BLUETOOTH TRANSMITTER DESIGN FOR IOT NODES

M.Tech Thesis

By

ANUJ PRATAP SINGH
1502102001

DISCIPLINE OF ELECTRICAL ENGINEERING

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ANUJ PRATAP SINGH
(Roll No.1502102001)

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **BLUETOOTH TRANSMITTER DESIGN FOR IOT NODES** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DISCIPLINE OF ELECTRICAL ENGINEERING, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from July 2016 to July 2017 under the supervision of Dr. Santosh Kumar Vishvakarma, Associate Professor, Indian Institute of Technology Indore

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

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ANUJ PRATAP SINGH

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ANUJ PRATAP SINGH has successfully given her M.Tech. Oral Examination held on **____________________.**

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Date:

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Anuj Pratap Singh

M.Tech, (Communication and Signal Processing)

MT1502102001

Discipline of Electrical Engineering, IIT Indore

Dedicated to My Parents

Abstract

In the recent year, there has been a marked growth in technologies such as Bluetooth and 802.11b (Wi-Fi) have increased the growth of the short-range communication industry. Bluetooth, the leading WPAN (wireless personal area network) technology, was designed primarily to reduce the cable applications. Bluetooth operates internationally in unlicensed ISM frequency band i.e. 2.4GHz due unlicensed ISM band, it is very popular in short-range wireless communication and support a wider range of applications. In this thesis, Bluetooth transmitter has been discussed and implemented using a mixed signal technology in low cost for IoT nodes. Bluetooth transmitter architecture include GFSK (Gaussian frequency shift keying) modulation scheme which fully in digital domain and remaining stage like digital to analog convertor, Op-Amp based low pass filter, up-conversion mixer and class E power amplifier are designed in 180nm CMOS technology. In this thesis, partially discussed about GFSK (Gaussian frequency shift keying) modulation scheme and DAC and mainly focus on Op-Amp based low pass filter, up-conversion mixer and power amplifier.

Op-Amp based low pass filter are designed to remove the glitches which are occur at digital to analog convertor (DAC) due fast switching. Gilbert cell based up-conversion mixer is designed to translate the incoming frequencies from the modulator to desired ISM band i.e. 2.4 to 2.485 GHz. In the thesis, there are two mixer circuit has been implemented i.e. conventional Gilbert up-conversion mixer and current controlled up-conversion mixer, where conversion gain is around 13dB at 5dB LO power. Class E power amplifier circuit for 50Ω load is implemented to provide additional gain to send the signal from the RF antenna.

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List of Abbreviation

IoT	Internet of Things
M2M	Machine to Machine
BLE	Bluetooth Low Energy
PADs	Personal Digital Assistants
LAN	Local Area Network
USB	Universal Serial Bus
IRDA	Infrared Data Association
SRW	Short-Range Wireless
PAN	Personal Area Network
UWB	Ultra Wide Band
WPAN	Wireless Personal Area Network
ISM	Industrial, Scientific, And Medical
GFSK	Gaussian Frequency Shift Key
OFDM	Orthogonal Frequency-Division Multiplexing
IEEE	Institute Of Electrical And Electronics Engineers
UNII	Unique Ingredient Identifier
FH	Frequency Hopping
DSSS	Direct Sequence Spread Spectrum
QPSK	Quadrature Phase Shift Keying
BPSK	Binary Phase Shift Keying
API	Application Programming Interface
L2CAP	Logical Link Control And Adaptation
SIG	Special Interest Group
MAC	Media Access Control
CMOS	Complementary Metal Oxide Semiconductor
PSRR	Power Supply Rejection Ratio
CMRR	Common Mode Rejection Ratio

IF	Intermediate Frequency
LO	Local Oscillator
RF	Radio Frequency
SSB-NF	Single Sideband Noise Figure
DSB-NF	Double Sideband Noise Figure
RMS	Root Mean Square
P1dB	1 dB Compression Point
IP3	3^{rd} Intercept Point
IM3	3^{rd} Order Intermodulation
IMD	Intermodulation Distortion
PA	Power Amplifier
PAE	Power Added Efficiency
ACPR	Adjacent Channel Power Ratio
EER	Envelope Elimination And Restoration
AM	Amplitude Modulation
IIP3	3^{rd} Order Input Intercept Point
DAC	Digital to Analog Convertor
LPF	Low Pass Filter
OIP3	3^{rd} Order Output Intercept Point

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CHAPTER 1

Introduction

1.1 Overview

In present days there is an exponential growth of communication networks, both for its roundness and dissemination as well as the several applications that have emerged allied with different ways to communicate. The last few years have witnessed a remarkable reduction of portable equipment. Today the Internet - as a worldwide communication network that allowed the development of innovative technologies to intercommunication between people in different ways and in different atmospheres, whether for recreational purposes or for combined business environments in which many stakeholders in the communication process need to be connected among themselves by retrieving the updated info available on the network. The concept behind of Internet of Things (IoT) replicates the aim of not only people but also devices be connected to each other towards a common goal. Communications Machine-to-Machine (M2M) are open as a mean to achieve the purposes stated by the IoT vision [1].

1.2 Motivation

For several decades, the communicating objects invaded our everyday life and the number of transmitted data, associated with numerous standards of wireless communication, also exploded. Nowadays, objects are connected each other's, without sometimes human intervention, and connected to Internet; we speak then about Internet of Things (IoT). Many IoT applications require communicating wireless objects powered by autonomous battery for (mobility and easy to install) low cost and long autonomy (small reloadable battery, energy harvesting, low power consumption) systems. The transmission of a small quantity of data with regular interval of a large number of objects towards Internet imposes the use of a fixe (home, public places, etc.) or mobile (smartphone) gateway. The radio communication standards adapted to these applications are for example Bluetooth Low Energy (BLE), ZigBee.

Although well known among everyday wireless communication consumers, commercial wireless communications technology has also experienced a parallel motivation in its advancement, both in reduction and cost. In moveable wireless communication devices industry, it is well known that the design of the radio frequency transceiver is typically the key element that governs the cost, size, and useful battery life of the equipment, as well as uses of the devices. One of the primary goal supporting frequent research and development in the wireless communication area is the overall user acceptance of wireless communications standards. These wireless standards provide union within the industry to invest in the development of suitable microchip sets for the manufacturing of user subscriber units.

The central focus of this thesis is to present system level and building block level solutions for the most widely spread short-range communications standards i.e. Bluetooth. The motivation is to develop the bridge between the circuit and wireless vision in wireless design. Although the thesis focuses on Bluetooth transmitter implementations, many design aspects can be generalised to most other radio implementations. The Bluetooth standards operate at RF frequency 2.4GHz which are used in microwave ovens and cordless phones. Bluetooth was developed to replace cables that are used for relatively low-speed data transfer. Bluetooth's raw data rate is 1Mbits/s, but Bluetooth advance version has designed for enhanced data rate. Bluetooth is cheaper in cost and easy in uses than the other wireless devices. In this thesis, the design of a low-power Bluetooth transmitter fabricated in a low-cost mainstream mixed signal technology is presented.

1.3 Content and thesis organization

In Chapter 2, gives a brief description of the short-range communication standards. In this section basically focus on Bluetooth standard and compared with other wireless standards.

In Chapter 3, detailed description of basic Bluetooth transmitter architecture. In this section GFSK modulation approach have been described.

In Chapter 4, two stage CMOS based op-amp architecture and design methodology has been described and further filter application has been implemented.

In Chapter 5, Gilbert up-conversion mixer circuit implementation and simulation results have been described.

In Chapter 6, Power circuit implementation and simulation results have been described.

CHAPTER 2

Short-Range Communication Standards

2.1 Overview

In modern era electronic gadgets, for example, personal digital assistants (PDAs), cell phones, advanced cameras, and tablets have infiltrated the customer market. Each of these gadgets requires the capable short-extend specialized technique for information trade among each other, association with printers or neighborhood (LAN). The specific strategies can be founded on link associations, radio connections, or infrared connections as represented in Figure. 2.1. Since each has its qualities and shortcomings, each discovered its way into different products.

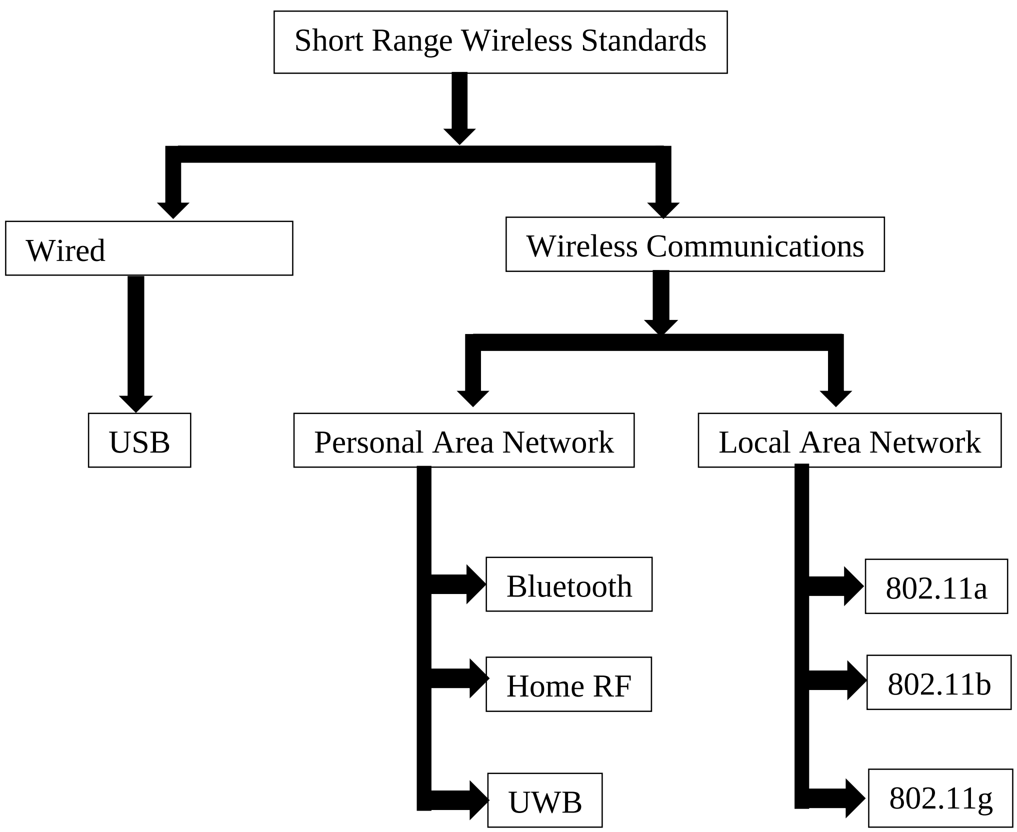

Figure 2.1 Short range communication standards

2.2 Short-Range Wired Communications

Information exchange using links is a settled strategy; universal serial bus (USB) has turned out to be utilized standard interface. USB exceeds expectations because of its high baud rates up to 480Mb/s, yet experiences its restricted portability because of link association. Consequently, USB is best for applications that require stable elite organizations for transmission of high information volumes, where portability doesn't matter. A use case would be the association of a video conferencing camera to your tablet.

2.3 Short-Range Wireless Communications

In spite of USB, infrared transmission given the Infrared Data Association (IrDA) standard empowers quick association foundation because of its simple to use the trademark. Along with the high baud rates up to 16Mb/s, this makes transmission appropriate to applications that require superior as hoc point-to-point associations. Examples like downloading an image from your electronic camera to your tablet or pay for your supper in your organization's cafeteria with your cell phone using IrDA port. IrDA measures have been there for quite a long time and are executed in portable PCs, PCs, and PDAs. Be that as it may, up to this point, either the cost was too high, or on account of infrared, the innovation was excessively troublesome, making it difficult to utilize. Radio-based short-range wireless (SRW) correspondence is another possible class of rising advances designed fundamentally for indoor use over short separations. It is proposed to give quick (tens or several megabits for every second) and minimal effort, cable free associations with the web. SRW highlights transmission forces of a few microwatts six up to milliwatts yielding a correspondence range in the vicinity of 10 and 100 meters. SRW will give network to handy gadgets, for example, tablets, PDAs, mobile phones and others. Short-run interchanges measures fall into two broad however overlapping classes: personal area network (PAN) and local area network (LAN).Remote PAN technologies emphasize minimal cost and low power utilization, more often at the cost of range and high speed. In a common remote PAN application, a short remote connection, normally under 10 meters, replace a PC serial link or USB link. Standards, for example, Bluetooth and HomeRF, have been made to manage short-range remote communication. Bluetooth has appeared in numerous cell phones. Bluetooth can transmit information through strong nonmetal object and backings a nominal connection scope of 10cm-10m at a direct baud rate up to 720kb/s (crude information rate is 1Mb/s) [1].A discretionary high power mode in the present specification takes into consideration runs up to 100m. Because of the idea of radio, Bluetooth is a point to multipoint correspondence framework, which provides associations of two devices as well as administration between a few gadgets. However, to counteract unapproved access, Bluetooth requires modern confirmation and encryption instruments, which hamper quick association establishment. Along these lines, Bluetooth is best for applications that require stable point-to-point or point-to-multipoint associations for information exchange at average speeds, where versatility is a key necessity. Ultra-wideband (UWB) is a rising innovation that shows incredible potential for SRW applications. Not at all like ordinary remote interchanges frameworks that are transporter based, UWB-based correspondence is baseband. It utilizes a series of short beats that spread the vitality of the energy from close DC to a few GHz. Wireless LAN technologies, stress max speed and longer range to the detriment of cost and power utilization. Normally, remote LANs give remote connections from convenient portable workstations to a wired LAN access point. To date, 802.11b has picked up acknowledgment quickly as a remote LAN standard. It has the symbolic open-space scope of 100m and a peak over-the-velocity of 11Mb/s. The consumer can expect most extreme accessible paces of around 5.5Mb/s. Other correspondence guidelines offer much higher information rates, as 802.11a and 802.11g. Table 2.1 analyzes between the main radio-based short-range communications principles.

2.4 What is Bluetooth?

Bluetooth innovation was produced to make a short-run remote voice and information connect between a wide scope of gadgets, for example, PCs, notebook PCs, handhelds and PDAs, Smart Phones, cell phones and computerized cameras. Reliable with its point of working in even the littlest battery-fueled gadgets, the Bluetooth determination requires a small form factor, low power utilization, and ease. The range and speed of the innovation were kept purposefully low to guarantee most extreme battery life and least incremental cost for gadgets incorporating the innovation. Bluetooth is about making a Wireless Personal Area Network (WPAN) comprising of all the Bluetooth-empowered electronic gadgets quickly surrounding a client, wherever that client might be located.

Table 2.1 Summary of characteristics of some leading WLAN/WPAN standards

Characteristic	**Bluetooth**	**IEEE 802.11b**	**IEEE 802.11g**	**IEEE 802.11a**	**UWB**
Standard version/status	V 1.1 (Low Rate)	IEEE approved	-	IEEE approved	-
Maximum distance	10-100m	100m	100m	50m	10m
Frequency allocation	2.4GHz (ISM)	2.4GHz (ISM)	2.4GHz (ISM)	5GHz (UNII)	3.1-10.6GHz
Number of RF channels	79	3	3	8	1-15
Modulation	GFSK	QPSK	OFDM	OFDM	BPSK, QPSK
Spreading	FH	DSSS	OFDM	OFDM	(Multiband)
Maximum RF power	0-20dBm	20dBm (EU)	20dBm (EU)	24dBm	-41.3dBm/MHz
Receiver sensitivity	-70dBm	-76dBm for 11Mb/s	-74dBm for 33Mb/s	-65dBm or 54Mb/s	

Details of Bluetooth give the limitations and potential outcomes of the innovation. Bluetooth works in the 2.4GHz frequencies which are free for use to everybody globally. This recurrence gives a powerful information rate of 720 Kbit/s. There are different classes of transmission qualities which decide the utilization and the vitality effectiveness of these gadgets. The Bluetooth network convention utilizes five layers which are executed by programming and hardware.

They are:

(a) Application Programming Interface (API) – Allows the working framework (OS) and different applications to get to the Bluetooth interface.

(b) Logical Link Control and Adaptation Protocol (L2CAP) – Maintains singularly connects to different gadgets in its transmission zone.

(c) Link Manager – Responsible for setting up and ending connections and connection security.

(d) Baseband – low-level errands including blunder adjustment.

(e) Physical – real radio transmitter and receiving the wire.

The topology for Bluetooth is exceptionally one of a type, and this component enables it to be adaptable. The system connection can be either point to point or can be the point to multipoint, and gadgets participating in the system can be characterized as master or slave. In the most simplified system of one master gadget connecting with one slave gadget, a piconet is framed, and all the data transfer capacity is committed to the connection between the two gadgets. Bigger systems can be shaped with a solitary master and up to 7 slaves. The system engineering, in any case, permits up to 255 slaves to be in a standby mode. Bluetooth figures out how to accomplish its usefulness through its balance and packeting plan. This is otherwise called Gaussian Frequency Shift Keying (GFSK).

Bluetooth hops to any of 79 unique channels (The US and Europe), recursive procedure that tries to minimize the error. It is this bundle bouncing strategy which prompts the obstruction with 802.11b innovation. The channel hopping innovation of Bluetooth is the mystery behind its low power utilization, error rectification, and the particular topology that it can support. Bluetooth separates the information to be sent into bundles. Every bundle is sent inside a 625-microsecond space. A frame is regularly characterized as a transmitting and a get opening, giving the full duplex correspondence between a master and a slave in the one-time allotment. To keep away different obstacles and obstructions, Bluetooth jumps to one of 79 unique channels each time allotment. The channel that it jumps to is controlled by the Master ID and the past channel number. This is a recursive computation. For instance, if there is serious noise in the vicinity of 2.408GHz and 2.410GHz, it will try to avoid most of the time. There is next to zero time conflict between masters inside the reach of each other which may bring about the master grabbing similar channels in the meantime. Because of channel jumping system, obstruction is kept to a minimum regardless of amazingly thick scatter nets. Master gadgets can utilize this casing division to connect with each slave on the piconet successively, with one outline each, or they can dedicate numerous frames to a similar slave gadget, contingent upon the need of the current task.

Bluetooth was initially brought about by Ericsson in 1994 when they started an investigation to look at other options to links that connected cell phone accessories. Ericsson as of now had a solid ability in short range remote, having been a key pioneer of the European DECT cordless media communications standard, which had been to a great extent given their prior exclusive DCT900 innovation. Bluetooth was named after Harald Blatand (or Bluetooth), a tenth century Danish Viking lord who had joined and controlled substantial parts of Scandinavia which are today Denmark and Norway. The name was highlighted the capability of the innovation to bring together the media communications and computing industries - in spite of the fact that it was picked as an interior codename, and it was never at the time anticipated that would get by as the name utilized as a part of the business field.

In February 1998, the Bluetooth SIG (Special Interest Group) was established by a little center of real organizations - IBM, Intel, Nokia, Toshiba, and Ericsson - to cooperate to build up the innovation and to in this manner advance it is across the board business acknowledgment. After six months the center Promoter Members openly reported the worldwide SIG and welcomed different organizations to join, with free access to the innovation as Bluetooth adapters as an end-result of the sense of duty regarding supporting the Bluetooth detail. The selection was fast, and 1998-1999 saw a blast in the market for Bluetooth meeting coordinators and immense measures of buildup in regards to the capability of the innovation. In December 1999 it was declared that four more real organizations had joined the SIG as Promoter Members, viz. Microsoft, Agere Systems (at that point Lucent), 3Com and Motorola.

The definite Bluetooth particulars are accessible in [2]. Table 2.2 is a synopsis of the key radio determinations.

2.4.1 Bluetooth Operation

Bluetooth controls timing on the system by assigning one of the gadgets as a master and alternate as a slave. The master is the unit that starts the correspondence interface, and alternate members are slaves. At the point when that connection is later broken, the master/slave assignments no more apply. Indeed, every Bluetooth gadget has both master and slave equipment. The system itself is named a piconet, which means little system. At the point when there is just a single slave, at that point, the connection is called point-to-point. A master can control up to seven dynamic slaves in a point-to-multipoint setup. Slaves discuss just with the master, never with each other specifically. Timing in such a way that individual from the piconet can't transmit at the same time so that these gadgets won't jam each other. At last, correspondence crosswise over piconets can be acknowledged if a Bluetooth gadget can be a slave in more than one piconet, or a master in one and a slave in another. Piconets designed in this way are called scatter nets. These different courses of action are shown in Figure 2.2 [3].

2.4.2 Bluetooth Standard

Mobility invented from the desire to exchange either toward resources or away from scarceness. Mobile computing is worried about the movement of physical devices, user applications, and mobile agents. The most well-known radio based wireless PAN is Bluetooth. Bluetooth technology established by Bluetooth Special interested Group and the central determination of this technology is to replace the connection cables used to connect devices, with one universal short-range radio link. The first version of the Bluetooth specification was released in 1999 and updated to the current version 1.1 in February 2001. It defines the entire system from physical radio layer to outlines of appropriate applications. The lower layers, the radio, and the MAC were standardized by the 802.15.1 task group in June 2002 after the Bluetooth consortium responded to the IEEE's 1998 call for proposals for a wireless PAN standard [4].

Table 2.2 Bluetooth Radio specification

Frequency Band		2400-2483.5MHz
Duplex		Time Division
Modulation		GFSK(BT=0.5,Index:0.28-0.35)
Channel Space		1 MHz
Sensitivity		- 70dBm(for 0.1%BER)
Maximum Signal Level		-20dBm
Interference Performance	$C/I_{co-channel}$	11 dB
	C/I_{1MHz}	0 dB
	C/I_{2MHz}	-30 dB
	$C/I_{2>=3MHz}$	-40 dB
	C/I_{image}	-9 dB
Out-of-band Blocking	30 MHz-2000 MHz	-10 dBm
	2000-2399 MHz	-27dBm
	2498-3000 MHz	-27dBm
	3GHz - 12.75GHz	-10 dBm
Intermodulation Characteristics	Interference Frequency	3,4,5 MHz
	Interference Level	-39 dBm
	Bluetooth Signal Level	6dB above sensitivity
RSSI	Range	-60dBm±4 to 20±6dB
	Accuracy	±4 dB
Radio Frequency Tolerance	Transmitted Frequency Accuracy	±75 kHz
	Frequency Drift	±25 kHz in one slot

Bluetooth (BT) is a wireless personal area network technology which is managed by Bluetooth Special Interest Group (SIG) and defined as an IEEE standard since its first ratified version in 2002 [5]. BT is aimed at replacing cables between devices to the short-range wireless radio channel communication. With the low power consumption and low-cost advantages, BT is widely used and developed over the years. It is nowadays one of the most attached wireless communication technology for the mobile communication equipment as it is completed through versions to support larger and varies files transmission with alternative data rates. Radio frequency waves are used as the communication medium. These radio frequency waves are operating in the free ISM band with 2.45 GHz frequency. Bluetooth uses a spread spectrum frequency-hopping technique which uses a narrowband signal and spreads it over a broader portion of the available radio frequency ISM band.

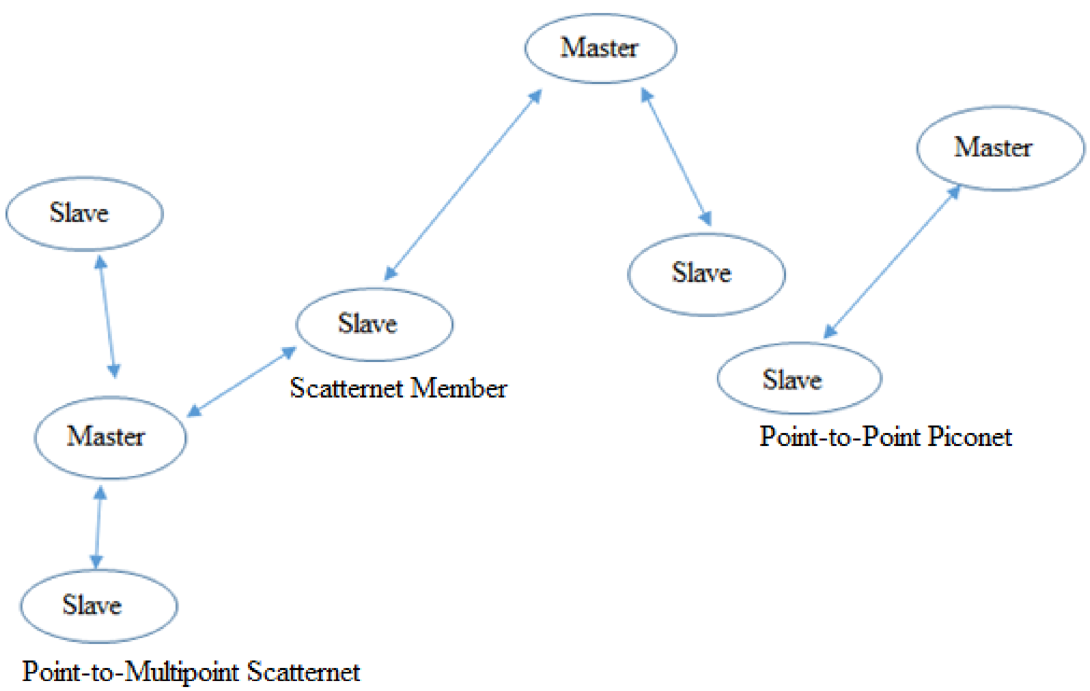

Figure 2.2 Point-to-point and point-to-multipoint and scatternet topology in Bluetooth.

2.4.3 Bluetooth Radio Specification

Bluetooth radios transmit and receive data using a type of Frequency Shift Keying (FSK). In FSK systems data symbols are transmitted at the different carrier frequency. Bluetooth uses a positive variation of between 115 KHz and 175 KHz to transmit a binary '1 ' and negative variation for a binary '0'. The center of these variations is termed the channel carrier frequency. The Bluetooth Physical Layer Radio Specification defines 80 channels with carrier frequencies of 2402 + n MHz where n is an integer channel number between 0 and 79. This channel number change pseudo-randomly between each data packet to aid immunity to noise and provide a measure of security.

The carrier frequency does not have to be exact, however. Defined in the Bluetooth Radio Specification are transmitter 'modulation characteristics' which allow carrier frequencies different to the ideal integer number of megahertz. At the start of each packet transmission, an initial error of ±75KHz is permitted. A further drift of 40 KHz from whatever the initial value was is then also allowed. These permissible differences from the ideal carrier frequency are an appreciable fraction of the frequency deviations used to modulate, and subsequently, demodulate data. In the case of a 75 KHz offset alone, the error is up to 65% of the keyed frequency shifts. While these limits on the accuracy of the carrier frequency are specified for a Bluetooth transmitter, no limits are placed on the accuracy of a receiver's channel frequency generation. This is reasonable as in most, if not all, cases the same circuitry will be used to generate carrier frequencies for transmission and reception. However, as there is no carrier synchronization in Bluetooth a situation will arise where a transmitter has a carrier frequency offset, and the receiver has a different offset. Both ends of the radio channel are making estimations of the channel frequency. If the transmitter were to have an offset of greater than 57.5 KHz and the receiver an opposite offset of greater than 57.5 KHz, then the combined error would be at least 115 KHz the minimum shift used to encode data.

CHAPTER 3

Bluetooth Transmitter Architecture

3.1 Introduction

In this chapter, a general introduction of transmitter blocks are presented, which explains the importance of each of the transmitter blocks to a RF transmitter system. In this section, a brief description about Gaussian filter, Modulator and DAC have been presented. In the later sections, a substantial discussion has been provided for several CMOS circuit configurations which are presented in the transmitter system architecture.

3.2 Bluetooth Transmitter Architectures

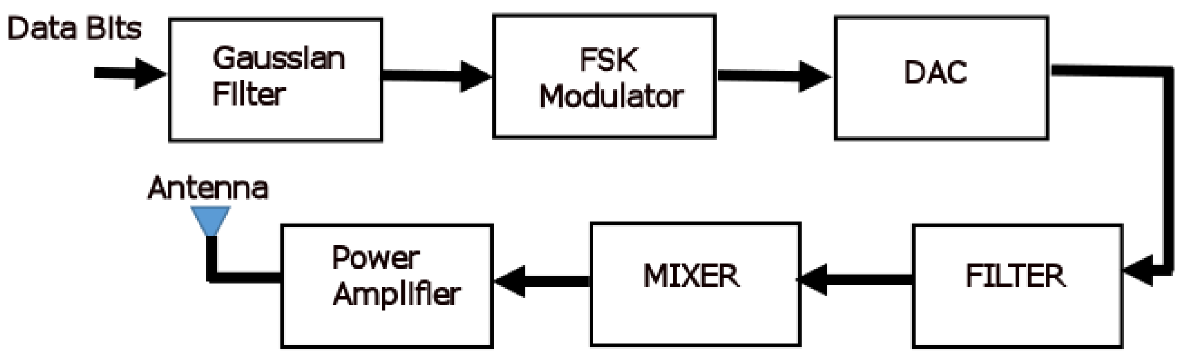

Figure 3.1 Bluetooth Transmitter Architecture

The Bluetooth transmitter architecture as shown in figure 3.1, In which data is pass through the Gaussian filter and then modulated by the FSK modulation Scheme. In Next Stage digital signal converted to analog signal with the help of DAC. Filter is used to remove spikes which are occurred due to fast switching. Here Mixer is used as an up-conversion signal which translates lower frequency to desired ISM frequency band with the help of off chip local oscillator then amplified by a power amplifier, before transmit it through Radio Frequency (RF) antenna.

3.3 Gaussian Low Pass Filter

Gaussian filter which is used to smooth the edge of input baseband data and limit the extent of transmitter data spectrum as well as remove the glitches created in the data level conversion technique. Gaussian filter has become the baseband filter in many wireless technologies, used in improving the power efficiencies of the personal communications systems (PCS). The advantage of GFSK (Gaussian filter minimum shift keying) with any modulation index m is attributed to the Gaussian filter. A Gaussian filter can be either analog or digital. A digital filter has an advantage over an analog filter in the size and precision.

3.3.1 Transfer Function of Gaussian Filter

The Gaussian filter has a transfer function is given by

$$H(f) = \exp(-\alpha^2 f^2) \tag{3.1}$$

As α increases, the spectral occupancy of the Gaussian filter decreases and the impulse response spreads over adjacent symbols, leading to increased ISI at the receiver. The parameter α is related to B, the 3-dB bandwidth of the baseband Gaussian shaping filter [6].

It is expressed as -

$$\alpha = \frac{\sqrt{(ln2)}}{\sqrt{2}} \cdot \frac{T_S}{BT_S} \tag{3.2}$$

The impulse response of the Gaussian LPF filter in the time domain is

$$h(t) = \frac{\sqrt{\pi}}{\alpha} exp\left[-\left(\frac{\pi}{\alpha} t\right)^2\right] \tag{3.3}$$

In the Gaussian low pass filter which are used for Bluetooth in which product of 3dB bandwidth B and bit symbol time T_s is equal to 0.5. In figure 3.2 impulse response for the Gaussian low pass filter is shown and in figure 3.3 shown Gaussian shaped bit response after pass through Gaussian filter.

Values used for Gaussian LPF filter are.

- $T_s = 1\mu$ sec.
- B = 500KHz
- $\alpha = 1.17\mu$

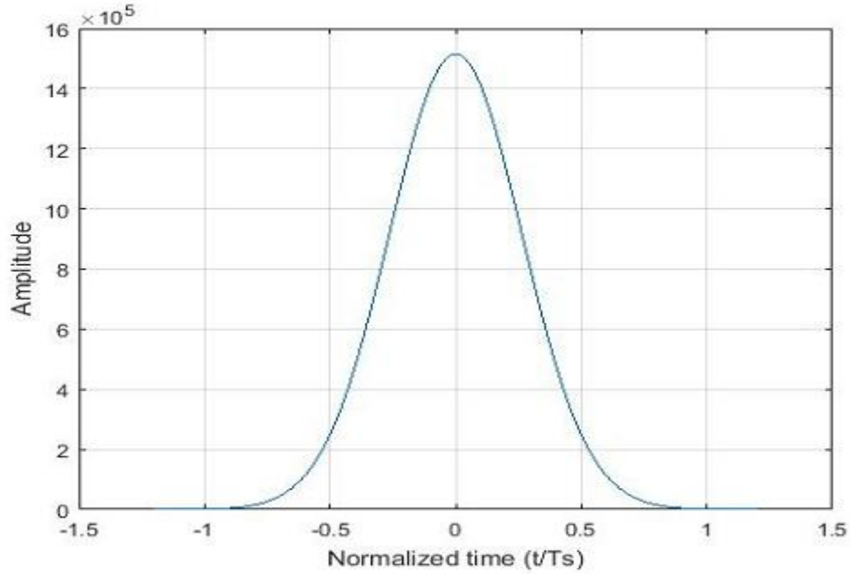

Figure 3.2 Gaussian low pass filter impulse response

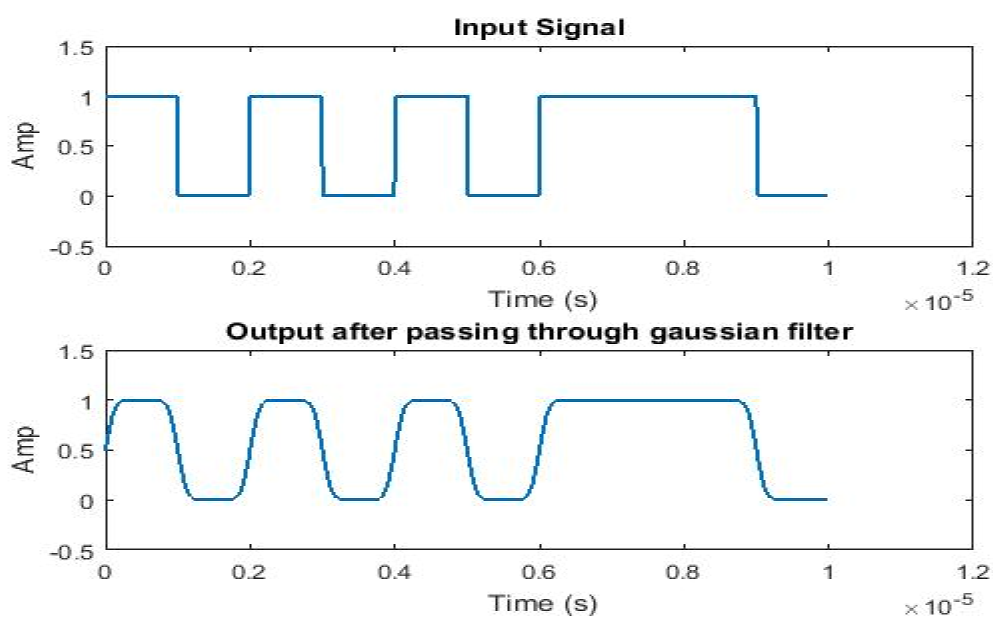

Figure 3.3 Bit response after Gaussian filter

3.4 FSK Modulation

DDFS based modulator, an integrator and a sinusoidal look up table as shown in figure 3.4.

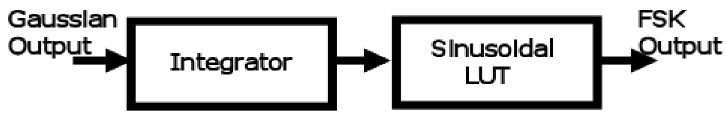

Figure 3.4 DDFS based FSK Block diagram.

The integrator is received the Gaussian output sample and integrates the incoming frequency samples to sequence of phase samples. The next sinusoidal LUT stage is received the sequence of phase sample from the integrator and then generate the cosine and sine sample for the baseband signal for each phase samples. The sinusoidal LUT stage store only one quadrant of the cosine samples value and compute cosine and sine samples value from the store samples value by using cosine symmetric properties and due to this properties ROM size of LUT has reduced significantly. In figure 3.5 output of DDFS with fixed reference clock for certain binary bits.

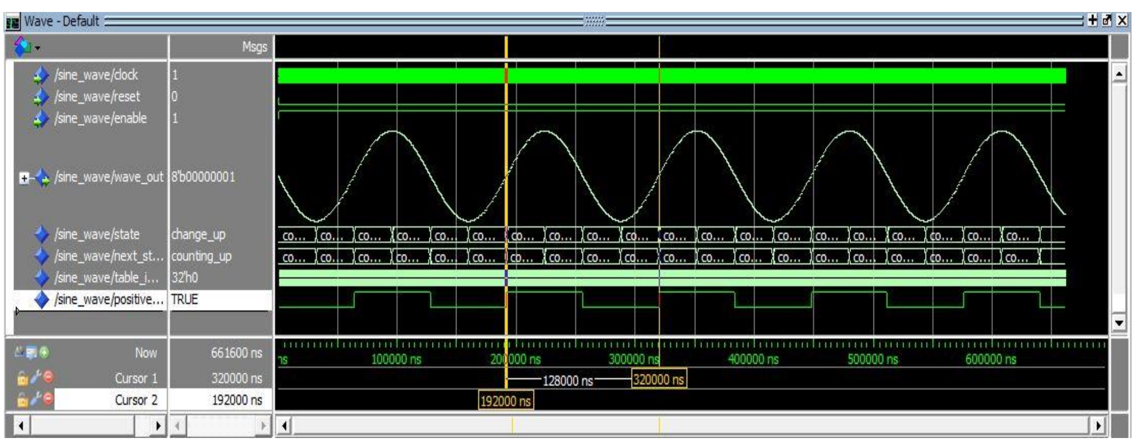

Figure 3.5 Output of DDFS with fixed reference clock period

3.5 Digital to Analog Convertor (DAC)

The digital output from the FSK modulator output is fed to the digital to analog convertor (DAC) which converts it to proportional analog voltage or current and output of the DAC is connected to the filter which removes the glitches from the DAC output.

CHAPTER 4

Low Pass Filter Using CMOS op-Amp

4.1 Two Stage CMOS Op-Amp Design

The design process starts with selecting suitable device length which can be further utilized in the circuitry. The value of design length will decide the value of λ (channel length modulation parameter), this is an important parameter in the computation of amplifier gain. Since transistor modeling differs firmly with the channel length, the determination of a device length to be utilized as a part of the design takes into account more exact simulation models. The minimum value can be built up for the compensation capacitor C_c by selecting minimal transistor device length. Putting the output pole p_2 2.2 times higher than the GB allowed a 60 phase margin [7]. It was demonstrated in the Equation 4.1 that such pole and zero positions bring about the accompanying necessity for the minimum value of C_c.

$$\mathbf{C_c > (2.2/10)\,C_L} \tag{4.1}$$

After that, governing the minimal value for the tail current I_5, given slew rate necessities. The value of I_5 determined by utilizing the Equation 4.2 as.

$$\mathbf{I_5} = \boldsymbol{SR(C_c)} \tag{4.2}$$

If the slew rate detail is not given, then one can select an estimated value based on prerequisites of settling time. Deciding an estimate that is about ten times of settling time description, expecting that the slew is roughly half of the supply rail. If necessary, we can later change the estimate of I_5. By utilizing the necessity of positive input common mode range, we can determine the aspect ratio of M_3. The accompanying design condition for $(W/L)_3$ was obtained from Equation 4.3.

$$\mathbf{S_3 = (W/L)_3 = \frac{I_5}{K'_3\,[V_{DD} - V_{in} - |V_{T03}|_{MAX} + V_{T1_{MIN}}]^2}} \tag{4.3}$$

In case the estimate for $(W/L)_3$ is less than one, then its value should be increased such that the final product of W and L is minimum. This limits the area of the gate region, which results in the decrease of gate capacitance. This gate capacitance adds to a mirror pole which may result in the loss of phase margin. From the knowledge of C and GB, we can determine the prerequisite for the transconductance. The transconductance can be figured utilizing the following Equation 4.4.

$$\boldsymbol{g_{m1} = GB(\mathrm{C_c})} \tag{4.4}$$

The aspect ratio $(\mathrm{W/L})_1$ is acquired directly from $g_m$as given below:

$$\boldsymbol{S_1 = (W/L)_1 = \frac{g_{m1}^2}{(K'_1)(\mathrm{I_5})}} \tag{4.5}$$

Enough data is accessible to compute the saturation voltage of transistor M5. Utilizing the negative ICMR eq., calculate Vd utilizing the accompanying relationship generated from Equation 4.6:

$$\boldsymbol{V_{DS5} = V_{in_{MIN}} - V_{SS} - \left(\frac{\mathrm{I_5}}{\beta_1}\right)^{1/2} - V_{T1_{MAX}}} \tag{4.6}$$

It may result in higher chances of large $(W/L)_5$if the estimate of V_{DSS} is less than 100. This may not be satisfactory. In case the value of V_{DSS} is under zero, then the ICMR determination might be excessively stringent. To resolve this issue, I_5 can be reduced or $(W/L)_1$ expanded. The impact of these changes must be accounted in past design steps. With estimated V_{DSS}, $(W/L)_5$can be derived utilizing Equation 4.7 in an accompanying way:

$$\boldsymbol{S_5 = (W/L)_5 = \frac{2(\mathrm{I_5})}{\mathrm{K}'_5(V_{DS5})^2}} \tag{4.7}$$

Now the outline of the main phase of the operation amp is finished. The output stage is considered in next step. For a phase margin of 60, the location of the output pole was supposed to be at 2.2 times GB. Given this presumption and the relationship for p_2 in Equation 4.8, the transconductance g_{m6} can be solved to utilize the accompanying relationship.

$$\boldsymbol{g_{m6} = 2.2(g_{m2})(\mathrm{C_L/C_c})} \tag{4.8}$$

For sensible phase margin, the esteem of gm is roughly ten times the input stage transconductance g_{m1}. Now, there are two potential ways to deal with finishing the design of M6. The first is to accomplish proper mirroring of the main stage current-mirror load. This requires $V_{SG4} = V_{SG6}$, utilizing the equation for gm, which is K $\frac{W}{L}(V_{GS}-V_T)$, we can compose that if $V_{SG4} = V_{SG6}$, then

$$\mathbf{S_6 = S_4 \frac{g_{m6}}{g_{m4}}} \tag{4.9}$$

Knowing g_{m6} and S_6 will characterize the DC I_6 utilizing the accompanying Equation 4.10.

$$\mathbf{I_6 = \frac{g_{m6}^2}{2K'_6 S_6}} \tag{4.10}$$

One should now check to ensure that the greatest output voltage determination is fulfilled. If this is not valid, then the current or W/L proportion can be expanded to accomplish a lower V_{DS}. If these modifications are made to fulfill the most extreme output voltage detail, then the best possible current reflecting of M3 and M4 is no longer ensured. The other way to deal with designing the output stage is to utilize the estimation of gm6 and the required V_{DS} of M6 to locate the current. Combining the characterizing condition for g_m and V_{DS} brings about a condition relating (W/L), V_{DS}, g_m and process parameters. Utilizing this relationship, defined below with the V_{DS} prerequisite taken from the output, one can derive $(W/L)_6$.

$$\mathbf{S_6 = (W/L)_6 = \frac{g_{m6}}{K'_6 V_{DS6_{(SAT)}}}} \tag{4.11}$$

Equation 4.10 is utilized as before to decide an estimate for I_6. In either way to deal with determining I_6, one should check the power dissipation prerequisites since I_6 will probably decide most of the power dissipation. The device size of M7 can be solved from the condition derived below:

$$\mathbf{S_7 = (W/L)_7 = (W/L)_5 \left(\frac{I_6}{I_5}\right) = S_5 \left(\frac{I_6}{I_5}\right)} \tag{4.12}$$

The first – cut design of all W/L proportions is currently complete. Figure 4.1 explains the above design method demonstrating the different outline connections and where they apply in the two-phase CMOS operation amp. Now in the design technique, the aggregate amplifier gain must be checked against the description.

$$\text{First- Stage gain,} \quad A_{V1} = \frac{-g_{m1}}{g_{ds2} + g_{ds4}} \tag{4.13}$$

$$\text{Second- Stage gain,} \quad A_{V2} = \frac{-g_{m6}}{g_{ds6} + g_{ds7}} \tag{4.14}$$

If the gain is too low, various things can be balanced. Ideally, we can utilize the Table, which demonstrates the impact of different design sizes and current on the distinctive parameters. Every modification might require another pass through this design technique to guarantee that all descriptions have been met. Table 4.3 briefly explains the above design technique [7].

No attempts have been made to represent noise or PSRR up to this point in design methodology. Since the preparatory design is complete, these two detail can be addressed to. The input reference voltage comes about basically from the load and input transistor of the main stage. Each of these contributes both thermal and 1/f noise. The 1/f noise contributes by any transistor can be diminished by expanding its device area. Thermal noise contributes by any transistor can be decreased by expanding its gm. This is accomplished by an expansion in W/L, an increment in present or both. Viable input noise voltage assigned to the load transistors can be decreased by decreasing the g_{m1}/g_{m2} proportion. One must be attentive that this adjustment to enhance noise performance doesn't adversely influence some other important execution parameter of the operation amp.

The power supply rejection proportion is to an expansive degree determined by the arrangement utilized. Some change in negative PSRR can be accomplished by expanding output resistance of M5. This is accomplished by expanding both W_5 and L_5 proportionately without truly influencing some other performance. Transistor M7 ought to be balanced for appropriate matching.

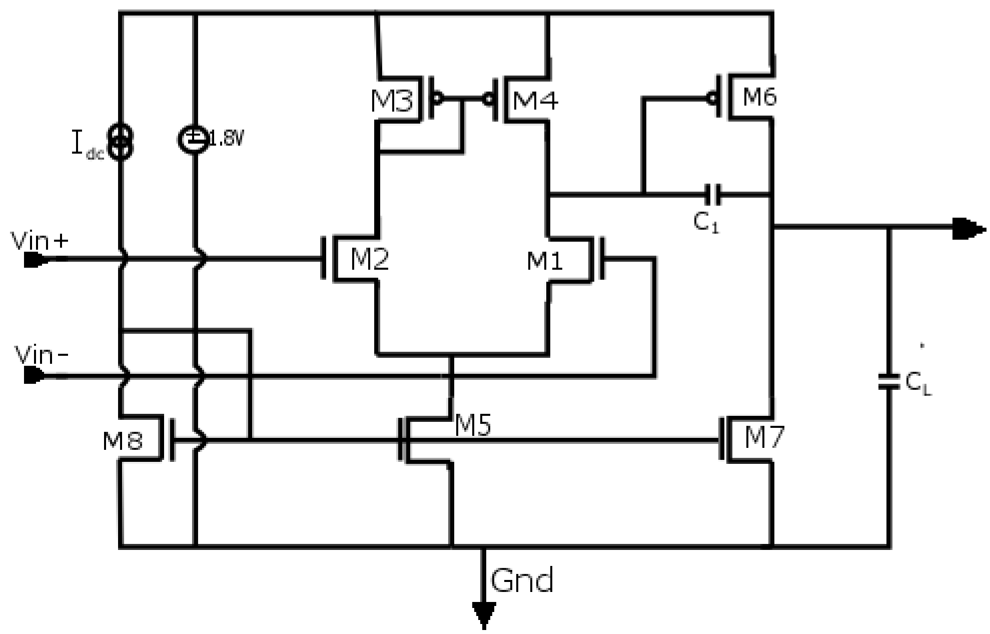

Figure 4.1 Circuit for a two stage CMOS op amp.

TABLE 4.1 Design Specification for two stage CMOS op amp.

Open loop Gain	≥7500V/V
Gain B/W at -3 dB gain ,(f_{3dB})	500KHz
Load Capacitance (CL)	10pF
Slew Rate	0.3V/μs
Maximum Power Dissipation	$> 2mV$
Phase Margin	$\geq\ 60^o$
Channel Length & supply	180nm & 1.8V
CMRR	$> 85dB$

4.2 Model or Device Parameters:

$Kn' = (\mu_n C_{ox}/2) = 270\mu A/V^2$, $Kp' = (\mu_p C_{ox}/2) = 67\mu A/V^2$,$V_{th} = 0.39V$

Table 4.2 MOS transistor designed for 180 nm technology for op amp.

MOS Transistor	Aspect Ratio (W/L)
M1	5
M2	5
M3	14
M4	14
M5	12
M6	174
M7	70
M8	12

Table 4.3 Modification in Figure 4.1 on dc current, W/L ratios and capacitor to get changes in circuit characteristics [7].

Circuit Parameter	**Drain Current**		**M1 & M2**		**M3 & M4**		**Inverter**	**Inverter Load**		**Compensation capacitor**
	I_5	I_7	$\frac{W}{L}$	L	W	L	$(W/L)_6$	W_7	L_7	C_c
Increase dc gain	↓	↓	↑	↑		↑	↑		↑	
Increase GB	↑		↑							↓
Increase Slew Rate										↓
Increase RHS Zero		↑					↑			↓
Increase C_L										↓

4.3 Simulation and Measurement of Op-Amp.

4.3.1. A method of measuring the open loop characteristics with dc bias stability.

This method is more suitable for the measurement of open loop gain as shown in figure 4.2. In this test bench idc and supply voltage are fixed as 20µ and 1.8V respectively and common mode dc voltage (vcm) as 900mV. In figure 4.3, open loop gain has been observed that approximately 64dB and phase margin observed is shown in figure 4.4.

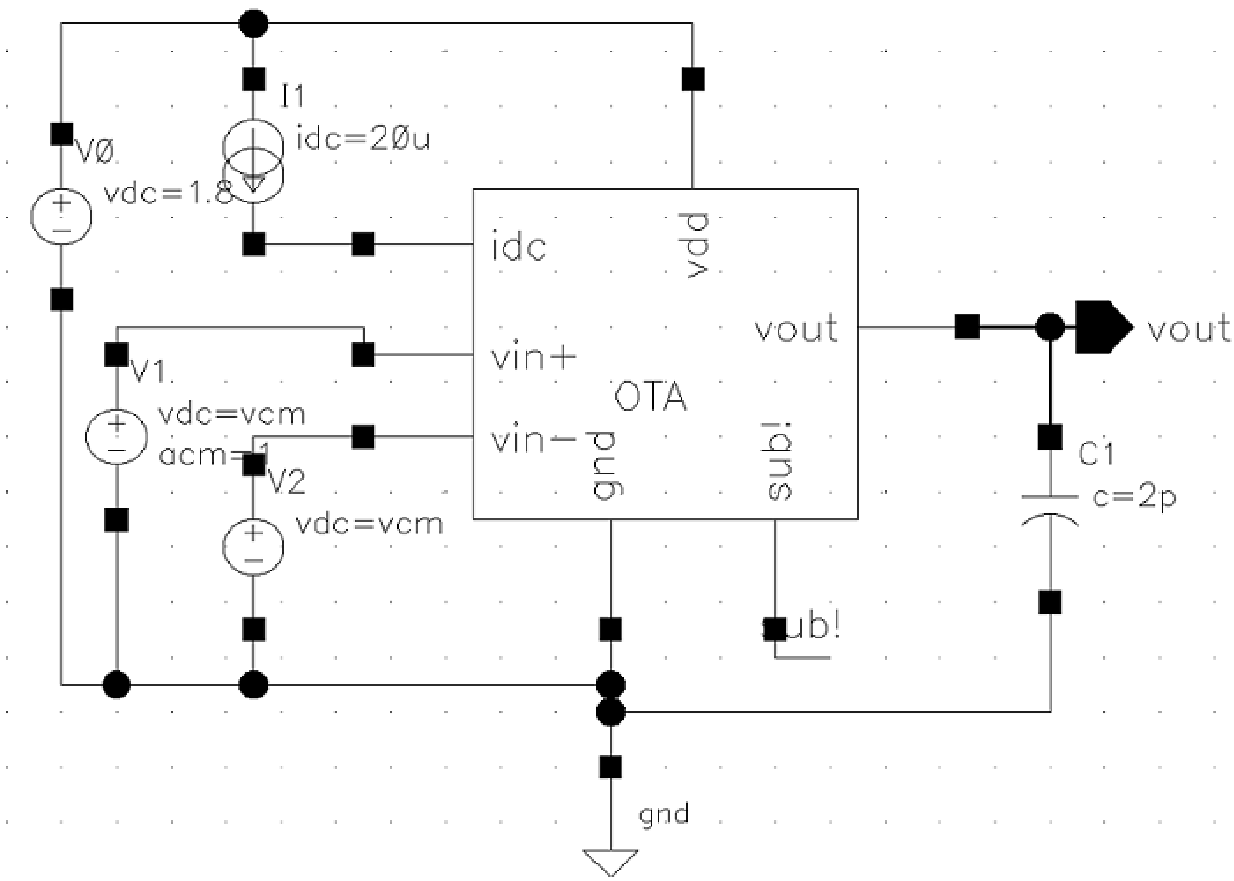

Figure 4.2 Test bench for open loop transfer function response.

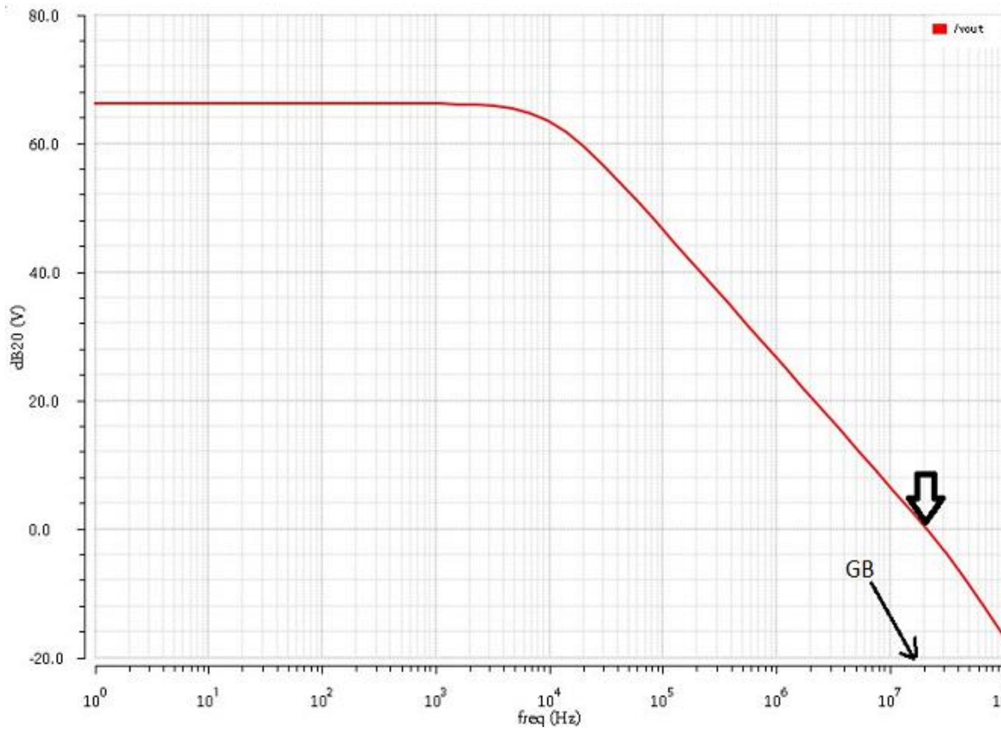

Figure 4.3. Open loop transfer function magnitude response.

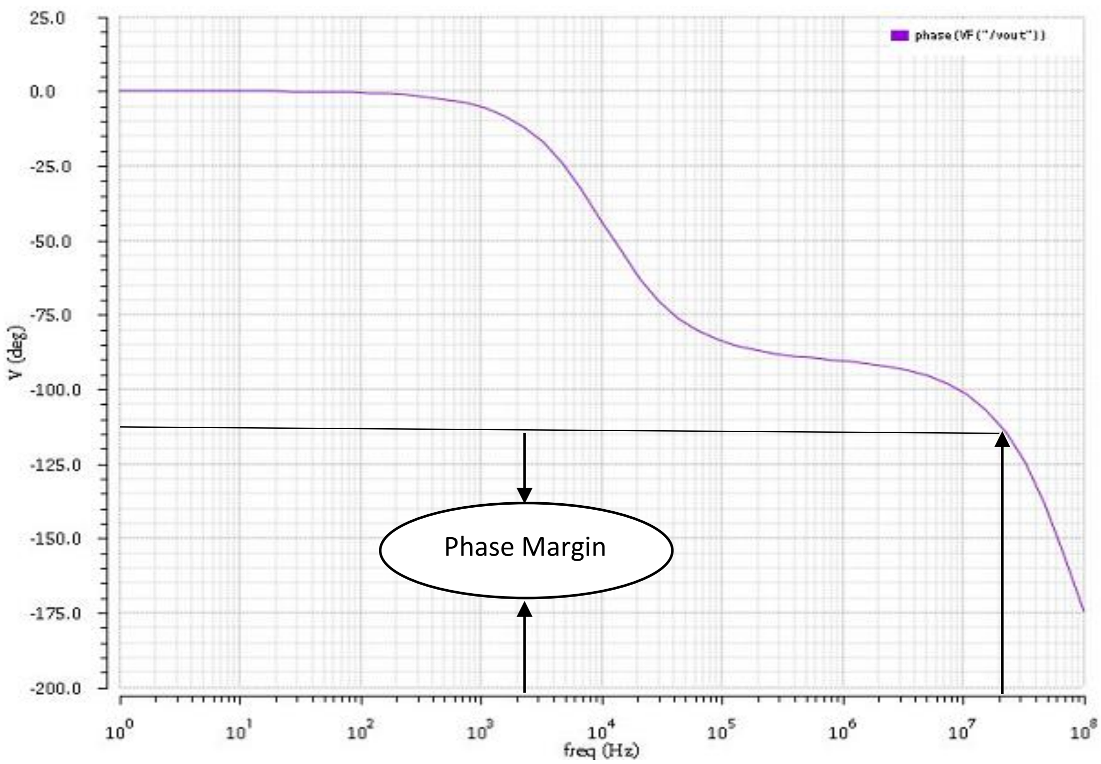

Figure 4.4 Open loop transfer function phase response.

4.3.2 Measurement of the CMRR of the Op-Amp.

To measure the CMRR of Op-Amp would be first measure the differential voltage gain in dB and then common mode voltage gain in dB by applying common mode input signal. CMRR can be calculated by subtracting common mode voltage gain in dB from differential voltage gain in dB. To get the simulation result of CMRR value is around 92dB is shown in Figure 4.6, there is an easier method that to get the output that can be related to CMRR as shown in equation 4.15. Figure 4.5 shown a method that can accomplish this goal. Two identical voltage source V_{cm} placed in series with both op-amp input where the op-amp connected in unity gain feedback configuration [7].

$$\frac{V_{out}}{V_{cm}} = \frac{\pm A_c}{1 + A_v - (\pm A_c/2)} \cong \frac{|A_c|}{A_v} = \frac{1}{CMRR} \tag{4.15}$$

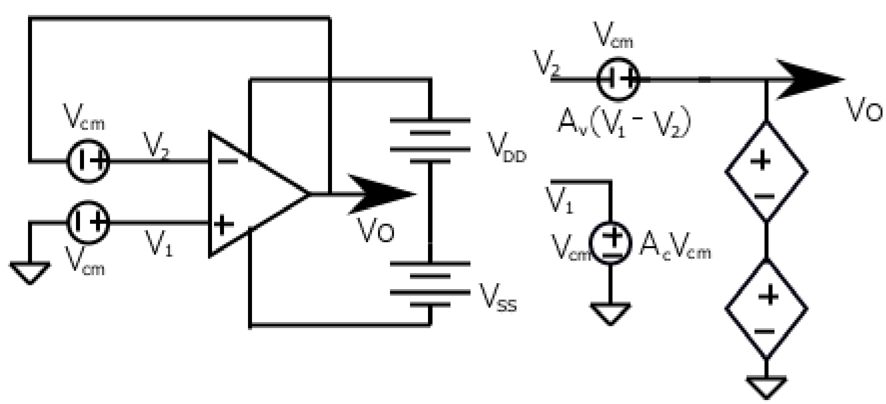

Figure 4.5 Measurement of the CMRR

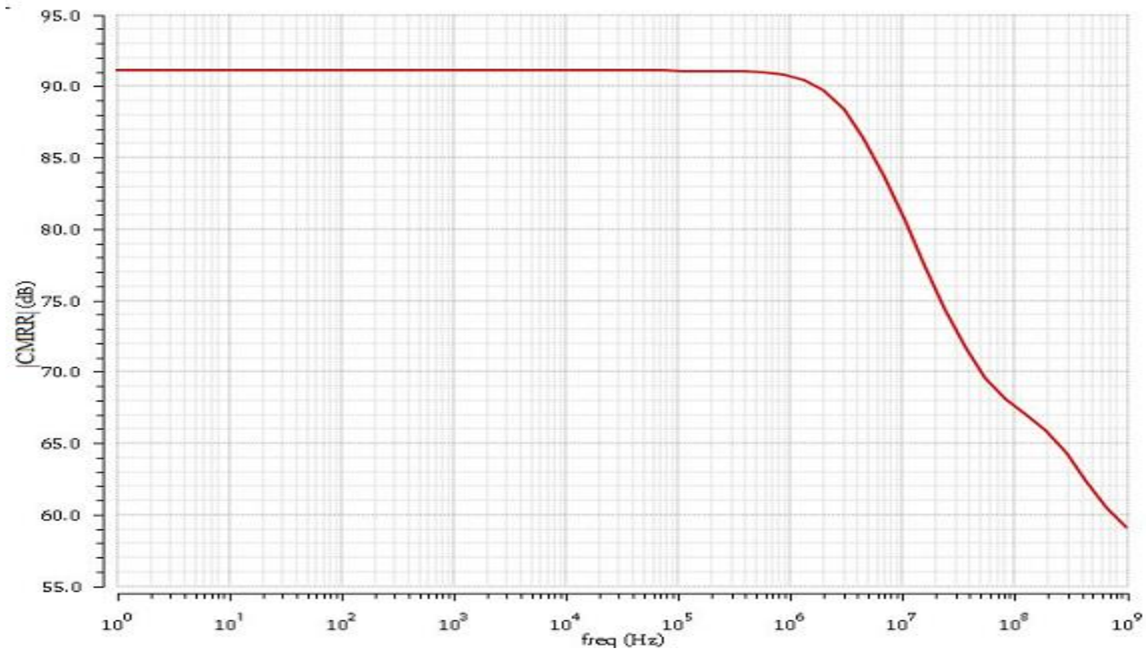

Figure 4.6 CMRR frequency Response.

4.3.3 Simulation result of RC Low Pass filter using op-amp

The operational amplifiers (op-amp) are basic building blocks in implementing a variety of analog circuits. Here it is used to design a low pass filter to remove the glitches. The low pass filter is a filter that allows low frequencies to pass and attenuates higher frequencies. The design of a low pass filter required maximum frequencies range which are allow to pass through .This is called the cut off frequency (or the 3dB down frequency)[8]. In figure 4.7, it is shown that 20 KHz for a certain value of R and C and by changing its value another cutoff value can be achieved and given result unity gain bandwidth frequency is around 335 KHz.

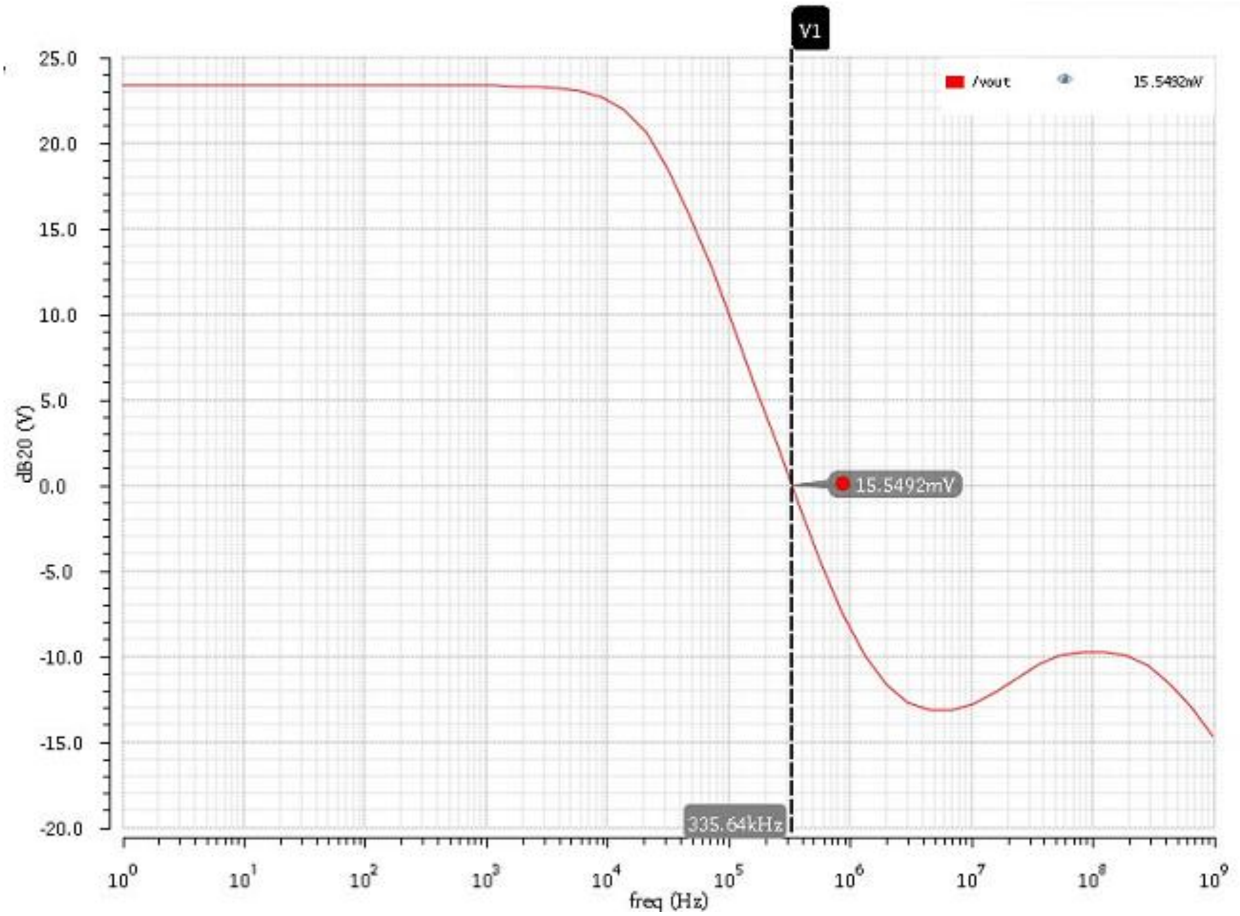

Figure 4.7 Low Pass filter using Op-Amp magnitude verses frequency Response.

4.4 Layout of Op-Amp Circuit.

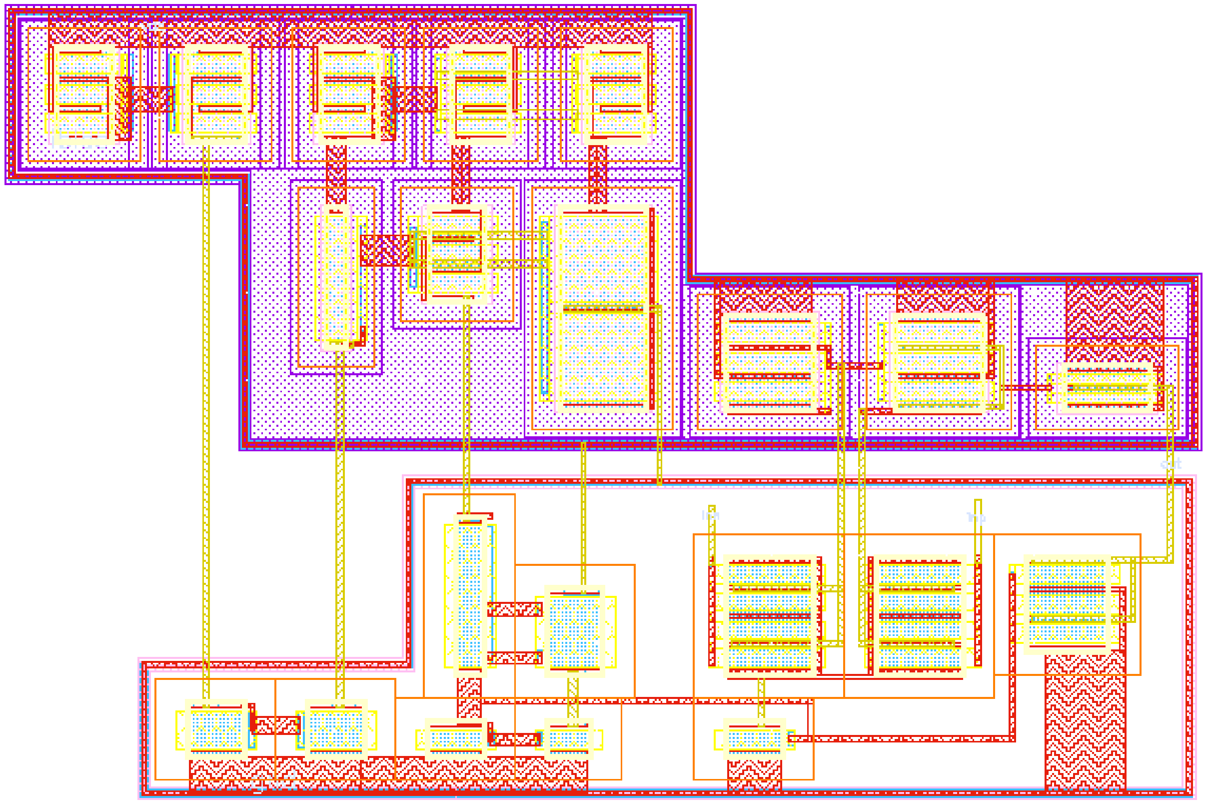

Figure 4.8 layout of Op-amp

CHAPTER 5

Gilbert Up-conversion Mixer

5.1 Basic Mixer Design

A mixer is a basic block of a radio transceiver which is generally signal frequency to a lower or higher spectrum generally by the multiplication of two different frequency signals. Depending on the type of application, the input to a mixer is either Intermediate Frequency (IF) signal or Radio Frequency (RF) signal multiplied by a reference Local Oscillator (LO) signal.

$$a_1 \cos(w_1 t) * a_2 \cos(w_2 t) = \frac{a_1 a_2}{2} [\cos(w_1 - w_2)\, t + \cos(w_1 + w_2)\, t\,] \qquad (5.1)$$

From equation 5.1, the multiplication of two different signals creates frequency components at the sum and difference frequencies, out of which only one is usually desired- Taking one frequency as the LO frequency, another would be either IF or RF signal. If the sum frequency is desired with IF input then the mixer is called as an up-conversion mixer, which is a part of the transmitter chain of the radio system as shown in figure 3.1. However, when the difference output signal is desired then the input RF signal use, the mixer is called a down-conversion mixer generally used at the receiver chain of a transceiver. Under this thesis up-conversion mixer has designed where the input to a mixer is Intermediate Frequency of 160 KHz or 320 KHz multiplied by a reference Local Oscillator of 2.4GHz to translate lower Intermediate frequency to the industrial, scientific, and medical (ISM) radio band. Ideally, this mixer would contribute no noise, no limit to maximum amplitude, no dependence on the LO signal amplitude and would develop no intermodulation products between several different RF signals. In addition, the waveform at the RF output would not contain any LO or IF components. However, an actual mixer will differ from the ideal behavior on the basis of above mentioned performance parameters.

5.2 Circuits Implementation

5.2.1 Gilbert Conventional Up-Conversion Mixer Design.

Gilbert Cell Mixer is a conventional structure which is usually used in designing active mixers and active generally used to design Up-conversion Mixer [9]. It has many advantages. Gilbert cell mixer has a privilege better conversion gain with appropriate load but as compare to passive mixer it has more power consumption. Local Oscillator required very low power to operate as a Gilbert Cell Mixer. Double-Balanced Gilbert cell structure leads to very low noise figure and good port-to-port isolation and this structure completely cancels out the quadratic even order term of the MOS transistor [12].

The Gilbert cell mixer topology is the most commonly design in CMOS technology. Pre-distortion and emitter degeneration is basic technique to get a reasonable linearity. These mixers have not only a limited linearity which mainly depends on matching; even more important is their restricted frequency range. Relatively small V_{gs} - V_{th} voltage applied across the input transistors of the mixers to keep them in the saturation region. Structure of Gilbert cell mixer is shown in Figure 5.1. Transistors TN5 and TN6 are a pair of transconductors and they are operating in the saturation region and transform the baseband input voltage of mixer to current. The conversion gain and linearity of the Mixer primarily depends on these two transistors. TN1, TN2 and TN3, TN4 are act as a pair of switches [14]. They operate in the saturation region and mixed the Local oscillator signal current with baseband signal current from transconductors TN5 and TN6 [10, 13].

5.2.2 Current Control Up-Conversion Mixer

In this section, the design of a mixer based on the scheme in Figure 5.1 and intended for Bluetooth transmitter applications in the 2.4GHz band using an 180nm CMOS technology and 1.8V of supply voltage. In Figure 5.2 shows the schematic of the proposed up conversion mixer with input biasing networks at LO and IF ports. Transistors TN5-TN6 and TP3-TP3 are used as a switching inverters for the RF input voltage and the LO transconductance stages by TN1-TN4. The common mode feedback structure are used at the output load stage with resistors R_L, transistors TP1-TP2.

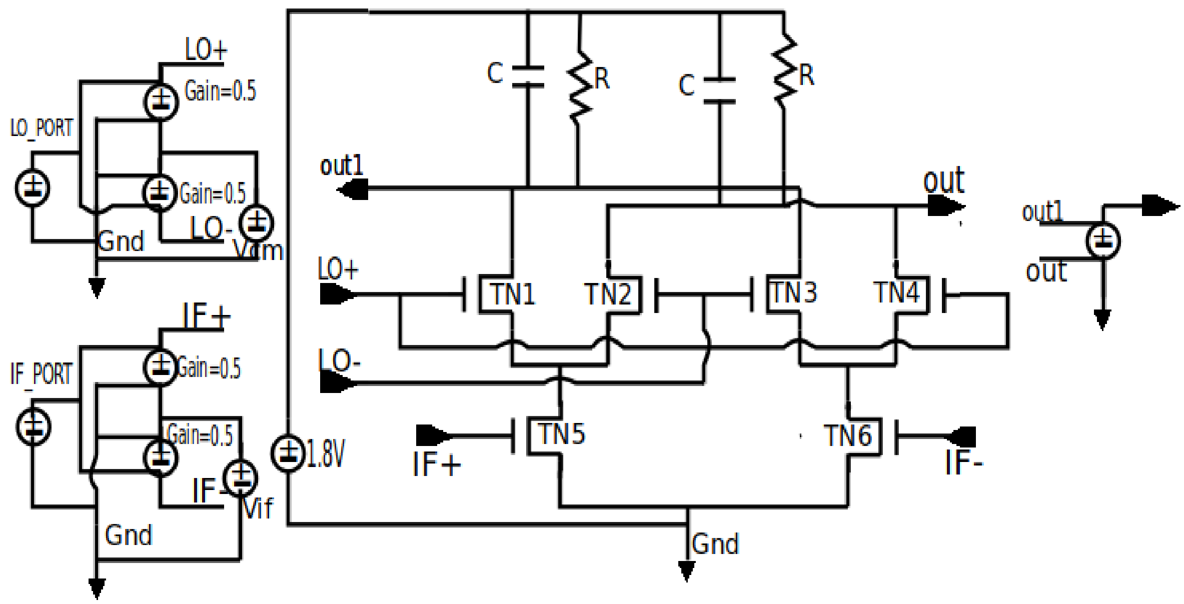

Figure 5.1 Basic Up-conversion Mixer

Power consumption of the circuit is directly interrelated to the bias voltage and size of the transconductance transistors (TN1-TN4). From the power consumption point of view, it is required to keep them in weak inversion mode and due to this large output swing can also be achieved even for low supply voltage. On the other hand, to get the high conversion gain. It is required to keep the W/L ratio of such transistors should be large and as W/L ratio increased, that increases the thermal Noise. Thus, the W/L of transistors TN1-TN4 must be select based on a tradeoff between power consumption and noise. Final adopted sizes were 30µm/0.18µm for these transistors. Moreover, the LO input biasing network modifies the conversion gain described in [11]. If two buffer inverter in cascade ate used to drive by the RF signal then the conversion gain will improve. Namely, it can be shown that the conversion gain [18] now becomes,

$$CG = \frac{2}{\pi} \frac{g_m R_l}{C_{gs} R_i w_o} \tag{5.2}$$

The RF signals are coupled to the RF input of the mixer by biasing networks with DAC output frequency 160 KHz/320 KHz Nevertheless, the switches can be directly driven by antiphase sinewave signals. Figure 5.4 shows the comparison of the simulated voltage conversion gain when input matching and LO signal are used and when the sinewave signals are directly driven to the switches. It can be seen that the input matching and the buffer inverters increases the conversion gain. Moreover, the LO buffer restores the LO levels, keeping the conversion gain constant when the LO amplitude is decreased.

The choice of the ratio WP/WN of the switch transistors affects the ratio between the ON and OFF-switching time and common-mode output currents. The ratio WP/WN is chosen to be about two by delay time considerations. If the switch width decreases, keeping WP/WN=2, the conversion gain results in a gradual degradation. The final decision was WN/LN=60μm/0.18μm and WP/LP=30μm/0.18μm.

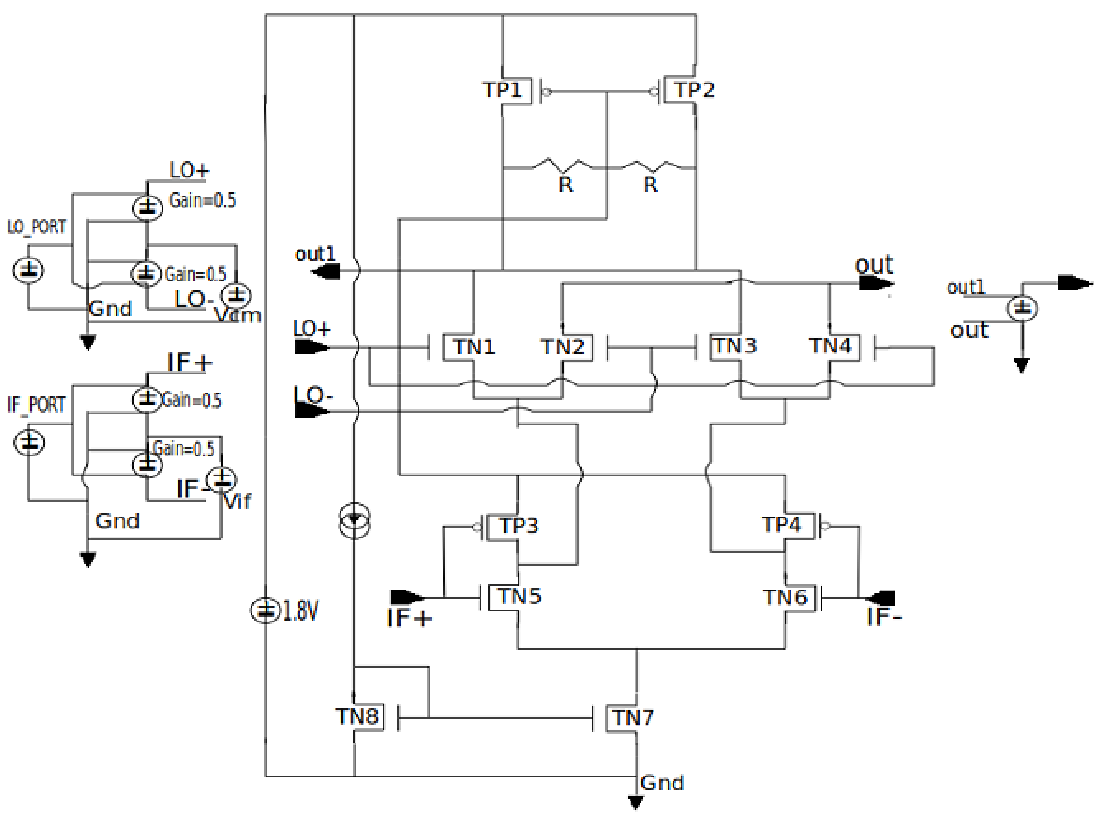

Figure 5.2 Current Controls Up-Conversion Mixer

5.3 Typical Issues Relating RF Up-Conversion Mixers

The desired characteristics of a RF Up-conversion mixer can be summarized as follows:

- Noise figure.
- Voltage conversion gain.
- Linearity and dynamic range.
- Port-to-Port Isolation.

To get a better understanding of the above point involved while designing an up-conversion mixer, these performance parameters are explained below.

5.3.1 Noise Figure

Noise figure is defined as the available output noise power divided by the available input noise power due to the source expressed in dBs. Typically, the signal present at the image frequency is not desired. The mixer translates both the IF and the image signals to the same RF. It is the measure of the degradation of a signal when it passes through the circuit.

$$NF = 10log_{10} \frac{SNR_{IF}}{SNR_{RF}} \tag{5.3}$$

For passive devices, the noise figure is equal to the attenuation of the signal. For active devices, additional noise is added to this insertion loss. Noise figure for mixer tends to be considerably higher than that of amplifiers, due to fact that the noise coming from the frequencies are also mixed at the RF port other than the desired RF signal. Also, referring to Equation 5.1, it can be observed that the output of even the mixer contains two sidebands. In the usual case, where the desired information exist only at a single sideband then the noise figure is called the Single Sideband Noise Figure (SSB-NF) and if both the sidebands contain useful information, then the noise figure is called the Double Sideband Noise Figure (DSB-NF). The SSB-NF is more specific to the receivers employing heterodyne architecture while the DSB -NF is applicable to the homodyne (direct-conversion) receivers [15]. In applications like homodyne (direct conversion receiver) the signal present at the image frequency holds useful information, and hence the DSB-NF is calculated. In Figure 5.5, it is observed that the Noise figure and output noise are 15.768dB and 28.6nV/$\sqrt{\text{Hz}}$ respectively at 320 KHz.

5.3.2 Voltage Conversion Gain

The voltage conversion gain is defined the ratio of the RMS voltages of the RF and IF signals. The power conversion gain is defined as the ratio of the power delivered to the load and the available IF input power. It could be either voltage or power conversion gain. However, when the mixer's input impedance and load impedance are both equal to the source impedance i.e. 50 Ω then the voltage and the power conversion gains of the mixer are equal when expressed in dBs. Referring to Equation 2.1, the conversion gain of a simple multiplier is RF output amplitude $a_1 a_2/2$ divided by the IF input amplitude 'a_1'. Hence the conversion gain is $a_2/2$ or half the LO amplitude. Assuming LO amplitude to be constant and a_2 = 1 then the output of even a simple multiplier suffers from a conversion loss of 6 dB. Positive conversion gain is desirable then the mixer then provides amplification along with the frequency translation. In figure 5.4, it is observed that at 5dB LO power output power is approximately 13dB. All other calculation have been done by assuming LO power at 5dB.

5.3.3 Dynamic Range and Linearity

Mixer are nonlinear devices by definition, hence it may seem paradoxical to mention mixer linearity. However, looking closer at the mixer operation we realize that there is a desired and an undesired nonlinearity. The desired nonlinearity stems from the switching nature of the upper transistors quad.

The 1dB gain compression point (P1dB) and the 3rd order intercept point (IP3) are the major figures which are widely used to describe the linearity of mixer circuit. They will be briefly discussed in the following sections.

5.3.3.1 1dB Gain Compression Point

When the small signals are process in the mixer circuits, the harmonic components generated in the mixer circuit are negligible because the gain is usually constant in the mixer circuits over a wide range of signal magnitudes. However, the circuit will get saturate, if the input signal is increased beyond a certain limit and then the level of harmonic components in the mixer circuit increase significantly and the gain starts reducing. The point at which the power gain drops by 1 dB with respect to the small signal gain of the mixer circuit is referred to as 1 dB Compression Point (P1dB) and it is used to measure the dynamic range of a mixer. The transmitter must operate several dBs below this P1dB level to avoid non-linear behavior and distortion at the output signal. The graphical illustration of the phenomenon is shown in figure 5.6, it is observed that the gain is fairly constant for input powers of -12dBm or less. The gain starts dropping considerably due to device saturation for input powers above -10dBm at 1st order frequency of 2.40032GHz.

5.3.3.2 Intermodulation Distortion and Third Order Intercept Point

The two-tone third-order Intercept Point (IP3) is a measure of mixer linearity characterization. Intermodulation (IM) products occur due to the multiplication of desired input signal with a potential interferer resulting in higher order product terms in addition to the desired fundamental. Third-order Intermodulation (IM3) products are, usually, of great concern, as they cannot be filtered out due to their close proximity with the desired output frequency. As a measure of the degree of departure from the mixer behavior, the desired output and the IM3 output can be plotted as a function of IF input power level. The IP3 is an extrapolated intersection of these curves as shown in Figure 5.7. In general, the higher the IP3, the more linear is the mixer. A high IP3 provides a measure of protection against large adjacent interferer signals causing large signal distortion in the transceiver. Referring to Figure 5.7, the non-linearity in the circuit causes the power gain to deviate from its idealized curve. In the Figure 5.7 is a simulation graph which gives the information about third order intermodulation distortion (IMD) and intercept**.** At 3rd order intercept point output (OIP3) and input (IIP3) is 5dBm and 6dBm respectively.

5.4 Simulation Results of Mixer

5.4.1 Transient Simulation

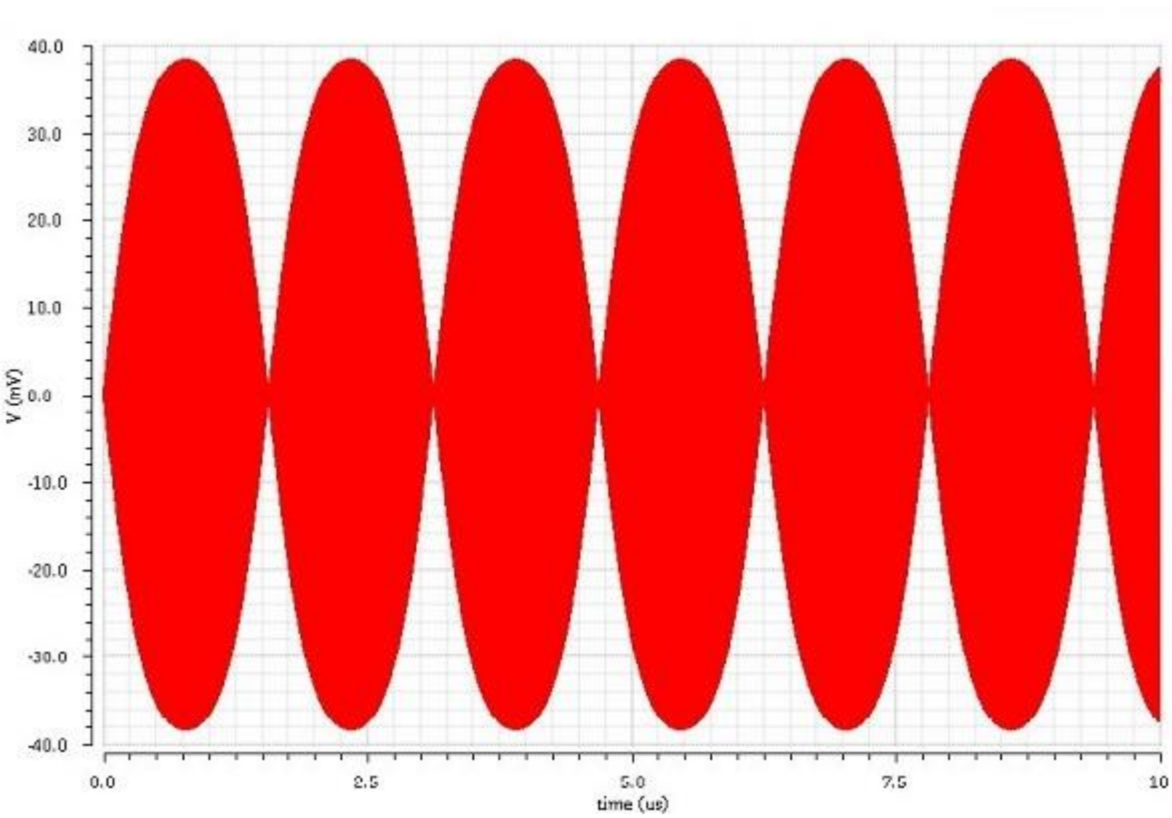

Figure 5.3 Transient simulation

5.4.2. Voltage Conversion Gain with respect to LO Power

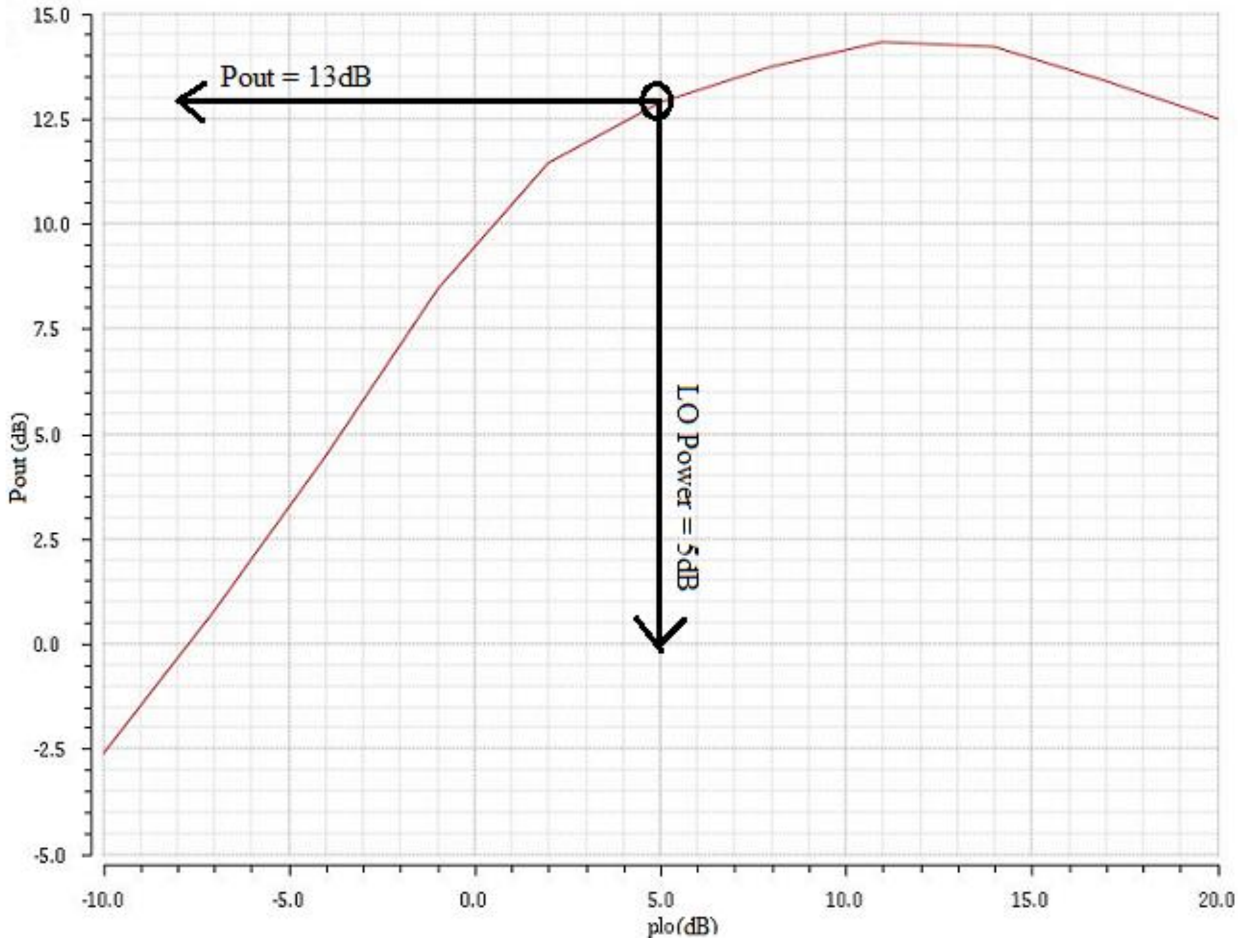

Figure 5.4 Voltage conversion gain with respect to LO level

5.4.3 Noise Figure and Output Noise

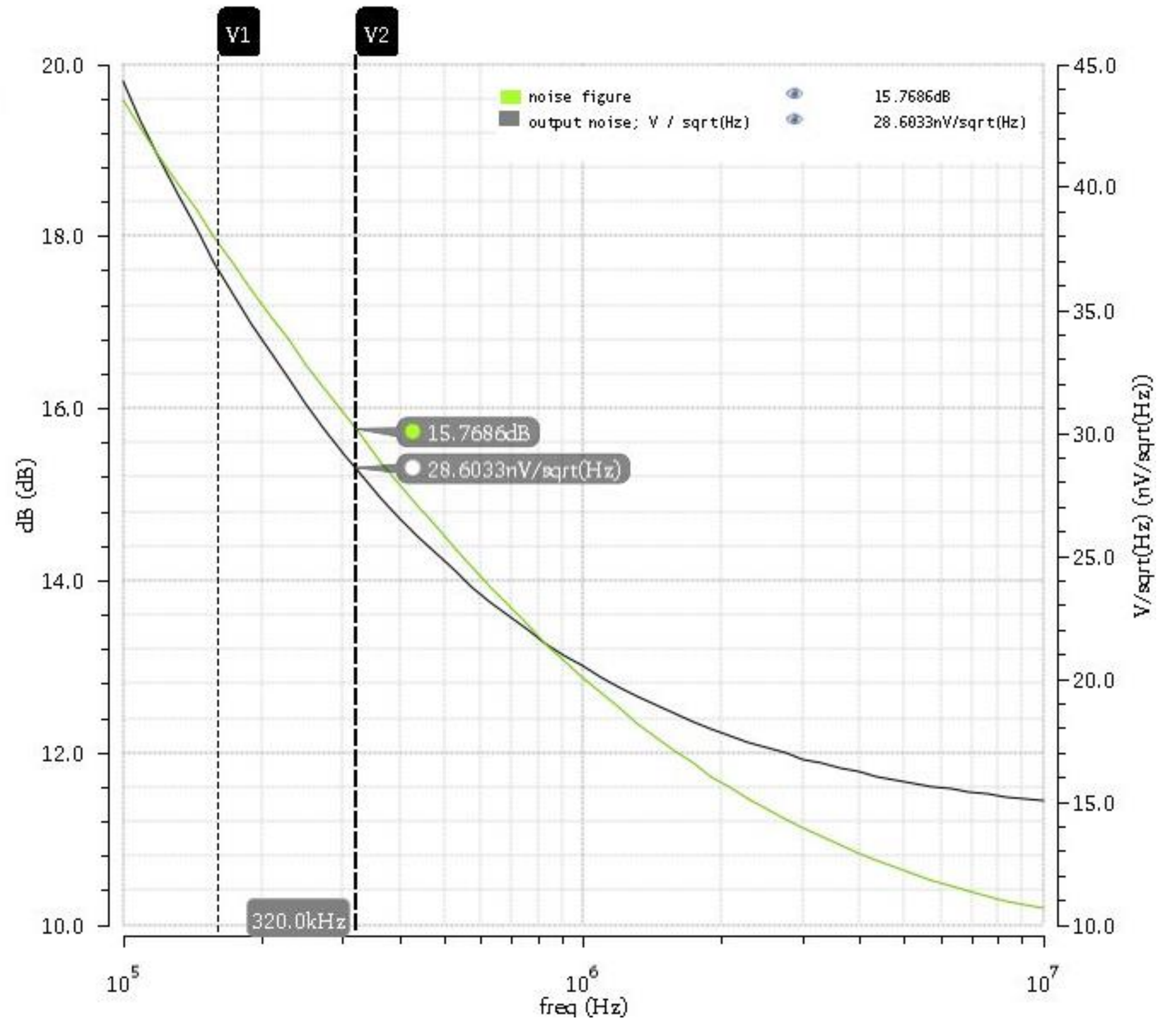

Figure 5.5 Mixer Noise Figure and Output Noise

5.4.4 1 dB Compression Point

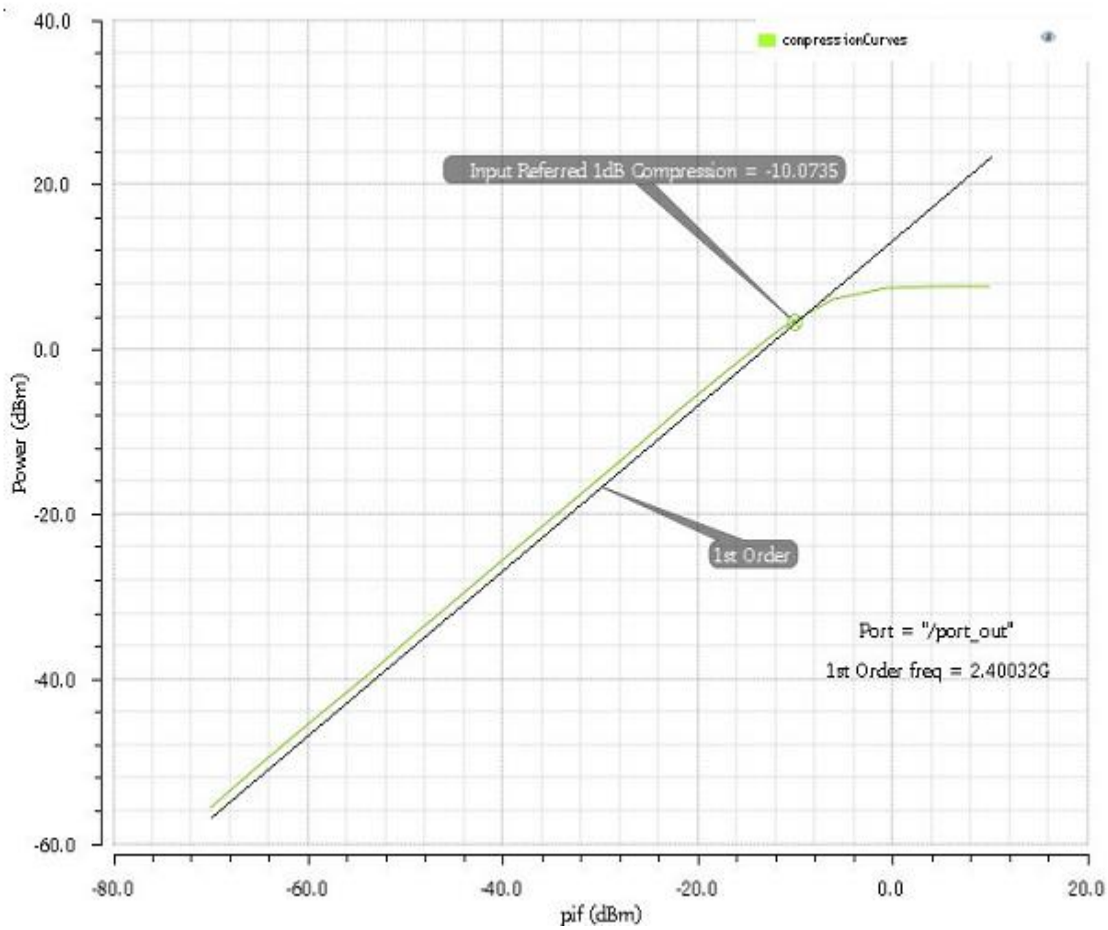

Figure 5.6 1 dB Compression point.

5.4.5 Third order Intermodulation Distortion (IMD) and Intercept Point

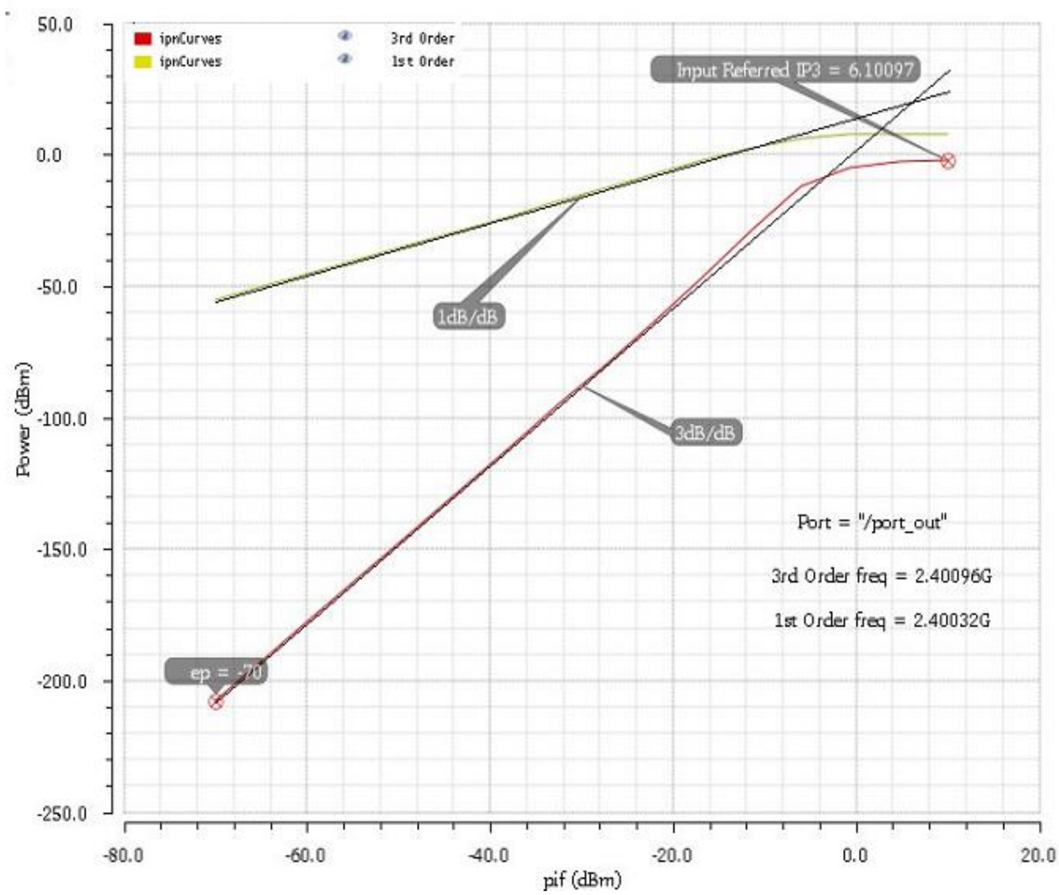

Figure 5.7 Third order Intermodulation distortion **(**IMD) and intercept point.

5.5. Layout of the Gilbert Up-Conversion Mixer Design

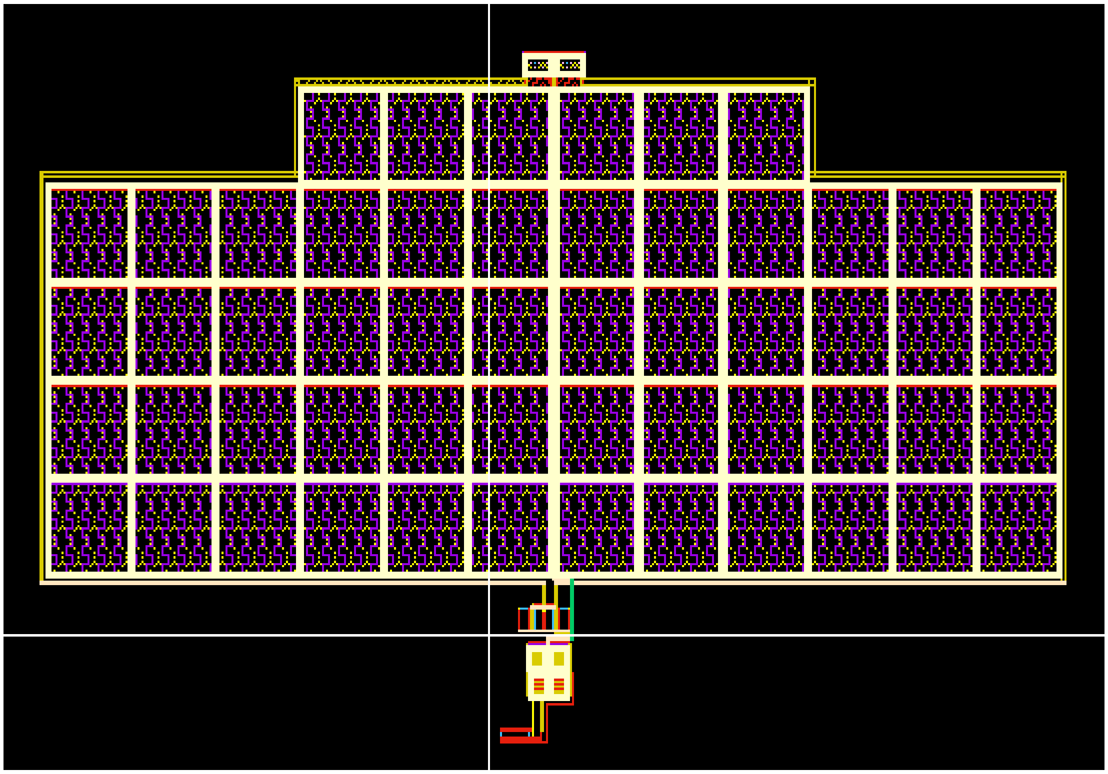

Figure 5.8 Layout of the Gilbert Up-Conversion mixer

CHAPTER 6

Class E Power Amplifier

6.1 Power Amplifier Basic

The RF power amplifier (PA), which is a critical element in a transmitter system, is expected to provide a suitable output power at a very good gain with high efficiency and linearity. The output power of a PA must be sufficient to get a reliable transmission. High gain reduces the number of amplifier stages required to deliver the desired output power and hence reduces the size and manufacturing cost. In another side, thermal management, battery lifetime and operational costs are improved by high efficiency. Also, good linearity is necessary for bandwidth efficient modulation [16]. All these requirements make a tradeoff and an optimization is needed for a typical power amplifier design. Power amplifiers show variation in terms of linearity, output power or efficiency. Some parameters are important to quantify an amplifier's performance. These can be listed as power gain, power output capability, power added efficiency (PAE), 1-dB compression point, intermodulation distortion (IMD), Adjacent Channel Power Ratio (ACPR), and intercept point.

6.2 Class E power Amplifier with finite DC-feed Inductance

The class-E PA is an exchanging mode amplifier which could give 100% efficiency under ideal condition. At low frequencies, an MOS transistor could model as perfect switch. Above this range of frequency, both transistor's exchanging time and the device parasitics become vital; this results in the reduction of efficiency of the amplifier. Nonetheless, the current and the voltage waveforms of a class-E PA are to such an extent that even a transistor with slow changing features prompts great execution. Also, when carefully model and fabricate, the class-E PA has high efficiency than others (class A, B or C), in this way suggesting it for ambulatory applications. We exhibit design formula demonstrating the connection between the information parameters and the circuit component estimations of the limited dc sustain inductance Class-E PA. It is conventional that utilizing limited dc feed inductance rather than an RF-choke in a Class-E PA has huge advantages, including [17]:

- A decrease in comprehensive size and cost.

- A higher load resistance, which ordinarily brings about a more proficient yield matching system [19].

- A conceivable reduction in the required supply voltage, which may empower the usage of the Class-E PA in low-voltage advancements.

- Larger switch parallel capacitor for a similar supply voltage, yield power, and load. This allows a higher recurrence of operation.

Further advantage of Class E amplifier using finite DC feed inductance are used in an envelope elimination and restoration (EER) system [18].
As an application for the utilization of the summed up Class-E design conditions, we likewise demonstrate the product of power and frequency (ω · POUT) can be advanced which, for low voltage operation, prompts a non-common Class-E outline.

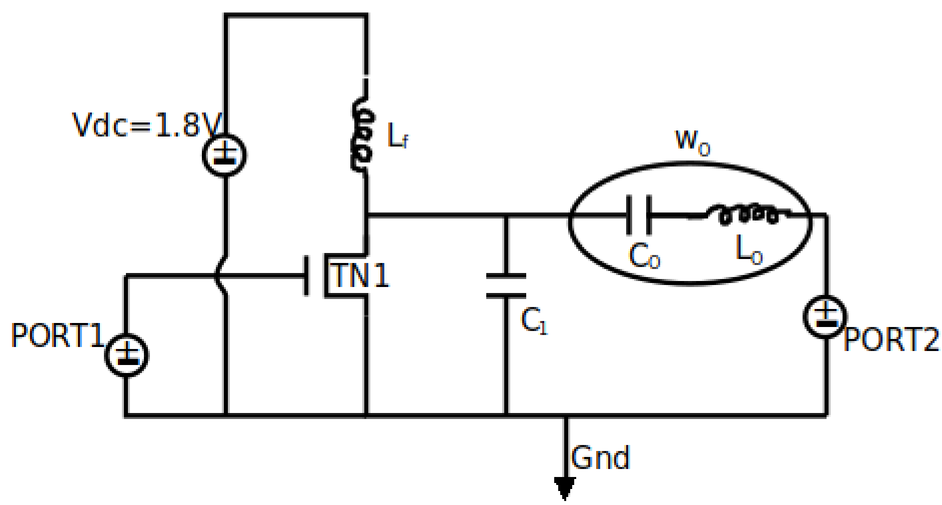

Figure 6.1 Class E power amplifier with finite DC- feed inductanceL_f.

The Class E Power can operate with a finite dc- feed inductance L_f in place of RF Choke as shown in Figure 6.1. The output Network if formed by a parallel-series resonant circuit. The inductance L_f and the shunt capacitor C_1 make a parallel resonant circuit other series inductance L_o and Capacitor C_o form a series resonant circuit and there designs are depend at operating frequency. Above circuit are easier to implement due to the dc-feed inductance is small. A small dc-feed inductance has lower loss because of the smaller equivalent series resistance. In addition, if the amplifier is used as a radio transmitter with AM or any envelope modulation, it is easier to reduce distortion. As $w_o L_f / R_{dc}$ decrease, $w_o C_1 R$ and $P_0 R / V_i^2$ increase, and $w_o L_b R$ decreases as shown in Table 6.1. The operating frequency can be using a relation $w_o = 1/\sqrt{L_o C_o}$ and loading quality factor expressed as

$$Q_L = \frac{w_o L}{R} = \frac{1}{w_o C_o R} \tag{6.1}$$

Table 6.1 Parameters of class E amplifier with finite DC-feed.

$w_o L_f / R_{dc}$	$w_o L_f$/R	$w_o C_1$R	$w_o L_b$/R	RP_o / V_i^2
∞	∞	0.1836	1.152	0.5768
1000	574.40	0.1839	1.151	0.5774
500	289.05	0.1843	1.150	0.5781
200	116.02	0.1852	1.147	0.5801
100	58.340	0.1867	1.141	0.5834
50	29.505	0.1899	1.130	0.5901
20	12.212	0.1999	1.096	0.6106
15	9.3405	0.2056	1.077	0.6227
10	6.4700	0.2175	1.039	0.6470
5	3.6315	0.2573	0.9251	0.7263
3	2.5383	0.3201	0.7726	0.8461
2	2.0260	0.4142	0.5809	1.0130
1	1.3630	0.6839	0.0007	1.3630
0.9992	0.7320	0.6850	0.000	1.3650

6.3 Simulation Results

6.3.1 Output power verse Input Power

An amplifier's gain can be described as voltage gain, current gain, or power gain. The power amplifier is generally defined as its power gain. If magnitude of the output signal is shown as P_0 and input signal is shown as P_i, the gain will be their ratio as shown below.

$$G = \frac{P_o}{P_i} \tag{6.2}$$

The most important parameter of power amplifier is output power. The output capability factor is defined as the output power produced by 1V and 1A on the collector of a transistor. After the actual voltage and current values of the collector are obtained, the product of these values gives the maximum output power of the amplifier. For the given Figure 6.2, when the input power level is 12 dBm, the output power level is close to 9 dBm. Thus, 12 dBm is assumed to be the normal operating condition for the power amplifier.

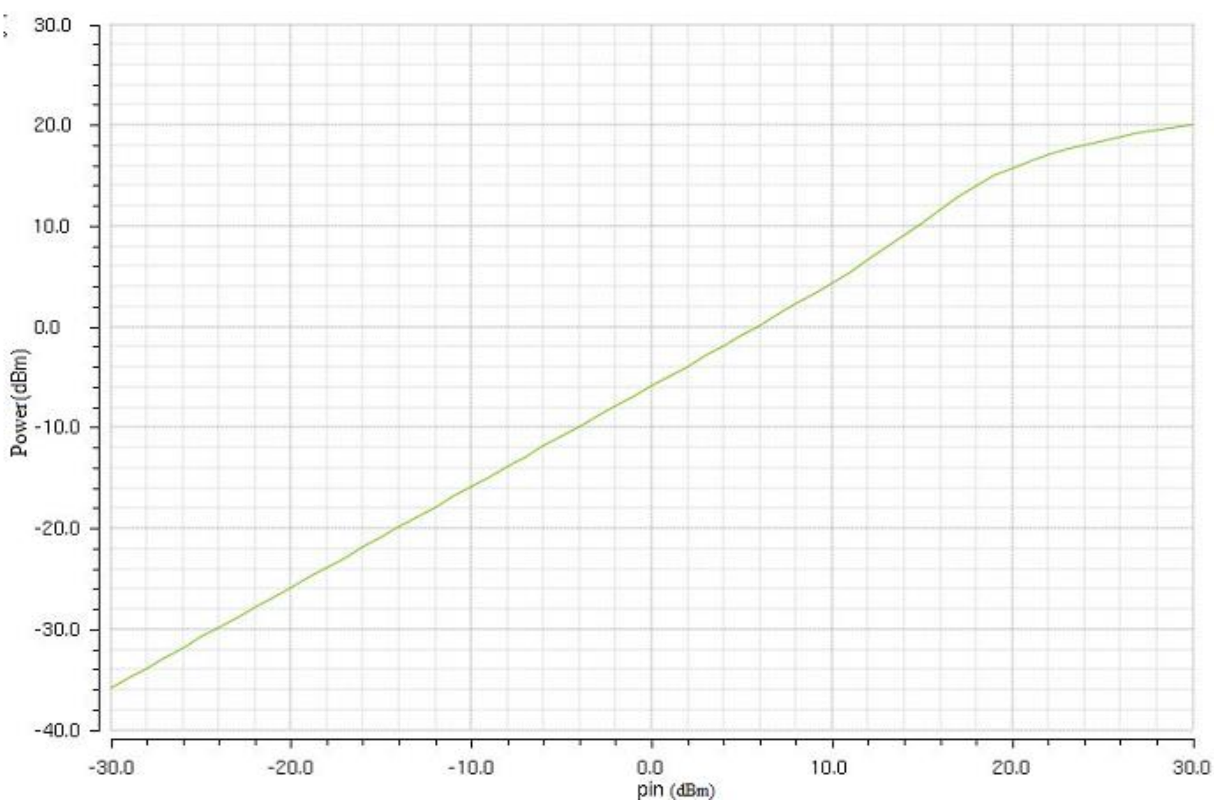

Figure 6.2 Output power verse Input Power

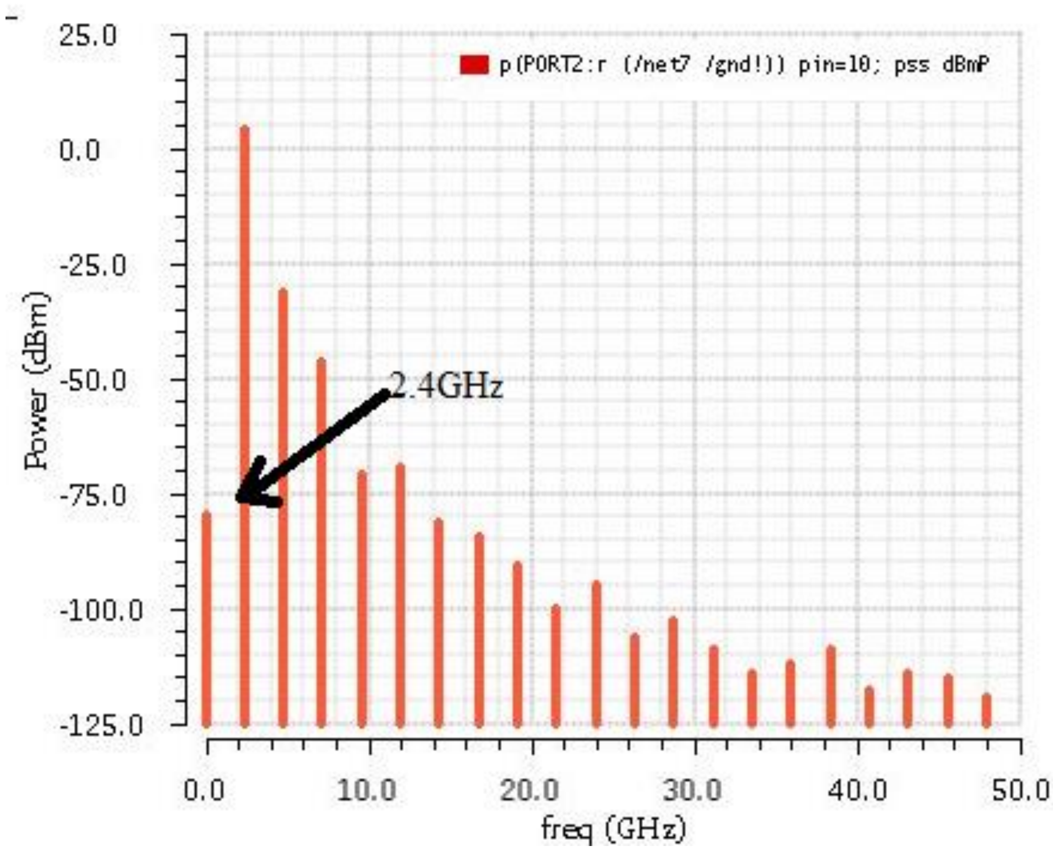

Figure 6.3 Output power spectrum

6.3.2 1 dB Compression Point for Class E Power Amplifier

The linear region of an amplifier means a constant gain for a given frequency. In the actual behaviour of an amplifier, this linear region ends at a specific frequency. This means, after this frequency, increasing the input signal does not guarantee that the output increase. The input 1dB compression point is defined as the power level for which the input signal is amplified 1 dB less than the linear gain as shown in figure 6.4. 1dB compression point can be shown as input or output referred. The gain decreases rapidly after this 1dB compression point. After this point, the amplifier operates in the nonlinear region. This means the 1dB compression point is a measure of the linear range of operation.

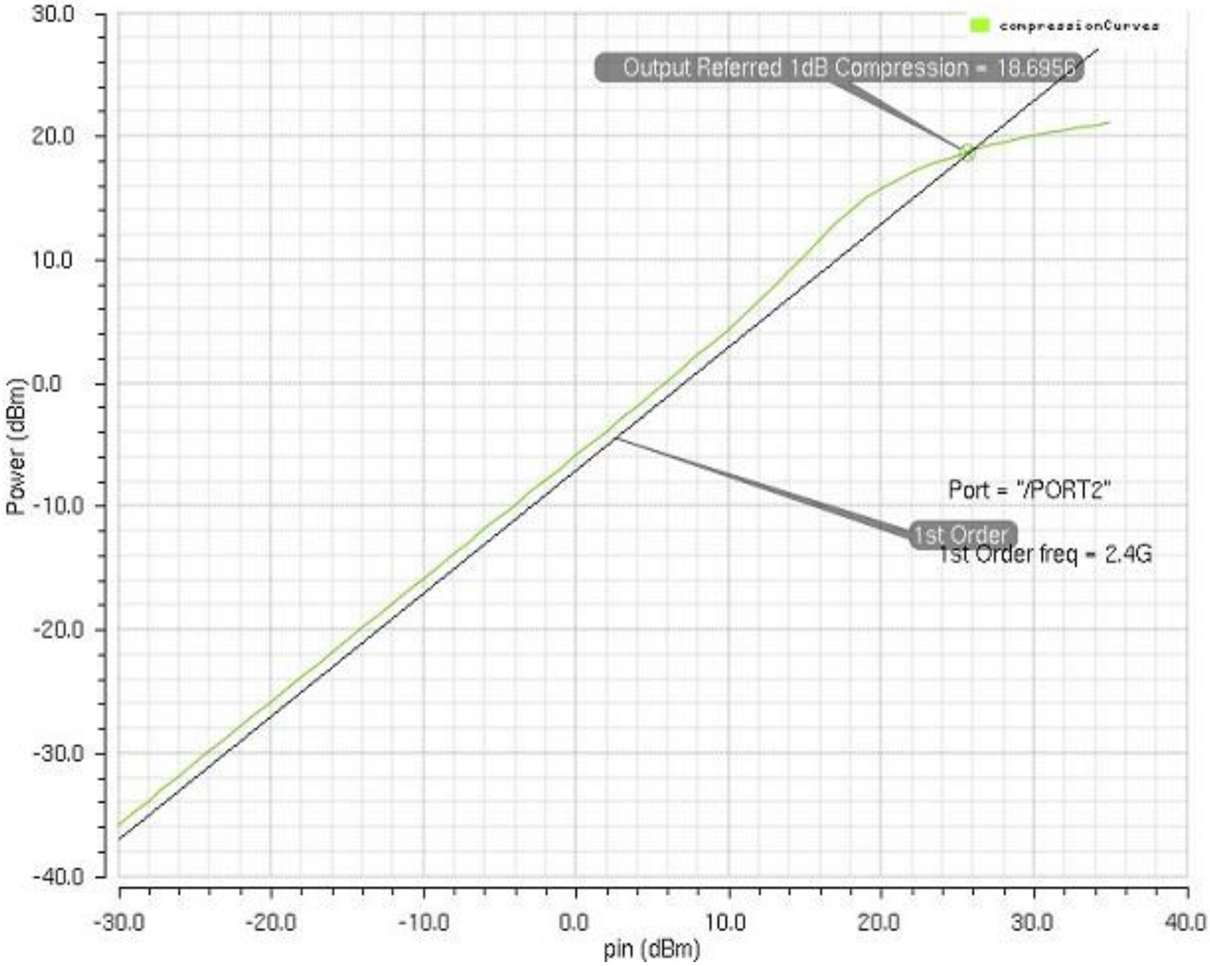

Figure 6.4 1 dB Compression point.

6.3.2 Third order Intermodulation Distortion (IMD) and Intercept Point simulations.

The linear combinations of the fundamental frequency and all harmonics present in the input signal compose a nonlinear distortion. Intermodulation distortion is characterized by this distortion [16]. If $f_1$and f_2 are the fundamental frequencies, then the intermodulation products are seen at frequencies given by

$$f_{IMD} = m_{f1} \pm n_{f2} \tag{6.3}$$

Where m and n are integers from 1 to ∞.

Intermodulation is specified by the ratio of power in the intermodulation product to the power in the fundamental frequencies. The third order intermodulation products ($2f_1 - f_2$ and $2f_2 - f_1$) are typically the most critical ones because they are the closest products to the fundamentals and it is difficult to filter them out from the desired pass band.

In the logarithmic input-output power curve, the fundamental frequency and intermodulation frequency behaviours of an amplifier can be shown together. The slopes of these two curves intercept on a point which is defined as the intercept point. At this point, fundamental and intermodulation products have equal amplitude at the output of a linear circuit. But practically, these amplitudes start decreasing before this point. As a result, the third order intercept point (IP3) is defined as an intercept point of linear extrapolation of the output behaviours for small input amplitude. In the Figure 6.5 is a simulation graph which gives the information about third order intermodulation distortion (IMD) and intercept**.** At 3rd order output intercept point (OIP3) and At 3rd order input intercept point (IIP3) is 26dBm and 32dBm respectively.

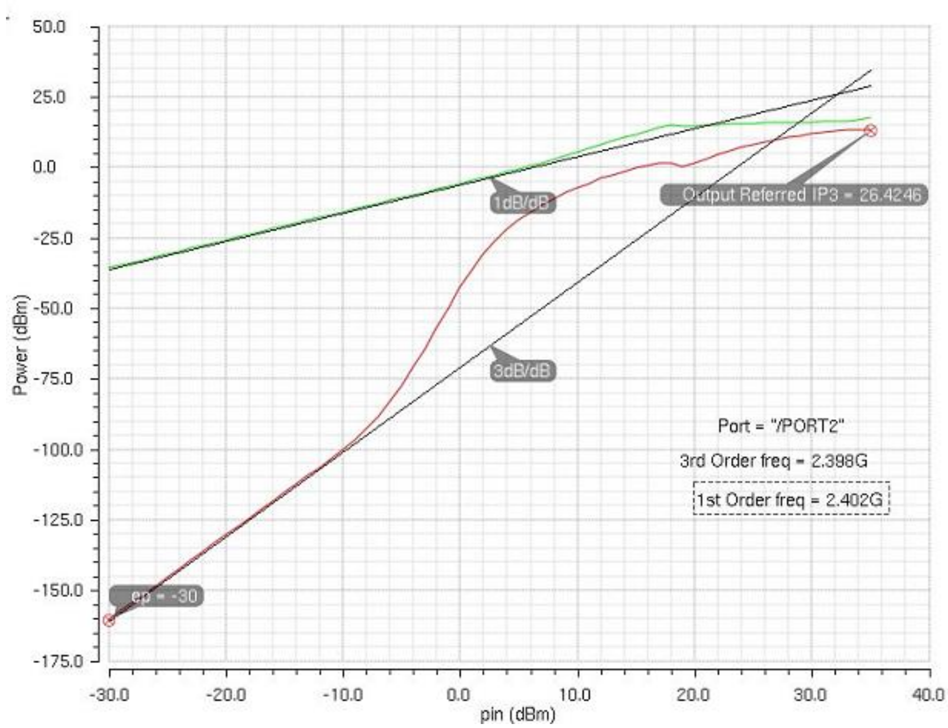

Figure 6.5 Third order Intermodulation Distortion (IMD) and Intercept Point

CHAPTER 7

Conclusions and Future Scope

7.1 Conclusion

In the recent years, the wireless sensor network market has grown rapidly and this growth in wireless sensor based semiconductor industries is attributed to its extensive use in IoT. Bluetooth system is one of the main wireless communication medium which can be used as a bridge between wireless sensor node and users. Bluetooth is widely used for low-power wireless communication in applications where data transfer is required within a small radius, typically less than 10 meters. In this system, the data is be collected from wireless sensor node and transferred to user's smartphone. Bluetooth system can be installed very easily at any remote location along with the wireless sensor nodes and can operate with very small power supply or an On-board battery.

This thesis has highlighted this aspect of the Bluetooth transmitter. Also, various passive circuits have been developed under Bluetooth transmitter chain to minimize the size and implementation cost as well as to maximize the application for wireless sensor nodes.

Tape out of Bluetooth transmitter upto DAC has been done along with PhD scholar Mr. Gaurav Singh and if we add Filter, up-conversion Mixer and Power amplifier with GFSK and DAC then standalone Bluetooth transmitter can be design.

7.2 Future scope

As of 2012, 8.7 billion IoT wireless devices are connected. Expected to grow to 50.1 billion IoT wireless devices by 2020 [19]. For these wireless devices, energy harvesting is the only solution to meet power requirements. Energy harvesting is a method, in which unharnessed energy collect from the surrounding environment and storing it. When sufficient energy has been store, a wireless sensor node can perform tasks such as collecting data and transmitting it over Bluetooth to the smartphone or another device.

Further intensive research in the development of Bluetooth system can be performed to reduce further its size and power consumption and energy harvesting circuits for its operation.

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