A 0.18µm CMOS LOW POWER CAPACITIVE-FEEDBACK TRANSIMPEDANCE AMPLIFIER FOR OPTICAL BIOSENSING INTERFACE

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ABSTRACT
This paper presents the design, implementation and simulation of a high-gain, low-power, low-noise CMOS front-end transimpedance amplifier (TIA) for optical interfacing between a biosensor array and analog neural circuits of biohybrid robot controller along with description of Central Pattern Generator (CPG) design used for Cyberplasm based biomimetic robot controller. The proposed TIA uses an improved capacitive-feedback TIA topology with an active load to avoid the design issue from large on-chip resistors and to increase the design flexibility in gain-bandwidth trade-offs, and it accomplishes a 100MΩ transimpedance gain, 1MHz bandwidth, 158fA/rt(Hz) input-referred current noise at sensing frequency, near 0° phase shift, and 1V peak-to-peak output swing. The proposed circuit dissipates 132µW from a 1.8V supply and the circuit is implemented and verified on silicon in a standard 0.18µm CMOS 1P6M technology.

KEYWORDS
Biosensing, Amplifier, Transimpedance, Cyberplasm, Center Pattern Generator

1. INTRODUCTION
Biomimetic robotics is attracting the interest of growing number of robotics researchers worldwide. The advancements of robotics technologies have recently led to an increased interest towards biomimetic robotics in the scientific fields related to biology and to the study of living organisms. Recent advances in synthetic biology suggested a new direction in design [1], which is to imitate neuron-based behavioral capabilities of simple animal models, such as the sea lamprey using sensors and actuators formed from engineered cells.

Prior research has shown that Central Pattern Generation (CPG) is an intrinsic mechanism of an animals' natural behavior. Studies over the past 40 years have demonstrated that the innate rhythmic behavior of animals is generated by central pattern generators (CPGs) distributed throughout the nervous system [2] and modulated by sensory feedback. CPGs are networks of neurons that can generate an excellent replica of the motor neuron discharge patterns underlying innate behavioral acts in the total absence of sensory feedback or patterned input from higher centers [2]. It acts inherently as a bio-oscillator to provide neural signal throughout the network [3]. Thus an electronic neuron based CPG module is the core of the behavior control circuit in a neural circuit system. At the same time, a biosensor array serves as the interfacing between the external environment, CPG, actuators, and the bio-feedback generators [4]. Due to the stringent power, area and robustness requirements in such applications, the integrated circuit approach for the CPG implementation becomes essential to the realization of biohybrid robots [5].
Figure 1. Block diagram of a biohybrid robot consists of: a front-end biosensor array, analog neural circuit with CPG, actuators followed by synthetic muscle, a back-end feedback biosensor, and a transimpedance amplifier in the optical-signal path. A bio-chemical battery provides power for the system.

One of the promising implementation methods for a biohybrid robot control system consists of biosensors, ultra-low power A/D converters, and a digital-domain processor [6]. However, the discrete time operation and deterministic programming inherently exhibit the shortcomings of slow reaction to the continuous time environment and they increase hardware complexity due to A/D and D/A converters as well as controllers. On the other side, an analog electronic implementation without the need for data converters and a FSM (Finite State Machine) provide the desired ability of continuous-time and adaptive control [7]. However, the latter topology also introduces design challenges in the form of trade-offs between noise, power dissipation, speed, and process variations. Figure 1 shows the block diagram of the proposed biohybrid robot system including CPG [8].

Figure 2. Sea Lamprey-based Biohybrid Robot ‘Cyberplasm’ [1]

The biohybrid underwater robot under our investigation called "Cyberplasm," contains an analog electronic nervous system shown in Figure 2. A novel optical-communication mechanism is adopted to propagate and feedback control signals among blocks. Photo-diodes
with a particular peak sensing wavelength are integrated in the front-end biosensors generating signals for the following stage(s). The amplitude of the current signal is constrained to the level of nanoamperes \[9\] due to low-power operation and low quantum efficiency of silicon, while the frequency of the signal is at kilohertz-level due to the limited sampling ability of the biosensor array. A low-noise, low-power, and high gain TIA is thus desirable in the signal path. Moreover, since the TIA works as a preamplifier for the level-sensitive analog neural circuit, its output swing should be high enough. At the same time, the biohybrid robot neural system also requires an in-phase operation to obtain real-time autonomous controllability \[4\]. Although the sensing frequency of the biosensor arrays in our system is around 20 kHz, the frequency response of the TIA should be well beyond the bio-oscillation frequency of CPG in order to reduce its phase noise \[10\]. In this paper, we present a novel front-end TIA design that provides a high gain, low input-referred current noise, high output swing, and proper flat phase response up to 100 kHz in a standard CMOS process for a biosensing application.

This paper is organized as follows: Section 2 describes about cyberplasm micro robot and Section 3 introduces and analyzes the topology used in the design. Simulation results are presented in Section 4, and Section 5 covers the performance of the TIA and contains a comparison with prior arts followed by the Conclusion in Section 6.

2. CYBERPLASM MICRO ROBOT

2.1. Description of Cyberplasm

The objective of the Cyberplasm program is to create a novel, autonomous bio-hybrid micro-robot shown in Figure 2\[11\]. The robot uses opto-genetically engineered muscles that respond to light and are coordinated to generate an undulatory movement of the body axis. Engineered cellular sensors will be fabricated in the head of the robot to guide its behavior through exteroceptive reflexes. The overall micro-robot is to be powered by a microbial fuel cell can be integrated into the robot body. The entire system will be integrated with an analog implementation of a biologically realistic nervous system. Biomimetic electronic CPG coordinates the output muscles to create a rhythmic swimming pattern (Figure 3). Excitation/Contraction coupling of the control signals to the muscles will be achieved by organic LEDs printed over an on a Kapton substrate. The engineered muscles are sensitive to blue light. Finally, the robot will be spin-coated with hydrogel and the cells plated over the optical interfaces.

2.2. Center Pattern Generator

Central pattern generator imitates neural and synaptic networks that produce rhythmic patterned outputs without sensory feedback or central input \[12\]. CPG is regarded as the origin of the most rhythmic motor patterns like walking swimming and breathing. In the study of lamprey based swimming pattern generator, results reveal that the two neurons in the same level on the two sides usually generate out-of-phase oscillation by reciprocal inhibitory connections, while the other two neurons on the same side exhibit a metachronal rhythm with a period varying phase delay \[13\]. Figure 3 depicts a simplified swimming pattern generator layout. Lseg1, Lseg2, Rseg1 and Rseg2 are four bursting neurons and they are turned on and modulated by a command system (Figure 3). Lseg1 and Rseg1 are connected by inhibitory synapses (shown as bubbles in Figure 3). (Lseg1, Lseg2) and (Rseg1, Rseg2) pairs are connected by delayed excitatory synapses (shown as triangles in Figure 3).

2.3. Hindermarsh Rose Neuron

Any neuron model must operate in real time to control a robot. However, the most important property for the proposed biomimetic neuron design is a stable facultative
bursting pattern to generate the swimming rhythm. Therefore, the "Hindermarsh-Rose" neural model is chosen in our research because it most accurately represents the behavior of living neurons. The model has more advantages in hardware realization because its behavior is described in lower order of equations and the frequency of the burst signal is accurately controlled by the input variable I, which is described as [14]:

\[
\begin{align*}
\frac{dx}{dt} &= ay + bx^2 - cx^3 - dz + I \\
\frac{dy}{dt} &= e - fx^2 - y \\
\frac{dz}{dt} &= \mu(S(x + h) - z)
\end{align*}
\]

Figure 3. The rhythm pattern for the proposed swimming pattern generator.

Where \(x\) is membrane potential, \(y\) is recovery current, \(z\) is adaptation current, \(I\) is applied current, and \(h\) is the leftmost equilibrium point of the neuron model without adaptation.

\[
\begin{align*}
\frac{dx}{dt} &= ay + bx^2 - cx^3 - dz + I \\
\frac{dy}{dt} &= e - fx^2 - y \\
\frac{dz}{dt} &= \mu(S(x + h) - z)
\end{align*}
\]

2.4. Mathematic Analysis of HR Model

According to the analysis in [19], by setting the \(z\) variable to zero, the HR neuron model is reduced to two differential equations with two unknowns. By setting the right half of equation (1) and (2) to zero, phase plane equations (4) and (5) can be obtained to reveal the spiking condition of this model. It is observed that increasing \(I\) lowers the curve of (4) causing the stable points to merge together and then vanish. This drives the system into an unstable region and limit cycle, causing output spiking, which is the exact property of tonic spiking.

\[
y = \frac{1}{a} (cx^3 - bx^2 - I)
\]

\[
y = e - fx^2
\]
Tonic bursting fires periodic bursts of spikes when it is activated, and it often remains silent until activated. The z variable in the HR equations controls this bursting mode in the three dimensional HR model. As the input increases, the stable equilibrium points vanish which causes a limit cycle.

3. CIRCUIT IMPLEMENTATION

3.1. Circuit Implementation of HR Neuron

![Circuit Diagram](image)

Figure 4. 180nm electronic neuron based on HR neuron model.

The integrated circuit of the HR neuron has been designed using 180nm CMOS technology based on the HR neuron model [15] as shown in Figure 4. By taking integral on both sides of HR neuron model, the circuit is created with analog integrators in voltage mode. Although the variables in HR neuron model have current representation, the circuit design becomes less complicated when designed in voltage mode. In order to meet the requirements of 1.8V supply rail and reduce passive components' area on chip, both time and amplitude scaling are employed, and the detailed information can found [15].

3.2. Circuit Implementation of Synapse

Figure 5 shows VLSI implementation of synapse. It is the hardware implementation of the three equations of (6) (7) and (8). The differential equation is achieved by integration, and the hyperbolic tangent function is approximated to polynomial expression of x using Taylor Series taking advantage of the small signal amplitude in this 1.8V supply system. The synapse between adjacent segments produces weak excitatory signals to modulate the two ipsilateral neurons to oscillate with a phase lag. In contrast, the two contralateral neurons will oscillate out-of-phase when the synapses...
are inhibitory. The coupling strength can be varied by the amplitude of synapse output. Therefore, a phase delay between the two neurons can be achieved by weak excitatory coupling between two neurons, which is done by the "Weak Excitatory".

\[ I = gS(t)(V_{\text{rev}} - V_{\text{post}}) \]  \hspace{1cm} (6)

\[ \frac{dS(t)}{dt} = \frac{S_\infty - S(t)}{\tau_s(1 - S_\infty)} \]  \hspace{1cm} (7)

\[ S_\infty = \tanh \left(\frac{V_{\text{pre}} - V_{\text{th}}}{V_{\text{slope}}}\right) \]  \hspace{1cm} (8)

Figure 5. 180nm electronic synapse circuit.

The Complete electronic CPG block diagram is shown in Figure 6. Both the electronic synapse and electronic CPG have been achieved at 1.8V supply voltage in 180nm standard CMOS process using sub-threshold circuit design technique. The whole circuit has been carefully optimized under this process so as to meet the 5% parameter variation tolerance in real process.

3.3. Transimpedance Amplifier (TIA) Design for Biosensing

As explained in the introduction, a novel optical-communication mechanism is adopted for the signal interface between the blocks in this particular biohybrid robot controller. As shown in Figure 1, there are many sensor arrays to make the robot behave adaptively to the environment changes. External environment changes are received by engineered cellular sensors through exteroceptive reflexes. The sensors then release command to CPG motion control unit to generate corresponding motion patterns. The sensor array outputs are propagated to the CPG through optical communications using photo-diodes with a particular peak sensing wavelength. All other signals except the photo-diodes' signals, however, are electrical signals. Because of
this reason, it is required to make the sensor outputs compatible with the rest of the electrical signals for proper communications. Since the photo-currents generated from the photo-diodes are the level of nanoamperes due to low-power operation and low quantum efficiency of silicon, it is imperative to design and develop a low-noise, low-power, and high gain TIA. This section describes the details of the low noise and high gain TIA design including Miller 2-stage OP Amp design used for the capacitive feedback of the proposed TIA.

3.3.1. Miller 2-Stage OP AMP

A Miller 2-Stage OP AMP with high gain, suitable GBW, and low-power is designed for the capacitive feedback loop of the proposed TIA. The circuit schematic of the proposed Miller 2-stage OP AMP is shown in Figure 7.

In the input stage, large-sized PMOS transistors (35µm/5µm) are used to minimize the input-referred flicker noise and mismatch. Meanwhile, the large transconductance of this stage (85µS) reduces the noise contribution of the other transistors [16]. Finally, to achieve a 1MHz bandwidth for the entire TIA, a large GBW (>7MHz) of the OTA is preferred. This gives an overall flat frequency-response for the TIA.

In the output stage, the values of the miller capacitor and its series resistor are chosen for an optimized stability and RHP-zero cancelling. Transistors in the current mirrors throughout the OP AMP are biased with large $V_{GS}$ to minimize device mismatch and noise. Non-minimal sized transistors are also used to improve the gain and mismatch. However, attention needs to be paid to the resulting increased $C_{GD}$ and $C_{GS}$ at high impedance node ($N_{m}$). Moreover, the body and source terminals of the PMOS transistors are connected together in the circuit, which is achievable in typical n-well
processes to reduce the potential hot-carrier effect. Table 1 summarized the simulated characteristics of the OP AMP.

![Figure 7. Schematic of the proposed miller two-stage OP AMP.](image1)

Figure 7 shows the schematic of the miller two-stage OP AMP. The highlighted components include biasing circuits and source degeneration resistors.

![Figure 8. Schematic of the weak inversion biasing circuit.](image2)

Figure 8 shows the schematic of the biasing circuits used in the design [17]. In order to improve the low-frequency stability of the amplifier, long-channel devices are used to boost the on-resistance of the transistors in the voltage biasing circuit and to improve mismatch in the constant-gm current biasing circuit. As a result, the common-mode voltage is delivered to the input nodes through a 2.5MΩ resistor, and the TIA achieves a 40Hz low cut-off frequency.

### 3.3.2. Improve Capacitive-Feedback TIA
Table 1. Summary of the simulated OP AMP performance.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measured Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>0.18µm CMOS</td>
</tr>
<tr>
<td>DC Gain</td>
<td>103dB</td>
</tr>
<tr>
<td>Unity GBW</td>
<td>20MHz</td>
</tr>
<tr>
<td>Phase Margin</td>
<td>63°</td>
</tr>
<tr>
<td>Noise Floor</td>
<td>25nV/rt(Hz)</td>
</tr>
<tr>
<td>Power Dissipation</td>
<td>110µW</td>
</tr>
<tr>
<td>Power Supply</td>
<td>1.8V</td>
</tr>
</tbody>
</table>

The most commonly used topology of a TIA applies a resistive-feedback mechanism, as shown in Figure 9(a). The feedback resistor $R_F$ with a parallel $C_F$ (not shown in the figure) sets the gain and frequency response. Another popular topology harnesses a capacitive feedback loop only, which eliminates the noise contribution from $R_F$ [18]. The improved TIA topology used in our low noise, high gain biosensor application is shown in Figure 9(c). First demonstrated in [17], it exhibits several advantages for our continuous biohybrid robot control application over the commonly used resistive method shown in Figure 9(a) or capacitive-feedback TIAs shown in Figure 9(b).

![Transimpedance Amplifier Diagram](image)

Figure 9. (a) Resistive feedback TIA, (b) Capacitive feedback TIA, (c) The Schematic of the proposed TIA design with the improved capacitive feedback single-ended topology.

First, the capacitive feedback current amplifier in Figure 9(c) drives current to the high impedance output with a gain of $(1+C_2/C_1)$. Meanwhile, the resulting large transimpedance gain of $(1+C_2/C_1) \cdot R_d$, which in turn, reduces the input-referred current noise due to the load $R_d$ by the same factor [10][17] as shown in equation (10), where $\omega$ is frequency, $k$ is the Boltzmann constant.
constant, T is temperature and $v^2_n$ is the amplifier input-referred voltage noise. Comparing with the resistive-feedback TIA, the proposed topology alleviates the trade-off between noise and gain.

$$\text{Gain} = R_d \cdot (1 + \frac{C_2}{C_1}) \quad (9)$$

$$i^2_n = \frac{4kT}{R_D(1 + \frac{C_2}{C_1})^2} + v^2_n w^2 (C_1 + C_{par})^2 \quad (10)$$

Second, comparing with the common capacitive-feedback TIAs shown in Figure 9(b), the OTA in the feedback loop adds an additional 180° phase shift to the improved topology in Figure 9(c), thus avoiding the nonzero phase-response seen in Figure 9(b). It also pushes the location of the pole from large $C_2$ away by a factor of $(1 + A_0)$ as shown in equation (11) [17], where $g_{m2}$ is the transconductance of transistor M2 and $A_0$ is the DC gain of the OTA. The equation also implies the possibility of increasing bandwidth by increasing the gain of the OTA in the new topology without reducing $R_d$ and the transimpedance gain.

As a result, the adopted topology relaxes the trade-offs among gain, noise, and bandwidth in the desired transimpedance amplifier design. However, the noise and bandwidth of this improved capacitive feedback topology will be affected by the parasitic of the photodiode, as shown in equation (10) and (11). This is because a high ratio between $C_2$ and $C_1$ is desirable in our topology and hence the capacitance of $C_1$ will be comparable to the parasitic.

$$BW_{\text{TIA}} = \frac{g_{m2}(1 + A_0)C_1}{C_2(C_1 + C_{par})} \quad (11)$$

Since the problem from feed-through capacitance is not serious in the desired system, a single-ended structure is used for saving power and transistor/pin count. For further power reduction, transistors in the proposed TIA operate in a weak inversion region. Meanwhile, the load $R_d$ of the TIA is implemented using a long-channel PMOS transistor to maximize the transimpedance gain. Finally, the TIA is followed by a buffer stage for driving the subsequent analog neural circuits.

4. SIMULATION RESULTS

Simulation results for the AC analysis are shown in Figure 10. The proposed TIA exhibits a 100MΩ transimpedance gain, which not only ensures the functionality of the level-sensitive analog neural circuit, but also relaxes the noise requirement of the system.

Meanwhile, it keeps a flat frequency response up to 1MHz, which is suitable for controlling the proposed underwater biohybrid robot. Moreover, the TIA shows a phase-response within 10° from 200Hz to 130kHz, thus the in-phase control of the system for our biosensing (20kHz) and oscillating (100kHz) application is achieved. Input-referred current noise, shown in Figure 12, is kept under 200fA/rt(Hz) at the sensing frequency of 20kHz. Meanwhile the flicker noise corner is located under 20Hz. Thus the desired low-noise performance of the front-end TIA at sensing frequency is assured. Figure 11 shows the signal waveforms representing the membrane potential of a CPG neuron and the bursting pattern from the fabricated chip.
The transient performance is also measured at the practical operating frequency of the biohybrid robot control circuit. The TIA exhibits a ~1V peak-to-peak output voltage swing as shown in Figure 13. The in-phase signal amplification of the circuit is also observed from the transient analysis. The simulation results in Figure 14 agree with the desired theoretical output in Figure 3.

Finally, the power dissipation of the TIA is measured and summarized in Table 2. The high performance OP AMP in the feedback loop introduces a new set of design trade-offs among transimpedance gain, bandwidth and power, thus providing the flexibility for further modification.
5. SUMMARY

The proposed design achieves 100MΩ transimpedance gain, 1MHz 3dB-Bandwidth, and ±10° phase shift between 0.2-130kHz. With an additional flexibility in design trade-offs between gain and BW, the AC performance of the proposed TIA is qualified for biosensing applications. Both low current consumption (73µA) as well as low input-
referred current noise (158fA/rt(Hz)) design goals are accomplished in the design. Finally, a 1V peak-to-peak output voltage swing is measured. This allows the easy integration of the design into the proposed autonomous underwater biohybrid robots control system.

![Electrical CPG](image)

**Figure 14. Simulation results of electronic CPG.**

Table 2. Power Dissipation of the TIA.

<table>
<thead>
<tr>
<th>Block</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>OP AMP</td>
<td>110µW</td>
</tr>
<tr>
<td>Biasing</td>
<td>11µW</td>
</tr>
<tr>
<td>Output Stage</td>
<td>11µW</td>
</tr>
<tr>
<td>Total</td>
<td>132µW</td>
</tr>
</tbody>
</table>

Table 3 shows a comparison of this design with prior arts. The topology of the proposed design was first demonstrated in [17]. TIAs in the second and third column were designed for MEMS applications, which have a very similar set of design specifications as the biosensing applications in the last two columns. The proposed design achieves the highest transimpedance gain and lowest power consumption with comparable bandwidth and noise.

Figure 15 shows the layout of the chip. There are 80 output pads, and some of them are internal signals, that are lead to output pads via buffer drivers for debug purposes. The electronic CPG needs to be interfaced with engineered cells to complete the input/output systems of the robot. The interface is for the communications between the electrical signals from the CPG and optical signals to the engineered cells. The experimental results validate the electronic CPG performance at a 1.8V supply voltage with parameter variation tolerance of 5% dissipating 3.28mW. The die size of the chip is 1.1mm² including I/O pads.
Table 3. Comparison with prior arts.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>[17]</th>
<th>[10]</th>
<th>[18]</th>
<th>[20]</th>
<th>This work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>0.6µm CMOS</td>
<td>0.18µm CMOS</td>
<td>0.6µm CMOS</td>
<td>0.35µm CMOS</td>
<td>0.18µm CMOS</td>
</tr>
<tr>
<td>DC Gain</td>
<td>8.7 kΩ</td>
<td>56 MΩ</td>
<td>1.6 MΩ</td>
<td>65 MΩ</td>
<td>100 MΩ</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>550 MHz</td>
<td>1.8 MHz</td>
<td>230 kHz</td>
<td>2 MHz</td>
<td>1 MHz</td>
</tr>
<tr>
<td>Cutoff Freq</td>
<td>50 kHz</td>
<td>&lt; 5 kHz</td>
<td>&lt; 1 Hz</td>
<td>100 Hz</td>
<td>40 Hz</td>
</tr>
<tr>
<td>Input Noise</td>
<td>4.5pA/rtHz</td>
<td>65fA/rtHz</td>
<td>88fA/rtHz</td>
<td>3fA/rtHz</td>
<td>158fA/rtHz</td>
</tr>
<tr>
<td>Power</td>
<td>30mW</td>
<td>436µW</td>
<td>400µW</td>
<td>25µW</td>
<td>132µW</td>
</tr>
</tbody>
</table>

Figure 15. Central Pattern Generator Layout in 180nm CMOS Process.

6. CONCLUSION

This paper describes a transimpedance amplifier design for biosensors along with CPG design for biomimetic robot application based on Cyberplasm. It utilizes an improved capacitive-feedback topology to avoid the design issue stemming from large on-chip resistors and increase the design flexibility in gain-bandwidth trade-off. The proposed TIA is implemented in a standard TSMC 0.18µm technology. The design demonstrates a 100MΩ transimpedance gain with 1MHz bandwidth, less than 10° phase shift between 0.2-130kHz, and 1V Peak-to-Peak voltage swing, 158fA/rtHz input-referred current noise at the biosensors sampling frequency while dissipating 132µW power from a 1.8V supply. The verified functions on silicon and the measured performance show that the proposed TIA design is a viable solution for the biosensing application. This approach will be a good reference for the future low power CPG design.
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