of Piezoelectric Micromachined Ultrasonic Transducers (pMUTs) arrays. The system allows to implement the phased-array technique and re-configure in quasi real-time the maximum radiation of the pMUT array through a commercially available micro-controller. The results in this work show an increase of the Sound Pressure Level (SPL) of 13dB when transmitting from a 10x5 pMUT array to a commercial hydrophone through the DMUT phased-array. The achievements are promising towards the improvement of intrabody and underwater communication networks.**

***Index Terms*—Piezoelectric Micromachined Ultrasonic Transducer (pMUT), Directly Modulated Ultrasonic Transducer (DMUT), Phased-Arrays, Underwater and Intrabody Communication Networks**

I. Introduction

DMUT systems have been recently proposed as an efficient method to drive pMUTs and achieve high SNRs for Underwater and Intrabody Networks (INs) [1]. Similarly, DMUTs were harnessed to achieve near zero-power acoustic wake-up receivers for Implanted Medical Devices (IMDs) [2], [3]. While the use of phased-array techniques has been previously exploited by other groups for conventional pMUTs [4], [5], the use of phased-arrays with DMUTs is still unexplored.

This work demonstrates, for the first time, a phased-array platform based on arrays of DMUTs. The reported system can be controlled by a commercial micro-controller, thus electronically re-configuring, in quasi real-time, the direction of maximum radiation. We show that the use of DMUTs, in this novel proposed system, permits to enhance the SPL by $13dB$, thus further emphasizing its impact in maximizing the SNR in intrabody and underwater networks [6]–[8].

The phased-array system has been implemented for ten individual DMUT channels and connected to a micro-controller. A fabricated 10x5 pMUT array has been wire-bonded to a Printed Circuit Board (PCB) and submerged in a silicone oil tank to transmit to a commercial hydrophone. The controlling signals are $3.5V$ pulses delayed accordingly and the relative generated DMUT outputs signals result in an amplification of up to $18Vpp$. The SPL was modeled based on the characteristics of the pMUT array, the medium properties and the receiver's sensitivity. Finally, the acoustic signal was measured. The results show an improvement of $13dB$ of the SPL, which matches the theoretical results.

II. Array of DMUTs

The main module of the phased-array platform proposed in this work is a single DMUT circuit shown in Fig. 1. The system allows to directly feed an ON/OFF keying signal into the transducer and at the same time boost the voltage on top of it, improving the output pressure and SNR. In this work the main focus is to exploit the DMUT circuit for its voltage boosting capability and take advantage of the low input signal. In particular, the circuit can be driven with signals of less than $3.5V$, which allows for its integration with commercial micro-controllers. This will allow to pilot multiple DMUT circuits and control their phase-shifting (or time-delay) in order to implement the phased-array technique.

The circuit consists of a Bipolar Junction Transistor (BJT) acting as a switch when driven in its cut-off region (low voltage) and saturation region (high voltage). By applying a train of pulses at the base of the transistor, this will connect and disconnect a DC biased LC tank to the acoustic transducer. When modulating the switch with an ON/OFF signal, the LC thank will abruptly change the resonance frequency due to the high capacitance of the pMUTs array. In this way, portion

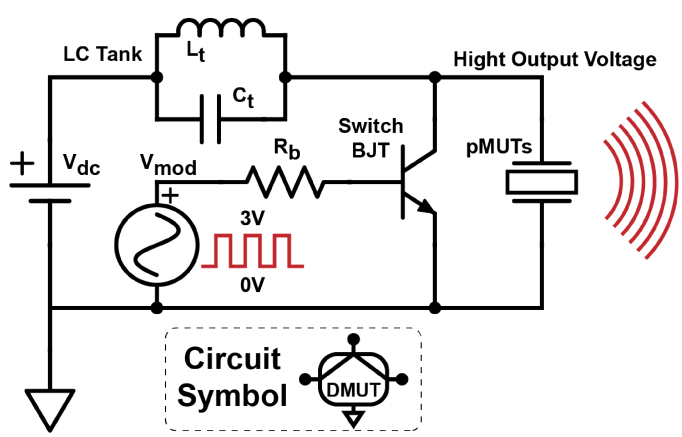

Fig. 1. Directly Modulated Ultrasonic Transducer (DMUT) electrical circuit diagram.

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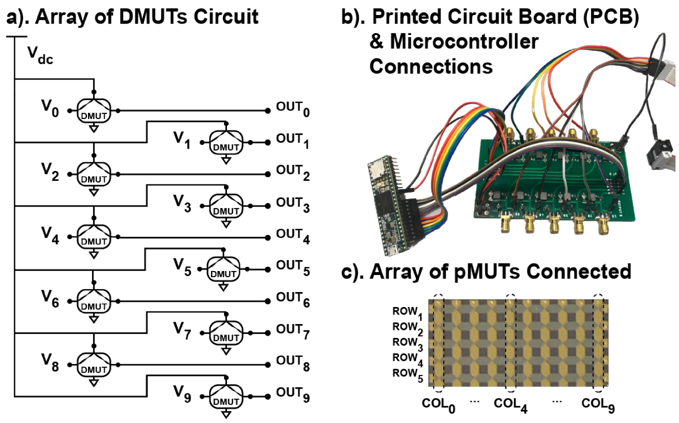

Fig. 2. a). Array of DMUTs electrical circuit diagram. b). PCB of the DMUT array connected to Teensy 3.6 micro-controller that pilots it. c). Fabricated 10x5 pMUT array.

of the energy stored by the inductance of the LC filter, will be stored by the transducer. This mechanism explains the generations of the high voltages at the output of the DMUT system.

The single DMUT circuit is laid out in arrays on a PCB in order to pilot ten individual channels of a pMUT array. The electrical diagram is shown in Fig. 2a. while the fabricated PCB and the connections to the micro-controller Teensy 3.6 to pilot the array are shown in Fig. 2b. An optical image of the fabricated pMUT array is also shown in Fig. 2c. This highlights the rows one to five (connected to ground) and the columns zero-nine (connected to the outputs zero-nine of the DMUT array).

III. Phased-Array Implementation

The objective of the phased-array technique is to generate constructive interference of the ultrasonic waves at a certain focal point in space. This allows to have a higher acoustic signal, improve the transmission distance and the SNR. The focusing is achieved by delaying the signals of different columns of the pMUT array in order for the ultrasonic signal to arrive in phase at the desired distance from the array. By doing so, the waves will add up constructively instead of creating destructive interference. The driving signals implemented in the micro-controller are shown in Fig. 3a and the relative outputs of the DMUT array, which connect directly to the columns of the pMUT array, are shown in Fig. 3b.

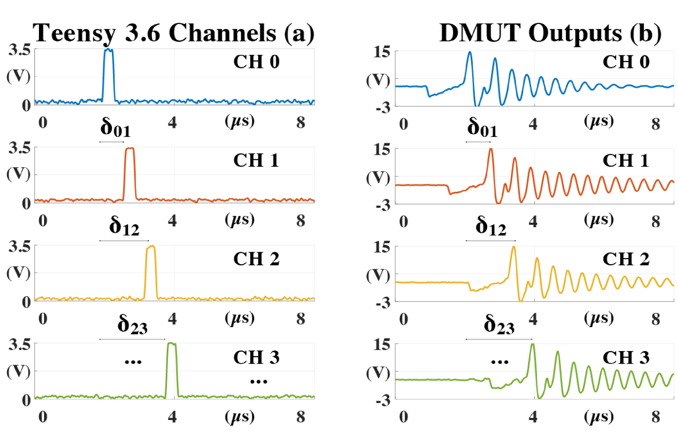

Fig. 3. a). Phased-array delays implemented in Teensy 3.6. b). DMUT array outputs relative to the signals generated with the micro-controller.

IV. Results

A. Testing Setup

The DMUT array functionality is tested by creating an ultrasonic link between a 10x5 pMUT array and a commercial Teledyne hydrophone submerged in a silicone oil tank, as shown in Fig. 4. Based on its data-sheet, the hydrophone has a sensitivity of $S = -228dB/V$, which allows to convert the received voltage signal into sound pressure and compare it to the mathematical model results. Furthermore, the pMUT array was wire-bonded to a PCB, the rows are connected to ground and the columns are connected to the outputs of the DMUT array respectively, allowing for the formation of 10 individual channels.

B. Mathematical Model

The mathematical of the output pressure of the pMUT array is modeled starting from experimental measurements with a Digital Holographic Microscope (DHM). The main parameters are the peak displacement (d_p) and resonance frequency (f_s) of the individual elements. The output pressure at the surface of one pMUT can be expressed as following:

$$P = v_p \cdot Z_a \cdot A_{eff} \tag{1}$$

$$v_p = 2\pi \cdot d_p \cdot f_s \tag{2}$$

$$Z_a = \frac{\rho_0 \cdot c_0}{A_{eff}} \tag{3}$$

$$A_{eff} = \frac{2\pi \cdot a^2}{3} \tag{4}$$

where v_p is the peak membrane velocity, Z_a is the acoustic impedance, A_{eff} is the effective area of the pMUT, a is the membrane radius, ρ_0 is the density of the silicone oil and c_0 is the speed of sound in the silicone oil.

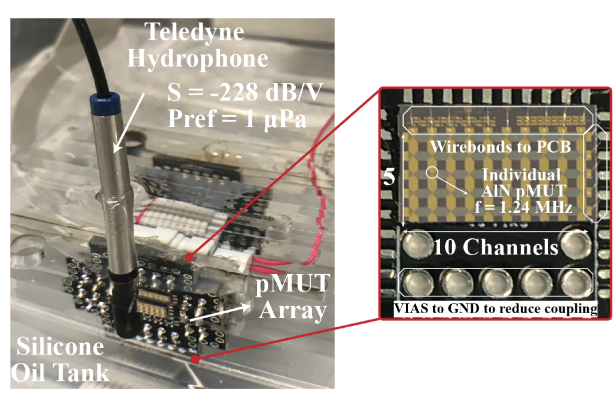

Fig. 4. The fabricated pMUT array and a Teledyne hydrophone are submerged in a silicone oil tank and fixed at 5 mm for measurements.

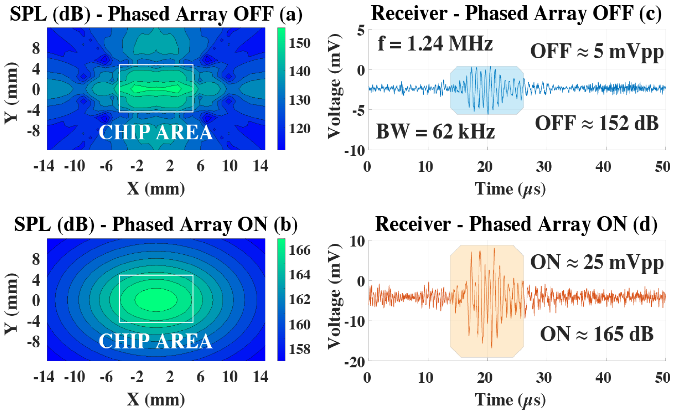

Fig. 5. (a-b) Mathematical model of the Sound Pressure Level (SPL) for the pMUT array at $5mm$. (c-d). Measured received acoustic signal on hydrophone: $13dB$ measured improvement of the SPL when using the dMUT phased array.

When driving an entire pMUT array, the output pressure will a function of the combination of all the ultrasonic waves based on: the phase-shift (or time-delay) of the elements, the geometric spread of the acoustic waves, the directivity of the array and the medium attenuation. A closed form of the output pressure of the array can be expressed as following:

$$P_{array} = \frac{P \cdot k \cdot a^2}{2r} \cdot D \cdot e^{-\gamma \cdot r} \cdot e^{-i \cdot k \cdot r} \cdot \phi(t) \qquad (5)$$

$$D = \frac{48 \cdot BesselJ_3(k \cdot a \cdot sin(\theta))}{(k \cdot a \cdot sin(\theta))^3} \qquad (6)$$

$$\gamma = \frac{\alpha}{20 \cdot log_{10} e} \qquad (7)$$

where r is the distance at a certain coordinate from the array, θ is the angle formed with the array at the distance r from the array, D is the directivity, γ is the attenuation term, α is the absorption coefficient of the silicone oil, k is the wave number, and $\phi(t)$ is the phased-array delay coefficient.

When all the pMUTs are driven with the same signal (equal delays) (Fig. 5a), both constructive and destructive interference will be happening at a certain distance from the array. On the other hand, when the delays are set for each column of the array to reach a certain focal distance at the same time, the acoustic waves will add up and maximize the pressure in that region (Fig. 5b). The mathematical model shows an improvement of $16dB$ SPL when applying the phased-array technique.

C. Measurements

In this work the DMUT array is employed to drive an array of pMUTs and implementing the phased-array technique. The time-delays of each column of the array are coded in a Teensy 3.6 micro-controller. The Teensy can only supply $3.5V$ for each channel, therefore driving the pMUT array directly will result into low output pressures. Instead, the DMUT system allows to output high voltage signals while being driven by low amplitude signals supplied by the micro-controller. The measurement results are shown in Fig. 5c and 5d with the phased-array OFF and ON respectively. The hydrophone measures a maximum amplitude peak-to-peak of $V_{OFF} = 5mVpp$ and $V_{OFF} = 25mVpp$. Given the sensitivity of the receiver, this converts into a sound pressure of $SPL_{OFF} = 152dB$ and $SPL_{ON} = 165dB$ respectively. The measurements show an improvement of $13dB$ SPL when using the phased-array technique implemented with the DMUT array, validating the mathematical model.

V. Conclusions

In conclusion, this work demonstrated the possibility to harness DMUT arrays to efficiently drive individual sections of a pMUT array and implement the phased-array technique. In particular, the system was piloted by a commercially available micro-controller (Teensy 3.6) with low input signal to the DMUTs. This generated the time-delays for each pMUT array column in order to focus the ultrasonic energy of the array at $5mm$ from the chip. Furthermore, the DMUT allows to boost the output voltage on top of the pMUTs, thus allowing a better transmission efficiency and increase the SNR. The experimental results show an improvement of $13dB$ SPL when actuating the pMUT array with the DMUT phased-array, with good matching to the mathematical model, thus being promising towards the improvement of intrabody and underwater communication networks.

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