An ultra low-power ECG amplifier for wearable devices using classical 2-stage OTA

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Abstract: Wearable smart devices have become an important method to monitor people's health. This research work aims to offer a relatively optimum solution to amplify the biomedical signal in the case of wearable devices. This is done by using the single-stage amplifier and Operational Transimpedance Amplifier (OTA) stage. The OTA stage uses a typical 2-stage amplifier topology, with first-stage differential pair, second stage a common source to provide high-gain. Simulation results showed that the amplifier has a differential gain of 40.04dB, a total integrated input-referred noise of 3.59\mu Vrms, a total power consumption of 1.44\mu W, a NEF of 21, and a CMRR of 82 dB. In conclusion, the results verify the single-stage amplifier topology is useful and satisfy the low-power requirement.

1.Introduction

According to the World Health Organization statistics, the mortality of cardiovascular disease has a high rank in the world, which is significantly higher than that of the tumor and other diseases [1]. Cardiovascular disease is caused by disorders of the heart and blood vessels. As a core part of the cardiovascular system, the heart is a key organ for humans. The heart is the power of blood pumping and also guarantees the operation of various organ systems. Therefore, monitoring heart activity is the most convenient and effective method to observe heart health.

The electrocardiogram (ECG) is a test that records the electrical activity of the ticker through small electrode patches [2]. The ECG as generally taken consists of three leads, obtained by using the two arms and the left leg as the contact or leading off points [3]. Therefore, recording the heart rate is one of the ECG functions. To review the information recorded by the ECG machine, several elements will be recorded: Heart rate, heart rhythm, heart attack, inadequate blood and oxygen supply to the heart, and structural abnormalities.

The amplifier plays an important role in designing an electrocardiogram, and there are several works about the amplifiers. Kumngern et al. proposed using the fifth-order butterowrth low-pass filter to amplify the signal and achieve filtering [4]. The used multiply-input technique simplifies OTA's structure and reduces the number of elements, but the overall structure is a little complex. In another research, Saeidian et al. used an additional stage to the second stage of conventional capacitive
instrumentation amplifier to have the least value in power consumption. This will reduce occupancy area on the chip [5], but the volume of the structure should be considered because they add more amplifiers to their structure.

This paper mainly focuses on designing an ECG using single stage amplifier and OTA stage. The single-stage amplifier is a common method to build the ECG, but the main problems are power budget and noise immunity. These elements will influence the cost and accuracy of the machine. One way to overcome these problems is to adjust the basic parameters and add an OTA stage that uses a 2-stage amplifier topology. For this design, it would be of special interest to study the method to build an effective amplifier. The aim here is to investigate and innovate the amplifier and make sure the machine is work. The contributions made here have wide applicability in the medical field.

2. Method
The design is carried out and verified using Berkeley Short-channel IGFET (BSIM) Model 180nm PDK simulated under LTSPICE. **Figure 1** shows the single-stage ECG amplifier’s schematic using capacitive feedback, which was first described in [6]. Such architecture is advantageous for bio amplifier applications because the input capacitors act as ac-coupling to eliminate electrode off-set voltage (EOV). For large gm, the mid-band gain is defined solely through feedback capacitors. As a result, the architecture uses a very large feedback resistor for biasing the OTA, which results in high input impedance. Furthermore, the architecture is particularly useful for wearable devices because a single-stage architecture is desirable in maintain low-power consumption.

The system has a zero at 0Hz and a low-frequency pole at:

$$f_p = \frac{1}{2\pi R_f C_f}$$  \hspace{1cm} (1)

where $R_f C_f$ are feedback resistor and capacitor values. And the closed-loop gain is defined by:

$$A_{cl} = -\frac{C_2}{C_1}$$  \hspace{1cm} (2)

![Figure 1. Schematic of the ECG Amplifier](image)
2.1. Operational Transconductance Amplifier

Figure 2 is the schematic of the OTA employed in the ECG amplifier. The OTA employed within the project uses a typical 2-stage amplifier architecture with miller compensation to provide high gain and stability. The bias current is set to 20nA, the resulted drain currents for each device are listed in Table 1. The sizing of the transistors is essential for determining the operating point of each device. By increasing the W/L ratio of devices M3, M4, we biased the input differential stage such that M3 and M4 operate in weak inversion, which is desirable particularly for a portable biomedical signal amplifier as such bias scheme provides very high $g_m/I_d$ efficiency and is very power-efficient [7].

2.2. Feedback resistors

The design uses PMOS-bipolar pseudo resistors to approximate large resistors to bias the OTA [8]. The pseudo resistors are advantageous over transistors biased in the subthreshold region in that the former does not require additional bias circuits. As was introduced, the pseudo resistor connects its gate to the drain, which behaves like a diode-connected pMOS transistor with negative Vgs and a diode-connected bipolar pnp transistor in the case of positive Vgs. As shown in Figure 1, each feedback resistor is made up of 4 pseudo resistors. It is hard to measure the exact small-signal equivalent resistance of the pseudo resistor element. Hence, in our simulation, the pMOS devices' sizing was fine-tuned until the first pole matches the frequency of our design.

2.3. Test circuits

The testing of the ECG amplifier is implemented with a typical Human Body Circuit (HBC). Figure 3 shows the schematic of the circuit used within out test. The HBC was first introduced and was widely applied in the simulation of ECG signal sources. A 60Hz current source was also incorporated to simulate the power line interference as a common-mode signal.
Figure 3. (a) A schematic of the HBC; (b) An instance of component X which simulate electrodes

Table 1. Devices parameters and operating points

| Device No. | W/L(um) | No. of Parallel Devices | $I_D(uA)$ | $V_{GS} - V_T(V)$ |
|------------|---------|-------------------------|-----------|------------------|
| M1,M2      | 12/20   | N/A                     | 0.4       | 0.08             |
| M3,M4      | 1000/10 | N/A                     | 0.4       | 0.057            |
| M5         | 20/10   | 4                       | 0.8       | -0.036           |
| M6         | 2/10    | N/A                     | 0.02      | -0.036           |
| M7         | 20/10   | 10                      | 2         | -0.036           |
| M8         | 32/10   | N/A                     | 2         | 0.08             |

3. Results and Discussion

3.1. Results

Figure 4 shows the simulated amplifier transfer function from 0.1Hz to 1000Hz. The mid band gain is 40.04dB, with corner frequencies 0.1Hz and 100Hz. The first pole at 0.1Hz corresponds to a MOS-bipolar pseudo resistor with incremental resistance of an order of $10^{12}$. 

Figure 4. Simulated frequency response of the amplifier
Figure 5 shows the input-referred noise characteristics of the amplifier. Integration of the curve from 0.1Hz to 1Ghz and divided by the mid-band gain yields an rms value of the IRN of 3.59uVrms.

![Figure 5. Simulated RMS noise behavior of the amplifier](image)

Figure 6 shows the CMRR (Common-mode rejection ratio) of the amplifier. The CMRR is measured at 50Hz: a common source of common-mode interference from power lines. The CMRR of the amplifier is reported as 82dB, which is not ideal for typical amplifiers but is expected for the single-stage architecture applied in this design, as reported by previous literature [6].

![Figure 6. Simulated CMRR of the amplifier](image)

The Noise Efficiency Factor (NEF) is a widely adopted benchmark for assessing the power-noise tradeoff of biomedical amplifiers [9]. For comparison, the NEF of a single bipolar transistor has a NEF of one. As a result, all practical circuits have values greater than one, and the lower, the better. The NEF is calculated as follows:

\[
NEF = V_{ni,rms} \sqrt{\frac{2I_{tot}}{\pi U_T 4kT \cdot BW}}
\]  

where \(V_{ni,rms}\) is the input-referred rms noise voltage, \(U_T\) is the thermal voltage \(\frac{kT}{q}\), \(I_{tot}\) is the total current consumed by the amplifier, and BW is the bandwidth of the amplifier in hertz. For our design, the NEF is calculated to be 21.
Table 2. A summary of amplifier results

| Bandwidth     | Mid-band gain | IRN        | Power  | CMRR | NEF |
|---------------|---------------|------------|--------|------|-----|
| 0.1Hz-100Hz   | 40.04dB       | 3.59μVrms  | 1.44μW | 82dB | 21  |

3.2. Discussion
Table 2 summarizes the characteristics of the design reported by this paper. Overall, this design can achieve desirable operating margins for applying ECG amplifiers within wearable devices by maintaining low power consumption and relatively low noise performance. Hence, the classical 2-stage OTA does still possess its figure of merit in modern biomedical instrumentation amplifiers.

It is noted, however, that the OTA architecture lacks a solution for providing high CMRR. This leads to saturation of the output when the input suffers from too much common-mode interference. In the case of Power Line Interference at 60Hz, this design can handle up to 0.06uA before it saturates.

There exist many architectures for improving CMRR. One such solution is to use classical 3-OpAmp instrumentation amplifier architecture. However, this will bring in more biasing and additional OpAmps, which impose a challenge on power consumption and suppressing noise.

4. Conclusion
Above all, this paper has demonstrated a 1.44μW integrated CMOS bio amplifier with integrated input-referred noise of 3.59μV RMS. By biasing transistors in the sub-threshold region and using resistor-biased capacitive feedback, we have proven that a simple amplifier topology, such as the 2-stage OTA introduced above, can be made low-power and low-noise while eliminating EOV. Thus, this amplifier will be suitable for embedded ECG amplifier applications, such as those present in wearable devices.

References
[1] P Pramparo, CM Montano, A Barcelo, A Avezum, R Wilks, Cardiovascular diseases in Latin America and the Caribbean: The present situation. 2006
[2] D.B. Geselowitz, On the theory of the electrocardiogram. Proceeding of the IEEE, June 1989, pp. 857-876.
[3] Hubert Mann, M.D. A Method of Analyzing the Electrocardiogram. Arch Intern Med, 1920, pp. 283-294.
[4] Montree Kumngern, Natthaninee Aupithak, Fabian Khateb, Tomasz Kulej, 0.5V Fifth-Order Butterworth Low-Pass Filter Using Multiple-Input OTA for ECG Applications. 21 December 2020
[5] Farida Saeidian, Mohammadreza Ashraf, An ultra-low, low-noise tunable electrocardiogram amplifier. 13 August 2020.
[6] R. R. Harrison and C. Charles, "A low-power low-noise CMOS amplifier for neural recording applications," in IEEE Journal of Solid-State Circuits, vol. 38, no. 6, pp. 958-965, June 2003, doi: 10.1109/JSSC.2003.811979.
[7] D. J. Comer and D. T. Comer, "Using the weak inversion region to optimize input stage design of CMOS op amps," in IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 51, no. 1, pp. 8-14, Jan. 2004, doi: 10.1109/TCSII.2003.821517.
[8] T. Delbrück and C. A. Mead, “Analog VLSI adaptive, loga-rithmic widedynamic range photoreceptor,” in Proc. IEEE Int. Symp. Circuits and Systems, vol. 4, pp. 339–342, 1994
[9] M. S. J. Steyaert, W. M. C. Sansen, and C. Zhongyuan, "A micropower low-noise monolithic instrumentation amplifier for medical purposes," IEEE J. Solid-State Circuits, vol. SC-22, pp. 1163–1168, Dec. 1987.