Low-Noise Ring Amplifier with Thermal Noise Cancellation

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EECS

Integrated Circuits

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

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Abstract of Low-Noise Amplifier Capstone

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Low power wireless medical devices are currently in the spotlight due to the development of remote medical diagnosis systems and long-term treatment assistances. In general, bio-signals detected by sensors are extremely weak for further processing. The quality of a low-noise amplifier (LNA) determines the accuracy of the original signals later on. Our main goal is to design an LNA that is suitable for bio-signal acquisition systems. We primarily focus on the implantable medical system recording an electrical signal of a person's heart. The LNA provides enough voltage gain to amplify the signals while reducing the noise contamination significantly. In addition, its power consumption is minimized to enhance the lifespan of the whole system.

Ring amplification technique is a new approach of medical device Low-Noise Amplifier, which provides high gain and low power features. We have a couple of issues in applying it to a low frequency low-noise amplifier, such as stability, and flicker noise reduction. We tried making the third stage wok in subthreshold region to resolve stability and we applied chopper to reduce the contamination of flicker noise.

My goal is mainly on reducing thermal noise when the other issues are resolved. Thermal noise is not a significant effect in wireless medical device because it works in low frequency region where flicker noise dominates. But as long as flicker noise is reduced by chopper, thermal noise will stand out. My approach is to apply feed-forwarding technique to cancel

thermal noise while not significantly influence the signal amplification. It is effective but due to the particular features of ring amplifier, the advantage of thermal noise cancellation is limited.

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Capstone Project Report

Department of Electrical Engineering and Computer Science

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Problem Statement

According to *Deaths: Final Data for 2013*, a recent statistical report issued by Centers for Disease Control and Prevention, life expectancy of people at birth in the United States in 1950 is only 68.2 years (Center for Disease Controls and Prevention). In contrast, life expectancy at birth in 2013 is 78.8 years. 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. Moreover, diabetes is the seventh leading cause of death (Center for Disease Controls 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.

Business Strategy

1. 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 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.

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 (Porter). 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. 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 on which we will deploy our design is able to operate at as low as 22nW per channel (Allstot). 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.

3. 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.

4. 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 service, 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 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 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.

5. 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.

6. 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 (PRNewswire). In addition, there are almost 6,500 medical device companies in the United States. 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 (PRNewswire). Although there are a plenty of buyers in the market, the other factor makes the power of buyers strong. An 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.

7. 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.

8. 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 (Center 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.

9. Technological Trend

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.

10. 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 (The World Bank). 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.

11. 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 huge change of the limitations 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.

12. 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.

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IP Strategy

1. Introduction

In July 1959, Robert Noyce was granted 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.

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 design. To achieve the goal of high signal-to-noise ratio, we will use techniques such as chopper stabilization method and low-pass filter.

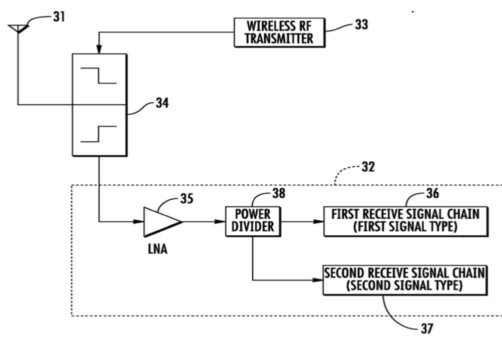
Here, we discuss some first order criteria for determining patentable ideas related to IC design. These criteria include usefulness of the design, novelty of the concept, the extent of innovation or differentiation compared to other designs aiming at the same functionality, the extent of clarity of the 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. 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).

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. As shown in the figure 1, 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.



< Figure 1>

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.

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.

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Technical Contributions

1. Overview

With the development of science and technology in all areas, people are getting increasing access to diagnosis and therapy. More and more diseases that were undetectable or incurable are becoming less lethal. However, diagnosis of chronic diseases is a limitation of the treatment process because they may need periodic physical examinations to get a long-term performance of the body. For example, heart diseases are lethal but they typically have incubation periods. Doctors have to test the heart rate of the patient, which is likely to be very inconvenient for both sides.

A new idea of doing the heart rate monitoring is to implant a medical device into the patient’s heart, which periodically sends out signals to report the behavior of the heart. This implanted medical device consists of roughly six components: the sensor, Low-Noise-Amplifier, Compressed Sensing Unit, Analog to Digital Converter, Power Amplifier and the Antenna. The last three parts will be done in the future, the sensor part is provided by some third-party supplier, the Compressed Sensing (CS) unit is done by previous Master of Engineering students in Berkeley and our team is doing the Low Noise Amplifier (LNA).

None of the components mentioned above is negligible, and our part plays an important role in its own way. The implanted medical device, as an electronic device, which does the work from sensing, compressing, converting to launching data to the space outside the patient’s body, requires some particular features. It has to be physically small, long lasting and has to work at a specific temperature (around body temperature). The LNA has to be low noise to maintain the correct information. Additionally, power dissipation is a crucial specification. If any of the components is consuming too much energy, we will have to replace the battery or charge it frequently, which is extremely inconvenient for a device implanted in human heart. Meanwhile, a large power consumption will lead to a high power density (power consumed per unit volume), which basically means the device will be heated up. The result is worse performance and maybe a burn of the heart if the temperature exceeds 55 degree Celsius.

As a conclusion, we are engaged into a task of designing a low-power LNA. The subdivision is done as the following: Zhiyang Song does the structure of the amplifier, focusing on energy reduction and distortion (which is a source of noise) elimination (Song, 2015), Jonghun Kwak applies different techniques to deal with flicker noise (which is supposed to be the main source of noise) and I focus on thermal noise cancellation (Kwak, 2015).

The reason behind this distribution is that the work is divided based on different parts on different levels. First, we have to build up an amplifier to basically work, and distortions will be induced easily if the amplifier is not perfectly done. Second, flicker noise is going to be the main source of noise due to the specifications of the LNA, which will be discussed later in detail. And the way to reduce flicker noise is to add some structure external of the amplifier so it can be done separately from the amplifier. And then, thermal noise cancellation, which is my role, is going to be done by applying some other techniques. Since it is not commonly used in a circuit like ours, we have to figure out some solutions, transplanting techniques used in other types of circuits to our product.

2. Literature Review

We are going to implement an LNA using Ring Amplifier, where I will apply thermal noise cancellation techniques. In this section, I will first talk about the role of thermal noise in our LNA and then come to the concept of ring amplifier.

Thermal noise has not been the main problem of noise reduction in heart rate monitoring system until flicker noise is significantly reduced. The reason can be divided into two aspects. And the reason also makes my work different from previous work. Before that, let me introduce the mechanism of the two main noise sources: flicker noise and thermal noise.

Flicker noise is a kind of noise that appears in all active devices (Grey 741). It also exists in discrete passive elements, for example, carbon resistors. If a Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) is working under some bias current (also mentioned as Direct Current), traps associated with contamination and crystal defects will capture and release carriers randomly. These affect the constant current through the channel of the transistor and appears as noise. The spectral density of it is

$$\overline{i^2} = K_1 \frac{I^a}{f^b} \Delta f$$

where

Δf is the small bandwidth of frequency f

I is the direct current

K_1 is a constant for a particular device

a is a constant in the range 0.5 to 2

b is a constant of typically 1.

As it is inversely proportional to the frequency, it is apparently large at low frequencies.

Thermal noise is something totally different from flicker noise (Grey 2009: 740).

Random thermal motions of electrons generate the noise, which is only related to physical temperature and has nothing to do with direct currents. As long as the temperature is above zero degree Kelvin, and since the most Integrated Circuits (IC) work at room temperature (about 300 degrees Kelvin), thermal noise always exists as an active component. The form of thermal noise is like the following

$$\overline{v^2} = 4kTR\Delta f$$
$$\overline{i^2} = 4kT\frac{1}{R}\Delta f$$

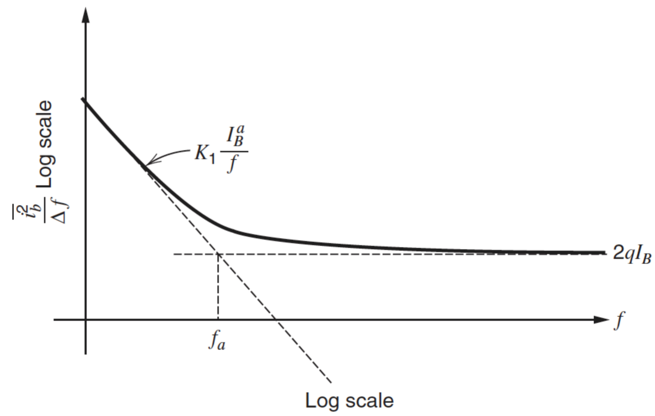
where k is Boltzmann’s constant, T is temperature in Kelvin, R is the value of the resistor and Δf is the small bandwidth of frequency.

Current integrated circuit devices do not really use passive resistors any longer, instead, most components are transistors. A transistor is providing a thermal noise component of

$$\overline{i_n^{\,2}} = 4kT\gamma g_m\Delta f$$

where γ is a device parameter (Razavi, 2001). As we can see, it has a feature of dependence of temperature and independence of frequency.

The spectrum of the two types of noise looks like this (Grey 2009: 746).



We see, at low frequency, the flicker noise which is represented in a style of 1/f is the dominant component, which decreases as frequency increases. At the frequencies larger than a particular value, flicker noise is too small and is taken over by thermal noise which is represented as a constant with frequency.

Then let's come to the reason why flicker noise is mostly the dominant component of noise performance in our product.

Firstly, each amplifier has to work on a particular frequency band and frequency performance is an important specification of amplifier design. In the old years, people developed circuits working on frequency of several kilohertz, megahertz and then moved to gigahertz. High frequency has always been the target because high speed is constantly wanted. But our product is not searching for high speed. Human heart is beating 60-100 times per minute, which is equivalent to 1-1.5 times per second. So the upper bound of the input signal is around tens of hertz. At such low frequencies, flicker noise is way larger than thermal noise because the frequency where flicker noise is equal to thermal noise is higher than 100 kHz at current semiconductor technology level (sub-micrometer level). So before the reduction of flicker noise, reducing thermal noise does not really contribute to the noise performance.

Secondly, the overall noise across a frequency band is proportional to the bandwidth.

$$\int_{f_L}^{f_H} \overline{v^2}(f)df = 4kTR\left(f_H - f_L\right)$$

where f_H and f_L are the high and low bounds of the frequency band, respectively.

So the influence of thermal noise of a circuit is dependent on the bandwidth. This is the reason why most thermal noise techniques are dealing with wide band circuits. But according to the Nyquist theorem (Nyquist–Shannon 2015), a bandwidth of 300 Hz is enough for our product because the input signal varies only up to several hertz. A bandwidth of a couple of hundred hertz is too low to make thermal noise crucial. However, after flicker noise is reduced to a magnitude comparable to thermal noise, it will be necessary to eliminate thermal noise.

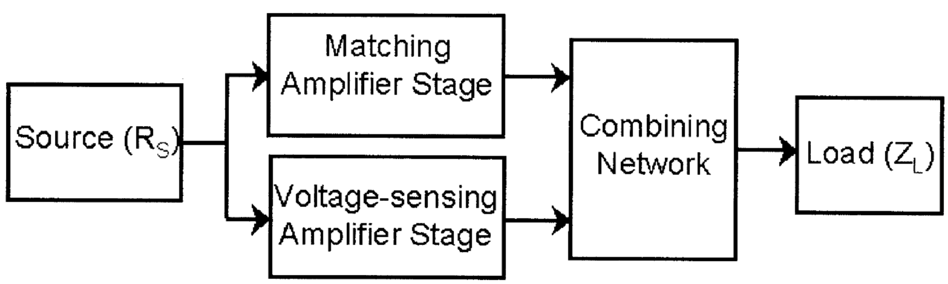
A recently developed method to reduce thermal noise is by cancelling it with feed forwarding (Nauta 2004). But this technology is mainly dealing with wide band amplifiers working on radio frequency (typically 3 kHz to 300 GHz), while our product is a narrow band amplifier working on frequencies less than 1 kHz. Different specifications mean different approaches, tradeoffs, costs and probably completely different outcomes. But the bottom line is that to do thermal noise reduction, feed forwarding is the fundamental idea.

Though thermal noise is not a concept that people are unfamiliar with, ring amplifier is. Ring Amplifier is an unconventional type of amplifier that uses digital style components to build analog devices. The idea of ring amplifier is most possibly from ring oscillator, which is often the basis of a clock generator in digital circuits (Sun, 2011). It makes use of the transition region of inverter to amplify signal. Not long ago, ring amplifiers have been implemented with switched capacitors, which enabled sufficient amplification in some scaled environment (Hershberg, 2012). However, a good explanation of how ring amplifiers work has not been found because traditional ways of analyzing amplifiers are hardly applicable to ring amplifiers. Probably the best job done so far is a self-biased ring amplifier in an Analog-to-Digital Converter (ADC) design (Lim 2012). It showed the transient behavior of a switched capacitor ring amplifier and discussed some methods to reduce the response time as well as the tradeoffs. Since ring amplifier is new, planting thermal noise cancellation techniques seems to be challenging.

3. Methods and Materials

Having got the idea of feed forwarding, the next step is to apply it to our own situation. Feed forwarding is talking about cancelling the thermal noise with itself by constructing a second path from the noise source to the output node.

The following diagram shows it clearly.



Let's say we have an input stage with source resistor of R_S , a matching amplifier stage with resistor R , the voltage sensing amplifier stage has a gain of A_v and the thermal noise is equivalent at the input node as a current source of $I_{n,i}$. The main amplifier has a transconductance of g_{mi}

Then the noise at the input node is

$$V_{in,n,i} = \alpha I_{n,i} R_S$$

where $\alpha = \alpha(R_S, g_{mi})$ is a function of the amplifier and the input stage.

Then at the output node of the amplifier, the noise is

$$V_{out1,n,i} = \alpha I_{n,i}(R_S + R)$$

Due to the second path, the noise is also amplified by A_v and then summed up with the output of the main amplifier, so we get overall noise at the output terminal is

$$V_{out,n,i} = V_{out1,n,i} - A_v V_{in,n,i} = \alpha I_{n,i}(R + R_S - A_v R_S)$$

And as long as we achieve a gain as

$$A_{v,c} = \frac{V_{out1,n,i}}{V_{in,n,i}} = 1 + \frac{R}{R_S}$$

the thermal noise on the two paths can be canceled with each other.

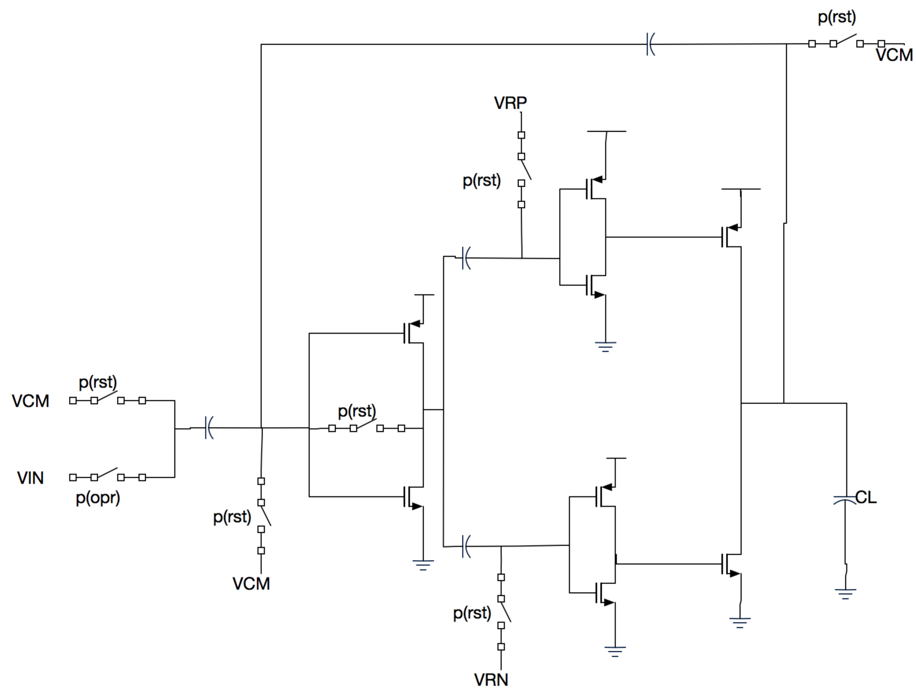
But there are some tradeoffs here. The feed forwarding resistor is going to cost some area on the chip and area means money in semiconductor industry. Meanwhile, the second amplifier usually means some additional circuitry, which will be another current consumer and hurt the overall power consumption figure of the design. Actually people are paying an increase of energy for a decrease of thermal noise (Federico 2004).

My strategy for this tradeoff is to make use of existing amplifier stages to have some of them be multi-function. In this way some current will be saved and we are closer to the goal of a low-power design.

The simulation tool to be used is Cadence developed by Cadence Design Systems, Inc. And the library being used is 32nm/28nm technology by Taiwan Semiconductor

Manufacturing Company, Limited (TSMC). This fake library, which does not have a good modelization is used in both EE241B and EE240B classes.

The first step is to implement a ring amplifier discussed in Yong Lim's work.



Here, we have three stages of inverters, in which the second stage is broken into two branches and each drives an NMOS transistor or a PMOS one. And the gate nodes are biased to V_{RN} and V_{RP} during setting phase to bias the third stage gates close to the supply or ground. The idea here is to push the third stage transistors into or close to sub-threshold region to save power and speed up the settling while third stage gain is a tradeoff. Some concerns are listed below.

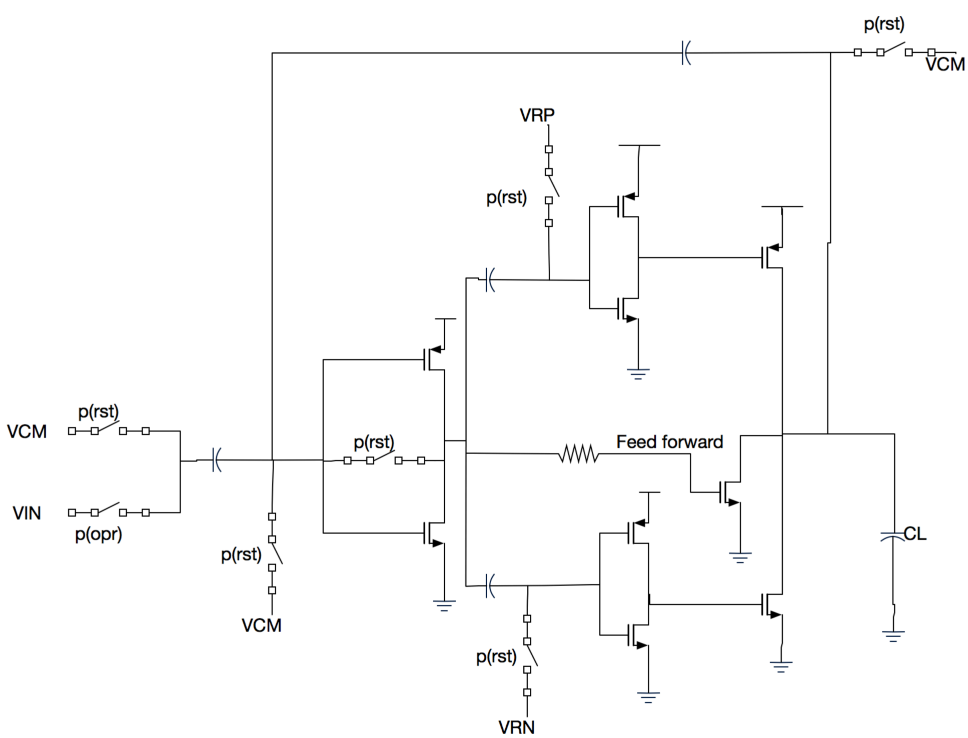
First, the first stage needs a V_M (where $V_{in} = V_{out}$) at exactly half of the supply to have appropriate reset in the reset phase.

Second, we need to have a good distribution of gain over the three stages. The first stage needs a high gain to reduce noise amplification in later stages. The second stage will be biased away from half of supply voltage, so a lower gain with a smaller slope in Voltage Transfer Curve is preferred. The third stage needs to work around sub-threshold region so the gain is limited. But we can manipulate the bias to adjust its gain.

Third, compared to the original version of ring amplifier in Lim's work, I removed a coupling capacitor before the first stage to reduce signal attenuation.

Fourth, feedback capacitors need to be appropriately chosen to have decent settling response.

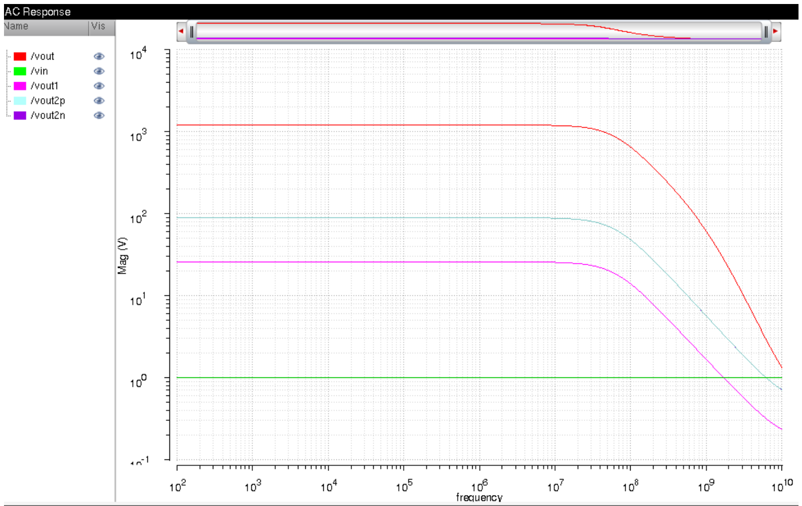
The next step is to apply thermal noise cancellation in the circuit. I created a feed forward path in this way.



In this circuit, the output signal of the first stage has two paths to the overall output node. One is through the second and third stage, the other is through a resistor to an extra NMOS transistor then to the output node. Noise of the output node of the first stage gets amplified through the paths with opposite phases and will be partly or fully cancelled. We need to appropriately choose the resistor in order to deliver the signal to the extra transistor. This resistor needs to be about the output resistance of the transistors, which may not be a huge number in 32nm technology. And since no DC current is going through it, its noise contribution is negligible.
If the gains of the two paths are the same in magnitude, the noise will possibly be completely cancelled. But as mentioned before, it requires burning more power. Another tradeoff here is the noise provided by the extra transistor. A larger current through it can contribute to the noise cancellation but will also lead to a larger noise by itself. To achieve a reduction of the overall noise, we need to carefully size the extra transistor and even sub-threshold bias it as well.

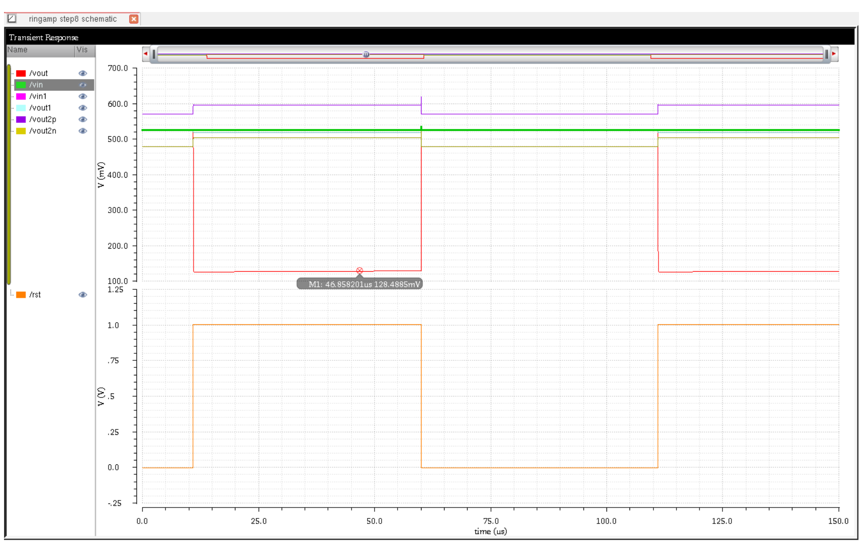
4. Results and Discussion

The gains through the stages (without third stage sub-threshold biasing) is like the following.



We see that the first stage has a high gain, the second stage gain is low, and the high gain of the third stage will be further reduced by sub-threshold biasing. The overall gain here is several thousand. Since the LNA will finally run in a really low frequency, bandwidth is not an important concern.

The close loop gain is nearly 800 in absolute value, in which case another stage of amplification may not be needed for our overall system.



Then let’s come to the noise part. Before adding the feed forwarding network, the noise summary is like this.

Window Expressions Info Help

Device	Param	Noise Contribution	% Of Total
M3.main	fn	9.7798e-19	26.98
M7.main	fn	9.47761e-19	26.14
M2.main	fn	9.30623e-19	25.67
M6.main	fn	6.76257e-19	18.65
M5.main	fn	5.23925e-20	1.45
M4.main	fn	3.69066e-20	1.02
M5.main	id	1.83527e-21	0.05
M4.main	id	1.24766e-21	0.03
M3.main	id	1.33888e-22	0.00
M7.main	id	1.02684e-22	0.00
M2.main	id	7.94393e-23	0.00
M6.main	id	6.7423e-23	0.00
M4.main	igd	8.73964e-28	0.00
M5.main	igd	2.11313e-28	0.00
M3.main	igd	6.05145e-30	0.00

Integrated Noise Summary (in V^2) Sorted By Noise Contributors
Total Summarized Noise = 3.62539e-18
No input referred noise available
The above noise summary info is for noise data

We see that flicker noise is playing a dominating role in the noise figure. Flicker noise will be reduced by my teammate’s work, here we only pay attention to thermal noise. The thermal noise by transistor M5 is about 1.84e-21.

After applying the cancellation network, the noise summary looks like this.

Device	Param	Noise Contribution	% Of Total
M7.main	fn	9.47761e-19	51.66
M6.main	fn	6.76256e-19	36.86
M3.main	fn	8.35247e-20	4.55
M2.main	fn	7.94802e-20	4.33
M4.main	fn	3.69066e-20	2.01
M5.main	fn	3.93277e-21	0.21
M8.main	fn	3.78162e-21	0.21
M4.main	id	1.24766e-21	0.07
M8.main	id	9.52836e-22	0.05
M5.main	id	5.6129e-22	0.03
M7.main	id	1.02684e-22	0.01
M6.main	id	6.7423e-23	0.00
M3.main	id	1.14347e-23	0.00
M2.main	id	6.78453e-24	0.00
M8.main	igd	6.6601e-27	0.00

Integrated Noise Summary (in V^2) Sorted By Noise Contributors
Total Summarized Noise = 1.83459e-18
No input referred noise available
The above noise summary info is for noise data

We can see the noise by M5 is reduced to 5.61e-22. Some of the thermal noise is not reduced because they are from the later stages. And also, an extra transistor, M8 is contributing noise. But the good point is that its contribution has not compensated the noise reduction by the feed forwarding network.

After all these trials, we know that thermal noise cancellation is applicable to ring amplifier. But its contribution is limited due to later stage noise and the noise of the extra transistors.

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Concluding Reflections

The outcomes at the end of the academic year are different from the original plan at the beginning. The definition was not clear and specific at the beginning and we narrowed it down along the way. We supposed to build a big system upon some previous work done by last year M.Eng students. Then we encountered time limitation and focused on one single component and decided to work on the lower level so that we can get to the details entirely. We tried different approaches and finally focused on something new to dig it deeply. Each approach has its own features and we took effort to make reasonable comparisons between the approaches. We have changed our directions and the way of address this problem.

The most important project management insight is to define the work, distribute and execute. It is usually hard for people to do work that is not well defined, in which people easily get lost. Though some of the work will later come out to be useless because of a wrong direction, it is always a good thing to keep going. That is not only the actual work that is done, but also the status and pace of moving on. It is similar to a machine, if it cools down, it will take another moment to warm it up again before the next operation begins.

In further research, I would recommend people to have a good design tool ready before the actually start. In our case, the design model library was not well defined and frequently we found the simulation result did not make sense. But due to the limited resources on our hands, we had no way to switch to another tool set.

The ring amplifier approach of low noise amplifier is worth working on, efforts taken to improve robustness and reduce flicker noise will really lead to great results.