A High-frequency Transimpedance Amplifier for CMOS Integrated 2D CMUT Array towards 3D Ultrasound Imaging

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Glaucoma imaging by 3D ultrasound bio-microscope:
- High-frequency (>30MHz) high-resolution
- CMOS readout with integrated CMUT array

3-D Imaging

Targets

High-frequency

2-D Transducer Array

High Bandwidth AFE

Transmitting

Receiving
Key components: CMUT array + analog-front-end (AFE)
Capacitive Micromachined Ultrasonic Transducer

CMUT Device

- A transducer that converts ultrasound acoustic waves into electrical signals and vice versa
- The energy transduction is due to capacitance change between membrane and substrate
- Easier CMOS integration with wider bandwidth

\[ I_{CMUT} = V_{DCbias} \frac{\partial(\Delta C)}{\partial t} = \frac{\partial(\Delta Q)}{\partial t} \]

Table I. Design Parameters for in-house fabricated CMUT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMUT array (elements)</td>
<td>16 × 16</td>
</tr>
<tr>
<td>CMUT cells per element</td>
<td>20 × 20</td>
</tr>
<tr>
<td>CMUT cell geometrical profile</td>
<td></td>
</tr>
<tr>
<td>Width</td>
<td>28μm</td>
</tr>
<tr>
<td>Depth</td>
<td>28μm</td>
</tr>
<tr>
<td>Thickness</td>
<td>3μm</td>
</tr>
<tr>
<td>Gap size</td>
<td>0.1μm</td>
</tr>
<tr>
<td>CMUT element dimension</td>
<td>600μm × 600μm</td>
</tr>
<tr>
<td>CMUT excitation voltage (V_p-p)</td>
<td>20V</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>17.5-52.5MHz</td>
</tr>
<tr>
<td>Capacitance variation</td>
<td>2.12aF/Pa</td>
</tr>
<tr>
<td>Capacitance per element (deflated)</td>
<td>44pF</td>
</tr>
</tbody>
</table>

(a) Diagram of CMUT array, (b) one CMUT element, (c) one CMUT cell, (d) cross-section view of CMUT cell, (e) top view of CMUT cells.
1. One preamplifier shared by two AFE channels considering bonding area constraint for 600μm×600μm CMUT element
2. Additional parasitic capacitance of 1pF included in simulation considering bonding for CMUT element and preamplifier
3. HV protection switch using HV double-diffused lateral MOS (DMOS) transistor to isolate preamplifier and avoid possible breakdown in transmission mode
AFE Preamplifier Circuit Specifications

- **Preamplifier:** trans-impedance amplifier (TIA) with specs by CMUT device and system dynamic range
  - **Receiving Bandwidth:** 100% fractional bandwidth of the CMUT center frequency 35MHz
  - **Gain:** output of the preamplifier able to produce a maximum of 1VP-P voltage to the TGC in next stage considering the maximum CMUT capacitance variation
  - **Input referred noise:** determined by the case when the minimum acoustic-wave pressure echo signal is received
  - **Output load:** determined by the input impedance of the next stage TGC on PCB

### AFE Receiver DR
- Attenuation rate: -0.5 dB/MHz/cm
  - Target focal depth: 1.2 cm
- Input signal DR: centre frequency + focal depth (back and forth) = 35MHz*2*0.5*1.2 = 42dB
  - 256 gray-scale display DR: 20*log(256) = 48dB
  - =90dB

=> ADC: 6.02*10+1.76=61.96dB, TGC=90-61.96=28.2dB

### Table. Design specs for preamplifier

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specs.</th>
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<tbody>
<tr>
<td>Supply Voltage</td>
<td>6V</td>
</tr>
<tr>
<td>Gain</td>
<td>61.18dBΩ</td>
</tr>
<tr>
<td>3dB Bandwidth</td>
<td>52.5MHz</td>
</tr>
<tr>
<td>Input Referred Noise</td>
<td>1.15uArms</td>
</tr>
<tr>
<td>Max Output Voltage</td>
<td>1VP-P</td>
</tr>
<tr>
<td>Output Load</td>
<td>3.2pF//310KΩ</td>
</tr>
</tbody>
</table>
AFE Preamplifier Circuit Design

- Resistive feedback TIA
  - Low-noise detection
  - Ease of biasing
  - High bandwidth capability

- Transimpedance Gain
  \[ R_f = 1.15K \Omega \implies \text{Gain} = 20 \times \log(1.15K) = 61.2 \text{dB} \Omega \]

- 3dB Bandwidth
  \[ \omega_{TIA,-3dB} = \frac{1}{R_{IN} \left( C_{CMUT} + C_{parasitic} \right)} \]

- Input Referred Noise
  \[ i_{N_{in\_total}}^2 = i_{N_{amp}}^2 + i_{R_f}^2 + v_{N_{amp}}^2 \times \left( \frac{1}{R_{in\_amp}} + \omega C_{in} + \frac{1}{R_f} \right)^2 \]
AFE Operation Principle

Basic timing diagram for ultrasound analog front-end (AFE)
AFE Implementation and Measurement

1. Tapeout Process: Global Foundry 0.18-μm Bipolar/CMOS/DMOS (BCD)
2. A unity gain analog buffer is included on chip for driving external load of the probe with over 280MHz bandwidth
3. CMUT array wire boned on PCB within a barrel glued on the PCB (QFN24 package)
4. External power supply of 6V and 80μA input bias current
AFE Preamplifier AC + Noise Measurement Results

Simulated closed-loop frequency response

### Parameters

<table>
<thead>
<tr>
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<th>Simulation</th>
<th>Measurement</th>
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<tbody>
<tr>
<td>Transimpedance Gain</td>
<td>61.18dBΩ</td>
<td>61dBΩ</td>
</tr>
<tr>
<td>-3dB Bandwidth</td>
<td>75MHz</td>
<td>100MHz</td>
</tr>
<tr>
<td>Input Referred Noise</td>
<td>16.8pA/√Hz</td>
<td>27.5pA/√Hz</td>
</tr>
</tbody>
</table>
1. Immerse CMUT array in the vegetable oil contained in the barrel to mimic the underwater testing environment.

2. Choose one CMUT element from the CMUT array for transmitting and provided it with 20V DC bias voltage.

3. Choose one other CMUT element for receiving the acoustic wave resulting from the reflection at the oil-air layer interface.

4. A hydrophone was immersed into the oil to measure the acoustic pressure as a reference to the TIA output voltage signal.
1. The delay of the received echo can show the pulse-echo distance, which is the depth of the oil inside the barrel.
2. Our in-house fabricated CMUT device successfully generated a 6mV acoustic pulse with the triggering from external pulser.
3. The peak-to-peak voltage of our first echo signal was about 7mV, which also successfully demonstrated the functionality of the developed TIA of the analog-front-end receiver.
Conclusions

- A CMOS analog front-end (AFE) receiver integrated with CMUT array is demonstrated (0.18-μm BCD process) for high frequency 3D ultrasound imaging
- The primary component, a transimpedance amplifier (TIA), achieves 61dBΩ gain with 17.5MHz to 100MHz bandwidth, and low input referred noise of 27.5pA/√Hz
- The TIA was successfully integrated with CMUT and the receiving functionality has been demonstrated with a pulse-echo acoustic testing
- Our future work is to demonstrate the whole 3D ultrasound imaging system with digital image processing
Thank you!

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