Design an amplifier to record electrodardiogram(ECG) signals

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Abstract. Heart disease is one of the most important causes of death around the world. To monitor and react to the condition of the patients in time and efficiently, ECG technology is rather essential because it not only has low cost and simple operation, but also can get results quickly. In order to capture the original differential signals produced from human body and suppress the electromagnetic interference, this paper has designed a differential amplifier which can apply subtraction to the original signals and amplify them to get a clear ECG signal. The circuit has been designed with 0.18 μm CMOS process. The plot of simulation results show that the total current consumption of the circuit is controlled to be 19 μA and the differential gain and the common mode gain are correspondingly 40.76 dB and -42.36 dB. According to the simulation result of ECG in this paper, the electromagnetic interference has been rejected and the acquired signal is amplified to be essay to observe. Such an ECG technology has a very positive effect on cardiovascular disease treatment.

Keywords: ECG signal, differential amplifier, CMOS process,restrain noise, total current.

1. Introduction

It is known that cardiovascular disease has a high mortality rate. The success rate of rescuing will be very low if someone has a heart attack. For this kind of disease, continuous and long-term detection is required. Hence, ECG technology appears to be more and more important as the incidence rate of heart disease increases nowadays. Electrocardiogram, namely ECG, is a very common clinical examination method. It has several advantages such as low cost, simple operation and getting results quickly. This kind of technology is especially useful to monitor shock, severe infection, acute myocardial infarction, heart failure, fulminant myocarditis and many other diseases related to the heart [1].

This paper has designed a differential amplifier which can reduce the common-mode noise because of electromagnetic interference as well as amplifying the input signals. This amplifier mainly consists of a single ended current mirror loaded differential pair and another current mirror. The former one was used to apply subtraction to the two input signals in order to restrain the noise and the latter one was used to control the value of the total current and make it constant. The paper is based on 0.18μm CMOS technology and 19μA current had been chosen to decrease the power consumption.

2. The capture of the original signals and how to process them to get ECG signal

2.1. Introduction to ECG

ECG, namely electrocardiogram, is produced by the depolarization and repolarization of cardiac cells [2]. The depolarization and repolarization are illustrated by Figure 1.

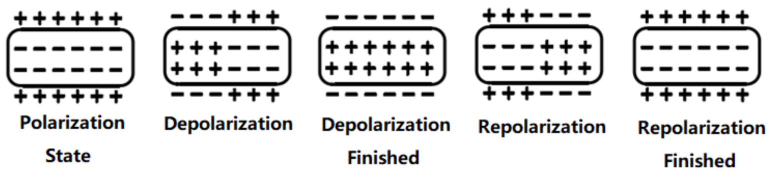

Figure 1. The depolarization and repolarization

Initially, the positive ions outside the cell have the same quantity as the inside negative ions. This condition is known as polarization state, in which the potential difference between the two sides of the cell membrane keeps constant. However, provided that the cardiac cell receives a stimulation, which leads to the transformation of the cell membrane permeability, then the potential difference starts to change due to the flow of ions. Subsequently, when depolarization has been finished, repolarization starts to be implemented. In this stage, the change of potential difference is opposite to that in depolarization, which finally leads to the polarization state of the cell again. Typically, the cardiac cells repeat depolarization and repolarization constantly because the sinoatrial node, an essential structure inside heart, keeps producing electrical stimulations periodically [3]. These stimulations will cause the transformation of electric potential on the skin. By recording the transformation of potential and plotting the data in time domain, ECG signal can be obtained [4]. ECG has numbers of important functions such as analyzing and distinguishing various arrhythmias, checking many heart diseases like ventricular and atrial hypertrophy and reflecting the degree of myocardial damage and the functional structure of atrium and ventricle [1]. Therefore, it can be said that ECG is of great significance in medicine.

2.2. The capture of the original signals

A human-model shown in Figure 2 has been chosen to simulate human body. Two electrodes have been used to capture the two different electric potentials on the skin, which are V1 and V2 in Figure 2.

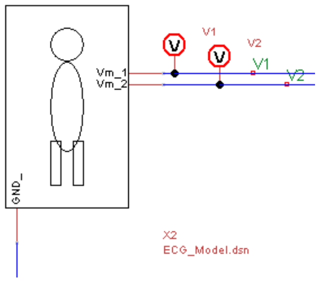

Figure 2. The human-model

Typically, as what is shown in Figure 3, electromagnetic interference will be picked up by the human body because it can act as an antenna, especially 50 Hz noise from the electrical power lines [5]. The external wires that contain an approximately 50 Hz signal couple with human body through electric field. The 50 Hz signal results in change of electric potential of human body, which also couples with the ground. As the result, it can be seen that two capacitors have connected the human body correspondingly to the external wires and to the ground. Then the 50 Hz sinewave signal flows from the wires through the human body to the ground and interferences the biological signals in human body.

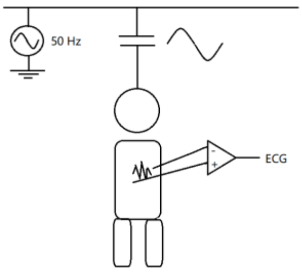

Figure 3. Interference from extra wires

This interference can make the ECG biological signals very hard to measure by adding to the biological signals [5]. To simulate this noise, a 50 Hz sinewave has been added to the biological signals produced by the human-model. After running a transient simulation, which plots the outputs in time domain, the transformations of V1 and V2 in time domain is shown in Figure 4.

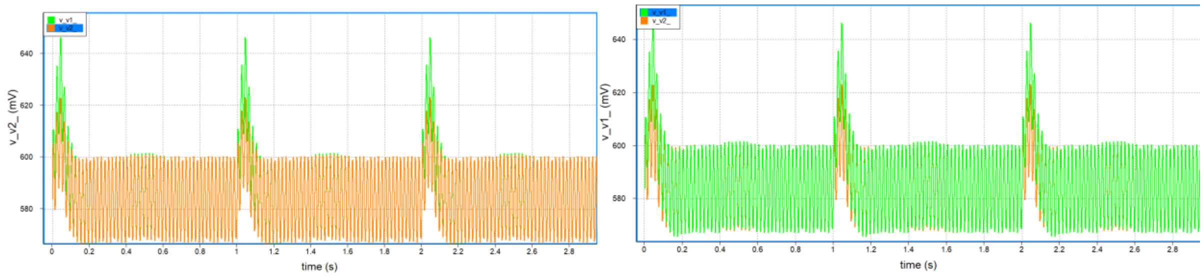

Figure 4. The plots of V1 and V2 in time domain

2.3. The method to process the original signals to get ECG

It is known that this 50 Hz noise is a common-mode noise, so to reduce it to observe the ECG signal clearly, subtraction can be applied here [6]. By applying subtraction to V1 and V2, an ECG signal without noise in Figure 5 can be gotten.

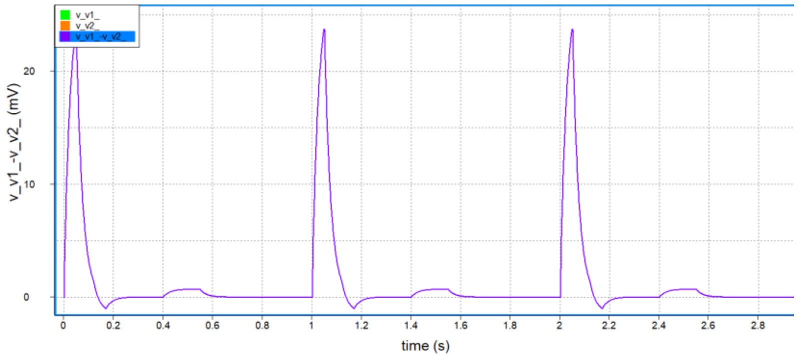

Figure 5. Subtraction of V1 and V2

The standard waveform of ECG signal is shown in Figure 6. Every segment and interval reflect the cell activity and can determine whether the heart has pathological changes. The amplitude of P wave varies from 0.05 mV to 0.25 mV, which represents left and right atrial depolarization; the QRS wave segment has amplitude less than 5 mV, which corresponds to left and right ventricular depolarization; the T wave has amplitude varies from 0.1 mV to 0.8 mV, which represents ventricular repolarization; the P-Q segment and S-T segment have the same level as the baseline that represents 0 amplitude. They correspondingly represent the process of stimulation transmission from the atrium to the ventricles and ventricular repolarization [7].

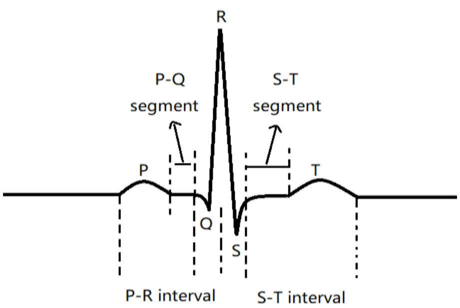

Figure 6. Standard ECG waveform

Moreover, ECG signal has the following characteristics:

(1) Low amplitude

Usually, the ECG signals can be obtained directly from human skin have very small amplitude, which varies from 100 μV to 5 mV. Therefore, though the 50 Hz noise has been reduced by subtraction, the ECG signal is still too small to observe. To solve this problem, the signal is required to be amplified.

(2) Strong background noise

Noise includes interference of external wires, interference of acquisition circuits, baseline drift and many other interferences. In this project, the 50 Hz noise is the simulation of the interference of the external wires.

(3) Low frequency

ECG has low frequency varies from 0.5 Hz to 150 Hz because the beat rate of human heart has low frequency.

To conclude, an amplifier which can implement subtraction to two input signals and has a gain that is large enough is needed.

3. Circuit designs and results

3.1. Considerations before designing circuit

(1) Common-mode gain that is small enough

Typically, common-mode signals are expected to be rejected. Diminishing common-mode gain is a very positive method to develop CMRR (common-mode rejection ration) to suppress the effect of common-mode signals. In this project, common-mode gain is required to be lower than -30 dB up to 5 kHz.

(2) Differential gain that is large enough

To ensure the ECG signal is easy to observe and also to improve CMRR, high differential gain is necessary. In this project, the differential gain is required to be more than 40 dB up to 5 kHz.

(3) Low power consumption

Low power consumption helps to improve the duration of ECG machine with limited power source when accidents happen. This also avoids producing too much heat which may do harm to human cells and the machine. low power consumption means smaller components which can raise more space to design other circuits to enable more functions and smaller size makes it more convenient for patients and medical personnel to diagnose. To achieve low power consumption, the method which is using low current is useful. In this project, the current consumption is required to be lower than 20 μA.

3.2. CMOS differential amplifier

3.2.1 Need for differential amplifier

One of the advantages of differential amplifier is suppressing the ripple and noise exist in Vcc. Ripple on supply voltage appears in many conditions like AC to DC conversion through rectifier [8]. In this condition the converted DC supply voltage cannot be entirely a DC voltage in reality, because of which the obtained signal will be distorted if this DC works as carry wave. According to Figure 7, by applying subtraction to X point and Y point, the ripple and noise in Vcc can be suppressed, which keeps V_{out} from distortion effectively [9].

Moreover, differential amplifier is needed in ECG because also by applying subtraction, it can reduce the common-mode noise exists in the input signals, which is rather important in this project [9]. This characteristic of differential pair makes the input signals highly immune to external electromagnetic interference (EMI) because when the input signals are influenced by the same interference source, the subtraction method can totally reduce it.

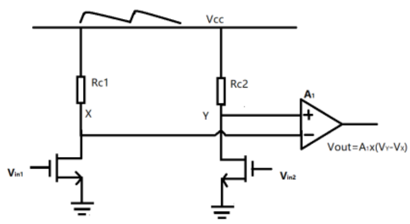

Figure 7. A differential amplifier with ripple on supply voltage

3.2.2 Differential amplifier analysis

Firstly, an introduction to differential signals is necessary. The answer to what are differential signals is that they are a pair of signals which have the same amplitude and frequency whereas 180°out of phase and transmit in a pair of lines that have equal length and equal width and are close to each other and on the same level [10].

The circuit shown in Figure 8 is a differential pair with a pair of differential signal inputs, where Q1 and Q2 are equal and R1=R2. Through small-signal operation, the differential gain is obtained to be $A_d = g_m(R_D \| r_o)$.

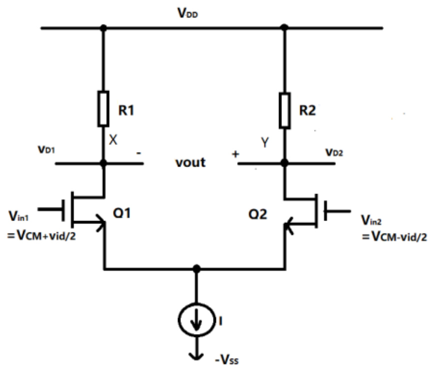

Figure 8. Differential amplifier with two resistors

The two resistors, R1 and R2, can be replaced by two equal transistors shown in Figure 9, Q3 and Q4, to provide resistance that is more stable and to save more space. Then the differential gain becomes $A_d = g_{m1}(r_{o1} \| r_{o3})$, where g_{m1} is the transconductance of Q1 or Q2, r_{o1} and r_{o3} are correspondingly the resistance of Q1 and Q3.

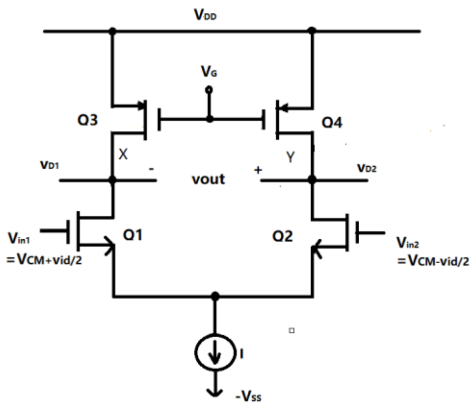

Figure 9. Differential amplifier with a current mirror

To make the differential outputs convert to a single ended output, v_{out}, current mirror loaded MOS differential pair has been developed as illustrated in Figure 10.

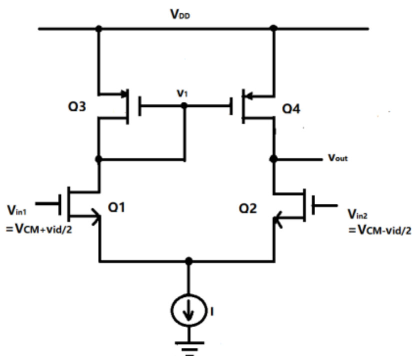

Figure 10. Single ended current mirror loaded differential pair

Now apply small-signal analysis. For V_{in2}, equation (1) can be gotten:

$$\frac{v_{out2}}{-\frac{1}{2}v_{id}} = -g_{m2}(r_{o2} \parallel r_{o4}) \tag{1}$$

For V_{in1}, equation (2) and (3) can be gotten:

$$\frac{v_1}{\frac{1}{2}v_{id}} = -g_{m1}(r_{o1} \parallel r_{o3} \parallel \frac{1}{g_{m3}}) \tag{2}$$

$$\frac{v_{out1}}{v_1} = -g_{m4}(r_{o2} \parallel r_{o4}) \tag{3}$$

According to equation (2) and (3), equation (4) is derived to be:

$$\frac{v_{out1}}{\frac{1}{2}v_{id}} = g_{m1}(r_{o2} \parallel r_{o4}) \tag{4}$$

From Eq. (1), (2), (3) and (4), equation (5) is obtained:

$$v_{out} = \frac{1}{2}v_{id}g_{m1}(r_{o2} \parallel r_{o4}) - \frac{1}{2}v_{id}g_{m2}(r_{o2} \parallel r_{o4}) \tag{5}$$

Finally, the differential gain of this circuit is evaluated to be:

$$A_d = g_{m1}(r_{o2} \parallel r_{o4}) \tag{6}$$

This is the circuit which can meet the requirements of reducing the common-mode noise by subtracting the two amplified differential signals.

3.2.3 Circuit designs to get ECG signal

Initially, a differential amplifier with an NMOS as the current source to control the total current shown in Figure 11 was chosen to reduce the common-mode noise as well as amplifying.

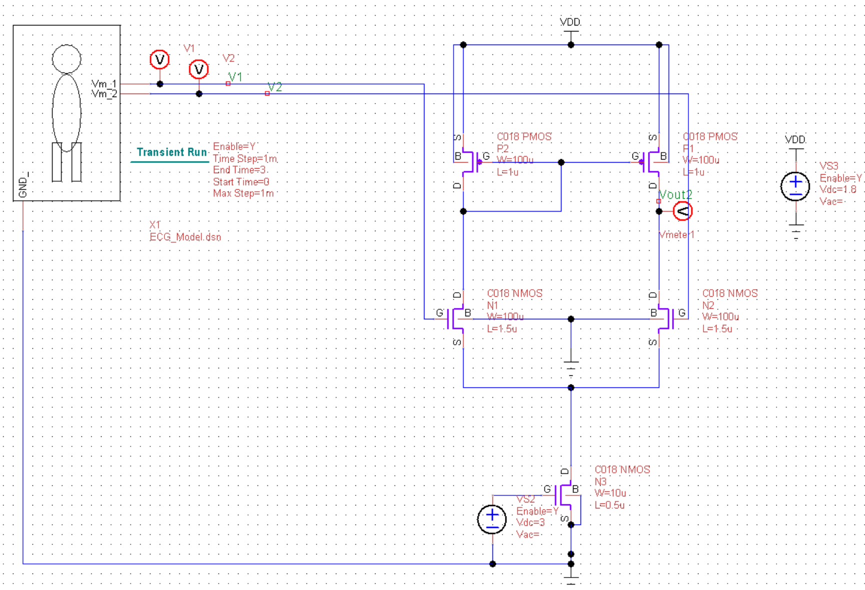

Figure 11. Differential amplifier with an NMOS as the current source

However, a problem appeared. It is known that if a transistor is considered ideal, the output resistance of this ideal transistor is expected to be infinite, which means that if it is operated in its saturation region, the drain current will not change with the drain-source voltage. But the transistors people use in real life are all non-ideal. Hence, provided that the drain-source voltage is oscillating, the drain current will also fluctuate. Then through analyzing Figure 11, transistor N3, which had been set there to control the total value of current, was found unable to provide a constant current flow because Figure 4 told that the two input signals concluded a 50 Hz common-mode noise. Besides, due to the characteristics of the two input signals, the drain-source voltage of N3 would keep oscillating. Therefore, the total current of this circuit was analyzed to fluctuate. It is known that for N1 and N2, the gate-source voltages namely V_{gs} would fluctuate because of the oscillating inputs and in this condition, if the drain current is unable to keep constant, the transconductance will also not be constant, which can cause an oscillating gain. This is harmful because an extra noise will be produced and make the ECG signal harder to observe.

After realizing the problem, a solution was raised. A current mirror had been used to replace the single transistor because a current mirror consists of two transistors with the same size and the same gate-source voltage can make the drain current of them equal to each other. The modified circuit is shown in Figure 12, which is called CMOS operational transconductance amplifier (OTA).

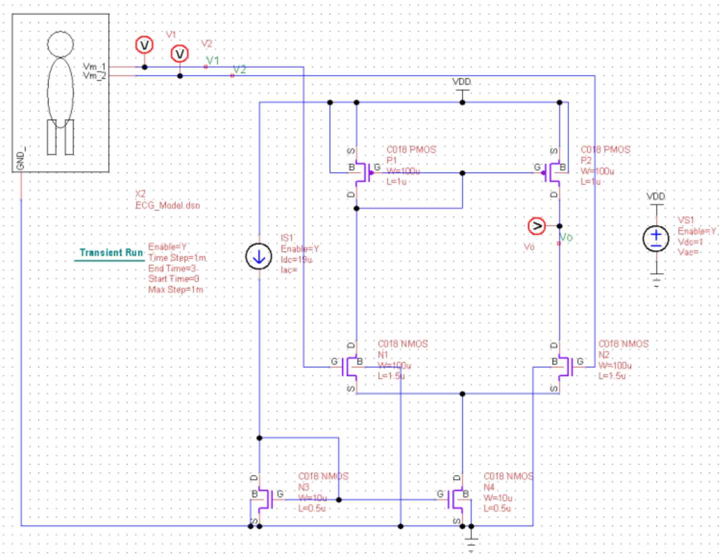

Figure 12. CMOS operational transconductance amplifier (OTA)

After finishing designing the circuit, all the parameters had been adjusted to meet the requirements raised in Chapter 3.1. The plot shown in Figure 13 corresponds to common-mode gain and Figure 14 corresponds to differential gain. The common-mode gain is adjusted to be -42.36 dB and the differential gain to be 40.76 dB.

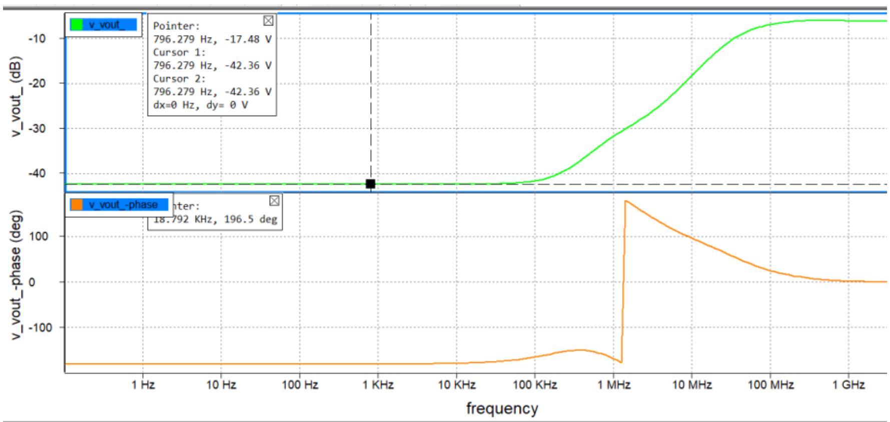

Figure 13. Common-mode gain

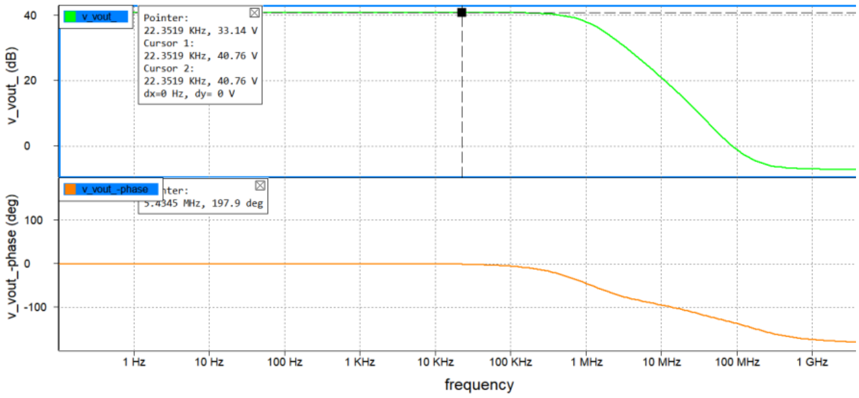

Figure 14. Differential gain

3.3. The simulation results and comparison

For the both two circuits raised above, the transient simulation had been run, which simulates the circuit in time domain to see how the output voltage changes with time. Figure 15 shows the result of the first circuit. It appears that the noise still exists in the ECG signal and influences the observation of the final signal. Because of the noise, P segment and T segment are very hard to observe and the whole signal is distorted seriously. Instead, the result of the OTA circuit plotted in Figure 16 looks clearer. In this plot, each part of the standard ECG signal can be distinguished clearly and the noise had been reduced well.

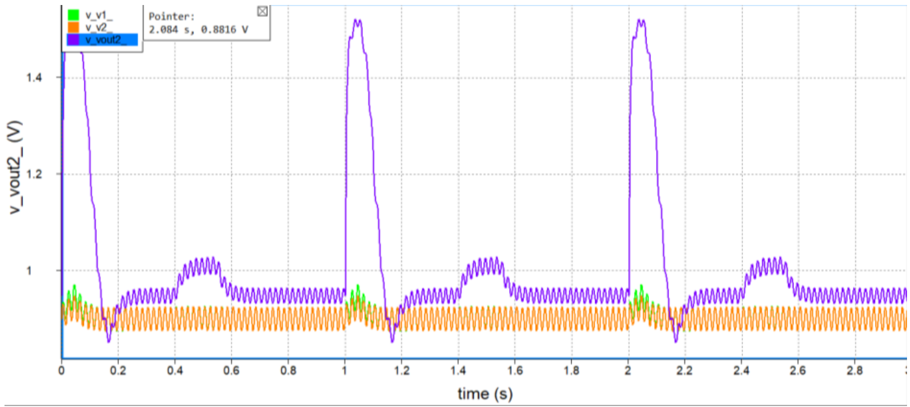

Figure 15. Result of the former circuit

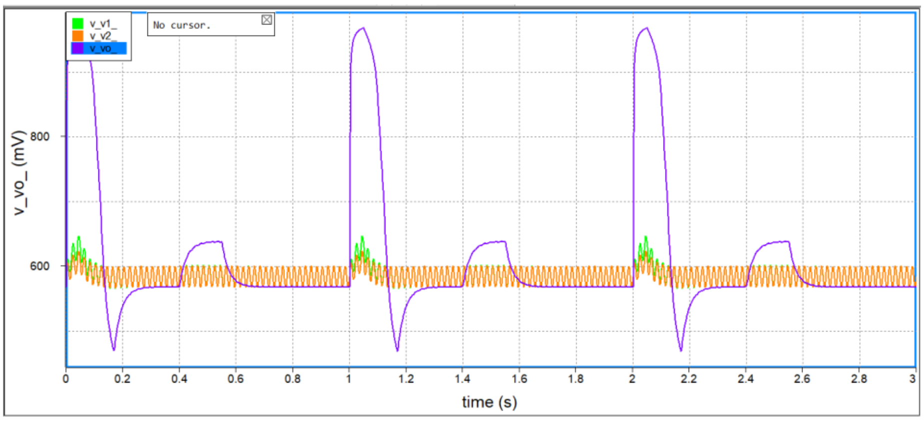

Figure 16. Result of the OTA circuit

Additionally, the signal in the OTA circuit appears to be different from the plot in Figure 5. The former one has distortion in R segment because of saturation compared with the standard signal. This is because that the expected gain is more than what the amplifier can provide. However, this kind of distortion has no effect on the observation of the ECG signal, every segment of the ECG can still be distinguished very well.

4. Conclusion

This paper has researched the circuit that is suitable to amplify the ECG signal and to reduce the noise resulted from electromagnetic interference. Because ECG signal has low amplitude and low frequency, it is easy to be interference by the background noise and it is hard to be observed. To solve those problems, this paper delivers a kind of differential amplifier which can reduce the electromagnetic interference. The main content is shown below:

Through analyzing the characteristics of the original signals produced by human body, this paper has raised the method to reduce the common-mode signal, which is applying subtraction to the two inputs. To get a well amplified ECG signal and to reduce the noise as totally as possible, this paper has proposed several requirements such as the differential gain should be more than 40 dB up to 5 kHz, the common mode gain should be smaller than -30 dB up to 5 kHz and the current consumption should be lower than 20μA. Then after considering the features of differential amplifier that this kind of amplifier can apply subtraction to two input signals, this paper has designed a differential amplifier with an NMOS as the current source to process the original input signals. However, considering that the oscillating signals may cause oscillation in current and may then result in distortion of the ECG signal, a current mirror which can provide stable current has been selected to replace the NMOS.

A clear, efficient and accurate ECG signal is rather essential for both medical workers and the patients to monitor the state of the illness. So, an efficient way to measure ECG and to reduce the noise is very important. Limited by time and knowledge, the amplifier proposed in this paper still need to take many other conditions into consideration. To protect human health, lots of researchers have already been devoted to this field.

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