

A Programmable Analog Front End for the Acquisition of Biomedical Signals

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Abstract— A programmable biosignal acquisition Analog Front End (AFE) is presented. It is programmable concerning noise, power consumption, gain and cut-off frequency and can be adapted to all commonly used biomedical signals.

Keywords— low noise amplifier; low power amplifier; programmable amplifier; biomedical signals

I. INTRODUCTION

Biomedical signals, such as Electrocardiogram (ECG), Electromyogram (EMG), Electroencephalogram (EEG) or Evoked Potentials (EP), imply different requirements on signal processing equipment. A mobile 24h-Holter ECG, for instance, has tight constraints concerning power consumption. Concerning noise, however, ECG requirements are not critical because of relatively high input signals, while for EEG and EP applications a low noise behaviour is absolutely necessary. On the other hand, power consumption is not that critical for these applications. Table 1 shows the characteristics of the signals mentioned above [1].

Table 1: Most commonly used biomedical signals

signal	frequency	amplitude
ECG	0.05 - 150 Hz	5 μ V - 8 mV
EEG	0.5 - 100 Hz	2 μ V - 200 μ V
EP	2 Hz - 5 kHz	20 nV - 20 μ V
EMG	0.01 Hz - 10 kHz	50 μ V - 10 mV

In [2,3] an integrated circuit was proposed where more than one biomedical signal, namely ECG and EEG signals are combined in one chip. Since the power consumption is not programmable, the chip has a relatively high power loss to achieve low noise behaviour for EEG equipment. This high power consumption makes it unsuitable for mobile medical applications, such as a mobile 24h-Holter ECG. Hence, programmability is absolutely necessary if different medical applications are combined in a single chip.

The presented AFE is programmable concerning noise behaviour, power dissipation, amplification and filtering. Table 2 shows the specification of the programmable Analog Front End regarding its noise and power behaviour in relation to the frequency band of the applied signal. Taking into account that the power for EEG and

Table 2: Noise - power specification of the AFE

signal	frequency	rms noise	power	remarks
ECG	0.05 - 250 Hz	833 nV	2 mW	mobile
EEG	0.5 - 70 Hz	250 nV	13 mW	USB
EP	0.1 - 3 kHz	440 nV	13 mW	USB
EMG	10 Hz - 5 kHz	1 μ V	13 mW	—

EP equipment will be provided by using a USB port, the power consumption is limited for these applications, as well.

The paper is organised as follows: Section 2 describes the basic architecture of the programmable AFE while in Section 3 all components are described in detail. Section 4 highlights the experimental results and in section 5 conclusions are given.

II. BASIC ARCHITECTURE

The programmable Analog Front End consists of 4 components integrated in a 0.35 μ m CMOS technology. It is shown in figure 1. The first stage (preamplifier) has

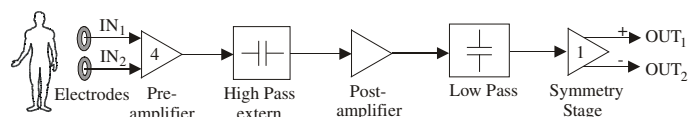


Figure 1: Architecture of the programmable AFE.

two high resistive inputs with an amplification factor of four. The second stage (postamplifier) is a programmable amplifier with four different gains, adaptable to the amplitude of the signal. Programmable opamps [4] regarding noise and power consumption are used in both

stages. An external high pass filter can be set between the first and the second stage to filter out the DC-offset coming from the contact between skin and electrode. A low-pass filter with two selectable cut-off frequencies is following as an anti-aliasing filter for a subsequent AD-Conversion. A symmetry stage is used as a fourth stage to achieve fully differential signals for the AD-Converter. All components of the programmable AFE are described in the following section.

III. COMPONENTS

A. Preamplifier

Acquiring biomedical signals, high resistive inputs of the first stage are absolutely necessary. The preamplifier provides two high resistive inputs and is wired as an unsymmetrical instrumentation amplifier as shown in figure 2. It mainly consists of 2 identical operational

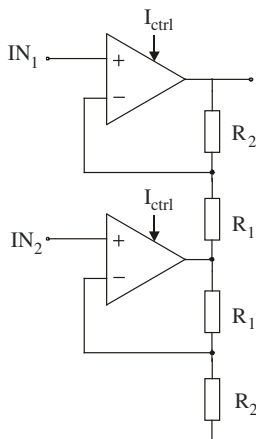


Figure 2: Preamplifier.

amplifiers [4], which are programmable concerning noise behaviour and power consumption by setting the control current I_{ctrl} . The crucial point in the design of the programmable opamp is to preserve the phase margin of the opamp throughout the operation region. By increasing the power consumption of the opamps, the input noise is decreased while the opamps remain stable. The opamp is designed with rail-to-rail input and output. Considering the amplification factor of the preamplifier, a DC-offset of max. ± 300 mV, a signal amplitude up to 80 mV at IN_1 , and a unipolar supply voltage of 3.3 V are taken into account. These requirements lead to a maximum possible amplification factor of four. Regarding the resistances, an optimum between noise behaviour and power dissipation of the preamplifier is found for $R_1 = 1$ k Ω and $R_2 = 3$ k Ω . The tolerance of the amplification factor has been specified to be smaller than 0.1 % by using large areas of resistors and common

centroid structures. This small tolerance ensures a CMRR of 60 dB.

B. Postamplifier

The postamplifier is wired as a noninverting amplifier, which is shown in figure 3. The same programmable opamp already used in the preamplifier is used here. Hence, the power consumption and the noise behaviour of the postamplifier can be programmed too. The amplification factor of the postamplifier can be changed by setting the switches sw_1 to sw_4 . At the same time only one switch is on while the others are off. Hence, 4 amplification factors can be set beginning with sw_1 : 3.86, 30, 111 and 248. The tolerance of these amplification factors is smaller than 1 %. A DC-offset of the opamps of 1 mV was considered.

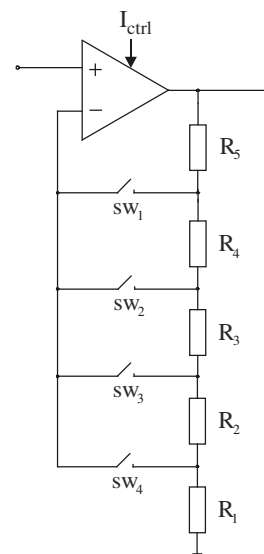


Figure 3: Postamplifier.

C. Low-pass Filter

An anti-aliasing filter for a subsequent AD-Converter, which is not included in the programmable AFE, is provided by the third stage. The low-pass filter shown in figure 4 is programmable concerning its cut-off frequency. The 6 dB cut-off frequency can be set either

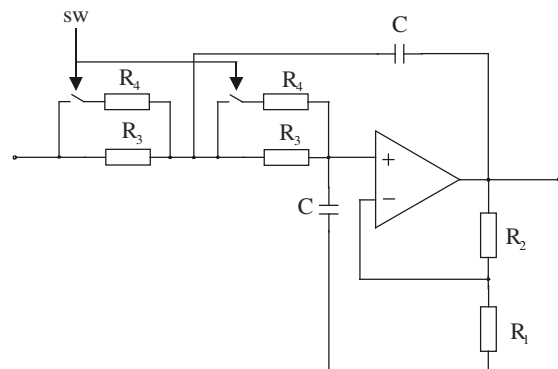


Figure 4: Low-pass filter.

at 3 kHz for ECG- and EEG-signals or at 15 kHz for EP- and EMG-signals. Sallen & Key architecture is used to provide a second order low-pass filter with Bessel characteristics using a single opamp [5]. Hence, the low-pass filter has an additional amplification factor of 1.26. Closing the switch, the 6 dB cut-off frequency of 15 kHz is set. If the switch is open, the 6 dB cut-off frequency is 3 kHz. The programmable low-pass filter was optimised concerning power and area constraints.

D. Symmetry Stage

To keep perturbations low, the subsequent AD-Converter should be implemented in fully differential mode. Hence, a symmetry stage is used as shown in figure 5. It acts like an inverter and provides the positive

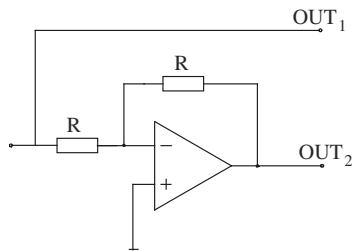


Figure 5: Symmetry stage.

and the negative value of the incoming signal. The amplification factor of the symmetry stage has a tolerance of smaller than 1 %.

IV. RESULTS

The presented programmable Analog Front End has been designed in a 0.35 μm CMOS process and has been fabricated at austriamicrosystems. Figure 6 shows the chip micrograph. The AFE has an area of approximately 3.1 mm^2 .

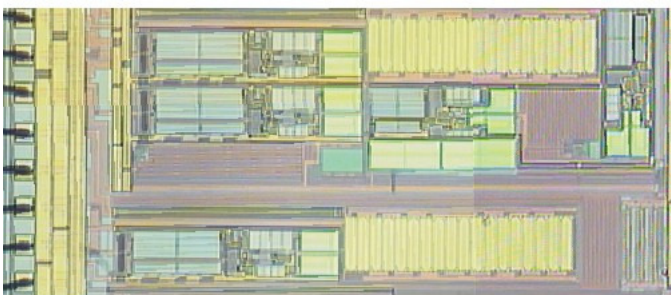


Figure 6: Chip micrograph of the programmable AFE.

A. Noise Spectrum

In figure 7 the measured input-referred noise voltage vs. frequency for two control currents I_{ctrl} of the opamps situated in the preamplifier and in the postamplifier is shown. For a control current of $I_{ctrl} = 1 \mu\text{A}$ an input

thermal noise voltage of 18.2 $\text{nV}/\sqrt{\text{Hz}}$ at 5 kHz is achieved. If a control current of $I_{ctrl} = 20 \mu\text{A}$ is applied, the input thermal noise voltage goes down to approximately 7.2 $\text{nV}/\sqrt{\text{Hz}}$ at the same frequency. Hence, the thermal noise is reduced by a factor of approximately 2.5 by adjusting the control current of the opamps accordingly.

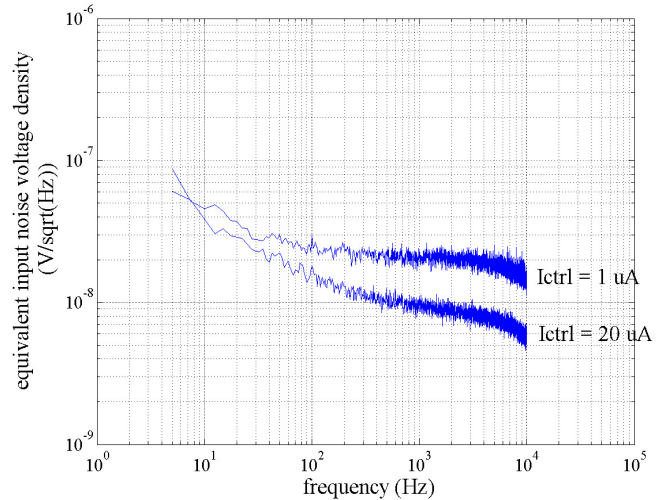


Figure 7: Measured equivalent input noise voltage density vs. frequency for $I_{ctrl} = 1 \mu\text{A}$ and $20 \mu\text{A}$.

B. Noise and Power Tradeoff

Table 3 shows the resulting rms noise and the power consumption related to the frequency bands of the applied biomedical signals.

Table 3: Measured rms noise and power consumption

signal	frequency	I_{ctrl}	gain	rms noise	power
ECG	0.05 - 250 Hz	1 μA	1	743 nV	1 mW
EEG	0.5 - 70 Hz	20 μA	4	250 nV	12.8 mW
EP	0.1 - 3 kHz	20 μA	4	410 nV	12.8 mW
EMG	0.01 - 5 kHz	20 μA	4	604 nV	12.8 mW

Comparison of table 2 with table 3 shows that all specifications have been met. In figure 8 the results considering the power dissipation and the related input thermal noise at a frequency of 5 kHz are shown. The control current of the opamps in the preamplifier and the postamplifier is changed between 1 μA and 20 μA . The total power consumption of the programmable AFE varies from approximately $P \approx 1 \text{ mW}$ to $P \approx 12.8 \text{ mW}$. Since the equivalent input thermal noise voltage density of the programmable opamps in the preamplifier and in the postamplifier decreases with approximately $1/\sqrt{P}$, the total equivalent input thermal noise voltage density of the programmable AFE shows the same behaviour.

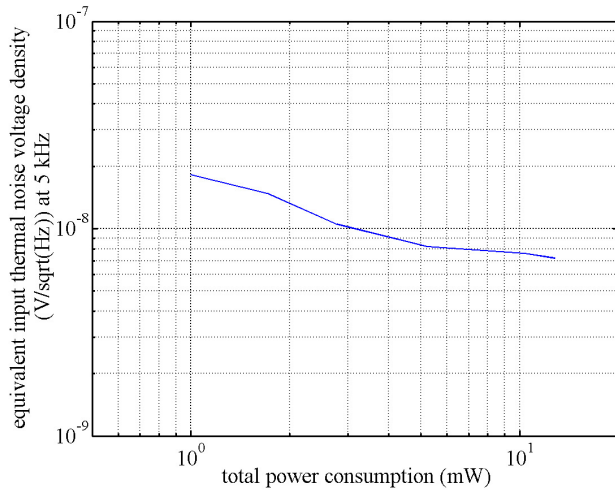


Figure 8. Measured input thermal noise voltage density vs. total current consumption.

C. Transfer Characteristics

In figure 9 the transfer function for different amplification factors is shown. The 6dB cut-off

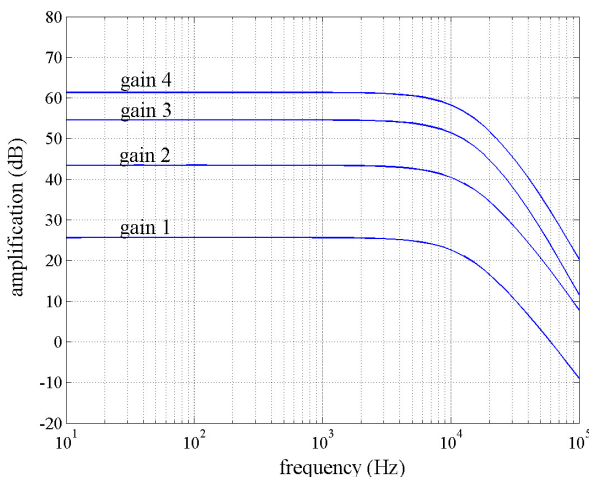


Figure 9: Transfer function of the AFE - amplification factors.

frequency of the low-pass filter is set to 15 kHz. The total amplification of the presented AFE consists of the amplification of the preamplifier, the postamplifier and the low-pass filter. Changing the amplification of the postamplifier leads to the following amplification factors of the AFE: gain 1 = 19.1, gain 2 = 148, gain 3 = 535 and gain 4 = 1168.

Figure 10 shows the transfer function of the presented AFE for the two cut-off frequencies. The amplification is set to 1168 or 61.3 dB. The diagram shows that the cut-off frequency of the AFE can be selected as specified.

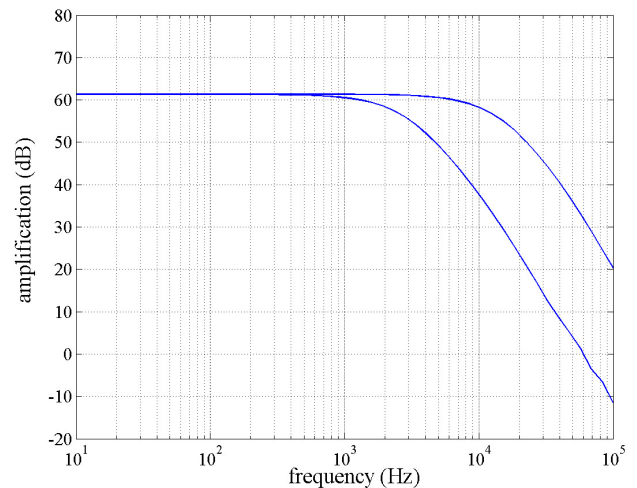


Figure 10: Transfer function of the AFE - cut-off frequency.

V. CONCLUSION

A programmable Analog Front End is described for the detection of all common biomedical signals. The Analog Front End is programmable concerning noise, power consumption, amplification and cut-off frequency, which makes it adaptable to all these signals. The lowest power consumption is found at 1 mW whereas the lowest thermal noise is 7.2 nV/ $\sqrt{\text{Hz}}$. Four amplification factors at 19.1, 148, 535 and 1168 and two cut-off frequencies at 3 kHz and 15 kHz can be set according to the amplitude and the frequency of the biomedical signal. The presented programmable Analog Front End represents the first part of a signal acquisition circuit that allows the design of different biomedical instruments with a single type of chip.

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