A Low-noise Amplifier for Electrocardiogram Signals

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by

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Integrated Circuits

A Low-Noise Amplifier for Electrocardiogram Signals

Jonghun Kwak

This **Masters Project Paper** fulfills the Master of Engineering degree requirement.

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1. Problem Statement (Abstract)

Wireless medical devices are currently in the spotlight due to rapid growth of interest in remote diagnosis systems and long-term medical assistances. In general, such medical device contains a sensor as a front-end to detect bio-signals of a patient or health-conscious person. The output of the sensor is extremely weak for further processing and susceptible to noise. Thus, a low-noise amplifier is connected to the sensor to amplify the original signal while minimizing the effect of noise. The performance of a low-noise amplifier (LNA) determines the quality of the original signals later on.

Our main goal is to design an LNA that is suitable for implantable bio-signal acquisition systems. Primarily focus is on the implantable medical system with an electrocardiogram (ECG) sensor, which records electrical activities of a person's heart. The designed LNA is inspired by a ring amplifier topology, and it provides enough voltage gain to amplify the ECG signals. Chopper stabilization is added to the structure to reduce the contamination due to flicker noise.

In addition, its power consumption is minimized to enhance the lifespan of the whole system. Currently, a bio-acquisition system's overall power consumption is dominated by a low-noise amplifier. The other module in the bio-acquisition system only consumes less than 1uW each while a typical LNA consumes more than 10uW. By reducing the power consumption of the LNA, the device can maintain its performance for a longer period of time.

2. Industry/Market/Trends

2.1. Introduction

According to *Deaths: Final Data for 2013*, a recent statistical report issued by Centers for Disease Control and Prevention (CDC), life expectancy of people at birth in the United States in 1950 is only 68.2 years (Centers for Diseases Control and Prevention). In contrast, life expectancy at birth in 2013 is 78.8 years (Centers for Diseases Control and Prevention). Nowadays, people are expected to live almost 10 years longer than the mid-90s. Although life expectancy at birth has been steadily increasing for the past years, people are still exposed to a danger of chronic diseases, such as diabetes, hypertension, and arrhythmia.

Deaths: Final Data for 2013 shows that the leading cause of death in 2013 is diseases in heart (Centers for Diseases Control and Prevention). Moreover, diabetes is the seventh leading cause of death (Centers for Diseases Control and Prevention). These chronic diseases have relevant bio-signals that indicate health status of patients. For an instance, blood sugar level of a person who suffers in diabetes tells when he needs to inject insulin. If real-time monitoring of bio-signals is possible, doctors are able to anticipate urgent situations so that more lives can be saved. Recently, wearable or implantable wireless medical devices are developed to detect bio-signals from a patient and send data remotely to other devices.

Our capstone project is designing a low-noise amplifier (LNA) with very low power consumption. This LNA is a part of the bio-signal acquisition system described above. When a sensor first detects a signal, the signal is extremely weak to perform subsequent processes. Thus, an LNA needs to amplify the signal without adding too much noise. Most importantly, the LNA should consume less power as possible to maximize lifespan of the medical device. Our LNA expects to consume less than 10uW and can minimize its power consumption depending on how the data is going to compressed in the next module called compressed sensing (CS) block.

The whole paper explains about our business strategy focusing on industry analysis, market analysis, and relevant trends that may affect our product. The paper identifies the industry and market to figure out the best way to present the product in the world. Assuming commercialization of the capstone project, we take accounts various trends to sharpen our strategy.

2.2. Identification of Industry

We are mainly engaged in the activity of designing a LNA for ultra-low power and long-durability applications. Our main target customers will be in the business of medical implantable devices for real-time monitoring. We identify ourselves as the industry of semiconductor & circuit manufacturing and design based on the IBIS World Industry Report (Ulama). Since the industry has various facets, we will need to identify ourselves in a more specific area of the industry. We specify our area as designing integrated microcircuits.

In the integrated circuit (IC) industry, there are three main types of companies. The first type is a company that both designs and manufactures microcircuits, such as Intel Corporation or Advanced Micro Devices (AMD). Also, there is a company that provides manufacturing services to other companies, often referred to as a foundry, such as Global Foundries or Taiwan Semiconductor Manufacturing Corporation (TSMC). The third type is an entity that only designs ICs, not actually manufacturing chips. The term, fabless, is used to describe a company that does not own a foundry for the production of wafers (Ulama). The emergence of fabless is due to the increasingly high capital barrier in the fabrication segment of the semiconductor industry (Chen). The fabless business model requires much lower initial capital barrier and has higher return of invested capital (McKinsey & Company).

The main activity of the fabless is using a design platform provided by Electronic Design Automation (EDA) companies. Cadence Virtuoso is the most popular platform for designing IC. We design a circuit schematic and simulate for its functionality and performance. The circuit schematic is only an abstract level of circuit representation. It is not the actual blueprint of device manufacturing. The next procedure is to design the layout of the device. The layout includes more detailed information of how the microcircuit device is manufactured. The layout file is what needs to be sent to the foundries so that the chip can be fabricated and sent back to the designers for post-silicon testing. The procedure is often referred to as tape out.

Since we mainly target our product application at the medical implantable devices, the performance of the medical devices industry also greatly affects the profitability of our product. Our potential customers will come from this industry. This industry includes manufacturers of electro-medical and electrotherapeutic apparatuses, such as magnetic resonance imaging equipment, medical ultrasound equipment, pacemakers, hearing aids, electrocardiographs and electro-medical endoscopic equipment (Ulama). The revenue of this industry has seen steady growth of around 5 percent per year over the past 4 years. This makes our industry more lucrative.

2.3. Potential Impact to the Industry

Our main goal is to provide a reliable solution for remote health monitoring. Patients with chronic illnesses have to visit the hospital on a regular basis, and this inconvenient practice may overlook short-term variability of the patients' health status. The main problem with remote real-time monitoring devices is power dissipation. In order to make these devices last long, conventional circuit design techniques are not practical. For these applications, special circuit design methods need to be employed to suit the purpose of ultra-low power dissipation.

In electronic sensing devices, analog components consume much more energy than digital components. In our case, the digital module (CS) on which we will deploy our design is able to operate at as low as 22nW per channel (Allstot 1). However, the LNA, the interface between the sensor and this digital module, can only operate at as low as microwatts of power dissipation. Therefore if we can bring to the table a design that reaches the sub-microwatt region, implantable devices for remote health monitoring are much more practical.

2.4. Threat of Alternative Technology

External health monitoring is the most threatening alternative technology that we are facing. With the advent of more compact and powerful mobile platforms, wearable devices are booming in performance as well as popularity. It is also a much safer application compared to surgical operations that is a required step for implantable healthcare devices.

However the advantage of implantable devices should not be neglected. Implantable devices guarantee more accurate results compared to external sensing. External monitoring is prone to environmental variability such as humidity and temperature. Implantable devices are more reliable because human bodies tend to maintain temperature and humidity. Implantable monitoring devices can also interact with other implantable medical devices, such as pacemakers.

2.5. Competition in the Industry

The wireless medical device market is at the verge of experiencing rapid growth in the near future. In addition, we are not in the position where the dependence on the suppliers has much force on the profitability of the industry. Our suppliers are EDA companies that provide IC and layout design platforms. That is, in terms of a fabless, we do not need to worry too much about the manufacturing services, or the "foundry", which is far more capital intensive and supplier dependent.

The driving force here is rivalry. Many large companies are beginning to pay more attention to the wireless medical device market, such as Analog Devices (ADI), Qualcomm, and Philips. The core of competition is expected to be the R&D of the technology and innovative approaches to resolve the issue of long-lasting miniature device suitable for implantation. Because the industry is demanding and tends to favor more advanced technology, the profitability of the industry is undermined.

The main strategy that we adopt to counteract the rivals is to focus on novel design. For instance, Texas Instruments (TI) is taking effort to improve the power consumption of its DSP products to suit the purpose of ultra-low power applications (Ulama). However, in a severely energy constrained sensor, Compressed Sensing (CS) eliminates the need for digital signal processing (DSP). New design methodologies tend to undercut the advantage of established rivals such as TI and (ADI), who have full-fledged analog circuit design solutions.

After all, the main tactic to tackle rivalry—the main threat in our go-to-market strategy—is to aim at new and unconventional design techniques for ultra-low power applications.

2.6. Potential Buyers, Suppliers, and End Users

As we have mentioned briefly in the introduction, our buyers are wearable or implantable medical device manufacturing companies. We are targeting these companies because their products need ultra-low power LNAs to maximize their lifespan. It will be a laborious task for a user if he has to charge or switch a battery everyday. If a device is implanted in a person's body, changing a battery frequently is not a feasible option. As a result, the companies value electronic components with low power consumption. Our product will be one of their interests. We plan to sell our LNA chips to the companies, and they can integrate the chips with other parts of a medical device.

Although our buyers are the medical device manufacturing companies, we also need to identify who our end users are. Our end users are a group of people who are willing to purchase medical devices that contain our LNA chips. The primary users will be people suffering from chronic diseases, such as diabetes, hypertension, and arrhythmia. In their cases, real-time monitoring is almost mandatory to avoid life-threatening situations. We predict that health-conscious people are also our potential end users because there has been a prevailing trend of healthy diet and lifestyle. Some wearable medical devices are able to record heartbeat and blood pressure. People who want to keep track of those signals to check their healthy lifestyles may buy the products.

There are two main suppliers for our product: computer-aid design (CAD) software company and semiconductor foundry. Specifically, we need a subset of CAD software called electronic design automation (EDA) software to design LNA circuits. As we have mentioned previously, we will adopt fabless manufacturing model to produce LNA chips. In other words, semiconductor foundry is required to provide service of fabricating our chip design.

2.7. Power of Buyers and Suppliers

According to Michael E. Porter's *The Five Competitive Forces That Shape Strategy*, it is essential to analyze power of buyers and suppliers and reshape them in our favor to be competitive in the market (Porter). Fastidious customers can influence on the product's price and induce hyper-competition against rivals. On the other hand, powerful supplier can limit our profitability by charging higher price.

In our case, power of buyers is moderate. The United States medical device market is currently the largest in the world with the size of $110 billion (PRNewswire). It is expected to reach $133 billion by 2016. In addition, there are almost 6,500 medical device companies in the United States (PRNewswire). The reason why the market has been growing rapidly is that more people are eager to buy medical devices to treat chronic diseases. For instance, Emily Krol, health and wellness analyst, says that there is a large market of consumers for products and services specifically aimed to treat diabetes (Mintel). Although there are a plenty of buyers in the market, the other factor makes the power of buyers strong. A LNA chip, which is a part of semiconductor chip, is standardized and there are many competitors in the world. Thus, buyers have few switching costs.

In contrast, supplier power is almost negligible and cannot affect our marketing strategy. Buying CAD software from the company is merely one-time expense. After the purchase, we can keep using the software to design circuits. The other supplier, semiconductor foundry, experiences high competition in its own field, and circuit design is very standardized (Ulama). As a result, we can switch easily among vendors, weakening the power of suppliers.

2.8. Basic Marketing Strategy

The marketing mix is a fundamental business tool to sharpen marketing strategy. It is associated with the four P's: product, price, promotion, and place. Our product has to have the advantages on power consumption and chip area over other competitors. Our main target is a medical device company that demands such specifications. Without differentiated technology, it will be hard to find buyers. In order to mitigate the power of buyers, we need to make sure that our LNA chips can affect the industry's product much. In other words, if our chips can make a medical device that lasts twice longer than other chips, the companies will purchase our products. We focus on wearable or implantable medical device segment because this segment is sensitive to power consumption.

Price of our products should not be high unless there is a huge technological gap between us and other competitors. When we think of the end users, such as people with chronic diseases, they are not particularly affluent. Medical device companies will try to minimize the price of their products so that average people can afford them. In other words, the companies will not pay a large amount of money on small components of their devices. However, we cannot lower our price below a certain point because there is a fixed cost of outsourcing manufacturing process.

Since our main type of transaction is business-to-business (B2B), there are not various options for promoting the products. As a new entrant, our primary strategy is to create a solid network in the market. To prove the product's reliability and technological advantages, we should hand out the samples of our LNA chips to the potential customers for free. Although this strategy may weaken our financial status in a short term, it will help us secure the customers in a long term. Because we deal with B2B transactions, there is no need for physical stores for distribution. We can directly sell the products to buyers. This strategy implies that the promotion and quality of the products are very important factors for our sales. As we expand the business, we may sell the products to different markets other than medical device market to increase profitability.

2.9. Social Trends

As we have analyzed about the buyers in his part, the U.S. society tends to pay more and more attention to health care. And the *Death: Final Data of 2013* reports the diseases in heart the dominant factor of death among diseases (Centers for Diseases Control and Prevention). This fact gives us an advantage to mitigate the force of customers, according to Porter's five forces theory, though the patients are not our direct customers (Porter). Our direct customers are wireless medical device companies, who will embed our design in their products. We identify the end-users of our product as patients who are using these implantable devices. In addition, people are becoming increasingly conscious of their well-being, which implies that there is a huge potential market for real-time health monitoring. In fact, CNBC is reporting a rapid growth of wireless medical device in the United States.

2.10. Technological Trends

As mentioned in previous section, social trends are opening a potential market for real-time health monitoring market. In addition, the rapid development of Information technology (IT), such as the advances in video communication, wireless connectivity to the Internet, and the increasingly popular web-assisted self-learning, is contributing greatly to the feasibility of exploiting this market.

Meanwhile, what plays a more important role in our product is low power semiconductor design and manufacturing. Moore's Law, which was proposed in 1965, predicted the roadmap of the technological and economical advance of Integrated Circuit industry (Schaller). However, as the semiconductor industry proceeds deeper into the submicron region, it is increasingly difficult for the industry to advance the technology at the pace that the Moore's law had successfully forecasted for the past half century.

Since leakage power is becoming the dominant aspect of power dissipation in Integrated Circuits, low power design technology is becoming the main effort taken during circuit design nowadays. The influence of this industrial trend is both challenging us and exposing us to opportunities. More competitions might be generated from academia due to research but we can also make use of lately published papers to help with our low power design. In other words, the field is moving forward and refreshing itself quickly and we are traveling in a fast train, experiencing both risks and opportunities.

2.11. Economic Trends

As we have discussed in the industry section, Integrated Circuit industry has high capital barriers for the fabrication segment, though fabless companies experience relatively lower barriers. Economic aspects play important roles in the industry. The Gross Domestic Product (GDP) growth rate in US has also increased in the past years (Schaller). And the termination of Quantitative Easing by the US government is attracting a large amount of hot money or refugee capital from the rest of the world to the US, which is good news for new entrants in this industry. Combined with the fact that the semiconductor industry is reaching the physical limitation of how small a device can be made, R&D investment in unconventional IC design techniques are attractive to investors targeting at new applications such as the wireless medical devices market.

2.12. Regulatory Trends

The U.S. government has well developed regulations in health care field. But as a relatively new set of products, wireless medical devices are not facing a strong limitation from the regulations. Since we are building a device that will be implanted in the patients' body and collect data for a long time, new regulations about this might appear in the future, which has not been seen. Regardless of this factor of potential change, regulatory factors are negligible in our business.

2.13. Business Strategy to Cope with The Trends

As mentioned in the previous section, social and economic trends are favoring our business, regulatory factors do not have strong influences on us, and the rapid development of the core technologies relevant to the industry is putting us into both risks and opportunities. Our strategy on these trends can be concluded as follow. We need to catch the opportunity provided by the rapid growth of the wireless medical device industry and the recent uprising trends of US economy, which means we need to act quickly. More importantly, we have to do well in the technology part to avoid being outcompeted by rivalries in the industry. On the technological aspect of the strategy, we should explore on novel design methodologies to gain technological edges over competitors. Thus, keeping firm connection with academia is also a crucial concern in our strategy.

3. Intellectual Property Strategy

3.1. Introduction

In July 1959, Robert Noyce was granted for the first integrated circuit patent for his innovative idea, and the actual functional prototype was fabricated in May 1960 (Computer History Museum). After his patent, the number of patents related to IC research and design has grown exponentially over the past half century. Protection of intellectual property is a sensitive issue in the realm of IC research and design because excessive time and resources are required to make a significant breakthrough. In reality, the situation of IP protection in the industry is unsatisfactory. SEMI has reported that over 90 percentage of the semiconductor R&D, design and manufacturing companies have experienced certain extent of IP violations (SEMI). To avoid such situation later on, we will discuss the patentability of our design and scrutinize other alternatives.

3.2. Patentability of Our Design

An Integrated Circuit is a product that includes at least one active element, in which majority of the components and interconnects are formed on a single piece of material to perform a desired function (World Intellectual Property Organization). Because the property of our product matches with this definition, we should attempt to patent our design as an IC product.

First, it is beneficial to clarify key technologies of interest in our project before discussing the patentability of our design. The key features of our design include two aspects: ultra-low power consumption and high signal-to-noise ratio. To achieve ultra low power design, we will employ techniques to reduce the DC bias current of the circuit, such as sub-threshold transconductance design. To achieve the goal of high signal-to-noise ratio, we will use techniques such as chopper stabilization method and low-pass filter.

Here, we discuss some first order criteria for determining patentable ideas related to IC design. These criteria include usefulness of the design, novelty of the concept, the extent of innovation or differentiation compared to other designs aiming at the same functionality, the extent of clarity of the design description, and the boundary of the scope of the definition (Bellis). There are plenty of applications that we can employ our low-noise amplifier (LNA), such as digital interface to the external off-chip components (Enz 335). Thus, assuming that we can meet all the required specifications, the usefulness of the design is unlikely to be contested. However, we are utilizing several existing LNA design techniques to design our prototype, so the extent of differentiation among counterparts is unlikely to be high. Therefore, we can conclude that it is unlikely for us to patent our design.

3.3. Existing Similar Patent

It was difficult to find a patent that is closely related to our design. The main reason was that we combined existing technologies to build up our LNA. After searching rigorously, we found a patent named Mobile Wireless Communications Device Including A Differential Output LNA Connected to Multiple Receive Signal Chains (U.S. Patent). It was published in 2010. In the semiconductor industry, it is better to pick up a patent published recently to compare because the technology life cycle tends to be very short (Rethinking Patent Cultures).

3.4. Possible Similarity and Distinction

The patent is about a whole communication system, including receiver, transmitter, antenna and other electrical components. In contrast, our LNA is merely a part of a bio-signal acquisition system. The reason why this patent may be related to our product is that the system contains an LNA as one of its components. The patent has an LNA that takes the output of a receiver as input and delivers the output signal to multiple signal chains through a power divider. However, our LNA is designed to take the output of an ECG sensor as the input and deliver the signal to the compressed sensing module.

Although it may seem that there is a little similarity, we do not think that there is a major overlap; there is almost no risk of developing our product without purchasing a license. The patent is about a whole system, and it contains a component whose functionality is similar to our product. The idea that is patented is focused on the whole functionality of system.

Even the system's LNA specification is different from our product. The specification of our product requires only a narrow bandwidth, low carrier frequency and ultra low power consumption. On the other hand, a mobile communication system operates at radio frequency with a relatively wide bandwidth, and the power consumption is not necessary to be very low. When we design circuits under different specifications, we basically deal with two distinct designs. In conclusion, we do not think a license is needed in our development process.

3.5. Alternative Options and Potential Risks

Since applying for a patent is not feasible in our current situation, other alternatives should be scrutinized carefully. There are four other ways to protect intellectual property from external usage: a trademark, copyright, trade secret, and open source (Intellectual Property Crash

Course). All of them have different characteristics from a patent, and each one has its own strength and weakness.

The first option is applying for a trademark. A trademark is simply a word or symbol that embodies the source or sponsorship of a particular product or service (Intellectual Property Crash Course). Our final product will be an LNA, and it does not have any particular name or symbol to strengthen its marketability. Also, a trademark does not protect the essence of our project.

The Second option is copyright. Unlike patent, copyright only protects the expression of an idea, and the idea itself is not secured (Intellectual Property Crash Course). Most importantly, in the United States, copyright only protects the layout design, not the circuit schematic (U.S. Copyright Office). Since our main focus is not the layout design, this option is not appropriate.

The third option is a trade secret. The recipe for Coke is a classical example of trade secrets. Unlike patent, a person can keep a trade secret for a long time. A person does not need to worry about other people seeing how his product works. A trade secret is perfect if a product is useful for several generations. However, in our case, the lifespan of the technology is very short.

The last point is an open source. This option is meaningful if we deal with software. The whole purpose of making a product as an open source is to contribute the invented technology to the industry. In our case, the project is a circuit design so that this option is also not applicable.

Finally, we should think of some potential risks of not protecting our ideas legally. We conceive that, at this point, there is no such risk. Usually it takes years for a patent to be issued after the first application. It means that we need to devote extra time and resources to such process. Knowing that technology life cycle is very short in our industry, it is better for us to focus on developing more superior technology until it is more suitable for a patent.

4. Technical Contributions

4.1. Overview

The ultimate goal of the whole capstone project is designing a low-noise amplifier (LNA) that is suitable for bio-signal acquisition systems. Although there are many different types of the acquisition systems available, the primary focus is on the system recording the electrical activity of a person's heart by an electrocardiography (ECG) sensor. In general, heartbeat signals detected by the ECG sensor are extremely weak to perform any kinds of signal processing. Thus, the proper LNA is needed to amplify the signals while not adding an excessive amount of noise to the original signals.

The appropriate amplifier topology should be chosen to achieve the desired gain while mediating the potential trade-offs. In addition, the major types of noise associated with the LNA have to be identified and minimized effectively. In the modern complementary metal-oxide-semiconductor (CMOS) technology, the 1/f noise, or flicker noise, performance is critical in the low-frequency application. A typical ECG signal consists of various kinds of waveforms, such as P-wave, T-wave, and QRS complexes (Lin 680). These signals are important for diagnostic purpose, and they are heavily concentrated in the range between 0 Hz and 20 Hz, where the 1/f noise is dominant (Lin 680). To keep the signals practical, a special circuit technique should be employed to reduce the effect of the 1/f noise. Moreover, the thermal noise is the other type of noise that is presented over all frequency range. If the thermal noise can also be minimized, the performance of the LNA will be improved.

The particular focus of the paper is to reduce the 1/f noise and amplifier design. Unlike the thermal noise, the 1/f noise affects ECG signals significantly due to its low frequency range. In other words, without the 1/f noise, the amplifier's signal-to-noise (SNR) ratio, one of the most important performance metrics of the LNA, goes up dramatically. In the next section, the basic characteristics of ECG signals and overview of the bio-signal acquisition system are presented. Moreover, the 1/f noise is briefly explained, and some circuit techniques to minimize the effect are scrutinized. After all, the chopper stabilization method is chosen for the LNA to reduce the 1/f noise. The details of the amplifier and chopper stabilization technique are described in the third section with the actual circuit schematic implemented with 32/28nm PDK provided by Synopsys. Cadence Virtuoso 6.1.5 tool suite is used to run simulations. The simulation results are shown in the last section to demonstrate the performance of the final LNA.

4.2. Knowledge Domains

4.2.1. ECG Signal Characteristics

It is important to understand the basic characteristics of the input signal of the LNA in order to maximize its performance. There are many types of bio-signals that facilitate a doctor's diagnostic: ECG, EEG, and EMG. Each bio-signal is a precise indication of a chronic disease. For instance, an ECG signal gives a general insight of whether a person suffers from a heart-related disease, such as arrhythmia or pericarditis (Silva 154). The primary purpose of the LNA is to amplify an ECG signal large enough so that it can be transmitted to other mobile devices. Ultimately, a doctor is able to receive the data from the mobile device and interfere it properly.

An ECG signal consists of the voltage differences between two of the electrodes (Bharadwaj). Because of half-cell potential produced at the electrodes, a maximum offset voltage of $\pm$300 mV is present while the actual desired signal is super-positioned on the offset (Bharadwaj). The desired signal is always the differential output of the electrodes, and its amplitude range should be identified to determine the required gain of the LNA. The typical range of the amplitude is from 0.02 mV to 5mV (Silva 154). Because the amplitude varies much within the signal, the reference amplitude needs to be chosen. The LNA is expected to achieve at least the gain of 60 dB to amplify the signal.

The frequency range of an ECG signal is generally from 0 Hz to 100 Hz (Silva 154). However, the most essential features that characterize the heartbeat are in the range between 0 Hz and 20 Hz. The QRS complex is a combination of three unique deflections seen on the ECG signal (School of Health Sciences). The individual QRS's frequency spectrum is shown in the range from 0 Hz to 20 Hz (Lin 681). In addition, the frequencies of ventricular tachycardia and ventricular fibrillation are concentrated between 4-7 Hz (Lin 681). Other than the noise generated by the amplifier stage, mainly 1/f noise, the noise introduced by the power lines should be concerned. Usually, power line interference generates common mode noise at 50 Hz or 60 Hz (Bharadwaj).

4.2.2. Bio-signal Acquisition Systems

A bio-signal acquisition system that the LNA is targeting is a wireless medical device detecting a heart signal. The device is either implantable or wearable, enabling real-time monitoring of a heart signal from the doctor's office. The block diagram of the system is shown in Figure 1. Minimizing the power consumption of the device is important because it is directly related to its lifespan. Various attempts are made to reduce the power consumption, and compressed sensing (CS) module is one of the examples. This sampling method is a data acquisition approach that only requires a portion of the measurements to compress the sparse signals (Dixon 156). Because a heart signal is relatively sparse, CS block can be used to reduce the size of the data needed to transmit outside.

The most front-end part of the system is an ECG sensor that detects a heart signal. Then the LNA amplifies the signal large enough so that the signal can be processed in the next steps. Amplified signal is compressed to reduce its data size by the CS block. The compressed signal is then modulated properly and transmitted through the antenna. Usually, the LNA consumes relatively much more power than other blocks. No matter how much the data is compressed or how much power consumed by other blocks, the power consumption of the LNA dominates the whole power performance of the system. Therefore, the LNA has to be designed in a way that its power consumption is comparable to other blocks.

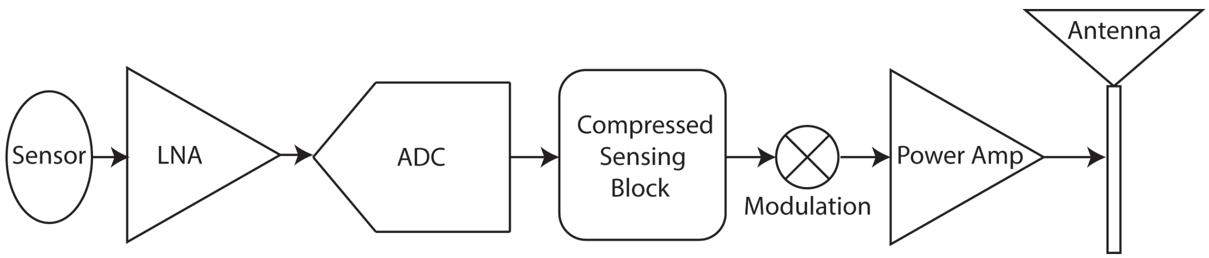

Figure 1: Block diagram of bio-acquisition system

4.2.3. 1/f noise

The 1/f noise is found in all active devices. Passive elements, such as resistors, capacitors, and inductors, do not exhibit such phenomenon. Although there are various causes of the noise, electron traps associated with device defects and contamination mainly induce this type of noise (Gray 741). These traps introduce a relatively high noise signal concentrated at low frequencies. Its spectral density is directly related to a flow of direct current, I.

$$\frac{\overline{i^2}}{\Delta f} = K\frac{I^a}{f^b}$$

The values of a, b, and K are constant, and the value of b is usually about unity, which indicates a 1/f frequency dependence. Usually, a PMOS transistor has a lower K factor. If a transistor that contributes overall noise the most can be replaced as a PMOS transistor, the noise performance would be maximized. Figure 2 visualizes the 1/f dependence of the noise-current spectral density.

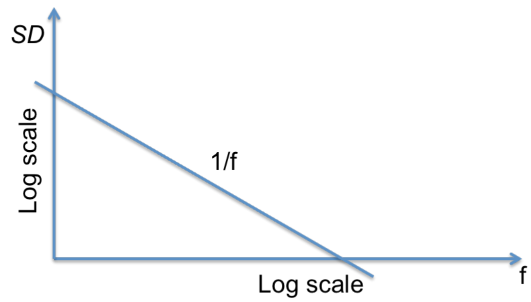

Figure 2: Flicker noise characteristic

4.2.4. Circuit Techniques for reducing 1/f Noise

One of the most important non-ideal effects of the amplifier is introducing the noise, such as 1/f and thermal noise. Besides choosing an appropriate topology for the amplifier stage, an effective circuit technique that reduces the effects of such non-ideality needs to be integrated to improve the performance the whole amplifier. The two most popular methods to attenuate 1/f noise are briefly presented.

4.2.4.1. Auto-zeroing

Auto-zeroing method reduces the effect of the 1/f noise by a simple sampling technique. The fundamental insight of the technique is sampling the undesired noise and then subtracting it from the instantaneous value of the original signal (Enz 1585). The two different phases are used for the entire process: a sampling phase and signal-processing phase. Although auto-zeroing technique attenuates the 1/f noise, the output noise is then dominated by the amplifier's under-sampled white noise; the white-noise component is multiplied by a factor of $\frac{\pi f_{chop}}{T_s}$ (Enz 336).

4.2.4.2. Chopper Stabilization

In contrast to auto-zeroing technique, the chopper stabilization method does not use sampling to reduce the noise. The modulation before the amplifying stage and the demodulation after the amplifying stage move the 1/f noise effect to a higher frequency while maintaining the amplified desired signal in the original band. The same square-wave carrier signal is used for both modulation and demodulation. After the demodulation, a low pass filter needs to be placed to attenuate the undesired signals at high frequency. Unlike auto-zeroing technique, the chopper stabilization process does not increase the white noise; therefore, the chopper technique is more adequate for the LNA design.

4.2.5. Ring Amplifier

Recently, a new amplifier topology called ring amplifier is discovered. A ring amplifier is thought of future of analog amplifiers because it enables efficient amplification in scaled environments (Hershberg 2928). A ring amplifier looks similar to a ring oscillator, which consists of three invertor stages with feedback. A ring oscillator structure can provide decent amount of gain; however, it has stability issues. To prevent oscillation, the second invertor stage is spitted into two and two different offset voltages are applied (Lim 202). Unlike a regular invertor, the third stage has two input signal paths. Two transistors in the third stage are biased in a way that both of them are in deep sub-threshold region to maximize the output-stage resistance (Lim 202). The detailed schematic of a ring amplifier is shown in Figure 3.

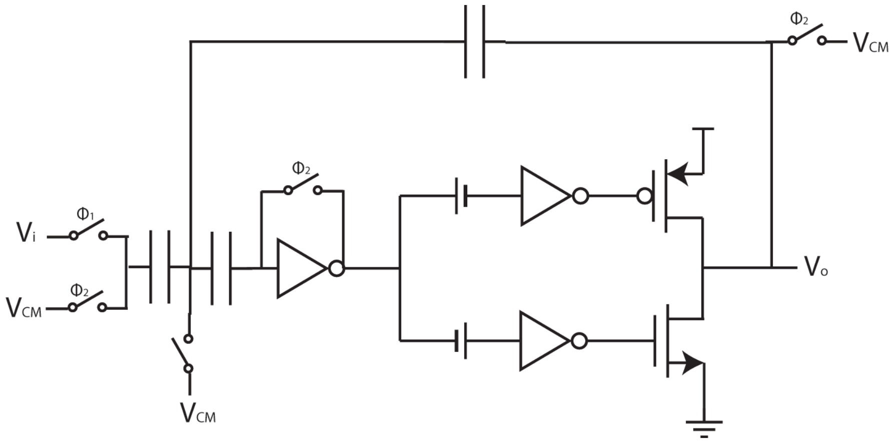

Figure 3: Schematic of a ring amplifier

A ring amplifier has many advantages over traditional amplifiers. The recent trend of integrated circuits is that using lower V_{DD} and smaller transistors, resulting low quiescent current. However, traditional amplifiers require high quiescent current for slewing, not taking advantage of the modern technology fully (Lim 202). A ring amplifier, on the other hand, has the benefits of efficient slew-based charging so that even small size transistors can still produce high slew rate (Hershberg 2933). Most importantly, its three-stage structure ensures that the overall gain is high. In addition, since the last stage operates in sub-threshold region, it guarantees high output voltage swing.

Similar to switched capacitor feedback structure, a ring amplifier operates in two different phases: Φ_1 and Φ_2. When Φ_2 is high, the DC operating points are set to V_{CM}. When Φ_1 is high, the input signal goes through the signal path. The clock signals should have non-overlapping regions to ensure that the amplifier is working correctly. The transistors should be sized properly so that linear region is maximized.

4.3. Methods and Materials

4.3.1. Theoretically Approach to Chopper Stabilization

The chopper stabilization technique is employed to minimize the effect of the 1/f noise of the amplifier. The ECG signal, $v_{in}(t)$ is first multiplied by the square-wave carrier signal, $m_1(t)$, with the period of $T = \frac{1}{f_{chop}} = \frac{2\pi}{\omega_{chop}}$. The square-wave signal has the amplitude of one and has ideally 50% duty cycle. To examine the effect of the signal multiplication, the Fourier series of $m_1(t)$ is calculated.

$$m_1(t) = \sum_{m=-\infty}^{+\infty} a_m e^{jm\omega_{chop}t}$$

$$a_m = \begin{cases} \dfrac{2sine(\frac{m\pi}{2})}{k\pi} e^{-\frac{jm\pi}{2}}, & m \neq 0 \\ 0, & m = 0 \end{cases}$$

a_m becomes zero if m is even, and $a_m = -a_{-m}$ if m is odd. The index of summation can be changed to the positive integer k, and the $m_1(t)$ can be represented with the sum of the odd harmonics of sine waves.

$$m_1(t) = \frac{\pi}{4} \sum_{k=1}^{+\infty} \frac{sin(2k-1)\omega_{chop}t)}{(2k-1)}$$

$$m_1(t) = \frac{\pi}{4}\left\{\sin(\omega_{chop}) + \frac{1}{3}\sin(3\omega_{chop}) + \frac{1}{5}\sin(5\omega_{chop}) + \cdots\right\}$$

The multiplication in time domain is the same as the convolution in frequency domain. The Fourier transform of $m_1(t)$, the sum of the odd harmonics of sine waves, is convoluted with the Fourier transform of $v_{in}(t)$. The Fourier transform of the modulated signal, $v_m(t)$, is shown in Figure 4. The input signal is transposed to the odd harmonic frequencies of the square wave after the modulation.

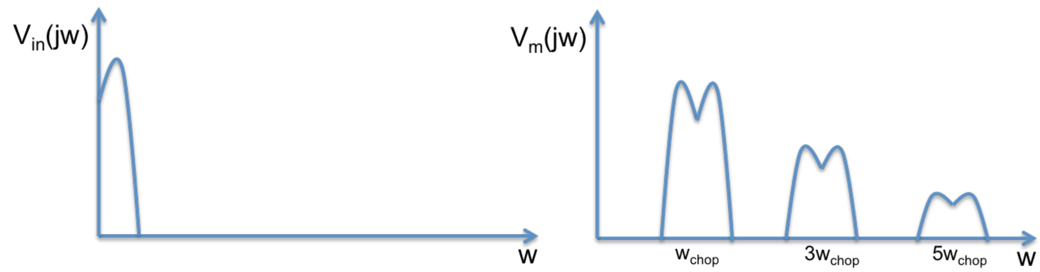

Figure 4: Effect of modulation

The modulated signal is then amplified by the amplifier stage of the LNA with the factor of voltage gain, A_v. As the signal is magnified, the 1/f and thermal noise of the amplifier interferes the modulated signal. Thus, the output signal of the amplifier stage is the superposition of noise and the modulated signal. The output signal is then demodulated with the square-wave signal, $m_2(t)$, which is the same as $m_1(t)$.

Assuming the noise and original input signals are independent, the effect of demodulation on those signals can be analyzed separately. Unlike the ECG signal, the noise from the amplifier is multiplied by the square-wave signal only once. The noise spectrum is now moved to the odd harmonic frequencies of the chopper stabilization. On the other hand, the modulated signal merely shifts to the even harmonic frequencies after the demodulation. It is important to choose the chopper frequency ω_{chop} properly to eliminate the contribution of the 1/f noise. It should be at least twice larger than the corner frequency. Figure 5 illustrates the whole process of the chopper stabilization.

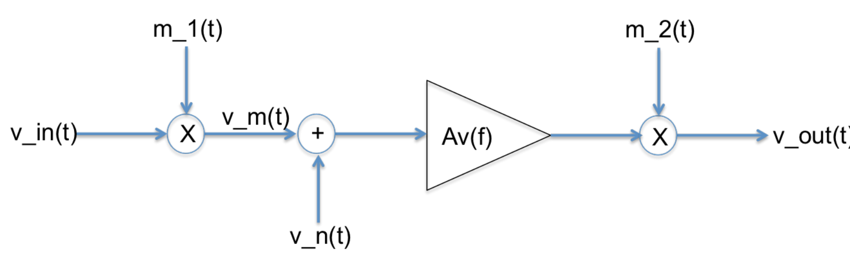

Figure 5: Chopper stabilization diagram

4.3.2. Physical Implementation of Chopper Stabilization

Multiplying the input signal, the ECG signal, with the square-wave signal with the amplitude of one is the same as alternating the sign of the input signal repeatedly. The product of two signals is identically to the input signal during the time when the square-wave signal is high. Whereas the product has the negative value with the same magnitude of the input signal during the time when the square-wave signal is low. This process can be realized physically using four ideal switches. Figure 6 shows how the switches are connected.

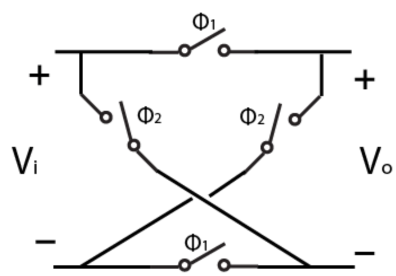

Figure 6: Physical implementation of chopper stabilization

Φ_1 and Φ_2 indicate two different phases. If two switches with Φ_1 are on, the other two switches with Φ_2 are off; only two out of four switches are on during a chopper period. When two switches with Φ_1 are on, the differential output signal of the structure is the same as the differential input signal. One wire connects the positive nodes while the other wire connects the negative nodes. When two switches with Φ_2 are on, the positive node of the input is connected to the negative node of the output, and the negative node of the input is connected to the positive node of the output. As a result, the differential output signal is the same as the negative differential input signal. There should no overlapping between clock signals that provide two different phases. If all four switches are either on or off, the structure does not provide the desired modulation.

An ideal switch is a short circuit when it is on while it is an open circuit when it is off. A switch can be implemented by using a single NMOS transistor. By manipulating its gate to source voltage, the amount of current flowing through the transistor is controlled. If the gate to source voltage is less than the threshold voltage, there is no current flowing so that the switch is off. If the gate to source voltage is higher than the threshold voltage, the transistor acts as a simple resistor so that the switch is on. Its resistance value varies depending on whether is on or off. On resistance, R_{ON}, and off resistance, R_{OFF}, are calculated below.

$$R_{ON} = \frac{v_{ds}}{i_d} \approx \frac{1}{\mu C_{ox}\left(\frac{W}{L}\right)(V_{GS} - V_{th})}$$

$$R_{OFF} \approx r_o = 1/\lambda I_D$$

In other words, to mimic the on characteristics of an ideal switch, $\frac{W}{L}$ ratio should be minimized. A chopper structure built with NMOS transistors is simulated while varying their $\frac{W}{L}$. The transient output waveform of the chopper stabilization exhibits larger spikes during non-overlapping region of clock signals when $\frac{W}{L}$ is bigger. This unwanted behavior seems to be caused by channel charge injection. When a NMOS switch is on, a charge is stored in its channel and this charge is discharged to both source and drain, influencing the output voltage level. A transistor with minimum size can reduce the effect of charge injection. Theoretically, a dummy transistor placed adjacent to the transistor can minimize the charge injection more; however, the simulation result shows that its effect was not significant. In addition, although the minimum size switch does not have the smallest R_{ON}, the simulation result indicates that the chopper stabilization with minimum size switches does not hurt its performance. The most important crucial downside of using a NMOS transistor as a switch is that it can only transfer a signal up to $V_{DD} - V_{th}$. A transmission gate may be used as a switch instead of an NMOS transistor to transfer a signal from 0 to V_{DD}. However, DC operating points of the amplifier will be around a half of V_{DD}, so a single NMOS transistor is sufficient.

After all, the chopper stage consists of four NMOS transistors with the minimum width and length. In 32/28nm PDK, the minimum width and length are 100 nm and 30 nm respectively. The gates of two transistors are connected to a clock signal with the phase, Φ_1, and the gates of the other two transistors are connected to a clock signal with the phase, Φ_2. The clocks signals have 48 % duty cycle and their on-amplitudes are equal to V_{DD}. In 32/28nm PDK, V_{DD} is set to 1.05 V. The bulks of the transistors are all connected to ground to insure that the bulk to source and bulk to drain pn junctions are reversed biased.

4.3.3. Physical Implementation of Amplifier

Various circuit topologies are available nowadays to design the LNA. Four most popular topologies are telescopic, folded-cascode, two-stage, and gain-boosted amplifiers. Each of them has a different set of advantages, and some of them are not appropriate for our application. For instance, telescopic topology is not a suitable approach because V_{DD} of the 32/28nm technology is set to 1.05 V. Gain-booted topology is also not appropriate for a LNA design since it consumes more power compared to other topologies. Typical folded-cascode or two-stage topology would have chosen to design the LNA; however, the team has decided to endeavor to adopt the idea of a ring amplifier and advance it to design the LNA.

First, a regular ring amplifier is designed in the 32/28nm technology to see whether it is appropriate for an LNA application. A ring amplifier structure is very sensitive to the offset voltages applied in the second stage. If their values do not set the transistors of the third stage in sub-threshold region, the amplifier starts to oscillate. In short channel technology, a transistor’s sub-threshold voltage is sensitive to its channel length. The length of the transistors in the third stage is set to maximize the sub-threshold voltage. The inverter in the first stage is sized to provide a large gain. In order to do that, characteristics of CMOS inverter's voltage transfer curve should be analyzed. The voltage transfer curve is shown in Figure 7.

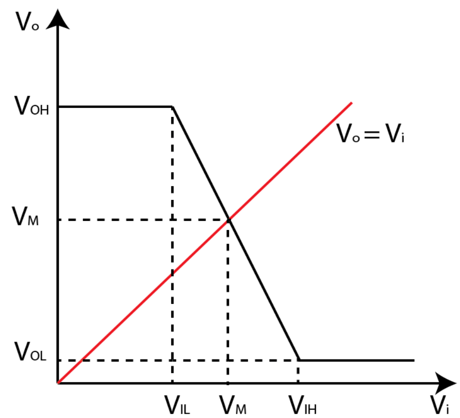

Figure 7: CMOS voltage transfer curve

In our case, $V_{OH} = V_{DD} = 1.05\,V$ and $V_{OL} = 0V$. The edges of linear region are not actually linear as shown in the figure. Thus, it is important to set V_M to $\frac{V_{DD}}{2}$ to maximize the linear region. The gain of small signal is the slope of the linear region around V_M. Current flowing both PMOS and NMOS transistor are same, and both of them are in saturation region.

$$\frac{\mu_p C_{ox}}{2}\left(\frac{W}{L}\right)_p \left(V_{DD} - V_M + V_{thp}\right)^2 = \frac{\mu_n C_{ox}}{2}\left(\frac{W}{L}\right)_n (V_M - V_{thn})^2,$$

$$ignoring\ a\ short\ channel\ effect$$

$$\therefore\ V_M = \frac{V_{DD} + V_{thp} + \sqrt{\frac{\mu_n\left(\frac{W}{L}\right)_n}{\mu_p\left(\frac{W}{L}\right)_p}}}{1 + \sqrt{\frac{\mu_n\left(\frac{W}{L}\right)_n}{\mu_p\left(\frac{W}{L}\right)_p}}}$$

Thus, the ratios between $\left(\frac{W}{L}\right)_n$ and $\left(\frac{W}{L}\right)_p$ are set properly to make V_M close to $\frac{V_{DD}}{2}$. The small signal gain of an inverter is simply $(g_{mn} + g_{mp})(r_{on}||r_{op})$.

The designed ring amplifier has a sufficient gain to use it as an LNA, but it is not exactly suitable for our application. Since the amplifier has single ended input and output, the chopper stabilization is hard to be employed within the amplifier. Most importantly, the ECG signal, as mentioned in the knowledge domain section, is a differential signal so that an amplifier with single ended input is not appropriate. The pseudo differential amplifier with two ring amplifiers is designed to receive a differential signal. However, its common mode rejection ratio (CMRR) is very low, resulting that the output signal is vulnerable to high common mode noise coming with the ECG signal.

To fix the problem of having a single ended input, the second version of amplifier is designed with a differential input. The first stage of the second version is a simple differential amplifier with a switched-capacitor common mode feedback (CMFB), so that the chopper stabilization can be added before the first stage and after the first stage. The second stage is the differential pair with a single ended output. The third stage of the second version is identical to the third stage of the previous amplifier to maximized the output resistance and add more gain. The overall schematic is shown in Figure 8, and its CMFB is shown in Figure 9.

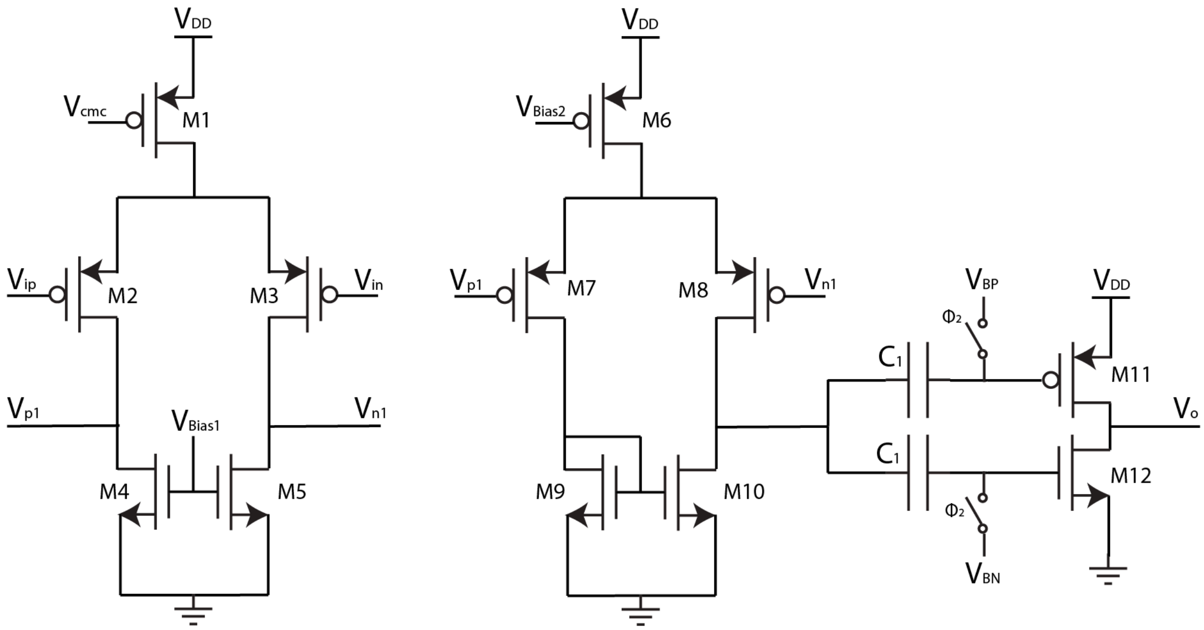

Figure 8: Schematic of the second version

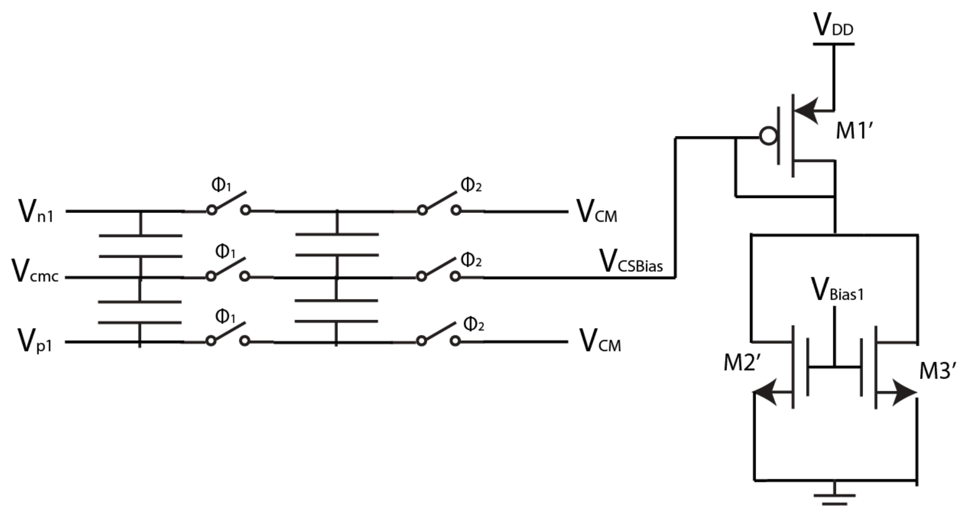

Figure 9: Schematic of the switched-capacitor CMFB

One of downsides of this design is that it needs extra time for CMFB to settle. In addition, it tends to oscillate when it is in closed loop. Thus, the third version of amplifier is designed to eliminate the switched-capacitor CMFB and still adopt the advantages of a ring amplifier.

The key idea behind the third version is that creating a new first stage that has differential input and output without complicated CMFB. Knowing that CMOS inverter structure can boost up the gain, two CMOS inverter structures with a PMOS current source are used as the first stage. Similar to the ring amplifier, this amplifier operates in two phases: Φ_1 and Φ_2. The output nodes of the first stage are connected to switch so that when Φ_2 is high those DC operating points are set to V_{CM}. The output and input of the entire amplifier are also set to V_{CM} when Φ_2 is high. The feedback capacitance C_f is set to 10fF while input capacitance is set to10pF to maximize the gain. Multiples of small metal fringe capacitors can be used to realize such small feedback capacitance in real application (Tripathi 2241). The second and third stage of the third version is identical to the second version with proper biasing. Since the third version demonstrates the best overall performance, the design is chosen as our final LNA design. The detailed schematic is shown in Figure 10.

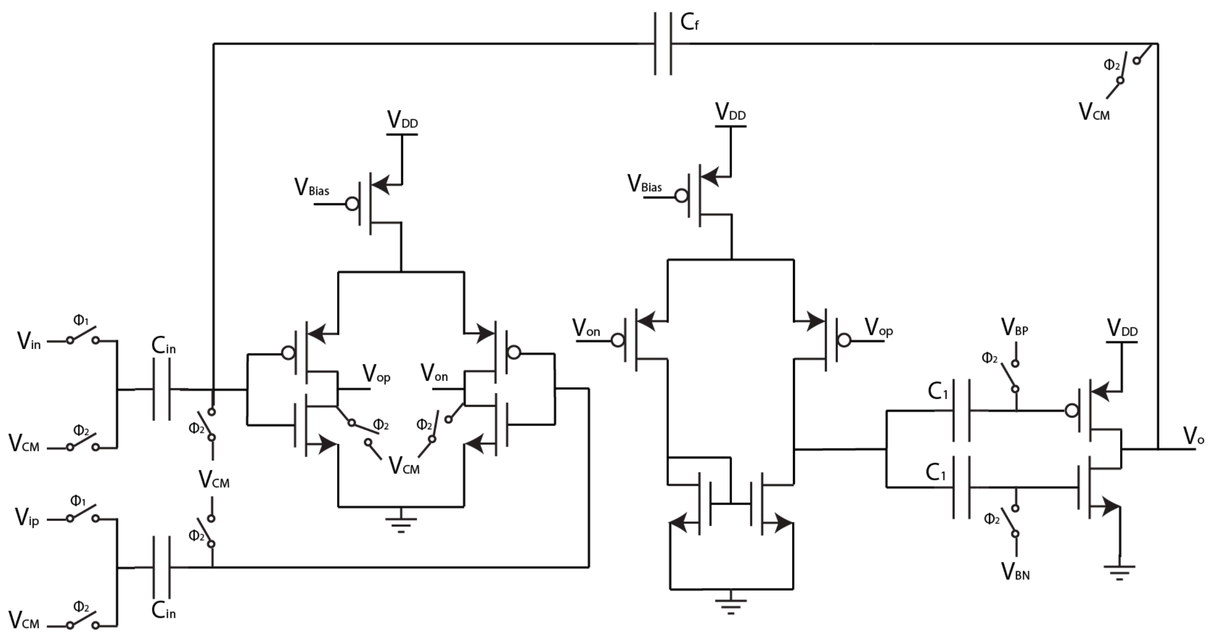

Figure 10: Schematic of the final amplifier

In addition to the amplifier structure, the chopper stabilization is connected to the input of the first stage and the output of the first stage to remove the 1/f noise. The diagram of the whole LNA is shown in Figure 11.

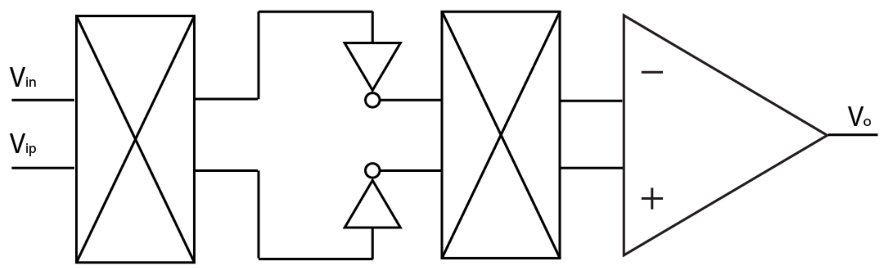

Figure 11: Diagram of the final LNA structure

4.3.4. Simulation

Cadence Virtuoso is used to run the simulations. The pulse generators are clock signals, and two sine wave generators are connected to the input of the LNA as an ECG signal. The amplitude of the sine wave is set to 0.1 mV. The chopper frequency is set to 10 kHz. Transient analysis is performed on the system to figure out the gain of the sampled output and check whether the input ECG signal is modulated and demodulated properly. Pnoise analysis is to verify whether the squared output noise is reduced significantly by the chopper stabilization.

In addition, to calculate noise metrics including SNR, the sampled transient output points are exported and analyzed by Fast Fourier Transform (FFT) in MATLAB. The needed input frequency is determined by the sampling frequency and the number of samples to ensure coherent sampling. In our case, the sampling frequency is 1kHz, and the number of samples is chosen as 256 (2^8). The desired input frequency is 10Hz, which a typical frequency of ECG signals. Since the closest prime number to $N\frac{f_{desired}}{f_s}$ is 3, the input frequency for this analysis is chosen as $\frac{3}{N}f_s$=11.72Hz.

4.4. Results and Discussion

The performances of three different versions of amplifier are compared in Table 1.

	Ring Amplifier (v1)	Intermediate Design (v2)	Final Design without Chopper	Final Design (v3)
Power consumption	2.75 uW	5.516 uW	5.315 uW	5.315 uW
Closed loop Gain	57dB	-	59dB	59dB
SNR	76.78dB	45.83dB	60.33dB	78.75dB
SNDR	28.09dB	45.44dB	60.33dB	53.57dB

Table 1: Performance Metrics

The detailed noise spectrums are show in Figure 12, 13, 14, and 15.

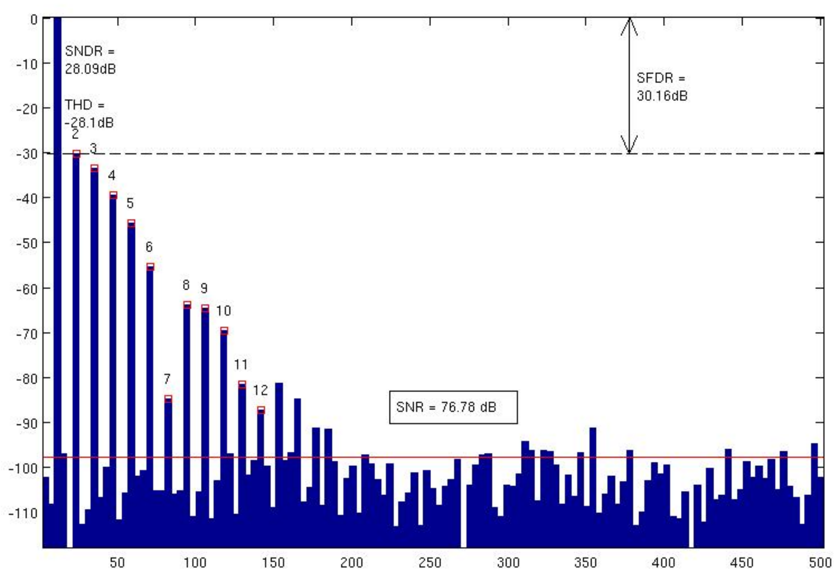

Figure 12: Noise spectrum of the first version

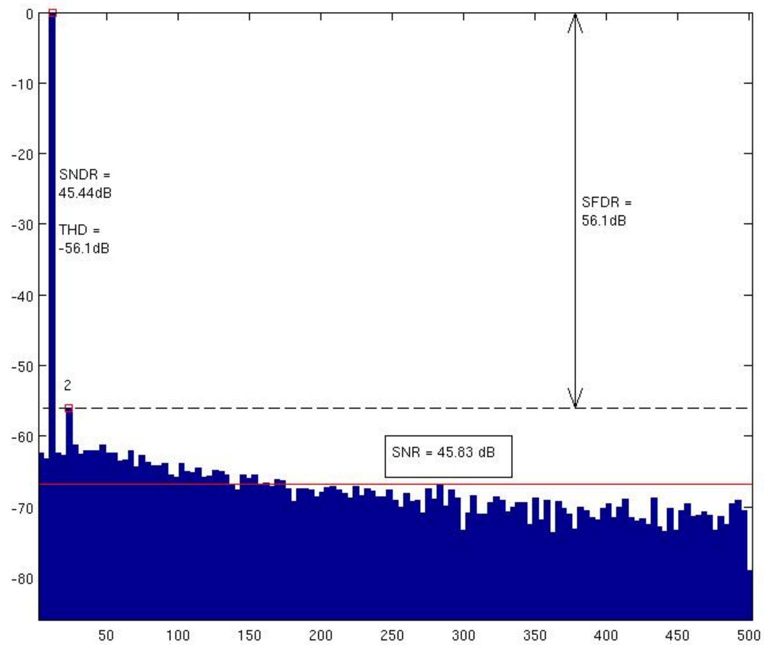

Figure 13: Noise spectrum of the second version

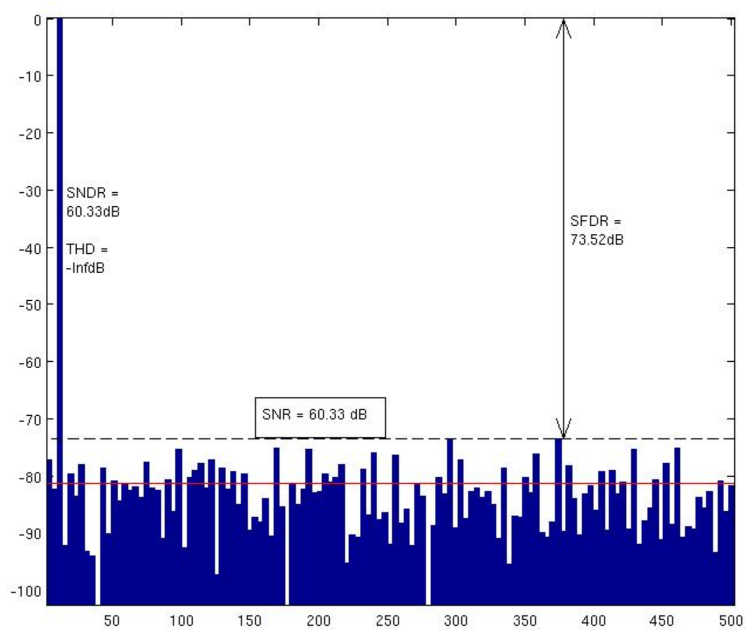

Figure 14: Noise spectrum of the final design without chopper

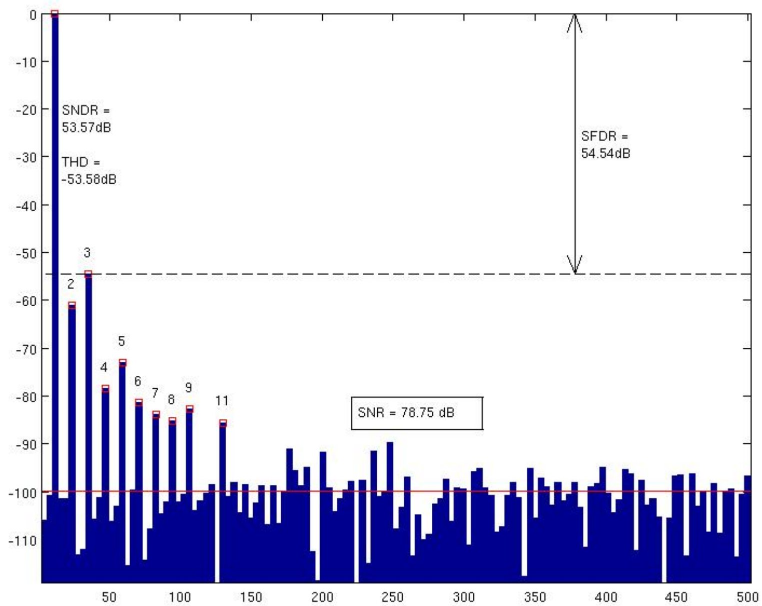

Figure 15: Noise spectrum of the final design with chopper

As above plots indicate, the final LNA design has the best overall performance. Its gain is 59dB, which is sufficient to amplify ECG signals. The other designs also have enough gain to be used in the application. However, the ring amplifier design, the first version, has the serious harmonic distortions, showing that its THD is -28.1dB. This kind of non-linearity degrades the quality of the original signal. The second version design shows better linearity compared to the ring amplifier; its THD is -56.1dB. Although it behaves linearly, the average noise level is higher than the ring amplifier. Its SNR is only 45.83dB.

The noise performance of the final design varies, depending on whether the chopper stabilization is included or not. Without the chopper, the LNA introduces almost no distortion to the output. However, when the chopper is added, its THD rises to -53.58dB. On the other hand, its SNR increases to 78.75dB. Increase in SNR indicates that the flicker noise is reduced, which means that the chopper stabilization has worked proper. The results show that there is a little trade-off between noise and linearity. Since the chopper consists of non-ideal switches, it increases the non-linearity of the LNA.

The output transient waveform of the final LNA is also shown in Figure 16. The input signal is a sine wave with 0.1 mV of amplitude. The figure verifies that the signal is sampled properly while the chopper stabilization modulates and demodulates the signal.

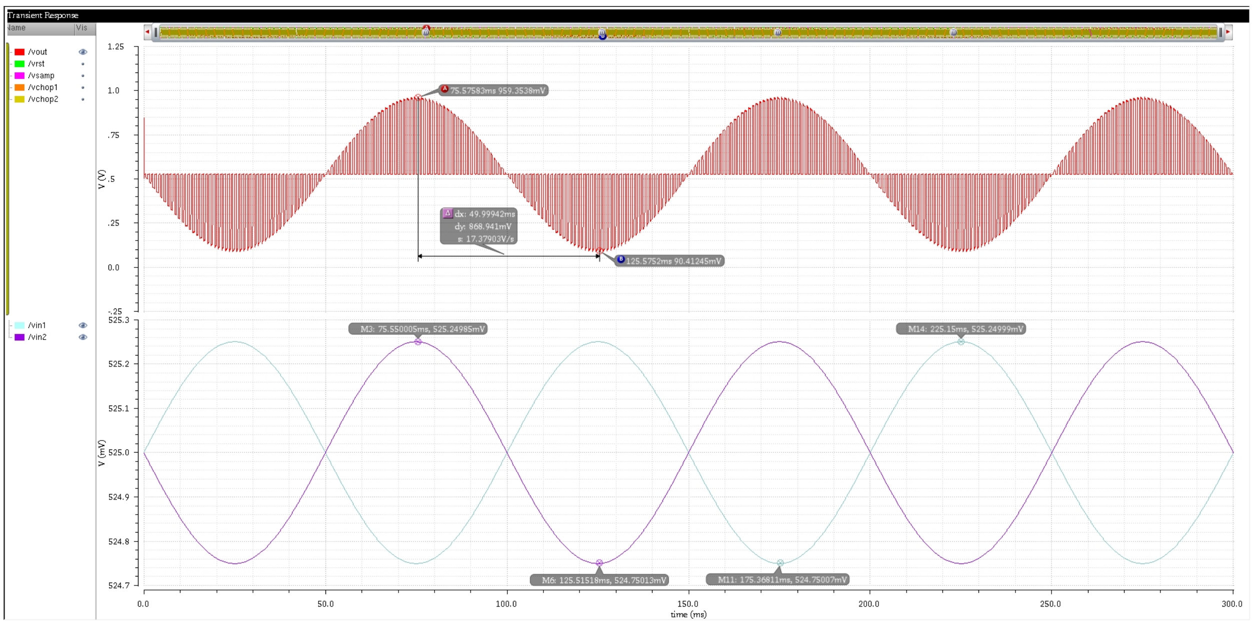

Figure 16: Output and input transient waveforms

After all, the final LNA design meets most of the important features of a typical LNA. In addition, its power consumption is 5.315 uW, which is closer to other blocks' power consumption levels in the bio-acquisition system. The LNA can successfully minimize the overall power consumption of the whole system, resulting its longer lifespan.

5. Concluding Reflections

Our team had to overcome many obstacles to reach this point. We changed our capstone project at the end of the fall semester and had less time to accomplish the goal compared to other teams. However, thanks to our new capstone advisor, David Allstot, the team could move forward to achieve something meaningful. Although the topics related to a ring amplifier were not familiar to all of us, it was fruitful to learn a new circuit topology.

For future research, more detailed analysis on a ring amplifier can be done. Not many papers have successfully analyzed the exact behaviors of the amplifier. If the accurate model can be derived, designing a LNA may be easier. In addition, the current design does not take account of the common mode noise from the input. It will be interesting to figure out how to minimize the common mode noise.

Bibliography

Allstot, David J. et al, Compressed Sensing Analog Front-End for Bio-Sensor Applications, IEEE Xplore Database, accessed February 15, 2015

Bellis, Mary. "How to Qualify for a Patent." About.com Inventors. About.com, n.d. Web. 24 Feb. 2015.

Centers for Diseases Control and Prevention. Deaths: Final Data for 2013. http://www.cdc.gov/nchs/fastats/life-expectancy.htm.

Chan, Wen-Yen. "Mobile wireless communications device including a differential output LNA connected to multiple receive signal chains." U.S. Patent No. 8,125,933. 28 Feb. 2012.

Chen, Roawen. The Future of Semiconductor Industry from "Fabless" Perspective, http://microlab.berkeley.edu/text/seminars/slides/RChen.pdf, accessed February 15, 2015

"Diabetes-US-August 2014." *Mintel*.

Enz, C.c., E.a. Vittoz, and F. Krummenacher. "A CMOS Chopper Amplifier." IEEE Journal of Solid-State Circuits 22.3 (1987): 335-42. Web.

"Global Wireless Portable Medical Device (Monitoring, Medical Therapeutics, Diagnosis, Fitness & Wellness) Market - Forecast to 2020." PRNewswire

Hershberg, Benjamin, et al. "Ring amplifiers for switched capacitor circuits."*Solid-State Circuits, IEEE Journal of* 47.12 (2012): 2928-2942.

Hoopes, Stephen. IBISWorld Industry Report 52411b Health & Medical Insurance in the US, http://clients1.ibisworld.com/reports/us/industry/default.aspx?entid=1324, accessed February 15, 2015

"Intellectual Property Crash Course:." *Patents, Copyrights, Trade Secrets, & Trademarks*. N.p., n.d. Web. 25 Feb. 2015.

Lim, Yong, and Michael P. Flynn. "11.5 A 100MS/s 10.5 b 2.46 mW comparator-less pipeline ADC using self-biased ring amplifiers." *Solid-State Circuits Conference Digest of Technical Papers (ISSCC), 2014 IEEE International*. IEEE, 2014.

McKinsey & Company, McKinsey on Semiconductors, https://www.mckinsey.com%2F~%2Fmedia%2Fmckinsey%2Fdotcom%2Fclient_service%2Fsemiconductors%2Fpdfs%2Fmosc_1_revised.ashx&ei=1ULhVOXwEZO1oQSK14LACQ&usg=AFQjCNHRZPaT50NgCWkGx0VR3EzWR00kgQ&bvm=bv.85970519,d.cGU

Porter, Michael. "The Five Competitive Forces That Shape Strategy."

Porter, Michael. What is Strategy? Harvard Business Review, accessed February 15, 2015

"Role of Intellectual Property in the Intellectual Property (IP) Challenges and Concerns of the Semiconductor Equipment and Materials Industry." Role of Intellectual Property in the Intellectual Property (IP) Challenges and Concerns of the Semiconductor Equipment and Materials Industry (2008): 1. SEMI. SEMI, Apr. 2008. Web. 24 Feb. 2015.

Schaller, Robert R. "Moore's law: past, present and future." Spectrum, IEEE 34.6 (1997): 52-59.
The World Bank “GDP growth (annual percentage)”
"The Role of Patents and the Wireless Medical Device Market." Rethinking Patent Cultures. N.p., 06 May 2014. Web. 26 Feb. 2015.

Tripathi, Vaibhav, and Boris Murmann. "Mismatch characterization of small metal fringe capacitors." *Circuits and Systems I: Regular Papers, IEEE Transactions on* 61.8 (2014): 2236-2242.

Ulama, Darryle. *2014 IBISWorld Industry Report 33441a: Semiconductor & Circuit Manufacturing in the US*. http://www.ibis.com.

"World Intellectual United States. U.S. Copyright Office. *UNITED STATES CODE TITLE 17—COPYRIGHT*. N.p.: n.p., n.d. *WIPO*. Web. 25 Feb. 2015.

Property Organization." Washington Treaty on Intellectual Property in Respect of Integrated Circuits. World Intellectual Property Organization, n.d. Web. 24 Feb. 2015.

Yang, Xiao. et al, Design of Low Power Low Noise Amplifier for Portable Electrocardiogram Recording System Applications, IEEE Xplore Database, accessed February 15, 2015

"1959 - Practical Monolithic Integrated Circuit Concept Patented" 1959 - Practical Monolithic Integrated Circuit Concept Patented - The Silicon Engine | Computer History Museum. N.p., n.d. Web. 24 Feb. 2015.