DIRECT MODULATION PIEZOELECTRIC MICRO-MACHINED ULTRASONIC TRANSDUCER SYSTEM (DMUT)

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ABSTRACT

This paper demonstrates, for the first time, a new underwater communication scheme based on the Direct Modulation (DM) of an array of piezoelectric Micro-Machined Ultrasonic Transducers (MUT). The use of this new modulation scheme permits to achieve more efficient data transmission compared to what could be attained through conventional continuous waves-based (CW) driving approaches. In addition, as the received information can be extracted without the employment of mixers or amplifiers, it enables lower power consumption and low noise-figures. In this work, we report on the performance of the first dMUT-prototype. This system, which relies on a Bipolar Junction Transistor (BJT) to periodically connect and disconnect an array of pMUTs to a DC-biased filter (Fig. 1), exhibits power consumption of $140mW$ and enables transmitted energy-per-bit of $0.7\mu J$. Such a value is two orders-of-magnitude more efficient than what attained through conventional communication approaches for underwater networks [1, 2, 3].

INTRODUCTION

In the past few years, MUTs have gained more interest in the research community and industry [4]. Both capacitive (cMUT) and piezoelectric (pMUT) MUTs have been explored [5]. Numerous applications have been developed by exploiting pMUTs, such as fingerprint sensors [6], range finding systems [7], power transfer [8], intrabody and underwater acoustic communication links [9, 10]. On the other hand, DM approach has been explored in the past for Radio Frequency (RF) antenna systems, to perform a direct data transition without the use of a carrier frequency [11]. The new approach proposed in this work, the dMUT system, has been envisioned to work in the context of acoustic communication links in order not only to directly modulate the bit-stream, but also to amplify the output transmission waveform and reduce the noise.

In this paper, the first dMUT-system is demonstrated. A BJT is used as a switch to turn ON/OFF the connection between an LC filter tank and a pMUTs array in order to built-up high AC voltages on the transducer, starting from only $7V_{DC}$. When applying a bit-stream to the BJT's base between -5V and +5V (working on cut-off region and saturation region respectively), this behaves as a switch. Fig. 1 shows the circuit of the dMUT system and the communication link while Fig. 3 shows the experimental setup, together with the Printed Circuit Board (PCB) and the optical image of the pMUTs array (fabrication process in Fig. 2). Particular attention was given to the LC filter design, which has to match the resonance of the transducer in order to fully harness the charging and discharging capabilities of the LC filter into the pMUTs array and maximize the voltage gain for the communication.

The dMUT system was tested for its functionality (as shown in Fig. 1 and 3) and experimental results closely match with the simulations (Fig. 4). The input bit-stream, fed into the BJT, results into a signal having voltages up to $85V_{pp}$ at the output of the dMUT. This allows a receiving voltage as high as $20mV_{pp}$ allowing a direct decoding of the data. The original bit-stream is recovered through a Hilbert envelope filter with a threshold voltage set at 20% of the maximum voltage (Fig. 5). The modulation frequency is $100kHz$ (period of $10\mu s$) which corresponds to a data-rate of $200kBps$ (two bits encoded per period). The hydrophone is placed $4cm$ away from the pMUTs array, in a De-Ionized (DI) water tank, resulting in a $27\mu s$ delay of received signal (Fig. 5). In conclusion, the overall current consumption of the dMUT system is 20mA, which leads to a power consumption of $140mW$ and an energy/bit of $0.7\mu J$. This is two orders-of-magnitude more efficient than what attained through conventional communication approaches for underwater-networks [1, 2, 3].

DIRECT MODULATION SYSTEM

The direct modulation piezoelectric micro-machined ultrasonic transducer system (dMUT) is shown in Fig. 1. The dMUT consists of two main parts: the direct modulation (DM) module and the ultrasonic link between a pMUTs array, for data transmission, and a commercial hydrophone, for data collection.

The DM module has as main purpose to dynamically charge the pMUTs array and build-up high voltages and at the same time modulate data for transmission. This is achieved by switching the connection between an LC filter, which is biased with a DC voltage (V_{DC}), and the pMUTs array. The LC tank is connected to the pMUTs for half of the modulation period (T_{MOD}), while for the other half is connected to V_{DC}.

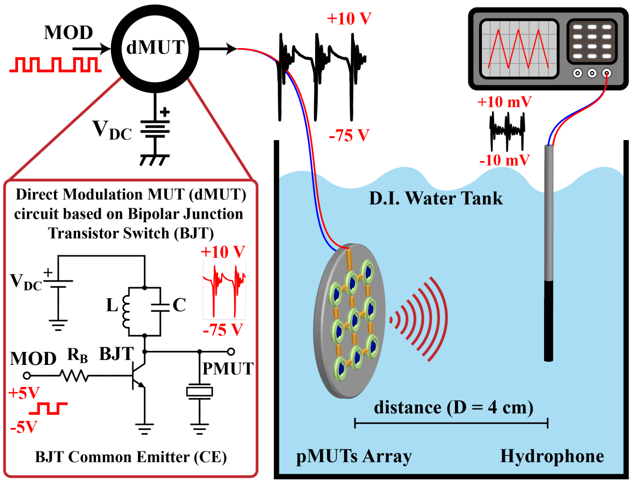

Figure 1: *This figure represents the Direct Modulation MUT (dMUT) system, implemented with a BJT behaving as a switch. The bit-stream ("010101...") is directly fed to the system and its own modulation allows to charge a transducer (in this case a pMUTs array), through an LC filter tank and at the same time amplify the output voltage. These high voltages will allow a better transmission capability for those transducers. Furthermore, this approach will make obsolete the use of amplifiers and mixers to achieve the same communication capability, thus simplifying the circuit and lowering the power consumption and reducing the intrinsic noise. The right side of the figure shows the communication link that is used to test this system: a pMUTs array is used to transmit to a hydrophone and the data is collected at the output of an oscilloscope.*

When transitioning from the first half of the period to the second, the LC thank will abruptly change the resonance frequency due to the high capacitance of the pMUTs arrays. In this way, portion of the energy stored by the inductance of the LC filter, will be stored by the pMUTs. This mechanism explains the generations of the high voltages at the output of the dMUT system. The LC tank is also designed to resonate at the main resonance of the pMUTs array in order to maximize the reactive energy it can store when connected to V_{DC}.

As a first prototype implementation for the dMUT, a bipolar junction transistor (BJT) is used as a switch. Since the BJT is current driven, it can withstand high voltages at the collector and emitter. The BJT is biased at the base through a resistor, $R_b = 1k\Omega$, with a square wave modulation signal (MOD). In order for the BJT to behave as a switch, it has to work in the cut-off region and saturation region, respectively biased at $-5V$ and $+5V$. A pMUTs array of 45 rows and 50 columns, for a total of 2250 individual elements, was used to implement the dMUT system. The array is connected to the LC tank through the collector of the BJT. In this node of the circuit, high voltage are built-up and the resulting signal is modulated with an ON/OFF keying (OOK) from the base of the transistor. To collect the transmitted data, a commercial Teledyne Marine hydrophone is used. Both hydrophone and pMUTs arrays are submerged in a DI water tank to emulate the underwater and intrabody medium and kept at a distance of $D = 4cm$ to avoid capacitive interference.

PMUTS ARRAY FABRICATION

The fabrication process starts with a double side polished silicon (Si) wafer of $300\mu m$ (1). Following, a layer of silicon dioxide (SiO_2) of $500\mu m$ is thermally grown (2). Then a layer of platinum (Pt) of $100nm$ is sputtered as bottom electrode (3). In the next step (4), $750nm$ of piezoelectric material aluminum nitride (AlN) is deposited. At this point, in order to create VIAs access to the bottom electrode, the AlN layer is patterned and etched with hot phosphoric acid (5). The last step before the device releasing is the lift of process of the top electrode (6). For this, negative photo-resist (PR) is deposited first and exposed with the top electrode pattern. Then in a second step, a gold (Au) layer of $150nm$ is sputtered. In the end, the whole wafer is sonicated in order to lift of the unnecessary parts of Au. Finally, a hard mask layer is used to pattern the cavities of the pMUTs with back side alignment (7) and etched (release) with deep reactive-ion etching (DRIE).

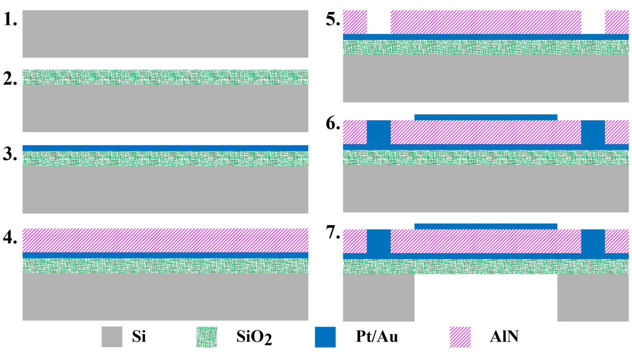

Figure 2: *Fabrication process of pMUTs array. 1-2. Oxide deposition (to protect from last step etch). 3. Bottom electrode metal deposition (Ti/Pt). 4. Aluminum Nitride (AlN) deposition. 5. VIAs patterning and etching. 6. Top electrode patterning and metal deposition (Ti/Au). 7. Back side cavity patterning and etching: Deep Reactive-Ion Etching (DRIE).*

EXPERIMENTAL SETUP

The experimental setup used to demonstrate the functionality of the dMUT system is shown in Fig. 3. First of all, in Fig. 3a, an arbitrary function generator is used to produce a square wave between $-5V$ and $+5V$ at certain frequency f_{MOD}, in order to emulate a data bit-stream ("010101...") and modulate the dMUT. The system is laid out on a Printed Circuit Board (PCB). A DC supply is connected to the PCB to bias the circuit. Instead, the pMUTs array is mounted on an external external PCB and submerged in the DI water tank. Once an underwater link is established, an oscilloscope is connected in parallel to the pMUTs array to read out the voltage amplification and the applied modulation, together with the output of the hydrophone.

The dMUT PCB is highlighted in Fig. 3b. The LC tank along with the BJT switch are shown in the insets. Moreover, the SMA port to bias the circuit with a V_{DC} voltage, the SMA port to connect the pMUTs array, the SMA port to modulate the dMUT (V_{MOD}), and the SMA port for the BJT's emitter, that is connected to ground, are also shown in the insets.

Finally, in Fig. 3c, an optical image of the pMUTs array is shown. Here it is to notice the grid arrangement of the single pMUTs, for a total of 2250 elements. The chip's array is wire-bonded to the PCB with gold wire-bonds and later encapsulated into silicone to protect them from breaking.

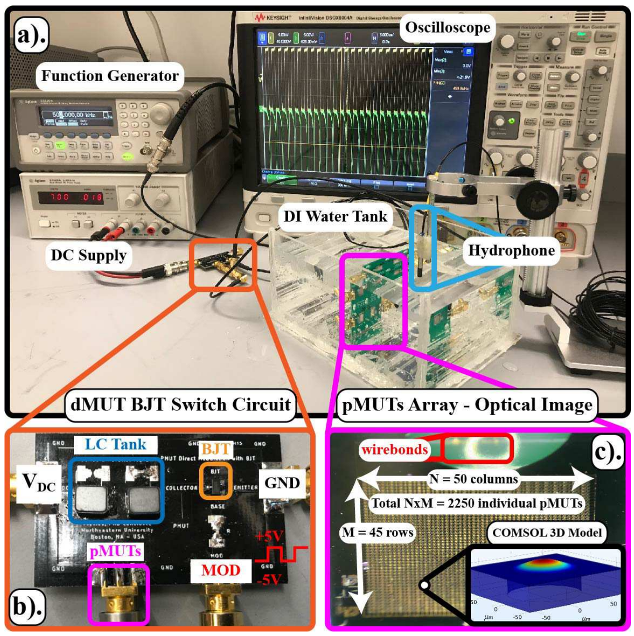

Figure 3: *a). Testing setup of the dMUT system. A function generator is used to generate a square wave (to emulate a bit-stream), and a DC supply, are all connected to the PCB that holds the dMUT system. A pMUTs array is employed to transmit the data through De-Ionized (DI) water tank (laser cut acrylic project) and a commercial hydrophone is adopted to receive it. b). Detailed PCB board of the dMUT system. c). Optical image of the pMUTs array employed to transmit for this experiment (fabrication process in Fig. 2). The array consists of 45 rows and 50 columns, for a total of 2250 individual pMUTs. The inset shows a 3D COMSOL Multiphysics model of a single device.*

WAVEFORM GENERATION AND COMMUNICATION

In order to generate high voltages on top of the pMUTs array, the LC tank is dynamically connected to the array. The tank is design to have the same resonance frequency as the radiating element but with a capacitance several times larger. This way the tank will be able to dynamically built-up the voltage on top of the pMUTs. As shown in Fig. 4, voltages up to $V_{pp} = 85V$ can be achieved with DC bias of the LC tank of $V_{DC} = 7V$. The current circuital implementation of the LC tank limits the maximum achievable voltage. In fact, the lumped inductors have a quality factors $Qs < 40$, which limits the maximum voltage to $V_{max} < 100V$. This can be overcome by using low frequency MEMS filter, which can be integrated in the fabrication process.

Another limitation is given by the resistance of the BJT. In fact this resistance will affect the overall Q of the LC tank, limiting the maximum achievable voltage. This can be overcome by using high-voltage MOSFET-based switches, such as SiGe-based single-pole double-throw (SPDT) switches.

The signal used to turn on/off the BJT-switch is also used to encode data in a bit-stream and transmit it through the pMUTs array, resulting into a direct modulation system. The modulation frequency used in this implementation is $f_{MOD} = 100kHz$ and it is mainly limited by the discharge constant of the LC tank. In a MOSFET-based implementation, this frequency can be higher than the resonance frequency of the pMUTs, which in this case is $f_{res} = 1.2MHz$, allowing a very large bandwidth modulation system.

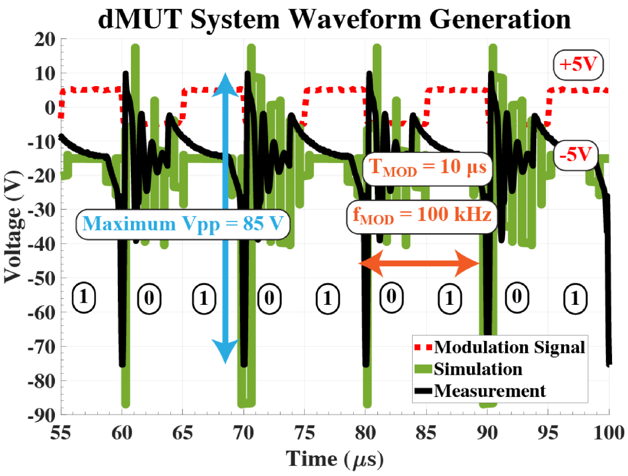

Figure 4: *Modulation signal (square wave at $100kHz$, $-5V$ to $+5V$ to generate the bit-stream "010101...") and output voltage of the dMUT system. Simulation and measured results are a good match. Here it can be appreciated the very high voltage gain on output waveform, thus allowing higher transmission capability. Furthermore, the dMUT configuration makes obsolete the use of mixers and amplifiers to modulate and transmit the data, since now the data stream itself modulates and amplifies the output waveform and reduces the noise.*

Once a high voltage waveform is achieved on top of the pMUTs array, an acoustic communication link can be implemented (Fig. 5). The transmitted waveform (blue curve) directly encodes the data stream ("010101...") at a high voltage, which allows a higher transmission capability and/or longer distances. The received waveform instead (orange curve), shows clearly the same encoded data. In fact the bit-stream can be easily decode with a Hilbert envelope filter set with a thresh hold of 20% of the maximum voltage (black curve). This waveform exhibits a $V_{pp} = 20mV$ at a receiving distance of $D = 4cm$. It is to be noticed that the bit-stream is delayed by a constant $\tau = 27\mu s$, which corresponds to the traveling time of the acoustic waves in water, with a sound velocity of $c = 1480m/s$. The power consumption was measured to be $140mW$, corresponding to a transmission energy-per-bit of $0.7\mu J$, which is two orders-of-magnitude more efficient than a conventional communication approach for under-water networks [1, 2, 3].

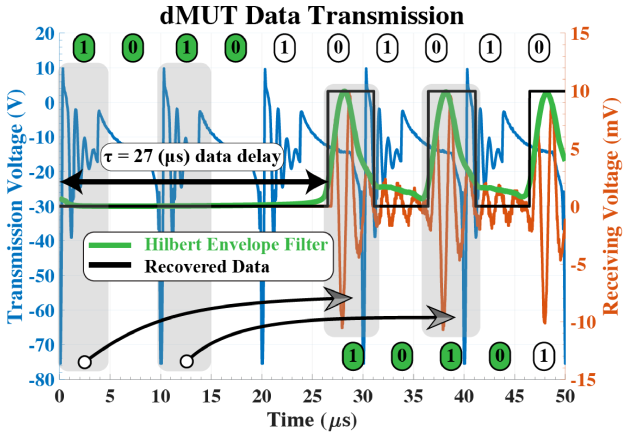

Figure 5: *Experimental results of the communication between the pMUTs array and the hydrophone (as per Fig. 1 configuration), by employing the dMUT system. The blue curve is the generated output waveform from the bit-stream while the orange one is the received bit-stream. This last one is attenuated through the DI water and the beginning of the stream is delayed by $27\mu s$, which corresponds to a distance of 4 cm between the transmitter and receiver. The green and black curves are the recovered data stream through a Hilbert envelope filter and a threshold voltage of 20% of the maximum voltage.*

CONCLUSIONS

In conclusion, this works shows, for the first time, the implementation of a direct modulation system based on a pMUT array as radiating element. Due to the switching mechanism between an LC tank and a pMUTs array, high voltages up to $V_{pp} = 85V$ are achieved on top of the pMUTs, improving the communication efficiency. Data-rates up to $200kBps$ are achieved with an overall transmission energy-per-bit of $0.7\mu J$ while using a low $V_{DC} = 7V$ and a $f_{MOD} = 100kHz$ for an ON/OFF keying modulation. This is two orders-of-magnitude more efficient than what attained through conventional communication approaches for underwater networks [1, 2, 3].

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