Low Cost ECG Amplifier

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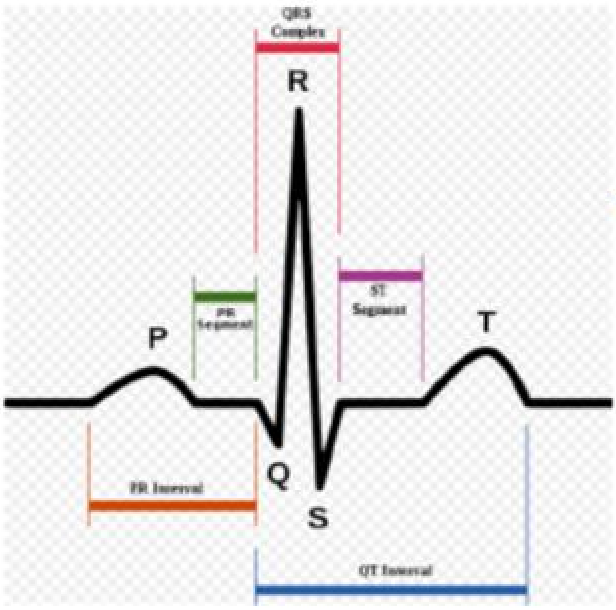
Introduction

The electrocardiogram (ECG) refers to the changes in bioelectricity that are accompanied by the excitement of the pacemaker, atria, and ventricles in each cardiac cycle. The electrical energy of the heart reflects the rhythm of the entire heart beating, as well as the weak part of the heart muscle. Therefore, it is possible to distinguish the health of the heart by measuring the ECG.
The following figure shows a typical ECG waveform in a normal cycle, which is composed of a P wave, a QRS complex and a T wave. The baseline of the ECG is called the equipotential line, which generally refers to a section of the waveform after the T wave and before the P wave.



Circuit Design

Notable Characteristics

The ECG signal has several notable characteristics.
① It is very weak. Its amplitude is 10 μV-4mV.
② Its frequency is very low. About 0.05Hz-75Hz.
③ It has strong randomness and is not stable.

④ As the signal source, the human body has a large internal resistance.
Therefore, there is a lot of interference. Human body noises such as myoelectricity, and equipment noises such as power frequency that are inevitable in ECG amplifiers.

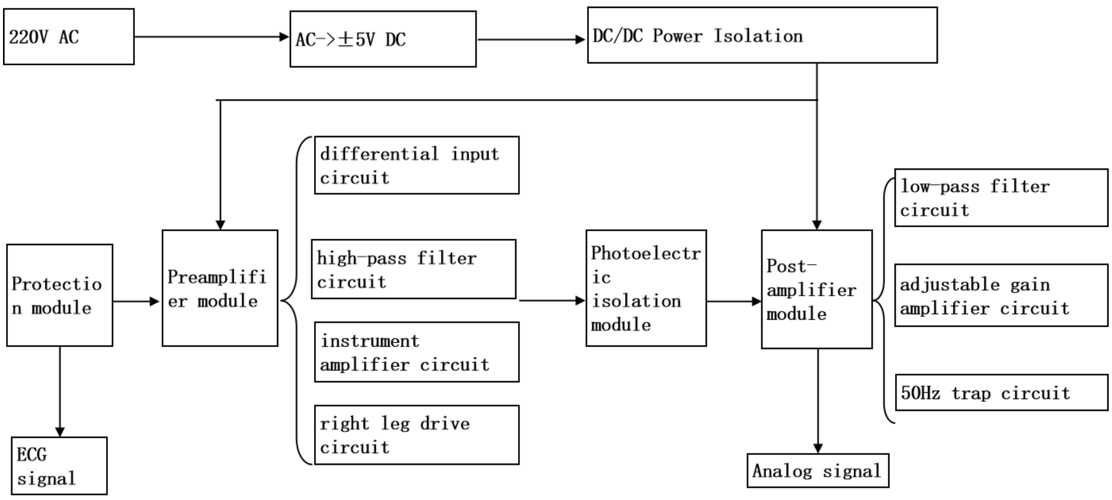
Design Requirements

Because of characteristics of these ECG signals, circuit design of amplifier ought to reach some requirements:

1) Input resistance>5M.
2) Common mode rejection ratio>80dB.
3) Output swing>2.5V. (Dynamic range≧28 when using single-chip microcomputer).
It is required that the ECG signal can finally be amplified to about 1000 times.
4) Frequency band: 0.05 to 100 Hz.
5) With photoelectric isolation.
6) AC power supply, make the corresponding stabilized power supply.

Flow Chart

This project directly outputs the analog signal through the circuit and displayed it on the oscilloscope.
After analyzing the design requirements and designing the circuit, the circuit was roughly divided into a power supply module, a protection module, a pre-amplification module and a post-amplification module, and finally an analog signal was output. The flow chart is as follows:



Power supply module: 220V AC, converted to ±5V DC, power isolation
Protection module: circuit protection; tester protection
Preamplifier module: differential input circuit, passive high-pass filter circuit, instrument amplifier circuit and right leg drive circuit.
Post-amplification module: active third-order low-pass filter circuit, 50Hz trap circuit, adjustable gain amplifier circuit.

Circuit Simulation

Pre-amplification module

①Pre-amplifier Circuit

The pre-amplifier circuit directly amplifies the collected ECG signal, which contains a lot of background noise and high common-mode signal. If these interference signals are also amplified along with the ECG signal, the signal will be completely amplified. Annihilated in the noise signal, the instrument amplifier AD620 was selected, which adopted the improved design of the classic three-op amplifier, and only needed a resistor to adjust the gain. It had high input impedance and common mode rejection ratio, which can meet the requirements well.

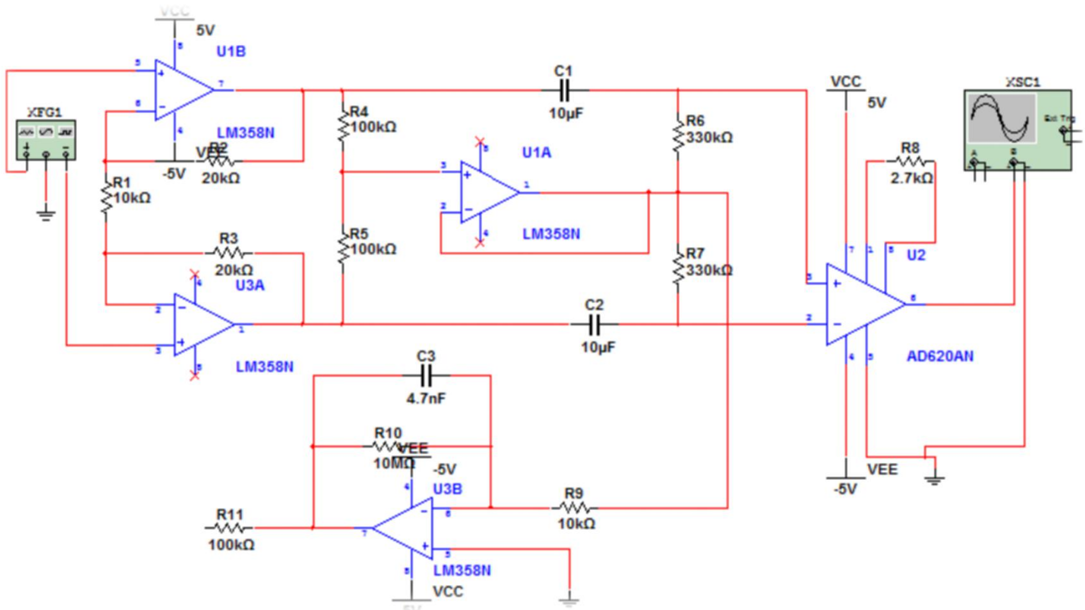


Figure 1.Pre-amplifier Circuit

The circuit diagram showed the equivalent resistance $R_G = xx\text{k}\,\Omega \approx xx\text{k}\,\Omega$ between pin 1 and pin 8. According to the equation $G = \frac{49.4\text{k}\Omega}{R_G} + 1$, the gain of the circuit is G=8.41. The matching of resistors R1 and R2 will directly affect the common-mode rejection ratio of the amplifying circuit, so one should tend to keep the resistance values equal.

②Pre-filter Circuit

The frequency band required by the circuit ranges from 0.5 to 100 Hz. The amplitude-frequency characteristics of a pure band-pass filter were not easy to control, two filters of low-pass and high-pass were selected in series to form a band-pass filter. The cut-off frequency of the low-pass filter was 100 Hz, and the cut-off frequency of the high-pass filter was 0.5 Hz.

In terms of chip selection, LM324N was chosen as the operational amplifier of the filter. We used a second-order voltage-controlled voltage source filter. Although the higher the filter order, the better the filtering effect. However, if the filter order was too high,considering the cost, the higher the order, the more complex the filter circuit structure will be. Compared with the first-order, the second-order low-pass filter has more stable filtering performance and better effect. The following figure shows the low-pass filter and the high-pass filter.

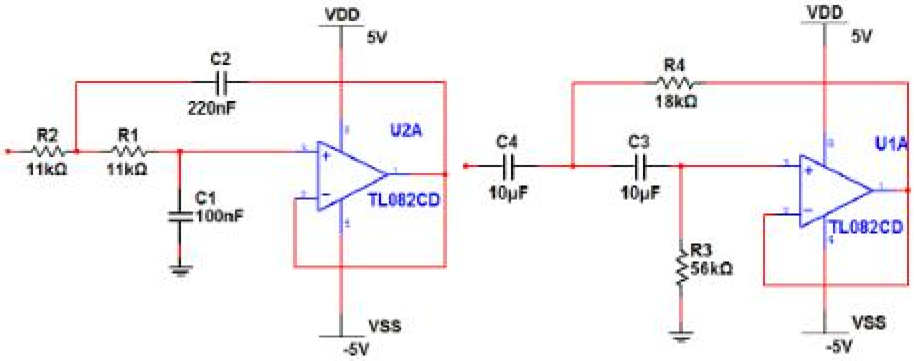


Figure 2,3.Low-pass filter and High-pass filter Circuit

According to the equation $f = \dfrac{1}{\sqrt{2\pi R_1 R_2 C_1 C_2}}$,the cut-off frequencies were 97.6 Hz and 0.5 Hz, and their gains were both 1.The following figure shows the simulation result of the circuit operation, and the result of the filter circuit can be observed.

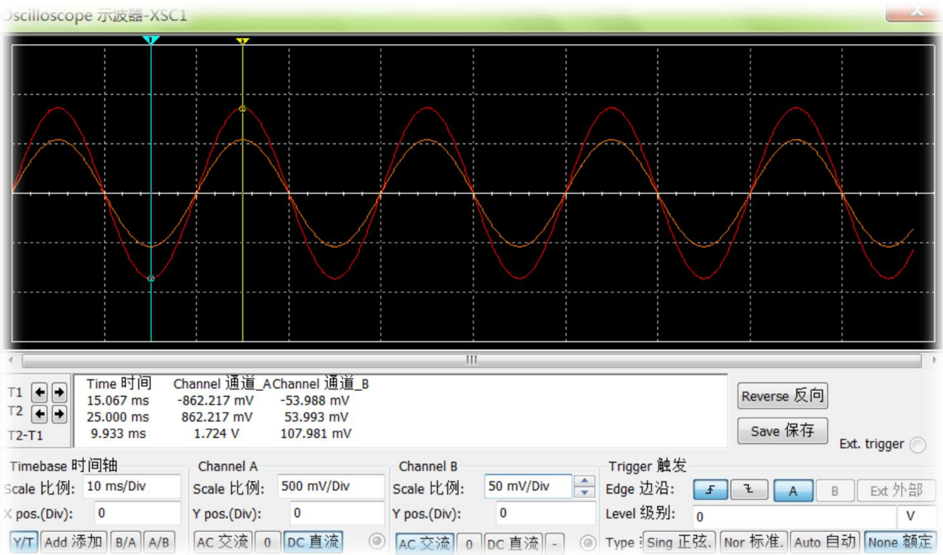


Figure 4.Simulation result

③Right leg drive Circuit

In this project, the ECG click was used to collect the ECG signal, and the standard lead was used to reflect the potential difference between the limbs to generate the ECG signal. Therefore, the right leg was required to drive the circuit. The circuit diagram is as follows:

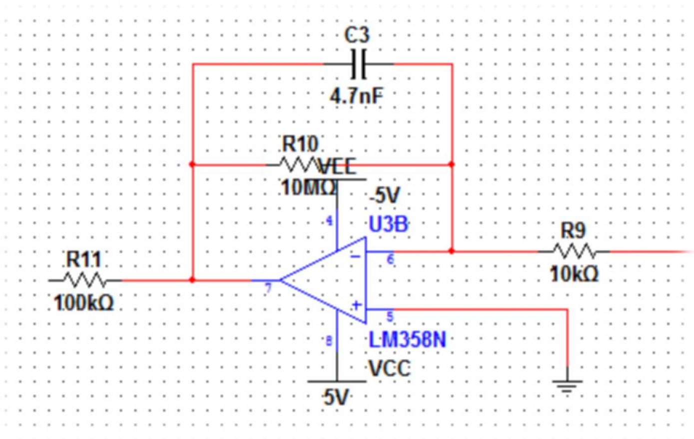


Figure 5.Right leg drive Circuit

Post-amplification module

①Post-amplifier Circuit

The amplifying part of the entire circuit was mainly undertaken by the post-amplification. Since the pre-amplification was 8.6 times, the post-amplification was set at 100 times. The total gain of the entire circuit was 860 times (not including the gain of the trap).

This part used the low bias voltage and low drift OP07 to bear. The 1k and 100k resistors at the inverting input terminal determine the 100 times gain, and the non-inverting input terminal used 100k resistors to balance the voltage at both ends to increase the common-mode rejection ratio.

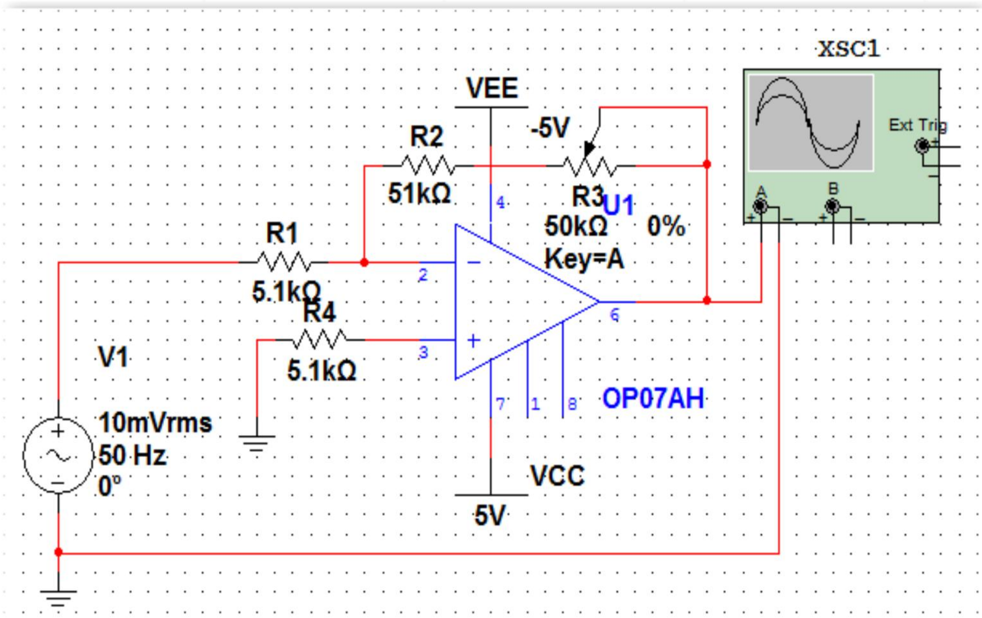


Figure 6. Post-amplifier Circuit

Input a 1Hz, 1V sine signal at the non-inverting input terminal. After being amplified by the operational amplifier, the signal measured at pin 6 was about 10.3V. The actual amplification of the post-amplification circuit was about 103 times. The error from

the theoretical value is determined by the chip which was caused by its own characteristics and the mismatch of resistors R4 and R5.
The input is a sine wave of 10Hz, 10mV, when the differential mode input was used, the output was 10.9V, and the differential mode amplification factor was 1090 times. When using common mode input, the output was 2.8V, so the common mode magnification was 0.28 times.According to the equation $CMRR = 10 \times \log(\frac{A_d}{A_c})^2$,The common mode gain of the whole circuit was 71.8dB

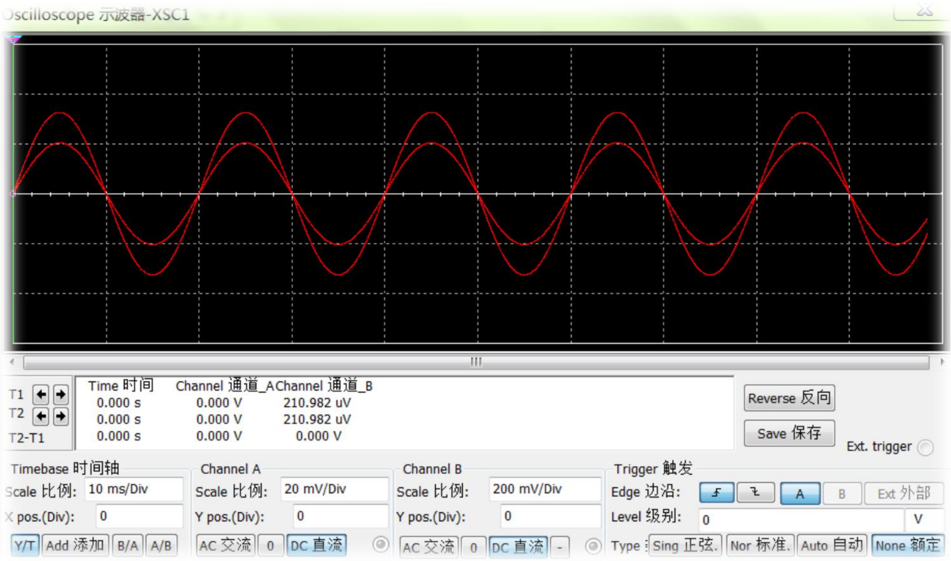


Figure 7. Simulation result

②Trap Circuit

Due to the use of AC mains, 50Hz power frequency noise will be generated in the circuit. The double T circuit is used in the project to eliminate the 50Hz power frequency signal.

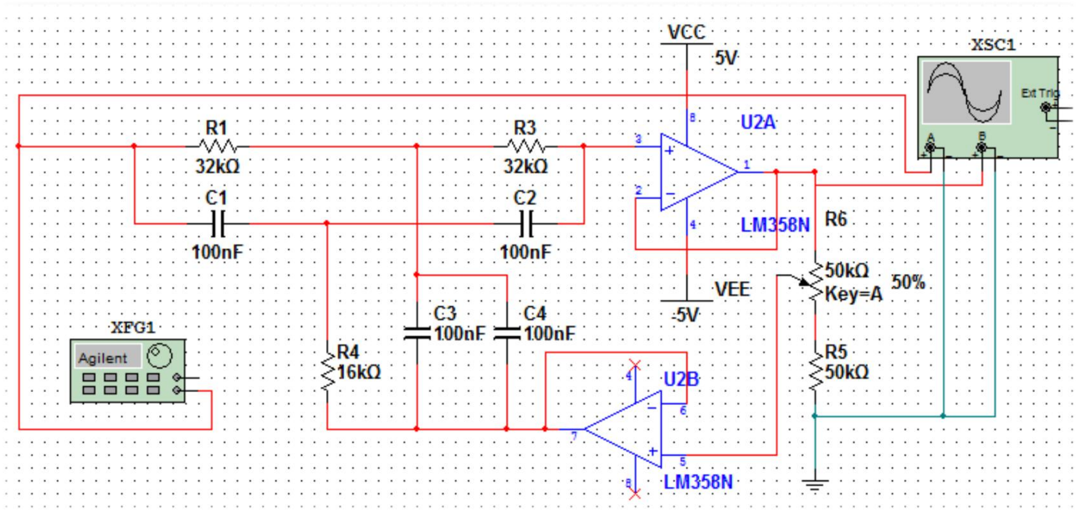


Figure 8. Trap Circuit

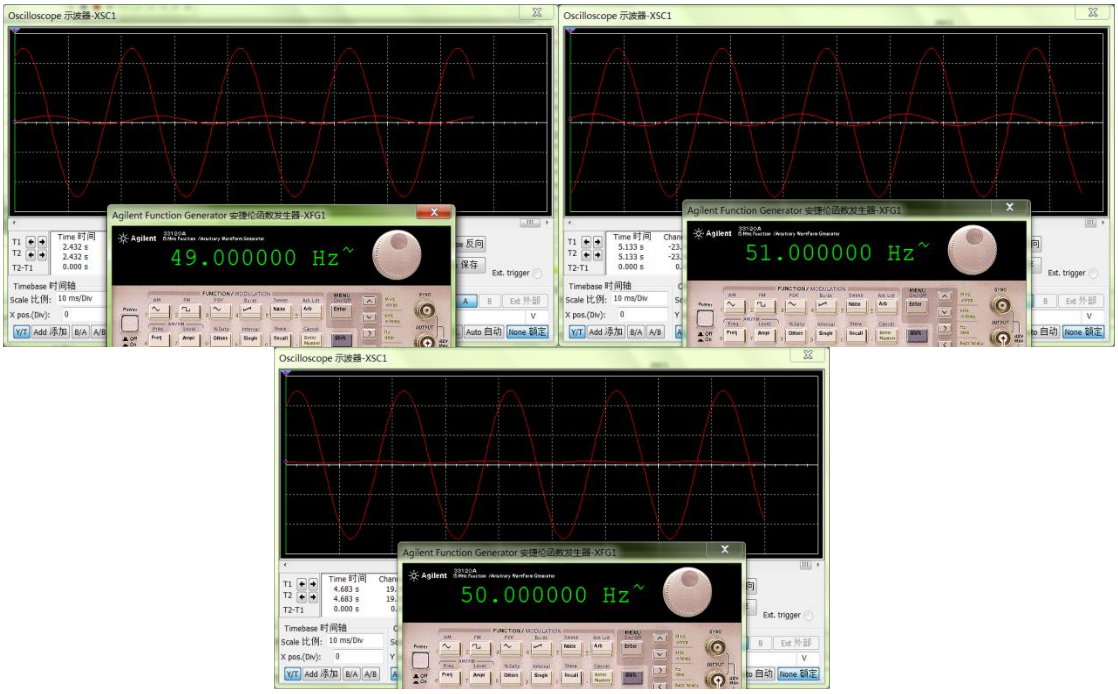
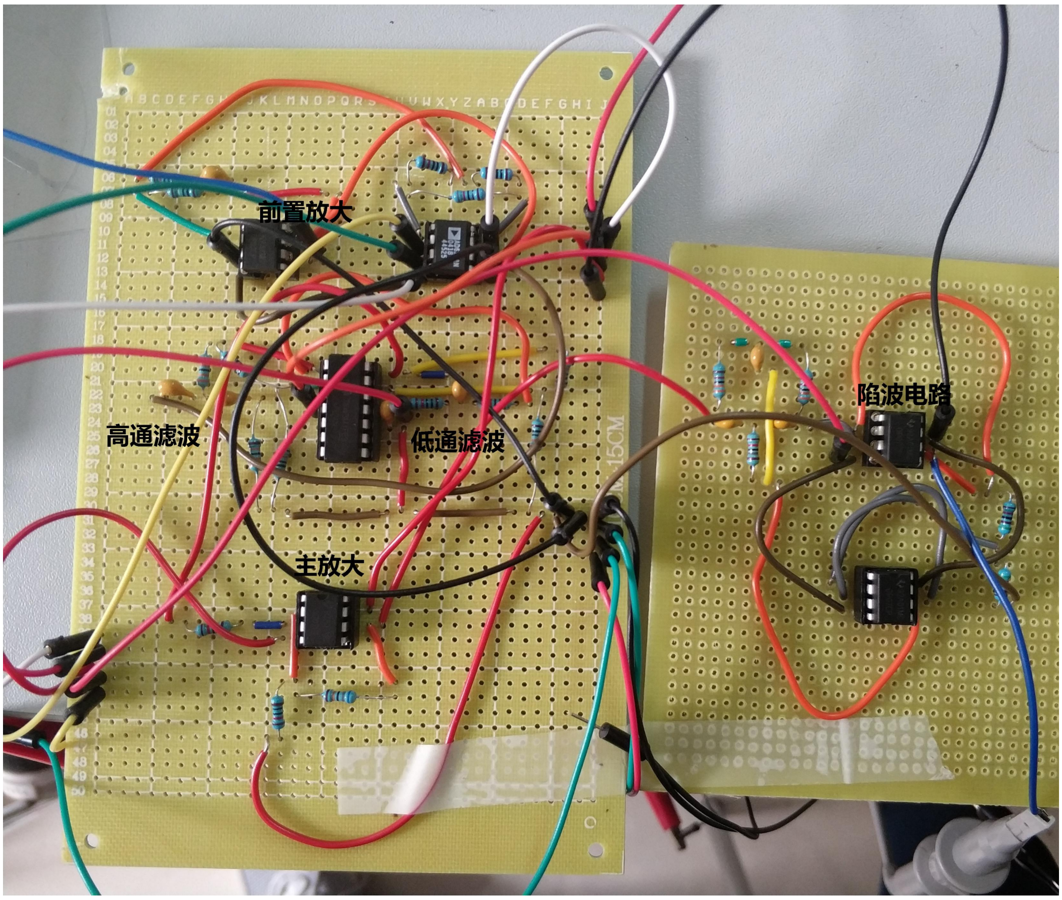


Figure 9. Simulation result

This circuit needs careful debugging in actual application.

Circuit Soldering



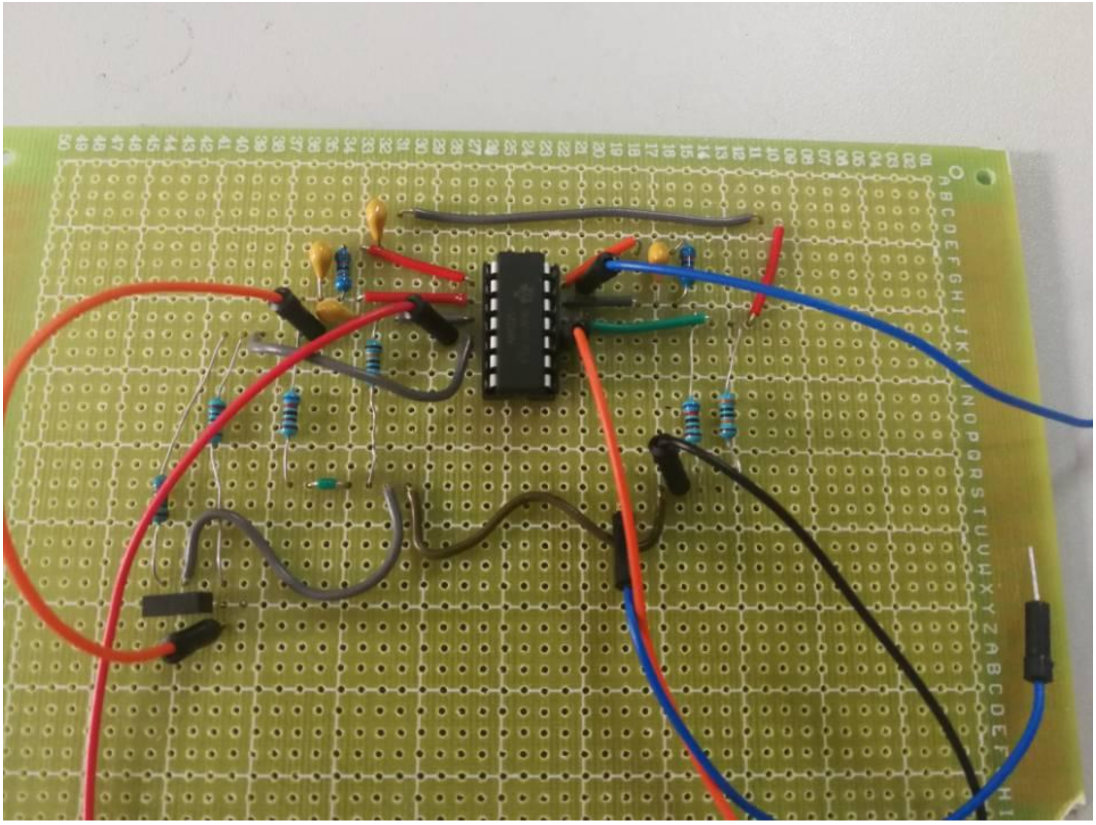


Figure 10. Physical Circuit

Circuit Testing

ECG

①Static operating point

Short-circuit the two input terminals of the amplifier to ground, observe the output waveform of each level and record the amplitude (the static noise of the amplifier). If the voltage amplitude of the output terminal of each stage is less than 0.5V, it is qualified.

The output static operating point of the pre-amplifier circuit: 0.35mV.
The output static operating point of the low-pass filter: 7.41mV.
The output static operating point of the high-pass filter: 12.45mV.
The output static operating point of 50Hz notch: 8.7mV.
The output static operating point of the main amplifier: 27mV.
Circuit testing qualified

②Circuit input noise

Short-circuit the two input terminals of the amplifier to ground, measure V_o, and calculate the input noise:

$$V_{in}=V_o/K$$

Actually measured V_o=27mV, that is, V_{in}=27μV, the electrocardiograph requires input noise to be <35μV, so the input noise of the circuit meets the requirements.

③Differential mode gain

A sine signal with a 30 Hz and amplitude of 10 mV is input to one input of the amplifier. Use an oscilloscope to observe the output waveform of the front stage and the amplitude of the output after the post-amplification circuit respectively. Use the oscilloscope to read the input and output voltage values to calculate the differential mode voltage gain of the pre-amplifier circuit:

$$A_d=V_{out}/V_{in};$$

The actual measurement is 125mV after preamplification, 33.4mV for band-pass amplification, and 120mV for post-amplification, and we get:

The differential mode gain of the preamplifier circuit

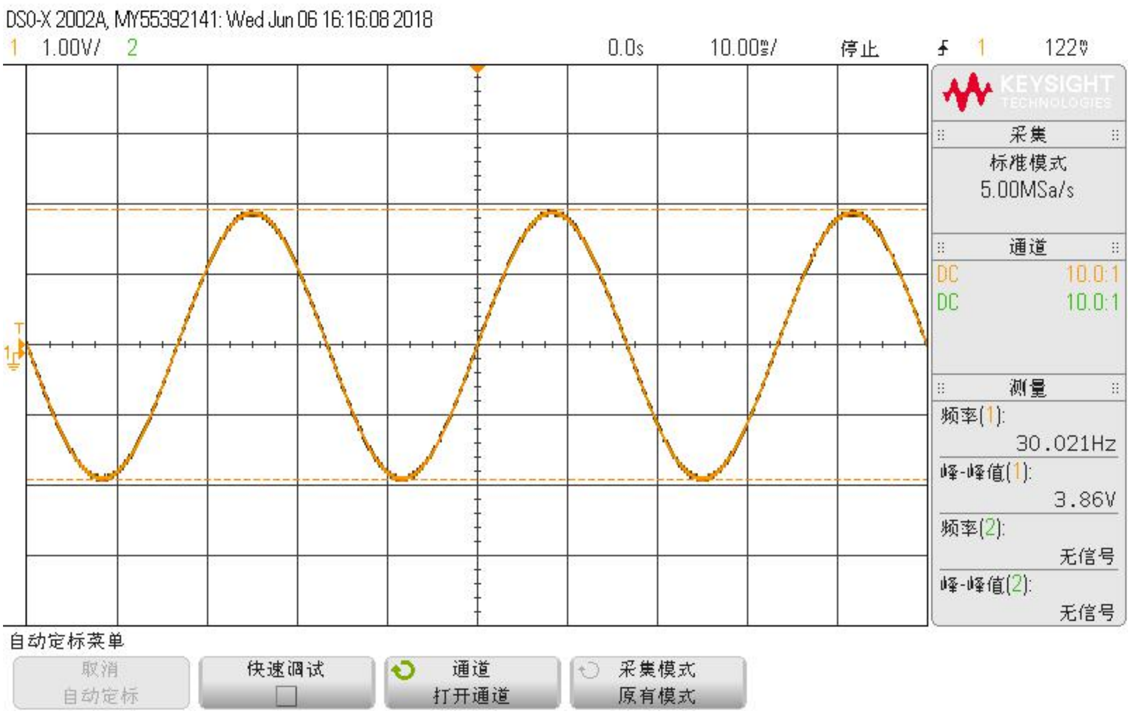
$$A_{d1}=125mV/10mV=12.5;$$

The differential mode gain of the post-amplification circuit

$$A_{d2}=120mV/10mV=12;$$

all meet the design requirements.

Input a 30Hz sine signal with an amplitude of 4mV (the minimum amplitude of the signal generated by the signal generator) into the input of the ECG amplifier. Use an oscilloscope to observe the output amplitude of the ECG amplifier and calculate the differential mode voltage gain of the ECG amplifier:



The actual measured output waveform amplitude is 1.125V—1.15V, that is, the differential mode gain Ad3 of the entire circuit is 1125~1150 times, and the amplification factor meets the design requirements.

④Common mode gain

Input two identical signals at the input end of the amplifier, both at 30Hz and 2V. Observe the signal output at the output end, and calculate the common mode gain, and get:

The common mode gain of the preamplifier is

$$A_{C1}=V_{OC1}/V_i=3.6mV/2V=0.0018$$

The total modulus gain of the ECG amplifier is

$$A_{C2}=V_{OC2}/V_i=48mV/2V=0.024$$

⑤Common mode rejection ratio

Calculate the common-mode rejection ratio of the preamplifier:

$$CMRR1=20\lg\left|\frac{A_{d1}}{A_{c1}}\right|=20\lg\left|\frac{12.5}{0.0018}\right|=86.83dB>80dB$$

Calculate the common-mode rejection ratio of the entire circuit:

$$CMRR2=20\lg\left|\frac{A_{d3}}{A_{c2}}\right|=20\lg\left|\frac{1150}{0.024}\right|=93.608dB>80dB$$

⑥Input impedance

Calculated 0.096MΩ

⑦Output impedance

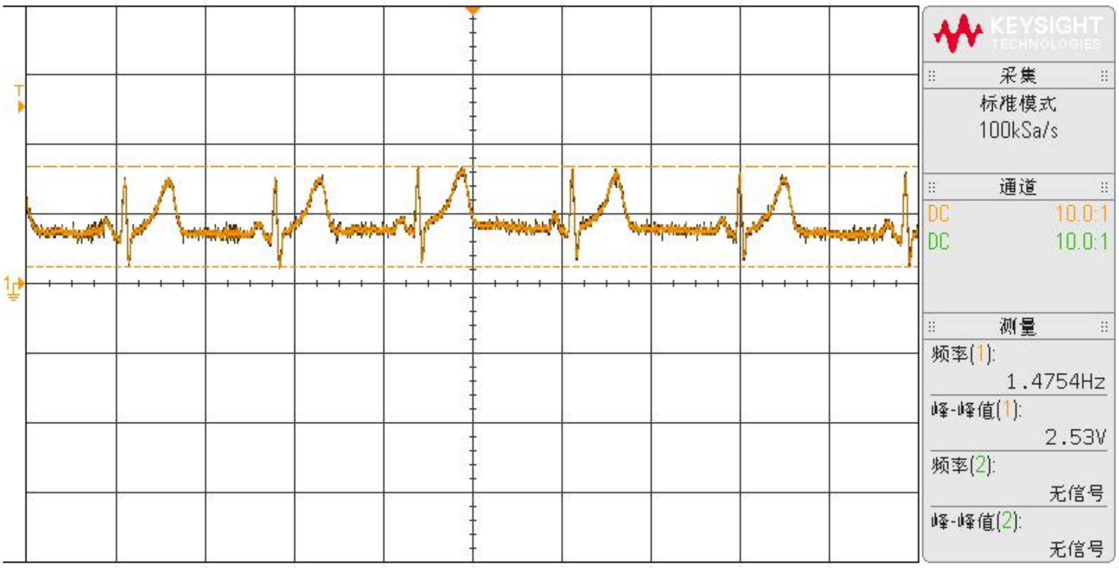
Calculated 1.16MΩ

⑧Zero drift

Ground the two input terminals of the amplifier, measure the output voltage amplitude, and measure the output voltage amplitude again at intervals. Calculate the zero drift:

$$\left|\frac{V_{o1}-V_{o2}}{Kh}\right|=\left|\frac{86.3-85.9}{1150\times\frac{1}{5}}\right|=1.7mV$$

⑨Output amplitude



According to the figure, output amplitude>2.5V

⑩Amplitude frequency characteristics

The theoretical bandwidth is: 0.05～100Hz.

Actually measured: the low-pass cut-off frequency is 90Hz; the high-pass cut-off frequency is 0.05Hz.

The input end of the second-order Butterworth low-pass filter inputs a sinusoidal voltage with an amplitude of 1V, and its amplitude-frequency characteristics are measured.

The measurement data of the low-pass filter is as follows:

Group	1	2	3	4	5	6	7	8
$f\,/\,Hz$	30	75	98	99	100	101	102	103
$V_o\,/\,V$	0.992	0.988	0.852	0.832	0.812	0.778	0.748	0.720
Group	9	10	11	12	13	14	15	
$f\,/\,Hz$	104	105	106	130	150	200	500	
$V_o\,/\,V$	0.706	0.668	0.624	0.512	0.424	0.242	0.112	

The cut-off frequency is about 90Hz, and the output signal has good attenuation above 90Hz, which meets the design requirements.

The amplitude-frequency characteristics of the notch filter:

Input a sine voltage with an amplitude of 1V from the input end of the trap, observe its output waveform with an oscilloscope, and record the amplitude of the output voltage at each frequency point.

Group	1	2	3	4	5	6	7
$f\,/\,Hz$	30	35	40	45	49	50	51
$V_o\,/\,V$	0.470	0.410	0.340	0.290	0.250	0.213	0.217
Group	8	9	10	11	12	13	14
$f\,/\,Hz$	52	53	55	60	65	70	75
$V_o\,/\,V$	0.217	0.221	0.221	0.239	0.257	0.285	0.322

It can be seen from the table that the bandwidth of the notch filter is about 49～55.00, and the attenuation amplitude of the 50Hz frequency component is (namely the depth of the notch)

K=0.213V/1V=20.13%   The center frequency is 52Hz.

Pulse

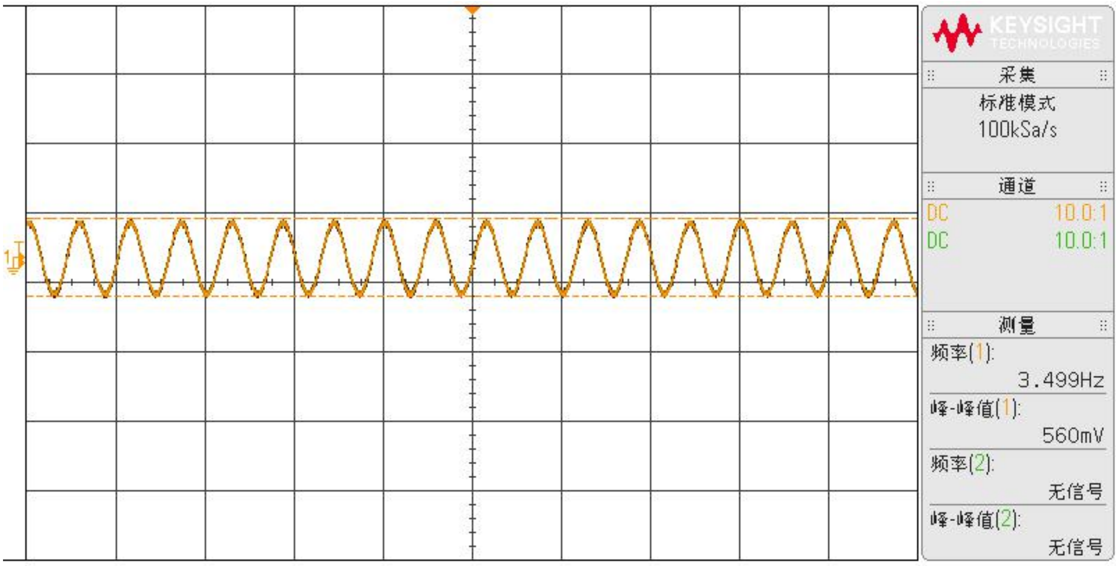
①Static operating point

Short-circuit the two input terminals of the amplifier to ground, observe the output waveform of each level and record the amplitude

Static operating point of primary output: 44.42mV

Static operating point of secondary output: 42.5mV.

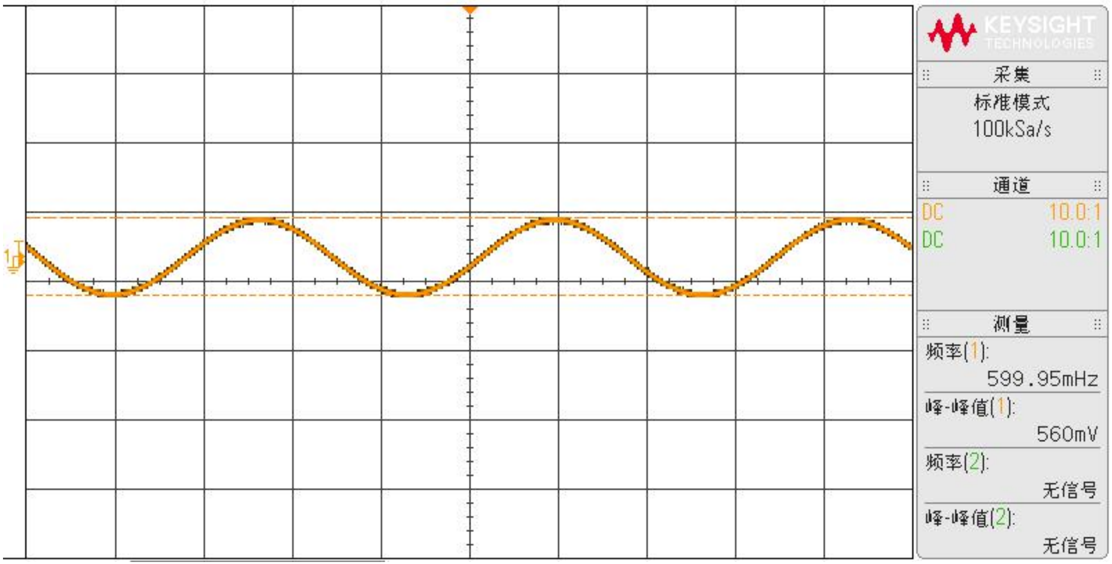
②Amplitude-frequency characteristics



Input a sinusoidal voltage with an amplitude of 10mV at the input, and measure its amplitude-frequency characteristics.

Group	1	2	3	4	5	6	7	8
$f\,/\,Hz$	0.6	0.8	1	2	3	3.5	10	20
$V_o\,/\,V$	0.560	0.620	0.780	0.689	0.601	0.560	0.153	0.064

It can be seen from the table that the bandwidth of the pulse amplifier circuit is 600mHz-3.5Hz, the low-pass cut-off frequency: 3.5Hz 560mV, the high-pass cut-off frequency 600mHz and 560mV respectively.



③input resistance

0.1MΩ

④Output impedance

Input terminal is shorted to ground

0.43MΩ

⑤Output amplitude