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Design of a Novel 2.4GHz RF Transmitter

Dhruthi Tejaswi [a], Samudrala Vinay [a], Vidyuth Sriram [a], Ananda M [b,1,*], Dr. Kalpana A.B [c]

[a] ECE, PES University, Electronic city, Bengaluru, 560100, India
[b] PES University, Electronic city, Bengaluru, 560100, India
[c] Bangalore Institute of Technology, Bengaluru, India
[1] anandam@pes.edu
* corresponding author

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ABSTRACT

The world of Wireless Technology has been improving consistently due to its high speed and reliability. Some of the demands that need to be fulfilled include larger network capacity, improved data rates and so on. This paper focuses on the design and simulation of the Transmitter, which is a key component in an RF Transceiver Module. It is built by cascading an Up Conversion Mixer, a Bandpass Filter and a Power Amplifier as its most fundamental units. The Cadence Virtuoso Tool was used to construct this Transmitter block in 180nm node technology. The IF signal to the Mixer is 100 MHz and the LO signal is 2.3GHz. The 2.4GHz amplified RF output is taken from the Power Amplifier. A 1dB compression point of -25.91 dBm and an IIP3 of 10.14 dBm is observed for the proposed design. Future work involves testing its integrity with an RF Receiver module that has appropriate modulation schemes in place and converting it into a physical layout-based IC.

1. Introduction

In today's ever-growing field of electronics the main aim is to work towards reducing costs which is the primary reason for the vast popularity of Wireless Technology in Communication Systems. Encountering multiple trade-offs while designing RF systems is inevitable in order to improve the system performance [2]. Recent trends focus on building Radio Frequency(RF) Transmitters that cater to the MU-MIMO domain which are spectrally efficient in design and are cost effective. The Transmitter module shown in Figure 1 involves meticulous design of its sub blocks where each of them focus on one key parameter that dictates the overall performance of the system.

In this work the Tx system includes the extensive analysis and optimization of the Up Conversion Mixer which aims to have a linear output and a good conversion gain, the Power amplifier which provides high PAE and higher output power as a result of reduced voltage swing [16], along with a Bandpass Filter to filter out the harmonics. The overall design of the transmitter involves cascading the aforementioned blocks to get a clean and amplified 2.4GHz RF signal at the output, with a presentable 1-dB Compression point and inter-harmonic distortion.

The structure of the paper is as follows. Section 1 gives an introduction to the world of RF Technology and its applications. Section 2 gives a detailed overview of the design methodology of the various blocks. It begins with the Power Amplifier design, followed by the Up Conversion Mixer design and the Bandpass Filter. This section also includes the final integration of the blocks. Section 3 focuses on the various results that describes the proposed system. It begins with the transient analysis and ends with the harmonic based IIP-3 results. Finally, Section 4 covers the notable conclusions, the comparison table of existing literatures and the future work.

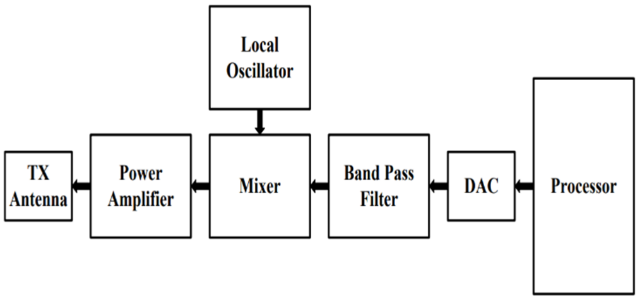

Figure 1. A simplified block diagram of an RF Transmitter Module

2. System Design

To be able to design and implement a 2.4GHz RF Transmitter system, the following sub-blocks need to be realized. Although a fully functional Transmitter requires other supporting modules in place (like DAC, Transceiver ICs and the antennae), this paper will focus only on the most fundamental parts of the system.

2.1. Design of Power Amplifier

There are various parameters based on which the performance of a Power Amplifier can be judged [1]. The most prevalent ones being high operating frequency and high power added efficiency (PAE). In order to meet these demands, the Class E power amplifier is an apt choice since it has the ability to theoretically provide a 100% efficiency and performs well at high frequency which makes them well suited for systems employing constant modulation schemes like FSK or FM due to their poor linearity. A CMOS PA fulfills all the requirements of wireless applications such as low power consumption, long battery life and good efficiency [25].

A Class E power amplifier is also called a switching amplifier because the output transistor behaves like a switch ideally toggling between the cutoff region and the saturation region. This leads to the drain current and voltage waveforms overlapping as less as possible and the transition times between the on and off states reduced significantly [2]. The other reason for using a Power Amplifier in a transmitter block is to obtain a higher output power as a result of reduced voltage swing [16]. Figure 2 shows a basic Class E Amplifier design. As mentioned before, the switch-like operation of the transistor gives rise to a non-sinusoidal output waveform. Due to the abrupt switching on and off of the power amplifier the output waveform we obtain is a square wave [3]. This implies that we need wave shaping circuits or harmonic circuits at the output to get a pure RF tone at 2.4GHz.

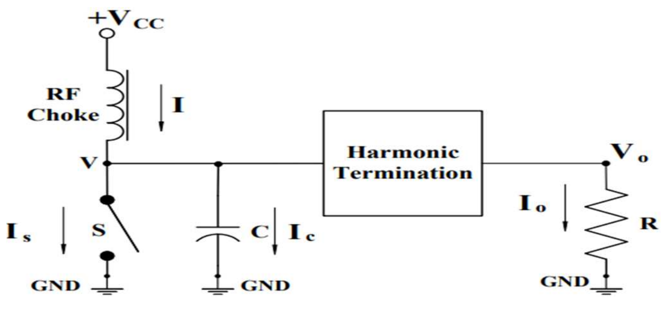

Figure 2. Basic Switching (Class E) Amplifier

The proposed design of the class E amplifier in our paper is shown in Figure 3. All the parameter values are mentioned in Table 1. Here L1 and L0 are used as DC Feed inductors. L2, C2 and C3 are used for harmonic terminations [4] that will waveshape the drain current and drain voltage of the transistor M1. The transistor M2 is used as a pre-driver. The W/L ratios are parametrically obtained for the highest PAE.

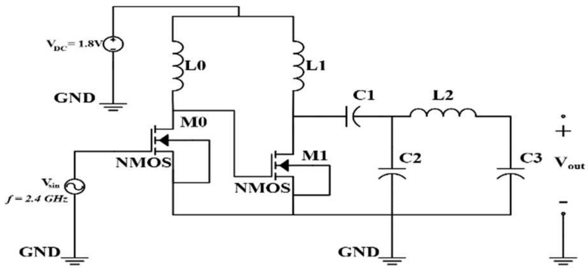

Figure 3. Proposed Class E Amplifier

Table 1. Class E PA Instance Values

Instances	Values
V_{DC}	1.8 V
Vsin	500 mV @ 2.4 GHz
M0	Aspect Ratio(w/l) = 20 / 0.18 μm
M1	Aspect Ratio = 150 / 0.18 μm
C1	1 pF
C2	515.5 fF
C3	1.6 pF
L0	9.2 nH
L1	3.3 nH
L3	3.3002 nH

2.2. Design of Up Conversion Mixer

In a regular up conversion mixer, the output is obtained by multiplying the local oscillator signal with the input intermediate frequency signal. This process plays an important role in the translation of the baseband IF signal to the high frequency RF signal. The design of the up-conversion mixer is of utmost importance in a high-performance RF Transceiver system [5].

There are different types of active mixers available but the Gilbert Cell is the most frequently used. This is due to the good Conversion Gain and the ports being isolated from each other to remove the DC offset issue [6]. A basic schematic of a Gilbert cell is shown in Figure 4 [9]. In Double Balanced Mixers Cross Coupling of transistors is a technique that is frequently used to increase the differential gain at the output. This leads to accurate matching of the LO signal with the input port IF signal as well as proper coupling of the RF signal at the output port [17]. The current mirror topology that has been used in this design is highly linear and it does not depend on the bias current unlike a conventional Gilbert cell Mixer. [7][8].

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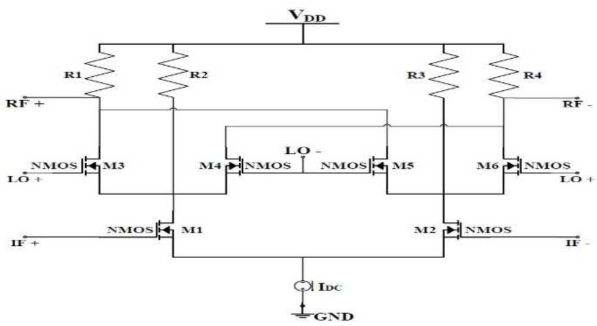

Figure 4. Gilbert Cell Schematic

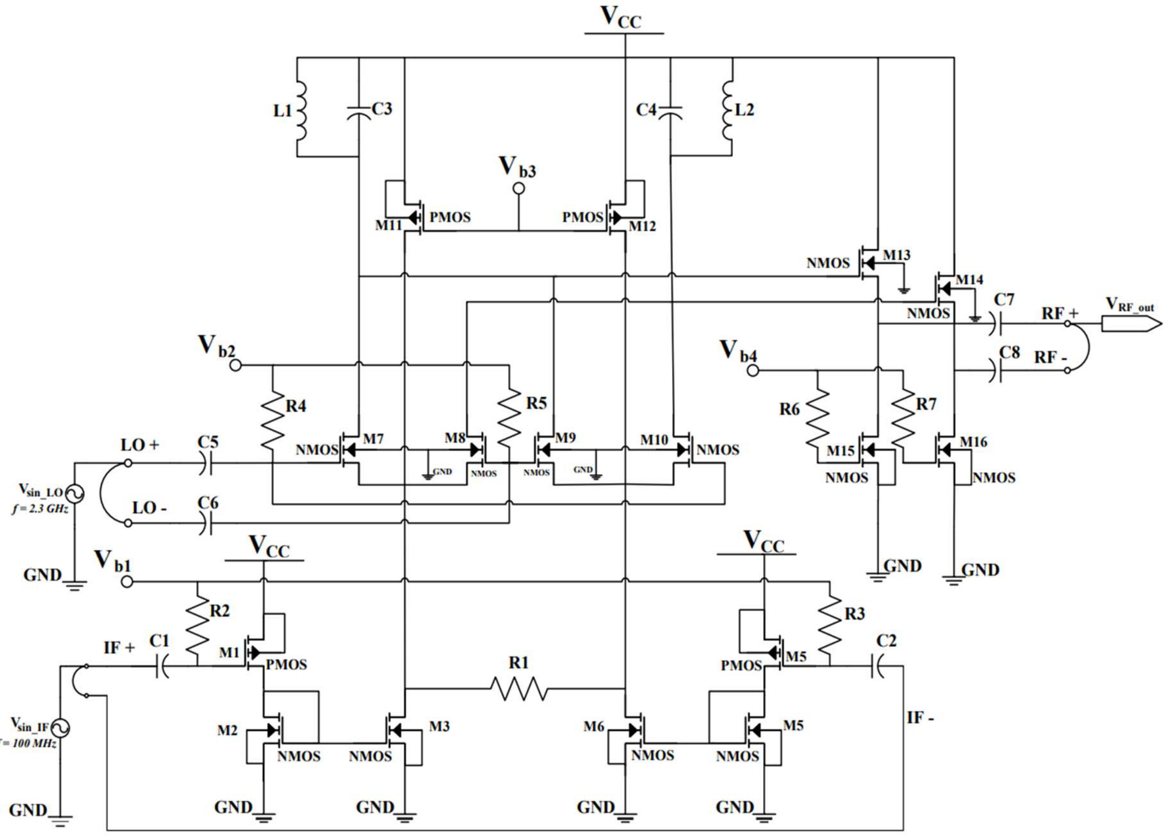

Figure 5. Proposed Up Conversion Mixer Schematic

Current bleeding can be of two distinct types- Static and Dynamic current bleeding. These are used mainly with the purpose of reducing the direct flicker noise [10]. A current bleeding network consists of two PMOS transistors and this allows DC current to flow into the driver stage. The switching pair transistors provide low input impedance which is obtained parallel to the high output impedance of the pair of PMOS transistors. This makes sure that the IF signal takes the switching pair path [7]. A square wave has characteristic fast switching and this is synonymous with the high gain of the mixer topology. The current bleeding technique used in the proposed up-conversion mixer ensures that the current flowing switching transistors and the load is maintained at the same value while the current flowing through the transconductance stage increases. Since the IIP3 is proportional to the biasing current, this leads to improved linearity [18].

In this work, a 2.4GHz RF signal is required as the mixer output. Here, we take an LO signal of 2.3GHz and an IF baseband signal of 100MHz to produce a sum frequency of 2.4GHz. Keeping all the previously discussed theory in mind, the topology used is a Gilbert Cell- Current mirror mixer with Current Bleeding technology. The schematic of the same, is shown in Figure 5. The component values are listed in Table 2. This design lends itself nicely towards the On-Off Shift

Keying(OOK) modulation scheme by switching the LO on and off using the encoded bits.

Table 2. Up-Conversion Mixer Instance Values

Instances	Values	Instances	Values
VCC	1.8 V	M1, M2	Aspect Ratio(w / l) = 40 / 0.18 µm
Vsin_LO	2 V @ 2.3 GHz	M4, M5	Aspect Ratio = 40 / 0.18 µm
Vsin_IF	500 mV @ 100 MHz	M3, M6	Aspect Ratio = 300 / 0.18 µm
Vb1	-1 V	M7, M8	Aspect Ratio = 80 / 0.18 µm
Vb2	+1 V	M9, M10	Aspect Ratio = 80 / 0.18 µm
Vb3	-1 V	M11, M12	Aspect Ratio = 160 / 0.18 µm
Vb4	+1 V	M13, M14	Aspect Ratio = 200 / 0.18 µm
L1, L2	2.4 nH	M15, M16	Aspect Ratio = 100 / 0.18 µm
R1	5 kΩ	C1, C2	4.6 pF
R2, R3	15 kΩ	C3, C4	1.5 pF
R4, R5	10 kΩ	C5, C6	4.8 pF
R6, R7	15 kΩ	C7, C8	6.8 pF

2.3. Bandpass Filter Design

The use of a filter in wireless applications is imperative especially in LTE communication. Within the various filters that are used in communication technologies such as lowpass filter, high pass filter, etc., the filter of interest in this work is a bandpass filter [12]. The main function of this filter is to pass a specific range of frequencies and to reject all the unwanted frequencies.

Table 3. Chebyshev Bandpass Filter Specifications

Parameter	Specifications
Passband frequencies	2.35GHz to 2.45GHz
Stopband frequencies	2.2GHz to 2.5GHz
Passband attenuation	3dB
Stopband attenuation	40dB
Passband ripple	0.1dB
Order	4

In this work, the BPF is used after the up-conversion mixer in order to pass only the 2.4GHz band of frequencies to the Power Amplifier. Table 3 shows the specifications for the Chebyshev Bandpass Filter.

The proposed design is an Order 4 Chebyshev BPF. The design parameters are based on the following fundamental formulae [13].

$$L_k' = \frac{L_k}{\Delta\omega_0} \quad (1)$$

$$C_k' = \frac{\Delta}{\omega_0 L_k} \quad (2)$$

$$L_k' = \frac{\Delta}{\omega_0 C_k} \quad (3)$$

$$C_k' = \frac{C_k}{\Delta\omega_0} \quad (4)$$

$$\Delta = \frac{\omega_2 - \omega_1}{\omega_0} \quad (5)$$

$$\omega_0 = \sqrt{\omega_2 \omega_1} \quad (6)$$

Equations (1) and (2) are for series inductor and capacitor values and in similar terms equations (3) and (4) are for shunt inductor and capacitor values. The final design is shown in Figure 6.

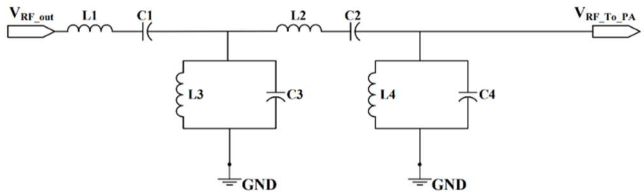

Figure 6. Proposed Bandpass Filter Schematic

There is another Bandpass Filter that is added, but its purpose is to reject any unwanted harmonics. It is a simple resonator at 2.4GHz, intended for use after the Power Amplifier with inductor value of 4.39nH and capacitor value of 1pF.

Table 4. Proposed Bandpass Filter Instance Values

Instances	Parameters
VRF_out	Signal from Mixer
VRF_To_PA	Signal to the Power Amplifier
L1	44.137 nH
L2	70.473 nH
L3	211.8 pH
L4	338 pH
C1	99 fF
C2	62.5 fF
C3	20.798 pF
C4	13.026 pF

2.4. Final Transmitter Design

The RF Transmitter is constructed by integrating three main building blocks: the Up conversion Mixer, the PA and the Bandpass Filter [15]. Recently, switching amplifiers are the most widely used amplifiers for efficient transmission of RF signals. This has led to constant improvements in the design of amplifier topologies like Class D, Inverse Class D and Class E [14]. Similar improvements were also done in mixer topologies which improved key parameters like noise figure and conversion gain. The bandpass filter is used to reject the difference, out of band frequency provided by the mixer. Some of the crucial advantages of using silicon CMOS technology is its ability to be merged with RF as well as mixed signal networks that use MOS technology. This integration can take place on a single chip at a low cost along with the required digital and analog functions which makes CMOS Transmitters a promising solution for modern wireless systems [19]. Figure 7 shows a basic block diagram of the transmitter.

In this paper, the choice of Power Amplifier is Class E configuration, owing to its high PAE. However, this design is highly non-linear and hence to strike a balance in the overall transmitter circuit, a linear mixer topology is adopted. The entire transmitter is put together by cascading the previously designed blocks. There are two main types of transmitter architectures: Direct Conversion and Dual Conversion. The proposed transmitter is based on the Direct conversion architecture as it allows high levels of integration and low power consumption. An RF transmitter is required to have a high output power in order to realize a good PAPR [24].

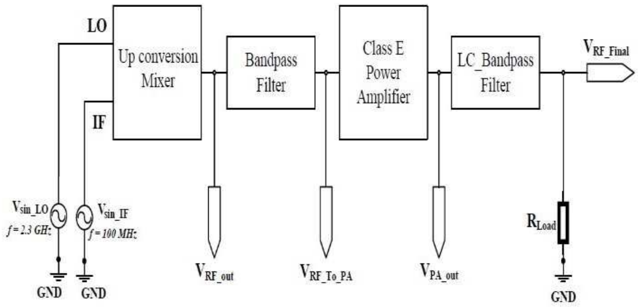

Figure 7. Block Diagram Schematic of Proposed Transmitter

3. Results Of The Proposed Design

This section focuses on the various results obtained after running the time based and frequency analyses. All the simulations are performed using the ADE utility in Cadence Virtuoso and the results are derived from the same.

3.1. Power Amplifier Results

The proposed Class E Amplifier is aimed at achieving a high Power Added Efficiency. The results are consolidated in Table 4.

Table 4. Proposed Class E Power Amplifier Results

Parameter	Value
Process Technology	180 nm
Supply Voltage	1.8V
Power Added Efficiency	62.77%
Power Output (0.5V input)	135 mW

The transient waveforms of the proposed PA is shown in Figure 8.

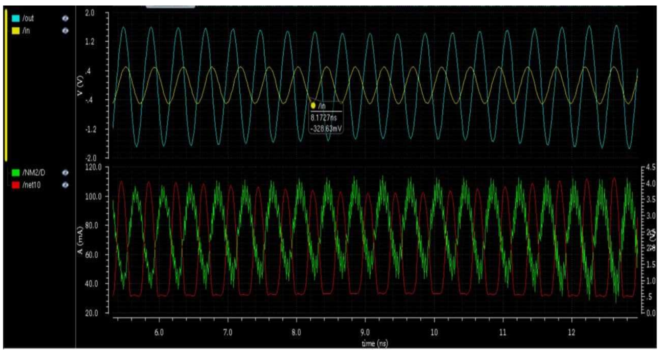

Figure 8. Transient Response of the proposed Power Amplifier

3.2. Up Conversion Mixer Results

The proposed design of the Up Conversion mixer is optimized to get an RF signal of 2.4GHz with a good conversion gain. Also, the design seeks to have an improved linearity to balance the non-linearity presented by the class E PA. The results of the same are shown in Table 5. The transient response of the proposed Up Conversion Mixer is shown in Figure 9.

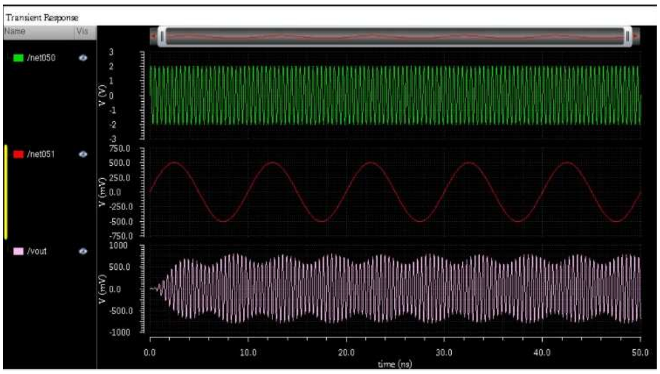

Figure 9. Transient Response of the proposed Up Conversion Mixer

Table 5. Proposed Up Conversion Mixer Results

Parameter	**Value**
Process Technology	180 nm
LO Frequency	2.3 GHz
LO Power	2.07 dBm
Conversion Gain	9.45 dB
IIP3	7.52 dBm
Noise Figure	39 dB

3.3. Bandpass Filter Results

The proposed bandpass filter is designed for passband frequencies centered around 2.4GHz. This illustrated in Figure 10 by the S21 Gain of the filter, when subjected to S-Parameter analysis.

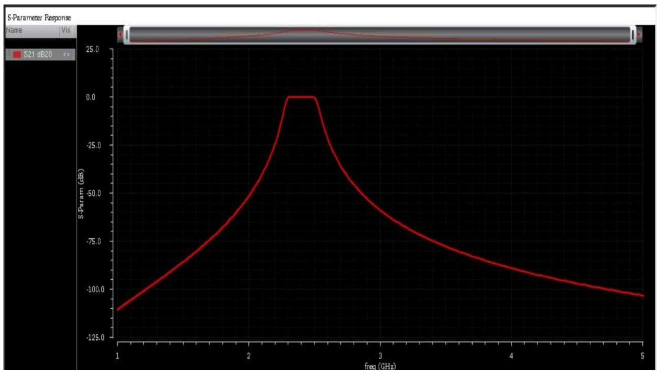

Figure 10. Gain Response of the proposed BPF

3.4. Proposed Transmitter Results

The final transmitter is an integration of the previously designed blocks. The TX was subjected to Transient and Frequency based analyses, each of which are displayed in the following figures. Figure 11 shows the Transient waveforms, tapped after each of the blocks in the design. As evident from the figure, the input signal is first translated to the RF Frequency range by the mixer (waveform 1), then filtered to a clean 2.4GHz signal by the BPF (waveform 2), followed by an amplification by the PA (waveform 3), and finally filtered by a resonator (waveform 4).

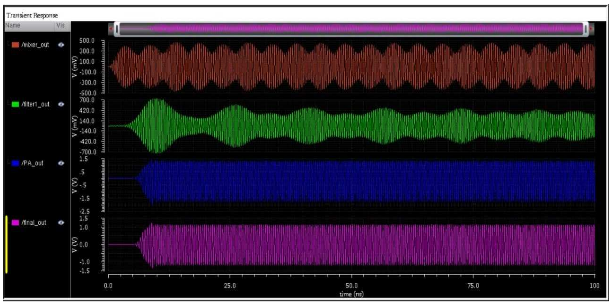

Figure 11. Transient Response of the proposed Transmitter

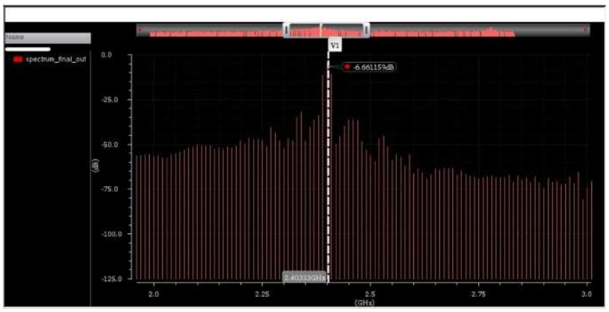

Figure 12. Spectrum Response of the proposed Transmitter

Figure 12 shows the spectrum of the final output. Here the transient signal taken from the final output pin is frequency tested by using an in-built FFT calculator in Cadence. The observed signal has a spectrum peak at 2.4GHz.

The proposed design was subjected to Periodic Steady State Analysis for extracting the frequency-based parameters of 1-dB Compression point and IIP3. Figure 13 shows a 1-dB Compression point of -25.916 dBm and Figure 14 shows an IIP-3 10.138 dBm.

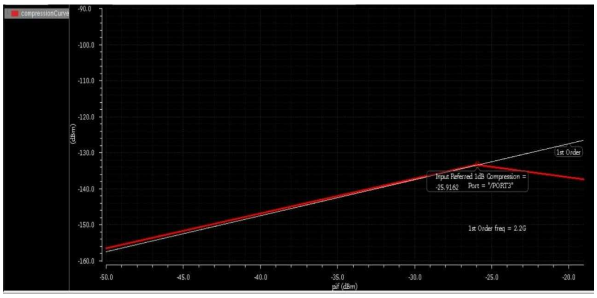

Figure 13. 1-dB Compression Curve of the proposed Transmitter

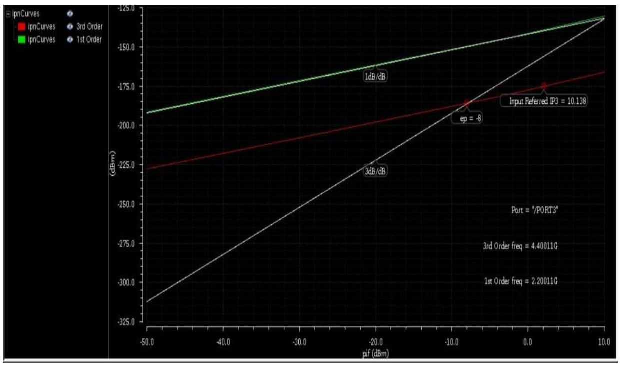

Figure 14. IIP3 Curve of the proposed Transmitter

4. Conclusion

A wireless communication system requires an RF Transmitter in order to convert the analog input signals into digital baseband signals. This determines how reliable the signal that is being transmitted is and also the overall performance of the communication system [24].

The proposed transmitter is designed for the S-band frequency of 2.4GHz at 180nm technology which is suited for wireless applications. The fundamental blocks are individually designed and each of them focuses on one key parameter. For the Class E Power Amplifier, a PAE of 62.7% is obtained and for the Up Conversion Mixer a Conversion Gain of 9.45dBm is observed. The Bandpass Filter is centered around 2.4GHz which yields a clean RF Signal at the design frequency. Finally, the individual blocks are integrated to form the proposed RF Transmitter which has an 1-dB Compression point of -25.91 dBm, Power Output of 10.8 dBm, and an IIP3 of 10.138 dBm.

The future work for this project will include the layout conversion, layout simulation, area and power consumption analyses and design of secondary blocks such as DAC and Antenna for the Transmitter.

Table 6. Comparison Table for The Proposed Transmitter

Reference	[20] 2015	[21] 2016	[22] 2019	[23] 2017	This Work 2021
Process Technology (nm)	65	130	180	130	180
Frequency (GHz)	240	240	4.02	190	2.4
Proposed Modulation	QPSK/BPSK	-	-	OOK	OOK
Power Output (dBm)	0	-4.4	12.0	-6	10.8
1-dB Compression Point (dBm)	-	-25	3.24	-	-25.91

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