A Low-Noise Integrated Bioamplifier with Active DC Offset Suppression

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Abstract—This paper describes a novel low-power, low-noise amplifier for neural recording applications. The bioamplifier achieves the best power-size tradeoff compared to the previous design. By means of a new active feedback configuration, the DC offset is rejected without the large capacitors. An active differentiator with an amplifier in the feedback path places a high-pass cutting frequency in the transfer function. The midband gain consists of the passive components, and is insensitive to the mismatch of process. The bioamplifier has been implemented in the Chartered 0.35-μm 2P4M CMOS process and occupies 0.022mm² of chip area. The current consumption of amplifier is 2μA at ±1.5V supply. The bioamplifier achieves a midband gain of 46dB and a -3dB bandwidth from 13Hz to 8.9kHz. The input-referred noise is 5.7μVrms corresponding to an NEF of 3.1.

I. INTRODUCTION

The clinicians demand a system to record the simultaneous activities of large numbers of neurons in the brain for understanding how the brain works. Neural recording from the large-scale chronic multi-electrodes has been widely used in many biomedical applications [1], [2], [7]. The bioamplifier is one of the most important parts in this system.

Neural signals from extracellular recording are very weak. The amplitude is in 50−500μV range with the noise level in 5−10μV. Such signals cannot be processed further without amplification. To increase the SNR of the system, the input referred noise of the amplifier need to minimize. However, the tradeoff between low-noise and low-power designs puts the challenge to the designers. The multi-electrodes recording system incorporates a large number of neural amplifiers. Too much power dissipated by the amplifiers may damage the surrounding issues by heating. The electrode shape restricts the size of the each amplifier as low as 0.16mm² [1]. Due to the electrode potential mismatch, the DC offset up to 1V is cross the recording electrodes. The offset which is orders of magnitude larger than the biopotential signal, must be rejected to prevent the saturation of the amplifier. The power, noise, size and DC offset are the major problems faced by designers.

A large amount of neural amplifiers have been presented in the literature. There are few DC offset suppression schemes adopted for on-chip integration in neural recording system. First method that uses a capacitor feedback network with ac coupling of input devices to reject the offset is very popular in designs [1], [3], [5]. The MOS-bipolar pseudo-resistor component in parallel with a capacitor feedback provides the very small low-cutoff frequency. The midband gain is the ratio of feedback capacitors. The major drawback is this configuration requires very large capacitors which occupy great percents area (>60%) of chip. The second method employs a closed-loop resistive feedback and electrode capacitance to form a highpass filter [4], [6]. The performances of this approach depend on the electrode parameters which change from one site to another. The third method adopts active low-frequency suppression that an active integrator in the feedback path of low noise amplifier forms a highpass cutoff frequency response [2]. This technology achieves small size without large passive devices. However, the amplifier works with the open-loop mode in the midband, and the gain suffered from the variation of the open-loop gain of low noise amplifier.

This paper presents a bioamplifier by means of a novel active DC offset suppression which takes the merits of capacitors feedback network configuration [1] and active low-frequency suppression configuration [2]. The midband gain is determined by the ratio of the capacitors, and size of capacitors is similar to the active cutoff-frequency suppression configuration without increasing the power and noise.

II. ARCHITECTURE OF BIOAMPLIFIER

Fig. 1(a) shows a schematic of our bioamplifier design with the proposed DC offset suppression configuration. This design consists of a differentiator and a close-loop amplifier within its feedback path. The differentiator is made from an amplifier (Aₙ), capacitors (C₃, C₄), and a high-value resistor (Rₚₜ). A close-loop amplifier is composed of an amplifier (A₂), and feedback capacitors (C₁, C₂). The differentiator is equivalent to a highpass filter to reject the DC offset. The
close-loop amplifier in feedback path corrects the highpass function of the differentiator to form the stable midband gain.

Fig. 1(b) shows a functional block diagram of the bioamplifier which consists of differentiator \( F_1, F_2 \) and amplifier \( G \) with capacitors feedback network. In the case of all the amplifiers are ideal with no parasitic capacitance, the transfer function of the ideal bioamplifier is

\[
\frac{V_{out}(s)}{V_{in}(s)} = \frac{F_1}{1 - F_2 \cdot G} = -\frac{sR_{eq}C_2C_3}{sR_{eq}C_2C_4 + C_1}
\]

where \( F_1(s)=-SR_{eq}C_3, F_2(s)=-SR_{eq}C_4, G(s)=-C_1/C_2. \)

The midband gain \( A_M=-C_2C_3/C_1C_4 \) is comprised of two capacitive ratios. The gain of the new bioamplifier architecture equals two previous amplifiers working in series. For a given gain, the bioamplifier demands smaller capacitors.

The transfer function reveals the \(-3\text{dB} \) cutoff frequency to be

\[
f_H = \frac{C_2}{2\pi R_{eq}C_2C_4} = \frac{A_M}{2\pi R_{eq}C_3}
\]

To achieve \(-3\text{dB} \) highpass cutoff frequency around 10Hz would requires the resistor \( R_{eq} \) in the order of \( 10^{12} \Omega \). Transistors \( M_{e1}=M_{e2} \) are MOS-bipolar devices which act as pseudo resistors [1]. For small input amplitude, the equivalent resistor is more than \( 10^{13} \Omega \).

In the previous section, the transfer function is deduced under ideal conditions. The amplifier finite DC gain, parasitic capacitances and noise are devoted to errors that alter the transfer function of bioamplifier. Equivalent model of these non-ideal factors in the circuits is shown in Fig. 2.

### A. Effect of amplifier finite gain

The finite gain of the amplifier \( (A_1 \text{ and } A_2) \) donated by \( A_{V1} \text{ and } A_{V2} \), respectively. \( C_{in1} \text{ and } C_{in2} \) are the input parasitic capacitors of the amplifier. For the case where \( A_{V2}C_2C_1 \gg C_1+C_2+C_{in2} \text{ and } A_{V1} \gg 1 \), the transfer function is

\[
\frac{V_{out}(s)}{V_{in}(s)} = -\frac{sR_{eq}A_{V1}C_2C_3}{sR_{eq}[A_{V1}C_1C_4+(C_3+C_4+C_{in1})C_2]+A_{V1}C_2}
\]

When \( A_{V1} \) satisfies the following relationship

\[
\frac{V_{out}(s)}{V_{in}(s)} \approx -\frac{sR_{eq}A_{V1}C_2C_2}{sR_{eq}[A_{V1}C_1C_4+(C_3+C_4+C_{in1})C_2]+A_{V1}C_2}
\]

\[
A_{V1} \gg \left(\frac{C_1+C_4+C_{in1}}{C_2}\right)\frac{C_2}{C_1C_4}
\]

the midband gain of bioamplifier is the same as ideal condition.

If \( A_{V1} \) fails to satisfy (4), \( |V_{out}(s)/V_{in}(s)| \) will be smaller than \( C_2C_3/C_1C_4 \). In order to characterize the effect of finite gain on the midband gain, a parameter \( \alpha \) is defined as

\[
\frac{|V_{out}(s)/V_{in}(s)|}{A_M} = \alpha A_M\n\]

The actual midband gain falling into \( \alpha \) times of ideal value requires the gain \( A_{V1} \) to be

\[
A_{V1} \geq \frac{1}{1/\alpha - 1}|A_M|\n\]

The gain \( A_{V2} \) of amplifier \( A_2 \) has no effect on the midband gain in the case of \( A_{V2} \gg (C_1+C_2)/C_2 \) which can achieve easily.

Considering the \( A_1 \) as a simple first-order model for the transfer function of a dominant-pole compensated amplifier, \( A_{V1}(s) \), is given by

\[
A_{V1}(s) = \frac{A_{V1,open}}{1+s/\omega_0}
\]

Where \( A_{V1,open}=G_mR_{out} \) is the DC gain of amplifier \( A_1 \), and \( \omega_0=1/(R_{out}C_L) \) is the dominant pole. The \(-3\text{dB} \) lowpass cutoff frequency can be evaluated from (3)

\[
f_L = \frac{1}{2\pi C_L C_2C_3} = \frac{1}{2\pi C_L} |A_M|\n\]

The \(-3\text{dB} \) lowpass cutoff frequency depends on the transconductance \( g_m \) of \( A_1 \), load capacitor \( C_L \) and midband gain \( A_M \) of bioamplifier.

### B. Effect of noise

Noise sources associated with the amplifier \( A_1 \text{ and } A_2 \) are represented as \( V_{n1} \text{ and } V_{n2} \), respectively. Thermal noise source of the equivalent resistor \( R_{eq} \) is \( V_R \), as shown in Fig. 2.

The input referred noise power of the bioamplifier can be obtained, as follows
The flick noise limits the performance of the low power, low frequency amplifier. In order to minimize the flick noise, the input devices of amplifier are PMOS transistors with large area. The large input transistors increase the input capacitance, and decrease the noise performance as shown in (9). The design of amplifier $A_1$ needs to take care of the tradeoff between the flick noise and input capacitance. The noise of amplifier $A_2$ has less contribution to the input referred noise of bioamplifier. For the case where $C_2=C_3=10C_1=10C_4$, $C_{in1}=C_{in2}$, the input referred noise related noise source $V_{n2}$ is

$$V_{n2}^2 = \frac{1}{s R_{eq} C_1} \cdot V_{n, r}^2 + \left( \frac{C_1 + C_4 + C_{in}}{C_1} \right) \cdot \frac{1}{s R_{eq} C_1} \cdot V_{n, a}^2 + \left( \frac{C_1 + C_2 + C_{in}}{C_2 C_3} \right) \cdot \frac{V_{n, a}^2}{C_2 C_3}.$$  

(9)

The gain and noise of $A_2$ have less effect on bioamplifier $A_1$. The differentiator $A_2$ has the dominant pole of the amplifier $A_1$ is $\tau_p$. As the frequency is higher than $\omega_1$, the phase shift $\varphi_G$ will be large than $90^\circ$. Therefore, the total phase shift introduced in the loop gain is $\varphi_{LG}(j \omega)=180^\circ-90^\circ+\varphi_G$. At unity-gain frequency, the phase margin (PM) of the whole bioamplifier is

$$PM = \varphi_{LG}(j \omega) - 180^\circ = \varphi_G - 90^\circ$$  

(12)

Hence at $\omega_1$, a phase shift of $\varphi_G=90^\circ$ yields a PM of zero. Where a phase shift of $\varphi_G=90^\circ$ yields the PM>0.

III. CIRCUIT IMPLEMENTATION

The midband gain of the bioamplifier is the product of $C_2/C_1$ and $C_3/C_4$. If the gain is constant, decrease the total capacitance demands minimum the $C_1$ and $C_4$. However the parasitic capacitance restricts the minimum value of $C_1$ and $C_4$. The total size of capacitor is minimum under the relation of $C_2/C_1=C_3/C_4$. This scheme is not the optimization of noise. Increase $C_3/C_4$ can attenuate the noise with $V_{n1}$ as given in (9). The optimal value of $C_3/C_4$ is select to achieve the minimum noise-capacitor product for the bioamplifier. With the midband gain of 200, the normalization of noise-capacitor product varies with $C_3/C_4$ is show in Fig. 4.

![Figure 4. For the midband gain is 200, the normalization of noise-capacitor product varies with $C_3/C_4$.](image)

The proposed bioamplifier configuration presents a phase shift of $180^\circ$ between node $V_{out}$ and $-V_{out}$. The differentiator $F_2$ (Fig. 1(b)) generates a negative phase shift of $-90^\circ$ in loop gain. The block $G$ introduces a positive phase shift $\varphi_G$. The $\varphi_G$ equals $90^\circ$ under the assumption that the amplifier $A_2$ has only the dominant pole $\omega_1$. If the $\omega_2$ has the other pole high than $\omega_1$, the phase shift $\varphi_G$ will be large than $90^\circ$. Therefore, the total phase shift introduced in the loop gain is $\varphi_{LG}(j \omega)=180^\circ-90^\circ+\varphi_G$. At unity-gain frequency, the phase margin (PM) of the whole bioamplifier is

$$PM = \varphi_{LG}(j \omega) - 180^\circ = \varphi_G - 90^\circ$$  

(12)

Hence at $\omega_1$, a phase shift of $\varphi_G=90^\circ$ yields a PM of zero. Where a phase shift of $\varphi_G=90^\circ$ yields the PM>0.

The block $G(s)$ which consisted of the amplifier $A_2$ and capacitors feedback network as show in Fig. 1 (b) has the DC gain ($-C_3/C_2$). In the case of the amplifier is the simple pole configuration, the open-loop gain is $A_{V2,open}$ and the main pole is $\omega_1$. The block $G$ has the corner frequency that is equal to the gain-bandwidth product ($A_{V2,open}/\omega_1$) and the phase is $90^\circ$. The neural signal bandwidth must be within this corner frequency.

![Figure 5. Circuit schematic of the low power, low noise amplifier $A_1$.](image)
The noise-capacitor product has the minimum value of
\( C_3/C_4 = 16 \) by setting the value of \( C_3 \) to 1.6pF, \( C_4 \) to 1.25pF, \( C_1 \) and \( C_4 \) to 100fF using the poly-poly capacitors. The total capacitance of the full differential scheme is only 6.1pF.

The amplifier \( A_1 \) has a folded-cascode topology with source-degenerated current mirrors [3] showed in Fig. 5. The full differential configuration which has the high CMRR to reject interference is adopted. The common mode feedback circuit is formed by the transistor M13-M14 in triode region to sense the CM level. The DC gain of \( A_1 \) should satisfy the relation given in (6). For \( \alpha = 0.95 \), the gain cannot be low than 72dB. The –3dB bandwidth of \( A_1 \) is determined by neural signal bandwidth. Simulations show that the amplifier \( A_1 \) has a DC gain of 138dB, a phase margin of 65°, and a bandwidth of 1.9MHz.

As stated above, the finite DC gain, noise and bandwidth of amplifier \( A_2 \) have less impact on the bioamplifier. The specifications can be relaxed for \( A_2 \) to save the power. \( A_2 \) has the same configuration as \( A_1 \) except using the common current mirrors instead of the source-degenerated current mirrors. The DC gain of \( A_2 \) is 136dB. The bandwidth is 892 kHz and the phase margin is 57°, while consuming 300nA.

IV. RESULTS

The bioamplifier with the proposed active dc offset suppression architecture was designed using the Chartered 0.35\( \mu \)m 2P4M CMOS process. The midband gain of 46dB and the bandwidth from 13Hz to 8.9 kHz have been shown in Fig. 7. The bioamplifier with full differential scheme fits in 120\( \mu \)m\times184\( \mu \)m area.

Fig. 8 shows a plot of the simulated input-referred noise.

![Figure 8. Input referred voltage noise density of bioamplifier.](image)

**TABLE I**

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<tr>
<th>Performance Characteristic of Bioamplifier</th>
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<td>Gain (dB)</td>
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Figure 6. Layout of the bioamplifier.

The thermal noise level is about 56nV/\( \sqrt{Hz} \). Integrated noise from 10Hz to 10kHz yields an RMS noise of 5.7\( \mu V_{\text{rms}} \). Table I shows the state of the art in bioamplifier. The noise efficiency factor (NEF) is a measure of the noise performance of a given bioamplifier as a function of its power consumption and the bandwidth. Base on the simulation results, the NEF of this bioamplifier is found to be 3.1.

V. CONCLUSION

A novel active dc offset suppression structure has been proposed which can be applied to low power, low noise, and area efficient bioamplifier. This structure features the small feedback capacitors and less gain variation. Simulation results of the bioamplifier with a midband gain of 46dB have the input-referred noise of 5.7\( \mu V_{\text{rms}} \) over 10Hz-10kHz. The full differential bioamplifier with the small chip area as single-end output amplifier has high immunity to interference.

REFERENCES


