Integrated Signal Amplification and Conditioning of Pyroelectric Sensor Elements

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Summary:
The signal conditioning of sub-pA pyroelectric currents with a monolithic circuit is a challenging task. A switched capacitor enables the emulation of high-ohmic resistance values in the GΩ-range for a high amplification on a small chip area. Different circuit topologies are simulated and measured whereby the realized digital detector achieves a specific detectivity of $2.5 \cdot 10^8$ cm√Hz/W at 10 Hz.

Keywords: Switched capacitor, Transimpedance amplifier, ASIC, SPICE, Pyroelectrical detector

Motivation

Pyroelectrical detectors are used in numerous applications like high-performance gas analysis, contactless temperature measurement and fast flame detection. Miniaturization and digitization are important subjects of current research. One aim is to increase the integration density, e.g. by including the signal conditioning inside the detector. This is possible by using an application-specific integrated circuit (ASIC), which combines a lot of different functions on a small silicon chip. Until now, mostly circuits with discrete resistors in the GΩ-range are used to amplify the pyroelectric current. These resistance values would cover large chip area on a wafer, which is why other circuit approaches need to be implemented [1].

The contribution of this paper are the simulations and measurements of circuit topologies for the integrated amplification of pyroelectric signals.

Circuit Topologies

The crucial part of the readout circuit is the high-ohmic resistance. Figure 1 illustrates a typical single supply transimpedance amplifier (TIA), continuously converting the pyroelectric current I_{pyro} to an output voltage V_{out}.

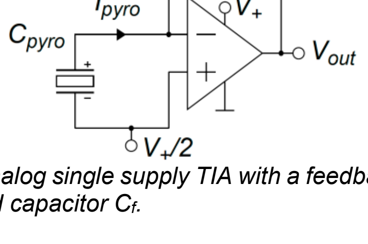

Fig. 1: Analog single supply TIA with a feedback resistor R_f and capacitor C_f.

The demand to achieve very high resistance values on a small silicon area is examined in several publications, e.g. for large time constants of electrical filters or current amplifications [1] [2]. A common approach is to replace the ohmic resistor with a switched capacitor (SC). Two adapted principles to discretely convert the pyroelectric current are shown in Fig. 2. The charge-voltage (QU)-converter in Fig. 2(a) integrates the input current on C_{int} and is reset periodically to return to the working point of the operational amplifier. Shortly before the reset, the output voltage is sampled. Figure 2(b) behaves like an analog TIA where the resistor is replaced by the stray insensitive circuit built by C_{sw} and four switches S_x resulting in an effective resistance of:

$$R = \frac{1}{f_{sw} \cdot C_{sw}} \quad \text{Eq. (1)}$$

with the switching frequency f_{sw}. Afterwards the output signal is low pass filtered with the corner frequency f_c to smooth the switching transients.

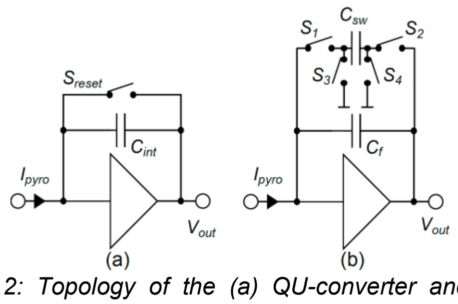

Fig. 2: Topology of the (a) QU-converter and the (b) SC-TIA as analog frontend of the ASIC.

Circuit Simulations

For a comparison, the circuits are simulated with *LTSpice*. A rectangular input current I_{pyro} (±1 pA, 50 % duty cycle, 10 Hz) is chosen. The capacitors $C_{int} = C_{sw} = 100$ fF with a switching frequency of $f_{sw} = 1$ kHz lead to an effective

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R_f = 10 GΩ. Figure 3 shows the output voltage of the analyzed circuits for different off resistances $S_{x\ off}$ of the switches and C_f = 200 fF.

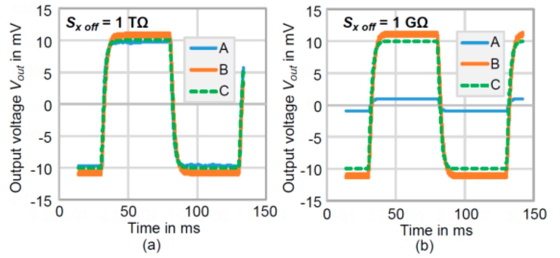

Fig. 3: Low pass filtered (f_c = 200 Hz) output signal in the time domain of A…QU-Converter, B…SC-TIA and C…discrete TIA for (a) 1 TΩ and (b) 1 GΩ off switch resistance.

The signal of the SC-TIA (B) is nearly insensitive to the off resistance of the switch but has a small voltage ripple compared to the analog counterpart (C), which can be further smoothed by a larger spacing between f_c and f_{sw}. The signal of the QU-converter (A) highly depends on the switch properties of S_{reset}. With $S_{x\ off}$ = 1 GΩ the capacitor C_{int} discharges faster and the output amplitude decreases in Fig. 3(b). Moreover, non-ideal behavior like charge injection, clock feed-through and noise folding effects due to the switches have a negative impact on the noise behavior in the frequency domain. Some techniques like correlated double sampling (CDS) or the use of dummy switches can minimize those effects. A profound noise analysis for a discrete-time integrated amplifier can be found in [3].

For a first run, the SC-TIA of Fig. 2(b) is realized, because it is stray insensitive, it needs no reset, and it is better suited for low-frequency pyroelectric applications with lower switch requirements.

Measurements

An overview of the whole developed ASIC is shown in Fig. 4. The analog part amplifies and filters the pyroelectric current of up to four parallel sensor elements.

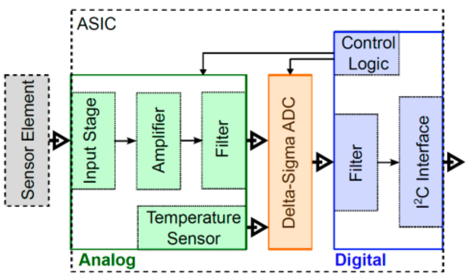

Fig. 4: Main components of the realized ASIC.

Afterwards the voltage is fed into a 16-bit delta-sigma converter and the digitized counts can be read via a I²C communication interface (FM+). A huge advantage compared to a discrete setup is the flexible configuration of the input stage, because the emulated feedback resistance and capacitance can be adjusted over a wide range of 2 GΩ … 1 TΩ and 50 fF … 6400 fF, respectively. That is why the measured responsivity of the detector in Fig. 4 can be adjusted over more than two decades, in comparison to the fixed responsivity of the commercial detector LRM-244.

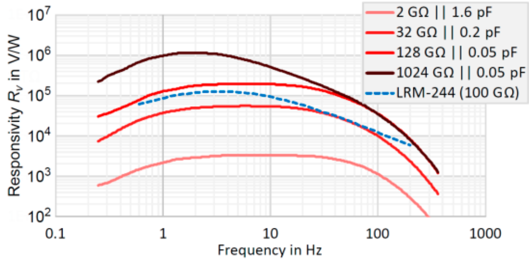

Fig. 5: Responsivity of the digital detector for different feedback configurations in the frequency domain.

The output noise densities of the discrete TIA and the SC-TIA theoretically are the same because the noise folding effects of the SC circuit result in a white noise corresponding to the realized resistance value R_f at low frequencies. Measurements show that the noise density of the SC-TIA is ≈ 180 µV/√Hz (128 GΩ, 10 Hz) and higher than for a discrete R_f, due to several other impacts like the current and voltage noise of the operational amplifier or the specific implementation of the switches. In total, a specific detectivity of $2.5 \cdot 10^8$ cm√Hz/W (10 Hz, 500 K) could be achieved with the integrated SC-TIA.

Conclusion

An ASIC for the signal conditioning and digitization of sub-pA currents was successfully integrated in a pyroelectrical detector to minimize the external hardware effort. The input stage is realized as TIA in which the discrete high-ohmic resistor is replaced by a switched capacitor. This leads to a similar signal behavior for low frequencies and much less chip area is needed for the monolithic circuit. But the measured noise density of the whole digital detector is higher than for state-of-the-art analog pyroelectrical detectors with identical setup. This is for example due to different operational amplifiers, leakage currents and the integrated switches. Still, the digital detector achieves a high specific detectivity of $2.5 \cdot 10^8$ cm√Hz/W and offers a lot a flexibility for different applications.

References

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