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Optimizing Analog Front End Architectures for Enhanced SNR in Photoacoustic Imaging

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Summary:
In the field of photoacoustic imaging, systems with light sources with low pulse energy are currently being investigated. This study presents an analysis of different analog front-end architectures for such imaging, in particular their impact on the signal-to-noise ratio (SNR). The focus is on systems with high pulse repetition frequencies (PRF) and sampling rates of up to 50 Mega-Samples per second (MSPS). The architectures, which is tailored to Piezoelectric and Capacitive Micromachined Ultrasonic Transducer (PMUTs & CMUTs), include combinations of analog front-ends (AFE), preamplifiers, transimpedance amplifiers, and analog-to-digital converters (ADC). For testing purposes, the MUTs are simulated and set up with passive components.

Keywords: readout, signal conditioning, digitalization, analog front-end, photoacoustic imaging,

Background Motivation

High-power lasers with low pulse repetition frequencies (~10-20 Hz with ~20 mJ/cm^2) are often used in photoacoustic imaging. To increase system integration, the pulse energies can be reduced when the PRF is increased (kHz-range with ~1mJ/cm^2) to generate an image by averaging. These reduced energies allow lasers with a smaller footprint to be used. Both variants aim to exploit the full maximum permissible exposure (MPE) [1].

In photoacoustic imaging with low pulse energy, it is necessary to make the signal amplification and acquisition as low-noise and sensitive as possible. In this work, an analysis of different analog front-end architectures for photoacoustic imaging, with particular emphasis on their impact on the SNR is presented. Different integration times (Allan deviation) and pulse frequencies are investigated.

Systems operating at high repetition rates with sampling rates of up to 50 MSPS are being investigated. The system has been tailored to suit PMUTs and CMUTs. The architectures include different combinations of AFE, preamplifiers, transimpedance amplifiers and ADCs. The potential of using different types of ADCs and AFEs to improve the system's sensitivity and SNR is also being explored. The aim is to optimize the sensitivity of AFE for sonography and especially photoacoustic imaging.

Readout architectures for MUTs

There are two main approaches for recording analog ultrasound signals. One approach is to use transimpedance amplifiers to amplify the charge generated from the MUT and convert into a voltage. This signal is digitized by an ADC. Another approach is to use a fully integrated circuit to amplify and digitize the data in one chip. A printed circuit board (PCB) is used to build and test various useful combinations of amplifier and digitalization components. The different system architectures are shown in Fig. 1.

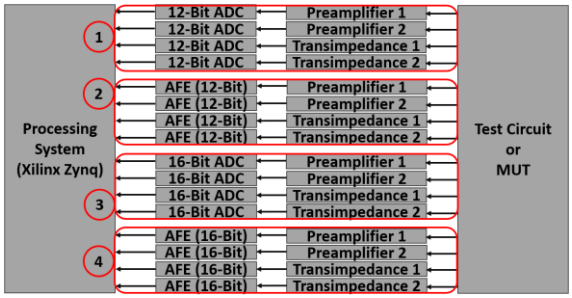

Fig. 1: Overview of the different system architectures. Four architectures with four channels each. 12- & 16-bit ADC and AFE with two different preamplifier and transimpedance amplifiers.

ADCs and AFEs are read out using serial low voltage differential signaling (LVDS). To ensure

comparability, all 16 channels are read out at a uniform sampling rate of 50 MHz. The readout is made by a Xilinx Zynq XC7Z020. This System-on-a-Chip (SoC) combines two ARM processor units with FPGA logic, providing high flexibility. The use of the Xilinx Zynq for data processing enables efficient management of multiple parallel input data streams from various channels.

Simulation of MUT

In photoacoustic imaging, typically small signals are recorded that follow a damped harmonic oscillation. Most ultrasound systems utilize lead zirconate titanate (PZT) transducers rather than CMUTs. MUT technology provide benefits such as enhanced bandwidth, the simplicity of constructing large, compact arrays, and the ability to integrate with supporting electronics [2]. MUTs can be used in pulse-echo mode for sonography or in receive mode for photoacoustic imaging. The received signals of both methods are similar. The main difference is that the signals in photoacoustics are an order of magnitude lower than in pulse echo, leading to a decrease in the SNR. Fig. 2 shows typical photoacoustic signals. High power lasers with low pulse repetition frequencies are compared with low power lasers with high repetition rates. The axes on the left and right illustrate the demands on the sensitive electronics since the signal decreases a hundredfold at low pulse energies.

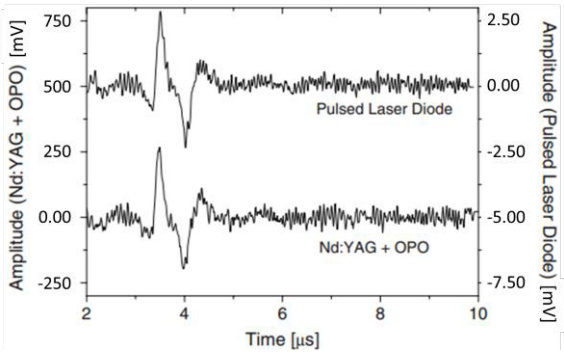

Fig. 2 Typical photoacoustic impulse response generated by a vessel in the hand. Comparison between high power Nd:YAG laser + optical parametric oscillator (OPO, single shot 0.45 mJ pulse) and low power pulsed laser diode (4.4 uJ averaged 10,000 times) [3] .

To study the different channel architecture of the AFE, a test circuit is developed to ensure comparability. In a multi-channel MUT, the photoacoustic signals are different depending on the position relative to the sound source. Another option, a digital-to-analog converter (DAC), can produce a synthetic fast waveform, but as a voltage source it does not simulate the reality of a MUT, which produces a finite charge. Both variants therefore do not provide reliable or realistic photoacoustic signals as from MUTs for a comparison of the channels and are therefore unreliable as a source. For this reason, a circuit is to be developed that uses an analog filtered pulse as a photoacoustic source. With the help of a simulation, a circuit consisting of passive components is developed that behaves like MUTs. In this way, millivolt signals with similar wavefronts and limited charge input can be generated to obtain a reliable method for validating the channels. This simulation is shown in Fig. 3. The attenuation, which determines the decay behavior, and the voltage amplitude, which influences the SNR, can be regulated by the values of the passive components.

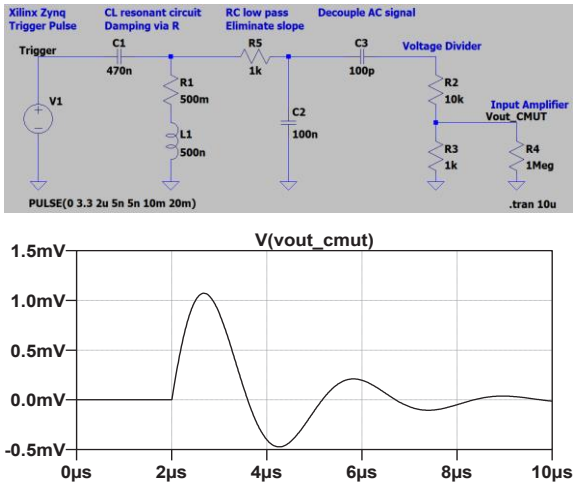

Fig. 3 The top image shows the setup using passive components in LTSpice, which behaves similarly to a MUT. The lower picture shows the simulation result.

Conclusion

In summary, this work demonstrates a way to characterize different analog front-end architectures for photoacoustic imaging using a synthetic signal. A simulation of a real MUT provides a reliable method to validate the channels using an analog filtered pulse as input signal.

References

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