# Research on Improving Amplifier Used in Brain-Computer Interface Technology

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**Abstract.** With the rapid development of science and technology, the demand for human-computer interaction in many fields is increasing, and the requirements are getting higher and higher. As the most important part in human-computer interaction, the demand for Brain-Computer Interface (BCI) technology in medicine, games, military fields, etc. is increasing. Therefore, more and more scholars and institutions have begun to study BCI technology. In this paper, an experiment is designed to improve the performance of two-stage CMOS amplifiers, an important component of BCI technology. The experiment uses CoolSpice to build a basic model of the two-stage CMOS amplifier for simulation, replacing brain waves with a small signal, and adjusting the performance of the two-stage CMOS amplifier by adding a compensated capacitor and resistor. Through experimentation, it can be concluded that selecting an appropriate compensated capacitor can significantly improve the performance of the amplifier. Improving the performance of amplifiers can help improve the efficiency of BCI technology and help people collected the information emitted by brain waves more accurately in the future.

**Keywords:** Brain-Computer Interface, Amplifier, Simulation, Performance.

## 1. Introduction

Brain-Computer Interface (BCI) is a technology that using computers or other external electronic devices to connect the human brain and the outside world. BCI technology has been investigated for a long time [1]. As the development of technology and science, the requirement for BCI technology has been higher and higher. Although there has been a great breakthrough in the performance of brain-computer interface systems, for now, BCI systems are not yet reliable and universal [2].

This article mainly focuses on researching the performance of the amplifier inside the BCI technology, introduces the research status and basic theory of BCI technology. BCI technology is based on recording and processing the brainwaves that are output by human’s brain, then analyzing the meaning of order sent by brain. Also, the information from external environment can be transmitted into brain as feedback by translate the electrical signal into EEG to brain [3]. Amplification is a crucial part in signal processing. It exists in filtering, recording and translation.

In this article, a experiment is made to investigate what factors have influences on performance of a two-stage CMOS amplifier. Brain waves is simulated by a small electrical signal. The whole experiment is simulated on Cool Spice. The experiment explains the importance of compensated capacitor and resistor in amplifier. They can increase the voltage gain and adjust phase margin in a proper range. It helps people to get better quality of amplification then get better results in where need amplification. Thus, it can accelerate the popularization and improvement of BCI technology in various fields.

## 2. Research Status and Basic Theory of Brain-Computer Interface Technology

### 2.1. Research Status of BCI Technology

In 1924, German scientist Hans Berger discovered the existence of brain electrical activity, known as brain waves. In 1973, American scientist Vidal announced the concept of Brain-Computer Interface (BCI) and defined BCI technology as a computer system technology capable of reflecting brain functions [4]. Neuralink, founded by Elon Musk, the CEO of Tesla, is dedicated to the development of brain-computer interface technology. The company is involved in the research and development of high-bandwidth, wireless transmission brain-computer interface devices and is in the animal experimentation phase. In 2021, Neuralink shows a monkey who is playing 'Mind Pong', with the help of 'Mind Pong', Neuralink decoded the brain waves for controlling the hands and gestures of monkey. The Figure of investigating process is shown in Figure 1 below.

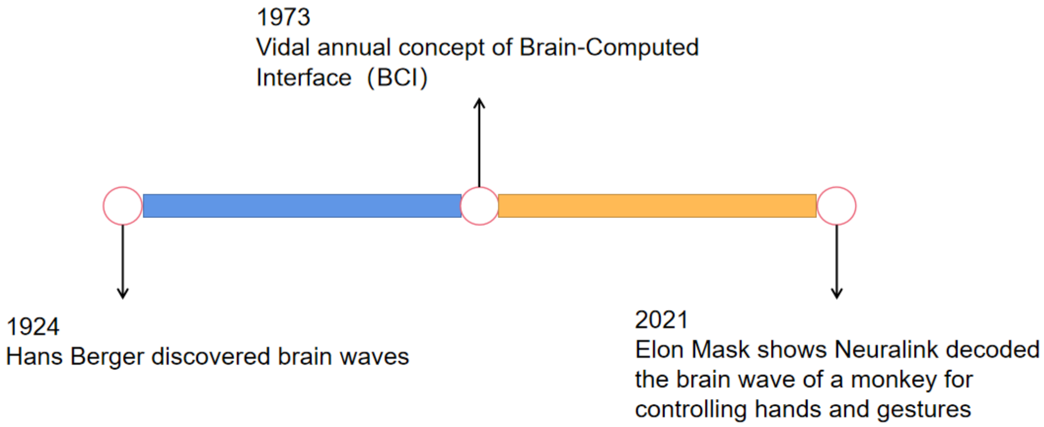


**Figure 1.** The process of BCI technology investigating (Photo/Picture credit: Original)

Since the beginning of the 21st century, research, practical applications, and commercialization of Brain-Computer Interface (BCI) have made huge progress. However, there are still several limitations in development and bottlenecks slow down the speed of achieving comprehensive implementation of BCI technology.

Firstly, despite advances in controlling external devices such as robotic arms through BCIs, the sensitivity and accuracy of such control have not yet reached the level achieved by natural limb control [5]. The complex neural control and feedback mechanisms involved in executing fine motor actions with human limbs have not been fully replicated by current BCI technology.

Secondly, the installation and connection of BCI electrodes and interfaces remain relatively complex and entail certain risks. Conventional invasive BCIs require surgical implantation of electrodes, a high-risk and costly procedure for patients. Furthermore, implanted electrodes may lead to infections or other complications, restricting their widespread clinical application [4].

Therefore, ongoing BCI research aims to address these technical challenges and limitations. Many scientists and engineers are dedicated to developing more advanced non-invasive BCI technologies to reduce the risks associated with implantation and enhance system sensitivity and accuracy [4]. Moreover, the scale of BCI research continues to expand, attracting increasing involvement from academic and commercial institutions to drive advancements and applications in this field. With continued scientific and technological progress, BCI holds promising prospects for broader and more profound applications in the future.

### 2.2. Basic Theory of BCI Technology

Brain-Computer Interface (BCI) is a form of information communication where in the brain interacts with the external environment or devices by emitting and receiving signals. Through BCI technology, external devices can receive and process brain-generated electroencephalographic signals, or the brain can receive and process electrical signals emitted by external environment or devices. The Figure 2 below shows the process of BCI technology.

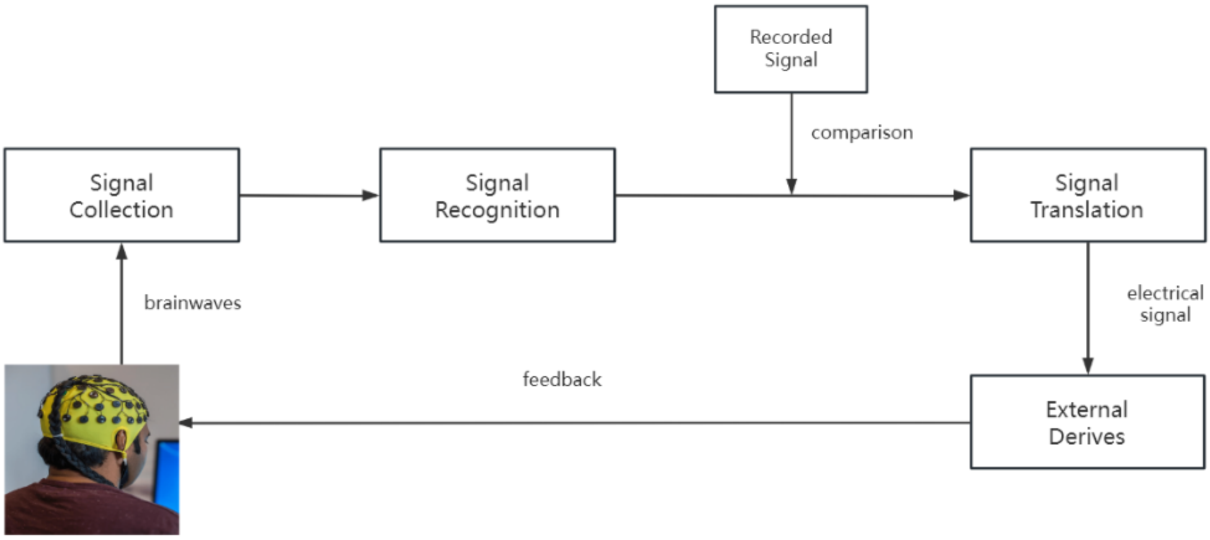


**Figure 2.** The basic process of BCI technology (Photo/Picture credit: Original)

BCI technology can be categorized into two modes of communication: unidirectional and bidirectional. Unidirectional communication involves the brain transmitting signals to external devices or the environment, while bidirectional communication entails both the brain and external devices transmitting and receiving signals [6]. In addition to the types of communication, Brain-Computer Interface (BCI) external devices can also be classified into two categories: implanted and non-implanted interfaces. Implantable interfaces typically require more precise calibration and are more complex in nature.

Based on their functionalities, Brain-Computer Interface (BCI) systems can be primarily classified into three types: motor function-based, sensory function-based, and cognitive task-based BCIs [6]. Among them, cognitive task-based BCIs are more complex and are primarily designed to recognize brain-issued commands and provide feedback to external devices. For instance, using a BCI to control the forward, backward, or turning movements of a wheelchair. BCI research is based on the analysis of brain electrical signals. Brain electrical signals, specifically electroencephalographic (EEG) signals, are complex, non-stationary bioelectrical signals generated by the human brain. They possess characteristics of extreme complexity, weak amplitude, and susceptibility to external influences [7]. The working principle of Brain-Computer Interface (BCI) typically involves the detection of electrical potential changes in different regions of the human brain during various activities, such as thinking, imagining, moving, or in response to external stimuli. BCI devices detect these electrical potential changes as brain electrical signals, which are then processed through signal processing chips to obtain distinct electrical patterns [4]. By comparing and analyzing the collected brain electrical signals, different commands issued by the brain are translated and output to external devices. This enables direct control of external devices by the human brain without the involvement of muscles or peripheral nerves.

Generally, after recording, brain electrical signals undergo processes such as amplification, filtering, and analog-to-digital conversion to be transformed into digital signals. These digital signals are then utilized to command external devices [8]. Additionally, for providing feedback information to the user, other signals need to be converted into electrical signals as well. This also requires processes like amplification, filtering, and analog-to-digital conversion.

To be more specific, amplifiers are commonly used in the whole circuits due to amplification exists in almost every step of BCI technology. The quality and the gain of the amplifiers become important. The reason is the brain waves generated by human-body are always small, which are not easy to be detected or differed by external devices. Thus, the signals need to be amplified first before they are processed by computer. While if the factors which influent the quality of amplification, for example, phase margin, complexity of the circuit etc., are not adjusted to the proper value, the ratio of signal and noise (SNR) will be reduced. It means more noise will be produced which will make it difficult for computer to process the signals generated by brain. The amplitude of scalp EEG signals is very small and there is a large low-frequency shift. When acquiring signals, it is usually interfered by a lot of noise, so the common-mode rejection ratio is an important technical indicator to measure EEG signal acquisition devices. Under the same process conditions, the way to further improve the common-mode rejection ratio is to increase the preamplifier voltage gain [1]. However, the presence of low-frequency shifts in EEG signals limits the amplification of EEG amplifiers.

Consequently, the quality of amplification becomes crucial as it directly affects the final control outcome. Thus, this study focuses on modeling and analyzing amplifiers in Brain-Computer Interface (BCI) to explore the core working principles and performance of amplifier circuits. Specifically, the second-order operational amplifier, which is widely used for amplifying small signals, is chosen as the modeling template for this experiment.

## 3. A Two-Stage CMOS Amplifier Simulation Experiment

A two-stage CMOS amplifier is a kind of Operational Amplifier(op-amp). It has two input pins and one output pin. It is used to amplify the differential inputs EEG signal and output it through the other side. Due to EEG signals import through input pins are too small to be operated in the designed circuits. The op-amp can amplify or strengthen the signals in order to make them easier to be processed. To be more specific, the two different stages have different functions. The first stage is used to generate high gain of the amplifier, while the second stage is used to generate high swing.

### 3.1. The Design Process of the Circuit of a Two-Stage CMOS Amplifier

In order to investigate the characteristics of a two-stage CMOS amplifier in BCI, CoolSpice is used to simulate the result of a designed two-stage CMOS amplifier circuit. This tool can output the graph needed for analysing the two-stage CMOS amplifier. In this investigation, a fundamental circuit of a two-stage CMOS amplifier used in BCI is built at first, then the circuit is simulated for checking and recording the performance (DC gain, total current consumption, -3dB bandwidth, magnitude of phase margin etc) of this amplifier. As the brain waves are always small signals, then the input signal is set to 1.5 uA for simulating. In the practical experiment, the noise inside the brain waves should be considered into calculation.

In this experiment, a good two-stage CMOS amplifier that is used in BCI devices is regarded as having DC gain more than 80dB, the total current consumption is no more than 6 uA, -3dB bandwidth is at 3kHz and phase margin is closed to 60 degrees. Therefore, the aim of simulating the circuit is to check which factors will affect the designed amplifier to meet the requirements. In this design circuit, several current mirrors are used to copy the current from a bandgap circuit to various sub-circuit. They can help decrease the number of current sources used in the circuit. Putting too much current source in an integrated circuit is impractical because it will cause complexity and power consumption being huge. Amplification is one step of signal processing, there are quite lot steps for processing signals, too many sources in the circuit will cause more problems and uncertainty. According to the theory, the magnitude of copied current is based on the ratio of W(width)/L(length) of copied side MOSFET and referenced side MOSFET. Therefore, the current in different sub-circuit can be controlled.

The circuit designed at first time did not have a good performance, the -3dB bandwidth is much larger than 3kHz and the DC gain of this circuit is 60.7dB which is lower than required 80 dB. At first, the input current and the ratio of width and length of MOSFETS is adjusted for a larger voltage gain while it cannot reduce the bandwidth or adjust phase margin. In order to reduce the bandwidth and adjust the phase margin, a compensated capacitor can be added to the circuit between two outputs of stages of the circuit. Then the compensated capacitor and resistor are added into circuit between output of two stages of the circuit. The improved circuit in shown below as Figure 3.

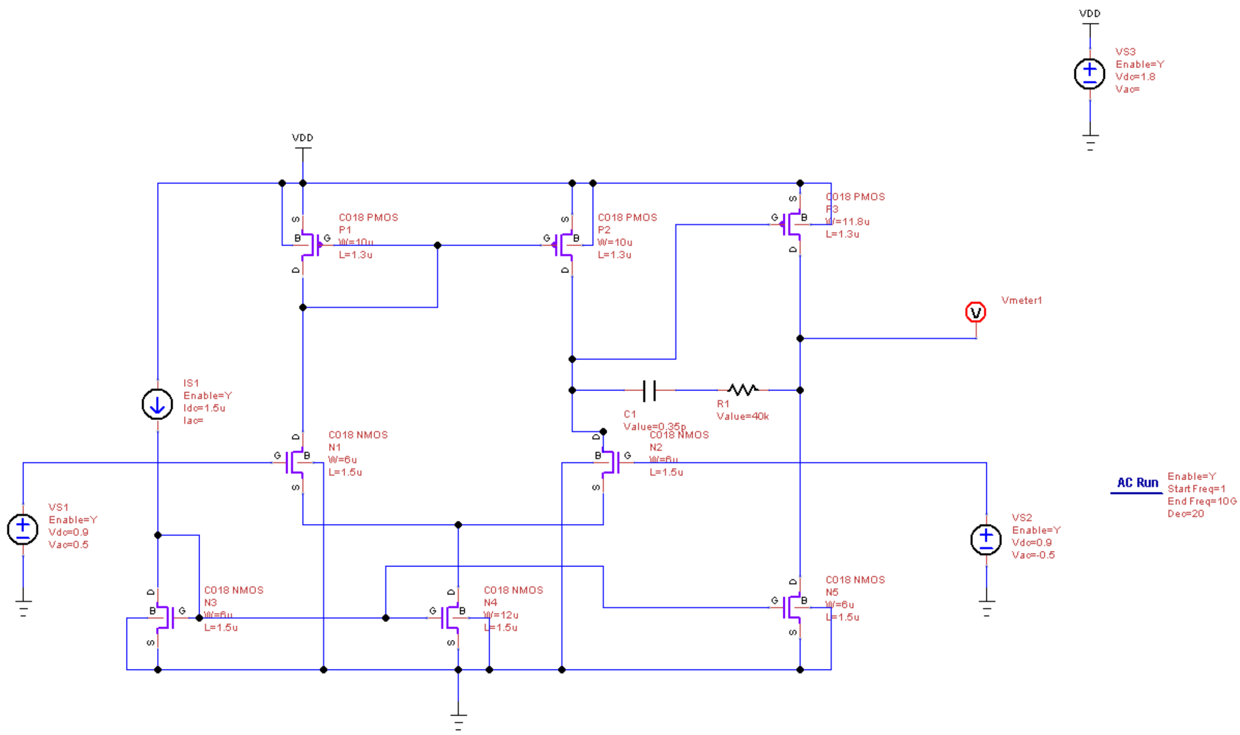

**Figure 3.** The improved circuit of the experiment (Photo/Picture credit: Original)

The two stages of this circuit can be divided stage one, which is formed by P1, P2, N1, N2, N3 and N4, the second stage is formed by P3 and N5. The function of each stage has been mentioned in the previous section. Total DC voltage gain is the gain of first stage times the gain of the second stage. So, the total gain can be controlled by adjusting the value of output resistor of MOSFETs.

The circuit in the Figure 3 meet all requirements, the simulated result will be shown in the next section.

### 3.2. Simulation Result and Analyzing

As it is mentioned in previous section, the simulation result of the initial circuit which did not meet the requirements is shown below in Figure 4.

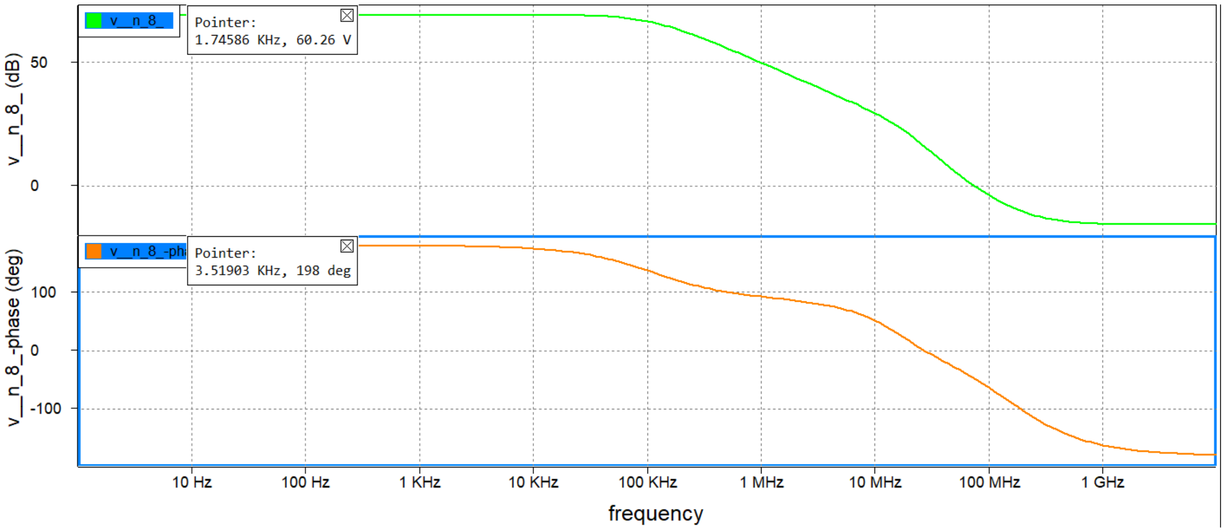

**Figure 4.** The simulation result of initial circuit (Photo/Picture credit: Original)

The -3dB bandwidth is at 73 kHz that is much higher than3 kHz, and the phase margin of this circuit is 119 degrees (-61 degrees + 180 degrees) which meet the requirement (larger than 40 degrees), but it is too high. Afterwards, the result of the final design of the circuit is also shown in Figure 5.

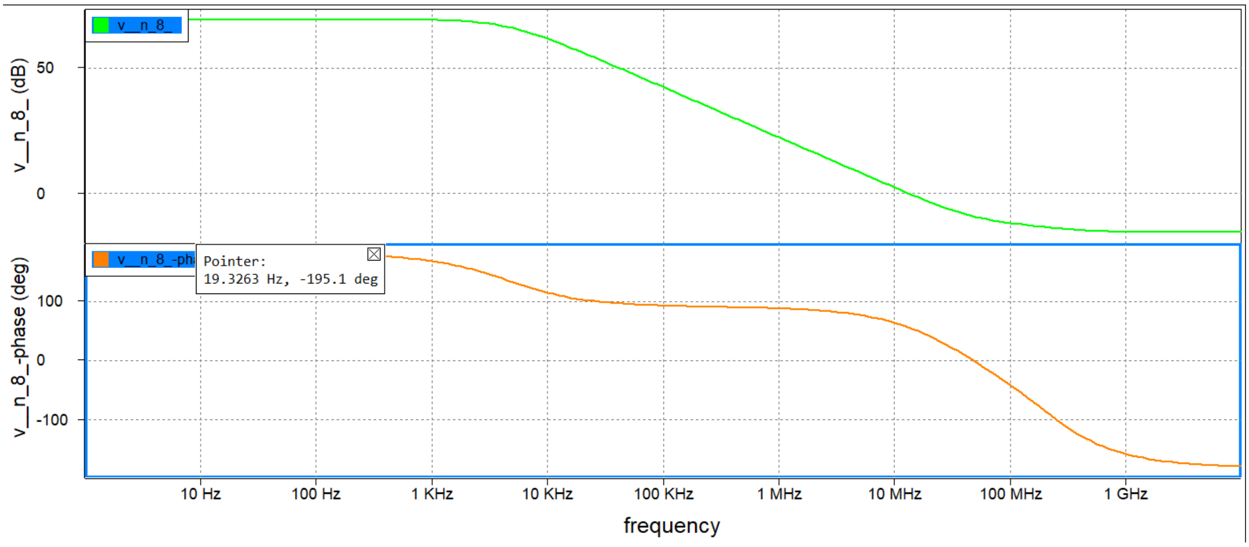


**Figure 5.** The simulation result of improved circuit (Photo/Picture credit: Original)

Through Figure 5, it is obvious that -3dB bandwidth is decreased to 3kHz and the phase margin is reduced to 58 degrees successfully by adding a 0.35 capacitor and a 40k Ohm resistor. In addition, DC voltage gain is raised to 81.7dB. Finally, the total current consumption is 6 uA which contain the current from IS1 in Figure3(1.5 uA), the current from N4 in Figure3(3 uA), the current from N5 in Figure3 (1.5 uA).

## 4. Applications and Challenges

### 4.1. Applications of BCI Technology

With the advancement of brain-computer interface (BCI) technology, an increasing number of fields are embracing its application due to its high potential and vast prospects in cognitive science, information science, military, education, art, entertainment, medical rehabilitation, and other domains [2]. For instance, in the military domain, BCI can be utilized to detect soldiers' brainwave states in harsh environments, providing timely information about their physical conditions and offering effective protection recommendations. However, BCI technology is used most in helping disabilities to use equipment that help them live such as robotic arms or wheelchair [9, 10]. In the realm of gaming and entertainment, BCI greatly facilitates recreational activities, liberating users from manual input and enabling seamless immersion in games. Players can control the game solely through mental visualization. Therefore, BCI is anticipated to remain a highly sought-after research direction in the future.

Although the use of BCI technology in Industry 4.0 is still theoretical, SSVEP-based BCIs represent a device control technology that is particularly important for industrial manufacturing, such as fatigue monitoring seems particularly well suited to prevent damaging errors and safety risks in hazardous environments, or to optimize upstream training in these critical situations [11].

### 4.2. Challenges of BCI Investigation

Although the future of investigating BCI technology is bright, there are still many challenges that need to be taken. Nowadays, two aspects of challenges are considered most.

First, the way of brain processes the signals that were feedback from external BCI devices is still not been programmed precisely [2]. The human eye is very stable in identifying objects, even if the surface is covered, as for any small change in the image, it has almost no effect on the correct judgment of the human eye. But on the other hand, the signals that were feedback from external BCI devices, which is the extension of the human eye for instance, is another matter. The automatic adjustment capability of the BCI system needs to be improved. Due to the different physiological structure and composition of the brain between different individuals, the EEG signals produced by different individuals will have certain differences, and because the EEG signals are easily affected by various factors such as the body's own state and external interference, the EEG signals of the same individual will also change differently due to their own states and different environments, so the adaptability of the BCI system to different individuals and the same individual state changes needs to be improved [4].

Secondly, recording the output signals of brain is a huge work. Currently there are two main possible way to collect EEG signals. One is based on neuroimaging technology, which detects large by non-contact means metabolic activity of the brain, for example, Magnetoencephalography (MEG), Positron Emission Tomography (PET), Functional Magnetic Resonance Imaging (FMRI) and Functional Near-Infrared Spectroscopy (FNIRS). Another type is the real-time acquisition of potential changes through different types of electrodes, for example, Micro-Electrode (ME), Micro-Electrode Array (MEA), Action Potential (AP), Local Field Potential (LFP), Electrocorticography (ECoG) and Electroencephalography (EEG). Signal acquisition such as MEG, PET, FMRI, and FNIRS is convenient and has high spatial resolution, but has high requirements and high acquisition price limit the widespread use of this method in BCI systems. In addition, the acquisition principle of this type of method is complex, and under the current technical level, the time resolution is low, which is not suitable for real-time BCI system [2]. According to statistics, at the current rate of BCI technology that doubles the number of neurons that can be recorded simultaneously in an average of 7.4 years, it will take 2100 years to record 1 million neurons at the same time, and until 2225 to record all neurons in the human brain.

## 5. Conclusion

After analysing the result of simulation, the conclusion can be given by the key of designing a good-qualified amplifier for BCI devices is choosing a right compensated capacitor. It will not only narrow the bandwidth and adjust phase margin but also can increase the voltage gain. According to the simulation, it is also found that using small magnitude of current can increase the DC gain effectively for improve the common-mode rejection ratio, that is because when reducing the input current, the dynamic range of the signal may change. If the input signal decreases but the input voltage remains the same, the input impedance of the amplifier increases. The voltage gain of an amplifier is usually proportional to its input impedance, so as the input impedance increases, so does the voltage gain. In the practical design of amplification of signal processing, using small signal and selecting proper compensated capacitor can make BCI devices transmit the amplified signal to next step more precisely.

In the future experiments, there are still many points can be improved to make the experiments more accurate and more practical. Firstly, using realistic experiment or devices instead of virtual laboratory. In the real applications, there are many factors need to be considered such as component loss, interaction between different components and parameters error of PMOS or NMOS. Secondly, the position of compensated capacitor also can be set at output of whole amplifier instead of the position between output of two stages. Then two different results can be compared and investigated about which kind of design is more suitable for BCI technology. Thirdly, more research should be done on brainwaves as 1.5uA may not be an appropriate value, more accurate magnitude of current can be chosen in the future experiment.

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