Design of GaN based RF Power Amplifiers for Space Application

Major Project

Submitted in partial fulfillment of the requirements

for degree of

Master of Technology

in

Electronics and Communication Engineering

(Communication Engineering)

By

Abhishek J. Pandya
(12MECC38)

ELECTRONICS AND COMMUNICATION ENGINEERING BRANCH

ELECTRICAL ENGINEERING DEPARTMENT

INSTITUTE OF TECHNOLOGY

NIRMA UNIVERSITY

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Declaration

This is to certify that

I) The thesis comprises my original work towards the degree of Master of Technology in Electronics and Communication Engineering (**COMMUNICATION**) at Nirma University and has not been submitted elsewhere for Degree.

II) Due Acknowledgment has been made in the text to all other material used.

Abhishek J. Pandya
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SAC- ISRO

Certificate

This to certify that Mr. **Abhishek Jayprakash Pandya** (12MECC38), a student of M.Tech EC (Communication), Institute of Technology, Nirma University was working in SAC-ISRO since 26^{th}June,2013 and carried out his thesis work titled **"Design of GaN based RF Power Amplifiers for Space Application"**. He was working in SNPA/RFSG/AD under supervision of **Mr P S Bharadhwaj**, Sci/Eng-G and **Mr A H Bhatt**, Sci/Eng-SG. He has successfully completed the assigned work and is allowed to submit his dissertation report. We wish him all the success in future.

Authorised Signatory

Date:
Place:

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Certificate

This is to certify that the Major Project entitled **“Design of GaN based RF Power Amplifiers for Space Application”** submitted by **Mr. Abhishek J. Pandya (Roll No: 12MECC38)**, towards the partial fulfillment of the requirement for Semester-IV of the Degree of Master of Technology in Electronics and Communication Engineering (**COMMUNICATION**) of Institute of Technology, Nirma University, Ahmedabad is the record of work carried out by him under my supervision and guidance. In my opinion, the submitted work has reached a level required for being accepted for examination. The result embodied in this major project, to the best of my knowledge, haven’t been submitted to any other university or institution for award of any degree or diploma.

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Abstract

Rapid growth in communication applications leads to the necessity of the integration of complicated circuits into one single chip. It is expected to be low-cost, small and light-weight. In order to achieve the final goal of system on chip (SoC), the design of front end is very crucial. As the operating speed of the devices are getting faster and more power is being consumed. Criticality lies there for the space application. being the most power hungary component of the RF front end, RF Power Amplifier(RFPA) is one of the critical builiding blocks in low power SoC integration. An increased design research has been done to remove the bottleneck for development.

Nowadays more and more satellites have been launched to satisfy the requirement for navigation, data communication, remote sensing etc.Until now Travelling Wave Tube Amplifiers(TWTA) have been placed for power amplification but **Solid State Power Amplifier(SSPA)** have better lifetime and reliablity. with the great advancement in semiconductor technology, the newer **GaN pHEMT** devices are capable enough to mitigate the challenge. In this dissertation, research and investigation on the performance of GaN based power amplifiers have been proposed.

The Power Added Efficiency, Output Power, Gain, Stability and S-Parameters calculation for **Class-B** configuration has been included in this thesis. Moreover, the inclusion of results on **Class-F** configuration using the platform **Agilent's Advanced Design Software(ADS)**. The realization of both the configuration is also done.

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Acronyms

2DEG	Two-Dimensional Electron Gas
CP	Carrier Plate
FET	Field Effect Transistor
GaN	Gallium Nitride
HEMT	High Electron Mobility Transistors
HFET	Heterostructure Field Effect Transistor
MMIC	Monolithic Microwave Integrated Circuit
MODFET	modulation-doped Field Effect Transistor
pHEMT	pseudo-morphic High Electron Mobility Transistors
RFPA	Radio Frequency Power Amplifier
SEDI	Sumitomo Electric Device Innovations
SSPA	Solid State Power Amplifier

Chapter 1

Introduction

Satellites serve a large number of purposes like military and civilian, Earth observation satellites, communications satellites, navigation satellites, weather satellites, and research satellites. Satellites are placed in the earths orbits, depending on the purpose of the satellite. The particular communication satellites need more power to cover more surface on the Earth, also it also required to work on the higher datarate. So the power requirement for communication satellite(e.g. INSAT, GSAT) needs the power amplifier to fullfill the power requirement to send the signal to the Earth station more effectively and efficiently.

1.1 Motivation

Due to incredible evolution of the communications, demand for the more no of satellites to be placed. Particularly for the communication payload, there have been increased requirement for higher-power solid-state devices in both terrestrial base stations as well as Satellite-communications (satcom) systems. Until now, Travelling wave tube amplifier (TWTA) and Solid state power amplifier (SSPA) has been used for the purpose of power amplification. In communication satellite, (i) some operators simply want to transmit their signals further to extend their services to a wider area,

(ii) while others want to send more data over the existing frequency spectrum by using a high-level modulation scheme combined with a complicated multiple-access scheme, which requires high linearity or high peak power capability. In both the cases, the required output power level has been pushed higher for both earth-station and satellites.

Although, GaAs FET technology has been a proven performer in these applications for several decades, still designers have sought even higher power levels at these frequencies. Recently, GaAs-based technology with different structures such as metal-epitaxial-semiconductor FET (MESFET) topologies, high-electron-mobility-transistor (HEMT) structures, and heterojunction FETs (HFETs) are in quest of achieving higher solid-state power levels at RF frequencies. This discussion would have encouraged the researchers and designers to use the SSPA instead of TWTA. Although they both have their own adavantages and drawbacks. Some of them is briefly discussed below:

TWTA vs. SSPA

Function	**TWTA**		**SSPA**	
	All units have the same linearity, intermodulation and spectral regrowth performance.			
	Advantage	**Disadvantage**	**Advantage**	**Disadvantage**
Size and Weight	TWTA packages including power supplies are larger and weigh high		Basic RF modules are smaller than TWTA and the package ligheter	

continued on the next page

TWTA vs. SSPA ***(continued)***

Function	**TWTA**		**SSPA**	
	Advantage	**Disadvantage**	**Advantage**	**Disadvantage**
Linearity & Inter-modulation Distortion	No memory effects			Memory Effects
Available Output Power	TWTAs have higher available output power		SSPAs also produce comparable output power	
Efficiency of Ope. i.e. AC Power Consumption	TWTAs are more efficient in the back-off state	High Voltages	Recent SSPAs have higher efficiency	Higher Currents
Sources of Supply	Foreign and domestic tube suppliers			Almost all power FET suppliers are foreign
Heat Dissipation	Power distributed over a relatively large area, making heat sinking a less challenging			Power FETs dissipate large amounts of power at a concentrated point.

continued on the next page

TWTA vs. SSPA ***(continued)***

Function	**TWTA**		**SSPA**	
	Advantage	**Disadvantage**	**Advantage**	**Disadvantage**
Reliablity	TWTAs have logged many years of reliable operation on spacecrafts	Tubes have a limited life, from 70,000 to 100,000 hrs of continuous operation	No limited life & theoretically could have MTBFs greater than 1,000,000 hrs	Reliability of Power supply network is a problem
Temp. Stability	TWTAs are very stable over temperature			SSPA and driver amplifiers need to be temperature compensated

Table 1.1: Comparison between TWTA vs. SSPA

1.2 Comparison of technologies

Due to the fabrication schemes have been evolved. Many semiconductor technologies have been discovered. Following is the comparison for the different technologies:

More detail can be observed in the table 1.2 on the next page:

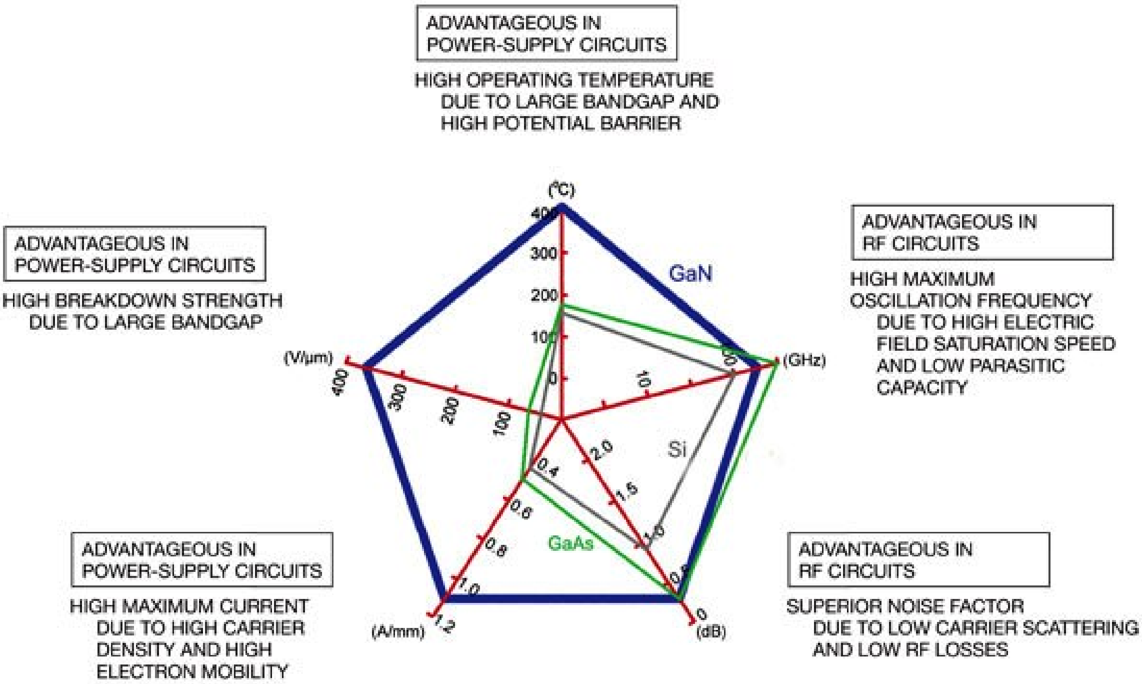


Figure 1.1: Comparison between GaN, GaAs and Si technology
[1]

Parameters	**GaAs**	**GaN**
Output Power Level	upto 5 W	upto 50 W readily available
Power Density	1.5 W/mm	5 to 12W/mm
Current density	upto 1.1A/mm	0.5 A/mm
Breakdown voltages	15 to 20 V	upto 200 V
Maximum PAE	20 to 50%	40 to 80%
Carrier Mobility	Moderate	higher than GaAs
Cost	Lower	High but the as volume increases, production costs will come down

Table 1.2: Comparison between GaAs vs. GaN

1.3 High Electron Mobility Transistor

High-electron-mobility transistor (HEMT), also known as heterostructure FET (HFET) or modulation-doped FET (MODFET), is a field-effect transistor incorporating a junction between two materials with different band gaps (i.e. a heterojunction) as the channel instead of a doped region (as is generally the case for MOSFET). A commonly used material combination is GaAs with AlGaAs till now in the satellite payload for the purpose of power amplification. Although there are wide variations, which are depended on the application of the device. Devices incorporating more Indium (In) generally show better high-frequency performance.

But in recent years, Gallium Nitride (GaN) HEMTs have attracted attention due to their high-power performance. HEMT transistors are able to operate at higher frequencies than ordinary transistors, upto mm wave frequencies. They are used in high-frequency products such as cell phones, satellite television receivers, and radar equipment.

1.4 Developement of GaN HEMT

Semiconductors are doped with impurities which donate mobile electrons (or holes) for better conduction property. However, these electrons collides with the impurities (dopants). HEMTs avoid this scenario by using high mobility electrons generated from the heterojunction of a highly-doped wide-bandgap n-type donor-supply layer (AlGaN) and a non-doped narrow-bandgap channel layer with no dopant impurities (GaN).

The electrons generated in the thin n-type AlGaN layer drop completely into the GaN layer to form a depleted AlGaN layer, because the heterojunction created by different band-gap materials forms a quantum well (a steep canyon) in the conduction band on the GaN side where the electrons can move quickly without colliding with any impurities because the GaN layer is undoped, and from which they cannot escape. This effect creates a very thin layer of highly mobile electrons with very high concentration. These electrons give the channel very low resistivity. Rather we can say these electrons are highly mobile. This layer is called a two-dimensional electron gas 2DEG. As with all the other types of FETs, a voltage applied to the gate alters the conductivity of this layer.

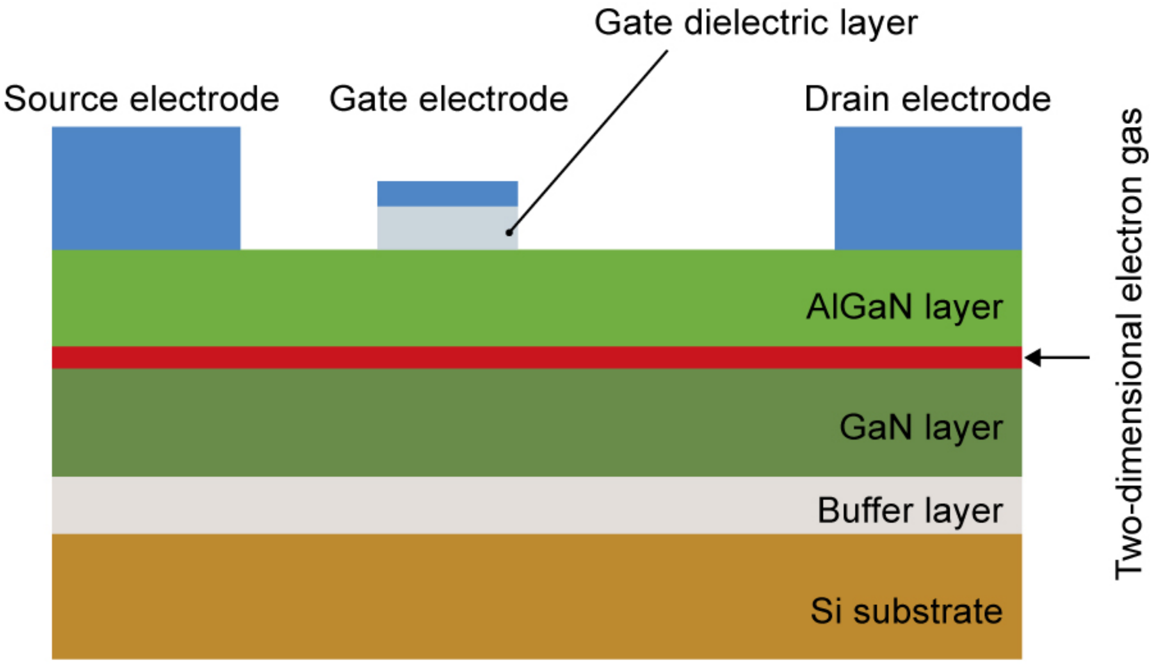


Figure 1.2: Cross-section of typical GaN HEMT
[2]

1.5 Advantages of GaN

The key advantages of GaN technology can be outlined as follows with refernce to the fig. 1.1.

- High Power density capability that is due to higher charges (i.e. than GaAs) which result in higher current (1 to 1.4 A/mm). Accordingly, reported power densities are with an order higher than that of GaAs based devices [2].
- High breakdown voltage, typically 250 V to 600 V, caused by high breakdown field [2]
- High Temperature, that is due to low minor carrier density as well as high thermal conductivity [2].
- High tolerance to radiation by reason of high carrier generation energy and small lattice constant [2].
- High speed due to high carrier velocity [2]
- Low Noise [1]

1.6 Types of HEMTs

There are various versions of HEMTs depending upon the placement of the buffer layer between materials of different lattice constants.

- **pseudomorphic HEMT (pHEMT)**
  The two different materials used for a heterojunction would have the same lattice constant. At regular interval two teeth clump together. A HEMT where this rule is violated is called a pHEMT or pseudomorphic HEMT. This is achieved by using an extremely thin layer of one of the materials - so thin that the crystal lattice simply stretches to fit the other material.

- **metamorphic HEMT (mHEMT)**

  In mHEMT or metamorphic HEMT, a buffer layer is placed between the materials. The buffer layer is made of AlInAs, with the indium concentration graded so that it can match the lattice constant of both the GaAs substrate and the GaInAs channel.

- **Induced HEMT**

  Induced HEMT provides the flexibility to tune different electron densities with a top gate, since the charge carriers are “induced” to the 2DEG plane rather than created by dopants.The absence of a doped layer enhances the electron mobility significantly when compared to their modulation-doped counterparts.

1.7 Applications

Here are the some of the applications in which GaN HEMT is used.

- Microwave and millimetre wave communications
- Remote Sensing & Imaging
- Radar
- Radio astronomy any application where high gain and low noise at high frequencies are required.
- More usually used in the form of a ’monolithic microwave integrated circuit’ (MMIC).
- HEMTs are found in many types of equipment ranging from cell phones and DBS receivers to electronic warfare systems.

1.8 Dissertation Outline

The whole dissertation is mostly concentrated on designing of PAs those are being used in the RF frequencies, GaN pHEMT based active device, Linearity-Efficiency compromis on designing RFPA and the analysis of efficient classes of PA.

Chapter 3,*Basics of Power Amplifier*, describes the basics of RFPAs. Why it is so important, is illustrated in this chapter. Where its is placed in the typical payload or in any high frequency systems. The parametes those can be considered by the designer. Some equations regarding the parameters. Basically, this chapter provides us all necessary parameters before designing RFPA.

Chapter 4 & 5,*Designing of RF Power Amplifiers*,describe the typical design problem for the Class-B & Class-F type of configuration for the RF Power Amplifier using GaN HEMT. Agilent's Advanced Design Software(ADS), which is the software tool being used for the simulation persepective. The chapter includes the problems arose when it was iimplemented. It also include the Harmonic Balance simulation results with circuit and EM-momentum with the layout generated by the ADS.

Chapter 6,*Conclusion*,describes the future work can be carried out in designing RFPA with greter efficiency. The Inverse-Class F, Class-J type of configuration is also mentioned briefly for the RFPA based on GaN HEMT.

Chapter 2

Literature Review

In this modern age, Wireless communications need linear and efficient RF power amplifiers. With the emergence of new generations of wireless devices and modulations that have non-constant envelopes, more attention has been given to the importance of the linear behaviour of power amplifiers. Because they must accurately reproduce the signal present at their input. But every active devices face the trade-off between linearization-efficiency [3], if it is on a limited power supply. Therefore, to be more power efficient, the system needs to draw less power from the supply for the same amount of output power. This leads to gain compression which makes the system less spectrum efficient. This trade-off is so critical that designers prefer to slightly distort the peaks of the amplitude envelope and then compensate for the distortion.

In [4], there is a discussion of predistortion methods, which are being used for the linearization of RF power amplifier. If we design a power amplifier to have a high efficiency, certainly, this amplifier will not have an acceptable linear behaviour.

In the predistortion concept, a predistorter block is placed before the amplifier block, and this predistorter should exhibit a behaviour which is the inverse of the amplifiers nonlinear behaviour, so that the two blocks together ultimately behave linearly. Thus, predistorter should have a transfer function to compensate for the non-linearities. And it should adjust its characteristics according to time and environmental factors.

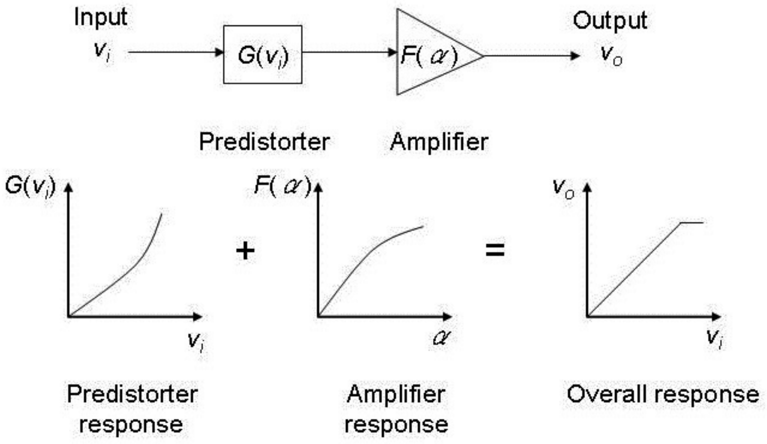


Figure 2.1: Predisrtortion scheme for increasing linearity

But, due to the highly advantageous characteristics of GaN for the RF circuits influence designers to design RFPAs based on GaN. The parametric comparison can be observed in [5]. This comparative study would surely influence the designers and researchers to design PA based on GaN HEMT.

RFPAs are not only used in any particular field of operation. They are being used in every possible areas those are related with the Power transmission. [6] describes a high efficient PA with high reliable GaN HEMT devices in space application. And it shows that by precise matching we could have better efficiency, which is not in the case for previous technologies.

Earlier in the satellite payload TWTAs were used and still being used for power amplification as they are providing higher gain for the input signal. But, [7] has provided the comparison on TWTA and SSPA in L-band, which is the prominent reason, for researchers, concentrates on the design of SSPA than TWTA for power amplification. More detailed comparison can be found in [8].

SSPA have comparatively narrowband to the TWTA. To employ the broadband efficiency for SSPA we can design it with the different classes of power amplifier. Mainly linear classes of amplifiers are used in SSPA, and navel design of Class-F and Class-F^{-1} power amplifers are produced in [9]. There is also configuration named contionuos inverse Class F has been proposed in [10]. It presents a novel formulation for the inverse Class-F mode of operation, termed the "Continuous inverse Class-F mode", resulting in an extended or continuous set of 'allowed' current waveforms. In comparison to the Classical inverse Class-F mode, this approach provides a much wider design space for the realization of broadband power amplifiers. The output performance can be maintained through proper termination for 2nd and 3rd harmonic terminations. The details for the harmonic termination for the Class-F and Inverse Class-F can be found in the [11]. In [11], there is the typical VI waveforms are given for both configuration.

In [4], there is a discussion of the integrated design of Class-J PA using GaN based device. It derivatives of optimum load impedance to demonstrate their dependency on output matching network. And the integrated design could exhibit more than 50% of efficiency over wider frequency range.

Chapter 3

Basics of Power Amplifier

RF Power Amplifier is one of the most common electrical elements in any system. The requirements for amplification are as varied as the systems where they are used. Whether they are used in Wireless Communication, Satellite Communication, TV transmissions, Radar, RF heating, etc. The basic techniques for RF power amplification can use classes as A, B, C, D, E, and F, for frequencies ranging from VLF (Very Low Frequency) through Microwave Frequencies.

RF Output Power can range from a few mW to MW, depend upon application.

3.1 Block diagram of typical PA

A typical single-stage power amplifier illustrated in figure 3.1 consists of at least four parts:

a. A power supply network

b. Input and output matching networks

c. Input and output bias networks

d. An active device.

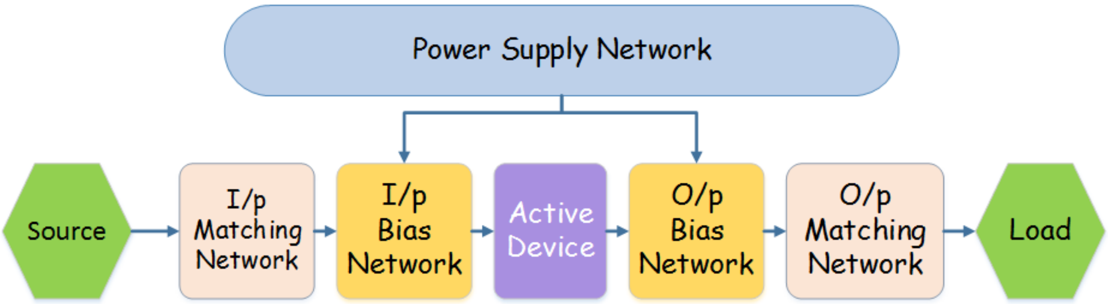


Figure 3.1: Block diagram of generalized single-stage PA

A **power supply** network provides desired voltage supply and/or current source. The **input and output matching networks** convert the source and load to certain impedances so that the amplifier can achieve better overall performance at desired frequencies. **Input and output matching networks** typically consist of only passive components. An active device ideally acts as a current/voltage controlled current/voltage source, or just some sort of switch. **The input and output bias networks** determine the operating point of the active device and output signal level, respectively. The same active device can work at different modes if its operating point is intentionally set to different values. The source is the previous stage while load is latter stage.Typically, they both have of 50 Ω impedance.

Our primary focus of this report would be on the design of the power amplifier using HEMTs. The designing method is relying on the terminal characteristics of the transistor, which can be represented by either scattering parameters or one of the equivalent circuit models. **Power delivered to the load, Efficiency, Gain, Linearity** and **Bandwidth** are the most important parameters considered in power amplifier design, which are briefly introduced in the following sections.

3.2 Key parameters in PA Design

3.2.1 *Power Calculation*

Power is one essential figure for evaluating the capability of power amplifiers. Two power concepts are widely used in PA design. One is the DC power consumption, which is defined as below:

$$P_{DC} = V_{DC} I_{DC} \tag{3.1}$$

The other is AC power, which is the average power of signals varying over a certain period. For a sinusoidal signal, AC power is defined as the product of the *rms* values of voltage and current. The RF power delivered to the load R is defined as:

$$P_O = \frac{1}{2} Re\{V_O I_O^*\} \tag{3.2}$$

3.2.2 *Power Gain*

There are many definitions of gain in RF circuit design, such as power gain, available gain, exchangeable gain, insertion gain and transducer power gain. Consider an arbitrary two-port network, characterized by its scattering matrix [S], connected to source and load impedances Z_S and Z_L, respectively, as shown in the below Figure

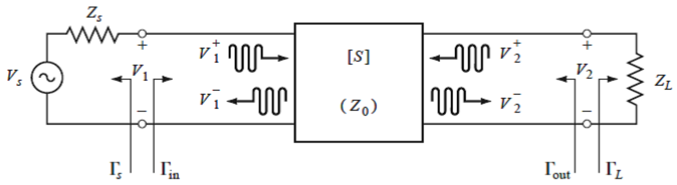


Figure 3.2: Block diagram of generalized single-stage PA

We will derive expressions for three types of power gain in terms of the scattering parameters of the two-port network and the reflection coefficients, Γ_S and Γ_L, of the source and load

a. ***Power Gain***

$$G = \frac{P_L}{P_{in}} \tag{3.3}$$

is the ratio power dissipated in the load Z_L to the power delivered to the input of the two-port network. This gain is independent of Z_S, although the characteristics of some active devices may be dependent on Z_S.

b. ***Available power gain***

$$G_A = \frac{P_{avn}}{P_{avs}} \tag{3.4}$$

is the ratio of the power available from the two-port network to the power available from the source. This assumes conjugate matching of both the source and the load, and depends on Z_S, but not Z_L .

c. ***Transducer power gain***

$$G_T = \frac{P_L}{P_{avs}} \tag{3.5}$$

is the ratio of the power delivered to the load to the power available from the source. This depends on both Z_S and Z_L.

3.2.3 *Efficiency*

Efficiency is used to measure the quality of an amplifier in converting input supply energy to output usable energy. Higher efficiency means less power loss in the amplifier. Efficiency is a very important merit for evaluating the overall performance of power amplifiers, especially for switching power amplifiers, the power gain of which may not be meaningful. There are several kinds of efficiencies in use: Drain efficiency and PAE are the most commonly used; sometimes overall efficiency and long-term mean efficiency should be applied if some other costs like that of the cooling systems are comparable to the price of the system and need to be taken into consideration [12].

a. The **drain efficiency** is defined as:

$$\eta = \frac{P_O}{P_{DC}} \tag{3.6}$$

This efficiency definition does not provide information about the input. An amplifier of low power gain could exhibit high efficiency.

b. **PAE**

The power added efficiency, on the other hand, takes the input driving power into account and thus can better evaluate the performance of some high-efficiency power amplifiers. The power added efficiency is defined as:

$$\eta_{PAE} = \frac{P_O - P_{in}}{P_{DC}} \tag{3.7}$$

3.2.4 *Linearity*

Linearity is defined as the property of a system in which the outputs are scales of the inputs without introducing new elements. It is another very crucial specification for power amplifiers in practice. For example, wireless communication standards supporting high-speed data rate services usually employ PSK and QAM modulations for higher spectrum efficiency, and hence demand for good linearity in power amplifiers. In practice, acceptable linearity could be achieved via using linear amplifiers or employing some linearity enhancement techniques to switching amplifiers.

The typical linearity enhancement techniques include applying high profile technologies or adding some compensation circuits. As a result, the system complexity and the cost increase dramatically. Therefore, for economic reasons, linearity and efficiency have to be traded off in practical power amplifier designs. Nonlinearity is usually caused by the undesired features of the active device in an amplifier. Nonlinear effects in active devices can be classified into two categories kenn00:

a. Strongly nonlinear effects are introduced by the limiting behaviour of the transistor such as cut-off, pinch-off, saturation and some other secondary effects. They can be predicted using device models based on I-V curve-fitted equations.

b. The other category, weakly nonlinear effects, can be examined by analysing the output of the amplifier using sinusoidal signals as input. Several useful concepts like 1-dB compression point, Harmonics, IP_3 etc. are used for assessing weakly nonlinear effects.

3.2.5 *Bandwidth*

Power amplifiers should be able to provide relatively constant performance in their desired bands. The bandwidth can be narrowband, wideband or ultra-wideband. Amplifiers with wider operational bandwidths usually have lower gains. Narrowband power amplifiers are most widely used in recent wireless communication applications.

Nevertheless, since supporting high speed data rate multimedia services has become a trend nowadays, power amplifiers of wideband and ultra-wideband attract more and more attention. But as the performance more and more go toward wider BW , max gain of the PAs reduce significantly. So as the efficiency is also getting reduced in band of interest for our application.

3.3 An Overview of Classical Power Amplifiers

The basic specifications for power amplifier include output power level, gain, efficiency, linearity, bandwidth and cost. Some of these design goals are in conflict with one another: gain vs. bandwidth, output power vs. input power, linearity vs. efficiency, and high-profiled technologies vs. cost are the most common conflicts considered in RFPA design. Designers have to make trade-offs among these various specifications to obtain the optimized performance for different applications.

To meet different demands, a variety of power amplifiers were invented to maximize certain features. These power amplifiers have either different circuit configurations or different working conditions. Power amplifiers are classified into several classes for practical reasons, although the boundaries between different classes are not very clear sometimes.

The most common classes are Classes A, AB, B, C, D, E, F, G, S, and H. Each class of power amplifiers offers some advantages over another. For example, Class-A has better linearity but poorer efficiency than other classes. Hybrid amplifiers, such as Classes AB, CE, DE, E/F amplifiers, usually enjoy the benefits of more than two basic classes. Based on the most important trade-off in power amplifier design, efficiency and linearity, power amplifiers can be further divided into two groups:

- Linear Amplifiers consists of Classes A and AB amplifiers
- Nonlinear (constant envelope) amplifiers consist of Classes B,C, D, E, F, G, S, and H amplifiers

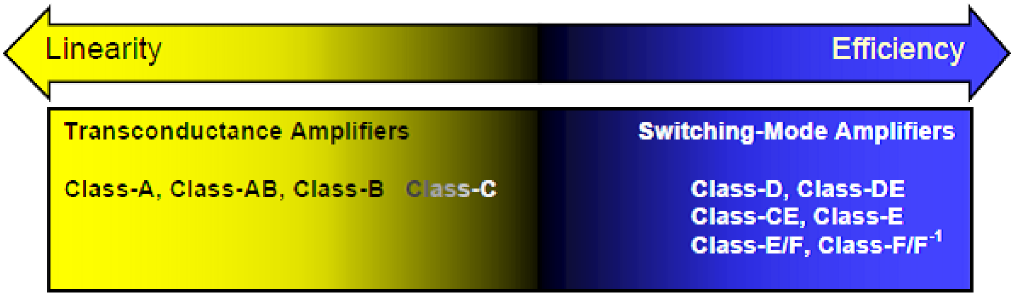


Figure 3.3: Transconductance and switching-mode amplifiers

Based on the working style of the active devices, power amplifiers can also be categorized into two groups, transconductance and switching-mode, which are shown in Figure 3.3

- Transconductance amplifiers include the linear amplifiers and Class-C because they share the similar topology and employ the active device as a voltage controlled current source.
- Classes D, E, F, G, H and S belong to switching-mode amplifiers due to the fact that the active device could be ideally viewed as switches.

3.4 Classes of RF Power Amplifier

In this dissertation prime focus is on only class-B because bias conditions for the Class-F is same as in the Clsss-B. So it is very suitable for comparative study of both the classes.

3.4.1 *Class B type of amplifier*

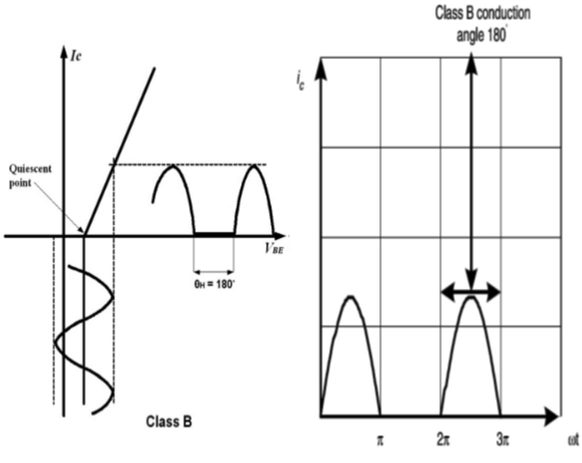


Figure 3.4: Transconductance and switching-mode amplifiers

This is an amplifier in which the conduction angle for the transistor is approximately 180°. Thus, the transistor conducts only half of the time, either on positive or negative half cycle of the input signal. For the simplicity the positive half cycle is considered for the conduction. The DC bias applied to the transistor determines the Class-B Operation.

Class-B amplifiers are more efficient than Class-A amplifiers. The instantaneous efficiency of a Class-B PA varies with the output voltage and for an ideal PA reaches $\pi/4$ (78.5%) at PEP. However it is much less linear. Therefore a typical Class-B amplifier will produce quite a bit harmonic distortion that must be filtered from the amplified signal.

A single transistor may be used in a Class-B configuration. The only requirement in this case is that a resonant circuit must be placed in the output network of the transistor in order to "reproduce" the other half of the input signal.

In practice, the quiescent current is on the order of 10 % of the peak collector current and adjusted to minimize crossover distortion caused by transistor nonlinearities at low outputs. In theory 6dB or more power-drive is needed to achieve Class-B compared with Class-A. In practice this 6dB reduction in power gain is lower; for BJT amplifiers is lower than FETs, approximately 2dB. The efficiency of the push-pull power amplifier is the same as that of the single ended power amplifier with the same conduction angle. But the output power capability of the push-pull power amplifier is twice that of the single-ended power amplifier (3dB higher).

3.4.2 *Class-F type of amplifier*

Class-F boosts both efficiency and output by using harmonic resonators in the output network to shape the drain waveforms. The voltage waveform includes one or more odd harmonics and approximates a square wave, while the current includes even harmonics and approximates a half sine wave. Alternately ("Inverse Class F"), the voltage can approximate a half sine wave and the current a square wave.

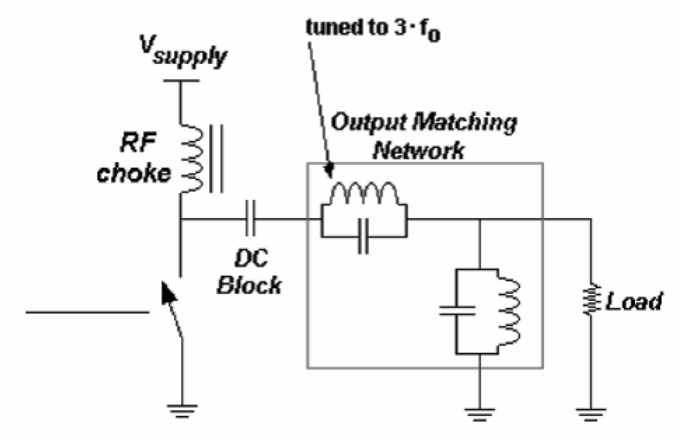


Figure 3.5: Typical output matching network for Class-F RFPA

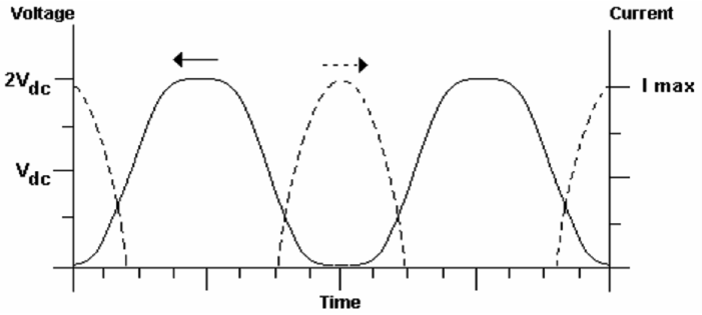


Figure 3.6: Voltage and Current waveform for Class-F

In practice, the transistor is driven into saturation during part of the RF cycle and the harmonics are produced by resonant circuits. Use of a harmonic voltage requires creating a high impedance (3 to 10 times the load impedance) at the drain, while use of a harmonic current requires a low impedance (1/3 to 1/10 of the load impedance).Which describes that the Class-F requires a more complex output filter than other PAs. Also the impedances must be corrected at only a few specific frequencies. Lumped-elements can be used at lower frequencies but distributed elements are preferred at microwave frequencies.

Typically, a shorting stub is placed a quarter or half-wavelength away from the drain. Class-F amplifier designs intentionally squaring the voltage waveform through controlling the harmonic content of the output waveform. This is accomplished by implementing an output matching network which provides high impedance open circuit to the odd harmonics and low impedance shorts to even harmonics. Class-F amplifiers are capable of high efficiency (88.4% for traditionally defined Class-F, or 100% if infinite harmonic tuning is used). Class-F amplifier design is difficult mainly due to the complex design of the output matching network.

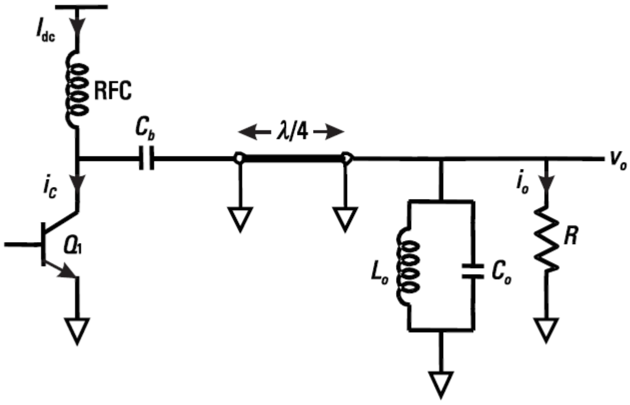


Figure 3.7: Output matching network for Class-F

A $\lambda/4$ transmission line transforms an open circuit into a short circuit and a short circuit into an open circuit. At the fundamental frequency (F_o), the tuned circuit (L_o and C_o) is an open circuit, but at all other frequencies, the impedance is close to zero. Thus, at the fundamental frequency the impedance into the transmission line is R_L. At even harmonics, the $\lambda/4$ transmission line leaves the short circuit as a short circuit. At odd harmonics, the short circuit is transformed into an open circuit. This is equivalent to having a resonator at all odd harmonics, with the result that the output voltage waveform is a square wave.

3.5 Summary

The purpose of power amplifiers is to deliver amplified power to the load according to the input signal. For wireless communication systems, the most crucial criterion for PA is that a desired power is delivered with high efficiency and good linearity. Designers must make complicated tradeoffs to meet the desired specifications. Researchers have discovered and employed a great variety of power amplifiers in practical applications. The power amplifiers can be divided into two categories: **Transconductance** and **Switching-mode** amplifiers. There are a number of classes under these two categories. Every class has its own advantages and disadvantages, whereas some newly introduced **hybrid** amplifiers combine the strengths of two or more classes. Generally, the transconductance amplifiers have better linearity, while switching-mode amplifiers offer higher efficiency. To evaluate the performance of switching-mode power amplifiers, power added efficiency, instead of power gain, is the most important criterion.

Chapter 4

Designing RF Power Amplifier: Class-B

In this chapter, the design of Class-B type of Power Amplifier in the L-band frequency is presented. At the end of this chapter, the simulatioin and the measured data is compared.

4.1 Stability Analysis

Power amplifier design aims for maximum power gain and efficiency for a given value of output power with a predictable degree of stability. Instability of the power amplifier will lead to undesired parasitic oscillations, which results to the distortion of the output signal. Reasons for amplifier instability are as follows:

- a positive feedback from the device output to its input through the internal feedback capacitance
- inductance of a common ground
- external circuit elements

Consequently, a stability analysis is crucial to any power amplifier design, especially at high frequencies. Rather say before starting to the designing we should stabilize the active device in our band of frequency. There are two types of stability:

- *Unconditional stability* : The network is unconditionally stable if $|\ \Gamma\_in| < 1$ and $|\ \Gamma\_out| < 1$ for all passive source and load impedances (i.e.,$|\ \Gamma\_S| < 1$ and $|\ \Gamma\_in| < 1$).

- *Conditional stability*: The network is conditionally stable if $|\ \Gamma\_in| < 1$ and $|\ \Gamma\_out| < 1$ only for a certain range of passive source and load impedances. This case is also referred to as *potentially unstable*.

To ensure the stability of the power amplifier, we could do loading in the input network. There are various ways to do loading. We can put small value resistor in shunt to the gate terminal, or can be put in a series. Also we can put the high value resistor in the bias circuits to ensure the stability. By the virtue of the loading we can ensure the unconditionally stability. We could find the range of Γ_S and Γ_L where the amplifier will be stable by using the smithchart and plotting stability circles. In ADS , source and load stability circles can be found out by L_StabCircle and S_StabCircle pallete and can be plotted in Fig 4.1.

In fig. 4.1, the load & source stability circles of the design is shown. It is noted that all the circles are out of the $\Gamma = 1$, that is the reason we can say the design is unconditionally stable. If the circles of are passing or intersecting the $\Gamma = 1$ on the Smith Chart, the design is unstable for that particular frequency of operation.

Also the Stability Factor or Rolletes Factor κ calculation can be done by StabFact pallete in ADS. It uses the S-parameters etracted from the design. Fig. 4.2 shows the κ is always greater than 1 over 0 to 4 GHz, which shows the design is stable over this whole range of frequencies.

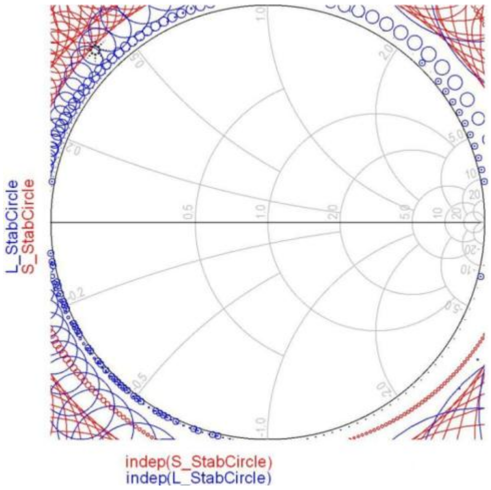


Figure 4.1: Stability circles for the Load and Source of the device.

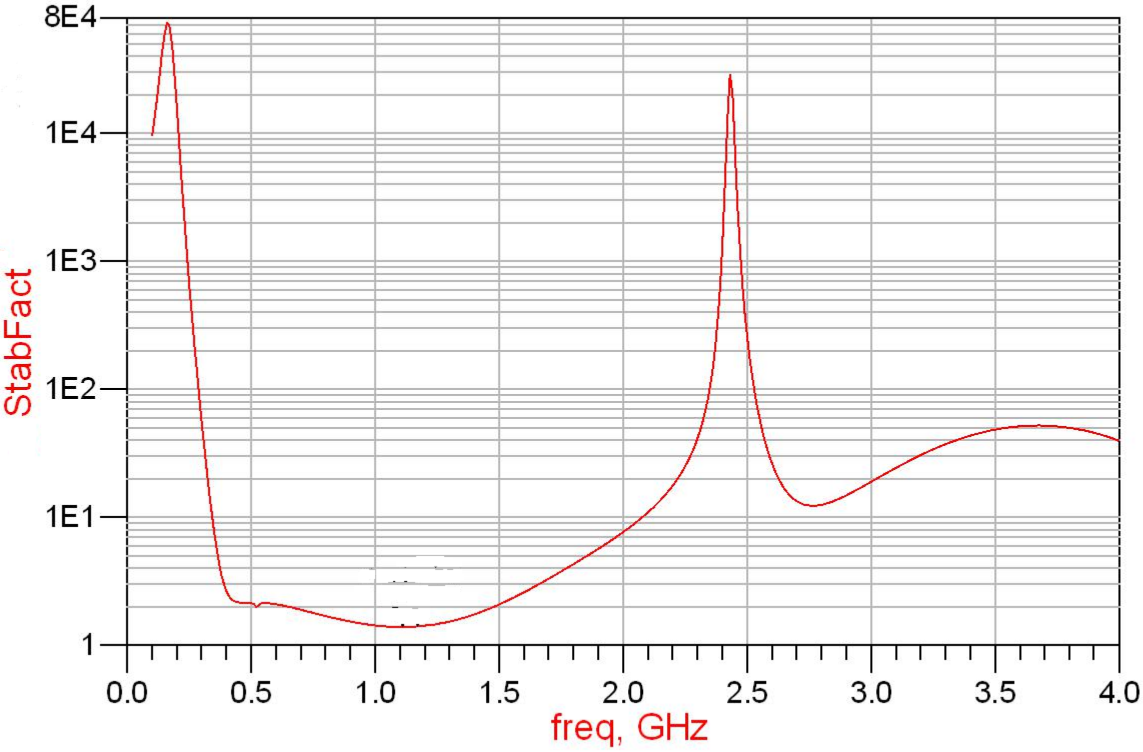


Figure 4.2: Stability factor for the stability analysis

4.2 Conjugate Matching

After the stability of the transistor has been determined and the stable regions for Γ_S and Γ_L have been located on the Smith chart, the input and output matching sections can be designed.

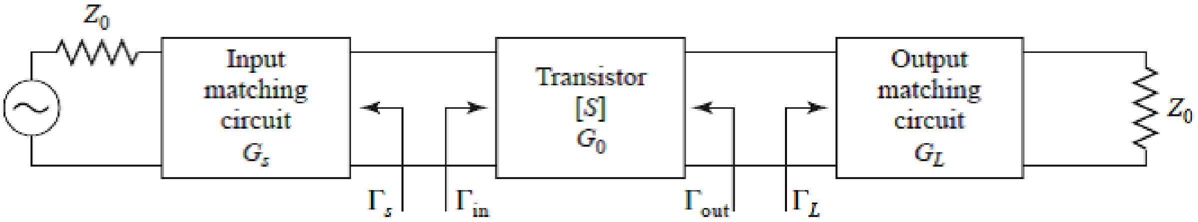


Figure 4.3: I/p and O/p matching analysis

Since G_0 is fixed for the transistor, the overall transducer gain of te amplifier will be controlled by the gains, G_s and G_l of the matching sections. Maximum gain will be realized when these sections provide a conjugate match between the amplifier source or load impedance and the transistor. Because most transistors exhibit a significant impedance mismatch (large $|S_{11}|$ and $|S_{22}|$), the resulting frequency response may be narrowband.

Maximum power transfer from the input matching network to the transistor will occur when

$$\Gamma_{in} = \Gamma_S^* \tag{4.1}$$

, and that maximum power transfer from the transistor to the output matching network will occur when

$$\Gamma_{out} = \Gamma_L^* \tag{4.2}$$

,

4.3 Design flow in ADS

One must needs to follow the steps below for any amplifier design. Before that one must have the model of the device, which one has to test in hardware. Also the parameters which can be changed by the variation of channel Temperature, are required.

a. First decide the operating voltage or bias voltage for the device.

b. Secondly ensure the unconditional stability for the device configuration.

c. Calculate the I/p and O/p impedance required for maximized PAE particularly.

d. According to the values of the impedance, design the matching network that can provide maximized power transfer. The Smith Chart utility in the ADS can be used for designing matching network.

e. Similarly design the matching network for the output terminal to the load, which is 50Ω line.

But in the field of RF where you are dealing with the typical behaviour swing of basic elements in electronic components like Resistor, Capacitor and Inductor, one must take care that behaviour. Though the electrical simulation is important but designers should consider the effect of magnetic field on the circuit. So dont just stop with the electrical schematic but also simulate the circuit with EM momemtum for the whole Power amplifier design.

Another important parameter is the area in which the whole circuit should be accommodated. Because size and weight are the prime factors those affect the cost of the satellite payload. So the circuit design uptil now in the schematic form but to accommodate it on the specific size (here size is particularly $1'' \text{ X } 2''$), it needs to be bent this track while keep in mind that the track should be far enough from each other, as such the mutual coupling wont happen or less coupling happens. Layout

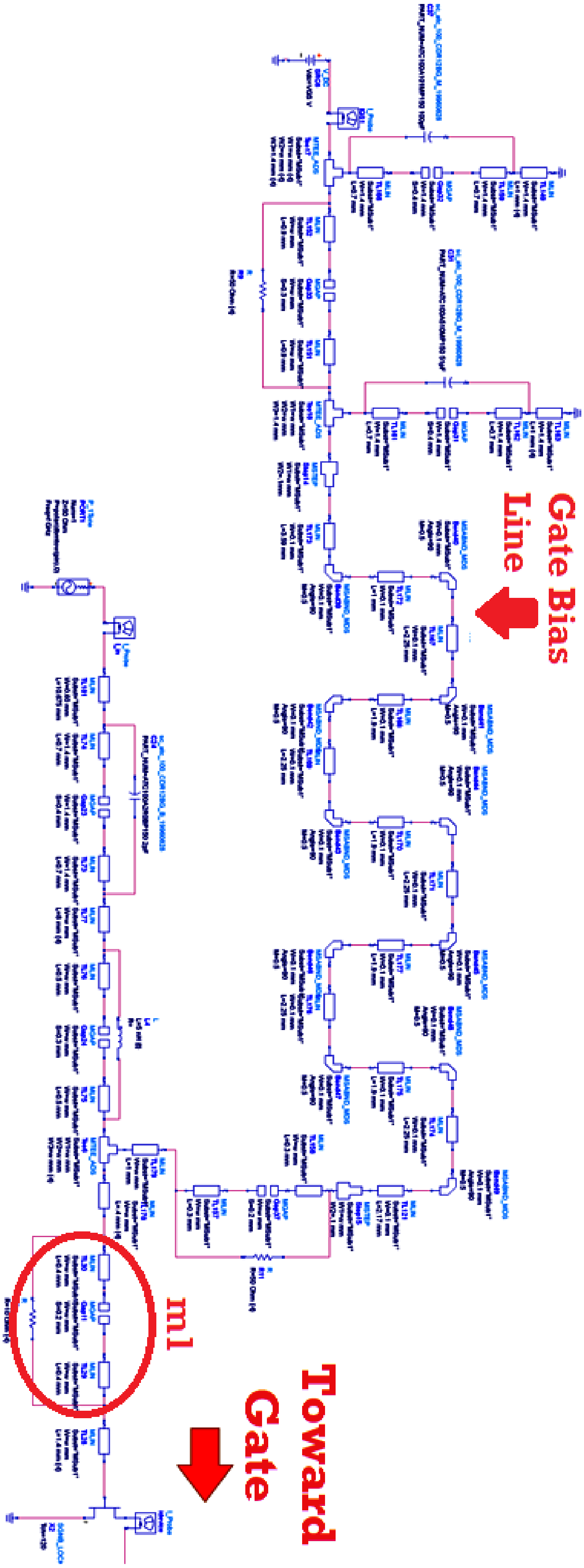


Figure 4.4: Inputstage schematic of the Class-B

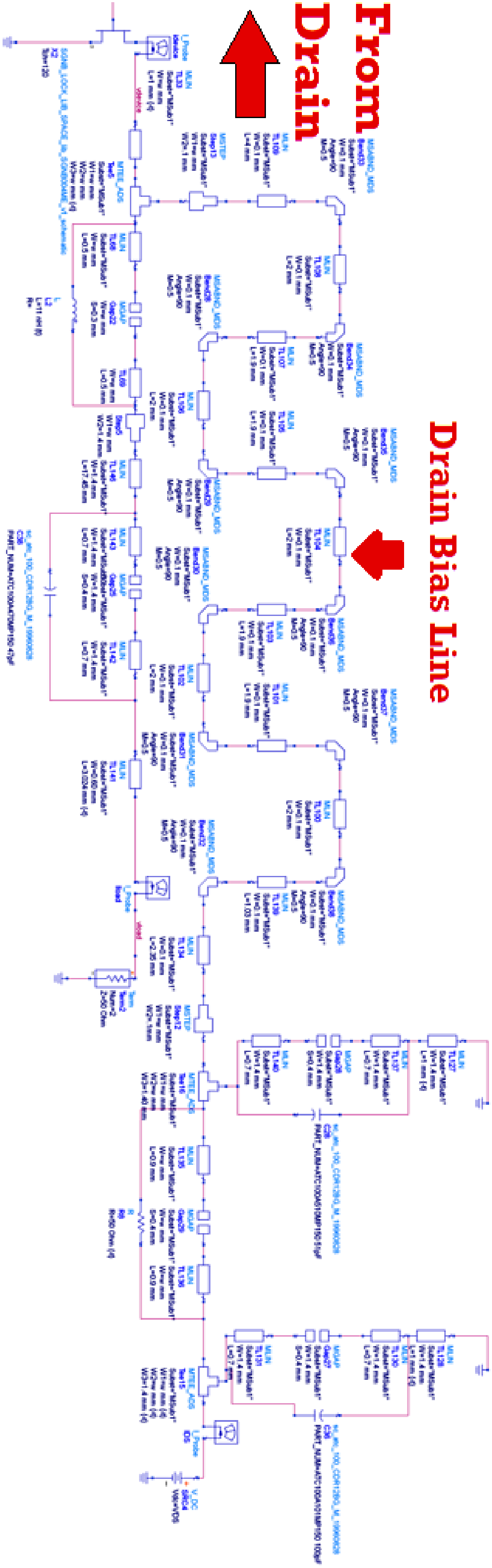


Figure 4.5: Output Stage Schematic of the Class-B

generation in ADS can be done by bending bias line, while the performance should not degrade drastically. One can compromise some efficiency over particular size. For the better analysis, one must generate layout for I/p matching network and O/p matching network simultaneously. Also check the effects of bending on the performance of the amplifier:

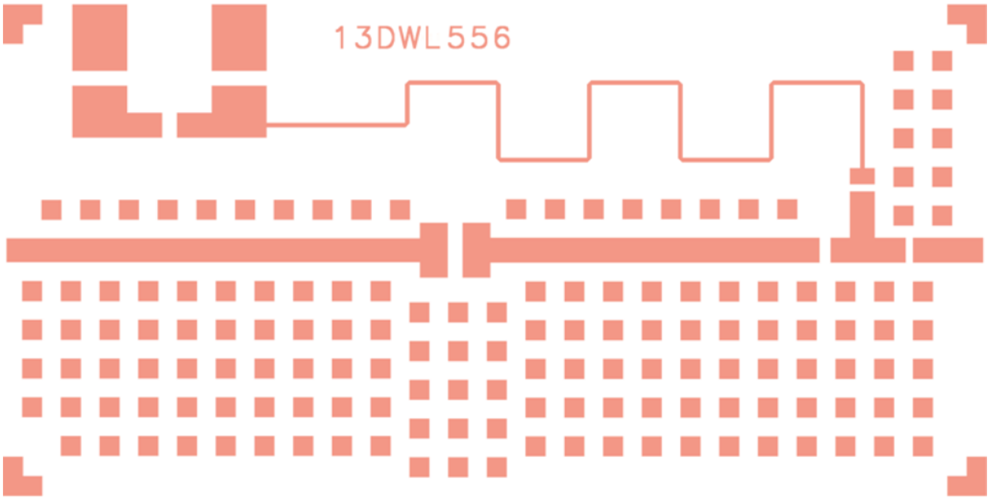


Figure 4.6: Layout of the i/p matching card with Gate biasline

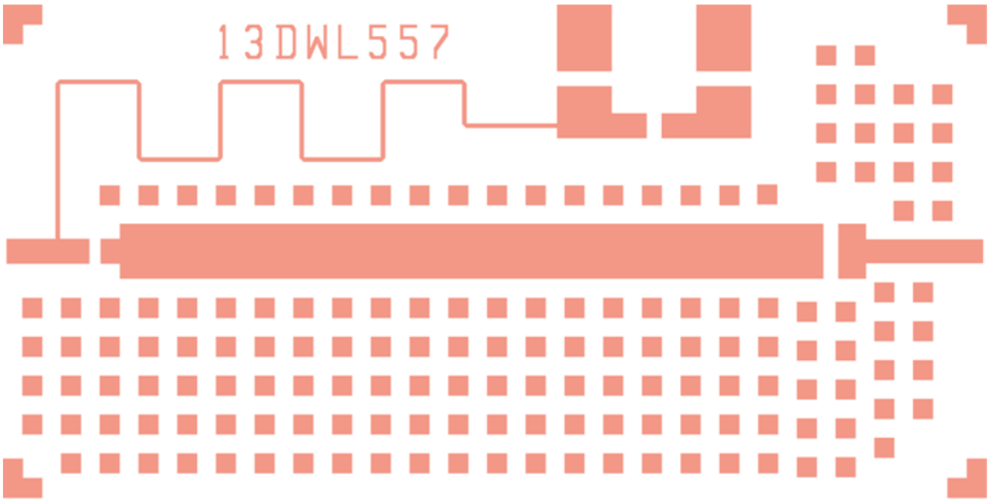


Figure 4.7: Layout of the o/p matching card with Drain biasline

Here the circuit is implemented on the Al-substrate with Cu-Cr-Au plating, and the conductor is Au. The corners are indicating the edge for the substrate cutting. The square pads are also added to tune the line. The sole reason is that the actual circuit wouldnt give the exact impedance as in the software (the software consider the ideal situation for calculation). While designing one must consider the mechanical errors of the machine and human for the substrate cutting and trace impression. Before finalizing the layout of design, one must consider the design rules(for fabrication and component assembly).

Than the actual co-simulation of this both CPs are to be observed, the observation is that the efficiency is slightly degraded but the linear gain can be found over wider bandwidth, typically flatness 0.7dB over 60 MHz with the efficiency of nearly 60%.

4.4 Results for Class-B

In this section, the simulation results have been reproduced. Also comparison between the simulation results with the tested or measured results of the Class-B configuration is being proposed. Gain, P_{out}, PAE and Gain compression etc. parameters results are shown in later section.

4.4.1 S-Parameters

S_{21} =16 dB with flatness of 0.5dB over 50 MHz of bandwidth. Same can be measured via PNA. The result is shown in fig 4.9.

4.4.2 Power Measurements

Simulated output power at F_0, $2F_0$ and $3F_0$ for the different input power is shown in the figure 4.10.The power calculation from the harmonics is very important. Because the harmonics cause the great trouble when the power amplifier is attached

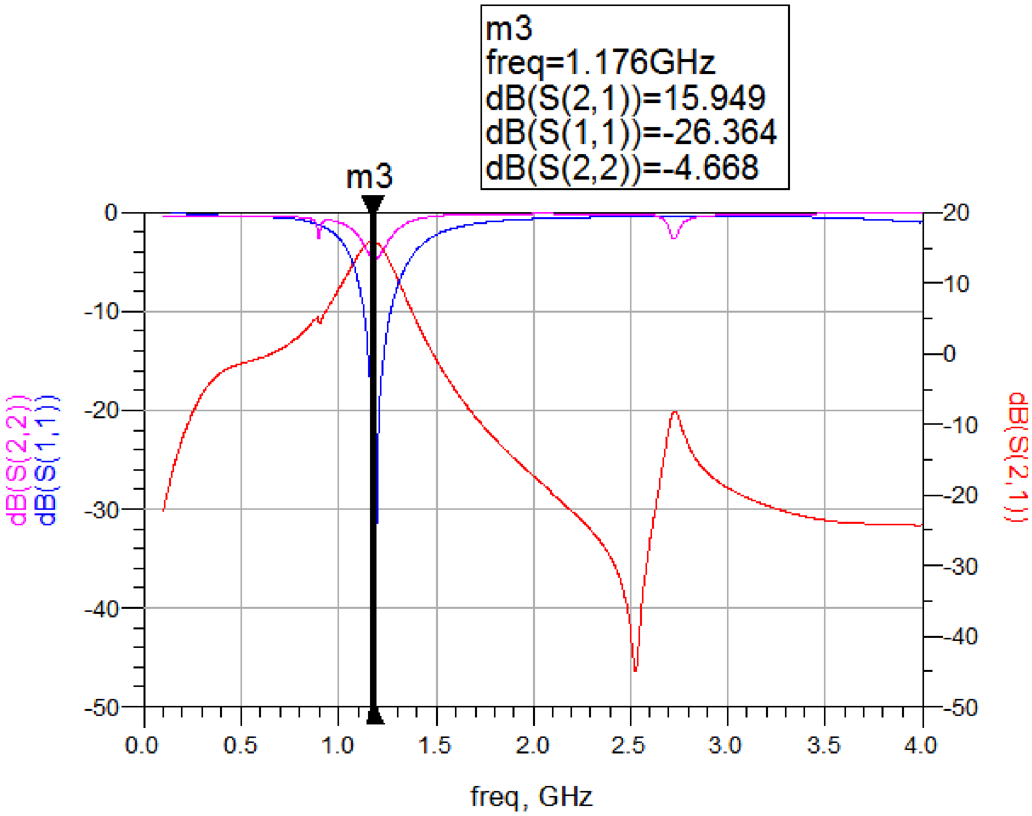
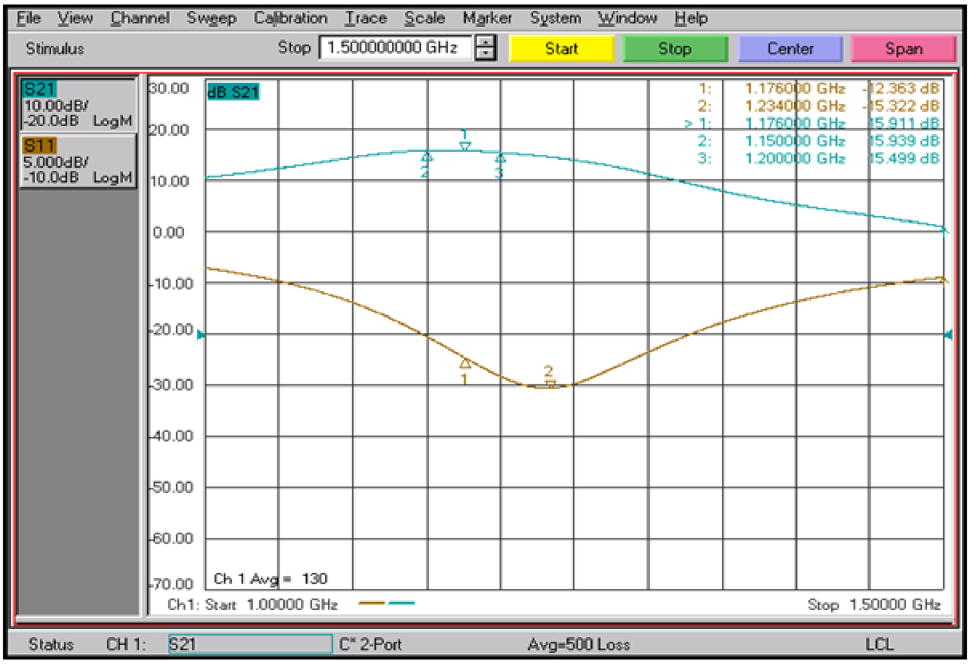


Figure 4.8: S-parameters of Class-B



```
  1:  1.176000 GHz  -12.363 dB
  2:  1.234000 GHz  -15.322 dB
> 1:  1.176000 GHz   15.911 dB
  2:  1.150000 GHz   15.939 dB
  3:  1.200000 GHz   15.499 dB
```

Figure 4.9: S(1,1) & S(2,1) for the Class-B

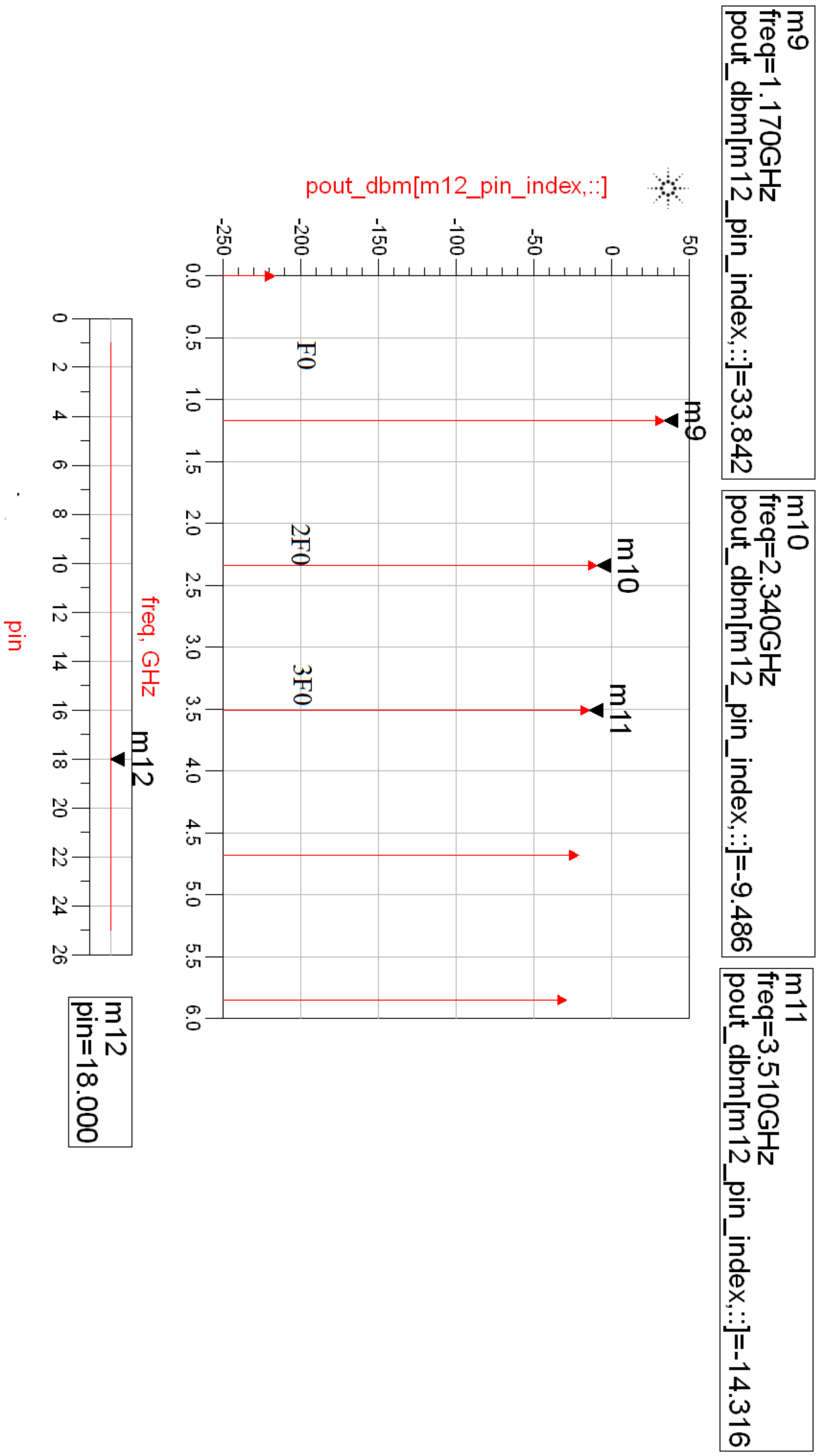


Figure 4.10: P_{out} in dBm at Fundamental (F_0), 2^{nd} hamonics ($2F_0$) & 3^{rd} hamonic($3F_0$)

with other reactive parts of communication link like mixers. It also considered for the IMD measurements.

4.4.3 Gain Measurements

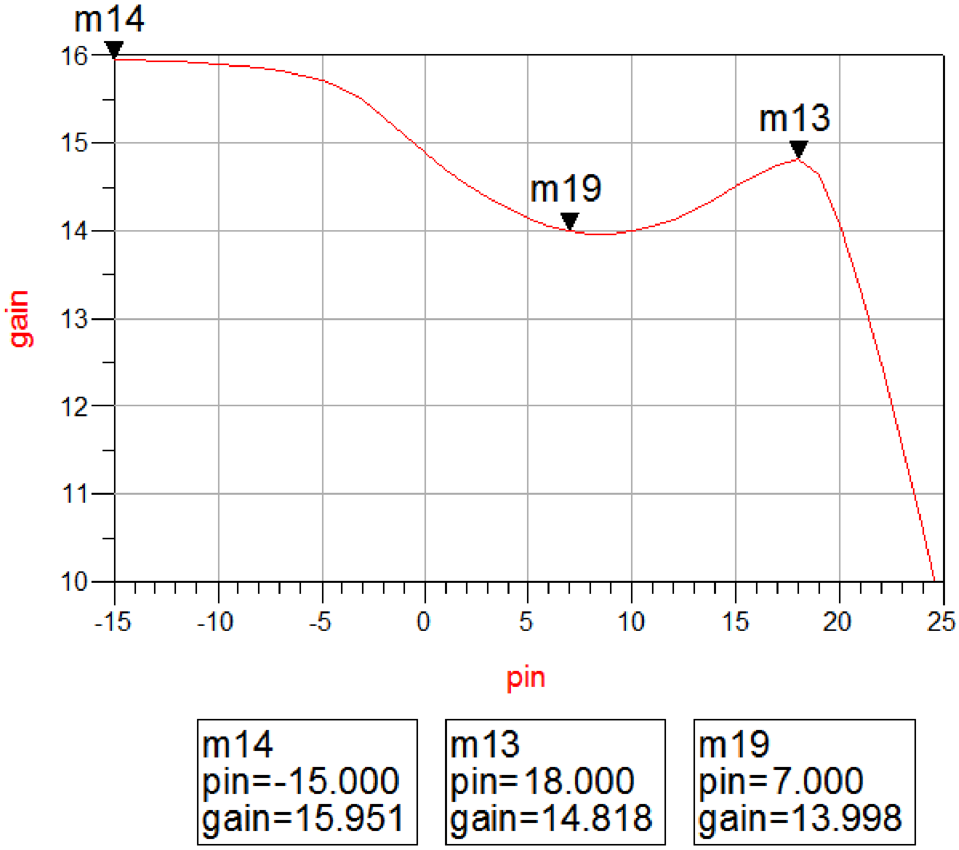


Figure 4.11: Simulated Gain measurement

The gain of an amplifier is shown in the Fig. 4.12. It is clear that the Gain expansion is observed and also it is not out of the margin for the design specifiaction. It is also supporting the current collapse phenomenon of the GaN HEMT. The bulk traps in AlGaN/GaN layers which absorb electrons from channels and virtual gate effects, which deplete the channel in the device by the accumulated negative charges in the surface. It has been the main reason, causing the reduction of 2DEG in channels. But at higher power, electrons will be excited and continue to flow in the 2DEG channel.

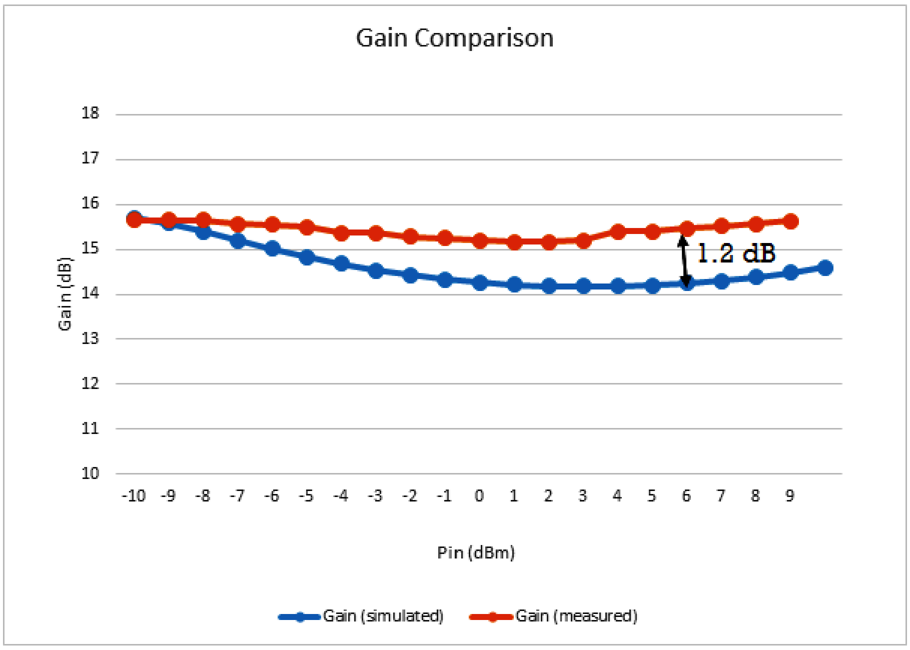


Figure 4.12: Comparison of Simulated & Measured Gain

Thus, the expansion of the gain is observed.

4.4.4 PAE mesurement

In any kind of active device, the drain efficiency is being considered. But, drain efficiency does not depend upon the present input signal, rather to say the Drain efficiency does not consider the Input power. Thus, the effect of the Input power to the device can not predicted by simply Drain efficiency. But, PAE consider the input power level currently present at the input terminal. Thus, PAE is the important parameter in design Power Amplifier.

The peak PAE is realised as high as 61%, which shown in the fig. 4.13.

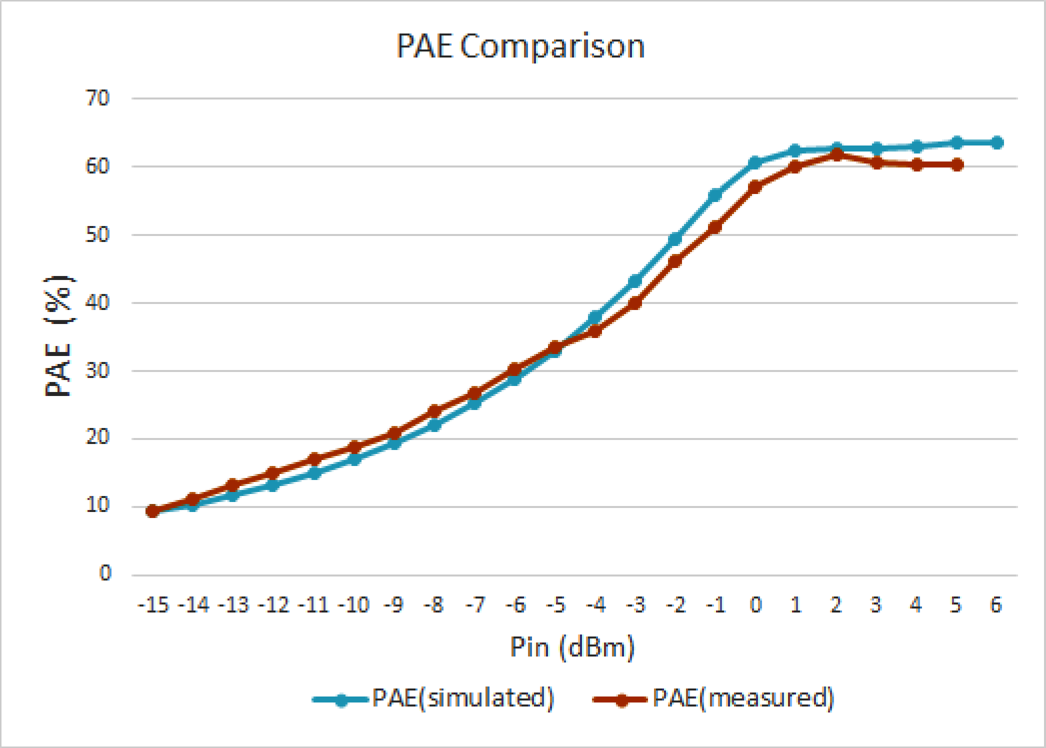


Figure 4.13: PAE Comparison

4.5 Observation

The observation of the package is the simuation results to the measured results are very closely related. Though the difference is present in each parmater measure because of the fabrication errors, component's tolerance, environment temperature, etc.

Chapter 5

Designing RF Power Amplifier: Class-F

In this chapter, the Class-F type of Power Amplifier is discussed, in the same band of frquency as in the earlier chapter for the Class-B. At the end of this chapter, the simulatioin and the measured data is compared.

5.1 Stability Analysis

Consequently, a stability analysis is crucial to any power amplifier design, especially at high frequencies. Rather say before starting to the designing one must stabilize the active device in the frequency band of interest. As discussed earlier, in ADS source and load stability circles can be found out by L_StabCircle and S_StabCircle pallete. The analysis for Class-F is shown in the fig. 5.1:

It is noted that all the circles are out of the $\Gamma = 1$, that is the reason one can say the design is unconditionally stable. Hence, one can find the matching network for the input and output stages because now the device is stable enough. It can not oscillate over the 0-4.0 GHz because of the unconditional stability. Fig. 5.2 shows the κ is always greater than 1 over 0 to 4 GHz, which shows the design is stable over

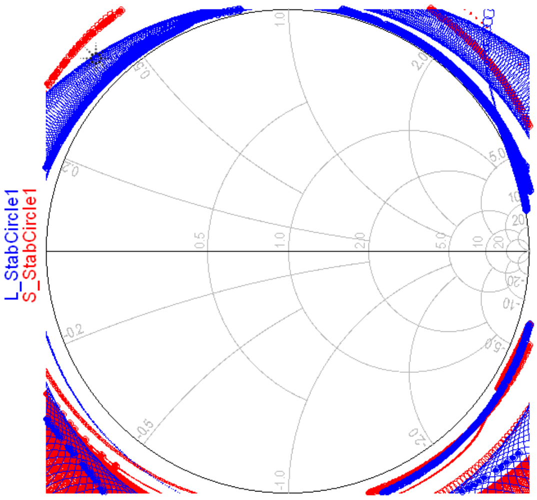


Figure 5.1: Stability circles for the Load and Source of the device.

this whole range of frequencies.

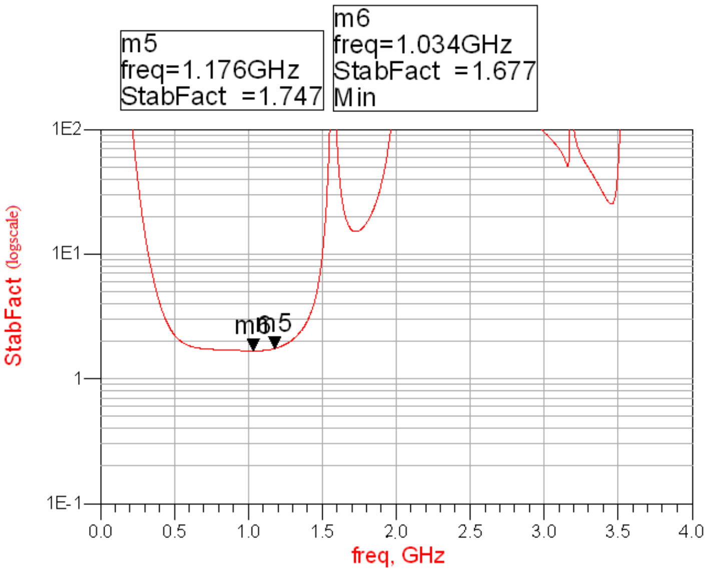


Figure 5.2: Stability factor for the stability analysis

5.2 Design of Class-F

The design flow of ADS for the amplifier is mentioned in Chapter 4, one has to find the impedance required for the device to transfer the maximum power to the load. But, one has to take into consideration that the termination required for the higher order harmonics. For typical design, one just provide the needed termination to the 2^{nd} & 3^{rd}. Because the design would be much complex, for provinding the proper termination of higher order harmonics.

As in the theory of Class-F the termination required in ideal condition for the odd and even harmonics are as follows:

a. **ODD** Harmonics:->	Open circuit condition
b. **EVEN** Harmonics:->	Short circuit condition

Schematic of Class-F

By considering the previous discussion on harmonic terminations, one should not forget that the marching of the fundamental frquency would got affected by the insertion of the stubs. Following is the schematic for the Class-F type of configuration:

In the fig 5.3, we have placed the stubs to terminate the harmonics as well as the matching for the fundamental. The Circles with the marker m1, for the termination of the 3^{rd} harmonic. The stubs are placed in both ways to trap the 3^{rd} harmonic at the junction of those stubs. Also the marker m2, is the matching network for the 2^{nd} harmonic termination. It also trap the 2^{nd} harmonic at the point. Later part of the schematic is for the fundamental matching.

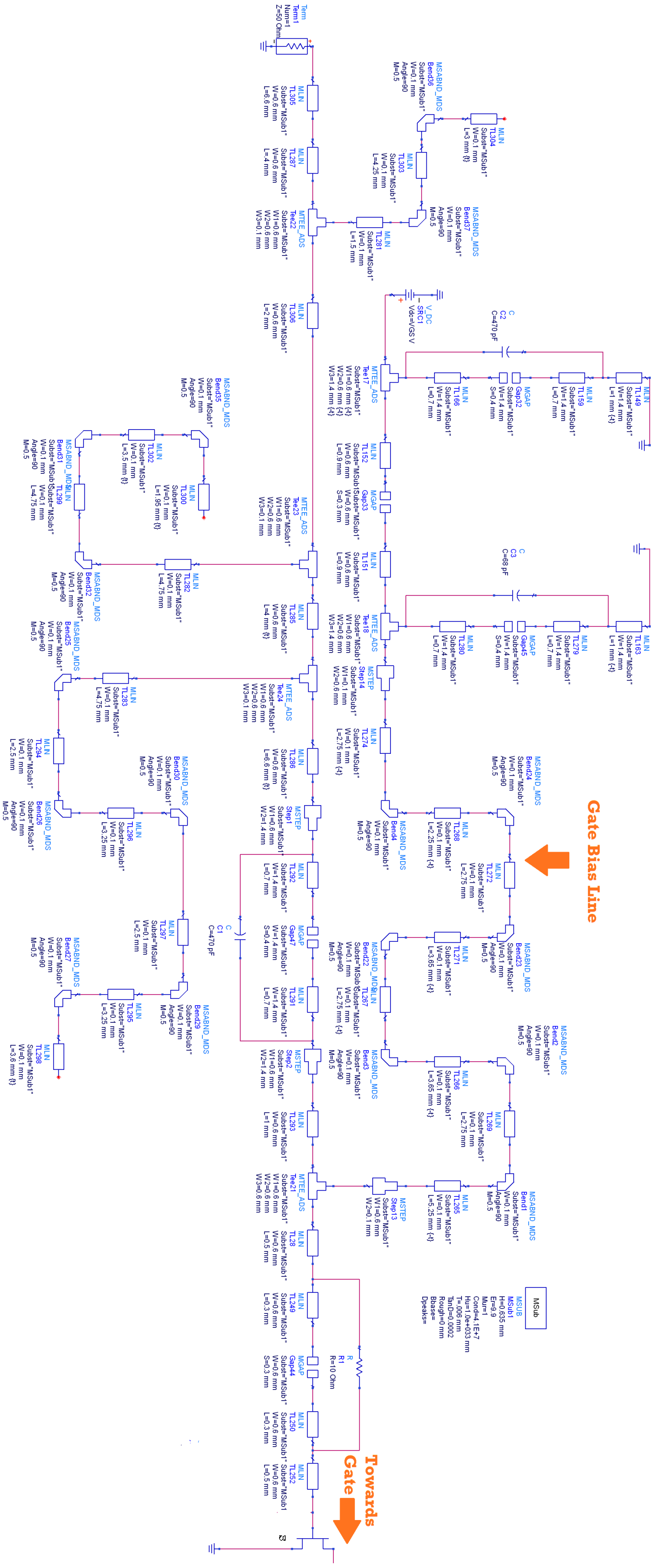


Figure 5.3: Inputstage schematic of the Class-F

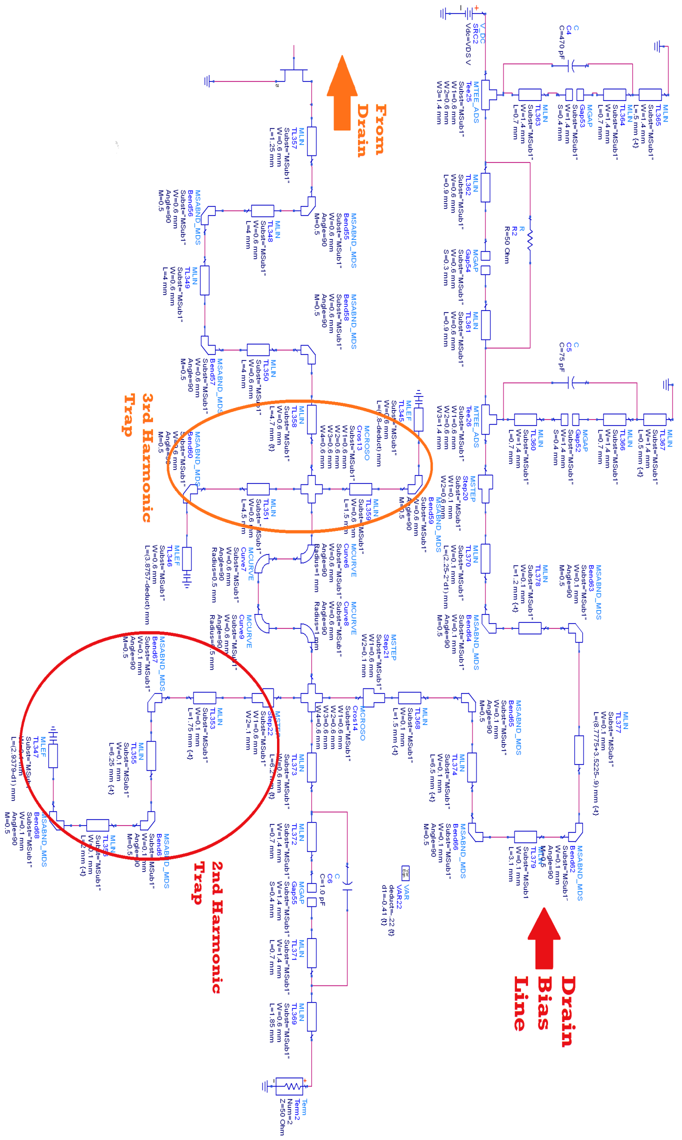


Figure 5.4: Output Stage Schematic of the Class-F

After the electrical analysis, the layout of the Input & Output matching networks with harmonic traps is generated. The criticality lies in placment of the stublength of for the harmonics are very near. This would create the mutual coupling between the RF tracks, which would ultimately change the impedance seen by the Active device. In generation of the layout, one has to follow the guidlines for the fabrication. Good designers are those who first calculate the future errors that would be significant in the fabrication and probably come up with the idea to negate that error. After considering all the constraints and guidelines, layout of the Input and Output matching networks are as follows:

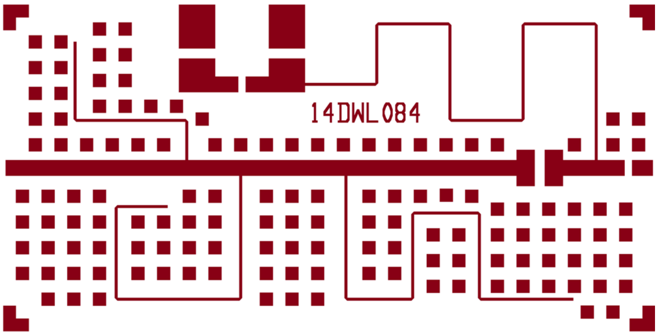


Figure 5.5: Layout of the I/p matching card with Gate biasline

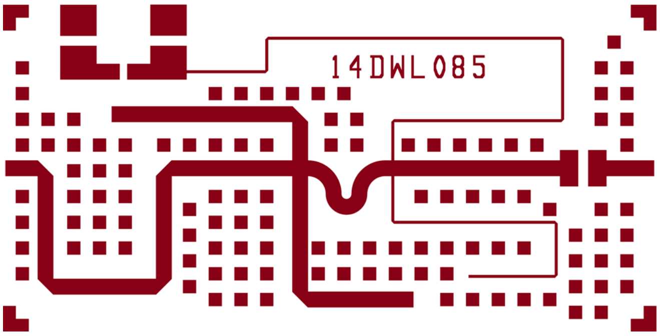


Figure 5.6: Layout of the O/p matching card with Drain biasline

As seen in Chapter 4 that in the microwave and mm wave range of frquencies, the typical behaviour swing of basic elements in electronics like Resistor, Capacitor and Inductor, is observed. Designer must consider the effect of the magnetic field on the circuit. Therefore, one must perform the EM momentum in ADS. Than the co-simulation of that both the desgins (* input & output stage) can be done later.

5.3 Results for Class-F

The simulation results for the Class-F configuration by considering the available components can be extracted from the ADS. Following are the results of the Class-F.

5.3.1 S-parameters

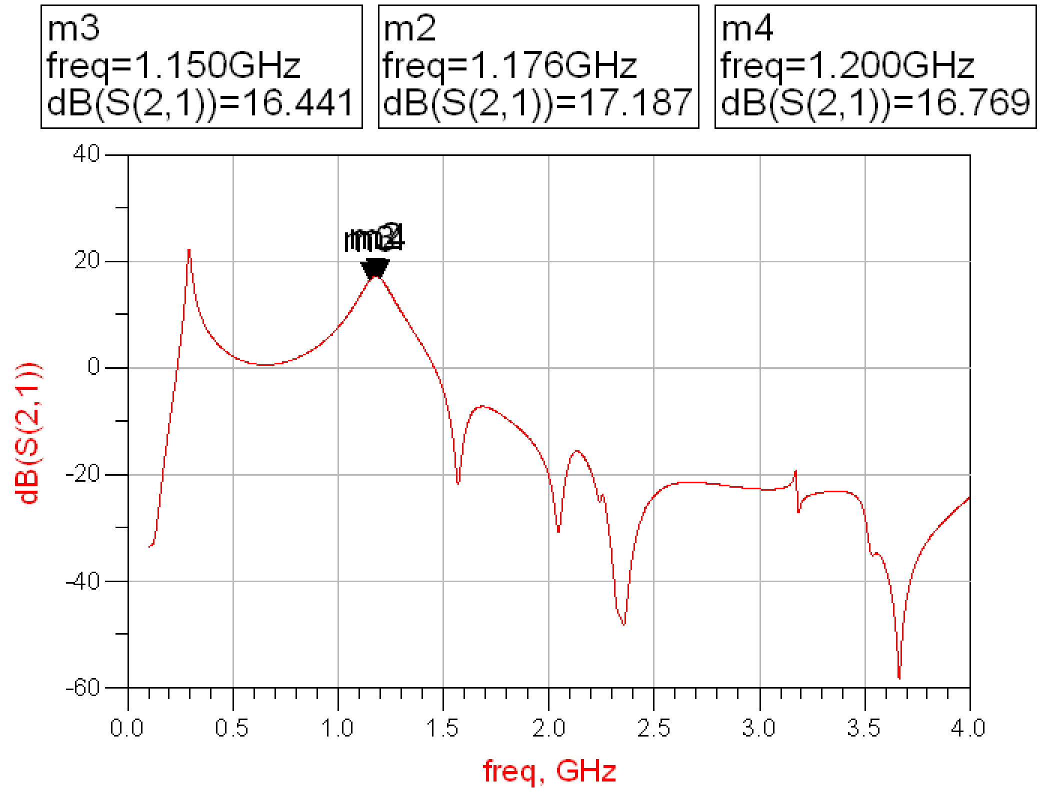


Figure 5.7: S(2,1) from Simulation

```
Marker 2 1.1500000000 GHz
```

```
  1:   1.176000 GHz  -11.491 dB
> 2:   1.150000 GHz  -14.508 dB
  3:   1.200000 GHz  -9.6518 dB
  1:   1.176000 GHz  16.768 dB
  2:   1.150000 GHz  16.605 dB
  3:   1.200000 GHz  16.099 dB
```

Figure 5.8: S(2,1) from Network Analyzer

First the response of the module is shifted towards the lower frequency. Speculation for the shift can be because of,

1. Lead misalignment at the Drain terminal & Gate terminal
2. The gap between the CP to the device's package.

Therefore, the tuning pad is placed at the Drain terminal to negate the shift.The tuning pad can be clearly seen in the Package.

5.3.2 Output Power

Simulated output power at F_0, $2F_0$ and $3F_0$ for the different input power is shown in the below figure. Also to check whether the the design is Class-F by observing the

Voltage and Current at the harmonics according the termination.As 3^{rd} harmonic is open circuited, must show higher voltage than 2^{nd}. Also the 2^{nd} harmonic is short circuited, must flow more current than 3^{rd}.

The fig 5.10 shows the comparison of Output Power from the tested & simulated result of the Class-F. Tested results are also nearly matched to the simulated results.

5.3.3 PAE measurement

The efficiency calculation is most important in any power amplifier design as mentioned before. Particurly, if one is designing power amplifier he/she must consider PAE, because drain efficiency would not consider amount of power currently presented at the input terminal. The comparison between the simulated result with the measured result is shown in the figure 5.11.

5.3.4 Gain Measurement

The Gain of the Class-F power amplifier can be found out by the following equation.

$$Gain = P_{out} - P_{in} \tag{5.1}$$

The power amplifer design must consider the gain compression. One must calculate the amount of gain compression at the saturated power or peak PAE. For that refer to the fig 5.12.

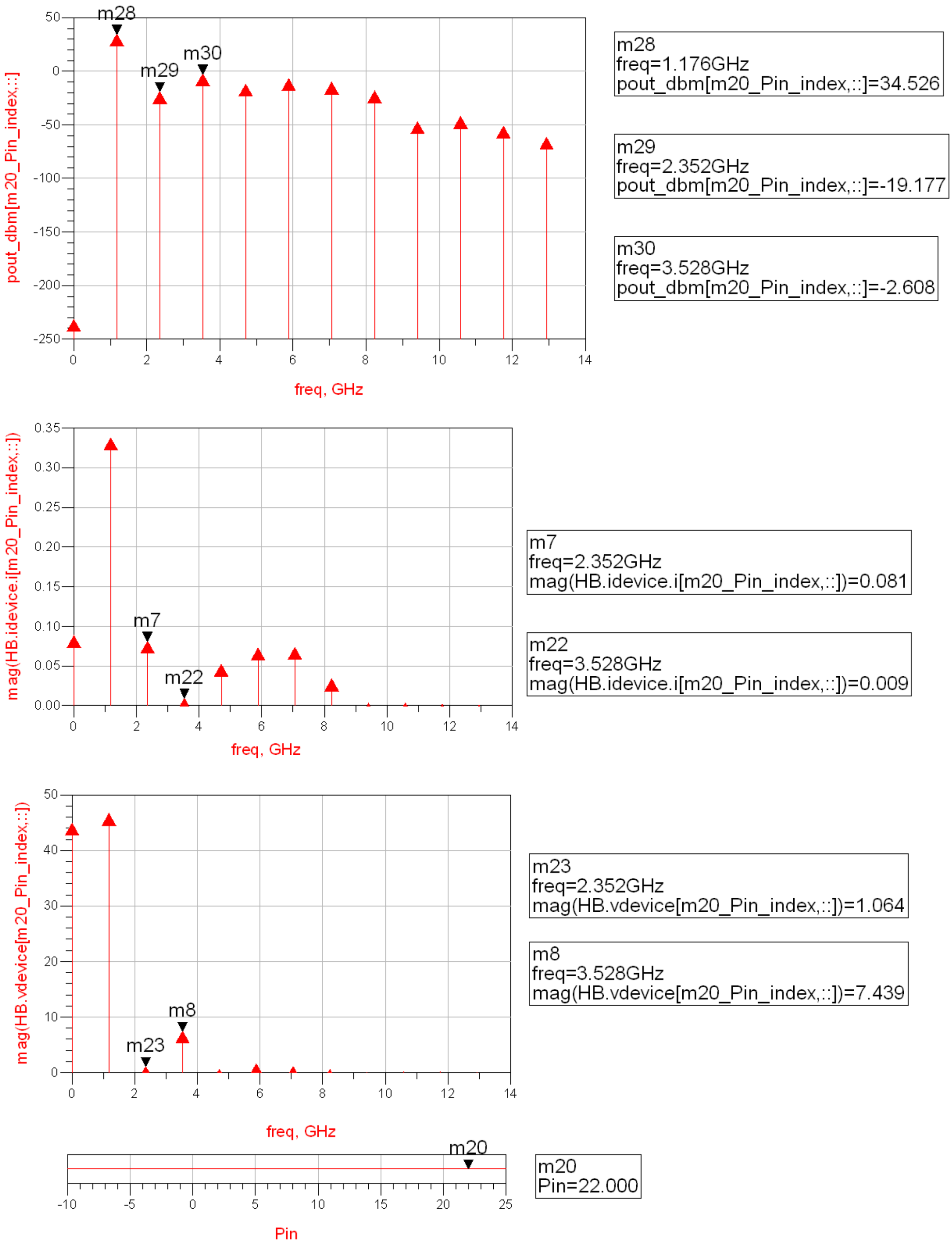


Figure 5.9: Pout Spectrum, V-I Spectrum at Pin

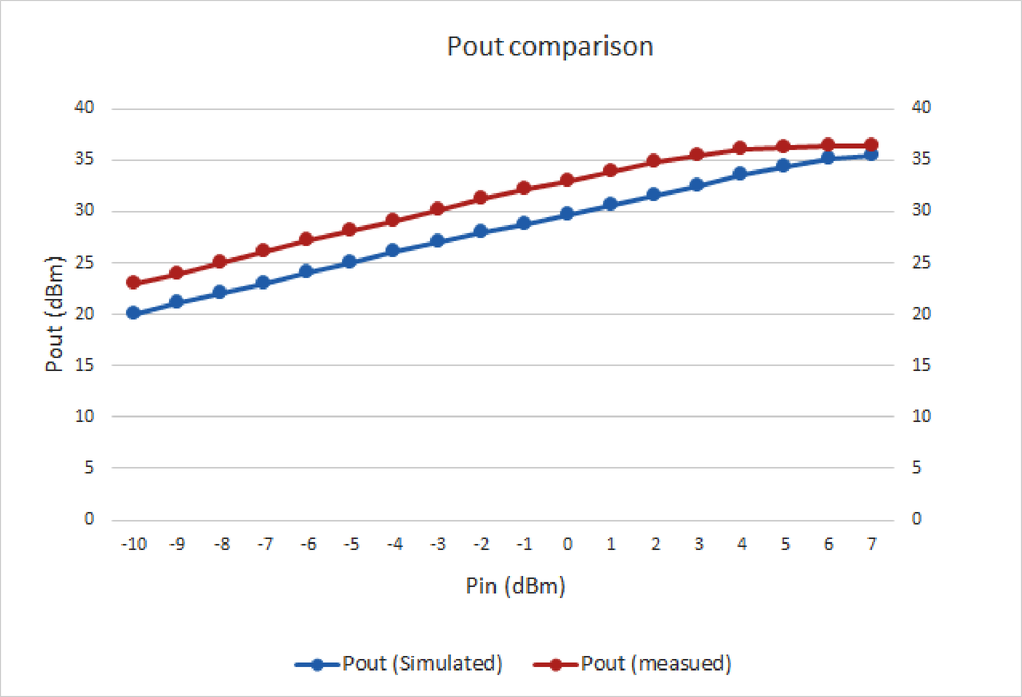


Figure 5.10: Comparison of measured & simulated P_{out}

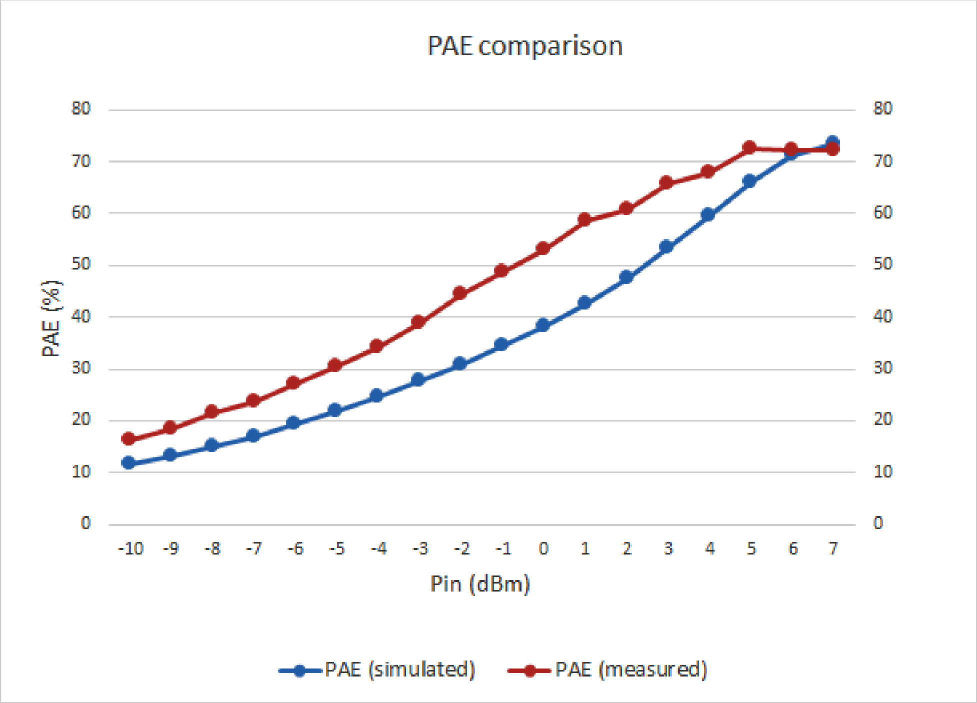


Figure 5.11: Comparison of measured & simulated PAE

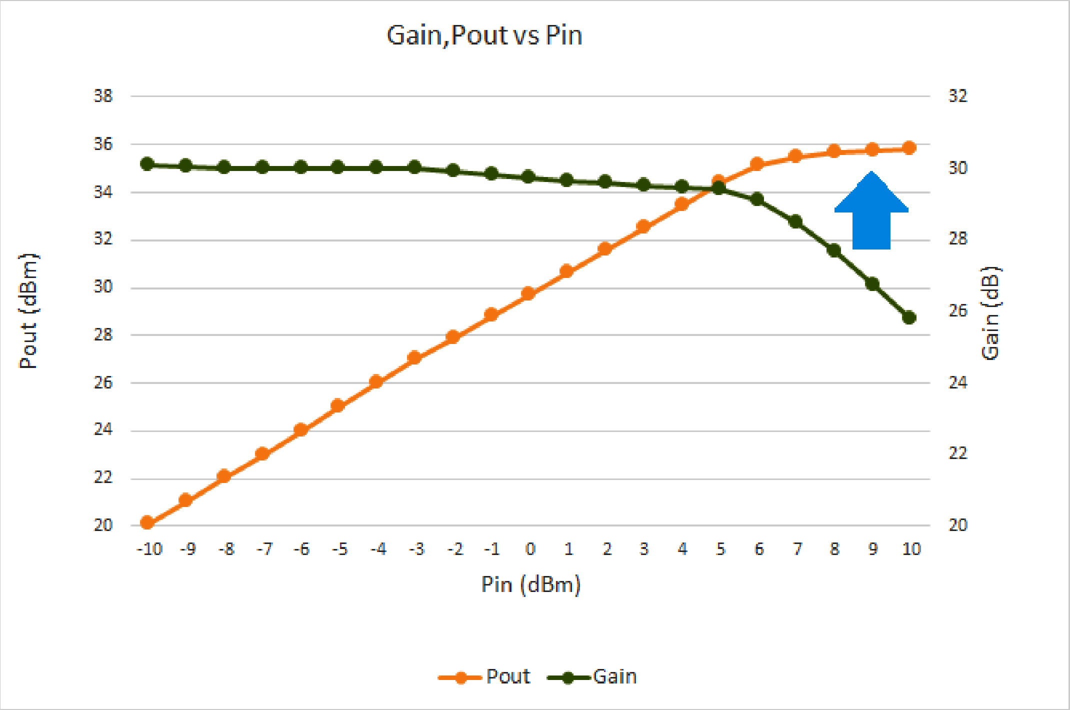


Figure 5.12: Gain, P_{out} Vs. P_{in}

As seen in the fig 5.12, the maximum P_{out} can be found at the Gain compression of 3dB.

5.4 Observation

It is observed from the results are that the harmonics effect the performance of the Power Amplifier. As tuning of the harmonics are done, the Gain, PAE & P_{out} improves. Here only 2^{nd} & 3^{rd} harmonic tuning is considered, but for better performance one can tune the higher order harmonics.

Chapter 6

Conclusion

6.1 Conclusion

Basics of GaN HEMT has been learnt, also discussed about RFPA parameters. Particular design the Class-B & Class-F PA with 4W GaN device by SEDI [14] is also mentioned in the previous chapters. But in this era, where multimedia communication is growing leaps and bounces, one needs higher datarate. To fulfill this requirement, the amplifier should provide the Gain over wider bandwidth.The higher datarate cause the amplifier design to be broadband or say wideband for the application. Also higher PAE is one of the key requirements in RF/microwave PA designs, as it will lead to low power comsumption, reduced cooling requirements, small battery size and low cost in RF front ends. From the previous chapters the conclusion is made that the Class-F has higher peak PAE than the Class-B. Thus, we can say that the harmonic terminations is helpful to improve efficiency of the device.

Fig. 6.1 shows that the PAE of Class-F is much better than Class-B. In this case 10% of PAE has being improved. Also the fig. 6.2 shows the P$_{out}$ of the Class-F is >1dB from the Class-B.

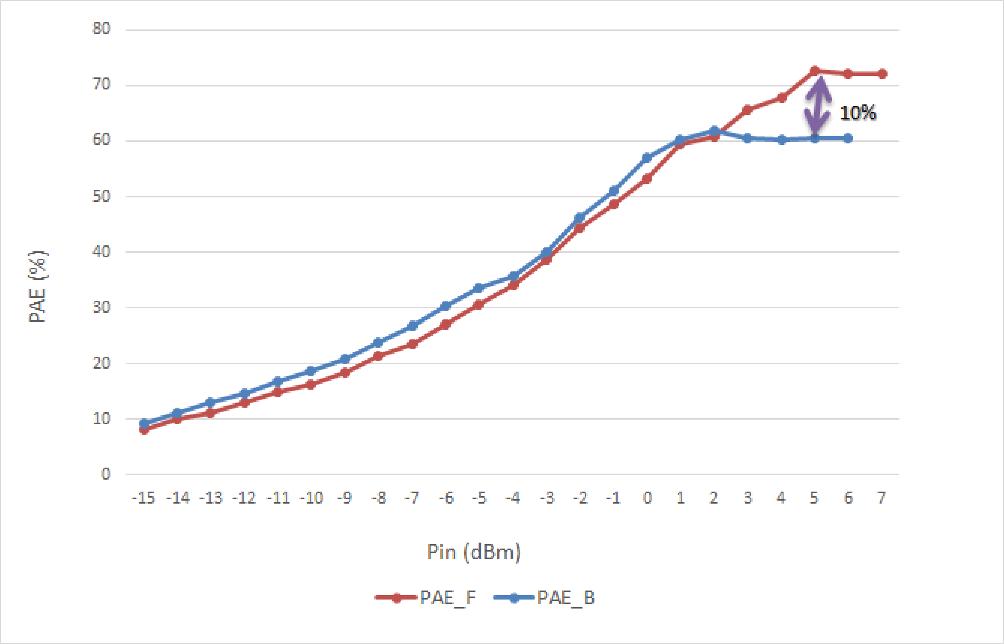


Figure 6.1: PAE comparison between Class-B & Class-F

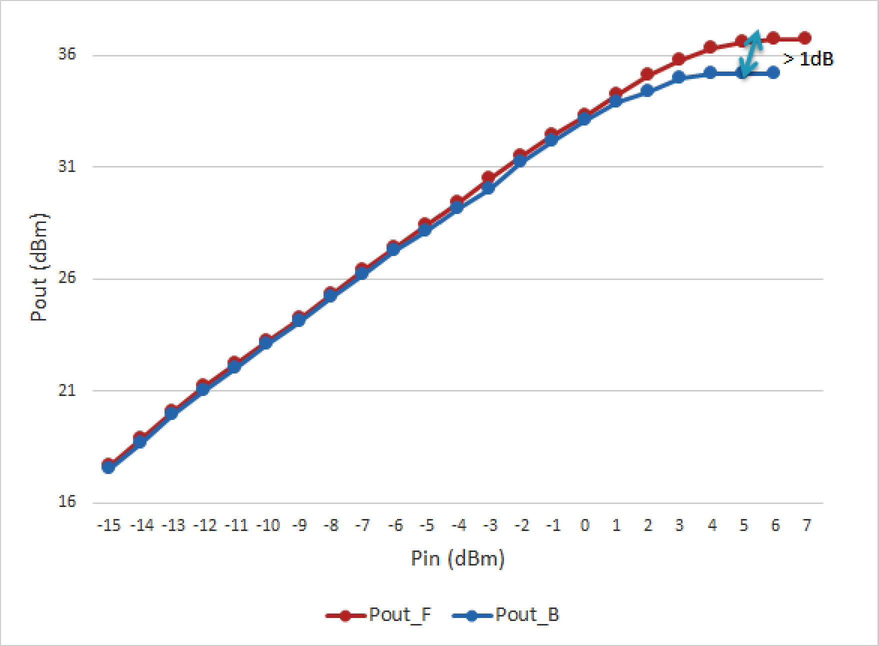


Figure 6.2: P_{out} comparison between Class-B & Class-F

6.2 Future scope of work

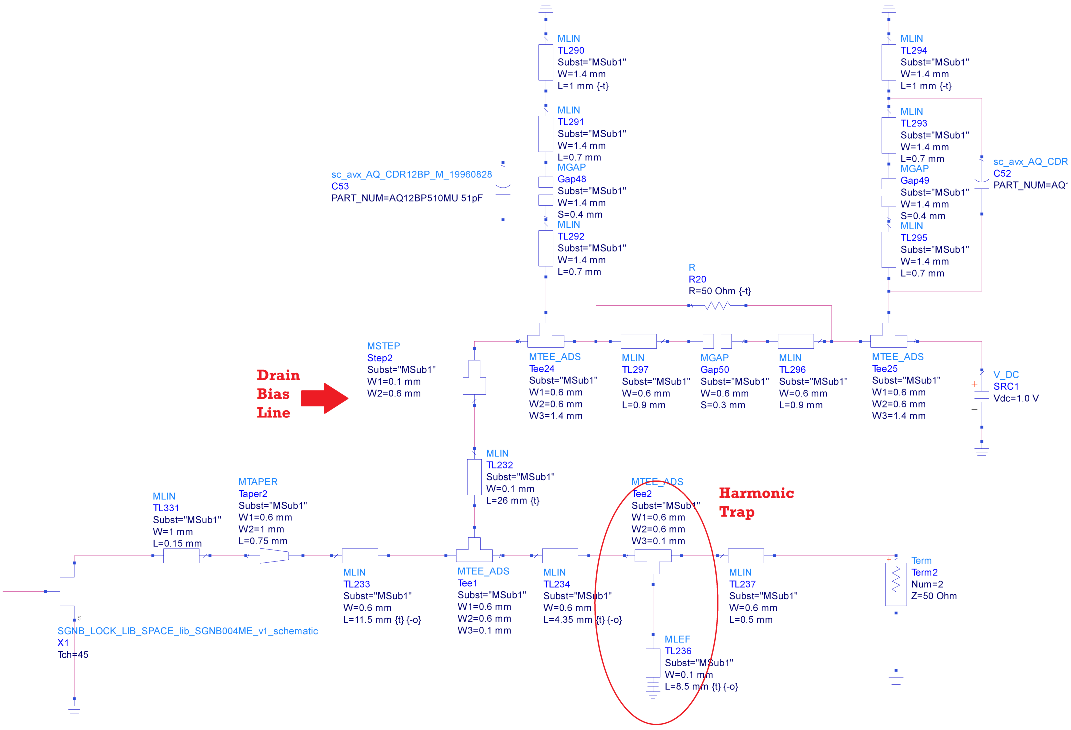


Figure 6.3: Inerse Class-F configuration

Proposed configuration would terminate the 2^{nd} and 3^{rd} harmonic to the open load and short load respectively. By the waveform engineering we can make the design which has higher efficiency over wide range of frequency. Above figure is similar to the Class-F but only the terminations are altered. Thus this configuration usually called the Class Inverse-F. [15] shows by providing the different termination for 2^{nd} and 3^{rd} harmonics could possibly give the 78% PAE.

The smithchart would verify the schematic is providing 2^{nd} harmonic the open circuit load and 3^{rd} harmonic the short ciruit load. Also [16] has described about one novel class of amplifier named class-J which is yet to be exploited fully. In future we can also implement the class-J PA configuration using GaN HEMT.

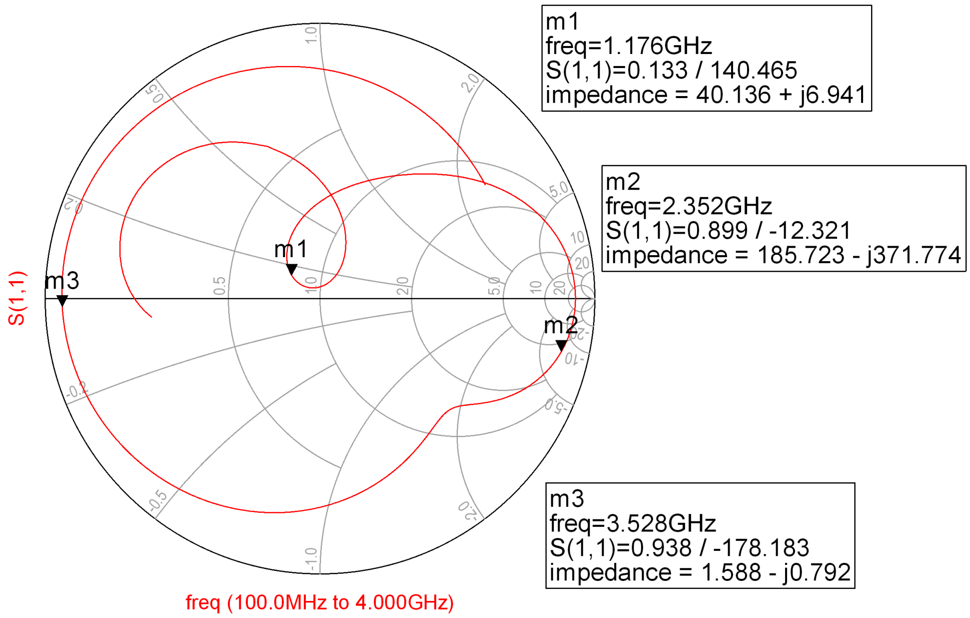


Figure 6.4: S(1,1) of Inverse Class-F

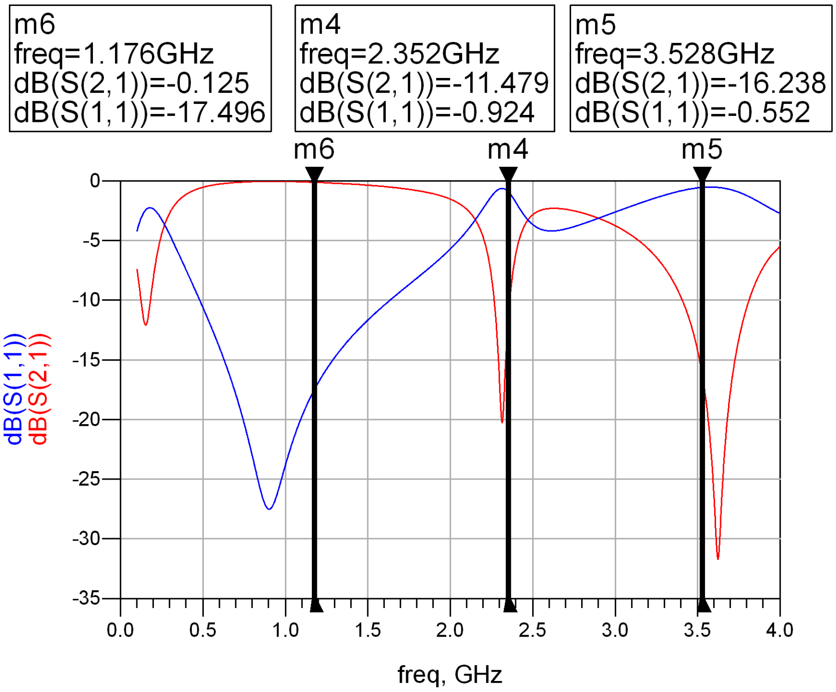


Figure 6.5: dB(S(1,1)) of Inverse Class-F

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