DESIGN AND PERFORMANCE ANALYSIS OF A LOW POWER SMALL AREA RFID TRANSPONDER FOR WIRELESS COMMUNICATION APPLICATIONS

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DEDICATION

To my husband and parents

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ABSTRACT

Today RFID technology is mostly used as a medium for numerous tasks including managing supply chains, healthcare, tracking livestock, preventing counterfeiting, controlling building access, and supporting automated checkout. Contactless RFID technology is adding speed, accuracy, efficiency and security to an ever-expanding range of applications. As RFID transponders are embedded in the objects for tracking purposes it is necessary to make the transponders as small as possible. The passive type transponders do not require any battery of their own to operate; they retrieve the power from the radio signal of the reader. RFID technology can operate in low frequency (LF), high frequency (HF), ultra-high frequency (UHF) and microwave frequency. Higher the frequency better the read range of the transponder. So, to keep the read range higher this research work focuses on the design of a passive RFID transponder at 2.45 GHz microwave frequency. Analog circuits of the transponder i.e voltage controlled oscillator (VCO), rectifier, charge pump and voltage regulator circuits are designed for the transponder in such a way that the device consume less power as well as require small area.

The VCO works as the clock generator for the transponder. In this work a low power, low phase noise, small area 3-stage differential ring VCO is designed and analyzed. The transponder receives the RF signal when it is within the read range of the reader and with the help of a rectifier circuit it converts the RF power to DC. To enhance the rectified output voltage a charge pump circuit is used. In this work, to reduce the circuit area the rectifier and the charge pump circuit is designed together. To protect the circuit from high or unstable voltage, a low power linear regulator is designed which produces stable DC output. Moreover, to assess all the circuits in diversified environments process corner analysis, temperature sweeping, Monte Carlo analysis and stability analysis has been performed in this research. Designed in a 90nm CMOS technology, the proposed VCO oscillates at 2.45 GHz microwave frequency with an area of 1316 $\mu\mathrm{m}^2$ and consumes only 2.27 mW power. The charge pumped rectifier circuit occupies 3884 $\mu\mathrm{m}^2$ space having a high power conversion efficiency of 78.5%. With an active chip area of 1557.7 $\mu\mathrm{m}^2$, the proposed voltage regulator circuit gives a stable output of 1 V with a low power consumption of 10 μW only. Finally, after the post-layout simulation in each circuit, it is found that the parasitic components didn't change the circuit performances drastically from the schematic based simulations.

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LIST OF ABBREVIATIONS

ADC	Analog-To- Digital Converters
AIDC	Automatic Identification and Data Capture
ASK	Amplitude Shift Keying
CDR	Clock and Data Recovery
CMOS	Complementary Metal Oxide Semiconductor
CRC	Cyclic Redundancy Check
FOM	Figure of Merit
HF	High Frequency
OCR	Optical Character Recognition
PSRR	Power Supply Rejection Ratio
RFIC	Radio Frequency Integrated Chip
RFID	Radio Frequency Identification
SOI	Silicon On Insulator
UHF	Ultra-High Frequency
VCO	Voltage Controlled Oscillator
QR	Quick Response

CHAPTER 1

INTRODUCTION

1.1 Background

Automated Identification and Data Capture (AIDC) provides support for a progressive group of tasks in which sensor systems often manipulated by humans, are used to detect objects and collect measurements about them. Identification uses tools like bar codes or Radio Frequency Identification (RFID) tags with radio readers or optical. Data capture encompasses both manual input and an increasingly rich collection of measurement devices often connected wirelessly to computer. Technologies characteristically considered as part of AIDC include bar codes, QR codes, RFID, magnetic stripes, biometrics (like iris and facial recognition system), optical character recognition (OCR), voice recognition and smart cards. Many studies over the world aim to specify new approach of identification in order to help the follow-up of objects. Barcode systems are predominantly used these days are based on the scanning and recognition of a barcode. While being economical and easier to implement, their potential is limited by low storage capacities, line-of-sight requirements and the fact that they cannot be reprogrammed [1]. RFID evades the limitations of barcode scanning which does not need line-of-sight, and multiple RFID tags can be identified and read remotely and simultaneously. They can be read from a variety of distances based on the type of tag and the use of a handheld reader or a fixed RFID reader combined with an antenna. Recently, RFID technology has achieved extensive applicability in different application areas such as healthcare, manufacturing, telecommunications, public transportation, airline bagging and are considered as an substitute of barcode system in the distribution industry and access control. Thus, using RFID technology increases the security in identification of a product. Moreover, this technology is simple, easy to use, and provides faster communication speed and hence, reduces processing time, increases productivity and improves the quality of service. An RFID system comprises of a small low-cost device called a tag or a transponder and a more complex device called reader or interrogator. Commonly, RFID tags are attached to objects, which need to be tracked and the reader is separate and usually connected to a data processing unit. RFID technology can work at the high frequency, ultra-high frequency and microwave frequency. It uses radio frequency to transfer data between readers and tags. RFID tags are placed into objects such as cars, products in grocery stores. RFID readers in the vicinity of a tag read tag's data whenever is required. The RFID systems are becoming increasingly used to support internet of things deployments.

1.2 Motivation and Related Works

RFID tags have received a lot of attention in the recent past because of the multitude of applications they serve. Associated to the recent development in RFIC technology that made it possible to have very low cost RFID transponder chips, RFID tags are increasingly becoming an integral part in our day to day lives. Therefore, it is really essential to find out the steps for design and assembly of the tag to efficiently use this technology in different applications. The objective of this thesis is to design the analog circuits of 2.45 GHz RFID tags (for a passive tag) and to make it area efficient with low power. A block level design was performed for the RFID transponder design. The major analog building blocks of a RFID transponder are oscillator, rectifier and voltage regulator. Being the portable technology, major concern of RFID technology is small area with lower power consumption. Although some systems have already existed for several years, the double challenge of low power consumption for the tags and small area is very hard to achieve. To achieve the low power consumption in a ring Voltage Controlled Oscillator (VCO) the simulations have been performed using the software SPICE in 0.18 µm Complementary Metal Oxide Semiconductor (CMOS) technology [2], EldoRF simulator (Mentor Graphics) in 0.18 µm CMOS technology [3], Cadence Virtuoso Analog Design Environment in 0.35 µm CMOS technology [4]. The low power/ power efficient voltage regulator is designed in 0.18 µm 2P5M EEPROM process [5] and 0.18-µm CMOS process with the Design Architect (DA-IC) and IC station tools of Mentor graphics [6]. A power efficient and ultra-low power rectifier is designed in 0.18 µm CMOS technology with Cadence tools [7], and for 60 GHz in CMOS Silicon On Insulator (SOI) process [8] respectively. In those proposed techniques low power consumption is achieved but small area was unnoticed and also combinedly the oscillator, rectifier and voltage regulator for designing a low power RFID chip was not discussed. But these need to be comprehensively addressed to develop a low power small area RFID transponder.

The designed analog circuits can be used in any of the personal identification applications. Moreover, the designed transponder can also be deployed commercially.

1.3 Methodology

Good number of works related to RFID transponder or the VCO, rectifier and the voltage regulator have been studied to identify the spaces where further development can be done. Thus arises the question: Can a RFID transponder be designed for wireless applications with low power as well as small area with a very low noise? To answer this question the building blocks of the RFID transponder needs to be analyzed. In order to achieve desired performances (low power and small area) fitting the wireless application specifications, this work is being concentrated on the design and development of RFID transponder for the three most important blocks; VCO, rectifier and voltage regulator. The design and performances of these blocks are analyzed in cadence virtuoso tool for 90 nm CMOS technology. The transponder is being considered for the healthcare application in 2.45 GHz frequency. The research work is aimed to the development of an RFID transponder for wireless applications that will have low power and small die area in a cost effective manner.

In this work, the first goal is to enhance the performance of the analog circuits of a passive RFID transponder, because the analog circuits of a RFID transponder consume more power. The main objectives of the thesis are as follows:

- To design a Voltage Controlled Oscillator, Rectifier and Voltage regulator for 2.45 GHz healthcare applications.
- To achieve lower power consumption for the blocks compared to the existing technologies.
- To get smaller area for the portable RFID transponder compared to the existing technologies.
- To compare layout based design performance with the state-of-the-art.

1.4 Organization of the Thesis

This thesis outlines the overall design of the RFID transponder and is organized as follows.

Chapter 2 discusses the background of an RFID transponder including the literature review. Starting with the history of RFID transponder, the chapter proceeds to describe the infrastructure of an RFID transponder, its types, operating frequency, application in different fields and then to overview the RFID technology with its building blocks.

Chapter 3 starts with an overview of voltage controlled oscillator for RFID transponder. The Proposed design with the simulation results and performance analysis are also presented in this chapter.

Chapter 4 outlines the design of a rectifier with charge pump with its general idea. All the analysis and the results are also presented in this chapter.

Chapter 5 deals with the voltage regulator design of the RFID transponder. It first introduces the fundamentals of voltage regulator and its design considerations and then the results.

Chapter 6 summarizes the work presented in this thesis and main contributions. Possible future works are also suggested in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 History of RFID

The expansion of the RFID technology can be attributed to the convergence of radio broadcast technology and radar. An initial work, which can be thought as one of the first in the field of RFID technology is “Communication by means of reflected power,” published in 1948 [9]. Since then, the RFID technology has progressed over the years to reach what it is now. With the technical expansion in radio and radar in the 1930s and 1940s, the 1950s saw the exploration of RFID techniques. Some of the landmark inventions and papers published after this laid the foundations for the explosion of RFID technology. Some of those were “Theory of Loaded Scatters” in 1964 [10], “Remotely Activated Radio Frequency Powered Devices”, and “Passive Data Transmission Techniques Utilising Radar Echoes” [11, 12]. The 1960s also saw the commencement of commercial activities in the arena of RFID. This was followed by increased interest among academic institutions, government laboratories, companies, inventors and developers in the 1970s [12]. Hence initiated the advancement of practical tags with an operational range of tens of meters. The 1980s saw full fledge implementation of RFID technology in personnel access, transportation, and animal tracking [12]. The 1990s witnessed extensive deployment of RFID tags in electronic toll collection, access control and a wide variety of other commercial applications all over the world. This time, a lot of companies joined the RFID race, such as, Micro design, Texas instruments, Alcatel, Bosch, CGA, and Philips. New technological advancements also accompanied this growth. One example is the fabrication of microwave Schottky diodes on CMOS Integrated Circuits (IC). Low forward voltage drop and fast switching action of a Schottky diode makes a voltage multiplier to operate at low input power levels. Several books were published in the field of RFID technology. One of the first was written by Klaus Finkenzeller in 1999 [12]. The later part of this decade saw tremendous growth of RFID technology with a lot of companies entering the industry.

The 21^{st} century saw the execution of smallest RFID tags with noteworthy advancements in the IC technology. Number of components was scaled down to two namely, single CMOS IC and antenna, and RFID tags in different shapes started to emerge. Technical breakthroughs in the late 1990s made tremendous growth in the use of RFID tags in supply chain management and article tracking. The growth of RFID still continues and its full potential is now limited only by the advancements in the regions of application software; development of supporting infrastructure to design, development of privacy policy; installation and maintenance, and others. Table 2.1 shows the major milestones in the RFID technology over the years [12] .

Table 2.1: Brief history of RFID

Decade	**Event**
1940 – 1950	Further advancement in Radar; RFID invented in 1948
1950 – 1960	Early exploration of RFID technology; laboratory experiments
1960 – 1970	Development of the theory of RFID; start of applications field trial
1970 – 1980	Explosion of RFID development; tests of RFID accelerates; very early adopter implementation of RFID
1980 – 1990	Commercial applications of RFID enter mainstream
1990 – 2000	Emergence of standards. RFID widely deployed; RFID becomes part of everyday life
2000 onwards	Walmart starts using RFID (2005) and RFID explosion continues

2.2 Basic Infrastructure of RFID

Radio stands for invocation of the wireless transmission and propagation of information or data. For functioning RFID devices, Frequency defines spectrum, which may be low, high, ultra-high and microwave depending on the application. Identification means to identify the items with the aid of codes existing in a data carrier and accessible via radio frequency reading.

This technology has the same principle as power transformers found in most houses though typically a transformer's primary and secondary coil are wound closely together to guarantee efficient power transfer [13]. So it can be said that RFID is a form of wireless communication that integrates the usage of electromagnetic or electrostatic coupling in the radio frequency portion of the electromagnetic spectrum to distinctively recognise an object, animal or person from a specified distance. RFID Technology has recently apprehended the thoughts of scholars and practitioners because of its high operational and strategic potential in various sectors [14]. RFID takes auto-ID technology to the next level by allowing tags to be read without line of sight and, depending on the type of RFID, having a read range between a few centimetres to over 20+ meters.

Basic RFID system consists of three components: an antenna, reader and a transponder (the tag). The antenna transmits a signal through the reader that activates the tag, which then transmits data back to the antenna. The data is used to notify a programmable logic controller circuit that some specific action should occur. Now a days, RFID tags are replacing barcodes in many applications as they don't need to be in the sight line of the objects. Actually RFID tags are intelligent bar codes that can talk to a networked system to track every product that we put in our shopping cart. Figure 2.1 shows the basic RFID system.

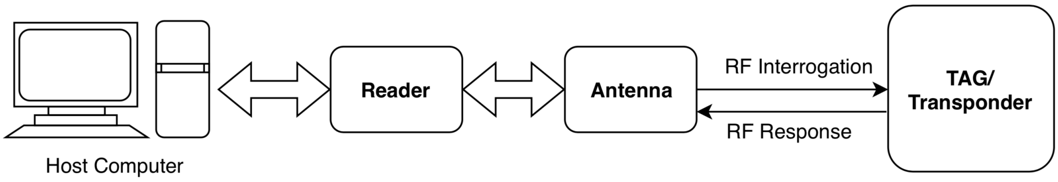

Figure 2.1: Basic RFID infrastructure

2.3 Comparison with other Technologies

RFID has high robustness, high data capacity, low cost and high operation distance. RFID is often thought-out as next generation barcodes because of its real paybacks over other existing automatic identification techniques. In barcode technology we cannot read or write any additional data once it is printed. Moreover, in RFID technology the object must not be in line of sight of the reader.

One of the biggest benefits RFID offers is that items can be traced across the supply chain and can be located in a warehouse within seconds [15]. Reading any object with biometric system or barcode is time consuming in the sense that if the object is not properly oriented/ adjusted it may take seconds to read it.

The main features of RFID which make it unique includes:

- As no line-of-sight is essential, tag placement is less constrained
- Tag detection not requiring human intervention reduces employment costs and eliminates human errors from data collection
- RFID tags have a longer read range than, e. g. barcodes
- Tags can have read/write memory capability
- An RFID tag can store large amounts of data additionally to a unique identifier
- Unique item identification is easier to implement with RFID than with barcodes
- Its ability to identify items individually rather than generically

- Tags are less sensitive to adverse conditions (dust, chemicals etc.)
- Several tags can be read at the same time
- RFID tags can be combined with sensors
- Automatic reading at several places reduces time lags and inaccuracies

Table 2.2: Wireless standards in ISM Band

Features	802.11	Bluetooth	Zigbee	RFID
Power Profile	Hours	Days	Years	Battery less
Complexity	Very complex	Complex	Simple	Simple
Modulation	QPSK	FSK, GMSK	BPSK, O-QPSK	ASK, PSK
Range	100m	10m	10m	10cm-20m
Frequency	Microwave	Microwave	Microwave	LF, HF, UHF & Microwave
Data Rate	11Mbps	1Mbps	250 kbps	64 kbps

Also in other identification technologies there may have possibility of read write errors, miss scanning whereas RFID system is fully automated with greater accuracy. In comparison to the barcode technology RFID systems are found more robust and reliable in manufacturing. Table 2.2 illustrates the comparison of properties between 802.11, Bluetooth, Zigbee and RFID system [16].

Although many RFID implementation cases have been reported, the widespread diffusion of the technology and the maximum exploitation of its potential still require technical, process and security issues to be solved ahead of time. In RFID system any unauthorised person can read the object. So security must be a major concern in this technology. Another main drawback of RFID with other technology is it has costly tags.

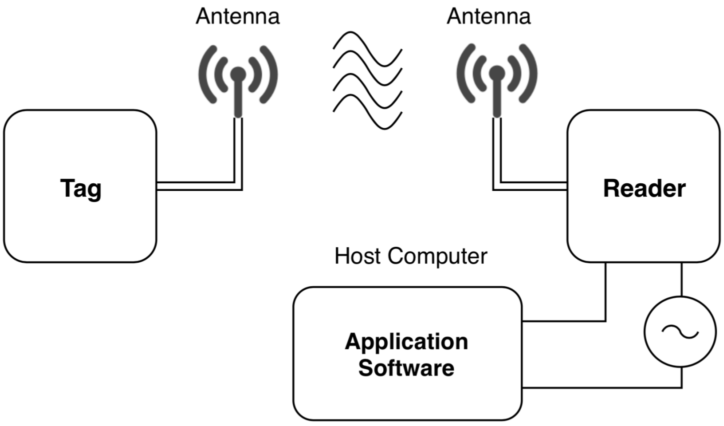

Figure 2.2: Components of an RFID system

2.4 Components of RFID

An RFID system uses wireless data exchange technology which is an integrated combination of various components for detection and identification of objects. Following are the key components in a basic RFID system:

- Host Computer with appropriate software
- Antenna
- Reader
- Tag/ transponder

There can be additional components associated with these components. Figure 2.2 shows the components of the RFID system.

2.4.1 Host computer

A host computer has a database that updates and keeps track of the data acquired from the readers. It runs software to control the readers and has many other features such as data filtering and manipulating, integration with multiple real-time network platforms, and the ability to incorporate cameras, sensors or other components.

2.4.2 Antenna

Antenna makes it promising for readers and tags to interconnect with each other in RFID tracking system. This device is responsible for sending and receiving radio frequency in a defined frequency for system. Antenna should be positioned in an appropriate location and correct direction. Angle and location of installing antennas (polarisation) in addition to number of required antennas in order to cover the desired space, will be determined by advanced mathematical and telecommunication relations by experts. These devices are produced in different types and sizes which work in different frequency bands. Also, according to terms of use of HF and UHF waves, different types of antenna are needed. It is worth observing that choosing a suitable antenna and determining the number of required antenna, location, capacity, and angle of coverage is very essential. It is obvious that if it is not installed properly and precisely, desired coverage and performance cannot be achieved. Generally, antenna is a device that is used to transmit or receive electromagnetic waves. Both tag and reader comprises of antenna which makes it possible for them to communicate with each other and is an essential component in RFID systems. Different types of antennas are as follows:

- Gate antennas
- Patch antennas
- Linear polarised
- Circular polarised
- Di-pole or multipole antennas
- Stick antennas
- Beam forming or phased array element antennas
- Adaptive antennas
- Omni directional antennas

2.4.3 Reader

An RFID reader's function is to interrogate RFID tags. A reader may have multiple antennas that are responsible for sending and receiving radio waves [13]. It consists of three main parts: micro-controller, receiver/ signal detector and RF signal generator. The reader/ interrogator transmits the read results to the host computer. An RFID reader acts as a link in the middle of the RFID tag and controller and it has the following functions:

- Reading the contents of RFID tag
- Writing data on tags
- Releasing data for controller and vice versa
- Acting as the source of power for tag (passive tags)

Additionally, more composite RFID readers are able to communicate with several tags, approve tags to avoid possible misapplication and unauthorised access to controller and ensure the integrity and reliability of data by means of encryption.

2.4.4 Transponder

An RFID tag is a small electronic device that is attached to the object that needs to be tracked/ identified. The tag is also known as transponder. The primary task of a tag is to store data and send it to the reader. RFID tags/ transponder contain microchips that can store unique identification of each object. The chip is made up of integrated circuit and embedded in a silicon chip. Tags contain specific serial number for one specific object. Since they have individual serial numbers, the RFID system design can discriminate among several tags that might be within the range of the RFID reader and read them simultaneously. The tags can be of different size and shape depending on the application and environment [13].

Classifications

(i) Based on the type of battery, RFID tags can be of three types:

Ser	Item	Detail
1.	Active	• Has its own transmitter and power source (Battery) • Transmits signal from the microchip circuit through the power obtained from the internal battery • High signal range • Larger in size • Expensive than passive • The batteries must be replaced periodically
2.	Passive	• Operate without a separate external power source • Obtains operating power from the reader • Low signal range • Cheaper than active tags • Smaller in size
3.	Semi passive/ Battery Assisted Passive (BAP)	• Has a small battery and is activated when in the presence of an RFID reader • Communication method is same as the passive tag

(ii) Based on the mode of operation, RFID tags can be of three types:

Ser	Item	Detail
1.	Read-only	• Has its own transmitter and power source (Battery) • Transmits signal from the microchip circuit through the power obtained from the internal battery • High signal range • Larger in size • Expensive than passive • The batteries must be replaced periodically
2.	Read-write	• Operate without a separate external power source • Obtains operating power from the reader • Low signal range • Cheaper than active tags • Smaller in size
3.	Write Once Read Many (WORM)	• Has a small battery and is activated when in the presence of an RFID reader • Communication method is same as the passive tag • It can write data only once, after that works as read only

2.5 Operating Frequency

Different type of RFID systems operate at different radio frequency for different applications to make them more useful. Each radio frequency has its own read distance, power requirements, efficiency and performance [17]. RFID tags are categorised according to the frequency at which they are designed to operate. Four primary frequency i.e. low frequency (LF), high frequency (HF), ultra-high frequency (UHF) and microwave frequency ranges are allocated by various government authorities for use by

Table 2.3: RFID operating frequency

Frequency Band	Read Distance	Data Speed	Application
Low Frequency (120–150 kHz)	10 cm	Low	Animal identification, factory data collection
High Frequency (13.56 MHz)	10 cm – 1 m	Low to moderate	Smart cards , Non fully ISO compatible memory cards
Ultra-High Frequency (868-928 MHz)	1-12 m	Moderate to high	Electronic toll collection, Baggage handling
Microwave (2.45-5.8 GHz)	Several meters	High	Supply Chain applications, vehicle tracking, Electronic toll collection

RFID systems. The cost of the RFID tags is dependent on its operating frequency [18] and the selection of the frequency depends on the application. Table 2.3 illustrates the details of the mostly used frequencies in RFID technology.

2.6 Working Principle

The working principle depends upon the frequency of operation. For the low frequency and high frequency operation it is based on the inductive coupling (near field) and for the ultra high frequency and microwave frequency operation it is based on backscatter coupling (far field).

i. Inductive Coupling: Inductive coupling refers to the transfer of energy from one circuit to another circuit component through a shared magnetic field. As shown in the Figure 2.3 an inductively coupled tag consists of an electronics data carrying device usually a single microchip and a large coil that functions as an antenna [13]. The distance between the reader and tag are very close to each other so it is called near field coupling.

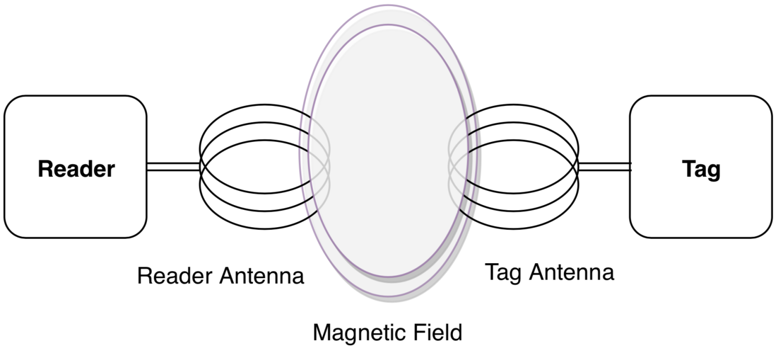

Figure 2.3: Inductive coupling of RFID

ii. Backscatter Coupling: The electromagnetic waves are used to transmit energy and data to the transponder. The electromagnetic waves are reflected by objects with the dimensions greater than half the wavelength of the wave. RFID backscatter coupling uses the RF power transmitter by the tag reader to energise the tag. Essentially they "reflect" back some of the power transmitted by the reader, but change some of the properties, and in this way send back information to the reader. The working principle is shown in Figure 2.4.

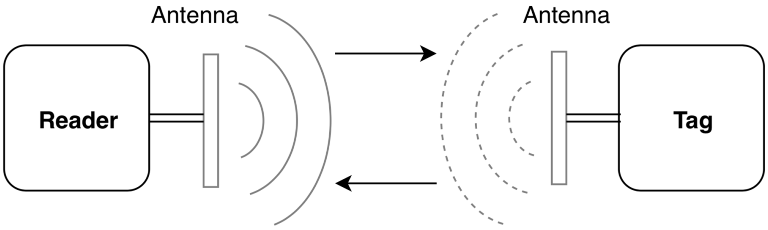

Figure 2.4: Backscattering coupling of RFID

2.7 Applications in Various Field

RFID is used for everything from tracking animals to real time location tracking of assets, employees or customers. Day by day this technology is receiving more and more attention in agriculture, retail, healthcare [19], industries, parking management and transportation [20]. Some applications of RFID technology include:

- Security applications
- Warehousing and stocking goods
- Livestock management
- Controlling entry and exit of vehicles
- Books and libraries management
- Healthcare systems
- Access control
- Controlling the number of rounds. For example, number of rounds a runner should run will be automatically recorded
- Vehicle identification

2.7.1 Security applications

In addition to the precise RFID tags for product tracking and security applications, identification cards and other types of RFID transponders can also be produced. The reader will read the data in identification card. The reader will read the data in identification cards that contain RFID tags as soon as people pass a specific gate. RFID tags embedded in the security bags are considered to be an alternative method to control access to critical information or access to a specific area [21].

2.7.2 Warehousing and stocking goods

When using this technology in commodities and stock control, computers, manage and record data received by readers from tags so that production manager can use this information to always keep the warehouse stock under control. Reader antennas are placed within the warehouse doors to read the data from goods, boxes and pallets containing tags. The whole tracking and data collecting process is performed automatically without any human intervention apart from unpacking, labelling and packing operations in the warehouse [22].

2.7.3 Livestock management

Perhaps it could be said that one of the oldest applications of RFID technology in tracking and control, have been controlling the movement of livestock especially dairy cows. Nowadays, as a quite common process, animals are equipped with this technology by injectable capsules or tags that are attached to their ears. The tags are used to identify lost pets and to sort and taking care of livestock medical records. In recent years this technology has been widely applied in agriculture and medicine. Information about livestock, food and medicine can be very useful in times of crisis for the health of human society. RFID has also been applied to the livestock farming industry for disease LI control, breeding management and stock management [23].

2.7.4 Controlling entry and exit of vehicles

Another common application of RFID technology is controlling vehicles in places that security of vehicles which enter or exit seems crucial. This system is possible by placing a tag on the vehicle and entering all its information in this device memory. Before the vehicle reaches the entrance or exit, it passes through a place that have an antenna to receive the information from a tag which is attached to vehicle. Reader review the information on tag from antenna and if the information on tag shows that vehicle has permission to exit or enter, gates open. If there is no tag or if the information on the tag indicates vehicle is not allowed to enter or exit, security guards inspect that vehicle.

2.7.5 Books and libraries management

Libraries are deploying Radio Frequency Identification (RFID) technology as a substitute for barcode systems for item identification and tracking, and this ultimately enables the automation of the majority of their processes [24]. Sticking a tag on a book and placing series of antenna and reader in the library, has the following benefits:

- Prevention of theft of available books
- The implementation of automated return system and even withdrawal of books from the library
- Track and control the correct arrangement of books on their respective shelves

This application of RFID technology is widely used in large libraries. [7]

2.7.6 Healthcare systems

RFID technology has very wide applications in healthcare systems. This technology not only offers tracking capability to locate equipment and people in real time, but also provides efficient and accurate access to medical data for doctors and other health professionals [25]. This interesting technology begins since the entrance of patient in a well- equipped hospital by a bracelet that all information about the patient is placed in that. Record or storing patient information such as name and address, date of admission and hospitalisation and type of disease, name of doctor and type of surgery plays a vital role in reducing errors and irreparable damages. Escaping or stealing a patient and switching new-borns seems almost impossible with this technology. Also in drug storage areas, by attaching a tag on drugs, expiration date and the amount that has been used can be easily learned.

The RFID technology brings new scopes as well as challenges to the automated identification infrastructure. If the expense and the privacy issue can be solved RFID technology will be incorporated more in our life.

2.8 RFID Standards

RFID standards, as any other standards enable manufacturers to make the same products for a variety of markets and in this way gain the economies of scale. There are two main international RFID standards bodies or standardisation bodies:

- ISO - International Standards Organisation
- EPCglobal - Electronics Product Code Global Incorporated

ISO: The International Organisation for Standardisation provides the ISO/IEC 18000 standards for the air interface standards, which includes different frequency air interfaces. Depending on the functionality of the RFID system, specific frequency air interface will be applied.

EPC: The Electronic Product Code (EPC) is the unique identification number, which is assigned to object or specific entity in logistics activities. The purpose of EPC is that each item can be individually identified in the logistics system, for example, pallet, container, case, etc. (GS1 AISBL) [26].

2.9 Building Blocks of RFID Transponder

An RFID transponder consists of mainly two parts:

- Analog front-end
- Baseband processor

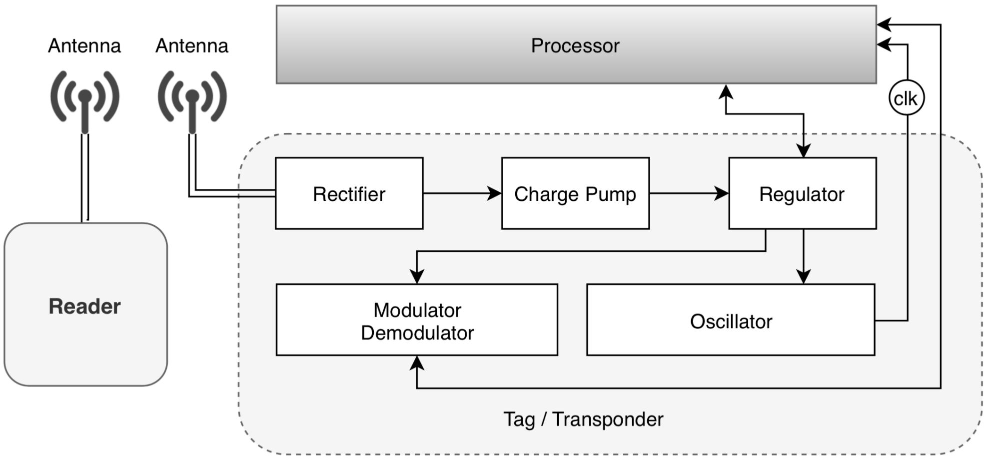

Figure 2.5: An RFID transponder

2.9.1 Analog front-end

Provides multiple supply voltages for all the building blocks to save the power of the whole system. It also generates bias voltage for the analog modules. The analog front-end consists of oscillator, rectifier, charge pump and regulator blocks as shown in Figure 2.5. The functions of each block is summarised as follows:

• **Rectifier:** The reader acts as the power source for the passive transponders. When the reader is within the range of the transponder it extracts RF power from the transmitted signal and with the help of the rectifier circuit it is converted to DC.

• **Charge Pump:** When the rectifier converts RF to DC, the extracted voltage may lower. Here comes the application of the charge pump that is used to raise voltages by minimising power consumption by controlling supply voltages carefully.

• **Regulator:** Voltage regulator is used to get a fixed output voltage that remains constant for any changes in an input or load conditions. Another important characteristic of the block is that it is to suppress supply voltage noise.

• **Oscillator:** In the RFID transponder, a clock is required to enable the analog and digital circuits, such as encoder/decoder, encryption/decryption, synchronisation, and switched-capacitor circuit. It is also used to avoid the use of an excessive power.

- **Modulator and demodulator:** Most of the digital modulations employed in RFID application are the ASK and the PSK. In general, the ASK modulation is commonly used in RFID communications and biomedical systems. The modulator transforms the input impedance of the RFID tags for data transmission and thus modulates the backscattered electromagnetic waves which are further detected and treated by the RFID reader. The demodulator retrieves the baseband data from carrier frequency. It converts the Amplitude Shift Keying (ASK) modulated input signal into digital values.

2.9.2 Baseband processor

The processor digitises the acquired baseband symbols to identify the instructions received from the reader, which consist of reading data from or writing to the implemented one time programmable memory. So digital section is the baseband processor of the Tag, it performs decoding, CRC checking and calculation, command process, accessing memory, and encoding message back to Reader. The main focus is on the reduction of the instantaneous power and how to make the power consumption more evenly distributed over the whole operation period. So, the architecture of baseband processing of passive UHF RFID Tag is fully compatible with the EPC Gen2 protocol.

2.10 Conclusion

In this chapter, basic theory and background of RFID transponders have been reviewed, highlighting the fact that the analog front-end is the key block of a passive RFID transponder. It rectifies the incoming RF signal, providing a regulated voltage supply for the digital core and other circuits. For correct transponder operation at the longest possible readout distance, the RF to DC conversion efficiency must be optimised. In transmitting mode, it changes the input impedance of the transponder between two states, in order to realise the backscatter modulation. In addition, it generates the clock signal that is very necessary for the synchronisation of the overall circuit. The following chapters discuss the design of oscillator, rectifier with charge pump and voltage regulator; building element of the analog front-end of a passive RFID transponder where achieving low power with small area was the main concern.

CHAPTER 3

LOW POWER SMALL AREA WIDE TUNING RANGE VOLTAGE CONTROLLED OSCILLATOR

3.1 Introduction

Passive RFID transponder is a tiny device that has unique ID information for communication with RFID readers and relies on the reader as a source of power supply. The main components of a typical transponder IC include antenna, analog front-end circuit and baseband processor, where the system clock is provided by an oscillator. One of the biggest challenges for the oscillator is to ensure the lowest possible power consumption for passive RFID applications. Oscillators with complementary metal oxide semiconductor (CMOS) technology has been used in numerous products for a long time. Its presence has been extended to high-speed clock and data recovery (CDR) circuits for optical communication, analog and digitally controlled oscillators, frequency dividers of high-frequency synthesizers, clock generators of digital circuits, analog-to-digital converters (ADCs), and many more applications [27]. Oscillators have numerous applications from serving as reference tone generators for receivers to clocks for digital circuits. Most applications especially RFID transponders require the oscillators to be tunable. So, a voltage controlled oscillator or as more commonly known, a VCO, is an oscillator where the output frequency can be adjusted by tuning the control voltage. The general tuning characteristics of a VCO is shown in Figure 3.1.

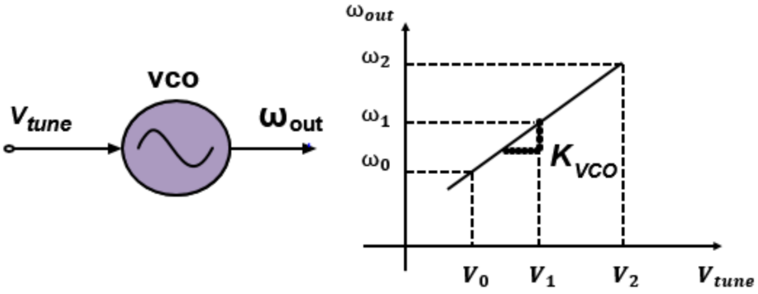

Figure 3.1: Tuning characteristics of voltage-controlled oscillators

Here, from the figure it can be said the output frequency varies from ω_0 to ω_2 (the required tuning range) as the control of the tuning voltage is tuned from V_0 to V_2. For an ideal VCO, the output frequency can be expressed as,

$$\omega_{out} = \omega_0 + K_{VCO} \times V_{tune} \tag{3.1}$$

Where, ω represents the intercept corresponding to $V_{tune} = 0$ and K_{VCO} is the tuning gain or the sensitivity of the circuit. The achievable frequency range is called the tuning range of the circuit.

3.2 Performance Parameters

There are several factors to influence the performance of VCO in general.

- **Centre Frequency:** The centre frequency is the midrange value in the characteristics curve shown in Figure 3.1 which is determined by the particular application the VCO is designed for.

- **Tuning Range:** For most applications it is better for the VCO to provide a wide tuning range to make sure the output of the circuit can be driven to the desired value for process and temperature variation. Wide tuning range in oscillators has a direct conflict with the phase noise performance. To optimise phase noise, the VCO should be designed to have minimum sensitivity to the control lines which reduces the gain of the circuit and degrades the tuning range.

- **Tuning Linearity:** The output frequency of the VCO must be linearly proportional to the control voltage. It is desirable to minimize the variation of Kvco across the tuning range.

- **Output Amplitude:** It is desirable to have large output amplitude which makes the oscillator less sensitive to noise. The output amplitude has trade-offs with power dissipation, power supply and tuning range. The amplitude is desired to be constant across the tuning range.

- **Power Dissipation:** The design of oscillators is a tradeoff process that involves power consumption, speed and phase noise performance. Depending upon application some metrics need to be traded for the others. Sometimes if the power consumption of an oscillator is to be optimized, its phase noise performance degrades.

- **Phase Noise Performance:** The output signal of the oscillator is not perfectly periodic as generally assumed. The intrinsic noise of the devices and the sensitivity if the oscillator results in random variation in output phase and frequency leading to undesirable effects. These effects are characterized by phase noise and determined by the requirements of each application.

3.3 VCO Topologies

Phase noise, power dissipation and tuning range are the most important performance metrics to consider in VCO design. Due to the co-existence of multiple communication standards, multi-standard transceivers are needed to address the market requirements. The choice of VCO topologies depend on the performance parameters that the application needs to be focused. LC and ring VCO are the primary VCO topologies circuits which are used for signal generation purpose.

3.3.1 LC VCO

LC oscillators have low phase noise which makes them appropriate for use in radio frequency frameworks. They have a larger area when contrasted with ring oscillator. LC-VCOs are utilized to give input for mixers to up-convert and down- convert signals and have primary significance in fully-integrated transceivers. The best combination of very low phase noise specifications with very low power utilization (battery operation) urges the VLSI planners to use LC-VCOs in different areas. Inductor and capacitor combined together with active circuit to compensate the passive elements losses build the LC VCOs. The LC resonator forms feedback mechanism to obtain steady oscillations and determines the frequency of oscillation. The oscillation frequency will be-

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{3.2}$$

Voltage dependent capacitors called "varactors" are employed for frequency tuning. In CMOS technology, a varactor can be realized by a regular MOS transistor where the source and drain terminals are tied together as shown in Figure 3.2.

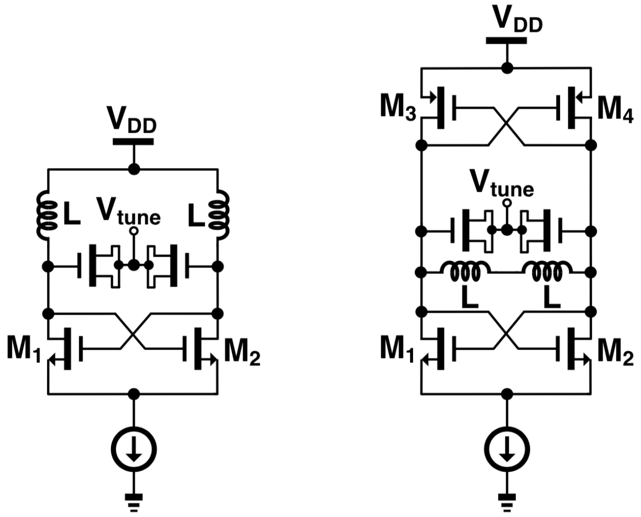

Figure 3.2: LC VCO

3.3.2 Ring VCO

Ring oscillator (RO) is formed by using an even and odd number (N) of open loop inverting amplifiers (A) or delay cells (or stages) coupled in a feedback loop with positive value [28]. To accomplish oscillation, open loop gain of the oscillator should be higher than unity and the ring requires a phase shift of 2π. If the propagation signal passes twice over the chain of N no of delay cells with propagation delay t_d, the oscillation frequency of the ring oscillator would be-

$$f_O = \frac{1}{2Nt_d} \tag{3.3}$$

Ring oscillators can be designed with single-ended or differential structures [29]. The total number of inversions in the loop must be odd so that the circuit does not latch up. Single-ended structures can be implemented only with odd number of delay stages. Differential structures can be designed also with even number of delay stages simply by configuring one stage such that it does not invert.

3.3.2.1 Single ended topology

The basic single-ended topology consists of CMOS inverters. Here, the number of delay cells must be odd. Current is consumed in CMOS inverters when the output node capacitances are charged and discharged. At an input step the capacitances is charged/discharged by a constant current generated by the transistor that is currently on. Consequently, a lower charging current would cause a longer transition time that translate to a longer delay and lower frequency of operation. A typical single ended ring oscillator topology for is shown in Figure 3.3.

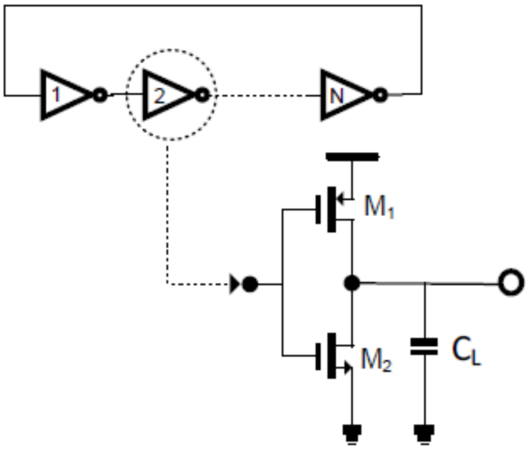

Figure 3.3: Single ended ring oscillator

3.3.2.2 Differential topology

In the differential ring oscillators the total delay cells can be odd or even. The differential configuration requires more area and has a complex design compared to a single-ended but it is frequently used due to its frequency stability and better phase noise performance for high frequency applications. However, in various circuits differential ring oscillators are often preferred because they have much better common noise rejection of substrate-coupled noise than its single-ended counterpart, even if the single-ended topology has a superior phase noise. Differential ring oscillators also have a lower noise injection into other circuits on the same chip. The topology is shown in Figure 3.4.

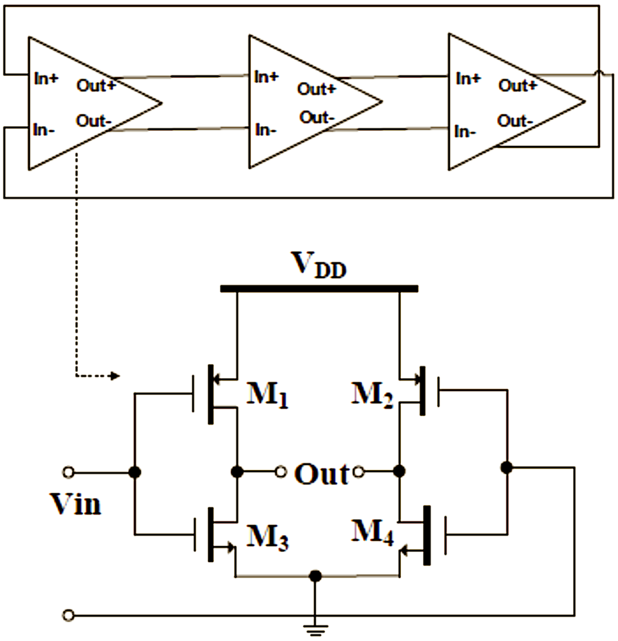

Figure 3.4: Differential ring oscillator

3.4 Proposed VCO

A 3-stage differential ring VCO is designed and the delay cell for each stage is shown in Figure 3.5. It is focused on designing a VCO for RFID transponder for microwave frequency range which demands for the required oscillation frequency of 2.45 GHz. Beside the oscillation frequency, the low phase noise, low power consumption, low area and a good tuning range is also taken into account. The differential configuration is used to reduce the substrate noise. The output frequency of the structure is controlled by the tuning voltage (V_{tune}) that is connected to the gate of the two PMOS transistors. Positive feedback is used to increase the speed, whereas for the same speed the negative feedback needs more resistance. This is less favourable in integrated circuit [30]. For the high frequency oscillator, choosing optimal number of stages is a vital part to design a ring VCO. Two, three, and four stages are frequently used structures for the Differential Ring Oscillator (DRO) in wireless communication systems.

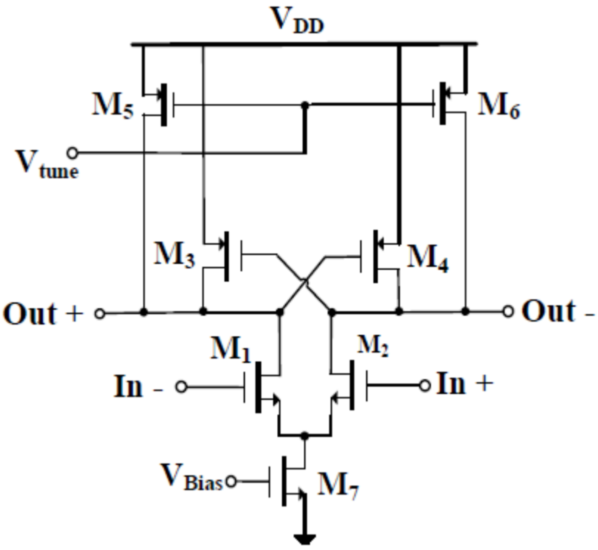

Figure 3.5: Proposed delay Cell

The two or four stage ring oscillators give quadrature outputs but 3-stage RO is faster. Moreover, start-up condition is easily attained in odd number of stages in comparison to the even counterpart. Therefore, for designing the proposed VCO, the 3-stage RO is preferred to increase the oscillation as well as to minimise power consumption. In the proposed delay cell, input pair is represented by the two NMOS transistors M_1 and M_2. M_5 and M_6 are the controllable PMOS transistors that are controlled by gate voltage V_{tune}. For oscillation, positive feedback is given by the cross-coupled transistors M_3 and M_4. The tuning range is controlled by regulating the tail current source M_7 with bias voltage V_{bias}. In [31], a resistor is used in place of the tail current source. But to decrease the power dissipation and die area, MOSFET based current source (M_7) is used in this design. The sizes of the MOSFETs (Table 3.1) are calculated considering the existing equations paying attention to the optimisation of power consumption and phase noise.

Table 3.1: Transistor configuration

Name of the Transistor	**Size W/L** (µm/µm)	**Category**
M_1, M_2	10/0.1	nMOS
M_3, M_4	20/0.1	pMOS
M_5, M_6	20/0.1	pMOS
M_7	25/0.1	nMOS

3.5 Layout

Layout had been done to measure the area of the VCO. It was performed in virtuoso cadence environment in Layout XL where only Metal 1, Metal 2 and Poly-Silicon were used for layout purpose. Next, the layout had been passed through DRC checker to ensure that the layout follows proper design rules. After that LVS checking was executed to ensure that the layout is perfectly matched with the schematic. Lastly, RC extraction was executed to detect the parasitic capacitance and resistances. This RC extraction had shown that, this VCO circuit has 184 parasitic capacitances and 380 parasitic resistances. Figure 3.6 depicts the layout of the circuit which has the total area of 47.79×27.55 µm^2 which is a very low area compared to the state of the art as this circuit doesn't contain any energy storage element and resistance.

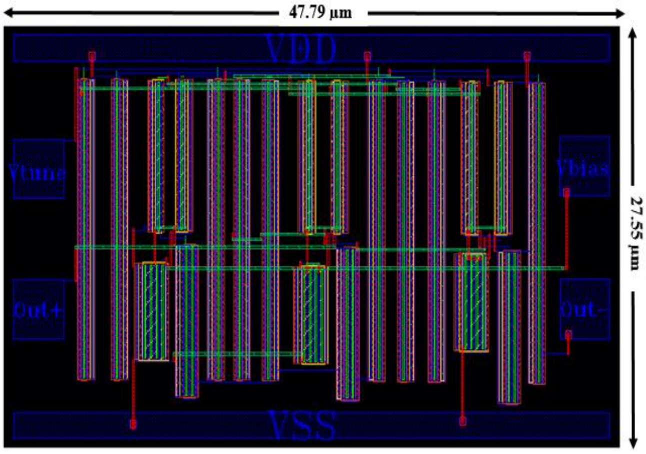

Figure 3.6: Layout of the proposed ring VCO

3.6 Simulation Results

The proposed differential ring VCO is designed and simulated in cadence virtuoso environment in 90 nm CMOS process technology. Transient analysis, periodic steady state (PSS), pnoise and DC analysis have been conducted to determine the performance parameters such as oscillation frequency, oscillation's amplitude, output power, phase noise and DC power consumption. Though it is feasible to conduct schematic based simulation, there is a slight deviation after post layout simulation due to the presence of parasitic resistances and parasitic capacitances. For this reason post layout simulation is also performed to check the variation of the output results. In addition, analysis of corner conditions, temperature variation, stability and Monte Carlo analysis have been done to evaluate the proposed design's sustainability.

3.6.1 Transient response

Figure 3.7 shows the transient characteristics of the proposed VCO where (a) is the differential output and (b) is output of the two terminals. This response illustrates that the oscillator provides a sinusoidal oscillation. But it is also observed that a slight asymmetric waveform has been appeared. This is due to the phase noise of the VCO.

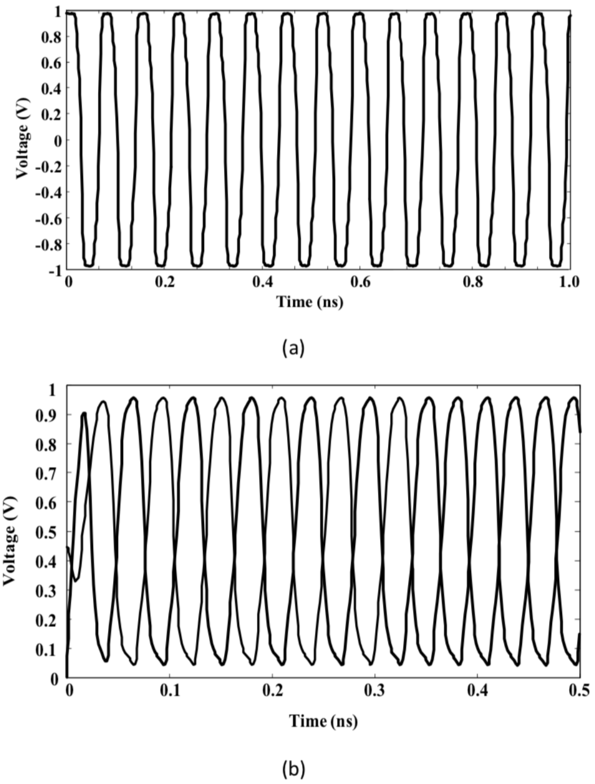

Figure 3.7: Transient response of the VCO (a) Differential output (b) Output at two terminals

3.6.2 Tuning range

To determine the tuning range of the VCO, the tuning voltage (V_{tune}) is varied from 0.5 V to 1 V keeping the V_{bias} fixed to ensure M_7 operates in saturation. As depicted in the Figure 3.8, the tuning range of the VCO is 1.04 GHz to 4.21 GHz for the schematic based simulation and 0.98 GHz to 3.49 GHz in post-layout simulation. The tuning range of the oscillator is –

$$\text{Tuning range} = \frac{f_{max} - f_{min}}{\frac{f_{max}+f_{min}}{2}} \times 100 \tag{3.4}$$

For the schematic circuit the tuning range is 120.7$\%$ but due to the effect of the parasitic components it reduces to 57$\%$. Even then it can be said that the oscillator shows a wide tuning percentage. The desired frequency 2.45 GHz for the RFID transponder is achieved when the V_{tune} is set at 0.7 V in schematic and 0.58 V in post-layout simulation.

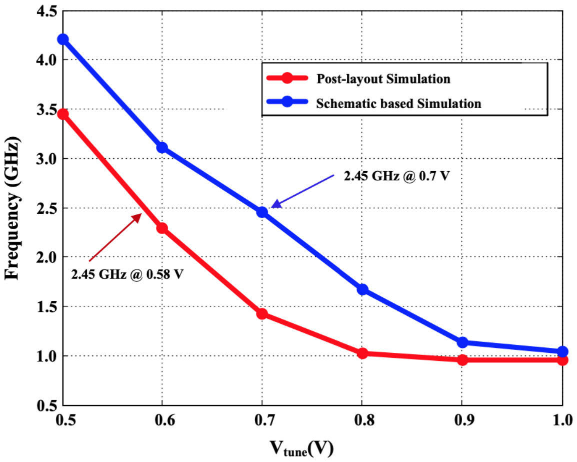

Figure 3.8: Oscillation frequency for different tuning voltages

3.6.3 Power consumption

It is very obvious that when the control voltage increases, the oscillator runs faster, therefore consumes more power. Graphical representation of the variation of power with the change in tuning voltage is shown in Figure 3.9.

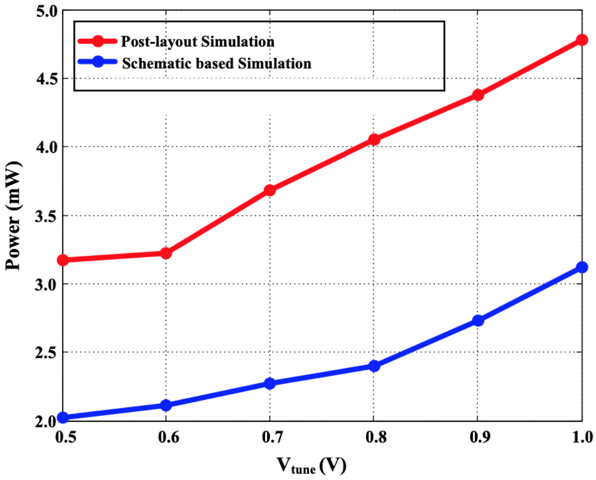

Figure 3.9: Power dissipation for different tuning voltage

Here the power dissipation ranges from 2.02 mW to 3.12 mW for the schematic simulation whereas for post-layout simulation it varies from 3.17 mW to 4.78 mW.

3.6.4 Phase noise

If the short term stability of an oscillator is examined using a spectrum analyzer, it shows a spectrum consisting of random and discrete frequency components causing a broad skirt and spurious peaks. If the oscillator is noise free the spectrum would consist of a single spectral line. The broadening of the spectrum is caused by various noise sources including thermal noise, shot noise or flicker noise in active and passive devices. This broadening is due to the phenomenon of phase noise. Phase noise is determined by the following equation-

$$L(\Delta\omega) = 10 \times log[(\frac{2FkT}{P_S}) \times \{1 + (\frac{\omega_0}{2Q\Delta\omega})^2\} \times (1 + \frac{\Delta\omega_{1/\mathrm{f}}{}^3}{\Delta\omega})] \tag{3.5}$$

Where:

k = Boltzman's constant = $1.38 \times 10^{-23} J/K$

T = absolute temperature

F = a fitting factor depending on the particular circuit used

P_S = power of the carrier

Q = loaded quality factor of the circuit

L($\Delta\omega$) = frequency offset from the carrier (HZ)

ω_o = carrier frequency (HZ)

The VCO has the phase noise of -92.01 dBc/Hz to -86.90 dBc/Hz at the offset frequency of 1 MHz. Figure 3.10 represents the phase noise for 2.45 GHz frequency. It is observed that the phase noise performance in better in case of post-layout simulation.

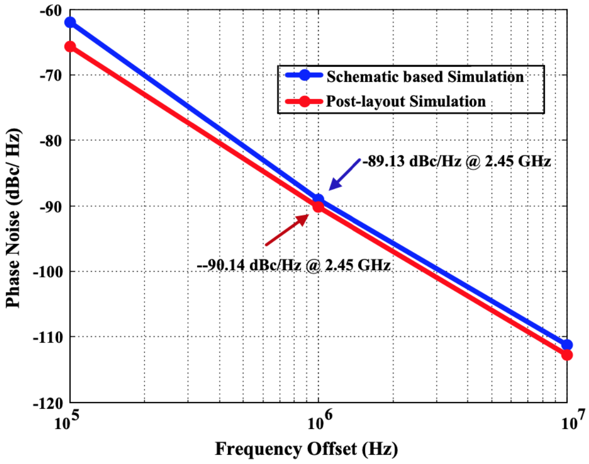

Figure 3.10: Phase noise vs offset frequency

3.6.5 Figure of merit (FOM)

A parameter that represents the performance of the VCO called figure-of-merit (FOM) is calculated from the phase noise and the power dissipation of the oscillation frequency with the following equation,

$$FOM = L(\Delta\omega) + 10 \times log(\frac{p_{diss}}{1mW}) - 20 \times log(\frac{\omega_0}{\Delta\omega}) \tag{3.6}$$

Where:

L$(\Delta\omega)$ = Phase noise at offset frequency

P_{diss} = Power dissipation

ω_o = Oscillation frequency

At the 1 MHz offset frequency the value of FOM for 2.45 GHz oscillation frequency is -153.35 dBc/Hz for schematic based output and for the post-layout output it is -152.87 dBc/Hz which indicates that for this circuit the performance of the VCO doesn't change significantly because of the parasitic components.

The output of the proposed VCO for the frequency, power consumption, phase noise and figure of merit with different tuning voltages is summarized in the Table 3.2.

Table 3.2: Simulation results for different tuning voltages

Ser.	V_{tune} (V)	Frequency (GHz)		Power Consumption (mW)		Phase Noise at 1 MHz (dBc/Hz)	
		Schematic	Post-layout	Schematic	Post-layout	Schematic	Post-layout
1	0.5	4.21	3.49	2.02	3.17	−92.01	−93.15
2	0.6	3.11	2.29	2.11	3.22	−90.80	−90.12
3	0.7	2.45	1.42	2.27	3.68	−89.13	−89.58
4	0.8	1.67	1.03	2.40	4.05	−87.67	−88.17
5	0.9	1.13	1.00	2.73	4.38	−87.20	−87.97
6	1.0	1.04	0.98	3.12	4.78	−86.90	−87.52

3.6.6 Process corner analysis

Process Lots (or corner lots) are special-modified-wafers that help verifying chip design robustness to accommodate process variations that statistically occur in wafer production over the years. It accounts for deviations within the semiconductor fabrication method. Variations in the process parameters can be impurity concentration densities, oxide thicknesses, threshold voltage and diffusion depths of the MOSFETs. The variations occur due to various causes such as the temperature and humidity where the wafers are prepared. The current passing through the MOSFETs relies on the process parameters. So the devices are necessary to experiment in the extreme process variations to make sure that the MOSFETs continuously show a good margin. A conventional name for process corner uses two-letter designators, where the first letter refers to the N-channel MOSFET (NMOS) corner, and the second letter refers to the P channel (PMOS) corner [32]. As in the proposed VCO, both NMOS and PMOS transistors are used, the combination of the corner analysis would be SS (Slow NMOS and Slow PMOS), SF (slow NMOS and fast PMOS), FS (fast NMOS and slow PMOS) and FF (fast NMOS and fast PMOS).

Figure 3.11 represents the frequency variation with the change in tuning voltages for all the corner conditions. Frequency of oscillation varies from 2.5 GHz to 4.06 GHz for SS, 2.55 to 4.38 GHz for SF, 2.58 GHz to 4.23 GHz for FS and 2.52 GHz to 4.12

GHz for FF corner condition.

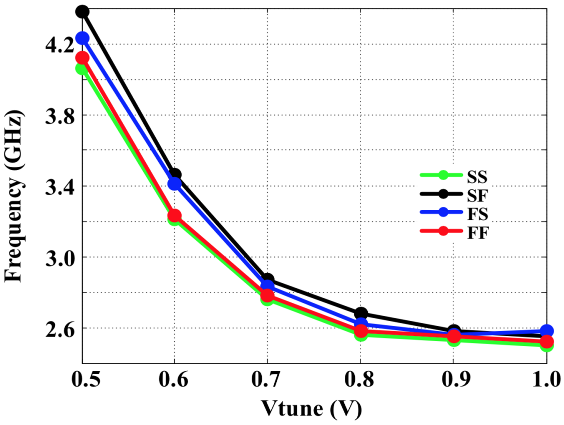

Figure 3.11: Oscillation frequency Vs tuning voltage for different corner conditions

Figure 3.12 illustrates the DC power consumption for different tuning voltages for the corner variations. SS shows the variation of DC power consumption from 1.59 mW to 3.0 mW, SF shows the variation from 3.15 mW to 5.2 mW, FS condition has power consumption from 2.46 mW to 4.3 mW and for FF it varies from 3.11 mW to 5.1 mW.

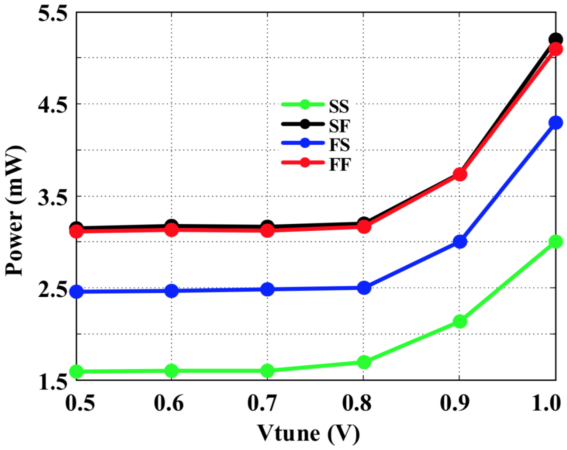

Figure 3.12: DC power consumption vs tuning voltage for different corner conditions

Figure 3.13, with the process corner variation SS, SF, FS and FF the MOSFETs phase noise at 1 MHz offset frequency is measured for different tuning voltages. SS has the variation of the phase noise (in the scale of dBc/Hz) from -87.6 to -91.8, SF has -87.5 to - 91.7, FS has 88.8 to 92. 3 and FF has -87.5 to -91.5.

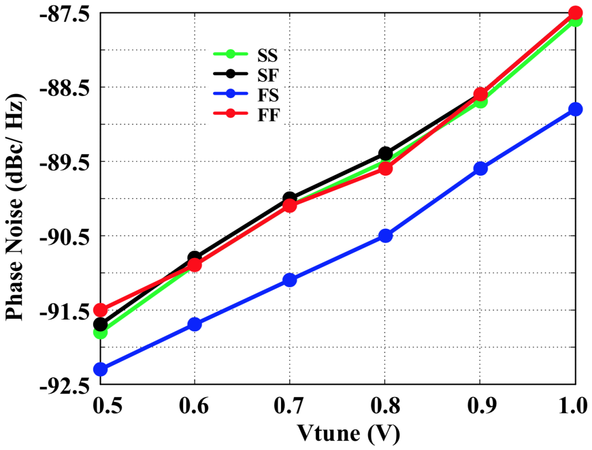

Figure 3.13: Phase noise vs tuning voltage for different corner conditions

3.6.7 Temperature sweeping

When a chip is functioning, the temperature can vary throughout the chip. The variation of temperature may affect the MOSFET parameters like threshold voltage, mobility etc. So while designing any circuit it should be kept in consideration that the device must have the constancy with variation of temperature. The VCO's performance parameters have been simulated for five different temperature ranges from $-50°$ C to $50°$ C (with the interval of $25°$ C). Figure 3.14 summarizes that higher the temperature lower the value of oscillation frequency. Though the frequency changes, it gives a consistent variation for all the temperatures.

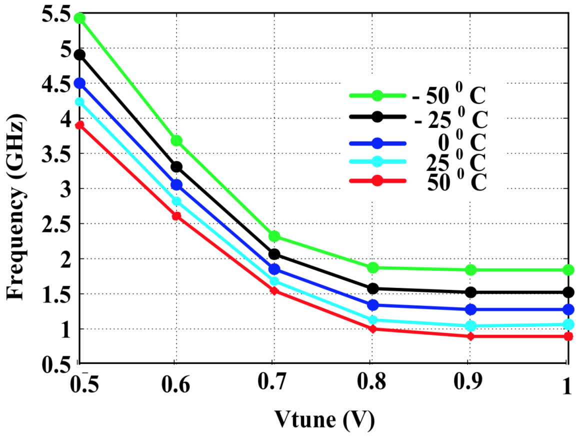

Figure 3.14: Oscillation frequency vs tuning voltage for different temperatures

In Figure 3.15, we can observe with increasing the tuning voltage of the circuit power dissipation increases for each temperature, but with higher temperature MOSFETs dissipates less power than lower power.

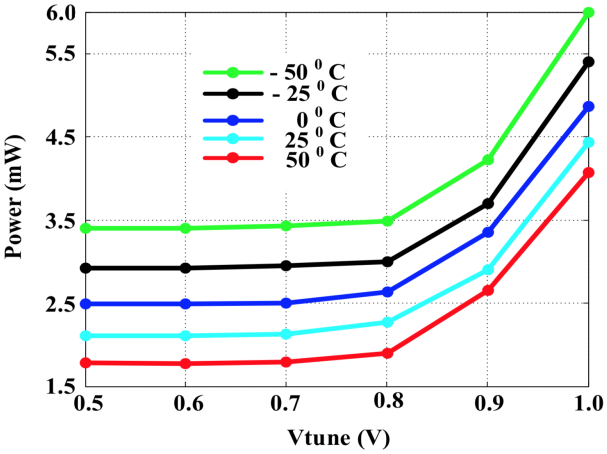

Figure 3.15: DC Power consumption vs tuning voltage for different temperature

However, it is noticed from the simulated output shown in Figure 3.16 that the phase noise does not have very significant effect with variation of the temperature.

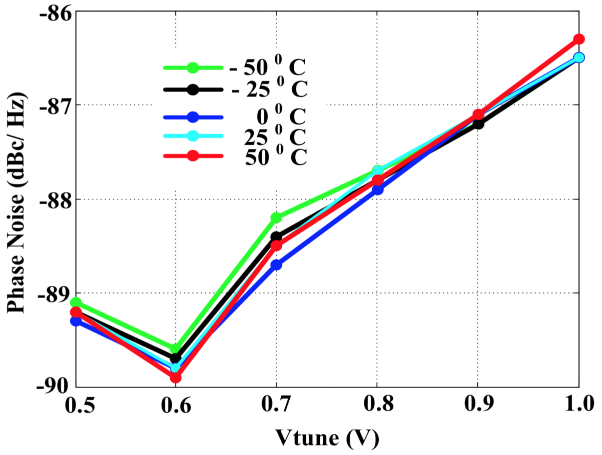

Figure 3.16: Phase noise vs tuning voltage for different temperatures

3.6.8 Stability analysis

Stability is defined in this context as the ability of an oscillator to maintain a consistent, fixed frequency over a given span of time. The more stable an oscillator is, the more reliable it is considered to be, and in applications like wireless communications and radar, stability is of utmost importance. Stability is determined by the loop gain. From the barkhausen criteria it is known that for an ideal oscillator the loop gain of a system at the oscillation frequency should be 1. So the magnitude (dB20) and the phase (deg) should be 0 at the oscillation frequency. Figure 3.17 shows the simulated output for stability where it gives magnitude (dB20) = 0 and the Phase (deg) = 0 at the oscillation frequency 2.45 GHz.

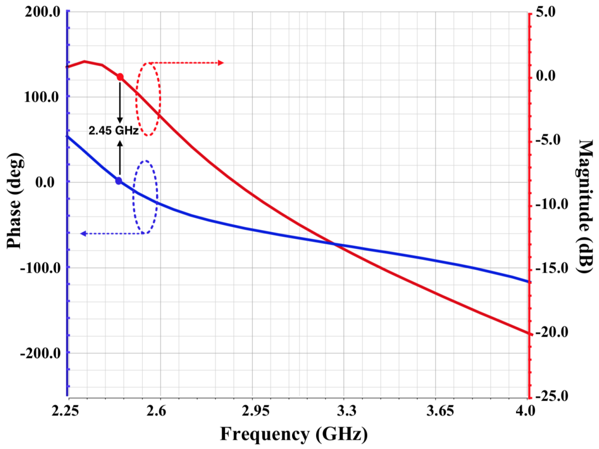

Figure 3.17: Loop gain (Mag and phase) vs frequency of the proposed VCO

3.6.9 Monte Carlo simulation

In electronic circuits, during manufacture, circuit parameters often vary from the designed values by small amounts. These small variations can cause changes in circuit functionality and could be hard to predict through simulation. One technique to analyse these variations and their impact on circuit behaviour is through Monte Carlo analysis. Monte Carlo analysis is a process that repeatedly runs a given experiment while randomising each component. Outputs from this procedure are organised and graphed to aid in visualisation of system trends and behaviour.

The frequency at which the RFID transponder will work is 2.45 GHz which is achieved by setting the tuning voltage at 0.7 Volts. The Monte Carlo Carlo analysis is done for 100 samples. Simulation has been done for oscillation frequency, DC power consumption and phase noise as shown in Figure 3.18, Figure 3.19 and Figure 3.20 respectively. With the 100 samples the statistical analysis of the frequency results in standard deviation of 22. 813 MHz with the mean value of 2.438 GHz as shown in Figure 3.18.

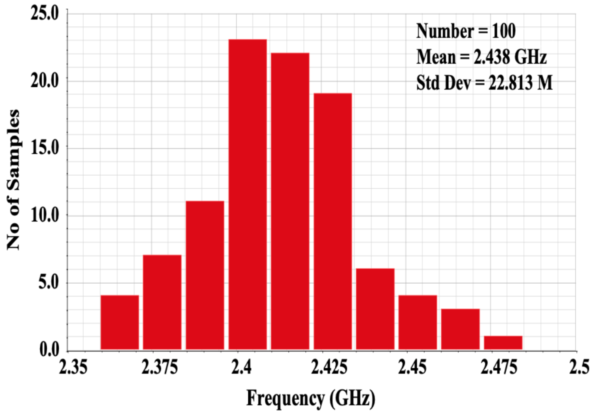

Figure 3.18: Statistical analysis of oscillation frequency for V_{tune} = 0.7 V

Figure 3.19 shows that the DC power has a very lower standard deviation with mean value of 2.276 mW.

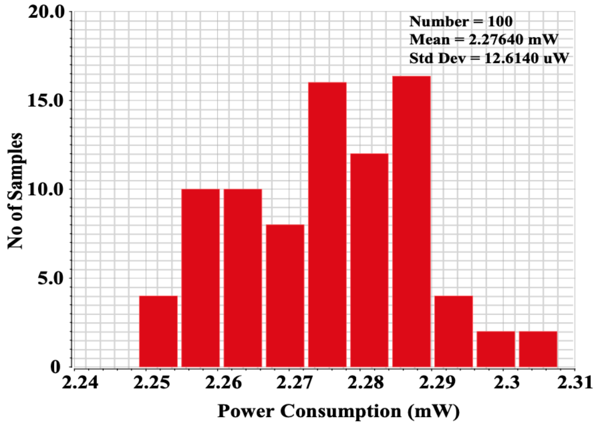

Figure 3.19: Statistical analysis of DC power consumption for V_{tune} = 0.7 V

Similarly, the phase noise at offset frequency of 1 MHz is examined and presented in Figure 3.20 that has mean value of -89.22 dBc/Hz.

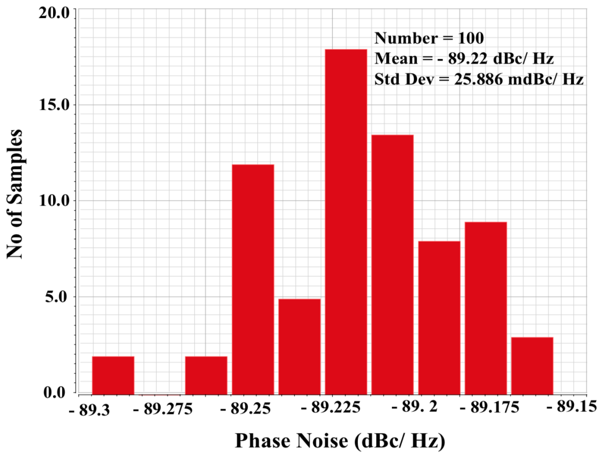

Figure 3.20: Statistical analysis of phase noise for V_{tune} = 0.7 V

3.7 Performance Comparison

Comparisons have been made with state-of-the-art and shown in Table 3.3. From the comparison it is easily understood that this circuit has very high tuning percentage with low power consumption. Basically, each oscillator design is based on the application. The proposed design is suitable for the 2.45 GHz RFID transponder as it consumes optimum amount of power and small area within this frequency range.

Table 3.3: Performance comparison of CMOS VCO with the state-of-the-art

References	**Jalil et al. [3]**	**Changchun et al. [33]**	**Kumar et al. [34]**	**Sakka et al. [35]**	**Kumar et al. [36]**	**Chien et al. [37]**	**This Work**
Technology (nm)	65	180	180	180	180	20	**90**
No of Stages	4	4	4	3	5	-	**3**
Supply Voltage (V)	1.2	1.8	1.8	1.8	1.8	1.1	**1**
DC Power (mW)	12.36	13.6	4.47	4.5	10.54	46.2	**2.27**
Tuning Range (GHz)	4.25 – 21.31	1.57 – 2.76	4.02 – 6.12	3.90 – 4.10	1.61 – 3.71	2.00 –16.00	**1.04 - 4.21**
Tuning Range (%)	80	-	41.4	-	78.52	-	**120.7**
Phase Noise (dBc/Hz)	-90.47	-91.12	-89.7	-85.31	-89	-136.6	**-89.13**
Offset Freq. (MHz)	1	1	1	1	1	10	**1**
FOM (dBc/Hz)	-184.72	-149.7	-155.9	-150.82	-150.1	-	**-153.35**
Area (µm^2)	145 × 64	-	-	-	2070	44x10^3	**47.79 ×27.6**

3.8 Chapter Summary

A new design of ring VCO has been projected for passive RFID transponder. Various parameters such as frequency, power consumption, tuning range, phase noise and FOM are analyzed. For oscillation frequency of 2.45 GHz, the circuit consumes very low power and also it occupies very less area. To see the effect of the parasitic components on the circuit, the performances are also compared with post-layout simulation results. Moreover, to check the stability and compatibility with different atmosphere, this design has undergone some simulations like Monte Carlo analysis, corner analysis, temperature sweeping and stability analysis. Finally simulated performance has been compared with the state of the art.

CHAPTER 4

HIGH EFFICIENT SMALL AREA CROSS-COUPLED RECTIFIER WITH CHARGE PUMP

4.1 Introduction

A rectifier is an electrical and electronic device, which is widely utilized in different applications. The function of a rectifier is to convert AC (alternating current) source to DC (direct current) ones, which is known as rectification. The first generation of rectifier is made of vacuum tube diode and copper oxide metal. The two technologies were widely used before the development of semiconductor industry. With the development of semiconductor technology, the rectifier consisting of vacuum tube diode gradually fade out the market. The traditional rectifiers can only be found in some vacuum tube audio equipment. Instead, the semiconductor diode, such as p-n junction diode and schottky diode became popular in the power rectification applications of both low current and high current fields. With the development of integrated CMOS technology, the diode connected MOS transistors are widely used in integrated circuits in place of the discrete diode components.

Rectifiers can be divided into multi-phase rectifier and single phase rectifier. Three phase (multi-phase) rectifier circuits are very important for industrial application and high voltage DC energy transmission. However, most rectifiers for domestic equipment are single phase, especially for low power, low voltage integrated circuits. Considering this research topics that is for RFID transponder, only single phase full wave rectifier is focused.

In RFID transponders amongst the three main categories; Active, semi passive and the passive transponders the passive transponder are mostly used as they don't need any external power source. Thus the passive transponders are light in weight, cheaper, smaller in size and more reliable. They use a rectifier block to extract the RF signal coming from the RFID reader. But the passive transponders suffer from a limited communication range. To increase this operating range the sensitivity and/or efficiency of the transponder rectifier has to be improved so that it can efficiently extract power from a weak received RF signal and give a noise free output voltage.

4.2 Design Considerations

Below factors are considered most important aspects while designing RFID transponder.

- **Output voltage:** The rectifier converts the AC/ RF voltage supplied by the receiver to the DC voltage and powers the load circuit. The efficiency of the rectifier depends on the voltage output. Higher efficiency is achieved by the larger output voltage.

- **Power efficiency:** In RFID transponders rectifier is one of the most important blocks. It is important to mention that the efficiency of the rectifier is usually the bottleneck. Higher power efficiency means higher total efficiency.

- **Working frequency:** The working frequency of a rectifier is very important. Depending on the application the working frequency also defers. As the above mentioned transponder works in microwave frequency range, this rectifier must have 2.45 GHz working frequency.

- **Temperature:** Change in temperature may affect the circuit performance as well as the sustainability. So it is necessary to design such a rectifier which does not change its performance and output voltage drastically with the variation of temperature.

Based on the above considerations, rectifier plays a very important role in the application of RF energy harvesting system and RFID applications.

4.3 Rectifier Topologies

The history of rectifier goes back to 1928. A device of electrolytic rectifier was patented by G. W. Carpenter in 1928 [38]. But it would be only suited to the use of low voltage applications, because the breakdown voltage of these rectifiers are very low and the electric shock is easy to happen, which is a big risk. With the development of semiconductor technology, discrete component was induced. Rectifiers achieved by diodes and capacitors were widely used. The half-wave rectifier consists of a single diode and very simple. The full wave rectifier composed of diode bridge makes full use of the input source, because both the negative and positive period pass to the load. Thus, the output ripple is much smaller than the half wave rectifier. So most of the applications follows the full wave configurations whatever the topology is. Mostly used topologies of the rectifiers are Dickson method, Schottky method and Cross-coupled method.

4.3.1 Dickson method

The basic charge pump architecture is proposed by Dickson in 1976 shown in Figure4.1. The Dickson voltage doubler [39] is a popular CMOS implementation for rectifiers, which is operated by pumping charges through the diodes and thereby charging the capacitors each clock cycle.

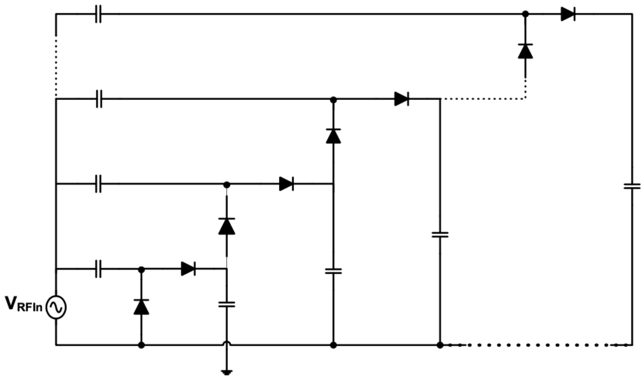

Figure 4.1: Dickson charge pump rectifier

If there input RF signal is V_{RFin} and V_{th} is the threshold voltage, the output voltage after operating in both positive and negative half cycle will be:

$$V_{out} = 2 \times (V_{RFin} - V_{th}) \tag{4.1}$$

The output voltage of N_{th} stage charge pump is given as:

$$V_{out} = 2 \times N \times (V_{RFin} - V_{th}) \tag{4.2}$$

From the above equation 4.1 and 4.2, it is obvious that the threshold voltage has a drastic effect on the output voltage. To obtain a decent voltage from small input RF signal, the threshold voltage must be minimised. Other way to increase the output voltage is by increasing the number of stages. However, in this method increasing the number of stages causes to degradation of power dissipation and power conversion efficiency.

4.3.2 Schottky diode method

A Schottky diode is one type of electronic component, which is also known as a barrier diode. It is widely used in different applications like a mixer, in radio frequency applications, and as a rectifier in power applications. It's a low voltage diode. It has a low-forward voltage drop, low junction capacitance and a very rapid switching capacity than the common PN junction diodes [40]. Figure 4.2 shows the equivalent circuit of a Schottky diode where R_s is the series resistance. I_d and V_d are the current and voltage generated by the equivalent current source. C_d is the junction capacitance. L_p is the parasitic inductance. The behaviour of diode is determined by its nonlinear parameters, by the barrier losses, and by the series resistance losses.

This type of rectifiers are generally used in RF applications because of it has low forward voltage and high switching speed but it requires additional manufacturing

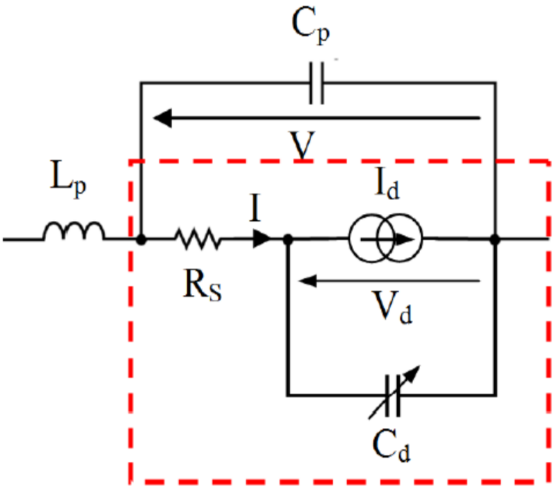

Figure 4.2: Equivalent circuit of a schottky diode

steps which limits its ON-chip usage. Also, a schottky diode rectifier is unable to function well at larger powers because of its small reverse breakdown voltage.

4.3.3 Cross-coupled rectifier

This configuration is also known as differential drive rectifier. Due to the differential drive active gate bias mechanism, the rectifier is capable of achieving low ON-resistance and small reverse leakage during the forward and the reverse conduction modes respectively. The conventional CMOS rectifier with differential drive configuration for single stage is shown in Figure 4.3.

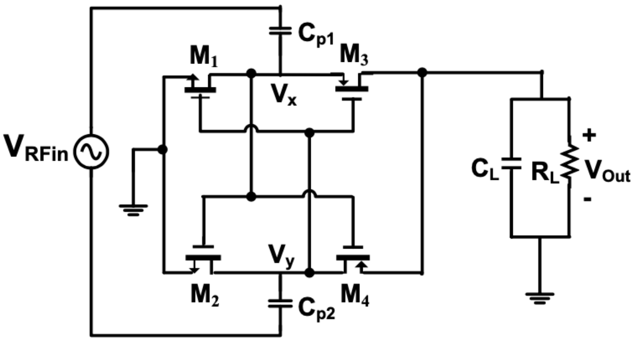

Figure 4.3: Single stage conventional cross coupled rectifier with charge pump

The structure represents the bridge structure with cross coupled CMOS configuration. The body of the transistors are connected to the source to remove the body effect. Differential RF input are connected through the pumping capacitors C_{p1} and C_{p2}. The gates of the nmos and pmos are connected together. The nmos transistor M_1 is forward biased when V_x is in negative half cycle. On the other hand, in positive half cycle of V_y transistor M_1 gets forward biased. It reduces the threshold voltage and drops the on resistance Similarly, the opposite mechanism happens to the transistors if V_x is in positive half cycle and V_y in negative. Here, the threshold voltage increases, reducing the leakage current.

If the applied RF signal is V_{RFin} and the voltage loss is considered to be V_{drop}, the output DC voltage of circuit will be:

$$V_{out} = 2 \times V_{RFin} - V_{drop} \tag{4.3}$$

If N no of stages are cascaded this configuration acts as charge pump rectifier and for that the output voltage will be:

$$V_{out} = 2 \times N \times (V_{RFin} - V_{drop}) \tag{4.4}$$

From equation 4.4 it is understood that the voltage loss will increase with the increase of number of stages.

4.4 Proposed Rectifier with Charge Pump

In this work the cross coupled bridge configuration is taken as the base which can convert the input into DC as well as works as voltage multiplier. This rectifier was at first used for low frequency signals but in 2007 that Facen and Boni [41] presented that it could also be used to rectify UHF signals. The reason is this type of rectifier has the

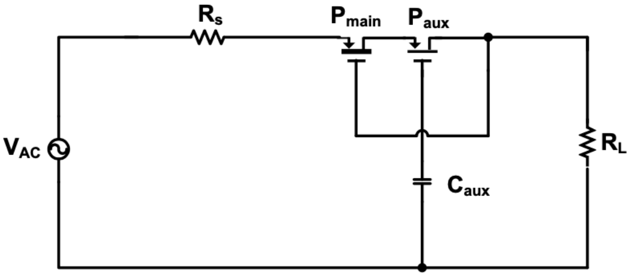

Figure 4.4: Auxiliary arrangement

capability to attain small ON resistance and very less amount of leakage current at the same time [42]. Proposed rectifier works in the 2.45 GHz microwave frequency. As the output voltage of cross coupled rectifier decreases with the increase of no of stages, to overcome this problem an auxiliary arrangement is added with the original PMOS as shown in Figure 4.4.

The threshold voltage (V_{th}) gives a limitation in the charge transferring ability of diode. This configuration is able to cancel the threshold voltages of transistors, thus increases the DC extraction capability. Thus the auxiliary PMOS is used to remove the V_{th} effect as well as the DC extraction capability. A part of the input voltage is stored in the capacitor (C_{aux}). So V_{aux} is the voltage stored across capacitor C_{aux}. The operation of the circuit is analysed as follows. The output voltage of the circuit is:

$$V_{out} = V_{ov2} + V_{aux} \tag{4.5}$$

$$V_{in} = V_{ov1} + V_{out} \tag{4.6}$$

Where V_{ov1} and V_{ov2} are the overdrive voltages of the P_{main} and P_{aux} respectively. Now subtracting equation 4.5 to 4.6 and rearranging it, we get:

$$V_{out} = \frac{1}{2}((V_{ov2} - V_{ov1}) + V_{in} + V_{aux}) \tag{4.7}$$

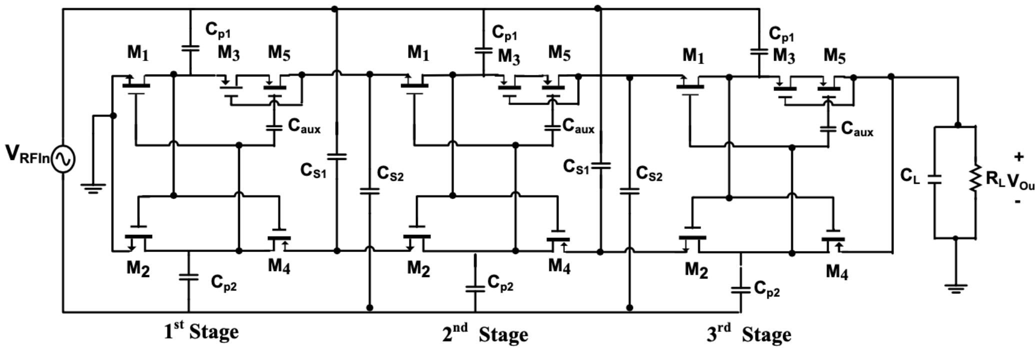

Figure 4.5: Proposed rectifier circuit

We know that,

$$V_{ov} = V_{th} + \sqrt{\frac{2I_D}{\beta}} \tag{4.8}$$

Hence, by substituting equation 4.8 in equation 4.7, it is obtained:

$$V_{out} = \frac{1}{2}((V_{th2} + \sqrt{\frac{2I_{D2}}{\beta_2}}) - (V_{th1} + \sqrt{\frac{2I_{D1}}{\beta_1}}) + V_{in} + V_{aux}) \tag{4.9}$$

$$V_{out} = \frac{1}{2}((V_{th2} - V_{th1}) + (\sqrt{\frac{2I_{D2}}{\beta_2}} - \sqrt{\frac{2I_{D1}}{\beta_1}}) + V_{in} + V_{aux}) \tag{4.10}$$

So from the equation 4.10 it is easily understood that the circuit is capable of cancelling threshold voltage effect thus enhances DC extraction ability. Using the auxiliary configuration a new circuit is proposed shown in Figure 4.5. Here the transistor M_5 works as the auxiliary transistor.

A part of the input voltage is stored in the capacitor (C_{aux}). So V_{aux} is the voltage stored across capacitor C_{aux}. With the addition of the auxiliary circuit the output DC voltage becomes:

$$V_{out} = N \times (2 \times V_{RFin} - V_{drop}) + V_{aux} \tag{4.11}$$

Table 4.1: Component sizes/ values of the rectifier

Components	**Type**	**Size W/L** (µm/µm)	**Value**
M_1, M_2	NMOS	30/0.1	-
M_3, M_4	PMOS	30/0.1	-
M_5	PMOS	30/0.1	-
C_{p1}, C_{p2}	Pumping capacitor	-	10 nF
C_{s1}, C_{s2}	Storage capacitor	-	1 pF

Due to multiple stages within acceptable area limit it can give proper DC output voltage with high efficiency than the single stage. So the proposed rectifier is designed for three stages. The storage capacitors C_{s1} and C_{s2} delivers the necessary current from their stored charge. One terminal of the storage capacitors are connected to the complementary input RF signal so that in the discharging phase the complementary input signal can also develop additional DC voltage. As this rectifier is designed for RFID transponder where achieving small area with low power is the main concern, the choice value of the circuit parameters must have an optimal value. So the sizes of the MOSFETs and other parameters (Table 4.1) used in the proposed design are calculated considering the existing equations paying attention to the optimisation of power consumption and rectified voltage output.

4.5 Layout

Layout had been done to measure the area of the rectifier. It was performed in virtuoso cadence environment in Layout XL in a very efficient way where only Metal 1, Metal 2 and Poly-Silicon were used for layout purpose. The layout had been conceded through DRC checker to ensure that the layout follows proper design rules. To perfectly match the layout with the LVS check was also done. Figure 4.6 depicts the layout of the circuit which has the total area of 99.21×39.15 μm^2 . If the rectifier was of single stage the area could be smaller but in that case the rectifier efficiency would also be lower. Moreover, here, the circuit not only acts as a rectifier it also works as a charge pump.

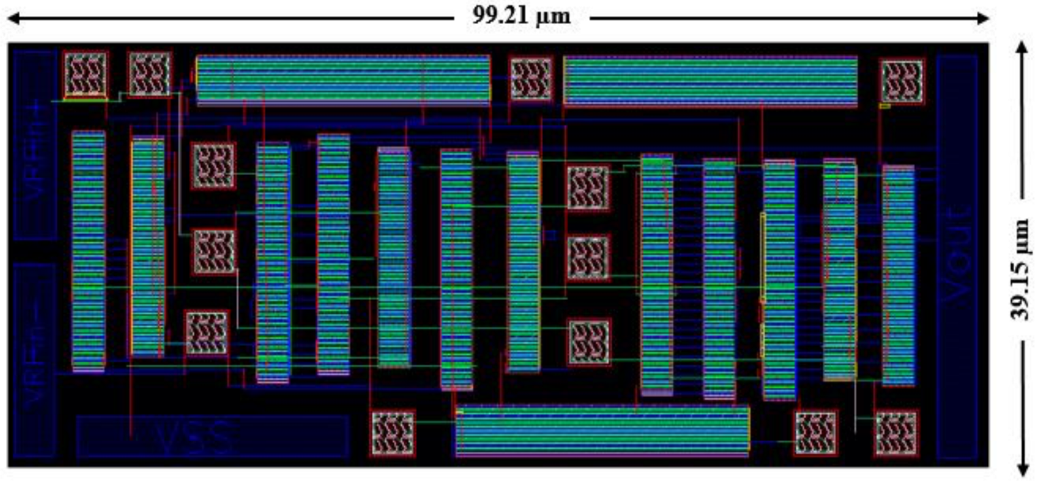

Figure 4.6: Layout of the proposed rectifier with charge pump

So in the proposed rectifier circuit requires a very less area in comparison with the other existing technologies. Besides, to check the effect of the parasitic components i.e parasitic resistance and capacitances RC extraction was also performed. It was found that this circuit contains 198 parasitic capacitances and 302 parasitic resistances.

4.6 Simulation Results

The rectifier is designed in 90nm CMOS technology using cadence virtuoso environment. The output is analyzed with different transistor width and three different load resistances. The power conversion efficiency is also measured to see the circuit performance. Layout diagram with post-layout simulation is done to measure the circuit area as well to check the deviation of the circuit performance considering the parasitic components. Moreover, process corner analysis, temperature sweeping and Monte Carlo analysis is also done to evaluate the circuit performance in different environment.

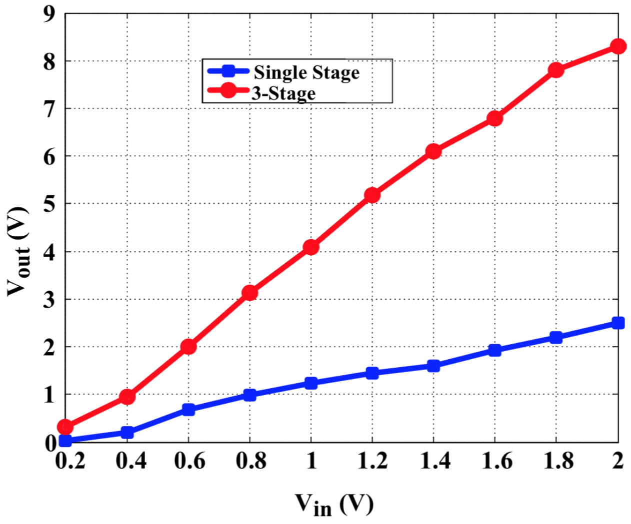

Figure 4.7: Output voltage vs input voltage in different stages

4.6.1 Rectified output with different stages

At first, the simulation is completed with different RF input voltages varying from 200 mV to 2 V both in single stage and 3-stages to compare their performances. The output voltage characteristics for both single and 3-stage rectifier is shown in Figure 4.7. From the figure it is clear that the rectifier gives better output voltage when it works as 3-stage. So 3-stage configuration is proposed in this work and all other simulations are done with proposed 3-stage configuration.

4.6.2 Rectified output for different frequency

Now the simulation is completed with frequencies 915 MHz and 2.45 GHz. Although the rectifier needs to work in the microwave frequency i.e 2.45 GHz, it is also analysed for 915 MHz to check the circuit's ability to perform in the different frequency if needed. Figure 4.8. illustrates the rectified output voltage versus input voltage for the change of frequencies. From the figure it is seen that, the rectifier circuit reacts to both input frequencies with the almost identical output with a load of 10 KΩ. It means the suggested rectifier scheme has the capability to rectify widespread

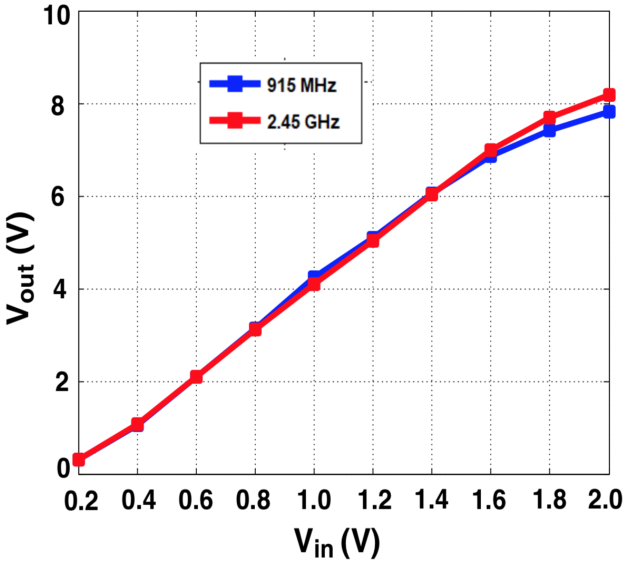

Figure 4.8: Rectifier output voltage vs input voltage with different input frequencies

frequency from 915 MHz to 2.45 GHz.

4.6.3 Rectified output for different load

The circuit performance with different load is also taken into account. The resistive loads tested are 10 kΩ, 50 kΩ and 100 kΩ. Figure 4.9 shows that the value of resistance is proportional to the output voltage. From observation it is depicted that when the load resistance increases from 10 kΩ to 100 kΩ, the output voltage increases. All other simulation in this work is performed with 10 kΩ resistance.

4.6.4 Output with different transistor width

Correspondingly the effect of width of the auxiliary transistor is studied. Two different values of width of the M_5 is used and the length constant at 100 nm to study the effect of the width. Then, the output voltage is analysed. Figure 4.10. explains that by using 30 µm of width the rectifier gives improved output voltage as compared to 4 µm width. So the width of the auxiliary transistor is kept 30 µm throughout the analysis.

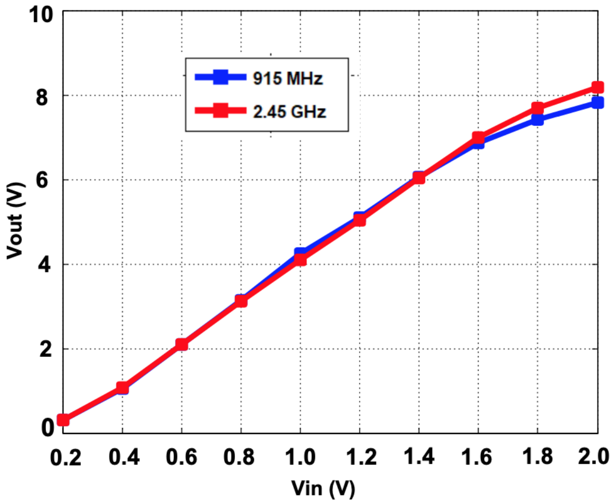

Figure 4.9: Rectifier output voltage Vs input voltage with different loads

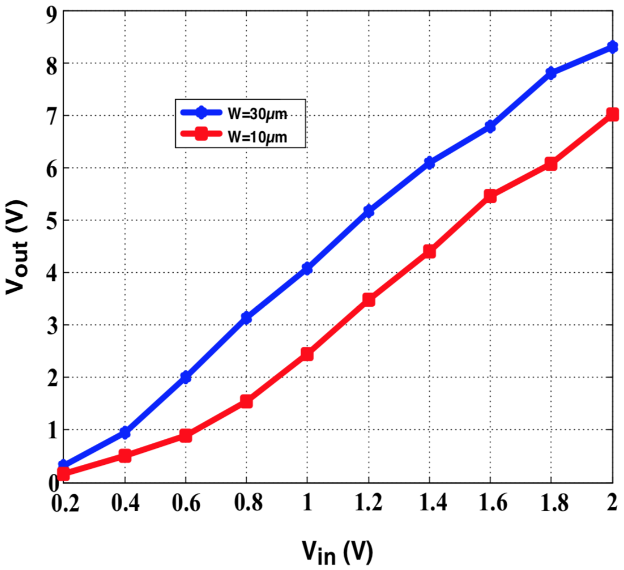

Figure 4.10: Rectifier output voltage Vs input voltage with different transistor width

4.6.5 Rectified output comparison

Besides the schematic based simulation, the output is also determined through post-layout simulation to see the discrepancies. It is observed that output voltage is reduced in post-layout simulation due to the effect of the parasitic components of the circuit as those were ignored in case of the schematic based simulation. Table 4.2 and Figure

Table 4.2: Output voltage of proposed rectifier for different input frequencies

V_{in}	V_{out}	
	Schematic based simulation	Post-layout simulation
0.2	0.32	0.17
0.4	0.95	0.50
0.6	2.01	1.32
0.8	3.14	2.13
1.0	4.08	2.89
1.2	5.18	3.49
1.4	6.09	4.19
1.6	6.79	4.83
1.8	7.80	5.59
2.0	8.03	6.14

4.11 shows the comparison of the rectified output for both type of simulations.

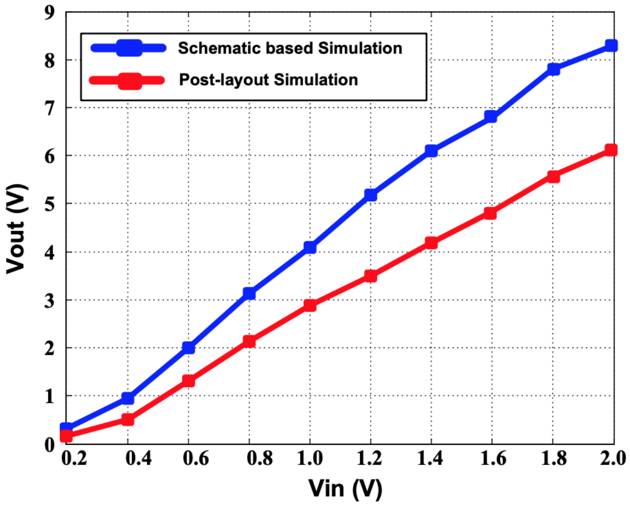

Figure 4.11: Comparison of rectified output voltage

4.6.6 Power conversion efficiency

Power Conversion Efficiency (PCE) is the measure of total percentage of RF input power that is converted to effective DC output power. The performance of the rectifier with charge pump is also measured in terms of power conversion efficiency (PCE) that is expressed as:

$$PCE\% = 100 \times \frac{P_{out}}{P_{in}} \tag{4.12}$$

Where P_{in} is the input RF power and P_{out} is the DC power. If V_{out} is the output DC voltage and RL is the load resistance output power will be:

$$P_{out} = \frac{V_{out}^2}{R_L} \tag{4.13}$$

$$P_{in} = \frac{1}{T}\int_0^T V_{in}(t) \times I_{in}(t)dt \tag{4.14}$$

Figure 4.12 hows the power conversion efficiency of the proposed rectifier with various input voltages where the maximum PCE is 78.5% for schematic based simulation and is reduces to 74.98% in post-layout simulation at the input voltage of 1.4 V. when the input RF voltage increases beyond the maximum PCE the V_{out} of the rectifier also increases, but the PCE drops; This is self-output power regulation function mentioned in [43] and practically effective in RFID operations.

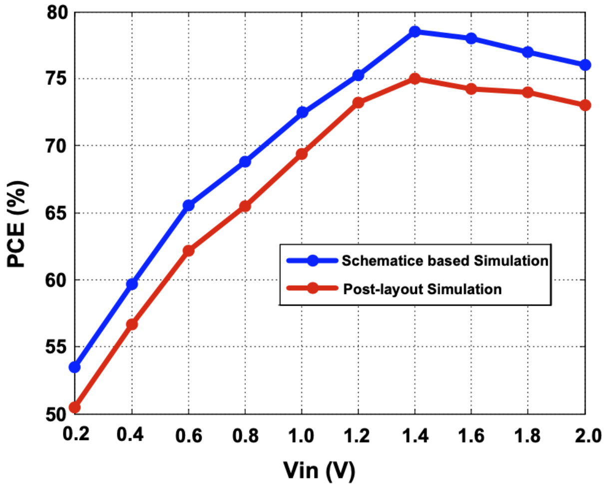

Figure 4.12: Power conversion efficiency vs input voltage

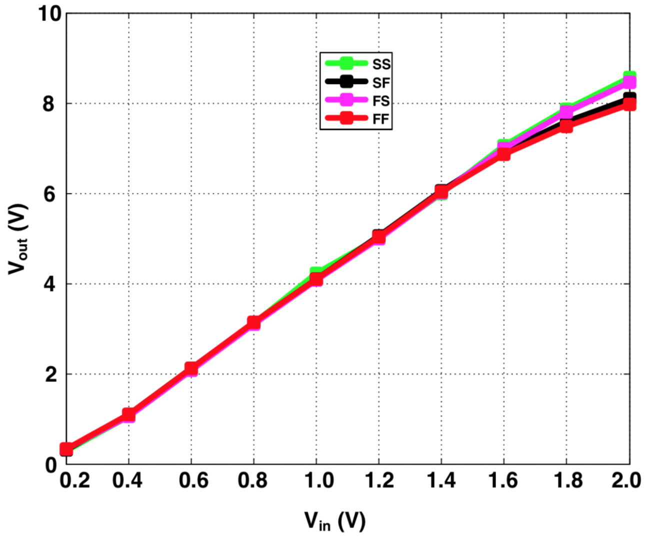

Figure 4.13: Output voltage vs input voltage for corner conditions

4.6.7 Process corner analysis

To authenticate the robustness of the rectifier, it is necessary to investigate the corner lots. So it is required to observe in the process variations to make sure that the MOSFETs used in the circuit has a good margin. In the proposed circuit, both NMOS and PMOS transistors are used. So the possible corner analysis would be SS (Slow NMOS and Slow PMOS), SF (slow NMOS and fast PMOS), FS (fast NMOS and slow PMOS) and FF (fast NMOS and fast PMOS).

Figure 4.13 represents the variation of output voltages with the change in input voltages in various corner conditions. The output voltage varies from 0.3 V to 8.21 V for SS, 0.3 V to 8.02 V for SF, 0.3 V to 8.2 V for FS and 0.3 V to 8 V for FF corner lots. It is observed that the different process corners don't give a significant effect on output voltages.

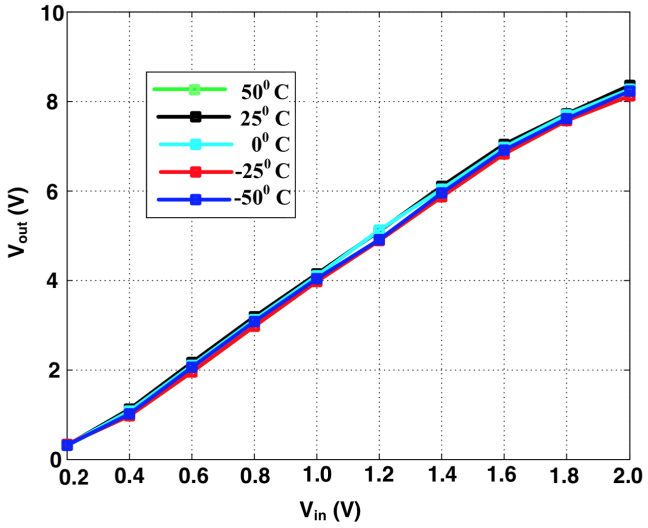

Figure 4.14: Output voltage vs input voltage for different temperatures

4.6.8 Temperature sweeping

While functioning, change in temperature may affect the rectifier's performance, thus the overall transponder's function may change. So it is required to study the rectifier circuit performance in various temperatures. Figure 4.14. shows the output voltages with the change in input voltages in various temperatures. The temperature sweeping is done from $-50°$ C to $50°$ C with an interval of $25°$ C. It is examined that in various temperatures the value of output voltages are almost same gives a consistent output thus assures the system stability.

4.6.9 Monte Carlo analysis

Monte Carlo simulation is used to model the probability of different outcomes in an electronic circuit that cannot easily be predicted due to the intervention of random variables. It is a technique used to understand the impact of risk and uncertainty in prediction and forecasting model. In a Monte Carlo simulation, simulations which reflect the variation in the different circuit elements are executed a number of times, and variation in the overall features can be assessed. As discussed in chapter 3, Monte

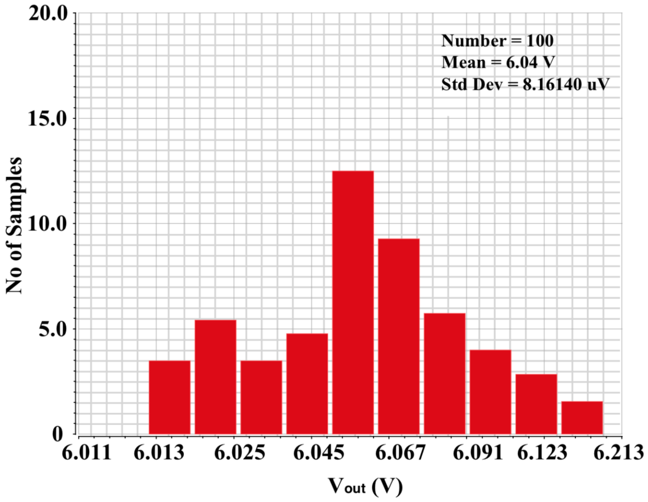

Figure 4.15: Distribution of the output voltage from Monte Carlo analysis

Carlo analysis is very important for an electronic circuit for the statistical analysis of the circuit. In this work, the Monte Carlo analysis is done for 1.4 V input voltage with 2.45 GHz frequency and 10 kΩ load resistance. In Figure 4.15 the statistical analysis is shown; 100 samples are taken which shows the mean value of 6.04 volts with standard deviation of 8.16 µV.

4.7 Performance Comparison

Comparisons has been made with other existing rectifiers and shown in Table 4.3. From the comparison it can be said that this circuit can give stable DC output with a wide variation of the frequency and a high power conversion efficiency. As discussed earlier power consumption of the circuits are always discussed but achieving the small area is not discussed in most of the works, so in the latest works with the rectifier it is hardly found the authors have mentioned about the area required for the circuit which is taken as a major concern in parallel to the output voltage and PCE for this work. In [44] the area achieved was lower than this work but they could not achieve a good power conversion efficiency.

Table 4.3: Performance summary comparison

Reference	**Tech (nm)**	**Frequency (MHz)**	**Load, RL (kΩ)**	**Peak V_{out} (V)**	**Peak PCE (%)**	**Area** (μm^2)
Chang et al. [45]	180	916	100	-	28.8%	3200x3500
Rosli et al. [46]	130	900 - 2400	40	1.25	-	-
Paradhasaradhi et al. [47]	250	-	10	3.17	78%	-
Zeng et al. [48]	-	1820	12	3.17	53%	-
Dastaninan et al. [44]	180	953	10,1	0.44 - 0.88	62.7% – 71.1%	75x70
Yao et al. [49]	350	900	-	1.5	13	780×490
This work	**90**	**915 - 2450**	**10**	**8.3**	**78.5%**	**99.21x39.15**

4.8 Chapter Summary

In this chapter a full wave cross coupled rectifier with charge pump for an RFID transponder for microwave frequency is projected with the purpose of removing the threshold voltage effect. The rectifier is simulated in 90 nm CMOS technology. At 2.45 GHz operation frequency for input voltage of 1.4 V and 10 k load, the power conversion efficiency of the proposed rectifier is very high compared to the state of the art. The rectifier gives also stable output frequencies in different temperatures and corner lots. It occupies an area of 99.21×39.15 μm^2.

CHAPTER 5

LOW POWER SMALL AREA LINEAR VOLTAGE REGULATOR

5.1 Introduction

With ever decreasing size of modern electronic devices, and not so much increasing battery efficiency, the electronic industry must push its limits in the power management systems. This lead to many different building blocks of it which may have different supply requirements and this is where a voltage regulator, DC-DC converter, switching regulator or their combination is utilized depending on the application.

In recent years, the demand for low-cost and low-power passive RFID transponders is significantly increasing, mainly due to its high data rates, small antenna sizes and low costs Long-range passive microwave transponders for RFID systems do not have an on-board battery and therefore must draw the power required for their operation from the electromagnetic field transmitted by the reader [50]. The rectifier block extracts the DC voltage from the RF signal coming from the reader when it is in the read range of the transponder. However, a high voltage variation at the rectifier input causes a large increase in its output voltage [51]. If the increase in the output voltage of the rectifier is excessive, subsequent blocks will be damaged. For these reasons it is necessary to integrate a voltage regulator which can provide a stable output voltage level against variations at its input and output voltage, thus protect the transponder from being damaged. As the RFID operates in the low voltage it requires the use of Low Dropout Voltage (LDOs). The low dropout nature of the regulator makes it appropriate for use in many applications, namely, automotive, portable, and industrial applications. Also all the portable electronics market requires low voltage and low quiescent current flow for increased battery efficiency and longevity. In this chapter the design of a new LDO is introduced. To characterize it properly, power, output current, quiescent current, input and output voltage and efficiency is necessary. Therefore, the LDO for the RFID transponder need to be carefully designed to enhance the system stability in various operating condition.

5.2 Design Parameters

Several factors required to consider when evaluating design circuit.

• **Output voltage:** The regulator converts the DC voltage supplied by the receiver to a constant DC voltage and stabilizes the whole circuit. So it is necessary to keep the output voltage stable at the value at which the circuit will perform perfectly as well as keep the overall circuit safe from being damaged.

• **Quiescent current:** Quiescent, or ground current is the difference between input and output currents. Low quiescent current is needed to maximize efficiency, especially in low power systems. Figure 5.1 shows how the quiescent current of the regulator is determined.

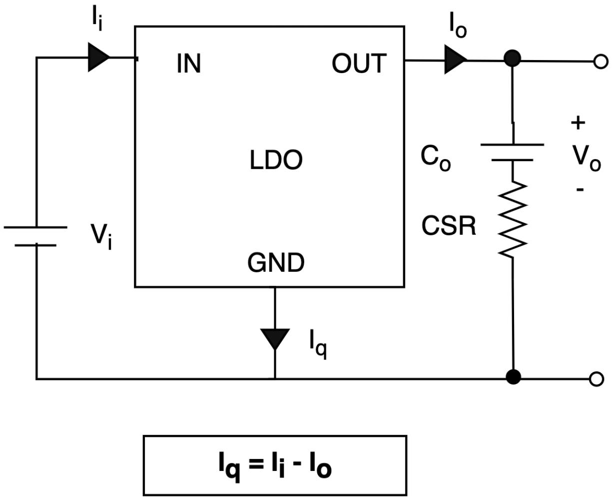

Figure 5.1: Quiescent current of voltage regulator

• **Line and load regulation:** Line regulation is a parameter defining the ability of the regulator to maintain the desired output voltage with varying input voltage. Similarly load regulation is a parameter defining the ability of the regulator to maintain the desired output voltage with varying load or the load current. It is required for a good regulator to maintain a constant output voltage with the change of the input voltages or the load.

• **Power supply rejection ratio (PSRR):** Power supply rejection ratio (PSRR), also known as ripple rejection is regulator's ability to prevent fluctuation of regulated output voltage caused by input voltage variation. Improving PSRR typically improves line transient response.

5.3 Regulator Topologies

Voltage Regulators can be implemented using discrete component circuits or ICs. Irrespective of the implementation, voltage regulators have two major topologies:

- Switching voltage regulators
- Linear voltage regulators

The transistor used as pass element in the voltage regulator can be operated either in its active region or as a switch in order to regulate the output voltage. When the transistor operates in cutoff state and saturation state i.e. it switches between OFF state and saturation state, then the regulator is called as Switching Voltage Regulator. If the transistor stays in active region or the ohmic region or Linear region of its operation during the course of voltage regulation, then the regulator is called as a Linear Voltage Regulator.

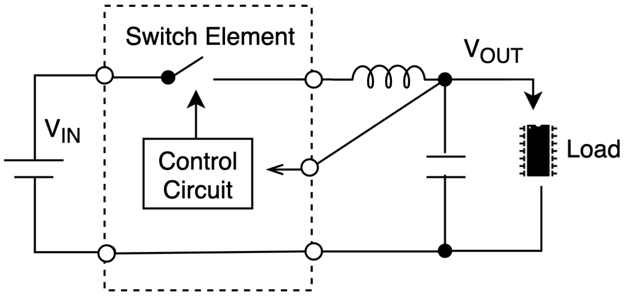

Figure 5.2: Fundamental switching voltage regulator

5.3.1 Switching voltage regulators

A voltage regulator that uses a switching element to transform the incoming power supply into a pulsed voltage, which is then smoothed using capacitors, inductors, and other elements in known as the switching voltage regulator. Power is supplied from the input to the output by turning ON a switch (MOSFET) until the desired voltage is reached. Once the output voltage reaches the predetermined value the switch element is turned OFF and no input power is consumed. Repeating this operation at high speeds makes it possible to supply voltage efficiently and with less heat generation.

Unlike linear regulators, these usually require an inductor that acts as the energy storage element. The basic switching voltage regulator is depicted in Figure 5.2. The main advantage of the switching power supply or switching voltage regulators is the efficiency. Usually, with a better design efficiency up to 95% can be achieved. As the transistor is oscillating between ON and OFF states, and the times it stays in active region is very less, the amount of power wasted is very less. Though it is efficient regulator but it has complex design and used for high powered circuits.

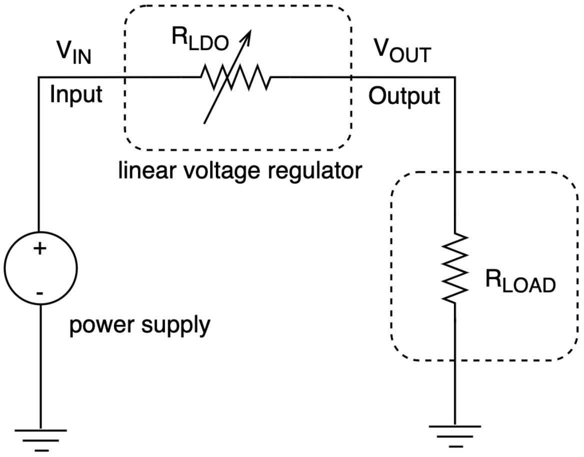

Figure 5.3: Fundamental linear voltage regulator

5.3.2 Linear voltage regulators

Linear regulators are the simplest and least expensive of the power-supply circuits, but this ease of use generally comes at a cost. The resistance of the regulator varies in accordance with the load resulting in a constant voltage output. As shown in Figure 5.3 the regulating device is made to act like a variable resistor, continuously adjusting a voltage divider network to maintain a constant output voltage and continually dissipating the difference between the input and regulated voltages as waste heat. Because the regulated voltage of a linear regulator must always be lower than input voltage, efficiency is limited and the input voltage must be high enough to always allow the active device to drop some voltage. It is mainly used for very low powered devices or applications where the difference between the input voltage and output voltage is small. It gives a low output ripple voltage and response is fast though the efficiency is not like the switching regulators Linear regulators exist in two basic forms: shunt regulators and series regulators.

5.3.2.1 Shunt regulators

The shunt regulator works by providing a path from the supply voltage to ground through a variable resistance. The current through the shunt regulator is diverted away from the load and flows uselessly to ground, making this form usually less efficient than the series regulator. It is, however, simpler, sometimes consisting of just a voltage-reference diode, and is used in very low- powered circuits where the wasted current is too small to be of concern. This form is very common for voltage reference circuits. A shunt regulator can usually only sink (absorb) current.

5.3.2.2 Series regulators

Series regulators are the more common form; they are more efficient than shunt designs. The series regulator works by providing a path from the supply voltage to the load through a variable resistance, usually a transistor (in this role it is usually termed the series pass transistor). The power dissipated by the regulating device is equal to the power supply output current times the voltage drop in the regulating device. For efficiency and reduced stress on the pass transistor, designers try to minimise the voltage drop but not all circuits regulate well once the input (unregulated) voltage comes close to the required output voltage; those that do are termed Low Dropout regulators; A series regulator can usually only source (supply) current, unlike shunt regulators. In this work the proposed voltage regulator is based on the low dropout regulator.

5.4 Low Dropout Linear Regulators

Low dropout regulators (LDOs) are a simple inexpensive way to regulate an output voltage that is powered from a higher voltage input. They are easy to design with and use for the low power applications. Since passive RFID tags are powered up by the

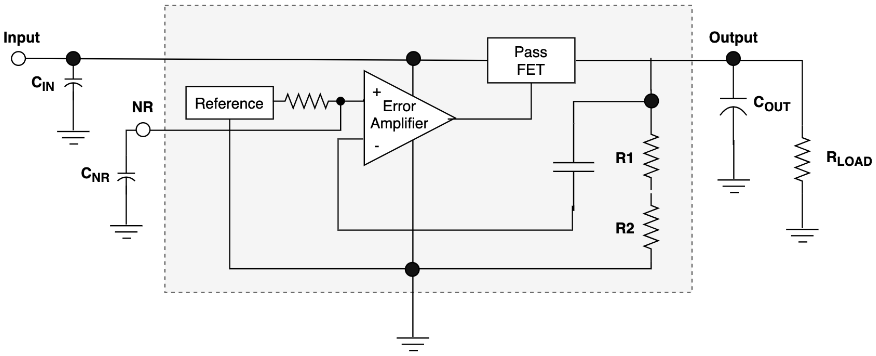

Figure 5.4: Low dropout voltage regulator

electromagnetic field, one of the major challenges of RFID circuits design is the ultra-low power LDO, for the limited received power, the LDO should function properly even under low supply voltage. The structure of LDO is shown in Figure 5.4. The building block of the LDO circuit consists of three parts: the error amplifier, the pass element, and the feedback resistor.

The feedback network comprises of resistive voltage divider, which delivers scaled output voltage which is equal to the reference voltage when the output is at its nominal voltage. The error amplifier is constantly comparing the reference voltage and the voltage being feed from the voltage divider. This difference is amplified and the output of the error amplifier drives the pass element to keep the output voltage level at desired value. Error amplifier design must be kept as simple as possible, so it does not draw too much of current. The less current branches it has, the less current it draws from the input and thus the overall quiescent current is lower. Resistive feedback network scales the output voltage V_{OUT} for the comparison against the reference voltage V_{REF} by the error amplifier. Due to the fixed V_{REF} the only way to change the output voltage is through ratio of R_2/R_1. The current flowing through the divider contributes to the quiescent current of the voltage regulator. Pass element is transferring large currents from input to the load and is driven by the error amplifier in a feedback loop.

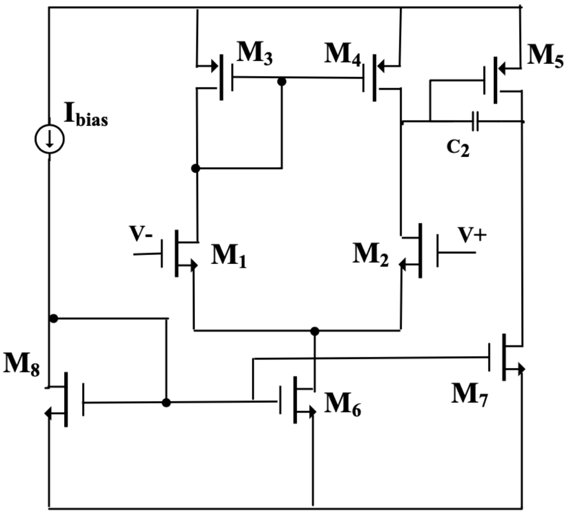

Figure 5.5: Proposed error amplifier circuit

5.5 Proposed Voltage Regulator

The building block of the proposed LDO circuit consists of three parts: the error amplifier, the pass element, and the feedback circuit. Figure 5.5 shows the error amplifier circuit. The NMOS differential pair error amplifier used to provide error signal for voltage regulation and common source amplifier which has a high output swing.

NMOS differential pair (M_1 and M_2) works with active load (M_3 and M_4) while the second gain stage is a common source stage (M_5) with a bias-current source (M_7). The output swing of the second stage is much better than the source follower in turning on or off the power transistor, and therefore this configuration is suitable for low-voltage LDO designs. The current mirrors (M_6, M_7 and M_8) provide current sources for both stages. The error amplifier is implemented using a two stage without miller compensation topology. The error amplifiers (M_1 to M_8) offer fast transient response and keeps the output voltage at a fixed level. The overall proposed LDO is shown in Figure 5.6. The error amplifier also regulates itself to get a drive of power stage transistor PMOS load current. From the figure it is seen that the negative terminal of the error amplifier is connected to the reference voltage and the positive terminal to the

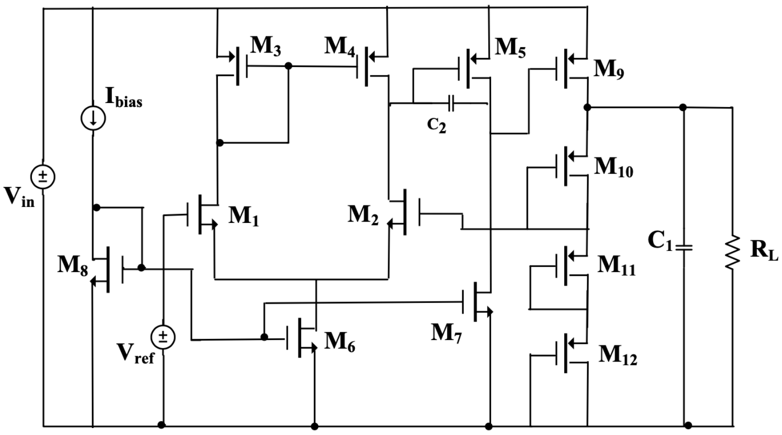

Figure 5.6: Proposed LDO circuit

Table 5.1: Component sizes/ values of the regulator

Components	**Type**	**Size W/L** (μm/μm)	**Value**
M_1, M_2	NMOS	6/1.2	-
M_3, M_4	PMOS	3.6/1.2	-
M_5	PMOS	30/1.2	-
M_6, M_8	NMOS	14.4/1.2	-
M_7	NMOS	30/1.2	-
M_9, M_{10},M_{11}, M_{12}	PMOS	30/1.2	-
C_1	Load capacitor	-	1 pF
C_2	Feedback capacitor	-	1 pF

resistive voltage divider of output voltage.

As the resistive voltage divider used in the conventional LDO regulator causes a thermal noise and also resistive loads occupy more area than MOSFETS, they are replaced by the PMOS transistors (M_{10} to M_{12}). PMOS transistor M_9 presents the adjustable series-pass transistor to deliver the required load current, keep the output voltage at a fixed value and it consumes a very less power. The small feedback capacitor C_2 connected to increase and ensure the system stability. In the proposed design, to get the good transient response and stable output the transistor and passive elements are chosen carefully. The parameter values are given in Table 5.1.

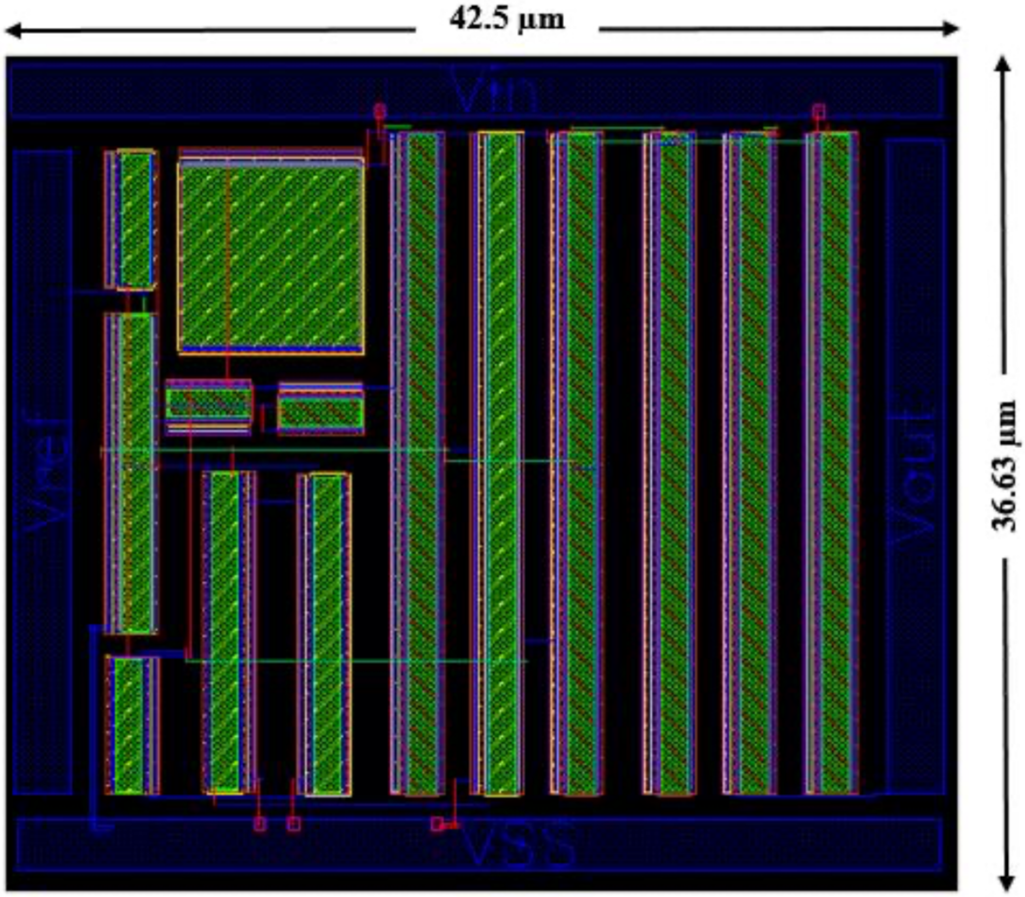

Figure 5.7: Layout of the proposed voltage regulator

5.6 Layout

To measure the active area of the voltage regulator in RFID transponder the layout is done. For the design cadence virtuoso is used. No resistors are used to reduce the active area which means the implementation cost is also less. This layout includes the error amplifier, pass transistor and the feedback circuit as well. It was performed in virtuoso cadence environment in Layout XL in a very efficient way where only metal 1, metal 2 and Poly-Silicon were used for layout purpose. As shown in Figure 5.7 the regulator occupies only 42.5 × 36.63 μm^2 area. It has total 96 parasitic capacitances and 210 parasitic resistances.

5.7 Simulation Results

The voltage regulator is also designed in 90nm CMOS technology using cadence virtuoso environment as the previous circuits of the transponder. The output is simulated to achieve a voltage regulator output of 1 V as the oscillator input dc voltage is 1V and this voltage comes from the regulator output. The post layout simulation is performed to check whether the output deviates from 1 V or not. Output voltage is also simulated for three different load resistances. The Power supply rejection ratio (PSRR) is analyzed to see how much the circuit rejects ripple. Moreover, process corner analysis, temperature sweeping and Monte Carlo analysis is also done to evaluate the circuit performance in different environment.

5.7.1 Line regulation

The line regulation defines how the output behaves with the change of the input supply. It is basically the steady DC power supply gain of the regulator. As the voltage at the input is swept, the changed value of the output is also observed. At first, the simulation is completed with different DC input voltages that varies from 0 V to 5 V. The aim of the output voltage to be stable at 1 V. By setting the reference voltage to 335 mV the desired regulated output is achieved.

Figure5.8 shows the regulated output voltage with the change in input voltage for both schematic and post-layout simulation. The deviation of the two types of simulation is so less that in both cases it is observed that the regulator gets stable at 1 V when the MOSFET are in typical-typical condition at a temperature of 27° C.

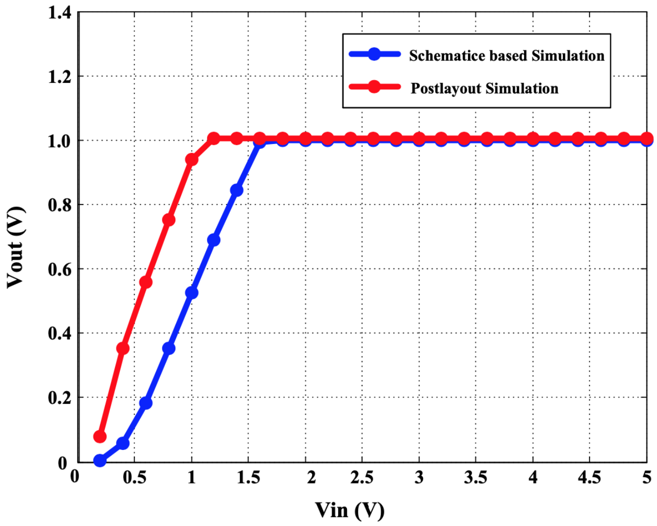

Figure 5.8: Regulated output voltage

5.7.2 Load regulation

Load regulation is the capability to maintain a constant voltage level on the output channel of a power supply despite changes in the supply's load. When the load increases, the load capacitor supplies the current to the load, this changes the output voltage which is the sensed by the feedback portion to the amplifier who compensates the change in the output voltage by allowing more current to flow through the pass transistor. To check the circuit performance in different load conditions the circuit is analyzed taking 3 different resistors as loads i.e with 10 kΩ, 50 kΩ and 100 kΩ.

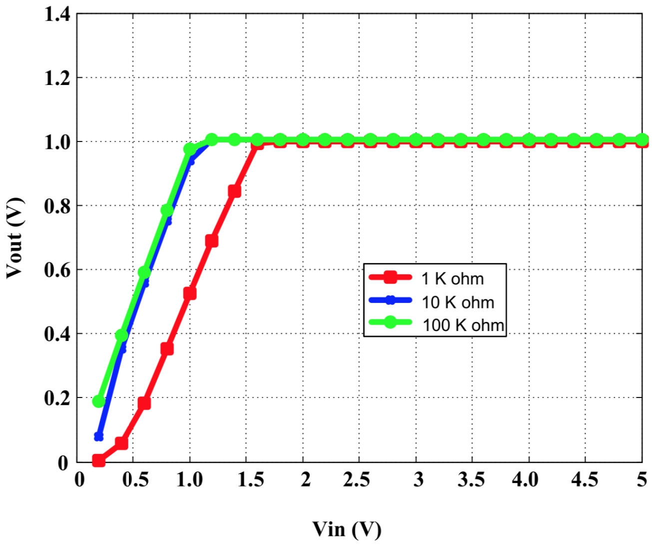

Figure 5.9: Output voltage with different loads

The regulator cannot completely cancel the effect of changing load current but it shows a very small deviation from the desired output. From Figure 5.9 it is seen that in each case the output voltage gets stable almost at 1 V.

5.7.3 Power supply rejection

Power supply ripple rejection ratio (PSRR) is a measure of how well a circuit rejects ripple coming from the input power supply at various frequencies and is very critical in many RF and wireless applications [52]. It is a measure of the output ripple compared to the input ripple over a wide frequency range and is expressed in decibels (dB). The basic equation is-

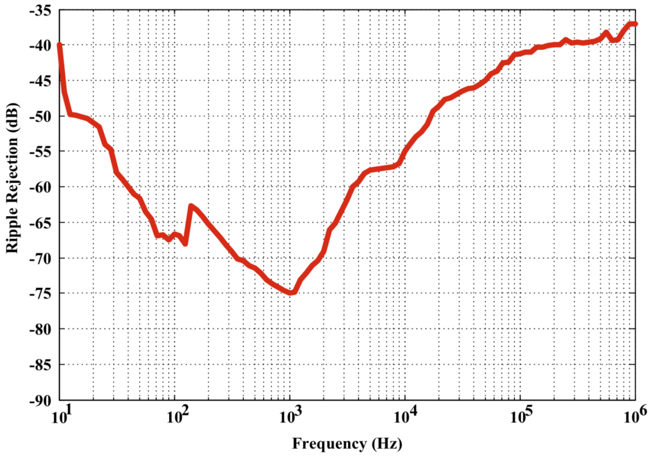

Figure 5.10: PSRR curve

$$PSRR = 20 \times \frac{Ripple_{input}}{Ripple_{output}} \tag{5.1}$$

A curve showing PSRR over a wide frequency range is shown in Figure 5.10.

5.7.4 Quiescent current

Quiescent Current is as the amount of current used by the circuit when in a quiescent state. The quiescent state being any period of time when the circuit is in either a no load or non-switching condition, however is still enabled. This is especially important for RFID transponders as it needs to last long periods of time. It is the difference between input and output currents. Quiescent Current,

$$I_q = I_i – I_o \tag{5.2}$$

In this design the input current is 17.324 µA and the output current is 10 µA, so from equation 5.2 the quiescent current achieved is 7.324 µA only. This circuit also consumes a very less amount of power that is 10.01 µW only.

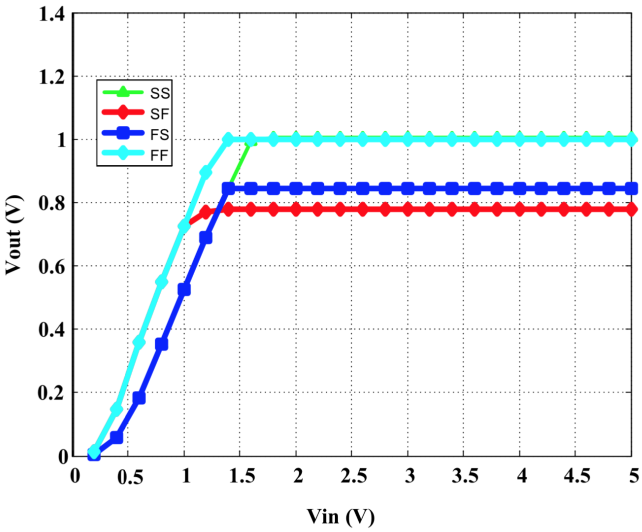

Figure 5.11: Regulated output voltage for different corner lots

5.7.5 Corner analysis

The process parameters like, oxide thickness, carrier mobility, width and length of the gate vary and different dies are fabricated with different absolute parameters. Especially passive components like resistors and capacitors may differ up to 20% in absolute value. These changes may affect the quiescent current. So this simulation is vital to verify, that whether the circuit is stable under all conditions. To predict the circuit behaviour and stability, the circuit is analysed for different corner lots. Figure 5.11 shows the output of the regulator for SS, SF, FS and FF process corners. The regulated output ranges from 0.788 volts to 1.01 volts from which it is assumed that the circuit has consistent output for each corner lots.

5.7.6 Temperature sweeping

It is useful to plot how the output changes with temperature, because the ambient temperature could vary significantly. Figure 5.12 shows the output voltages with the change in input voltages in various temperatures. The temperature is swept from -50° C to 50° C with an interval of 25° C. The output varies from 0.878 volts to 1.03 volts with the change in temperature.

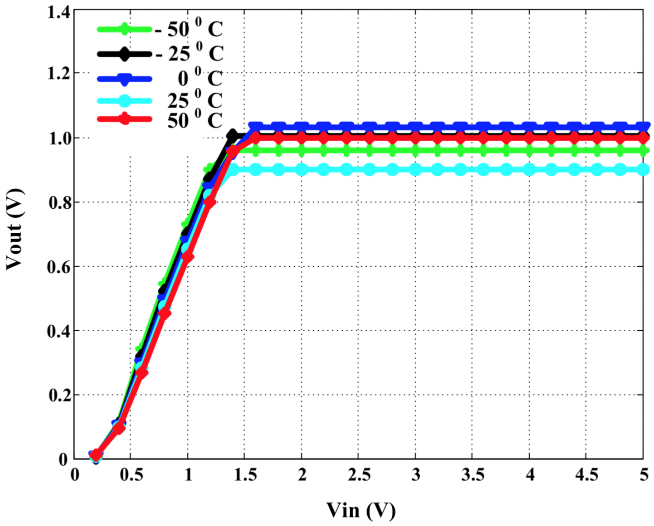

Figure 5.12: Output voltage with variation in temperature

5.7.7 Monte Carlo analysis

Now that it is assured that circuit is stable at the nominal corner, but it is also needed to check the variation of the output due to the random offset. This variation is analysed by Monte Carlo simulation. Figure 5.13 shows the distribution of the output voltage from Monte Carlo analysis. It showed 1.0314 V mean value of output voltage with a standard deviation of 1.78 µV only. The input voltage was kept at 1.4 V for this simulation.

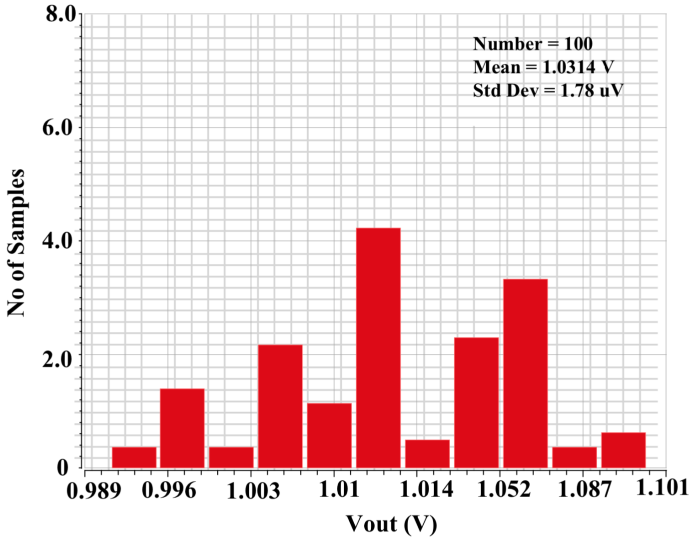

Figure 5.13: Distribution of the output voltage from Monte Carlo analysis

5.8 Performance Comparison

Table 5.2 compares the proposed LDO with state-of-the-art LDOs. It is observed that the PSRR of the proposed regulator shows a very good margin in comparison to the other works mentioned here. The total area and the power dissipation of the circuit is also less as this circuit doesn't contain any resistor.

Table 5.2: Performance comparison of the with the state-of-the-art

Reference	**Technology (nm)**	**Output voltage (V)**	**Quiescent Current** (μA)	**PSRR (dB)**	**Area** (μm^2)
This work	**90**	**1**	**7.324**	**-75 @ 1KHz**	**42.5 × 36.63**
Murad et al. [53]	180	2.41	15.08	-62.2 @ 1KHz	27× 34
Dawei et al. [54]	180	1.1	0.37	-	14600
Liu et al. [55]	65	1.01	0.63	-62 @ 1MHz	-

5.9 Chapter Summary

In this chapter a low power high PSRR linear voltage regulator is introduced for RFID application using 90 nm CMOS technology. The regulator consists of an error amplifier, pass transistor and feedback circuit with only MOSFETs to reduce the area. Most of MOSFET transistors in the design operate at sub-threshold region for low power dissipation. Simulation results show that the proposed regulator is capable of operating with a stable voltage of 1 V in various environment. The quiescent current is 7.324 μA and it consumes very low power of 10.01 μW only at room temperature. The layout occupies only 1556.7 μm^2 area. This regulator can also be used for other low power applications in microwave frequency range.

CHAPTER 6

CONCLUSION

6.1 Conclusions

Nowadays, across the globe and among many industries, RFID technology has evolved far beyond the days of barcodes in retail. Companies, individuals and states all benefit from such a technology. It has become very popular in many areas such as logistics, access control, transportation, healthcare, counterfeit struggle, e-documents, biometric passports, etc. Amongst all the main components of an RFID technology i.e the reader, antenna and transponder, the transponder is the most crucial one as it is attached to the object to be identified or tracked. For this reason this thesis focuses on the transponder design. In this technology the most popular transponders are passive transponder as it does not need any battery of its own. As they do not have the battery power, the operation life can be up to 50 years. So the research presented in this thesis aimed to design the analog circuits of a passive RFID transponder. This transponder works in microwave frequency as it gives greater read range.

6.2 Major Contributions

In various research works related to the transponder, only one of the blocks were discussed and analyzed. But most of the cases did not consider all the analog circuits together. So the first objective of this thesis was to design a voltage controlled oscillator, rectifier, charge pump and voltage regulator circuit for the transponder. Based on this objective, the design was achieved through a thorough analysis of each block and final design was proposed after considering different configurations. Besides the basic analysis of outputs of the proposed circuits, Monte carlo analysis, temperature swept, process corner analysis and stability analysis have been showed to investigate each of the proposed circuit's reliability in different cases. Moreover, layout based simulations were also performed to check the discrepancies for the effect of parasitic components of the circuit.

An oscillator circuit in RFID transponder works as clock generator and if the clock is not synchronized the whole operation of the circuit may fail. Moreover, the highest amount of power and area is consumed by the oscillator block in the transponder. So to achieve this, the aim was to make such an oscillator that will consume lowest possible power in 2.45 GHz frequency. Moreover, the stability of the oscillator is a major concern. The stability analysis was done to check whether the oscillator is stable at the microwave frequency or not. The ring voltage controlled oscillator had been proposed as it gives wide tuning range, low power consumption and small area in comparison to the other oscillator configurations.

As discussed earlier the passive transponder does not need any battery of its own. It increases the longevity of the circuit as well as requires less area. The reader acts as the power source of the transponder. The transponder extracts the RF power from the reader when it is kept within the read range. With a rectifier block this power is converted to DC. But after conversion, this DC voltage may give very low output which may have noise also. For this reason an additional charge pump or voltage multiplier circuit is required. In this research work, a cross coupled bridge rectifier is designed in such a manner that it rectifies the signal and pumps up the voltage in one circuit. So instead of using two circuits a rectifier is charge pump is proposed as it requires less area and consumes less power also.

In some cases, a small change in the circuit may upgrade the level of voltage. Being a low powered circuit the whole circuit may get damaged and also this fluctuations in voltage level may lead the circuit an unstable condition. Here comes the requirement of a circuit which will always keep the output voltage in a fixed level whether the input voltage and the load is changed or not. So a linear voltage regulator circuit is proposed which is suitable for low power circuits, gives lower ripple voltage and has faster response while comparing to the other configurations. It is to be also mentioned that, in this work in each of the circuits the energy storage elements was kept limited and resistors were not used to reduce the area and power dissipation as heat.

6.3 Recommendations for Future Works

This research work can be expanded in several other directions. These are as follows:

- Digital blocks can be designed to make a compact RFID transponder.
- In this work the simulation based results had been analyzed. However, more thorough testing is necessary before commercial services can be launched using this kind of circuits in the transponder. Several more performance measurements should be carried out practically in order to achieve statistically significant results.
- The prototype of the design can be fabricated and measured, and then reinvestigated with the simulation results.
- Here only the RFID transponder was the concern. In future, the RFID reader blocks and the antenna can also be analyzed.

LIST OF PUBLICATIONS

1. T. H. Saika, and M. T. Amin, “Low Power Wide Tuning Range Differential Ring VCO for RFID Transponder,” *22nd International Conference on Computer and Information Technology (ICCIT)*, Bangladesh, 2019.
2. T. H. Saika, and M. T. Amin, “A High Efficient Wide Range Cross Coupled Rectifier for RFID Applications,” *Accepted and presented in International Conference on Computer Electrical & Communication Engineering (ICCECE)*, India, 2020.

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