A High Gain, Low Power Operational Transconductance Amplifier Capable of Recording and Processing ECG Signals

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Abstract. Based on high output resistor current mirrors and differential pair inputs, a new operational transconductance amplifier (OTA) is designed in this paper that can collect, filter, denoise and amplify electrocardiogram (ECG) signals. The OTA is designed on a 0.18μm CMOS process with a supply voltage of 1.8V. In this experiment, the ECG signal generated by the human model is first simulated, which has a noise of 50 Hz from electromagnetic interference, especially the electrical power lines. The differential input pair is then connected to the model, and it is proved that it can denoise the common-mode noise. Finally, the designed OTA is connected to the manikin, and the experimental results are compared with the traditional OTA. The design achieves a differential-mode gain of 43.56dB and a common-mode gain of -31.36dB while maintaining a differential input voltage swing of 1Vpp. Experimental results show that the OTA can denoise and amplify the ECG signal without distortion.

Keywords: OTA; ECG; denoise; differential pair; human model.

1. Introduction

An electrocardiogram (ECG) is a graphic recording of the time point and intensity of the electrical signal sequence that triggers the heartbeat to show the activity of the heart. The ECG signal is characterized by its low amplitude and frequency, alongside a high impedance, necessitating preprocessing for accurate representation [1]. There are many interferences in ECG signals, and this paper mainly discusses the elimination of industrial frequency interference, which mainly originates from the electromagnetic field radiated by the industrial frequency power supply and the transmission line in the surrounding environment of the device, with a frequency of 50 Hz or 60 Hz. This interference is manifested as a periodic small ripple on the ECG, and its frequency components are mainly the industrial frequency and its harmonics.

Operational transimpedance amplifiers (OTA) can adapt to the system and filter, denoise, and amplify the signals of the circuit. Opting for fully differential OTAs over their single-ended output counterparts is advantageous due to their ability to minimize harmonic distortion, enhance the output voltage swing, maintain a stable input common-mode voltage, and lessen coupling noise [2]. OTA is currently mainly used in signal computing and processing in a variety of linear and nonlinear analog circuits and systems.

Traditional OTA consumes a lot of power, is unstable, and can be distorted when processing signals. In this paper, a novel OTA based on current mirrors and differential inputs is proposed, which solves the above problems and can record ECG signals well. In this paper, the optimal values of each component parameter are determined through theoretical and simulation experiments, and the experimental results are compared with the traditional OTA, which verifies that the new OTA proposed in this paper has superior processing capabilities.

2. Theoretical Basis

2.1. ECG Signal

ECG signals can track heart rhythms and many cardiac disorders, such as abnormalities in blood flow and structure of the heart. The diffused current produces different potentials in different parts of the body, which can be sensed by electrodes placed on the skin [3].

2.1.1 Basic Components of the Electrocardiogram

ECG signals are made up of multi-component local fractions, and these regions are commonly referred to medically as combinations of waves P, O, R, S, T and their complexes is shown in figure 1 [4].

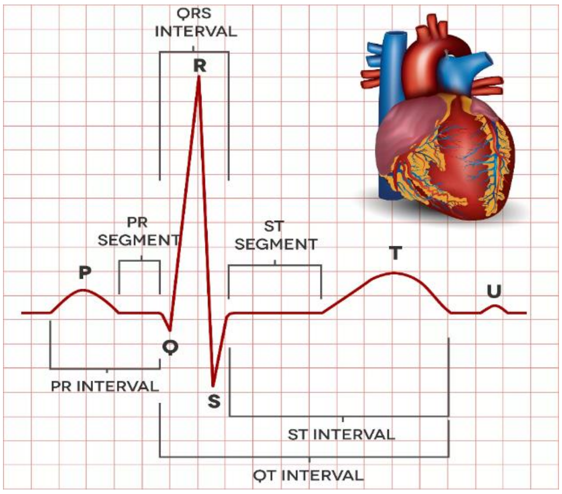

Fig.1 Electrocardiograph [4]

(1) P-wave

The P-wave represents the sequential depolarization of the right and left atria, and it is usually positively polarized with a period of less than 120 ms [5].

(2) PR interval

The PR interval signifies the duration required for the impulse initiated by the sinus node to traverse through the atria, AV junction, and AV bundle to the ventricles, initiating ventricular muscle excitation. This period is also referred to as the atrioventricular conduction time.

(3) QRS complex

The QRS complex represents ventricular depolarization with an activation time of less than 0.11 seconds. When there is block, ventricular enlargement, or hypertrophy of the left and right bundle branches of the heart, the QRS complex is widened, distorted, and prolonged [6].

(4) ST stage

Currently, repolarization is yet to commence, with each segment of the ventricular muscle undergoing depolarization, presenting no potential difference among the cells. Consequently, in a typical scenario, the ST segment aligns with the isopotential line. However, should ischemia or necrosis occur within a portion of the myocardium, a potential difference persists in the ventricles post-depolarization, evident through an ST segment deviation on the ECG.

(5) T-wave

It represents the change in potential caused by the ventricular muscle repolarization process.

2.1.2 process of ECG signals

The human ECG signal is a weak physiological signal that is non-stationary, non-linear and relatively random in nature. Processing of ECG signals includes acquisition, filtering, noise reduction, amplification and display, etc. The design of the system consists of hardware and software development. The analogue circuits of the hardware system include single-channel ECG and dual-channel pulse signal acquisition circuits, which can receive, filter and amplify the ECG and pulse signals; and digital circuits, which can convert the signals and transmit the data to a PC for processing [7].

2.2. Operational Transconductance Amplifier

An operational transconductance amplifier is an operational amplifier in which the input voltage controls the output current, and a simple OTA consists of a bias circuit, a differential pair input stage, and a current source load [8]. The high-resistance differential input stage and the ability to operate with a negative feedback loop make the transconductance amplifier similar to a conventional operational amplifier. After the input stage of the OTA converts the input voltage signal to a current signal, the current amplification of the backstage transistor can be used directly to amplify the current signal and transmit it to the output, which allows the OTA to record and amplify ECG signals well without extra distortion.

In addition, OTA has no impedance conversion, level transfer or other connections, and is characterized by simple circuitry and compact structure [9]. The gain of a transconductance op amp is directly proportional to the gm value of the input stage driver tube, which in turn is directly proportional to its bias current value. Therefore, the gain value of the transconductance type op amp can be adjusted by changing the bias current. Thus, the output current of a transconductance amplifier is controlled not only by the input voltage signal but also by a gain adjustment signal, adding a new control terminal to the amplifier. This feature will add versatility and flexibility to the application of transconductance op amps and allows for programmable control.

2.2.1 Basic Current Mirror

Current mirrors eliminate the effect of temperature variations in the operating environment on transistor bias currents which is shown in figure 2.

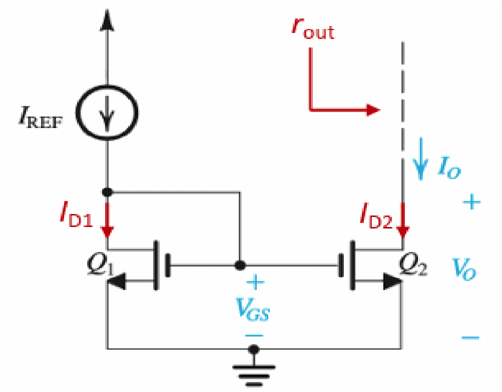

Fig.2 Basic Current Mirror (Photo/Picture credit: Original)

Transistor Q1 is diode connected forcing it to operate in the saturation mode (Vds > Vgs – Vth) with

$$k_n' = u_n C_{ox} \qquad I_{REF} = I_{D1} = \frac{1}{2} k_n' \left(\frac{W}{L}\right)_1 (V_{GS} - Vth)^2 \tag{1}$$

Where C_{ox} is the oxide capacitance, μ_n is the mobility of electrons, W and L are width and length of transistors and V_{th} is the threshold voltage of transistors.

Q2 has the same V_{GS} as Q1

$$Io = I_{D2} = \frac{1}{2} k_n' \left(\frac{W}{L}\right)_1 (V_{GS} - Vth)^2 \tag{2}$$

Thus

$$\frac{Io}{I_{REF}} = \frac{(W/L)_2}{(W/L)_1} \tag{3}$$

2.2.2 Small Signal Model of Current Mirror

The small signal model of current mirror is shown in figure 3.

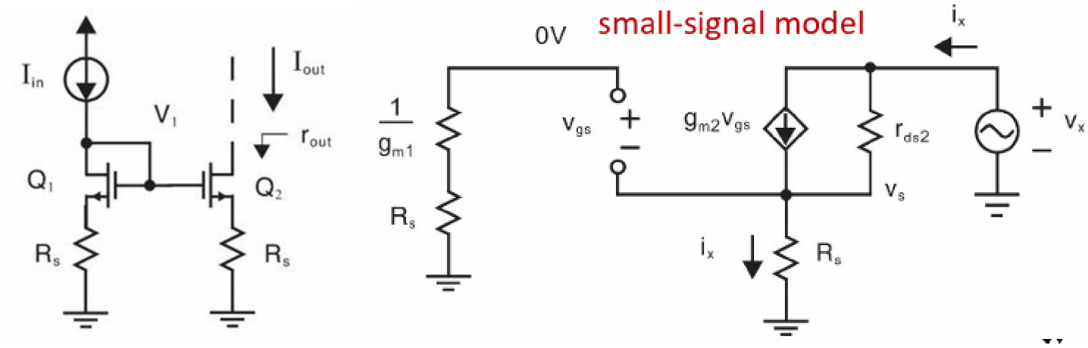

Fig.3 Small Signal Model of Current Mirror [10]

The output resistance is

$$r_{out}=v_x/i_x=r_{ds2}[1+R_s(g_{m2}+1/r_{ds2})]\cong r_{ds2}(1+R_s g_{m2})\cong r_{ds2}R_s g_{m2} \tag{4}$$

where r_{out} is the output resistance, r_{ds2} is drain-source resistance, R_s is the resistance between source and ground and gm is transconductance.

2.2.3 Cascode Current Mirror

It allows for more accurate current copying and greater output impedance than ordinary current mirrors which is shown in figure 4.

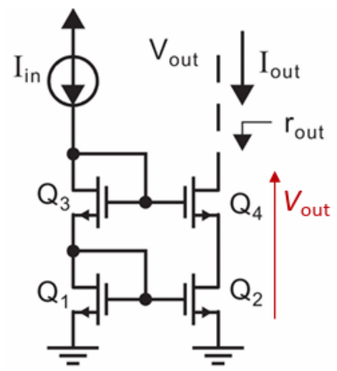

Fig.4 Cascode Current Mirror [11]

Making use of the equation above, and noting that Q4 is now the cascode transistor rather than Q2, and where now Rs = rds2, we obtain

$$r_{out} \cong r_{ds4}[1 + r_{ds2}(g_{m4} + g_{s4})] \cong r_{ds4}r_{ds2}g_{m4} \tag{5}$$

2.2.4 Differential Pair

As is seen in figure 5 that input voltage 1 and 2 are differential signals.

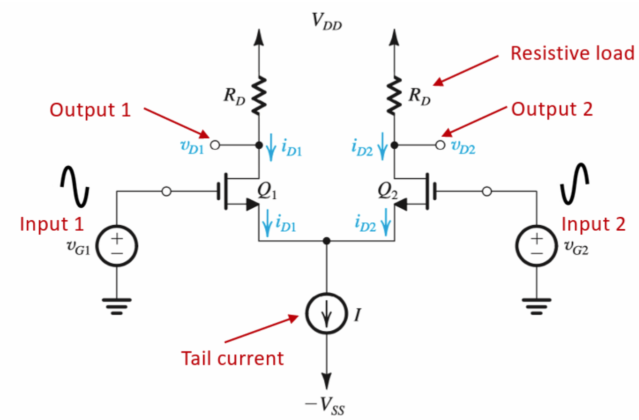

Fig.5 Differential Pair (Photo/Picture credit: Original)

$$i_{D1}+i_{D2}=I \qquad v_{D1}=V_{DD}-i_{D1}R_D \qquad v_{D2}=V_{DD}-i_{D2}R_D \tag{6}$$

2.2.5 Current-mirror loaded MOS differential pair

The current mirror loaded MOS differential pair is shown in figure 6.

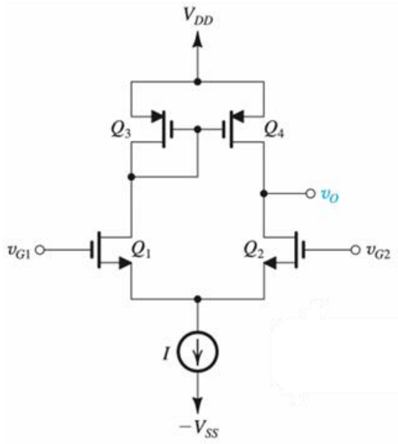

Fig.6 Current mirror loaded MOS differential pair (Photo/Picture credit: Original)

The voltage gain can be obtained by:

$$A_d = \frac{v_o}{v_{id}} = G_m R_o = g_{m1,2}(r_{o2}||r_{o4}) \tag{7}$$

$$G_m = g_{m1,2} \tag{8}$$

$$R_o = r_{o2}||r_{o4} \tag{9}$$

2.2.6 OTA Model

OTA model is shown in figure 7.

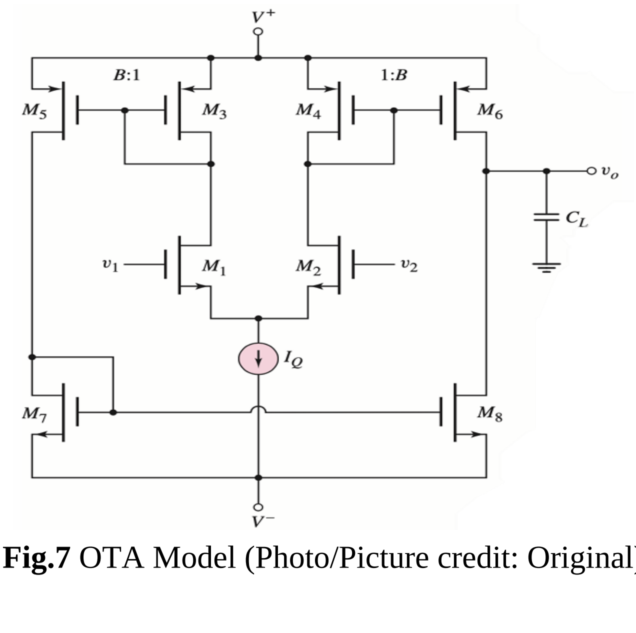

Fig.7 OTA Model (Photo/Picture credit: Original)

The Voltage gain is

$$A_d = Bg_{m1,2}(r_{o6}||r_{o8}) \tag{10}$$

where B is the ratio of the aspect ratio of two transistors.
The cut off frequency is

$$f_{(-3dB)} = \frac{1}{2\pi(r_{o6}||r_{o8})C_L} \tag{11}$$

where C_L is the capacitor at output node which turns the circuit into a filter.

2.3. Circuit Design

Based on the above theory, this paper will improve the traditional OTA to achieve the role of acquisition, noise reduction, filtering and amplification of ECG signal. The circuit was built on CoolSpice which is shown in figure 8.

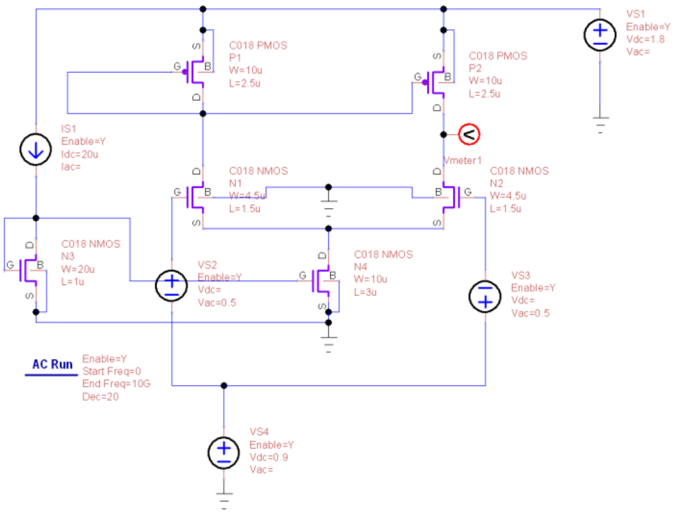

Fig.8 Designed OTA circuit (Photo/Picture credit: Original)

Vs1 and Vs2 are used to keep the transistors in the circuit in the operating region. N1 and N2 comprise a differential pair with differential signal input (VS2 and VS3), which is used to eliminate the industrial frequency interference.

In order to achieve low power consumption of the circuit, the input current of the circuit is set at 20uA. And the amplitude of differential signal is set at 0.5A. The voltage gain can be calculated by

$$A_d = \frac{v_o}{v_{id}} = GmR_o = gm_{N1,N2}(r_{oN2}||r_{oP2}) \tag{12}$$

N3 and N4 form a current mirror with

$$I_{\mathrm{DN3}}/\mathrm{I}_{\mathrm{DN4}} = \frac{(20u/1u)}{(10u/3u)}=6 \tag{13}$$

Thus

$$\mathrm{I}_{\mathrm{DN4}} = \frac{1}{6} I_{\mathrm{DN3}}=3.33\mathrm{uA} \tag{14}$$

For the differential mode gain, it is useful to improve transistor transconductance, and increase the width of the transistor. For the common mode gain, it' s better to use common mode feedback circuit and ensure the output resistance is very large. The expectation of this circuit is to maintain the differential mode gain at greater than 40dB and the common mode gain at less than -30dB.

3. Simulation and Testing

In this section, the SCL 180nm CMOS process is used to design and simulate the proposed OTA and filter at 1.8V supply voltage to design and simulate the OTA and filter. The whole process is accomplished using CoolSpice.

3.1. Simulation of Human Body Signal

The human body signal circuit is shown in figure 9.

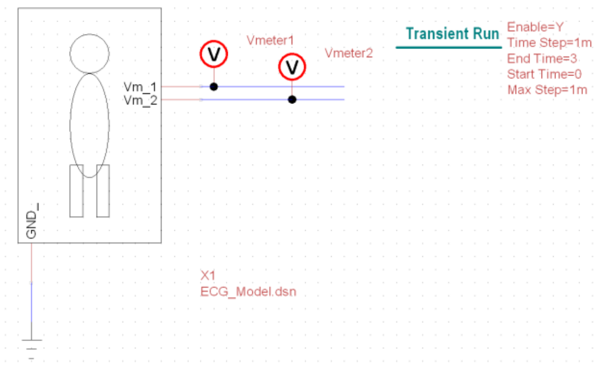

Fig.9 Human body signal circuit (Photo/Picture credit: Original)

Place the voltmeter on the human model and run a transient simulation for 3s with the time step 1ms.

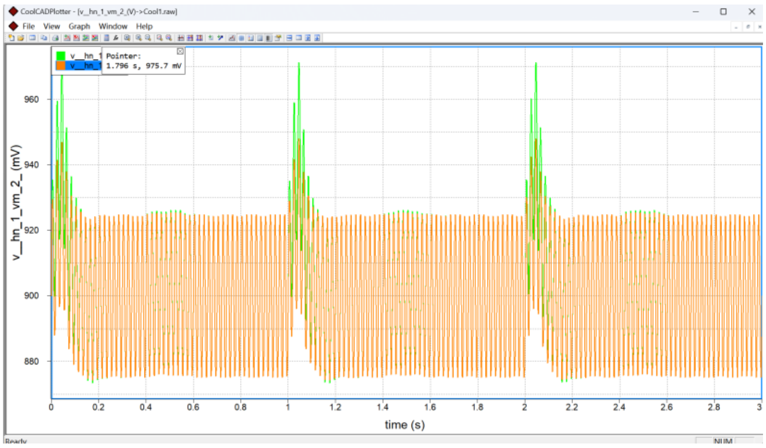

Fig.10 Transient simulation (Photo/Picture credit: Original)

It can be seen from figure 10 that the signal obtained from the mannequin receives noise interference at a frequency of around 50hz.

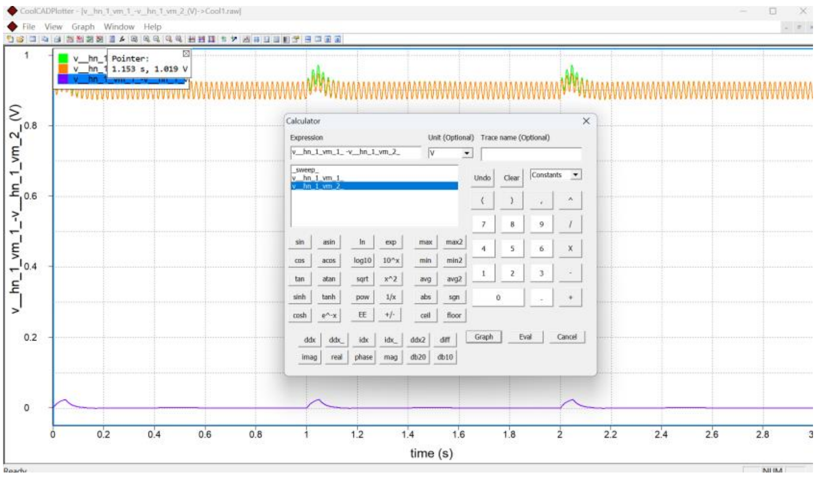

Fig.11 Calculator from the plot (Photo/Picture credit: Original)

Use the calculator from the plot and perform subtraction with signals from two voltmeters which is shown in figure 11.

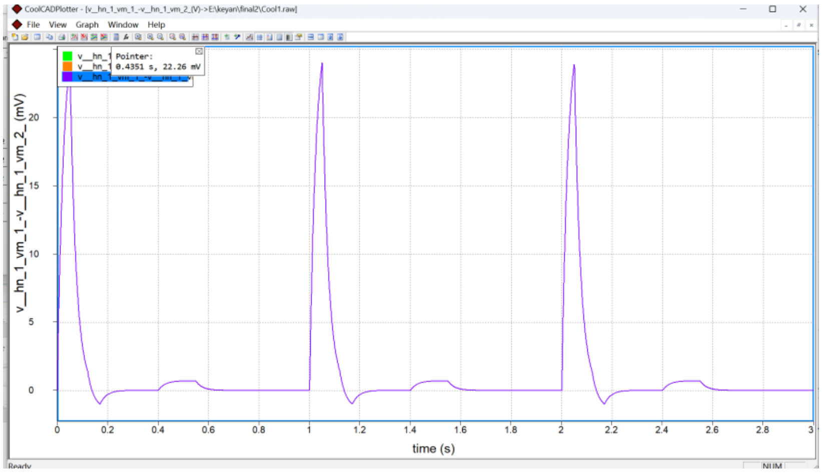

Fig.12 The signal after noise reduction (Photo/Picture credit: Original)

Since this noise is a common mode noise, it can be removed by differential recording or direct subtraction. The signal after noise reduction is shown in Fig.12.

Remove noise using differential pair

Remove noise using differential pair and the circuit is shown in figure 13.

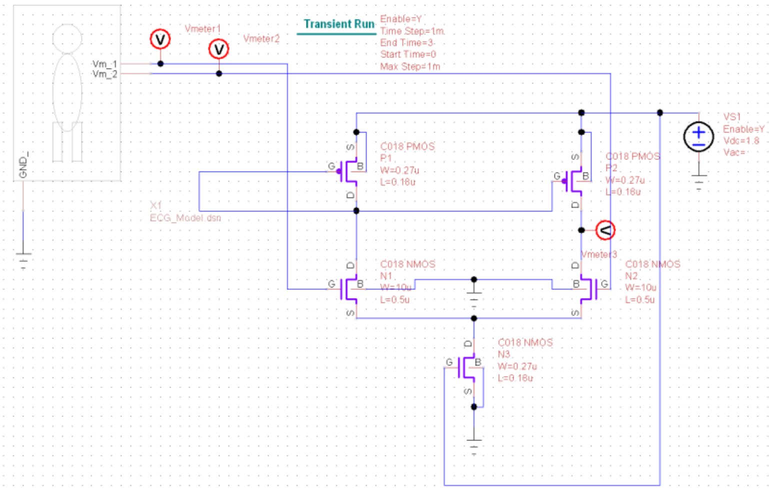

Fig.13 Remove noise using differential pair (Photo/Picture credit: Original)

Connect the human model to a current mirror loaded MOS differential pair with the voltage source set to 1.8V, which is shown before. Then place a voltmeter on the drain of P2 and N2 to display the output signal of this circuit.

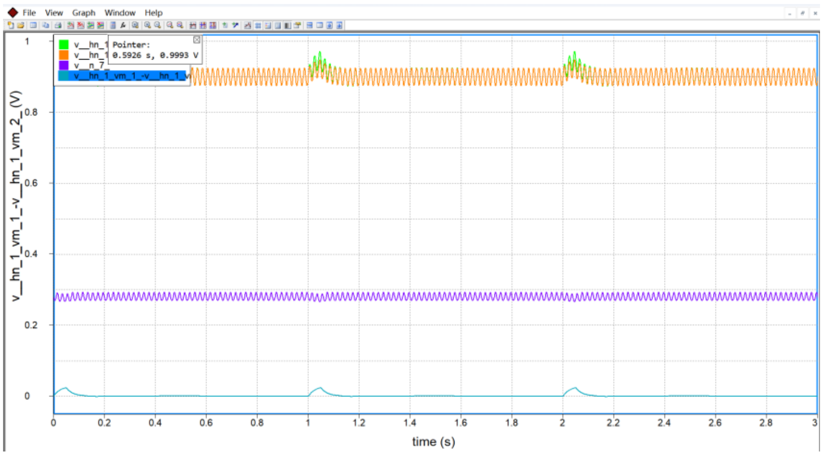

Fig.14 Simulation result (Photo/Picture credit: Original)

The essence of differential signal is to cancel out noise with noise --- converting the original signal into two signals with a 180° phase difference subtracted from each other. From the figure 14, the 50hz interference is eliminated by the circuit. Therefore, the differential signal input circuit does what the calculator has done.

3.2. Simulation of OTA Circuit

This section will simulate the OTA's differential mode gain, common mode gain and its effect on the ECG signal, the circuit is shown in figure 15.

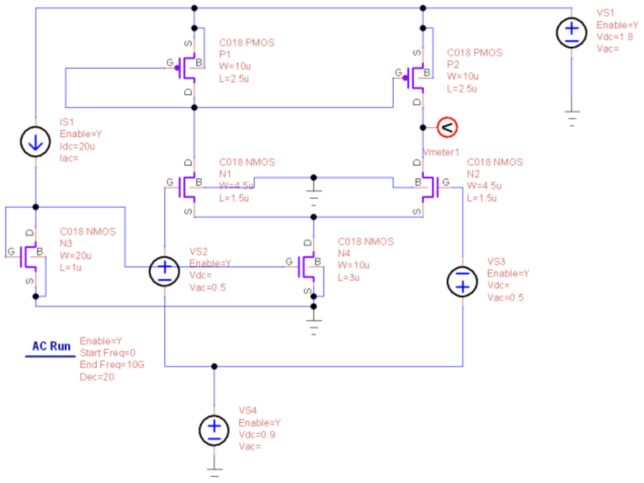

Fig.15 Simulation of OTA Circuit (Photo/Picture credit: Original)

This is the whole OTA circuit as shown before. The supply voltage of this circuit is 1.8V and a current source of 20uA is connected to the drain of N3. A voltmeter is placed at the output voltage terminal. Use AC simulation with an initial frequency of 0 and an end frequency set to 10 GHz.

3.3.1 Differential Mode gain

Differential mode gain of the circuit is shown in figure 16.

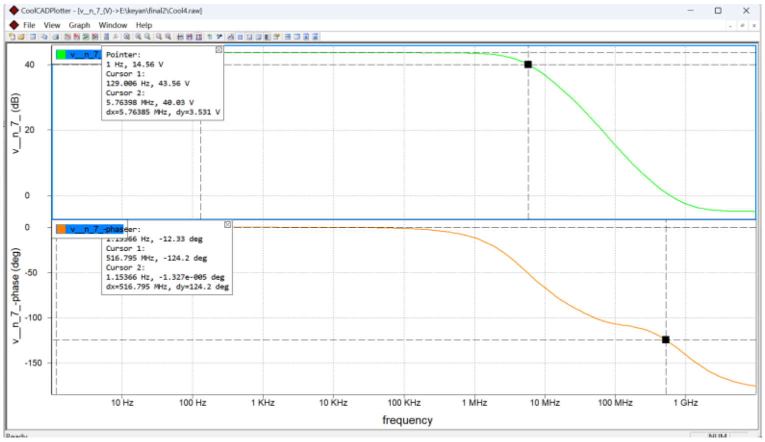

Fig.16 Differential mode gain of the circuit (Photo/Picture credit: Original)

This is the differential mode gain of the circuit; it can be seen that the result consists of two parts. The upper part is the voltage gain in dB. The gain of the circuit in the first 5kHz remains essentially unchanged at 43.56dB. After that, it starts to fall and goes all the way down to below 0. From the lower half, it can be seen that the phase margin of the circuit is 180-124=56°.

3.3.2 Common Mode Gain

The common mode gain circuit is shown in figure 17.

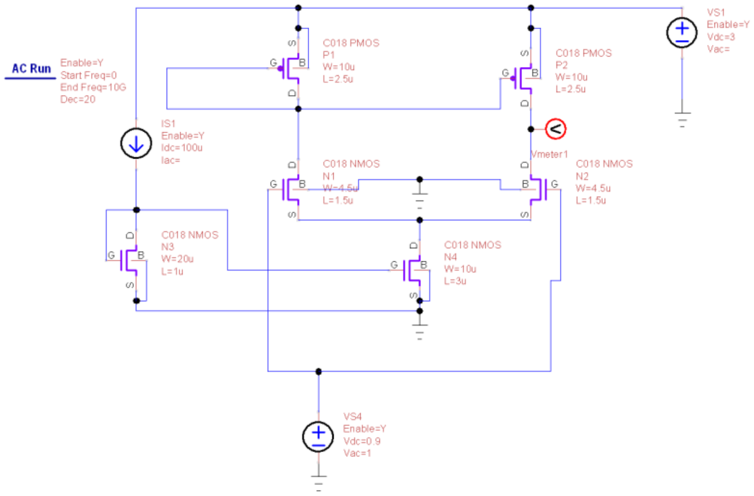

Fig.17 The common mode gain circuit (Photo/Picture credit: Original)

Common-mode gain indicates the ability of a transistor differential amplifier or integrated op amp to amplify a common-mode input signal. Common mode gain is measured by shorting both amplifier's inputs to a voltage source with AC amplitude set to 1.

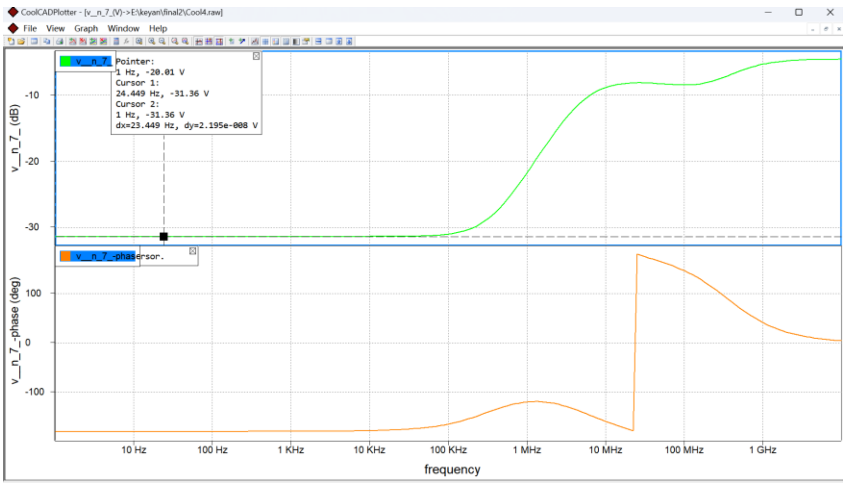

Fig.18 Common mode gain simulation result (Photo/Picture credit: Original)

From the figure 18 it can be seen that the common mode gain of this OTA is -31.36dB.

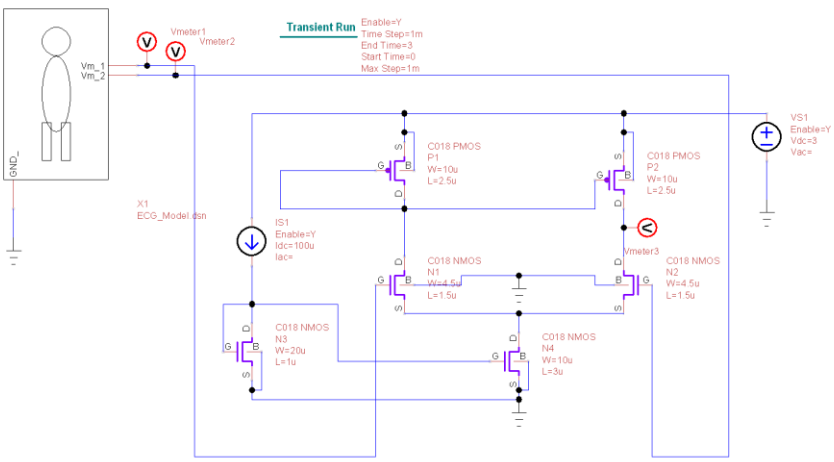

Fig.19 Entire OTA to the human model (Photo/Picture credit: Original)

Then connect the entire OTA to the human model ground the source of N4 and N3 and run the transient simulation which is shown in 19. The differential signal input can be replaced with an ECG signal input from a human body model.

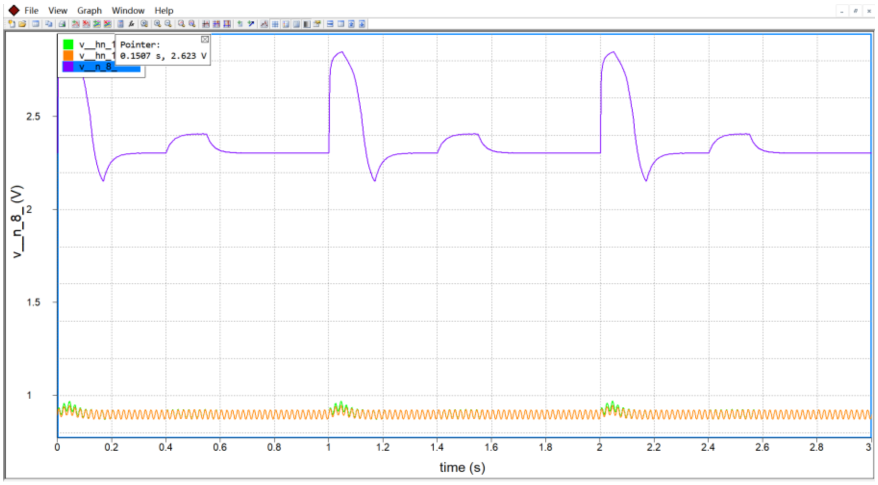

Fig.20 Signal mixed with noise and the displayed ECG signal (Photo/Picture credit: Original)

Fig.20 shows the signal mixed with noise and the displayed ECG signal. The confounding ECG signal fluctuates around 0.6V, while the OTA-processed signal fluctuates around 2.5V.

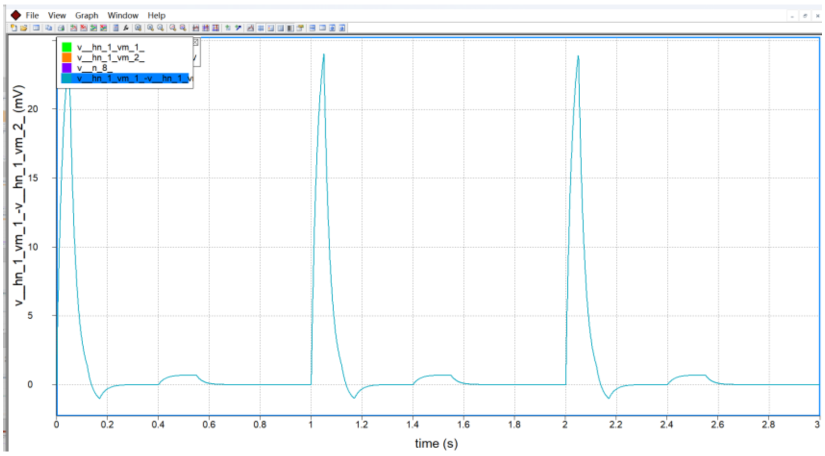

Fig.21 ECG signals generated by the human model (Photo/Picture credit: Original)

The ECG signals generated by the human model can be obtained by subtracting V1 and V2. It is shown in Fig.21.

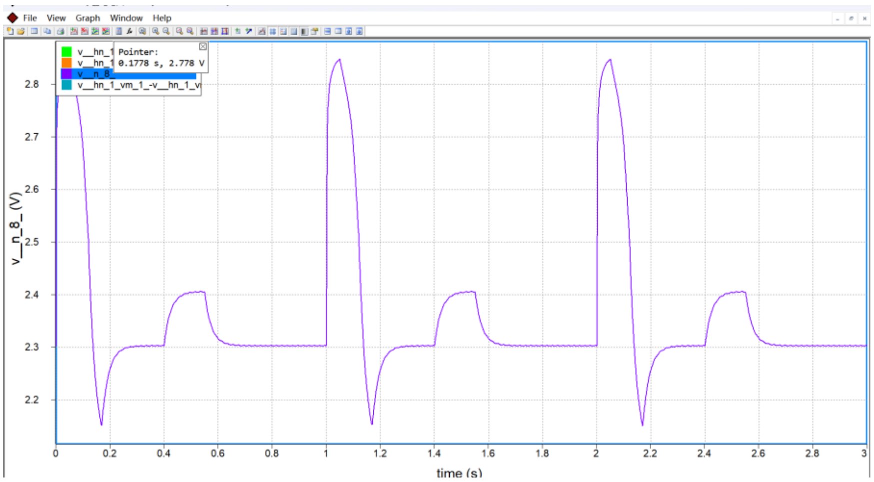

Fig.22 Final amplified ECG signal (Photo/Picture credit: Original)

ECG signal is noise-reduced and amplified by an operational transconductance amplifier, and the final amplified ECG signal is shown in Fig.22. By comparing Fig.21 and Fig.22, it can be seen that the ECG signals generated by the human model are well amplified and reproduced by the OTA.

4. Conclusion

In order to solve the problem of high-power consumption and distortion of traditional OTA, this paper proposes a new type of OTA based on current mirror and input differential pair. In conclusion, the experimental results show that the differential-mode gain of the OTA is 43.56dB and the common-mode gain is -31.36dB, which meet the expectations of the experiment. In addition, this OTA completes the process of collecting, denoising, filtering, amplifying and displaying ECG signals.

However, due to the limitations of the simulation software, the OTA proposed in this paper is single-stage, which makes the output common-mode level dependent on the degree of matching between the upper and lower current mirrors, and a common-mode feedback loop is required to stabilize the output common-mode level. Therefore, this paper makes the following assumptions and prospects. Multi-level OTA can be used to increase the maximum swing, thus increasing the gain. And the output voltage swing is no longer related to the input common-mode range. Adding a compensation capacitor between the two stages increases the capacitive impedance of the second stage at low frequencies and lower output impedance at high frequencies.

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