A Fast, Ultra-Low Noise Current Amplifier with Linear Range from Femtoamperes to Nanoamperes

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Abstract

In a large number of sensor principles, small currents are being measured and the performance of the current amplifier has a decisive influence on the performance of the entire measurement system. Usually current amplifiers are designed as a so-called resistive transimpedance amplifier, i.e. the current to be measured is converted into a voltage via a resistor. The higher its resistance, the lower the noise current density caused by thermal noise. At the same time, however, a higher resistance reduces the maximum measurable current at a given output voltage and the maximum bandwidth at a given parasitic capacitance. An alternative are capacitive transimpedance amplifiers, which integrate the current to be measured on a capacitor, corresponding to a nearly infinite resistance. However, leakage currents and charge injection of the switches necessary for resetting the capacitor in this setup result in new sources of error. These errors can be compensated successfully by the novel active reset architecture presented here, which actively regulates the voltage across the capacitor to zero during reset. This enables the design of a current amplifier with a unique combination of ultra-low noise, wide linear dynamic range and high bandwidth. A demonstrator of the current amplifier achieves a standard deviation of the measured current of 3.4 fA at a 3-dB bandwidth of 48 Hz, which corresponds to a noise current density of 0.49 $\mathrm{fA}/\sqrt{\mathrm{Hz}}$ assuming a uniform distribution over the frequency spectrum. Moreover, the demonstrator achieves excellent zero-point stability even without temperature control. Over a period of several days, the zero-point remained within ± 500 aA.

1 Introduction

The majority of measurement systems are based on sensor principles where the physical or chemical measurand is transformed into an electric current or a charge. In particular, ionization-based sensors such as photoionization detectors (PID) or flame ionization detectors (FID) output extremely small electric currents from femto- to nanoamperes. As the current amplifier is the link between the sensor and the rest of the measurement system, the performance of the current amplifier is crucial for the performance of the whole system. Low limits of detection require low noise current amplifiers. Short response times require current amplifiers with high bandwidths. As the noise increases with bandwidth, the faster an amplifier gets the smaller its noise has to be. Furthermore, it also must provide a continuous wide linear dynamic range. The combination of all these properties in a single current amplifier is a major design challenge.

2 Experimental

Generally, current amplifiers are designed using a resistor as the feedback element. This kind of current amplifier topology, known as a resistive transimpedance amplifier and shown in **Figure 1** a), uses an operational amplifier to regulate the output voltage so that the current to be measured flows through the parallel network of the feedback resistor R_f and its parasitic capacitance C_p.

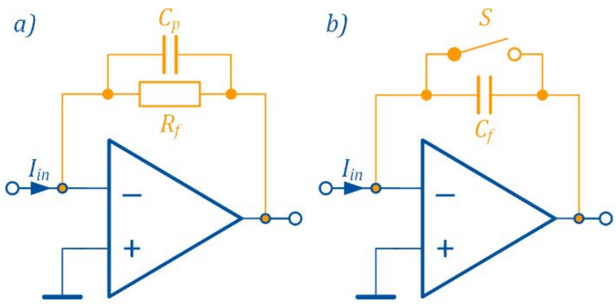

Figure 1: a) Resistive transimpedance amplifier with feedback resistor R_f and parasitic capacitance C_p. b) Capacitive transimpedance amplifier with feedback capacitor C_f and reset switch *S*.

The thermal or Johnson-Nyquist noise current standard deviation σ_i as given by eq. 1 [1,2] depends on the Boltzmann constant k_b, the absolute temperature *T*, the resistance of R_f and the noise bandwidth which can be approximated by the amplifier bandwidth f_g when assuming an ideal filter response. The higher the resistance of R_f, the lower the noise current standard deviation σ_i becomes.

$$\sigma_i = \sqrt{\frac{4\,\mathrm{k_b}\,T\,f_g}{R_f}} \quad (1)$$

Hence, to reduce the amplifier noise at a given temperature and amplifier bandwidth, the resistance of the feedback resistor R_f should be chosen as high as possible. Unfortunately, this also decreases the maximum measurable current at a given output voltage and the maximum bandwidth at a given parasitic capacitance C_p. The noise current only reduces with the square root of the resistance, but the maximum measurable current reduces linearly, thus achieving a wide dynamic range requires extremely high output voltages. Furthermore, extremely low parasitic capacitances or complex compensation schemes are needed to achieve a high bandwidth.

A different approach to overcome these restrictions is the use of a capacitor as the feedback element. The input stage of such a capacitive transimpedance amplifier is shown in **Figure 1** b) with the feedback capacitor C_f onto which the current to be measured is integrated. The resulting output voltage is subsequently differentiated. As the feedback capacitor C_f is nearly an infinite resistance, it is adding virtually no noise [3]. Furthermore, the maximum measurable current can now be increased by resetting the capacitor more often through the reset switch *S*. Nonetheless, leakage currents and charge injection of the reset switch result in new sources of error, limiting the performance of this otherwise superior concept. Here, we present an active reset architecture, which actively regulates the voltage across the capacitor to zero during reset [4], successfully compensating the errors introduced by the switches and reducing the needed reset time. This enables the design of a current amplifier with a unique combination of ultra-low noise, a continuous wide linear dynamic range and high bandwidth. The basic setup is shown in **Figure 2**.

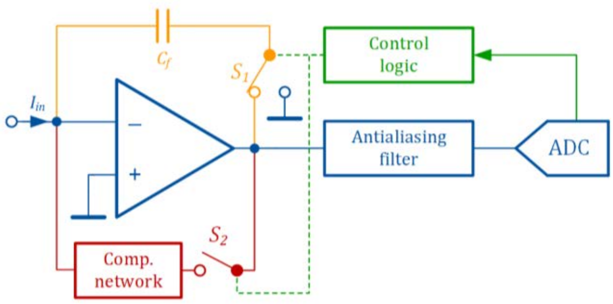

Figure 2: Basic scheme of a capacitive transimpedance amplifier with the active reset architecture, an antialiasing filter and the analog-to-digital conversion.

The significant advantage becomes more obvious when studying the equivalent circuits of the measurement and reset configuration as shown in **Figure 3**. In the measurement configuration, the circuit maximizes the open resistance of the critical switch S_2 through a current-limiting compensation network in series, preventing leakage current and charge injection. Hence, the circuit behaves like an almost ideal integrator. The output voltage of the integrator is directly sampled by the ADC and then digitally differentiated. The resulting amplifier gain after differentiation only depends on the size of the capacitor C_f. When a certain charge has been integrated, the output voltage of the operational amplifier reaches its preconfigured threshold and the control logic subsequently switches the circuit to the reset configuration. In this configuration, switch S_2 is closed, turning the operational amplifier into a simple buffer and switch S_1 is switched to ground. Since now one side of the integration capacitor and the non-inverting input of the operational amplifier are connected to ground, the voltage across the capacitor is regulated to 0 V - the capacitor is actively discharged in a fast and reliable manner by the operational amplifier. Thus, the current-limiting compensation network does not hinder the discharge process.

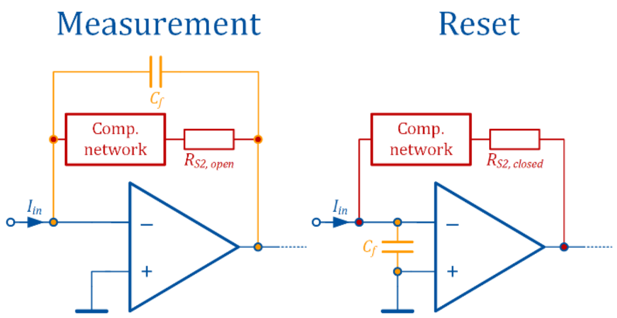

Figure 3: Equivalent circuit of the capacitive transimpedance amplifier with the active reset architecture in measurement configuration (left) and in reset configuration (right). Only the resistance of S_2 is shown, as S_1 is not connected to any critical nodes of the circuit.

This design has been successfully proven by the demonstrator shown in **Figure 4**. The capacitive transimpedance amplifier, the antialiasing filter and the ADC are shielded and galvanically isolated from earth in order to suppress unwanted electromagnetic interference signals. The control logic is implemented in a Cortex M0+ microcontroller. The digitized samples of the ADC and control signals are exchanged with the measurement computer via an USB interface. The data is oversampled with a frequency of 1 kHz, which simplifies the digital filter design.

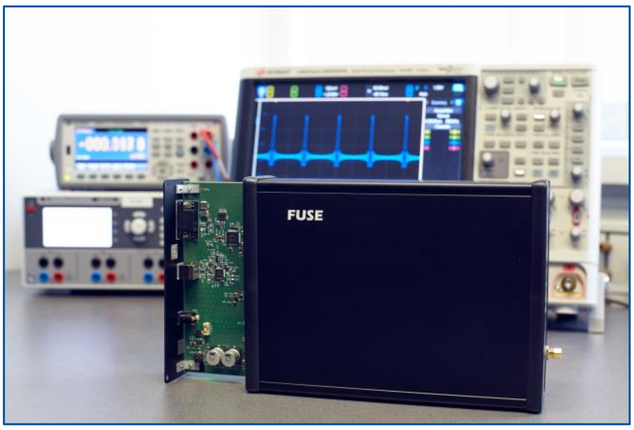

Figure 4: Photo of the capacitive current amplifier with slightly opened housing.

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3 Results and Discussion

The here presented demonstrator of the capacitive transimpedance amplifier shown in **Figure 4** achieves a standard deviation of the measured current of 3.4 fA at a 3 dB bandwidth of 48 Hz, which corresponds to a noise current density of just 0.49 $\mathrm{fA}/\sqrt{\mathrm{Hz}}$ assuming a uniform distribution over the frequency spectrum. This value is only 20 % above the theoretically possible noise current density of an ideal resistor with a resistance of 100 GΩ, (0.41 $\mathrm{fA}/\sqrt{\mathrm{Hz}}$) as shown by the comparison in **Figure 5**. Furthermore, in a real amplifier other noise sources from the operational amplifier and additional noise sources of the resistor beyond Johnson-Nyquist noise would add to this. At the same time, such a high resistance as the feedback element in a resistive transimpedance amplifier would already be completely impractical for many realistic applications. On the one hand, the parasitic capacitance of the circuit would need to be just 33 fF to achieve the bandwidth of 48 Hz achieved with the capacitive transimpedance amplifier. On the other hand, to amplify a current of 10 nA at a resistor value of 100 GΩ, an output voltage of 1 kV would already be required.

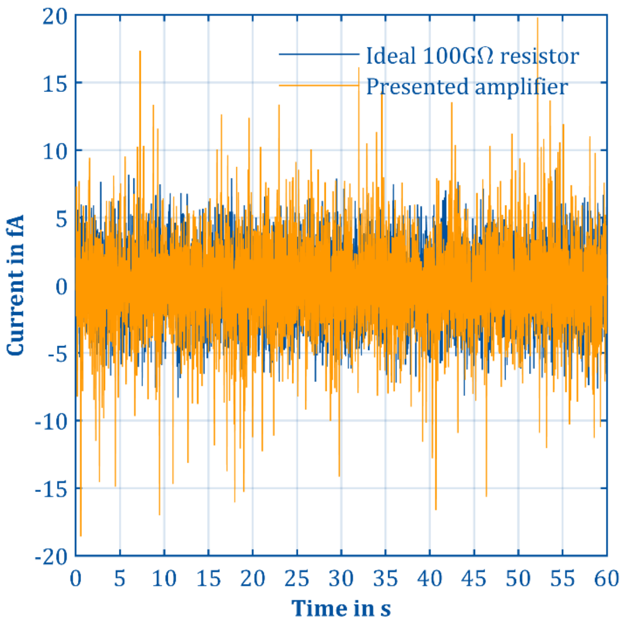

Figure 5: Comparison of the noise current of the developed capacitive transimpedance amplifier with the thermal noise of an ideal 100 GΩ resistor. Both traces use the same filter.

In contrast, the here presented capacitive transimpedance amplifier demonstrator runs with a conventional operational amplifier and is capable of covering a measurement range of six orders of magnitude from 10 fA to 10 nA without any range switching (**Figure 6**) while achieving the mentioned ultra-low noise current density of 0.49 $\mathrm{fA}/\sqrt{\mathrm{Hz}}$. Moreover, the demonstrator achieves excellent zero-point stability even without temperature control. The Allan deviation of the demonstrator as a measure for zero-point stability is shown in **Figure 7**.

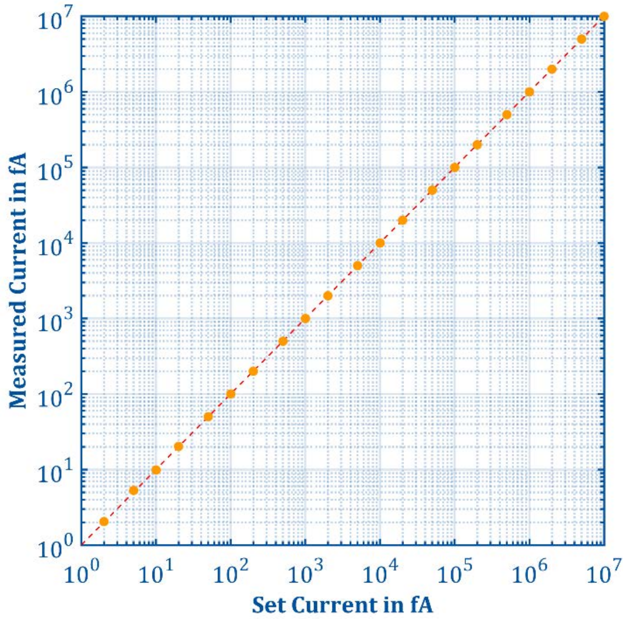

Figure 6: Current measured (dots) with the capacitive transimpedance amplifier against the set value of a custom low noise current source verified by a current meter from Keysight Technologies and linear regression (dashed line, $R^2 = 0.99$).

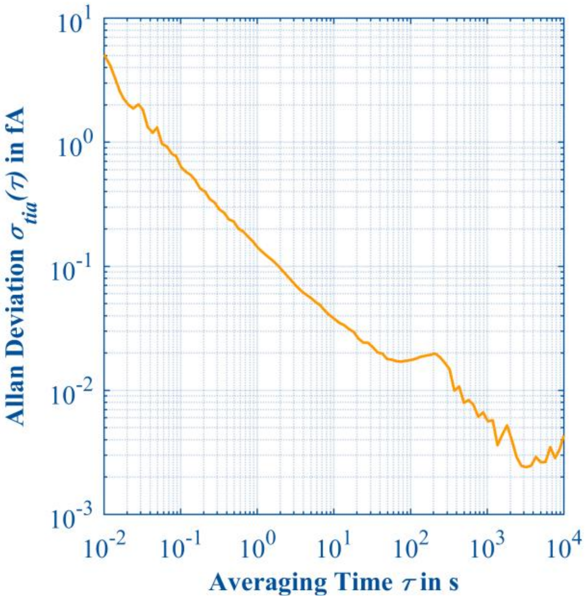

Figure 7: Allan deviation of the developed capacitive transimpedance amplifier.

Figure 8 shows an exemplary measurement of fast current pulses emanating from a flame ionization detector (FID) coupled to a hyper-fast gas chromatograph (GC) [5]. In this application, the characteristics of the presented amplifier are of particular advantage. The linear output signal of the FID can cover up to 7 orders of magnitude, while the hyper-fast GC generates current pulses with a full width at half maximum (FWHM) of less than 100 ms, thus requiring a high bandwidth for sampling.

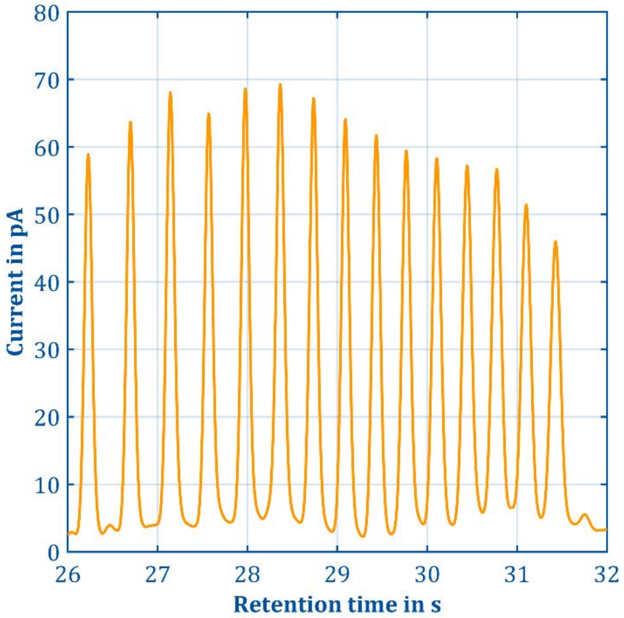

Figure 8: Measurement of current pulses generated by a flame ionization detector (FID) during a gas chromatograph (GC) run.

4 Conclusion

In this work, we presented a novel design of a capacitive transimpedance amplifier. The novel design enables the use a capacitive transimpedance amplifier with its inherent very low current noise density while overcoming major performance limitation of the usual amplifier designs through the here presented active reset architecture. This architecture with two switches in the feedback loop of the operational amplifier and the combination of minimum analog signal conditioning, direct digitization and digital signal processing enables a continuous measurement of the current with a unique combination of wide linear range, ultra-low noise, excellent zero-point stability and high bandwidth.

5 Acknowledgements

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6 Literature

[1] J.B. Johnson, Thermal Agitation of Electricity in Conductors, Phys. Rev. 32 (1928) 97–109.

[2] H. Nyquist, Thermal Agitation of Electric Charge in Conductors, Phys. Rev. 32 (1928) 110–113.

[3] R. Sarpeshkar, T. Delbrück, C. A. Mead, White noise in MOS transistors and resistors, IEEE Circuits and Devices, vol. 8 (1993) 23-29.

[4] A.T. Kirk, C. Wendt, S. Zimmermann, Rücksetzschaltung für einen kapazitiven Transimpedanzverstärker, PCT/EP 2019 077 364 A1, 2019.

[5] P. Boeker, J. Leppert, Flow Field Thermal Gradient Gas Chromatography, Anal. Chem. 87 (2015) 9033–9041.