Quad Mode of Sixteen-Channel Chopper AFE Design and Cascaded with Continuous Time $\Sigma$-$\Delta$ Modulator for Electro-Encephalogy Monitoring System

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Abstract - In this paper a 16-channel AFE is designed for low power consumption for neural activity applications. The new architecture is proposed with two different CT Modulators where the input signal is filtered from 8-channel to one modulator and another eight channel filtered signal is given to the other modulator which increases the performance. In this new design approach, the amplifier is low powered multi – Vt AFE which consumes less power by applying dual threshold voltage. Type –I category (4+4) 8 channel signals of first mode A & B: 10, 50, 70, 110 and 150 Hz amplified from AFE are given to a 2nd CT sigma delta ADC, which involves switched capacitor based resistors. Similarly, the other Type –II category (4+4) channel signals 30, 90, 180, 240 and 360Hz amplified from AFE are given to another 2nd order CT sigma delta ADC. The results in the first mode (4+4 channel ADC mode A& B) depict the SNDR and SNR as 67.3dB 65dB and 71.1db 69dB respectively, consuming power of 8mW. The results in the mode (8 channel ADC mode C & D) depict the SNDR and SNR as 68dB 66.5dB and 72 dB 70.1dB respectively, consuming power of 11mW. The design is simulated using UMC 180nm CMOS technology with 1 V supply and the post layout simulations are presented.

Keywords - Discrete Time (DT), Continuous Time (CT) Analog Front End, Signal Noise Ratio (SNR), SNDR Sigma Delta Modulator.

I. INTRODUCTION

Nowadays, non-contact bio-potential monitoring is the concern of many research works and it has been extensively employed in various applications including brain-computer interface (BCI) [1], heart rate detection [3], monitoring of lung activity [2], and electrocardiogram (ECG) measurement [4-6]. There are three types of the electrodes available which are generally used in clinical, personal and research applications; wet, dry and non-contact. The advantage of using non-contact and dry electrodes over their wet counterparts is the higher signal quality that they provide [7]. Moreover, these provide more comfort and are prominent for patients along with higher macro-biosis and safety against electrical shocks. These merits inspired many researchers attempt to present new designs for non-contact bio-potential measurements with improved characteristics [9]. The standard 10 to 20 EEG electrode array uses 19 electrodes; some electrode arrays used in brain research use 128 electrodes (Northrop, 2002).

EEGs have traditionally been divided into four frequency bands:
• Delta waves have the largest amplitudes and lowest frequencies (3.5 Hz); they occur in adults in deep sleep.
• Theta waves are large-amplitude, low-frequency voltages (3.5 to 7.5 Hz) and are seen in sleep in adults and in prepubescent children.
• The spectra of alpha waves lie between 7.5 and 13 Hz and their Amplitudes range from 20 to 200 mV. Alpha waves are recorded from adults who are conscious but relaxed with the eyes closed. Alpha activity disappears when the eyes are open and the subject focuses on a task. Alpha waves are best recorded from posterior lateral portions of the scalp.
• Beta waves are defined for frequencies from 13 to 50 Hz and are most easily found in the parietal and frontal regions of the scalp. Beta waves are subdivided into types I and II: type I disappears and type II appears during intense mental activity (Webster, 1992).

EEG amplifiers must work with low-frequency, low amplitude signals; consequently, they must be low noise types with low 1/f noise spectrums. EEG amplifiers can be reactively coupled; their 3-dB frequencies should be about 0.2 and 100 Hz. Amplifier mid-band gain needs to be on the order of 104 to 105.

Meanwhile, to increase battery life in wearable devices, the AFE should consume very little power satisfying all of these requirements that are in strict trade-off together makes the design of the AFE a challenging one.
The signal pickup of the device only provides a very weak signal, i.e. on the order of a few μV, which necessitates pre-amplification prior to any further processing. The main signal energy of human nerve signals lies in a frequency band from 400 Hz to 4 kHz. Due to the weak signal, low-noise operation of the preamplifier is crucial in order to retain a sufficient signal to noise ratio (SNR) for nerve signal extraction.

The paper is organized as follows. Section III presents a proposed architecture of Analog Front End with Chopper Technique. An AFE with sigma delta modulator is described in Section III. Simulation results and discussions are provided in Section IV. Finally, conclusions are drawn in Section V.

II. AN ARCHITECTURE FOR 16-CHANNEL NEURAL ACQUISITION USING CHOPPER TECHNIQUES

The microsystem for bio-potential acquisition is as shown in Fig. 2. Bio-signals are amplified by analog front-end (AFE) circuits and converted to digital codes by analog-to-digital converters (ADCs) [3].
Additionally, analog multiplexer switch large output current are designed to select the corresponding signals to ADCs. A trade-off between power and area exists in the micro system. The ratio between the number of AFEs and ADCs affects the overall performance. With the decreasing number of ADCs, the frequency of the system clock and output current of AFEs increases, and thus the power of system also increases significantly. For example, the output current of AFE in 16-channel AFE with one ADC would exceed 50µA for the required conversion rate. Based on the trade-off between power and area, 16-channel AFE with four ADCs are designed in the microsystem. The output current and the frequency of the switched clock of each analog multiplexer are 5µA and 8 kHz, respectively.

A. Noise Contribution at AFE Design

A Flicker Noise 1/f reduction is always a challenge in the bio-signal acquisition. This problem cannot be avoided completely. 1/f noise exist in all the devices of MOSFET due to their surface conduction mechanism. A proper sizing of transistors is required in the circuit design techniques. The most of noise contribution will come from the input signal of the first stage of the amplifier. A trans-conductance of MOS transistor is related to $I_{ds}$ by:

$$g_m = 2\pi f \frac{C_{ox}}{W} \frac{I_{ds}}{L}$$

Equation (1)

For a MOSFET in the saturation region the total 1/f noise power spectrum can be calculated as:

$$I_f^2 = \frac{q_m^2}{L^2 f} \frac{I_{ds} (V_G - V_T - n V_S)}{f_{ns}}$$

Equation (2)

The input referred noise spectral density for a MOST is given by [9]:

$$I_f^2 = 4kT^2 \frac{1}{3g_m} + \frac{K_f}{W L C_{ox} f}$$

Equation (3)

From Eq. (5), we see that the thermal noise contribution is inversely proportional to the MOST trans-conductance $g_m$. Using the EKV model [12], the trans-conductance normalized to the drain current for MOSFETs working in weak and strong inversion respectively can be found:

$$\frac{g_{trans}}{I_{ds}} = \frac{1}{n V_T}$$

Equation (4)

$$\frac{g_{trans}}{I_{ds}} = \frac{12}{V_{eff}}$$

Equation (5)

Where $V_T$ is the thermal voltage and $V_{eff} = V_G - V_T - n V_S$ is the effective voltage. $V_T$ is the threshold voltage and $n$ is the slope factor. All terminal voltages are referred to the bulk. Hence the thermal noise suppression is maximized by increasing the drain current $I_{ds}$, and biasing the MOSFET in the weak inversion region of operation.

The noise corner for MOSFETs can be located at several kHz. Thus, the 1/f noise dominates in the frequency range of interest for nerve signals. Equation (5) shows that the 1/f noise level can be minimized by maximizing the MOSFET area, however for the low noise levels necessitate by the weak input signal, the device dimensions become very large [3], implying poor PSRR at higher frequencies due to parasitic feedthrough. The amplifier noise is however only chopped once, which will shift the 1/f – noise to the odd multiples of the chopping frequency as illustrated in Fig. 5(b), leaving the thermal noise as the main in-band noise contributor.
B. A Low Noise Amplifier in AFE with Chopper Modulation and Demodulation

In the above figure 4 the entire AFE design for biomedical low-noise amplifier. The chopper stabilization can achieve good noise performance and DC offset rejection, the large power consumption of the high chopper frequency is the critical design challenge. Additionally, the MOS pseudo-resistor is usually implemented by employing series of diode-connect MOS to achieve good trade-off between power consumption and performance. In Single-channel AFE is composed with chopper (modulating), two stages amplifier, chopper demodulating and LPF and one output stage for amplifying neural signals and providing enough current to drive the following ADC.

A low-power, low-noise chopper stabilized CMOS instrumentation amplifier for biomedical applications. Low thermal noise is achieved by employing MOSFET biased in the weak/moderate inversion region, whereas chopper stabilization is utilized to shift 1/f-noise out of the signal band hereby ensuring overall low noise performance. The resulting equivalent input referred noise is approximately 7 nV/Hz for a chopping frequency of 20 kHz.

This stage can be used as the active electrode when closely adhered to the electrodes. One important point which should be emphasized here is that the Gm buffer should be designed such that it has a very high voltage gain which does not change with the DC level of the input signal. Also, the high pass filter should have a very low cut-off frequency to pass the slow components of the EEG signal without attenuation. The low cut-off frequency of this stage in this design is

\[
\frac{f_{3dB}}{f_{\text{inset}}} = \frac{1}{2\piRC_{\text{eq}}} = 0.013\text{Hz}
\]

Equation (6)

Where \( R \) is the equivalent resistance of the pseudo-resistor.

As seen in Fig. 4, the output of the Gm buffer is filtered to remove DC values of the input signal and hence, their difference EOV. Note that if this filter is employed at the front of the amplifier, the input impedance is considerably degraded. In the second stage shown in Fig. 4, the input signal with zero DC level is

The device sizing \( W/L \) of the input pair should be larger to optimize the noise at input level. The chopper technique is used frequent to reduce the noise; drawback of using this technique’s is power will dominate. In this paper without chopper the input inferred noise is reduce while doing proper sizing and biasing of the device taking different threshold voltage in the circuit it reduce the power budget with less noise without effecting the gain.

C. Circuit Description

In the Circuit level with chopper technique, in which the amplifier which operates in the sub-threshold region with greater ration of \( W/L \) to optimize the noise at two input pairs of differential amplifier with dual-ended output CMFB circuit is used at first stage of Analog Front End, with multi-threshold are used in the circuit, all transistor are in strong inversion (saturation region) as shown in Fig 4: the input pair the signal sensing which has take large \( W/L \) values its operated in the sub-threshold region to optimized noise and gain is less contributed in the first stage. The signal is further
demodulated within next stage chopping is done, and filter with single pole Low pass filter as show on the fig 4.

The bio signal electrodes show in Fig 1, the signal sensed is 10 µV chopped at the first stage which are connect with transmission gate to balance the average resistance value to immediate up-convert or chop the signal. The frequency signal is then coupled to the input gates of the chopper amplifier and down converted inside the amplifier. In this approach the NMOS devices are utilized for the differential input pair to get maximum open loop gain bandwidth. There is drawback its effects the clock feedthrough and clock injection problem in the AFE to avoid this the dummy switch are added across the AFE design with chopping technique as well as analog multiplexer to select the different mode of the modulator.

The cascaded devices W/L gate area is larger than the 1/f noise is reduced it has shown simulation in the fig no 5 while doing the QPSS steady state analysis where the output noise level are optimized significantly.

III. SIMULATION RESULTS

![Overall gain plot of the bio-LNA.](image)

![Output noise spectral density.](image)

**TABLE II: PERFORMANCE OF FOUR DIFFERENT MODULATORS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mode A</th>
<th>Mode B</th>
<th>Mode C</th>
<th>Mode D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>0.18µm CMOS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Voltage</td>
<td>1 V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sampling Frequency</td>
<td>64 kHz</td>
<td>32 kHz</td>
<td>256 kHz</td>
<td>128 kHz</td>
</tr>
<tr>
<td>Signal Bandwidth</td>
<td>100 Hz</td>
<td>150 Hz</td>
<td>350 Hz</td>
<td>500 Hz</td>
</tr>
<tr>
<td>Oversampling ratio</td>
<td>128</td>
<td>320</td>
<td>256</td>
<td>128</td>
</tr>
<tr>
<td>Peak SNDR</td>
<td>67.3 dB</td>
<td>65 dB</td>
<td>68 dB</td>
<td>66.5 dB</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>58.5 dB</td>
<td>73 dB</td>
<td>71 dB</td>
<td>58 dB</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>0.5 µW</td>
<td>1.81 µW</td>
<td>1.48 µW</td>
<td>1.2 µW</td>
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</tbody>
</table>
IV. DISCUSSION OF RESULTS

The proposed architecture is instrumental analysis with practical simulation. The input impedance has a very high value (>100GΩ) over the EEG bandwidth and its pole lies at (3 Hz – 10 Hz). The input voltage is 10 µ to 100 µ is amplified with chopping technique, further amplified with multi-VT technique. The power consumption of this AFE Instrumental amplifier is shown in the PI chart.

In the fig 5 overall gain bandwidth of the Low noise Chopper amplifier (AFE) is shown. The gain is 58.0dB. The output noise of Low AFE is simulated with QPSS is shown in fig 6. The SNR measured SNR, SNDR and ENOB of whole design with four different mode of 2nd order CT Σ-Δ modulator sufficient to amplify a few µV neural signal to the tens of mVs signal needed to meet subsequent ADC resolution and dynamic range requirements are shown in the fig 8.

Table I compares the achieved design performance with recent prior art. Noise Efficiency Factor (NEF) is a key figure-of-merit to evaluate competing designs:

\[
\text{NEF} = \frac{V_{\text{rms,in}}}{\sqrt{\frac{2I_{\text{total}}}{\text{BW}}} \text{Bandwidth}}
\]

Where \(V_{\text{rms,in}}\) is the input-referred noise, \(I_{\text{total}}\) is the total current drawn from the supply voltage, \(V\) is the thermal voltage, and BW is the bandwidth of the AFE with chopping technique is. As stated in[14], usually state-of-the-art AFE circuits achieve a NEF of 2.5 to 10.

The complete layout design with IO pad of the 16 channel AFE with modulator is shown in figure 11. The Area occupied by the filter is 1525 µm × 1525 µm = 0.02325 (mm)².
Power contribution of the different blocks is illustrated in Fig. 11.

As seen in this Figure, more than half of the power budget is dedicated to the different mode of 2nd order CT Σ-Δ modulator. The chopping switch and clock generator consume more power when compared to amplifier due to noise considerations. One of the most important parameters in evaluating the functionality of a biomedical amplifier is its under different conditions.

![Power Consumption distribution in Pie char of whole design](image)

**TABLE III. COMPARISON OF PRIOR ART**

<table>
<thead>
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<tbody>
<tr>
<td>Tech.(µm)</td>
<td>0.13</td>
<td>0.5</td>
<td>0.18</td>
<td>0.8</td>
<td>0.18</td>
</tr>
<tr>
<td>Supply (V)</td>
<td>1.2</td>
<td>2.8</td>
<td>1.5</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Bias (nA)</td>
<td>5800-9020</td>
<td>743</td>
<td>5000</td>
<td>1050</td>
<td>3480</td>
</tr>
<tr>
<td>Gain (dB)</td>
<td>40-83</td>
<td>40.9</td>
<td>40.8</td>
<td>41-50.5</td>
<td>58.9</td>
</tr>
<tr>
<td>Input Ref. Noise (µVrms)</td>
<td>2.06</td>
<td>1.66</td>
<td>1.27</td>
<td>0.98</td>
<td>3.5</td>
</tr>
<tr>
<td>HPF (Hz)</td>
<td>0.17</td>
<td>0.4</td>
<td>0.5</td>
<td>0.05-0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>LPF (KHz)</td>
<td>0.34-7.5</td>
<td>0.0455-5.3</td>
<td>0.1-0.4</td>
<td>0.120</td>
<td>7.0</td>
</tr>
<tr>
<td>NEF</td>
<td>3.28/4.11</td>
<td>3.21</td>
<td>6.1</td>
<td>4.6-5.4</td>
<td>3.0</td>
</tr>
</tbody>
</table>

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**REFERENCES**


