Current feedback neural amplifier with real time electrode offset suppression

(Invited Paper)

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***Abstract*—This paper describes a direct coupled neural amplifier with active electrode offset suppression in order to avoid large coupling capacitors and complex chopper circuits. It describes a novel feedback scheme, where a low pass current mode feedback is applied to a regulated telescopic cascode amplifer, at the cascode nodes by using a modified transconductance block. This solution leads to fully differential input-differential output direct coupled neural amplifier, achieving a DC offset suppression range of $\pm$200 mV, chip area area of 0.078 mm^2 per channel and an input referred noise of 2.5 μV_{rms} over 1 Hz 5kHz bandwidth.**

I. Introduction

Neuromodulation is an emerging interventional, non-invasive or minimally invasive therapy to treat intractable diseases and conditions not currently covered under existing therapies. There is a growing interest in developing therapeutic neuromodulation devices targeting the Peripheral Nervous System (PNS) to treat diseases with little or no known pharmacological interventions [1].

In order to record from central nervous system (CNS) such as the brain, challenges include developing a multichannel, low power, low noise solution to record from as many sites as possible, needs to be addressed. Whereas challenges involved in recording from the peripheral nerves, involve very low noise performance at low power, small size and especially high common mode rejection ratio (CMRR) to reject common mode electromyographic(EMG) signals.

Neural amplifiers are generally AC coupled to remove DC offset due to electrodes. Electrochemical reactions at interface between the electrode and neural tissue results in a dc offset depending upon on the type and material of electrode and type of neural recording site with the dc offset differing for different recording sites. The electrode offset can range from $\pm$ 10 mV to $\pm$ 200 mV depending on the type of electrodes and neural recording applications. For *in vivo* recording from the CNS, such as brain, DC electrode offset range tends to be in a range of $\pm$10 mV [2], [3], where spike electrodes are inserted into the neural tissue. In applications, involving recording from the PNS, the electrode DC offset tends to be higher in the range of $\pm$100 mV for cuff electrodes which are wrapped around the nerve [4].

The disadvantage of using an AC coupled front-end consist of large chip area as a result of the use of large capacitor size. In order to create a high pass cut-off, pseudoresistors are used which tend to be dependant on the voltage across them. Pseudoresistor non-linearities can lead to signal non-linearities and variations in high pass cut-off characteristics. Additionally, a reset signal is required to reset the pseudoresistor in order to stabilise DC operating points. The use of AC coupling capacitors also results in reduced input impedance [2]. A reduced input impedance lead to lower CMRR due to voltage division effect.

An alternative to AC coupled amplifiers are direct coupled amplifiers where the electrode DC offset is removed actively with the help of circuit techniques instead of discrete components [2]. It also enables recording of low frequency local field potentials (LFP) and high frequency neural spikes simultaneously. Previous solutions involve a low pass filter in feedback which provides an overall bandpass response to the entire system. However, previous voltage mode implementations suffer from single ended input which degrades CMRR [2]. Another implementation involves use of two feedback loops, digital for discrete tuning steps and analogue for fine tuning steps [3].

In this paper, a current mode feedback is applied to a regulated telescopic cascode amplifier to cancel electrode DC offset and achieve fully differential direct coupled inputs. This leads to a higher range of DC offset upto $\pm$200 mV being rejected actively and the overall transfer function of the LNA is a tunable bandpass filter.

In this paper, Section II describes the direct coupled amplifier in detail. It includes a description of the low noise front-end amplifier and analysis of the feedback loop. The results are discussed in Section III.

II. System Architecture

In this paper, the neural front-end amplifier is implemented as a telescopic cascode low noise amplifier. A

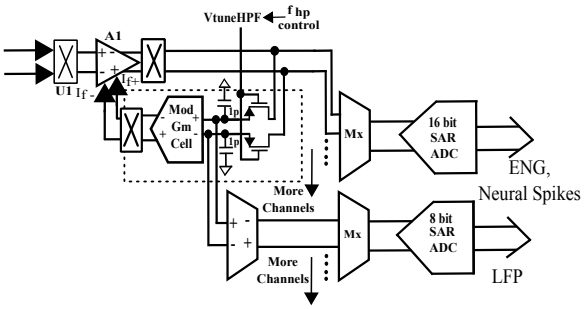


Fig. 1: System architecture with current mode feedback loop to suppress electrode DC offset and simultaneous LFP and neural spike recording for CNS.

negative feedback is applied to this amplifier in current mode by using a low pass filter and modified low power modified G_m cell. The G_m cell is biased with very low bias current, which scales up depending on the output current. The overall architecture of the neural amplifier is shown in Fig. 1 .

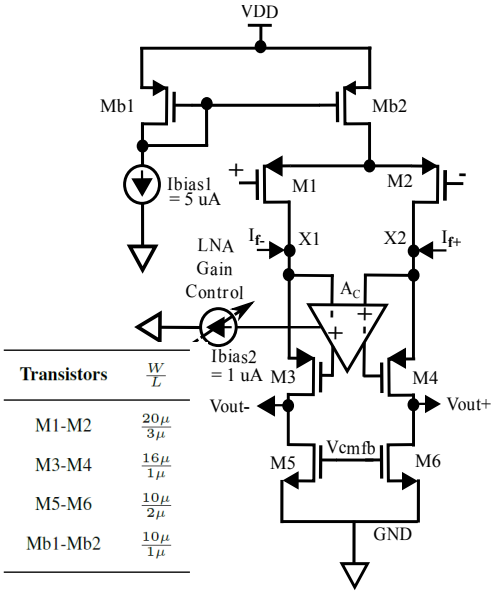
A. Front-end Amplifier

The front-end amplifier is implemented as a regulated telescopic cascode amplifier. A benefit of using telescopic cascode topology exhibits a good trade-off between low noise at low power. The cascode enables enhancing the gain of the overall stage in addition to providing higher output resistance. The use of the regulated telescopic cascode, provided higher gain and greater control on the gain of the cascode stage (A_c), hence overall open loop gain of the front-end amplifier, as shown in Fig. 2. Another advantage is, there was negligible noise contribution from this cascode amplifier to the overall input referred noise of the amplifier. The cascode stage A_c is implemented as a current mirror operational transconductance amplifier (OTA).

All transistors were biased in strong inversion, in order avoid large dimension transistors. The current feedback is fed into nodes X1 and X2 which are low impedance nodes looking into M3 and M4, before the cascode stage. In order to remove flicker noise contribution, the inputs were chopped at a frequency of 5 kHz. Common mode feedback was applied to M5, M6.

B. Modified Transconductance (G_m) Cell

The current mode feedback is implemented with the help of a modified G_m cell. The core of the G_m cell is a complementary pair (Mg1-Mg4), as shown in Fig. 3, also referred to as the floating current source (FCS). This has been used previously, as the output stage in current mode feedback amplifiers [5]. A disadvantage of the simple G_m cell is, for higher output current a higher bias current is needed to maintain biasing regions. In this paper, a modified version of the FCS has been used shown in Fig 3, in which the bias current scales



Transistors	$\frac{W}{L}$
M1-M2	$\frac{20\mu}{3\mu}$
M3-M4	$\frac{16\mu}{1\mu}$
M5-M6	$\frac{10\mu}{2\mu}$
Mb1-Mb2	$\frac{10\mu}{1\mu}$

Fig. 2: The front-end LNA (A1) has a cascode amplifier(A_c) with its gain being controller to remove LNA gain variation due to .

dynamically with the output current, with the ability to both sink in and source out current.

The bias current of the G_m cell is controlled by the output voltage of the cell, which in turn is proportional to the output current. If the common mode DC voltage exceeds 1.65 V due to the change in DC offset, the bias current of the G_m cell is progressively increased with the opposite happening when the DC offset voltage falls below 1.65 V. In the voltage domain, the AC response of the modified G_m cell, shown in Eq. 1, indicates the presence of a zero. In feedback, this zero is used to cancel the higher frequency pole due to A1 and simplify the loop analysis.

$$\frac{Vout_{Gm}(s)}{Vin_{Gm}(s)} = \frac{(-g_{m-Mg12})(sC_{ds-Mg12})}{g_{ds-Mg12} + s(C_{ds-Mg12})} \quad (1)$$

where,

$$g_{m-Mg12} = g_{m-Mg1} + g_{m-Mg2} \quad (2)$$

$$C_{ds-Mg12} = C_{ds-Mg1} + C_{ds-Mg2} \quad (3)$$

$$g_{ds-Mg12} = g_{ds-Mg1} + g_{ds-Mg2} \quad (4)$$

III. Results

The direct coupled front-end amplifier was designed using 0.35 μm CMOS process. The simulation results of the analogue front-end, presented in this section, demonstrate that the front-end is able to reject DC offset over a range of $\pm$200 mV. The highpass -3 dB frequency

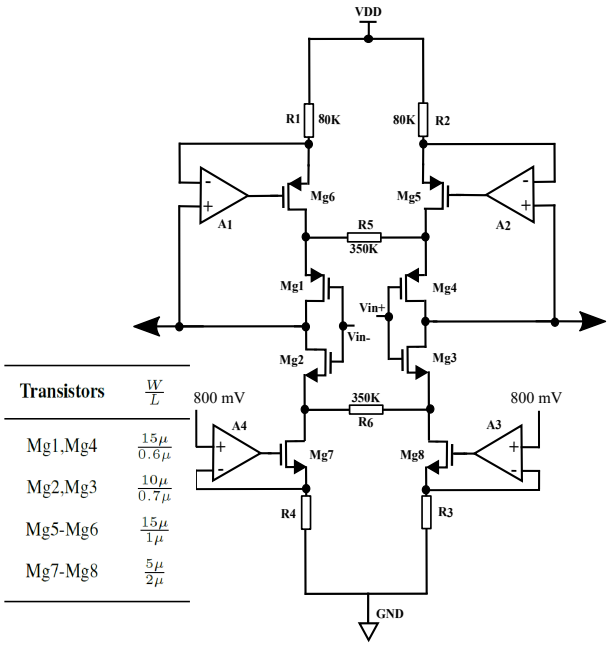


Fig. 3: Modified G_m cell with dynamic biasing ability. A1-A4 are single stage OTAs.

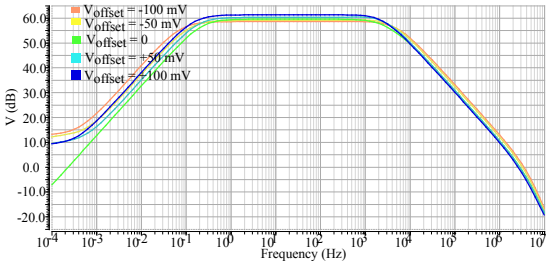


Fig. 4: AC response of the amplifier front-end for different values of electrode offset.

can also be tuned with the help of control voltage ($V_{HPFtune}$) to adjust the bandwidth of the analogue front-end.

A. *Electrode Offset suppression*

The electrode DC offset cancellation results in a higher current being drawn from the modified G_m cell, in order to balance DC voltage levels due to the offset, as shown in Fig. 5 . The cell is biased with a current of 200 nA, which can be scaled dynamically to upto 1 μA, depending on the electrode offset.

The AC response for varying DC offsets demonstrate successful offset rejection for a range of $\pm$200 mV, with small variation of gain, as shown in Fig 4.

The transconductance of the modified G_m, shown in Fig. 6 with respect to input DC voltage levels does not vary much within the range of input voltages from 1.5V

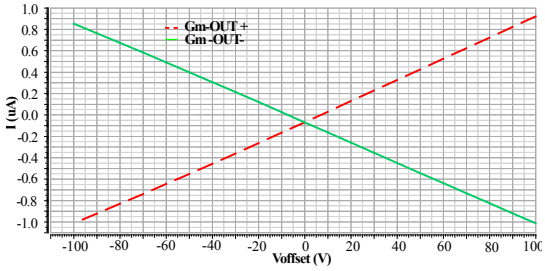


Fig. 5: The current output of the G_m cell changes linearly with electrode DC offset.

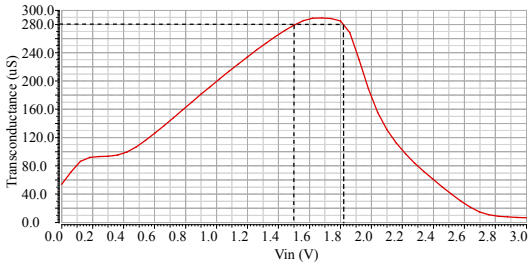


Fig. 6: The transconductance of the modified G_m with respect to input DC voltage levels.

to 1.82 V, thus indicating a range of 320 mV variation in DC levels due to electrode DC offset difference can be tolerated.

The high pass filter cut-off is achieved through a combination of a transistor, operating in sub-threshold linear region and capacitor. The high pass cut-off can be tuned with the help of a gate control voltage, as shown in Fig 7, in order to enable selection of high pass cut-off for different signals such as LFPs, EEG (0.1-100 Hz) neural spikes (200 Hz-2 kHz) [6] and ENG (100-1 kHz) [4].

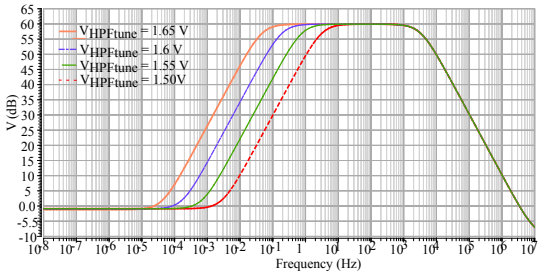


Fig. 7: AC response of the neural amplifier with tunable high pass cut-off frequencies.

B. *Transient Simulation*

In order to verify the functionality of the front-end, a transient simulation was performed using Compound Action Potentials (CAPs). The CAPs were recorded

on stimulation of rat vagus nerve during *in vivo* experiments. During the experiment, these CAPs were recorded using commercially available electrophysiology recording system Intan RHD2132. In order to perform transient simulations for the neural amplifier described in this paper, a 100 mV DC offset difference between inputs was added to the recorded CAPs. The front-end was able to separate the DC offset from the higher frequency CAPs and the amplified signal is shown in Fig. 8.

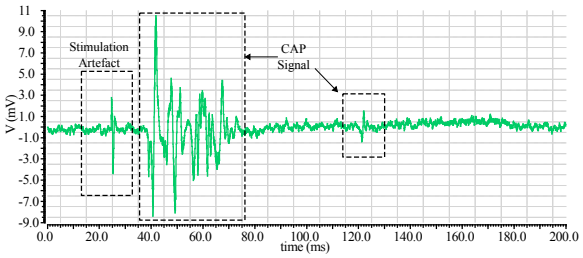


Fig. 8: CAP waveform on vagus nerve after amplification.

C. Comparison with previous work

The simulation results indicate the possibility to achieve wide rejection of electrode DC offset upto ±200 mV. This is useful in PNS recording where cuff electrodes are used and the observed *in vivo* electrode DC offset is in the range of 100-200 mV. In this neural amplifier architecture, the CMRR degrades with the introduction of chopping. This is because, the process variations introduced in the design are up-converted and are not present in the feedback for cancellation. Monte Carlo simulations, indicate that with chopping the mean CMRR is 60 dB. A 16 bit ADC has been used in order to provide larger dynamic range for ENG signals such as CAPs.

TABLE I: Comparison of direct coupled front-end amplifiers.

Parameters	[7]	[8]	[2]	**This Work**
Technology	0.18 μm	0.18 μm	0.13 μm	0.35 μm
Area (mm^2) / channel	0.135	0.99	0.018	0.078
DC Offset Range (mV)	-	±350	±50	±200
Input Configuration	Single Ended	Single Ended	Fully Differential	Fully Differential
Feedback Configuration	Analogue Current	Analogue Voltage	Mixed Signal Current	Analogue Current
CMRR (dB)	-	102	65	60†
Supply Current(μA) / channel	32	58	8.25	11
and Voltage(V)	1	1.8	1.2	3.3
Gain(dB)	55.9	40	52	60
IRN (μV_{rms})	4.4	1.75	5	2.5 μV_{rms}
over Bandwidth(Hz)	10k	1-100	-	1-5k
NEF	5.45	-	7	3.9

†Mean CMRR from Monte-Carlo simulations when chopping was active.

IV. Conclusion

The direct coupled neural amplifier described in this paper achieves successful rejection of wide range of electrode DC offset using an analogue current mode feedback technique involving a modified version of simple G_m cell. Current mode feedback enables a fully differential operation. In order to achieve a quiescent low power operation, a novel modified version of the G_m cell is used in which the bias current can be scaled dynamically with the output current. Apart from low power operation, this direct coupled amplifier offers an offset improvement of ± 200 mV, lower noise over previous designs and also a fully differential input configuration, thus broadening the spectrum of neural recording applications to include PNS. It also enables the separation of higher frequency neural spikes and low frequency LFP simultaneously.

Acknowledgment

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References

[1] M. Gofeld, "New horizons in neuromodulation." *Current pain and headache reports*, vol. 18, no. 3, p. 397, 2014. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/24500635

[2] A. Bagheri, M. T. Salam, J. L. Perez Velazquez, and R. Genov, "Low-Frequency Noise and Offset Rejection in DC-Coupled Neural Amplifiers: A Review and Digitally-Assisted Design Tutorial," *IEEE Transactions on Biomedical Circuits and Systems*, pp. 1–16, 2016.

[3] R. F. Yazicioglu, P. Merken, R. Puers, and C. Van Hoof, "A 200 μW eight-channel EEG acquisition ASIC for ambulatory EEG systems," *IEEE Journal of Solid-State Circuits*, vol. 43, no. 12, pp. 3025–3038, 2008.

[4] L. N. S. Andreasen and J. J. Struijk, "Signal strength versus cuff length in nerve cuff electrode recordings," *IEEE Transactions on Biomedical Engineering*, vol. 49, no. 9, pp. 1045–1050, 2002.

[5] A. E. Arbel and L. Goldminz, "Output Stage for Current-Mode Feedback Amplifiers , Theory and Applications," *Analog Integrated Circuits and Signal Processing*, vol. 255, pp. 243–255, 1992.

[6] R. R. Harrison, "A versatile integrated circuit for the acquisition of biopotentials," *Proceedings of the Custom Integrated Circuits Conference*, pp. 115–122, 2008.

[7] C. Y. Wu, W. M. Chen, and L. T. Kuo, "A CMOS power-efficient low-noise current-mode front-end amplifier for neural signal recording," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 7, no. 2, pp. 107–114, 2013.

[8] J. Xu, B. Busze, C. Van Hoof, K. A. A. Makinwa, and R. F. Yazicioglu, "A 15-Channel Digital Active Electrode System for Multi-Parameter Biopotential Measurement," *IEEE Journal of Solid-State Circuits*, vol. 50, no. 9, pp. 2090–2100, 2015.