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A Modular Analog Front-End for the Recording of Neural Spikes and Local Field Potentials within a Neural Measurement System

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Abstract

The measurement of neural signals is mandatory for an extensive and detailed understanding of the cortex. A parallel recording of multiple recording channels and varying neural signal types is required in order to cover a high density of neural information. Therefore, analog front-ends are required which record signals from the micro-mechanical electrodes and preprocesses these data for a transmission out of the brain. This paper presents an analog front-end for the recording of local field potentials and neural spikes. A modular approach is applied that enables the integration within a complete system or the operation as a single component. The use of configurable recording channels provides the capability to adjust the channels, dependent on the signal type of interest. The proposed front-end has been fabricated in a 0.35 μm-CMOS process, and performance values are demonstrated by measurements.

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Keywords: Neural Measurement System, Action Potentials, Spikes, Brain Computer Interface, Low Power, Low Noise

1. Introduction

The recording of neural activities is important to understand the basic operation of the human cortex and the perspective to analyze the visual and motorical perceptions [1]. Micro-electrode arrays and needles have been investigated and presented to record the activities of a single neuron (APs) or the interaction of multiple neurons within a dedicated area of the cortex (LFPs). These electrodes acquire signals with very small signal amplitudes and give strict limits to the specifications of the connected recording front-end [2]. In recent years many research institutes have developed biomedical components, which fulfill these requirements [3]. Recording arrays of more than 100 electrodes have been proposed, that enable a sufficient resolution for the analysis of fundamental neural investigations. However, to cover a larger amount of neural sources the demand for neural measurement systems with more parallel recording channels increases continuously. The rising complexity and the limitation of transmission bandwidth yield to restrictions in the design of fully integrated measurement systems [4]. Therefore, a modular approach is proposed, that enables the integration of the analog recording front-end within a complete mixed-signal design or the operation as a single external component.

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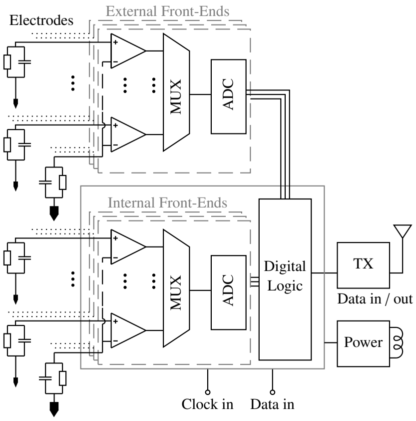

Fig. 1. The proposed measurement system for the recording of neural activities.

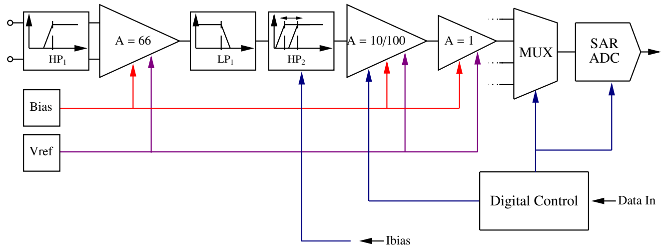

Fig. 2. Schematic of the analog recording front-end for the recording of up to 16 channels. Eight front-ends can be combined to record up to 128 channels.

2. Neural Measurement System

The architecture of the proposed system is based on the neural measurement system that we presented in [5]. Up to eight analog front-ends, with altogether 128 recording channels can be connected to a reconfigurable digital unit to adjust the bandwidth of the incoming data to the data-rate of the external wireless transceiver [Fig. 1]. The digital unit enables the reduction of the digital resolution, the limitation of the sampling frequency and the selection of dedicated measurement channels. Eight digital interfaces are provided by the reconfigurable part to individually connect each modular analog front-end. The interface is realized by a serial data protocol that is identical for each front-end. This configuration enables the connection of fully-integrated analog front-ends as well as the data transfer to external analog front-ends.

3. Analog Front-End

The proposed analog front-end can be adjusted to LFPs or to AP signals by configuration of the signal path, depending on the target application. Each front-end consists of up to 16 channels, enabling the parallel recording of multiple independent electrodes. A recording channel consists of a first stage low-noise amplifier, an adjustable high-pass filter and a second stage variable gain amplifier. A multiplexer is used to time-multiplex the analog signals and a 10-bit SAR-ADC samples and digitizes the incoming data stream [Fig. 2]. The adjustable time-continuous high-pass filter is used to adapt the lower cut-off frequency of the analog recording front-end to the specific needs of APs (f_{HP_2} = 350 Hz) and LFPs (f_{HP_2} = 1 Hz). Since the signal amplitude of a neural spike is less than the amplitude of an LFP signal the second stage amplifier can be set to a gain of A_1 = 20 dB and A_2 = 40 dB. Each recording amplifier can be individual adjusted to either LFP or AP configuration, making it possible to measure a variety of neural activities. The amplified signal is multiplexed and the output of the SAR-ADC is transmitted to a small protocol unit. The protocol unit preprocesses the acquired data for the transmission to the digital unit of the neural measurement system. Every analog recording front-end also consists of an integrated current source, bias distributors and a reference voltage for the ADC and analog amplifier.

4. Measurement Results

The modular analog front-end has been fabricated in a 0.35 μm CMOS process [Fig. 3] and relevant performances have been measured to evaluate the capability for the recording of neural signals. The frequency response of the first stage low-noise amplifier was measured [Fig. 4] and an amplification of $\mathrm{A}_{\mathrm{LNA}}$ = 36 dB and a corresponding bandwidth of $f_{3\mathrm{dB}}$ = 15.5 kHz was achieved. The input-referred noise of the low-noise amplifier has been evaluated and is $V_{\mathrm{noise,RMS}}$ = 6.1 μV [Fig. 6]. This is small enough for the recording of neural activities without significant distortions of the acquired signal.

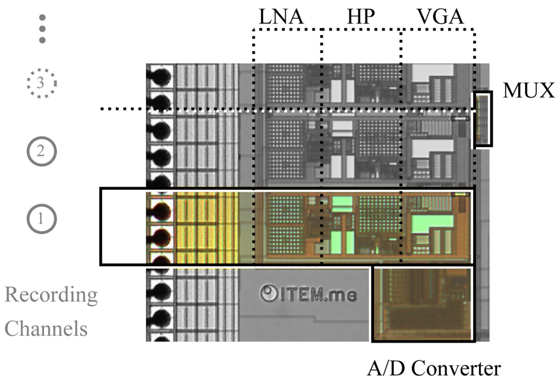

Fig. 3. Picture of the modular analog recording front-end. Electrodes are connected to the pad-cells for the recording of neural activities. The dimension of a single recording channel is 640 μm x 230 μm.

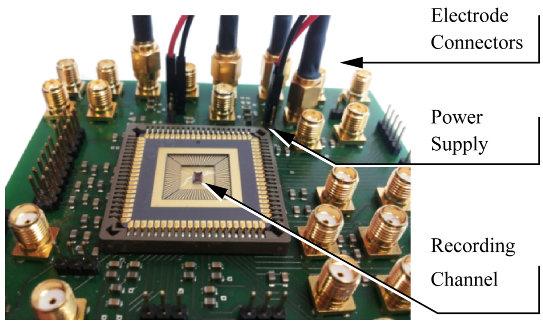

Fig. 4. Set-up for the measurement of the analog recording channels and for the connection to external electrodes.

Besides the performance values of the first stage low-noise amplifier, the output of the whole recording channel has been measured. This measurement covers the configuration for LFPs as well as AP signals [Fig. 5]. For the measurement of LFPs the overall amplification is set to A_{LFP} = 56.1 dB and the lower-cut of frequency of the adjustable high-pass filter is tuned to f_{HP} = 10 Hz. In AP configuration the demands vary and an overall amplification of A_{AP} = 76.1 dB is achieved, while the suppression of LFP components is obtained by tuning the high-pass filter to f_{HP} = 400 Hz. A summation of the overall system performances is depicted in Table 1. The overall current consumption is $I_{channel}$ = 40 μA at a power supply of V_{sup} = 3.3 V and permits the energy efficient operation of the proposed analog front-end.

Laboratory experiments have been performed with the proposed analog recording front-end to demonstrate the capability of recording neural activities. Typical spike signals have been amplified and digitized by the analog front-end in AP configuration [Fig. 7(a)] enabling a sufficient resolution for the reconstruction of the recorded signal. A neural input stimulus with both AP and LFP components has been acquired by a recording channel to analyze the transient behavior of the analog components [Fig. 7(b)]. The measurement illustrates the suppression of LFP components and also shows the noise that is added to the pure signal due to the electrodes and analog components of the system. For the measurement the time-continuous high-pass filter has been set to a cut of frequency of f_{HP_2} = 150 Hz and the amplification of the second-stage variable gain amplifier was set to A_2 = 20 dB.

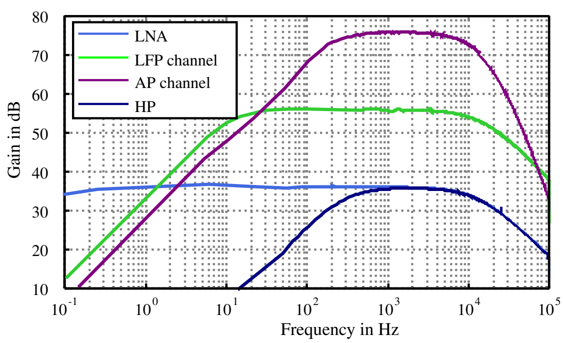

Fig. 5. Measured frequency response of a recording channel in AP and in LFP configuration.

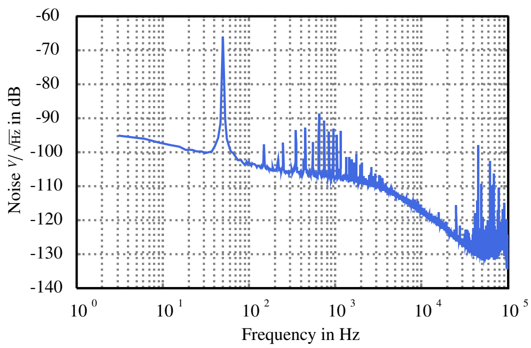

Fig. 6. Measurement of the output-referred noise of the first stage low-noise amplifier.

Table 1. Measurement results of the single analog components and the whole analog recording channel.

	LNA	HP	VGA + UGB	Channel
Gain	36 dB	×	20.1 dB / 40.1 dB	56.1 dB / 67.1 dB
Lower cut-off	1 Hz	1 Hz - 400 Hz	×	1 Hz - 400 Hz
Higher cut-off	15.5 kHz	×	159 kHz / 15.9 kHz	25.5 kHz
Noise	6.08 μVrms	×	×	×
PSRR	> 75.5 dB	×	> 40 dB	×
Current (±1.65 V)	4 μA	2.3 μA	20.2 μA	26.5 μA

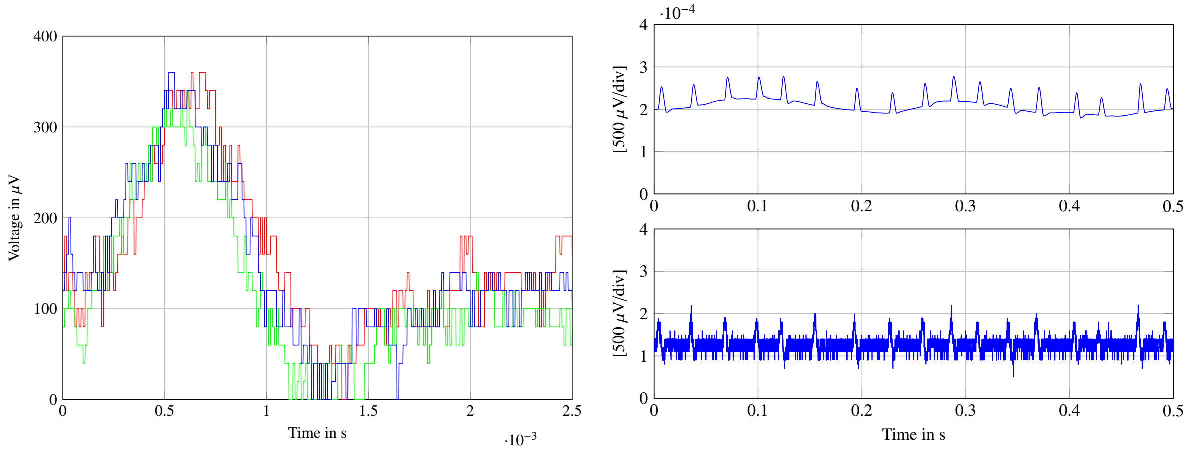

Fig. 7. a) A typical neural action potential acquired with the proposed recording front-end. The amplitude of the action potential is $V_{pp} = 350\mu V$. b) *top:* Neural input stimuli with action potentials and superimposed LFP components *bottom:* High-pass filtered and digitized signal.

5. Conclusion

In this paper we present a modular analog front-end for the recording of LFP and AP signals. The front-end has been fabricated in a 0.35 μm CMOS process and performance values are demonstrated by measurements. Besides the frequency response of the system in LFP and AP configuration, the capability of recording neural activities is presented. The modular approach enables the operation within a fully-integrated system and also the operation as a single external device.

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