Low-cost Circuit Design of EEG Signal Acquisition for the Brain-computer Interface System

Lei Zhang
Key Laboratory of Intelligent Computing & Signal Processing
of Ministry of Education Anhui University
Hefei 230039, c
zhanglei@ahu.edu.cn

Xiao-jing Guo, Xiao-pei Wu, Beng-yan Zhou
Key Laboratory of Intelligent Computing & Signal Processing
of Ministry of Education Anhui University
Hefei 230039, China
wxp2001@ahu.edu.cn

***Abstract*—Increasing number of research activities and different types of studies in brain-computer interface systems (BCIs) show potential in this young research area. However, BCIs have not become widely applied, most of them are still limited in the laboratory and off-line. One of the important reasons is that: EEG signal acquisition is completed by the professional medical equipments. They are expensive and the parameters of them cannot be flexiblely changed with the specific BCI experiment paradigm. In the paper, a single-channel low-cost circuit of EEG signal acquisition for the BCI system is designed. The circuit is composed of protection circuit, instrumentation amplifier, common mode rejection (CMR) circuit, gain adjustable amplifiers and filters. In order to test this circuit, the circuit simulation and the real-time EEG measurements are implemented. The experimental results show that the circuit is effective with good performance, it is very suitable for the online BCI system.**

Keywords- EEG;amplifier;CMR;filter;BCI;SSVEP

I. INTRODUCTION

A brain–computer interface (BCI) is a communication channel which does not depend on the brain's normal output pathways of peripheral nerves and muscles [1–2]. BCI provide a direct communication and control channel for sending messages and instructions from brain to external computers or other electronic devices [3]. Among various brain monitoring methods employed in current BCI research, electroencephalogram (EEG) is the main interest due to its advantages of low cost, convenient operation and non-invasiveness.

Increasing number of research activities and different types of studies in brain-computer interface systems (BCIs) show potential in this young research area. However, most of the current BCIs have not formed the popularization and practical application, they are still limited in the laboratory and offline. Compared with the offline systems, the online and practical BCIs for real-life applications play an important role in current BCI research, but they have much difficulties and challenges to implement. To design a practical BCI product, the following issues need to be addressed: convenient and comfortable to use; stable system performance; low-cost hardware [4]. Most of the EEG signal acquisition equipment for the current BCIs are completed by the commercial EEG devices, the recording hardware with a large amount of channels is too expensive, it is difficult for common users to afford.

For these reasons, many researchers have spent a great deal of energy to lower the cost of EEG signal acquisition. The OpenEEG project has created a low cost EEG device and free software for the amateurs who would like to experiment with EEG [5]. It has seen contributions from many hardware people over the years, resulting in several different designs which have been tested and tried by various people. Mehmet Engin and Tayfun Dalbastı had designed a prototype EEG recording system which consists of an analog and a digital part. Their analog module involves the following units: an input instrumentation amplifier, gain adjustable amplifier, band-pass filter, and a driven-right-leg (DRL) circuit. This proposed EEG system can be used for biomedical research applications [6]. Furthermore, Robert Lin and Ren-Guey Lee had developed a multi-channel wireless EEG acquisition and recording system. The acquisition circuit is composed of pre-amplifiers, filters, and gain amplifiers. Using this system, the non-successive brain activities such as epilepsy, sleeping disorder and abnormal behavior can be measured [7].

Through analysis and comparison of current EEG amplifier circuit methods, we learned from the advantages of the above papers, we designed a low-cost EEG recording circuit for the on-line BCIs. In this paper, we firstly introduce the EEG characteristics and the overall framework of EEG recording circuit. Secondly, we illustrate the details of the circuit. Furthermore, the experiment results will be showed. Finally, the advantages of EEG collection circuit are summarized, and the deficiencies and the future work are discussed.

II. CHARACTERISTICS OF EEG AND THE ACQUISITION CIRCUIT

A. Characteristics of EEG

EEG signal is usually acquired through electrodes from the head surface. It is normally range from 0.5 to 100 μV in amplitude and needs to be amplified several thousand times before it can be captured.It is very faint and easily drown in Artefacts [8]. These varieties of noise jamming of the recorded EEG may be either person-related or technical. Person-related artefacts are unwanted physiological signals that may disturb the EEG. They are particularly about EMG, ECG, EOG, minor body movements, sweating and so on.Technical artefacts, such as AC power line noise, can be decreased by decreasing electrode impedance or by shorter electrode wires. The most

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common EEG artefact sources can be classified in following way: 50/60Hz, impedance fluctuation, cable movements.

B. System architecture of the EEG acquisition circuit

EEG signal is very faint in amplitude and with much noise, it often corrupted by noises such as power line noise, EMG, EOG etc... The amplifiers for measuring EEG have to satisfy the following specific requirements. First, they have to provide amplification selective to the physiological signal and reject superimposed noise, interference signals; Secondly, they guarantee protection from demages through voltage and current surges for both person and electronic equipment [9]. To handle these, the circuit for EEG signal acquisition is designed as the Fig.1.

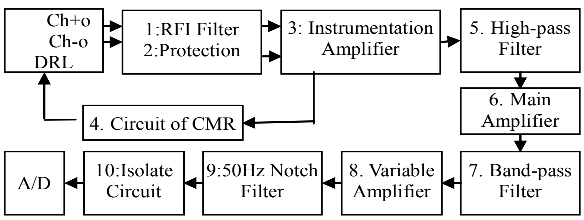

Figure 1. System architecture of the EEG acquisition circuit.

In our previous work, we had established a SSVEP BCI system, which could analyze and identify EEG signal on-line. The circuit module is mainly composed of protection circuit, instrumentation amplifier, common mode rejection (CMR) circuit, gain adjustable amplifiers and filters. But this system is not very stable in the larger noise interference. For example, when the subject's body has a larger swing, or the measuring electrodes have poor contact, the quality of EEG signal will descend. In addition, different analog-to-digital (A/D) converter card properties vary greatly, some acquisition cards have no signal isolation circuit, even if the front of noise suppression is better, in the back-end acquisition will string into the 50Hz interference signal. In view of the above situation, EEG collection circuit designed in this paper increases the 50Hz notch circuit and photoelectric coupling isolation circuit. At the same time the gain of the amplifier and filter parameters were modified, to further improve the quality of signal acquisition. The schematic diagram of EEG amplifier circuit is illustrated in Fig.2.

EEG was recorded from two bipolar AgCl electrode pairs, difference amplified, filtered and digitized to PC. The third electrode is as common signal input. The signal is picked up by AgCl electrodes and firstly passed through the radio frequency interference (RFI) filter and protection circuit. Then it is amplified about 13.5 times by an instrumentation amplifier, which measures the voltage difference between two locations on the scalp. The purpose of the circuit of common mode rejection is to reduce common-mode signals such as 50Hz interference. The next step is removing the DC component offsets by a passive high-pass filter with cutoff frequency of 0.5Hz. The signal strength is increased further by main amplifiers about 51 times in a second amplifier stage. Then a band-pass filter minimizes distortion. The gain of third amplifier can be adjusted with the requirement. Finally, the EEG will pass the 50Hz notch and photoelectric coupling isolation circuit .

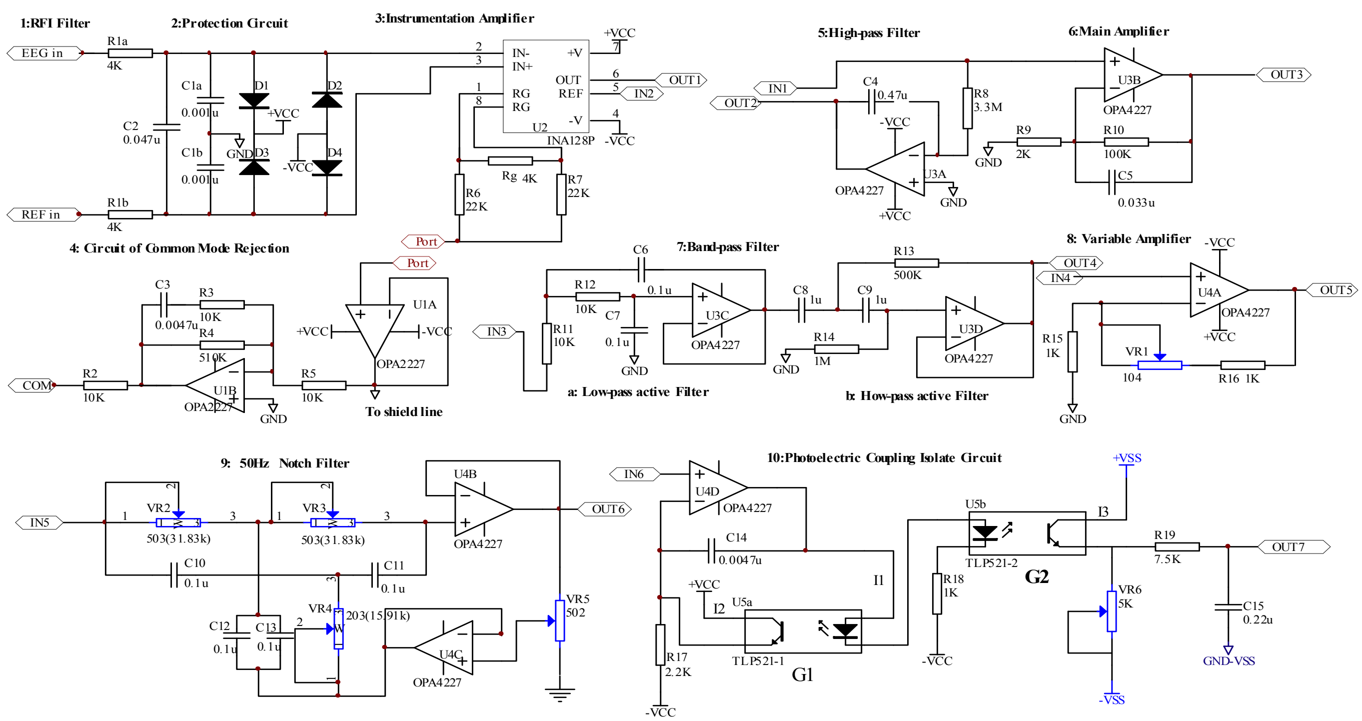

Figure 2. The schematic diagram of one channel EEG acquisition circuit

III. DETAILS OF DESIGN

The amplifier and filter circuit of EEG acquisition can be further sub-divided into ten stages. They are as follows:

A. RFI filter

Real-world applications must deal with an ever increasing amount of radio frequency interference [10]. When strong RFI is present, it may become rectified by the IC and then appear as a DC output offset error. The best practical solution is to provide RF attenuation ahead of the in-amp by using a differential low-pass filter. The filter needs to do three things: remove as much RF energy from the input lines as possible, preserve the ac signal balance between each line and ground, and maintain a high enough input impedance over the measurement bandwidth to avoid loading the signal source. The RFI circuit reveals that the filter forms a bridge circuit whose output appears across the in-amp' input pins. Because of this, any mis-match between the time constants of C1a/R1a and C1b/R1b will unbalance the bridge and reduce high frequency common mode rejection. Therefore, resistors R1a and R1b and capacitors C1a and C1b should always be equal. As shown in Fig.2, C_2 educes any AC CMR errors due to mismatching.With the values shown, the -3dB of this filter is equal to 400Hz by using (1)

$$BW_{DIFF} = \frac{1}{2\pi * R * (2C_2 + C_1)} \approx 400Hz \tag{1}$$

This RFI circuit provide adequate RF attenuation .

B. Protection circuit

As interface amplifiers for data acquisition systems, amplifiers are often subjected to input overloads, for example voltage levels in excess of their full scale for the selected gain range or even in excess of the supply voltage. The amplifier has to offer protection of the person from any hazard of electric shock. In addition, the amplifier itself has to be proteceted against demages that might result from high input voltages as they occur during the application of defibrillators or electrosurgical instrumentation.

C. Instrumentation amplifier

EEG signal is very weak, often buried in the strong noise signal interference. The preamplifier must have a high input impedance, high common mode rejection ratio, low noise, nonlinearity, strong anti-interference ability and proper frequency and dynamic range amplifier performance. So the preamplifier plays the most important role of the whole circuit design. It not only extracts the useful EEG signal, but also reduces the interference signals to the lowest level. We selected an instrumentation amplifier to achieve this function. The instrumentation amplifier is a type of differential amplifier that has been outfitted with input buffer amplifiers, which eliminate the need for input impedance matching and thus make the amplifier particularly suitable for use in measurement and test equipment. Additional characteristics include very low DC offset, low drift, low noise, very high open-loop gain, very high common-mode rejection ratio, and very high input impedances.

We used the chip of INA128 which is very suitable for this application. This chip has very low offset voltage of 0.5uV, and rejects common signal with 120dB [11]. The structure of INA128 is composed of 3 operational amplifier as the Fig.3. These are arranged so that there is one op-amp to buffer each input (+, −), and one to produce the desired output with adequate impedance matching for the function.

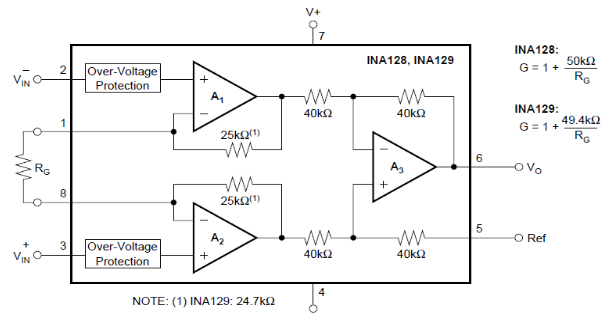

Figure 3. The circuit structure of INA128[11].

In this circuit, common mode signals will be passed through the input buffers at unity gain, but differential voltages will be significantly amplified. The gain of the circuit is

$$G = \frac{V_{OUT}}{(V_{IN}^{+} - V_{IN}^{-})} = 1 + \frac{50K\Omega}{Rg} = 1 + \frac{50K\Omega}{4K\Omega} = 13.5 \tag{2}$$

The gain can not be set to amplify too much because of DC component.

D. Circuit of common mode rejection

The purpose of the common mode rejection circuit is to feedback any noise from the signal to the body. This will naturally minimize any common mode interference on the body and strengthen the signal. Firstly, R_6 and R_7 form series circuit, they compose parallel connection with Rg. In the junction between R_6 and R_7 it is possible to measure the common mode voltage by U1A. Then the voltage passes the signal on to the shield cap, it forms a floating ground. It can attenuate mains hum up to 100 times more than the instrumentation amplifier can do by itself.Gain and BW setting as the Equation 3 will decide whether the OP AMP will work stably.

$$| G(s) | = \frac{R4}{R5} * \frac{1}{\sqrt{1 + (R2 * C * 2 * \pi * f)}} \tag{3}$$

As described in Fig.2,Gain =51, BW =70Hz.

E. High-pass filter

An active high-pass filter is used to remove DC voltage offsets. Some electrode materials, such as gold or steel, are polarizable. This means that electric charge can accumulate on the surface of the electrode, building up a relatively large DC voltage. As a result, the circuitry can handle about 2.5 V and not contain any EEG.The high-pass filter tries to solve this problem [12]. Its cutoff frequency（-3dB） is about 0.05Hz by C_4 and R_8. This frequency response can be achieved by adjusting the resistor and capacitor values. The high corner frequency is given by the equation 4 below:

$$Fh = \frac{1}{2\pi * R8 * C4} \approx 0.05Hz \tag{4}$$

F. Main amplifier

EEG signal is very faint in amplitude.It has been increased by the instrumentation amplifier about 13.5 times,but it is not enough for A/D converters. It is also with much noise. So EEG signal should be amplified with multi-stage amplification. In the process of amplification,it should add filter which reduce noise' interference.Now the strength EEG signal with faint noise after the front of instrumentation amplifier can be increased further by this main amplifier about 51 times in the second amplifier stage. The gain is worked out at

$$G2 = 1 + \frac{R10}{R9} = 51 \tag{5}$$

R_{10} and C_5 can also make up one order low-pass filter which attenuates high frequencies and other high frequency noise (50Hz). The cutoff frequency dependent on the resistor R_{10} and capacitor C_5, it is shown in the equation 6:

$$Fc = \frac{1}{2\pi * R10 * C5} \approx 159Hz \tag{6}$$

The value chosen as in the Fig.2 gives us the cutoff frequency of 33.8 Hz, which completely attenuates signals that are not from the EEG. The gain of this circuit is unity since the resistances are matched.

G. Active band-pass filter

The next component of the circuit is a band-pass filter, which contains a low-pass filter and a high-pass filter. What emerges from the series combination of these two filter circuits is a circuit that will only allow passage of those frequencies that are neither too high nor too low. The low-pass filter is an active two order Sallen-key filter by R_{11}, R_{12}, C_6, C_7 and U3C operational amplifier. The transfer function of this circuit as Fig.2 is:

$$H(s) = \frac{1/R_{11}R_{12}C_6C_7}{S^2 + (\frac{1}{R_{11}C_6} + \frac{1}{R_{12}C_6})S + \frac{1}{R_{11}R_{12}C_6C_7}} \tag{7}$$

In this circuit, R_{11} is equal to R_{12} and C_6 is equal to C_7. The damping coefficient is equal to 2, the -3dB cutoff frequency of this two poles of the filter is:

$$fc = \omega_c / 2\pi = \frac{\sqrt{\sqrt{2}-1}}{2\pi}\frac{1}{R_{11}C_6} \approx 102.43Hz \tag{8}$$

The filter is good enough to prevent all aliasing artifacts in the AD-converter. However, because the signal we are trying to measure (EEG) is naturally filtered fully, it is quite possible that a lower sample rate, for example 256 Hz or 512 Hz is sufficient for most purposes.

After the low-pass filter, the capacitor C_8, C_9 and the resistor R13, R14 provide a two order Sallen-key high-pass filter. The high-pass transfer function of this circuit as the Fig.2 is:

$$H(s) = \frac{S^2}{S^2 + (\frac{1}{R_{14}C_8} + \frac{1}{R_{14}C_9})S + \frac{1}{R_{13}R_{14}C_8C_9}} \tag{9}$$

The high corner frequency as Fig.2 is given by using (10):

$$f_c = \frac{\omega_c}{2\pi} = 0.23Hz \tag{10}$$

The high-pass filter makes further efforts to reduce the DC interference and baseline drift.

H. Variable Amplifier

Finally the variable amplifier is shown in Fig.2 and serves to amplify the EEG signal further that is enough for A/D converters. First different people have different range of EEG. Also different A/D converters has various input voltage range.The amplifier gain is changed by adjusting resistance, and then changes the range of EEG. It is to expand the scope of the acquisition system, the potentiometer VR_1 is variable in this case to give the operator greater control over how much gain is produced. For this circuit, the gain is shown by

$$G3 = 1 + \frac{VR_1 + R_{16}}{R_{15}} = 1 + \frac{1K\Omega + (0 \sim 100)K\Omega}{1K\Omega} = (2 \sim 102) \tag{11}$$

VR_1 is at optimum at 29K, giving the gain of 30. This value is variable and it is altered to fit the subject.

I. 50 Hz notch circuit

Before now, this circuit has good common mode rejection capability, without notch filter it can get good EEG signal acquisition effect. But in the more strong noise environment, 50Hz interference which is from the standard AC electrical line current still exists. It also can come from the computer and A/D converter card. The 50Hz interference sometimes string into the circuit. It could be also eliminated by a so called notch filter which selectively removes 50Hz activity from the signal. Especially the EEG is very weak, the interference is very serious, 50Hz notch filter circuit should be added. In addition, this EEG amplifier circuit with 50Hz notch circuit can greatly reduce this interference, the latter software processing stage will be more simple.

In this paper we used the double T network notch filter, it is shown in Fig2. The notch frequency parameter is 50Hz. The resistors and capacitors parameters: $VR_1=VR_2=2*VR_3$ =31.83K, $C_{10}=C_{11}=C_{12}=C_{13}$=0.1uF. The double T notch filter needs high accuracy resistance and capacitance, the component errors will deviate from the center frequency of 50Hz. So the resistances and capacitances must be used in high precision, each element should be used for accurate measurement of bridge, as close as possible to the ideal value. In fact, it is difficult to choose the same resistance and capacitance to the ideal value, 50Hz notch center will be difficult to realize. In order to ensure the 50Hz notch circuit effective, we used the precision potentiometers instead of common resistors, they were adjusted to the ideal value until the trap center at 50Hz. The variable resistor of VR_5 is used for determining notch depth and bandwidth. When increasing the VR5 value, the notch bandwidth and depth increase, and vice versa.

J. photoelectric coupling isolation circuit

The 50 Hz power-line interference is reduced by the notch circuit. However, the properties of different A/D converter card vary greatly, even some A/D card has no signal isolation circuit, the back-end acquisition will also string into the 50Hz interference signal. The photoelectric coupling isolation circuit was implemented to prevent it happens. The isolation circuit is composed of Toshiba TLP521-2 chip, which is a dual photoelectric coupler and offers two isolated channels. The input and output stage are completely isolated, so the interference between them will be removed. The detail design is as Fig.2. This circuit is the typical feedback circuit model, the two photoelectric coupler performance and specifications are the same. This circuit can realize the electrical isolation effect, and it also can achieve a level conversion and improve the driving capability, strong load capacity. In the back of a photoelectric coupling circuit, R_{18} and C_{15} constitute a one-order low-pass filter, the -3dB cut-off frequency is 96.5Hz. This design is intended to prevent aliasing in digital output signal when high frequency signal does not need to be converted.

Above all, the overall gain of the circuit as shown in the Fig.2 is about 20655(G=G1*G2*G3), cut-off frequency of high-pass filter is set at 0.56 Hz and of low-pass filter is set at about 90 Hz. After the filtering, the signal is sent to the A/D converter which in our case is located inside a microcontroller. It sends the digitized EEG to a PC. Then the EEG signal can be recorded and displayed on-line on the Vc-based software system. It also can be analyzed and identified by this software.

IV. EXPERIMENTAL RESULTS

The circuit was designed by protel software, the PCB board was produced. In order to validate the EEG acquisition system, real-time EEG measurements are established. The subject is a 28 year old boy. The electrodes are placed according to the international standard 10-20 system. There are three electrodes placed in OZ,A2,and FPZ of the subject. The referencing electrode and grounding electrode are placed at right ear lobe and forehead respectively. Numerous neurophysiologic studies indicate that brain rhythms can reflect changes of brain states caused by stimuli from the environment or cognitive activities. EEG rhythms can indicate working state or idling state of the functional areas of the cortex. Here we show the experimental results by two methods: one is alpha rhythm, second is steady-state visual evoked potential (SSVEP).

Firstly, the alpha rhythm recorded over the visual cortex is considered to be an indicator of activities in the visual cortex. The clear alpha wave while eyes are closed indicates the idling state of the visual cortex, while the block of the alpha rhythm when eyes are open reflects the working state of the visual cortex. Fig.4 shows 6 seconds recording data of the OZ and A2 bipolar measurements by this acquisition circuit. The data is without any software filter processing. The 3 seconds ahead is eyes open state, 3 seconds after is eyes closed state. The blocking phenomenon of alpha wave can be clearly observed.

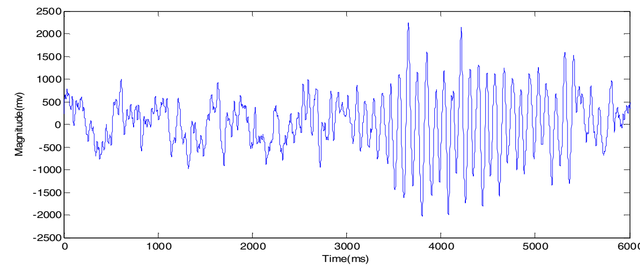

Figure 4. The alpha wave blocking showed in time domains

Secondly, an on-line BCI system of SSVEP had been set up by this circuit. The SSVEP system uses detection of frequency-coded to determine the gaze or spatial selective attention direction, it has been employed successfully in the BCI research [13-14]. The diagram of BCI system is as Fig.5.

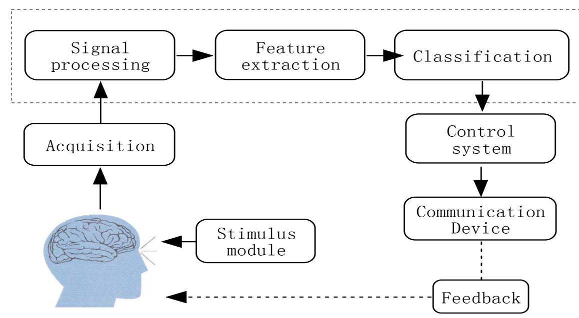

Figure 5. The diagram of BCI system

The design of experiment is as follows: 7Hz square-wave signal about 3.2v is added at both ends of the white light-emitting diode (LED), the LED will be blinking at this frequency. When the subject looks at the LED which is set in front of the subject about 50cm, EEG can be recorded from the subject's scalp. In the EEG measurements, one channel signal is captured by this acquisition circuit, and then the signal is analyzed and observed by software on the computer. The EEG signal is showed in time and frequency domains as Fig.6.

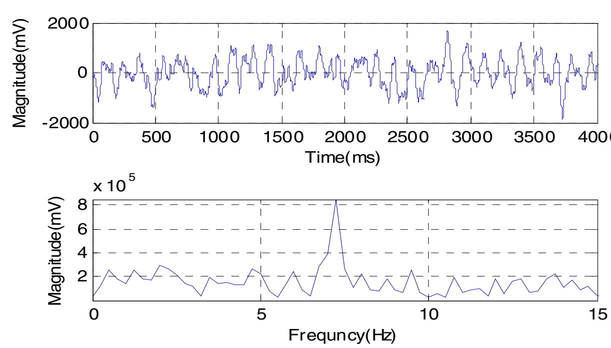

Figure 6. EEG showed in time and frequency domains

The results show that: It is difficult to identify EEG in time domain. But after the acquisition of EEG is processed through the FFT transform, it is showed in frequency domain, 7Hz can be seen clearly. So the signal feature extraction and classification is mainly from frequency domain identification. Useful information can also be extracted from brain wave that can be interpreted in terms of brain states. They are transmitted to and processed by a computer to activate a switch or drive a cursor and hence provide communication. If we set up the multi-frequency flicker source, a wide range of choices can be the target as the BCI system. 6.5 Hz, 7 Hz, 7.5 Hz and 8 Hz frequencies are selected as the stimulation frequency to drive the LED. This system achieves controlling switching of the media player using the characteristic of evoked potentials. It has four kinds of options, so it can control the media player to play four kinds of music by the different recognition results.

V. CONCLUSION AND FUTURE WORK

As a result, a single channel SSVEP BCI system based on this acquisition circuit has been builded in this paper, which can analyze and identify EEG signal on-line. It is very simple, reliable and low-cost. The experimental results show that the circuit is effective with good amplification ability and high CMR, and it is very suitable for the online BCI system. However, there are also many shortcomings in the BCI system, which should be solved in the future, such as the improvement of signal identification and processing. The next step is to make a more stable and powerful BCI system which is easier to operate. Therefore, we should perform EEG signal recording more clearly and process EEG signals more accurately. We hope that the BCI system has many more useful applications in future.

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