A design and optimization of CMOS ECG amplifier applied to medical monitoring system

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Abstract. ECG amplifier is widely used in medical monitoring system as a part of the transceiver circuit and sensors. For those who suffer from cardiovascular diseases, an ECG signal can reflect their heart conditions. This paper makes a research mainly on the design purpose of the ECG amplifier which includes low power consumption and high CMRR, and then presents the active load differential amplifier design to restrain the noise and to implement the function of amplify. The design also displays how to maintain a balance between high DC gain and less distortion by setting the parameters. As is displayed in the figures, the ECG amplifier successfully removes the common-mode noise and achieves the ideal wave shape with the use of a software built-in calculator. The DC gain is about 60.55dB. When increases the DC gain with a fixed power consumption to 40dB, the wave shape will be a bit distorted. The design explains the application of the ECG amplifier into medical monitoring system in section 2 and proposes an example of ECG amplifier which can amplify and filter the original signal in section 3. Background knowledge, working process and measured results are given in this paper.

Keywords: Medical Monitors, ECG amplifier, noise reduction

1. Introduction

Cardiovascular disease is one of the leading causes of death in China [1]. From early 2020, people with cardiovasuclar disease are especially at great risk of mortality owing to COVID-19 [2]. Under these circumstances, medical monitoring systems, which can examine the patients' conditions in real time, are becoming more and more important in medical industry. As for cardiovascular diseases, ECG amplifier is a crucial component in the system since it can capture the ECG signals and therefore reflect whether patients need further operation for cardiovasular diseases.

In this paper, a design of CMOS ECG amplifier based on differential circuit which can be used in medical monitoring system are proposed. The circuits consists of a differential amplifier, an active load and a bias current mirror. The paper also indicates how to adjust the design in order to satisfy different requirements of the system. Width and length of all the transistors should be modulated according to the equations to achieve ideal results. In section 2, the paper introduces constitution of the whole medical monitoring system, analyzes the application of ECG amplifier in the system and illustrates the related research in this field so that the design purpose of ECG amplifier in section 3 can be clarified.

This paper also gets some results. It displays the constitution of medical monitoring systems in section 2, so that readers can understand the working process of the system better. Based on section 2, an ECG amplifier with low power consumption and high CMRR is proposed in section 3, which can improve the efficiency of the medical monitoring system. And the design method can be referred to when designing differential amplifiers of various uses as well.

2. Mechanism of medical monitoring system

2.1. The practical use of medical monitoring system

A medical monitoring system is employed when doctors need to make a diagnosis and give treatment to the patient. A large number of physiological data are monitored in real time through the system. It can also analyse and transmit data automatically to help doctors know the physical conditions of their patients at all times. With the use of a medical monitoring system, working efficiency of the whole medical industry has been improved since medical staff can set the parameters in care provision. Consequently, the medical monitoring system is widely used in hospitals where exists a large number of patients. When the physical condition of a patient worsens, the system will produces an alert so that the medical staff can cope with the situation in time.

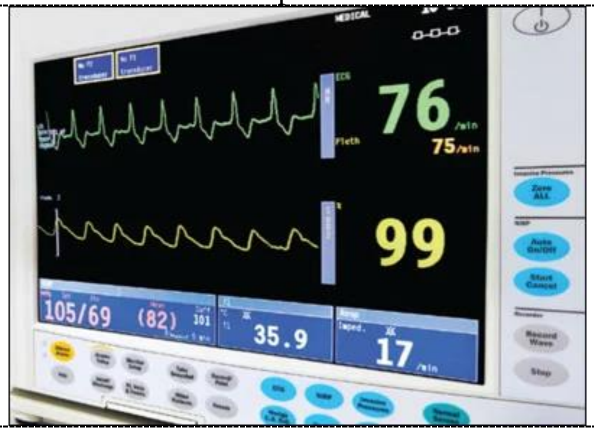

Figure 1. An example of medical monitoring system.

2.2. The working process of the medical monitoring system

One of the most important part of a medical monitoring system is the sensors [3]. There are many kinds of sensors such as ECG, temperature and blood pressure ones in the system to evaluate the patients' conditons completely. Micro-controllers with memory buffers can compute and analyse the signals. The data then transmitted by transceivers which are always with the patients. PCs in the hospital will receive these information through a receiver. Finally, the medical staff can make a diagnosis through these data analysed by the micro-processors in PCs.

The transceiver circuit, which conveys the data and receives it, is comsposed of several blocks as well. There are amplifiers and filters in the front-end of the transmitter transceiver circuit. After that, the signals will get through a micro-controller with ADC in it. The analog signals are converted into electrical signals, and then transmission frames are constructed. Then the signal transmits in the form of frequency modulation. The receiver, on the other hand, goes through an frequency modulation receiver first. After decoding it in the micro-processor, it will be placed somewhere in the PCs. The integrated data are transmitted by means of the transceiver to the computers in hospitals so that doctors can evaluate and adjust the treatment perscriptions instantly.

2.3. The design purpose and available technology of the medical monitoring system

ECG signals are able to reflect an important indicator of the patients' physical conditions in a medical monitoring system. There are several kinds of amplifiers using in different blocks of the circuit, especially in the transceiver circuit. Some amplifiers are used to process particular signals captured such as ECG signals. They can filter and amplify the original ECG signals.

As for ECG amplifier, the design purpose is that the accuracy and distortionless of the signals should be taken into consideration. When one is designing the signal processing modules, the DC gain should be high as well to make the signal easy to capture in the system. And considering the efficiency of the whole system, the power consumption of the amplifiers should be as low as possible.

As for the whole system, the keypoint of the design concentrates on how to make the system robust and reliable due to the security and confidentiality of patients' data. There are some methods to implement it as is proposed in related essays. Some security software systems are exploited to restrict malicious accesses to the data base [4]. To achieve it, only authorised users have access to the data, and different kinds of data are exposed to different kind of users with the permission of the patient himself. And as for the real-time monitoring, authorised users like the medical staff can view the monitoring graph with the patients' data on the software. In conclusion, to achieve the design purpose of a medical monitoring system, hardware as well as software system is needed to make the data and signal accurate, reliable and secure.

3. Design and implementation of an ECG amplifier

3.1. Introduction of an ECG amplifier

The ECG amplifier is used to amplify and filter original analog signals [5]. In this essay, a software called CoolSpice is employed to design the CMOS circuit. When we put electrodes on the patients' skin, we will find signals hard to analyse because of the 50Hz noise. The natural noise is common-mode noise. As a result, the noise captured by both electrodes should be approximately the same. In Fig 2, we use a calculator to eliminate the noise. After substracting the two voltage signals, we can observe the ECG signal clearly.

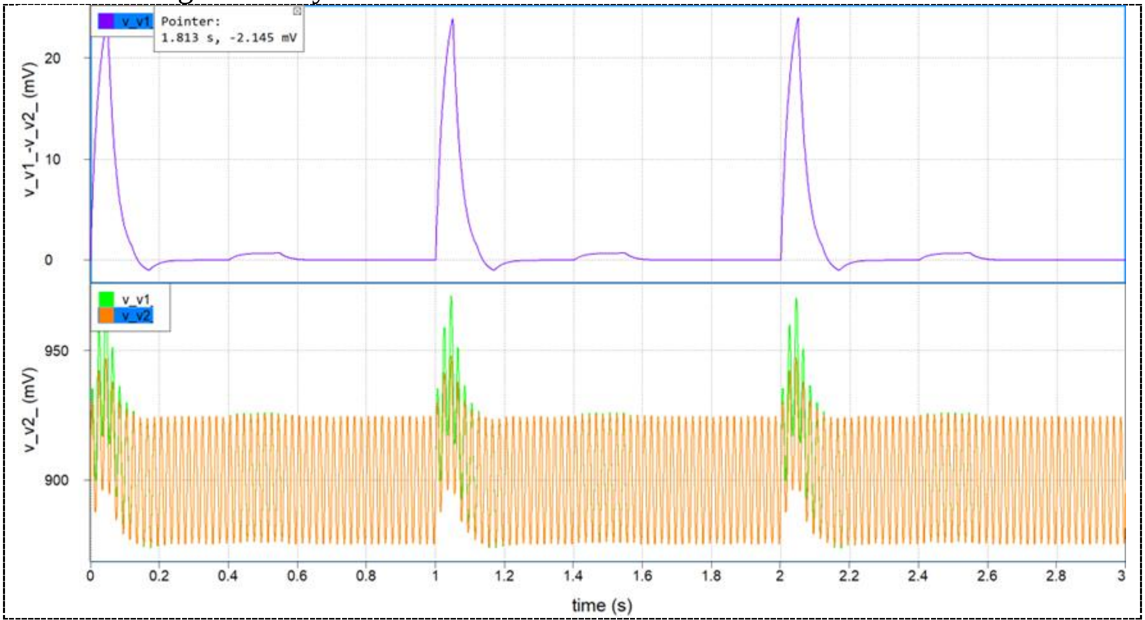

Figure 2. Use of the calculator to eliminate noise.

To realize the function of a calculator, the CMOS differential amplifier is a good choice [6]. A differential amplifier can restrain the common-mode noise and amplify the differential-mode signals. The fundermental differential circuit is an active load differential amplifier using five transisters. In this essay, we replace the transistor N3 with a current mirror to provide stable current as shown in Fig 4. There are some other researches about the ECG amplifier. A fully differential differential-difference amplifier (DDA) based ECG instrumentation amplifier is proposed in [7]. It can satisfies CMRR and Zin with low power consumption [8]. The circuit is composed of two single-stage operational transconductance amplifier (OTA), and the bias current of the OTAs can be shared. Finally it can achieve high CMRR and better linearity.

The advantage of the operational transconductance amplifier with five transistors, however, is that it's a single-stage amplifier, so the design is stable. And it has small power consumption, which suffices the need of the medical monitoring system. The area it takes up is also smaller than other complex design, which means it has a merit of low cost. To make the design, we should overcome the problem of distortion in order to make the analysis of the signals accurate enough to use in real-time monitoring system. But the 5T-OTA design still has some disadvantages. It has shown limited CMRR compared to a full-differential circuit, so the change in common-mode noise may have some impacts on the output voltage signal since the ECG signal is small and hard to capture. To optimize the circuit, we should pursue lower common-mode gain when adjusting the parameters.

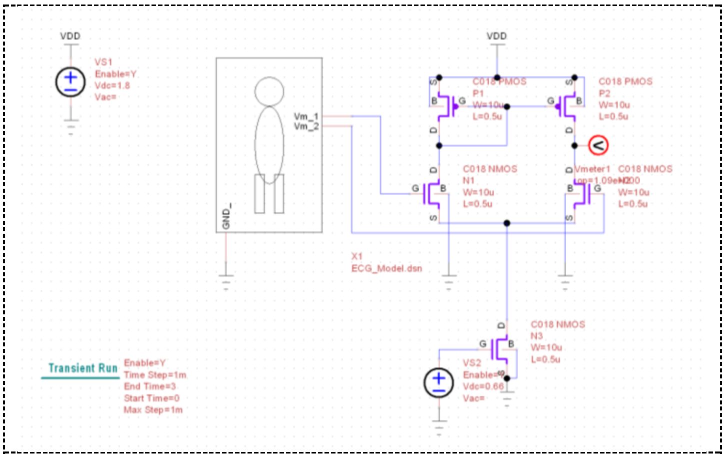

Figure 3. Fundermental 5T-OTA circuit design.

3.2. Proposed ECG amplifier circuit

To suffices the need of low power consumption, high common-mode rejection ratio (CMRR) and high differential-mode gain, we now proposed the design of the circuit in Fig 4 [9] .

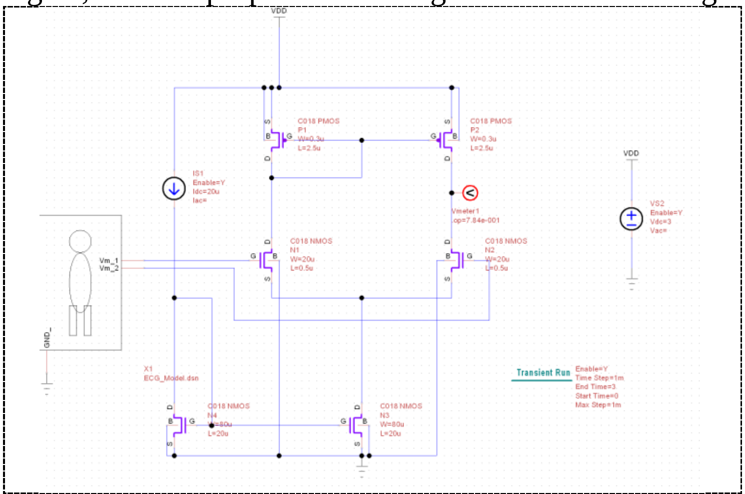

Figure 4. Use of current mirror to provide bias current.

The circuit is composed of six transistors, one current source and a V_{DD} which is 3V. The front end is the body. Two electrodes are placed on different part of it, while the body connects to the ground itself. The signal from electrodes is delivered into the gates of transistors N1 and N2, and the PMOS current mirror composed of P1 and P2 acts as an active load. Current mirror composed of N3 and N4 provides bias current for the differential amplifier.
DC gain of the OTA circuit should be:

$$A_{DC} = \frac{g_{mN1,2}}{g_{dsN1,2}+g_{dsP1,2}} \tag{1}$$

In equation 1, A_{DC} is the DC gain of the proposed circuit, $g_{mN1,2}$ is the transconductance of N1 and N2, $g_{dsN1,2}$ is the electric conductance of N1 and N2, $g_{dsP1,2}$ is the electric conductance of P1 and P2. From the equation, we can conclude that the parameters of N1 and N2 greatly affects the DC gain. After experiments, it can be concluded from the results that the length of N1 and N2 affects the gain more greatly than the width-length ratio. When we increase the length, the channel width modulation effect will be reduced, leading to higher V_A. Higher V_A means lower $g_{ds1,2}$, and therefore the DC gain will be increased. Finally the requirement of amplifying will be achieved. And we can also conclude the expression of common-mode gain to be:

$$A_{CM} = \frac{2g_{mN1,2}}{1+\frac{2g_{mN1,2}}{g_{dsN3,4}}}\frac{1}{2g_{mP1,2}} \tag{2}$$

In equation 2, A_{CM} is the common-mode gain of the proposed circuit, $g_{mN1,2}$ is the transconductance of N1 and N2, $g_{mP1,2}$ is the transconductance of N1 and N2, $g_{dsN3,4}$ is the electric conductance of N3 and N4.

If the width-length ratio of P1 and P2 increase, we will get higher $g_{mP1,2}$. Through adjusting the parameters, the A_{CM} will finally satisfy the requirement of filtering noise.

Based on the expressions, the designs of the parameters are as follows. First, ensuring the transisters to work in saturation areas. Volmeters can be employed to perform some mesaurements. Secondly, adjusting N3 and N4 to produce low bias current so that the power consumption goes down as well. The current source provides 20uA current. Thirdly, adjusting P1 and P2 to set the operation point and create lower A_{CM}. The operation point at about zero point eight voltage is suitable. Lastly, adjusting N1 and N2 to satisfy the differential-mode gain. The essay examines the result of two sets of parameters. The parameters are shown in Table 1 and Table 2. The difference lies in the value of $L_{P1,2}$ and $L_{N1,2}$.

Table 1. The first set of parameters in the ECG design

Parameter	Value	Unit
V_{DD}	3	V
$W_{P1,2}$	0.3	μm
$L_{P1,2}$	2.5	μm
$W_{N1,2}$	20	μm
$L_{N1,2}$	0.5	μm
$W_{N3,4}$	80	μm
$L_{N3,4}$	20	μm
I_{bias}	20	μA

Table 2. The second set of parameters in the ECG design

Parameter	Value	Unit
V_{DD}	3	V
$W_{P1,2}$	0.3	μm
$L_{P1,2}$	3	μm
$W_{N1,2}$	20	μm
$L_{N1,2}$	0.2	μm
$W_{N3,4}$	80	μm
$L_{N3,4}$	20	μm
I_{bias}	20	μA

3.3. Measured results

The first graph is the result of the first set of parameters and the second one is the result of the second set of parameters in Fig 5, 6, 7.

As the first graphs show, the DC gain of the ECG amplifier is 40dB, while the bandwidth is approximately 14.83MHz. And the common-mode gain of the ECG amplifier is -31.09dB as shown in Fig 6. As a result, the CMRR is about 71.09dB. When we connect the amplifier to the human body, the signals will be transmitted to the input end of N1 and N2. After amplifying and filtering, we can get the signal in Fig 7, which is much like the signal in Fig 2 using calculator provided by the software itself. However, the peak of the signal becomes a bit distorted, and that will be a big defect in practical use.

Then we slightly adjust the parameters. From the second set of parameters, the DC gain is much lower than that of the first set at about 28.62dB, which is approximately 26.98 V/V. And the common-mode gain is -31.93dB. So the CMRR changes to 60.55dB. However, the bandwidth expands to 43.91 MHz. And the distortion is less obvious as seen in the right graphs in Fig 7.

To understand the principle, we should analyse the signal using calculator first. The measured peak of the graph is about 23.62mV. When the gain is 40 dB, which is equal to 100 V/V, the peak should be at about 2.362V. However, to maintain a low power consumption, V_{DD} is only 3V, and the operational point is about 0.783V to ensure that all transistors working in saturation area. So there always exists distortion if we maintain the gain. However, when we reduce the differential-mode gain, the V_{DD} needed is much lower, which means that the second graphs will have less obvious distortion.

Section 2 has listed some uses of the ECG amplifier. Different devices have different requirments of the design. For instance, the medical monitoring system should be accurate, which means the results should be distortionless. Automated External Defibrillator, however, requires low power consumption in order to be portable and easy to use according to some papers [10]. Other uses of the ECG amplifier may have other demands. So when setting the parameters, we should also take the need of devices into consideration.

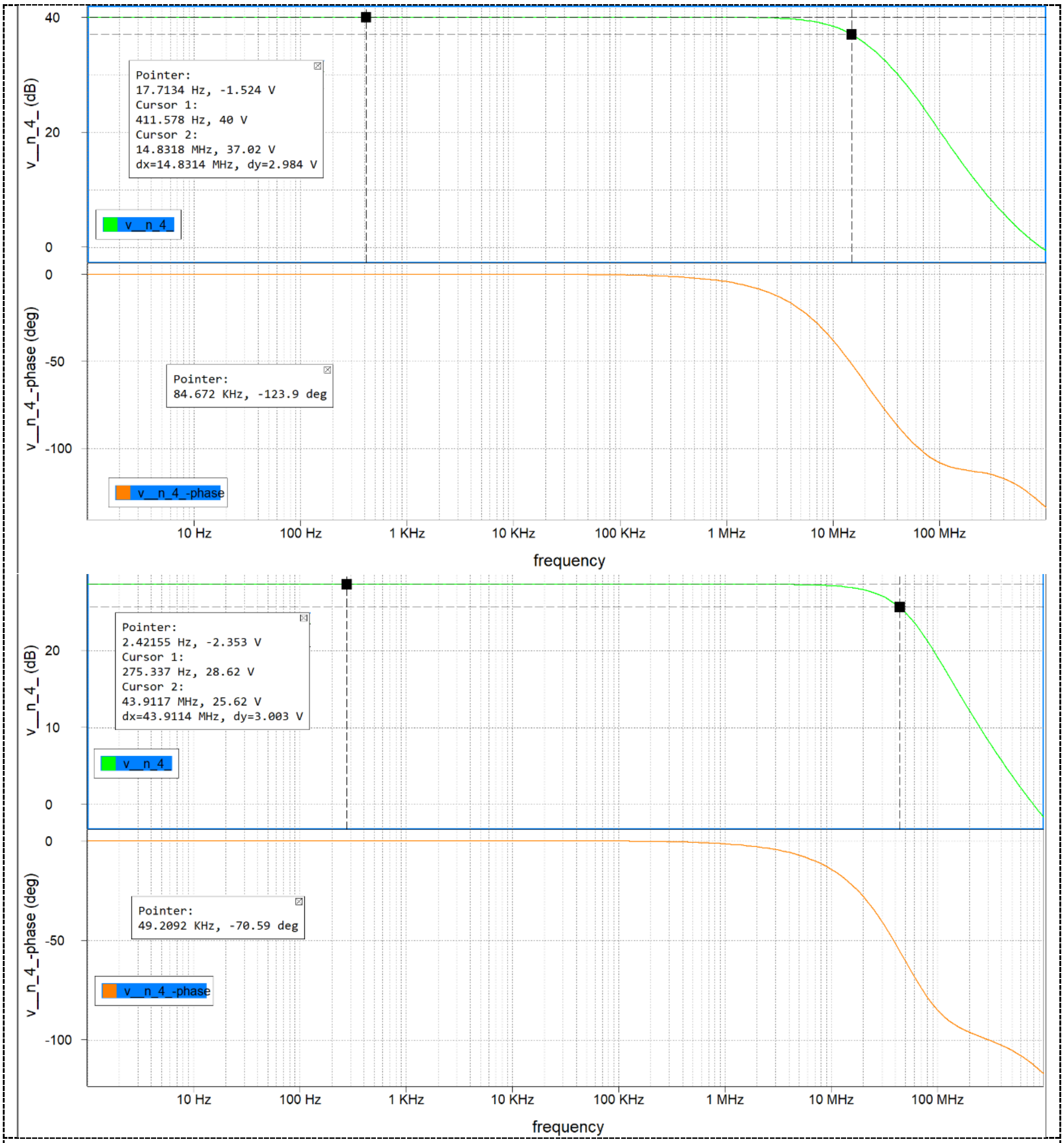

Figure 5. Differential-mode gain of the ECG amplifier.

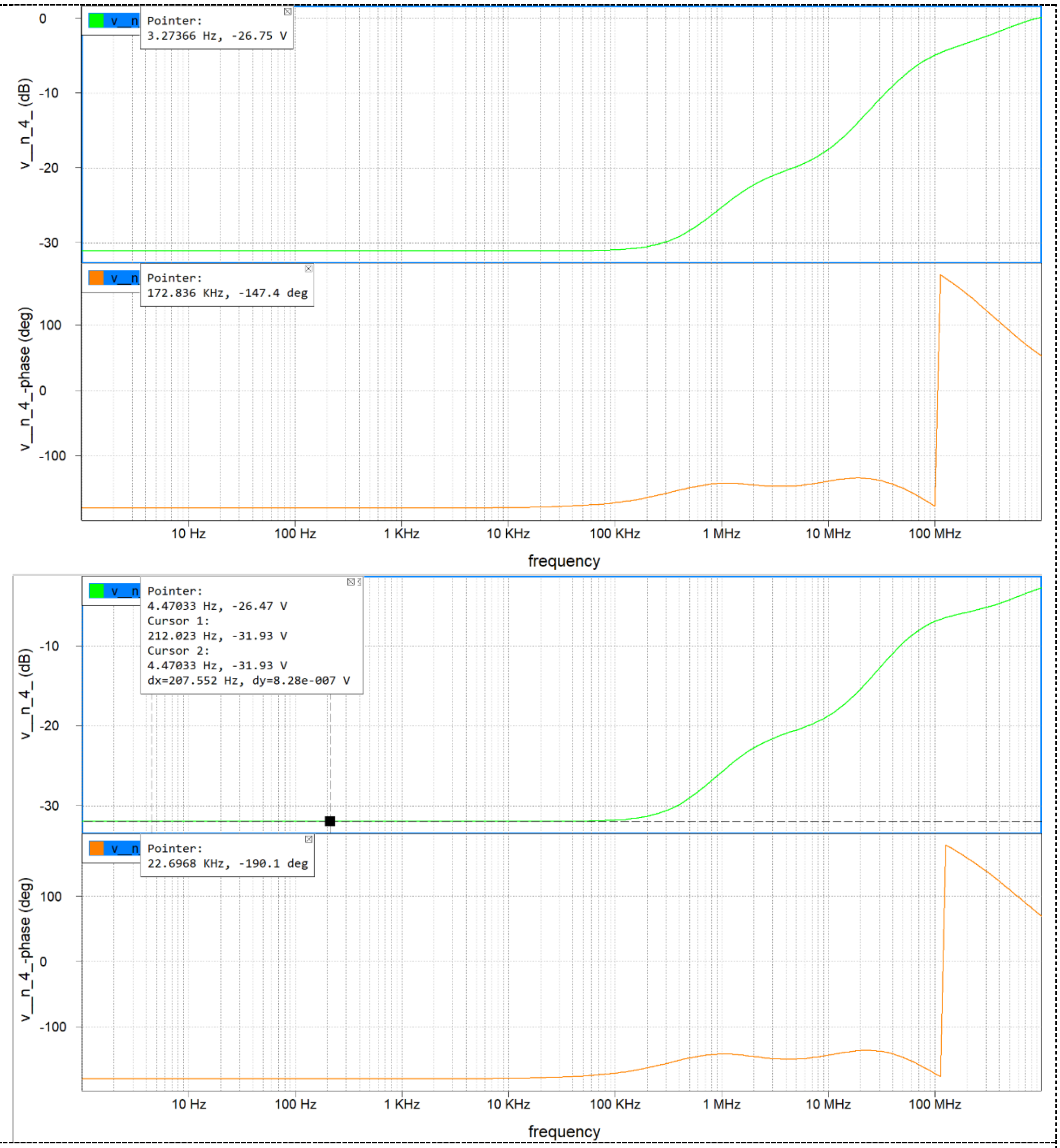

Figure 6. Common-mode gain of the ECG amplifier.

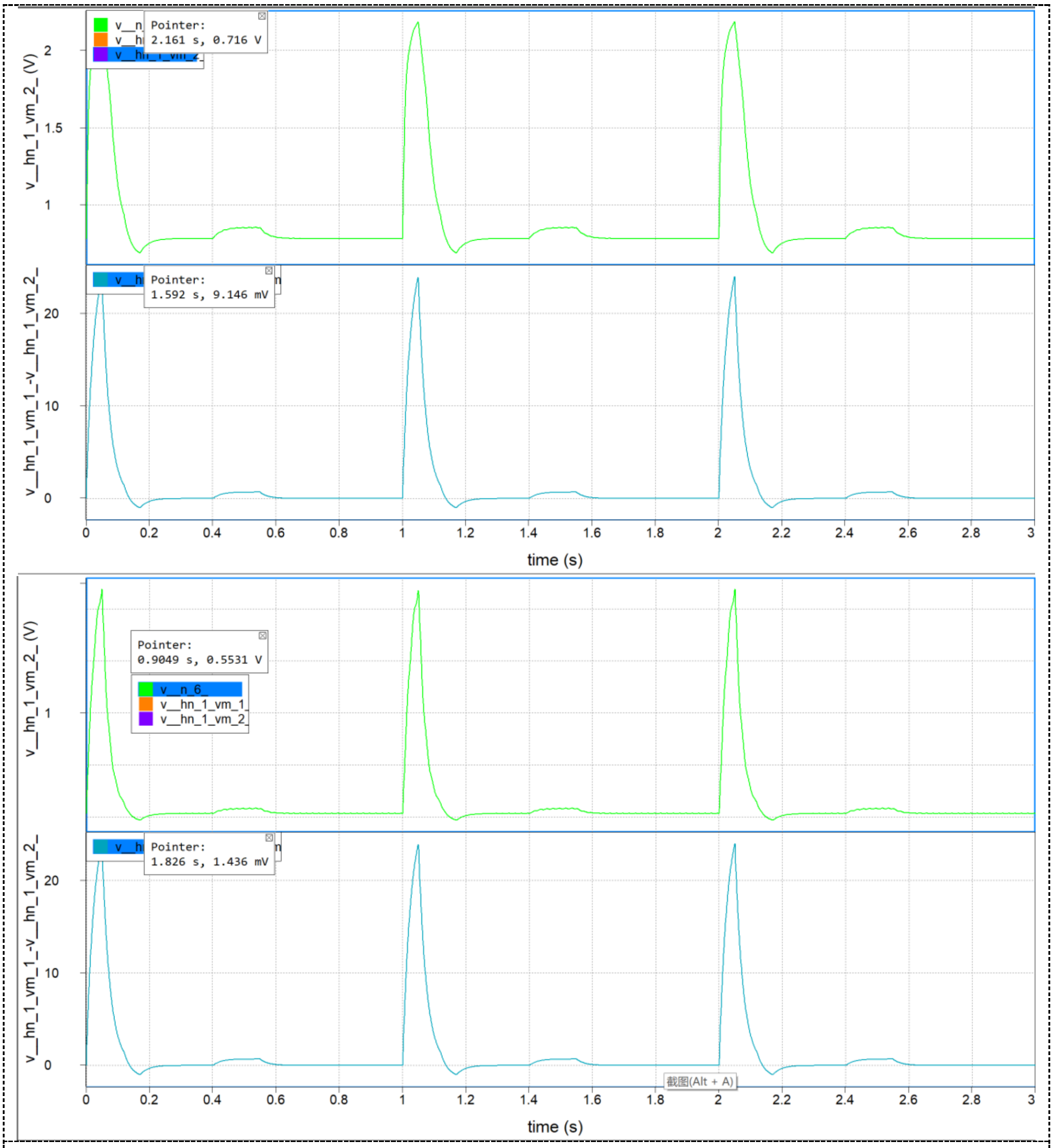

Figure 7. The ECG signal captured.

4. Conclusion

This paper discusses the practical application of ECG amplifier to medical monitoring system. In section 3, design of an ECG amplifier are proposed. The design uses a single-stage differential amplifier with active load and bias current mirror which can not only restrain the common-mode noise, but also amplify the signals. The CMRR of the amplifier is about 71.09dB and the differential mode gain is 100V/V, which is enough for the design. To maintain a low power consumption, the current source provides a fixed $20\mu A$ current and V_{DD} is only 3V. However, there exists distortion compared with graphs done by the calculator. Using the steps in section 3.2, the paper successfully reduces the distortion by changing $L_{P1,2}$ from 2.5 to $3\mu m$ and $L_{N1,2}$ from 0.5 to $0.2\mu m$. However, it is achieved at the cost of differential-mode gain, which reduces from 40dB to 28.62dB. So with a fixed power consumption, the design should balance the differential-mode gain and accuracy of the signal due to different design purposes.

The paper expounds the composition of the medical monitoring system and analyses the importance and design purpose of ECG amplifier in the system. To satisfy these purposes, in section

3, ECG amplifiers with low power consumption and high CMRR are designed. And through the parameter adjustment, the distortion can be eliminated to a large extent. This design method proposed in section 3.2 has some reference value for designs of differential amplifier of various uses as well.

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