# AlGaN/GaN HEMT Based L-Band Power Amplifier for LTE and Wireless Applications

By

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# DECLARATION

I hereby proclaim that I have written this thesis absolutely on the basis of my gentle hard work beneath the sincere supervision of my supervisor Dr. Faisal Amir. Everything used in this work have been cited and the contents of this thesis have not been plagiarized. No portion of the exertion presented in this thesis has been submitted in support of any application for any other degree of qualification to this or any other university or institute of learning.

# ACKNOWLEDGEMENTS

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# DEDICATIONS

I dedicate my dissertation work to my family, classmates and my teachers.

## Abstract

The rising demand for high data rates and longer ranges drives the mobile technology to develop enhanced services and standards. Currently, LTE systems are being designed to handle higher data rates; this sets condition for broader bandwidth and improved linearity together with demands for lesser cost and improved services. Moreover, higher output power is desired at both mobile user and Base Station to achieve longer ranges. However, challenge is to design a solid state Power Amplifier (PA) with small form factor. In this regard, GaN based solid state Power Amplifiers (PA) provides promising solution since they have a small form factor being operating on 28V DC, however, heat dissipation through a heat sink remains a challenge.

This thesis is therefore aimed to design a solid state GaN based two-stage PA for S-band applications. The proposed PA is designed with a centre frequency of 2.25 GHz and with 2-2.3 GHz Bandwidth (BW). The PA model was developed in ADS 2009 with State of the art Cree GaN transistors. In the $1^{st}$ stage, Cree unmatched transistor CGH40006P takes input of 10dBm or 100mW from a signal source and provides RF power of 29dBm at its output. In the $2^{nd}$ stage this RF power is fed into another Cree unmatched transistor 40010F through an attenuator so as to prevent any damage to the system. The attenuator also isolates both stages. The second stage provides RF output of 40dBm or 10W.

During the course of research, PA design, optimization and simulation have been performed. The designed amplifier was then manufactured and characterized in S-band (2-2.3GHz). Subsequently, both designed and measured results were compared to validate design. The designed PA shall provide cost effective high power solution in S-band for LTE and wireless applications.

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Chapter 1

# 1 INTRODUCTION

## 1.1 Background

Radio Frequency (RF) amplifiers are considered one of the most significant apparatus in almost every kind of wireless purposes. Every application has dissimilar necessities conditional on frequency and kind of input signal they are dealing with. This leads to the information that, different RF amplifiers have to be intended for every specific purpose. For every explicit purpose, they are anticipated to offer appropriate output and gain while achieving satisfactory competence under application-specific linearity concern. For instance, elevated efficiency and linearity are very important in mobile communication systems, whereas for military radars elevated output power is of first concern.

There are more than a few purposes which require elevated power at elevated frequencies jointly with efficiency and linearity. Such elevated efficiency and power purposes need transistors having characteristics of elevated electron speed, elevated breakdown voltage and elevated heat conductivity. For this reason, wide bandgap semiconductors transistors derived from such as GaN and SiC are favored alternative. RF Power Amplifiers (PA) is the most significant constituent in the RF frontend and is consider the holdup in elevated competent wideband transmitters. In the last two decades, communication systems have progressed considerably and turn out to be a vital means of carrying out everyday life activities in current societies for mingle with people and also in a variety of other sectors like health, defense and business,.

In this thesis, research work has been carried out to examine new method of improving bandwidth, efficiency and output power of Power Amplifier (PA) designed for s-band applications. This thesis initiates with an introduction that sets the background vital for all the following chapters of the thesis and starts with research stimulus.

## 1.2 Research Motivation

High power amplifiers (HPAs) considered essential ingredient of cutting-edge multifunctional wireless system. Owing to the elevated power dissipation of the HPAs and because of the inadequate key energy in self-sufficient systems, the progress of efficiency optimized power amplifiers are very hot topic among researchers in this field. They are utilized in present communication and self-sufficient radar applications like solid-state phased arrays in addition to for airborne and space purposes to conserve supplementary cooling energy. Of the various semiconductors and device technologies at present accessible, the most capable substance aspirant for these purposes is the wide bandgap gallium nitride (GaN). Because of its intrinsic and exceptional material properties such as power density of more than a factor of ten compared to GaAs devices, GaN enables a remarkable ability for elevated-power amplification resulting in a elevated output-power above 20W on circuit level. Consequently, GaN-based HPAs have prospective to accomplish future demands on elevated output power for large bandwidth applications at a reasonable gain compression.

**Table I: Material properties of semiconductors [28]**

| Material | Si | GaAs | 4H-SiC | GaN |
|---|---|---|---|---|
| Relative dielectric constant $\varepsilon_r$ | 11.8 | 13.1 | 10 | 9 |
| Bandgap $E_g$ (eV) | 1.1 | 1.42 | 3.26 | 3.39 |
| Lattice constant (Å) | 5.4 | 5.7 | 3.1 | 3.2 |
| Electron mobility $\mu$ at 300 K ($cm^2/Vs$) | 1350 | 8500 | 700 | 1200-2000 |
| Saturated electron velocity $v_{sat}$ ($10^7 cm/s$) | 1 | 1 | 2 | 2.5 |
| Breakdown field $E_{br}$ (MV/cm) | 0.3 | 0.4 | 3 | 3.3 |
| Transit frequency $f_T$ (GHz) FET | 20 | 150 | 20 | 150 |
| Thermal conductivity $\Theta$ (W/cmK) | 1.5 | 0.43 | 3.3-4.5 | 1.3 |

### 1.2.1 Evolution of Wireless Communication

In present times, wireless systems are the spine of the contemporary world. In accordance with current estimates, total quantity of wireless mobile users is rapidly growing and almost touched by millions yearly as well as revenues of the market are hundreds of billions of dollars. For instance, in OECD (Organization for Economic Co-operation and Development) countries, the wireless broadband users have shown an annual boost since the beginning of the 1990s. At the present time, wireless system is the fastest rising sector driven by the user demands for wireless purposes such as smart phones, mobile devices and internet access portable devices together with the mandatory elevated data throughput. Figure below depicts surge in demand in mobile communication alone.

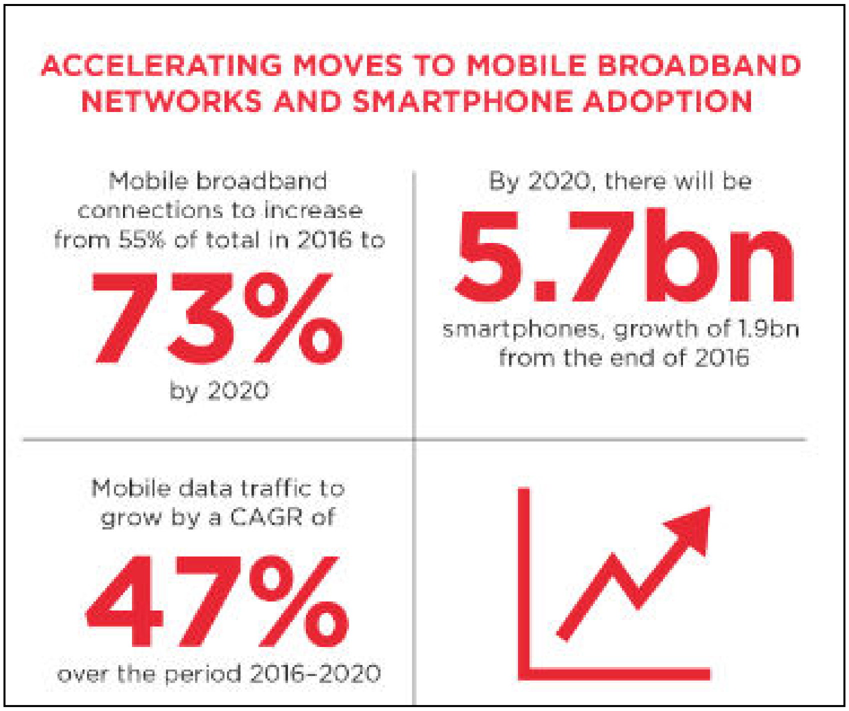



Figure 1: Wireless Communication surge by 2020 as depicted by Ecrisson [29]

### 1.2.2 Challenges in Improving Wireless Communication Systems

The rising demand for more data rate drives the mobile technology to act in response and offer enhanced services and standards. For instance, the first mobile generation (1G cellular) introduced in the early 80s was derived from analog network operated at 900 MHz band. The second mobile generation system (2G cellular) was derived from digital networks using TDMA, GSM TDMA, and CDMA modulation schemes and brings in a decade later in the early 90s. This 2G system offered much enhanced services compared with their forerunner 1G cellular system. The 2G cellular system has progressed to the 2.5G and 3G systems function in larger frequency bands to fulfill user demands of higher data rate and reaching up to 2.1 GHz. At the present time 3G systems are in action around the world, offering more data throughput and enhanced functionality [5]. The currently rising LTE systems are designed to propose even larger data rate; this sets condition for broader bandwidth and improved linearity together with demands for lesser cost and improved services.

## 1.3 Research Contribution

This thesis' research is aimed to simulate and design GaN based s-band power amplifier for s-band applications.

### 1.3.1 Key Features

- Number of stages: 2
- Frequency range: 1.8 GHz to 2.4 GHz
- Center frequency: 2.25 GHz
- Technology: GaN
- Final Output power: 10W

### 1.3.2 High Electron Mobility Transistor

The High Electron Mobility Transistor (HEMT) is a frequently applicable transistor extensively utilized in many devices deployed in domain of radar, satellite and aeronautics. HEMT was first introduced in era of early 80's [11]. Usual HEMTs on today's market has bits and pieces boundaries and researchers have pushed the GaAs up to its speculative boundary in last five decades. New techniques and materials are necessary for coping with current demands of elevated data rate and elevated power even at lower power consumption. GaN is the substance of preference for the next generation HEMT technology as a result of its tough electronics and physical properties.

Mobility transistors are originated form FET class of transistors that are well known due to its outstanding higher frequency uniqueness. It is made of epitaxial layers developed on apex with three conventional transistor contacts named as; drain, source and gate. These contacts developed over the surface of the transistor. HEMT devices developed form AlGaN more often than not works in depletion mode. In depletion mode, current flows from side to side the device even with no an external gate-voltage [22]. The gate voltage essential to discontinue the flow of electron in the middle of the source and drain contacts of the transistor. This voltage is referred as pinch-off. MESFET and HEMT operating principles are indistinguishable with the utilization of Schottky to reduce transistor channel [23]. When voltage at transistor gate is zero, there is a presence of potential well present at boundary of AlGaN/GaN. Within this potential well, 2D electron gas is present. The 2DEG is characteristically a pair of very fine nanometers thick where drifted electrons are collected to shrink their energy. This slight channel is acknowledged as conducting channel where electrons voyage from source to drain. Due to very thin wall, only sideways flow of electrons is possible in this 2D rather than up and down motion. This motion prevents transfer of electron from established well to undesirable energy state [24]. The AlGaN-GaN polarization fields need extraordinary consideration. GaN and AlGaN materials potential profile mainly dependent on polarization fields that [25]. The AlGaN HEMT not need highly doped n+ top layer (for electrons similar to AlGaAs HEMT). In actual fact, developed polarization fields strong enough to sustain and transfer enough quantity of electrons to the junction [22].

GaN HEMT technology offers following main advantages discussed in details in next chapter.

1. Elevated Power Added Efficiency
2. Elevated Operating Voltage
3. More reliable device

Following figure depicts relation of drain voltage and current in GaN HEMT transistors.

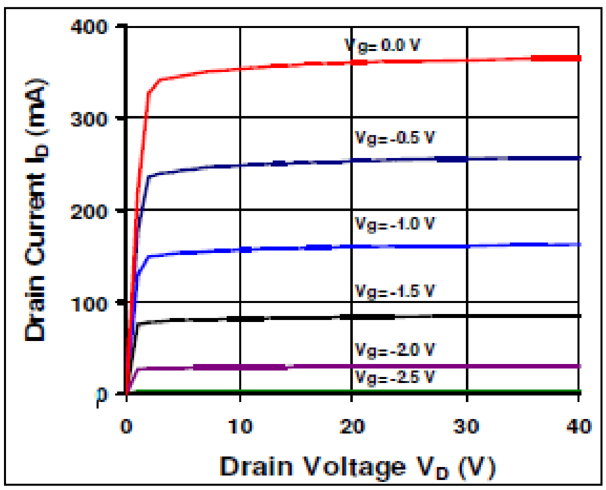



**Figure 2: IV characteristics of GaN HEMT**

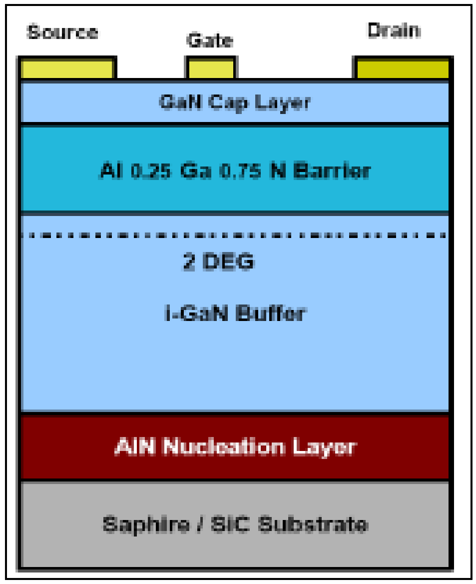



**Figure 3: Schematic of GaN HEMT**

## 1.4 Computer Aided Design (CAD) Simulation

To forecast circuit completion through complex device analysis, substrate, inter device, among devices and other similar issues before time and costly device physical prototype, computer simulations provoked as the most vibrant hands-on device appeared by 1970s. Computer aided simulations (CAD) is a prevailing tool used for analysis and design of almost all electronic circuits and RF devices. CAD tool cuts down design cycles and also reduce cost and remarkable human work to analyze devices and circuits especially in case of ICs with growing density and intricacy. CAD tool is also cooperative in inquiring within the circuit to calculate electrical parameters prior to device fabrication which cannot be calculated directly even after the device fabrication. CAD simulation tools can be categorized into following main kinds:

1. Simulations of device process

2. Simulations of device itself

3. Simulations of circuit

4. Simulations of overall system

Available CAD tools in the habit of simulating, developing and designing typical transistors whether HEMT, FET or advanced devices. Typical CAD tools based transistor structure in depicted in figure below.

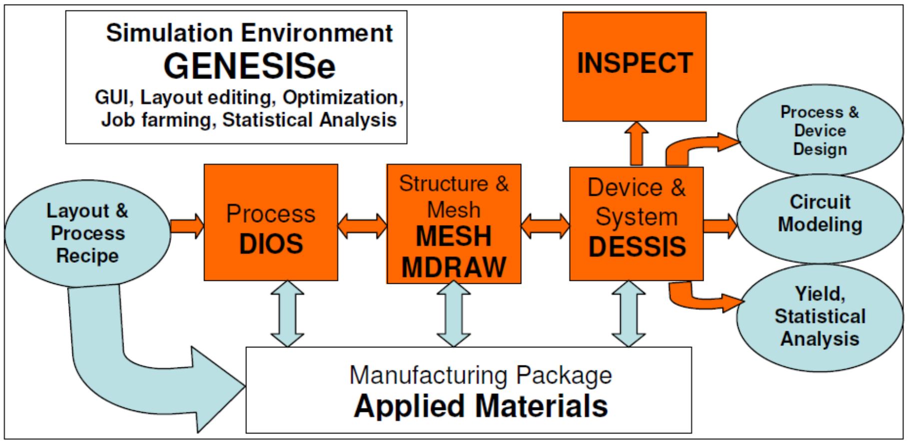



**Figure 4: CAD simulation environment**

## 1.5 Research Objective & Thesis Structure

This thesis seeks to deal with the design and development of proficient s-band PA for wide band purposes. The first purpose is to examine elevated efficient PA looking from a perspective of engineering and perform various simulations to analyze the device efficiency, efficiency and desired output. The second objective is to fabricate the device for intended applications.

Rest of thesis will comprise of following chapters.

Chapter 2 discusses HEMT in details

Chapter 3 discusses power amplifiers in detail.

Chapter 4 discusses GaN HEMT design and simulation results

Chapter 5 discusses HPA fabrication and performance tests

Chapter 6 discusses conclusion and future work

Chapter 2

# 2 HIGH ELECTRON MOBILITY TRANSISTOR (HEMT)

## 2.1 HEMT

The high electron mobility transistor (HEMT) is a highly developed hetero-structure material founded on the MESFET rule [13]. On the other hand, because of its better transport and general material characteristics, the HEMT device produce elevated power-added efficiency (PAE), elevated gain, elevated output power and improved low noise efficiency for a broader frequency range [83]. These characteristics make HEMT devices mainly appropriate for elevated-power purposes.

Wide-bandgap semiconductor technology developed for elevated-power microwave devices has developed swiftly over the last several years as supported by the fact that AlGaN/GaN HEMTs are readily accessible as commercial-off-the-shelf (COTS) devices since 2005. The matter characteristics of GaN compared to similar materials are already presented in chapter 1 of this thesis. As depicted, AlGaN/GaN HEMTs have elevated breakdown voltage, which permits larger drain voltages to be utilized, therefore lead to elevated output impedance for each RF watt, ensuing easier matching and lesser loss in matching circuits. The elevated sheet charge generates more current densities and transistor region can be abridged thus providing elevated watts per millimeter of gate margin. The elevated saturated drift speed responsible for elevated saturation current densities and watts per unit gate margin. Consecutively, this offers lower capacitances per output watt power. Characteristics of low output capacitance and drain-to-source resistance per watt also put together GaN HEMTs appropriate for switch-mode amplifiers.

### 2.1.1 Advantages of HEMT

Devices fabricated by using elements from group III-V of modern periodic table reported to slow down electron in case of environment where temperature is higher than normal room temperature. In contrast, GaN crystal lattice inherently avoid decelerating of electron and maintain steady current even at higher temperature. Inherent capabilities of GaN lattice to provide higher conductivity and effectual heat transfer capability. Therefore, wide band-gap based GaN devices can function at elevated working temperature of approximately 350 degree C prior to prominent degradation in efficiency characteristics.

Following points summarizes importance of GaN devices over conventional transistors:

- *Elevated Power Added Efficiency (PAE) of GaN devices:* GaN devices able to have efficiency up to 48% while usual GaAs or FET devices have C-band efficiency in range of 25- 30 %.
- *Elevated Operating Voltage of GaN devices:* Operating voltages vary of GaN HEMT devices is approximately 48Vdc. Furthermore, for required output power of GaN devices, current in device can be extraordinarily abridged contrast to other devices fabricated from elements of group III - V. Additionally, breakdown voltage of GaN devices also very high and lies above 100V (dc), which makes sure that the device survives elevated voltages with no damage intrinsically. This allows RF PA designers to lay comparatively less attempt in similar device impedances for 50 ohm and therefore, increase efficiency, power and efficiency, for example broader bandwidth and improved added efficiency [14].
- *More reliable device* - The inherent lattice structure of GaN devices provide elevated temperature managing competency that makes GaN devices suitable for vigorous and dependable part of Solid PA subsystem.

### 2.1.2 HEMT Technology Overview

Prior to breakthrough of GaN technology, RF engineers and designers mainly focus on following three domains:

1. Improvement in superiority of epitaxial material,
2. Looking for appropriate material for PA substrate, and
3. Unit process development (e.g., [7]).

Initially, MOCVD (metal-organic chemical vapor deposition) was very well researched in order to optimize PA efficiency. Successful achievements have been made possible through advancement in hetero-epitaxy of GaN and AlGaN. Other field of interests include molecular beam epitaxy (MBE) that support feasibility of GaN based device fabrication and its potential in the field of microwave system design as discussed in [9] and [10].Epitaxial progression were achieved due to its accessibility and interest of industry giants to produce mass production of GaN HEMT based devices for microwave applications. Maximum potential of GaN based devices is still to be unlocked since low cost Silicon substrate is major limitation that needs to be resolved. Other potential options include SiC based substrate that offer improved efficiency and better heat management.

High-tech power levels have been confirmed on SiC substrates with total output power of approximately 800 W at frequency of 2.9 GHz [6] and in excess of 500 W at frequency below 4 GHz [11]. The efficiency advantage of such semiconductor devices are extraordinary because of their capability to build hetero-structures in a material system that also sustains elevated breakdown fields. This has offered the main components essential for elevated breakdown voltage and elevated trans-conductance device outcomes as technology advanced in the mid-1990s [10]. Obvious consideration of the occurrence of improved carrier density of 2DEG carrier was accomplished when charges due to strain and polarization were elaborated in [11]. Consequent microwave device physical structure and development in handling directed to the passivity of GaN HEMTs. Results clearly indicate improved heat benefit through utilization of SiC as replacement of Si substrate for elevated total RF power discussed in [14] and [15].

The epilayers for Cree commercial model of HEMT devices are very matured by MOCVD in an elevated-volume reactor on scale of 100-mm semi-insulating substrate of 4H silicon carbide (SI 4H-SiC) that slit on-axis. The epitaxial development procedure is vastly reproducible and in manufacturing and production for more than a few years, in part because of the financial support on the Defense Advanced Research Projects Agency (DARPA) agency and Wide Bandgap Semiconductor (WBGS) Program originated in early 2000's [16]. Representative configurations include an AlN nucleation layer, roughly 0.6 nm of an AlN barrier layer, 1.4 m of Fe-doped insulating GaN and also 25-nm cap layer of un-doped Al Ga N. This insignificant layer thickness and mole fraction produce electron sheet concentrations in 8 to 10 10 /cm, but as a result of AlN interlayer has the resilient benefit of electron mobilities close to 20 m /V s at normal temperature [17]. Electron sheet resistance for this layer is about 335/square.

### 2.1.3 HEMT Device Structure

Figure below demonstrates distinctive Cree model of AlGaN/GaN HEMT device. The ohmic contacts are fabricated directly going on the top of AlGaN substrate layer. To attain a planar arrangement, separation of the device is comprehend by nitrogen implants. Electrodes of gate contacts are composed of Ni/Pt/Au installation are buried from side to side to the SiN dielectric to the AlGaN substrate. Sturdy electric fields survive at the metal semiconductor intersection on the drain side in sideways device configuration. To give an even incorporation of electric field figure using metallization of gate, the device structure is optimized in such a way that the gate electrode is crossways extensive on the drain side. Also, the source resistance is abridged and the gate-to-drain voltage collapse is augmented by slightly counterbalancing the gate footprint

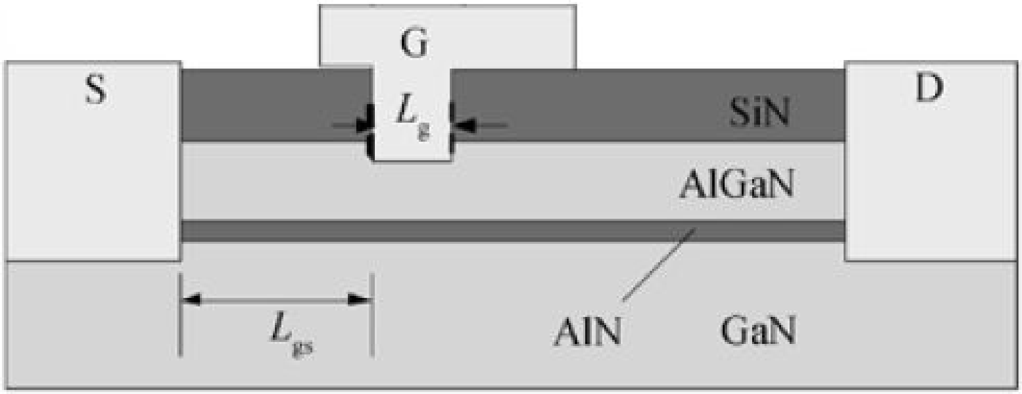



Figure 5: Schematic section of GaN HEMT

The device is made-up with ohmic contacts that are produced directly on the top AlGaN layer. Device separation is attained through nitrogen embed to attain a planar arrangement [18].

### 2.1.4 GaN HEMT Models

The utilization of tradition transistors needs a technique to assess device efficiency in a rapid and easy approach. By using a corresponding model of PA circuit, device distinctiveness associated with the looked-for PA efficiency is recognized and customized during simulation in any CAD software. This permits rapid union of most favorable PA device architecture and sizes in production cycle. Below figure below shows the PA design cycle where GaN HEMT device are planned, made-up, at that time by modeling the invented PA design whichever a new mask is aimed or PA may be planned and made-up. Discussed PA design cycle is accustomed to congregate on finest GaN or HEMT devices that fulfils the specified set of PA necessities.

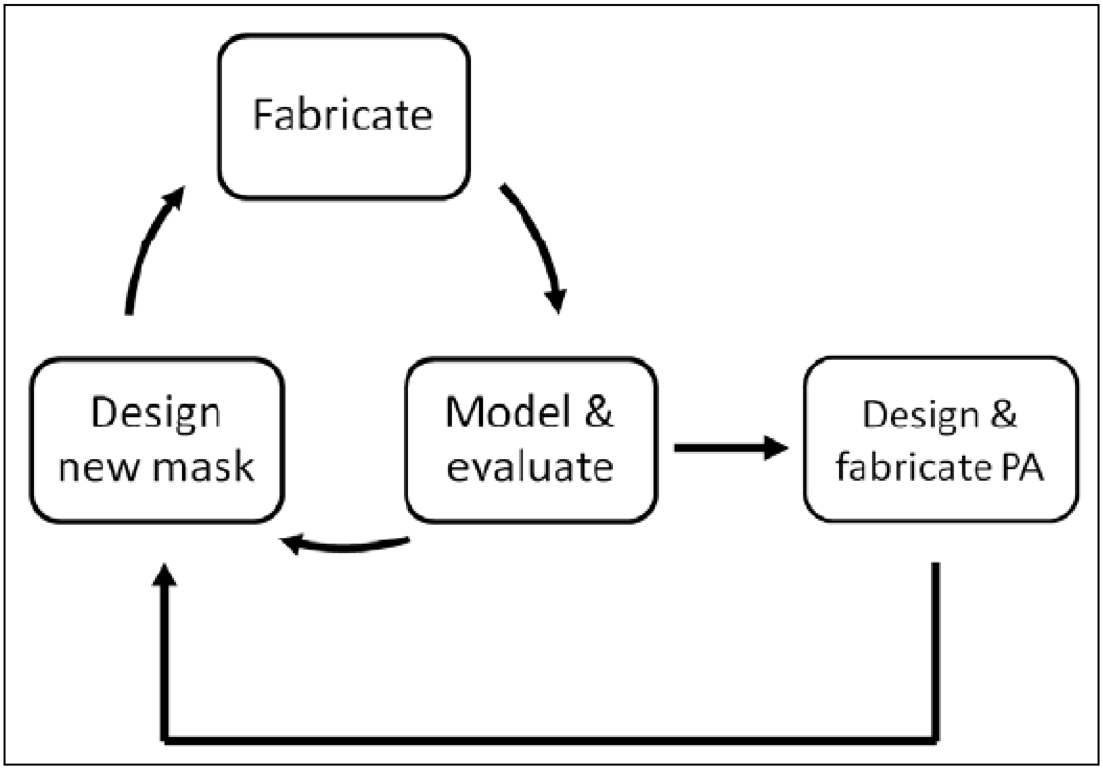



Figure 6: GaN HEMT PA Design Cycle

Design of RF power amplifier is usually derived from Load Pull measurements or the non-linear simulations. The last method is more often than not chosen as a result of its handiness and cost efficiency. On the other hand, the non-linear simulation technique requires a precise large signal device model and should be consequential prior to design of RF amplifier.

As per [17], there exist two device modeling methodologies: namely, physical and empirical methodologies. First approach is derived from device technology, device physics and also consider materials in consumption. It also takes into description the restrictions like material characteristics, agility of electron or charge carrier, lattice structure and device lattice configuration. This PA model forecasts design function in the form of device physics which is more appropriate for utilization by RF and design engineers [18], [19].

On the other hand, the empirical modeling technique is derived from S-parameter characteristics and also depend on pulsed I-V calculations in order to model device efficiency. Modeling of FETs using straight measurements have been further advanced by other researchers since then and great contribution was achieved through research in device modelling of HEMT based devices. This technique is more appropriate for amplifier design and offer precise results because the model is derived from measured data.

Empirical models further divided into two kinds: analytical [20], [21] and table based. To expand beyond model linearity for large signal model, precise calculation of S-parameters is essential for GaN based devices to take out inherent and additional parameters of small signal corresponding circuit model. Figure below represents approaches for HEMT modeling.

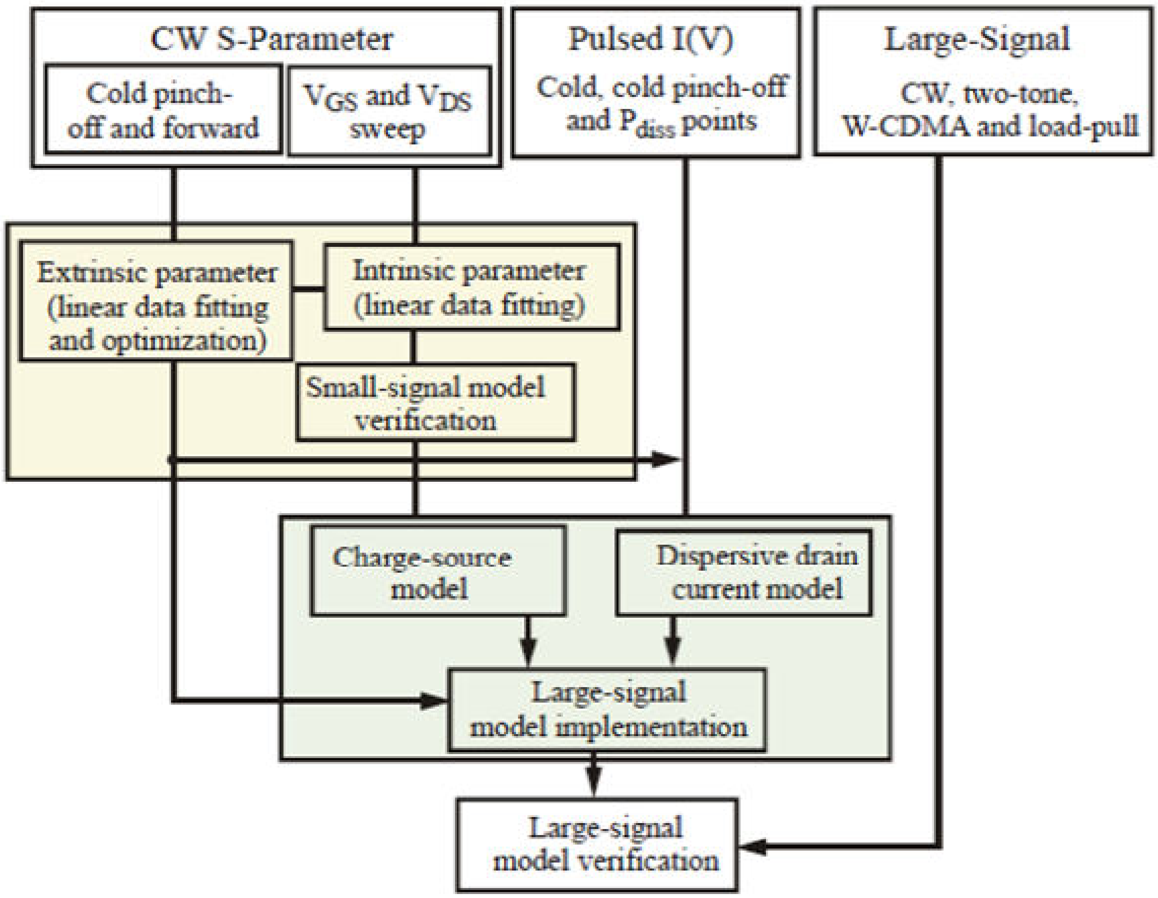



Figure 7: Approaches for HEMT Modeling

## 2.2 GaN HEMT Small Signal Model

Insignificant-signal model is helpful for the instant and estimated assessment of a device's capability to attain design objectives. Some uniqueness that can be pragmatic from the Insignificant-signal model comprises of highest operating frequency, input and output impedances and Insignificant -signal gain.

Small signal model for HEMTs associates calculated S-parameters of the device to the device efficiency dependent on given electrical conditions. Small signal model includes a set of lumped components, representing a correspondent circuit model. Each part of the model presents rough calculation to some feature of the device physics. The topology accustomed to construct a corresponding circuit model for the device, together with physical association to the device, offers good estimation over a wide frequency range. The equivalent circuit derived from 22 - elements dispersed model topology is presented in figure below. The model is useful for AlGaN/GaN HEMT on SiC substrate [23].

This model is composed of 12 extrinsic and 10 extrinsic parameters. The extrinsic parameters are taken out from a set of S-parameters simulations carry out under cold FET circumstances. The parameters can be extracted systematically or through optimization as proposed in [24], [25] and [26]. After de-embedding extrinsic parameters from small signal corresponding circuit, bias reliant intrinsic parameters are attained either through closed form analytical equations or through linear data fitting [26].

The capacitances $C_{gs}$ and $C_{gd}$ model the difference in weakening charge regarding the gate-to-source and gate-to-drain voltages respectively. Usually, the gate-to-source capacitance is bigger than gate-drain capacitance since it models the variation in the depletion charge as a result of variations in gate-source voltage. The drain-source capacitance, $C_{ds}$, make up the geometric capacitance effect connecting the drain and source electrodes. Usually, $C_{gs}$ is 10 times larger than $C_{gd}$ and $C_{ds}$.

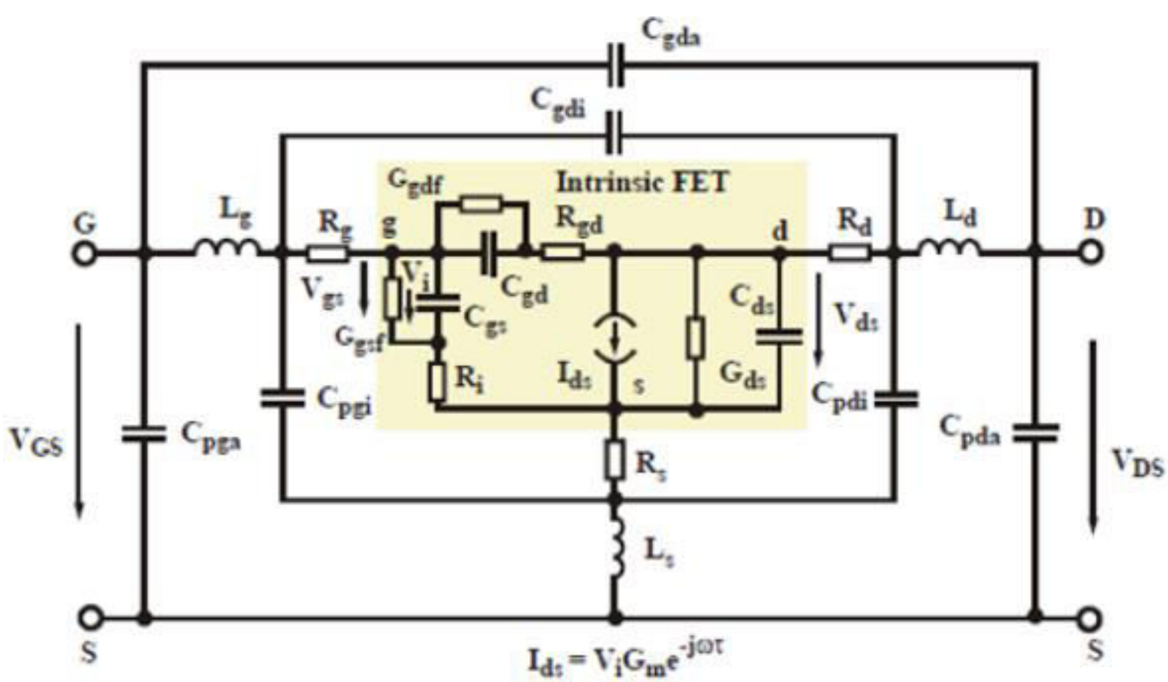



Figure 8: Typical HEMT Model

The resistance $R_i$ depicted in above model is called the charging resistance and is dispersed along the channel under the gate. It articulates the ratio of the voltage drop along the drain-source channel and the channel current. The consequence of $R_i$ is more important in the input reflection coefficient, $S_{11}$ of the device and is necessary to offer a better match to the calculated device behavior.

## 2.3 GaN HEMT Large Signal Modeling

GaN based HEMT's model of large-signal is useful in PA design since it permits visualization of nonlinear region of PA circuits. This permits evaluation and valuation of range of existing PA architectures and effects they might accomplish.

AS discussed in FET model work, a significant rally was consequential to estimate function of the junction FET (JFET). Models have established to describe and design novel FET based devices for potential advanced applications. Following on this line, there have been many innovative device structures and circuits produced in last 6 decades after FET popularity. This research was very well supported by industry and military applications specifically for radar and communication systems. Cost of system is derived by key power and cooling needs and enhanced efficiency is the main reason to reducing these costs. Enhanced power devices, along with appropriate calculation and models, have boosted efficiency.

In recent times, the majority attempt in PA design has been attentive on GaAs pseudo-morphic HEMTs (pHEMTs), GaN HEMTs and Si LDMOSFETs. Models have been proposed and modified for those devices and divide many widespread characteristics since they are all FET derivatives. The focus of this thesis is to design and develop high power PA for s-band applications.

The discussed approach can be very precise, but involves concentrated measurement resources. In order to progress accuracy, whole simulation space must be drawn utilizing both large- and Insignificant-signal measurements including load–pull and linearity. It is positively wanted to have the prime probable amount database from which to take out and confirm any model, but these calculations require larger time at the cost of other resources. A correctly developed model derived from physical equations allows decline in required capacity without an important loss in correctness.

Table II: Impact of GaN HEMT on PA Designs

| Concept | Silicon | GaN on SiC |
|---|---|---|
| Class E/F/J | Low $f_T$, moderate breakdown voltage | High $f_T$, high breakdown voltage |
| Doherty | Low off-state impedance, high output capacitance | High off-state impedance, low output capacitance |
| LINC | Large non-linear output capacitance | Small non-linear output capacitance |
| EER/ET | Poor amplitude to phase modulation conversion, moderate bandwidth | Good amplitude to phase modulation conversion, large bandwidth |
| Digital Pre-Distortion | High thermal time constant, moderate bandwidth | Low thermal time constant, large bandwidth |

Chapter 3

# 3 POWER AMPLIFIERS

Radio Frequency (RF) power amplifiers are considered one of the most significant part in almost every kind of wireless purposes. Every application has dissimilar necessities conditional on frequency and kind of input signal they are dealing with. This leads to the information that, different These amplifiers have to be intended for very specific purpose. For every explicit purpose, they are anticipated to offer appropriate output and gain while achieving satisfactory competence under application-specific linearity concern. For instance, elevated efficiency and linearity are very important in mobile communication systems, whereas for military radars elevated output power is of first concern.

## 3.1 Power Amplifiers

RF power amplifiers (PA) are broadly classified into two major groups: current mode where the transistor work as current source and another is switched mode in which transistor work as a switch. PAs that operate as switches are extremely proficient and appropriate for many purposes.

On the other hand, for purposes that need linear amplitude amplification, PAs are functioned as current source. There are a variety of RF power amplifier classes in each mode, each having its own pros and cons. As per the application and specific system needs, PAs can be designed to satisfy the application requirements. Figure below depicts typical single ended RF PA circuit.

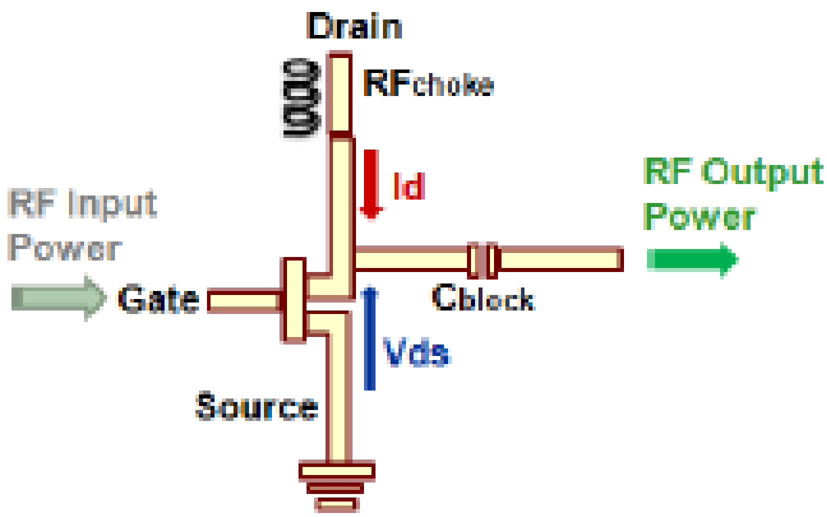



Figure 9: Simplified single ended PA

This chapter the thesis will deal with the necessary factors that depict PA operations and efficiency. After that, PA classes will be discussed following detailed efficiency of each class. Additionally, this chapter discusses brief overview of power amplifier classes, design guidelines along with basics theory. Considering thesis work, a typical 2 stage power amplifier design is shown in figure below.

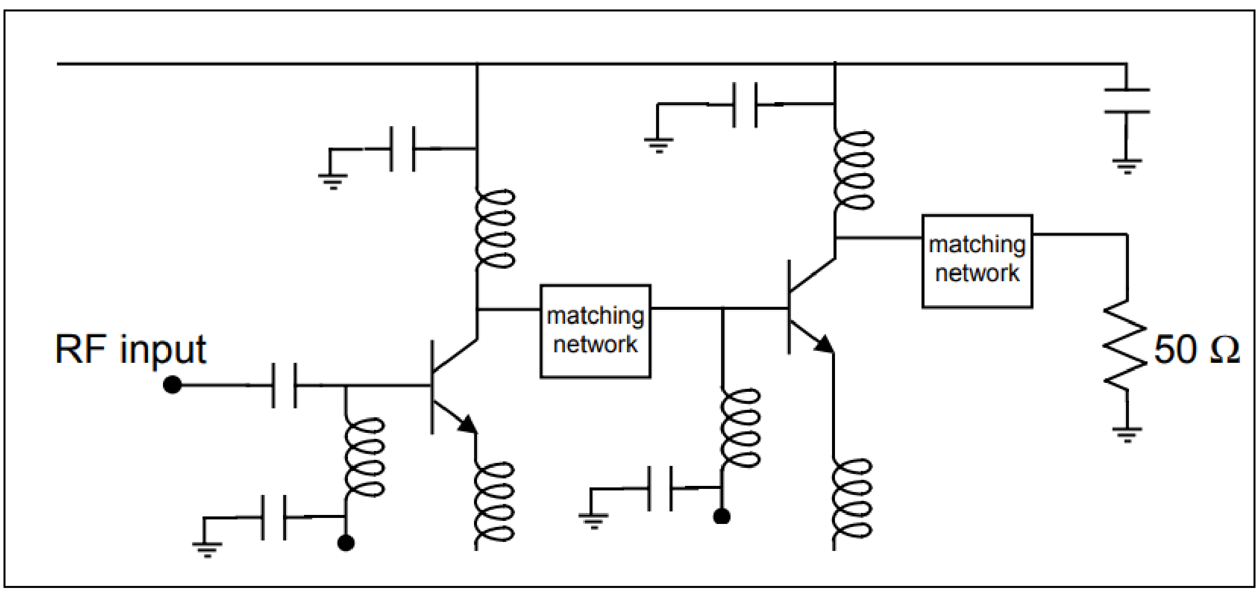



**Figure 10: Typical 2 stage PA design**

### 3.1.1 Essential Parameters

Following parameters need to be considered for designing good power amplifier.

1. Gain and output power of RF
2. PA Linearity
3. Efficiency
4. Bandwidth
5. Power Utilization Factor (PUF)
6. Voltage Breakdown
7. Implementation Losses

**RF Output Power (Pout)** is the RF output power transformed from the supplied DC power.

**Gain** is considered as the ratio of output RF power compared with the input RF power. Gain can be expressed as:

$$gain = P_{out}/P_{in}$$

**Linearity**, defined as the reliability of the transmitted signal. Linearity is the most vital design requirement for PA since non-linearity in transmitters is major source of distortion of the input signal that results in loss of transmitted data. The unclear signal is not only upsetting the reliability of the signal although also produces signals at nearby frequency channels. Such signals are referred as unwanted signals that are main source of distortion to nearby channels.

**Efficiency**, another critical factor in PA design, authors have defined it in many ways. Dissimilar definitions for efficiency that is preferable for different purposes. Efficiency is mostly referred to as Drain Efficiency which is actually the conversion of DC to RF fundamental power.

**Bandwidth (BW)** is referred as operating frequency range of the transistor. It is also called instantaneous BW if it means the BW without any tuning. BW can be expressed as:

$$BW = F_u - F_L$$

$$BW\% = \frac{F_u - F_L}{F_C}$$

$$Octave\ BW = \frac{log\frac{F_u}{F_L}}{log2}$$

In equations above, $F_C$ is the center frequency of operation, $F_L$ is the lowest frequency and $F_H$ is the maximum frequency.

**Power Utilization Factor (PUF)** defines the ratio of the output power transmitted in a particular mode as compared to the power in class A mode [19] as shown in following equation. Therefore, PUF is a factor that can be utilized to evaluate different PA classes as per the maximum power that any class can deliver for particular mode of operation.

$$PUF = 10\log(\frac{P_{out}}{P_{class\ A}})$$

**Voltage Breakdown** in PA refers to the greatest permissible voltage that a PA can bear during its normal operation. Breakdown voltage of transistor is calculated considering operational condition for toughness in a considerable inequitable condition.

**Implementation Losses** are intrinsic to the device technology and cannot be avoided. Thus, these losses must be incorporated in the design of a PA.

**Losses in Power Amplifiers**

The main restrictions of practical PAs are on-state resistance, voltage breakdown, and parasitic capacitance at output and implementation losses. That inevitable loss has an effect on the PA efficiency and thus reduces of output power, gain, operating frequency. $R_{on}$ is the on-state resistance that is observed across the transistor. The voltage built across it because of this resistance is typically fraction of DC supply voltage. $C_{ds}$ is the main noteworthy parasitic capacitance seen at output. This capacitance drastically alters load line path of RF where the RF voltage does not pursue RF current with opposite phase shift. Therefore, some output power will be abridged in relation to this impediment occurred by the shunt capacitor; for this reason a supplementary inductive part is needed to be added to compensate its effect.

## 3.2 Amplifier Classes

PAs are classified into two main categories based on operations; current mode and switched mode operations [19, 40]. In current mode, PA functions as a controlled-current source. On the other hand, in switched mode operation, PA functions as in saturation; consequently, the amplifier works as a switch.

### 3.2.1 Current Mode Operation

PA operated in current mode is further classified as class A, AB, B, C and F. Following are the basic assumptions for this mode of operation [5]:

• Input signal to PA must be a pure sinusoidal

• Output signal linearly follows the input, i.e. PA is an ideal current-source.

• RF current must swing between zero and saturation; still, transistor must not go in saturation.

• RF voltage must swing between zero and 2x of $V_{dc}$.

Conservatively, dependent on diverse biasing values on gate, following are main classes of amplifiers;

- Class A,
- Class AB,
- Class B and
- Class C,

Above mentioned transistor classes use well known VCCS model of transistor. Additionally, there exist other classes like Class D and Class E in case if transistors are replicate as switches. Considering modulation in transistor design, there exist another class termed as class F. For lower frequencies, there is not major difference in transistor's operations but transistors parameters drastically vary at higher frequencies. This makes challenging to design PA at higher frequency since transistor switching is mainly limited to inherent parameters at required higher rate.

### 3.2.2 Class A Amplifier

Class A amplifiers are biased midway between the saturation and conduction pinch-off. They operate in the active region for the full input cycle, for $360^0$ conduction angle and thus conduct throughout input signal. Class A amplifiers output waveform is copy of the input waveform having fixed gain and phase.

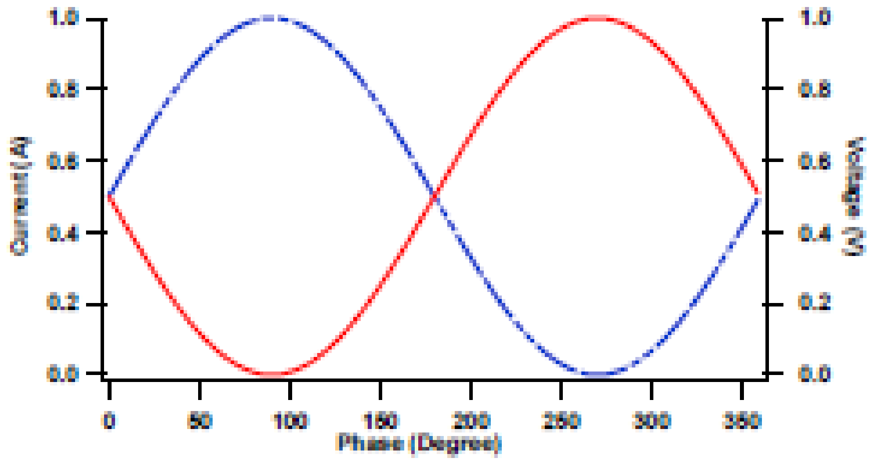



Figure 11: Current (Blue) and voltage (Red) waveforms for class A amplifier

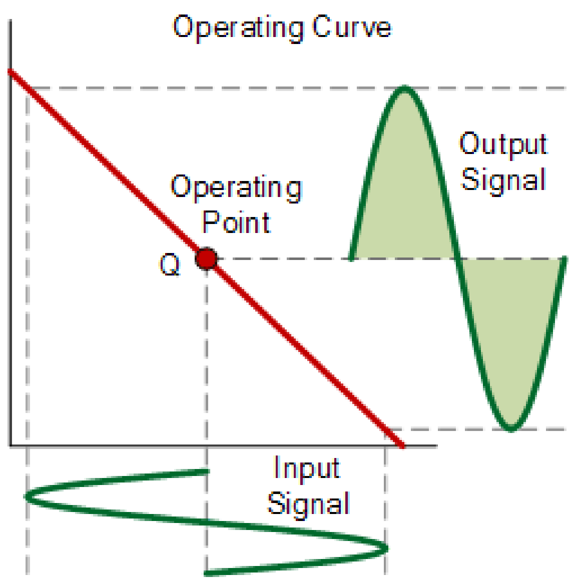



Figure 12: Operating curve of class A amplifier

The output current and voltage waveforms can be written as:

$$i(\theta) = I_{dc} + I_1 sin\theta$$

$$v(\theta) = V_{dc} - V_1 sin\theta$$

The output power, DC power, drain efficiency and PUF of class A can be formulated as:

$$P_{out} = 0.5V_1I_1 = 0.5V_{dc}I_{dc}$$

$$P_{dc} = V_{dc}I_{dc}$$

$$\rho = \frac{P_{out}}{P_{dc}}$$

PUF=0 dB

#### 3.2.2.1 Advantages of Class A Amplifier

Class A has a lot of advantages; it is intrinsically linear as no harmonics is present in the voltage and current signals. It has the maximum gain among all classes because both positive and negative waveform drives the output power. In addition, it is a broadband class because of the absence of highly reflective harmonic constraints.

### 3.2.3 Class B Amplifier

Class B is biased at pinch-off and therefore produces output for half of input cycle i.e., $180^0$ conduction angle. The quiescent drain current is ideally zero. Class B is appropriate for single ended or for push-pull topologies. The current waveform is half sinusoidal whereas voltage waveform is purely sinusoidal signal. In this class, all even harmonics are short.

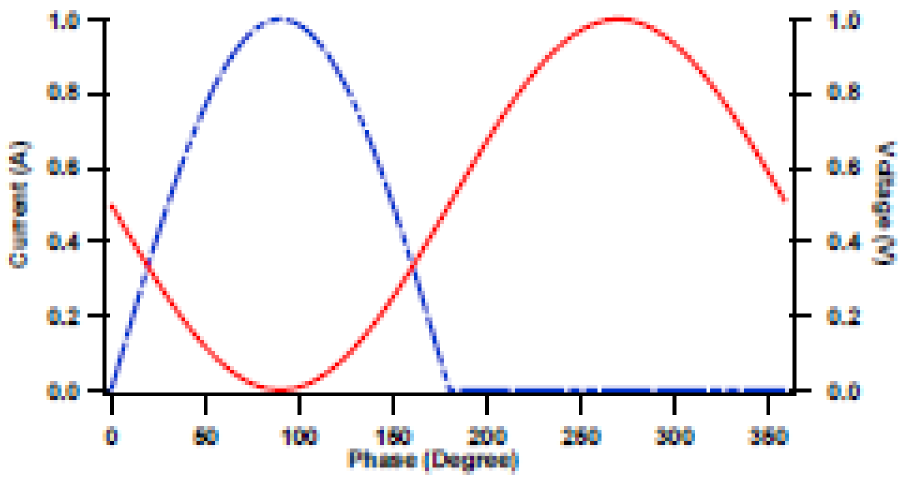



Figure 13: Current (Blue) and voltage (Red) waveforms of class B amplifier

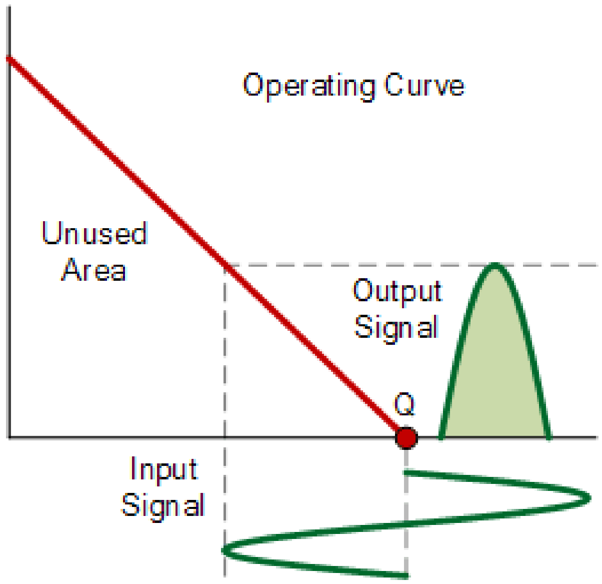



Figure 14: operating curve of class B amplifier

The output and DC power, PUF and drain efficiency are calculated as:

$$P_{out} = 0.5V_1 I_1 = 0.5V_{dc}\frac{I_{max}}{2}$$

$$P_{dc} = V_{dc}\frac{I_{max}}{\pi}$$

$$\rho = \frac{P_{out}}{P_{dc}} = 78.5\%$$

PUF=0 dB

### 3.2.4 Class C Amplifier

Classical class C amplifier is biased in portion less than the half of the RF cycle, i.e., greater than $180^0$ but less than $130^0$. Efficiency increases from class B to C while linearity and gain are reduced. Typically, conduction angle is $150^0$ with 85% ideal efficiency. The output network is designed in a way that drain-source voltage is free of harmonics.

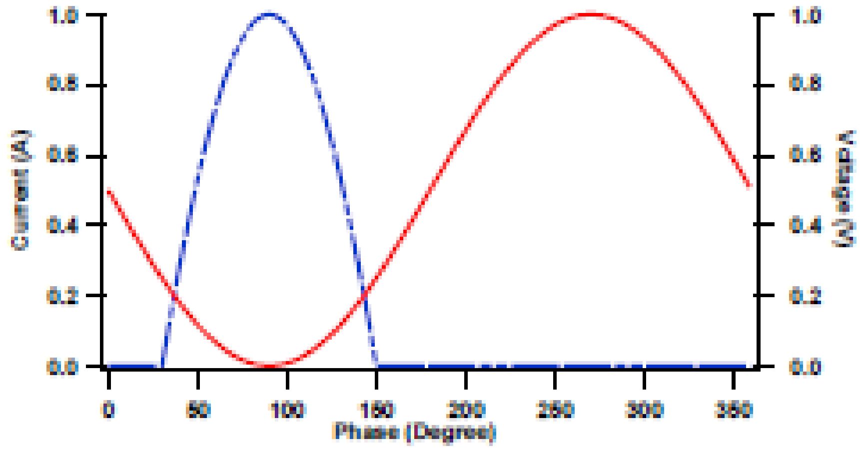



Figure 15: Current (Blue) and voltage (Red) waveforms of class C amplifier

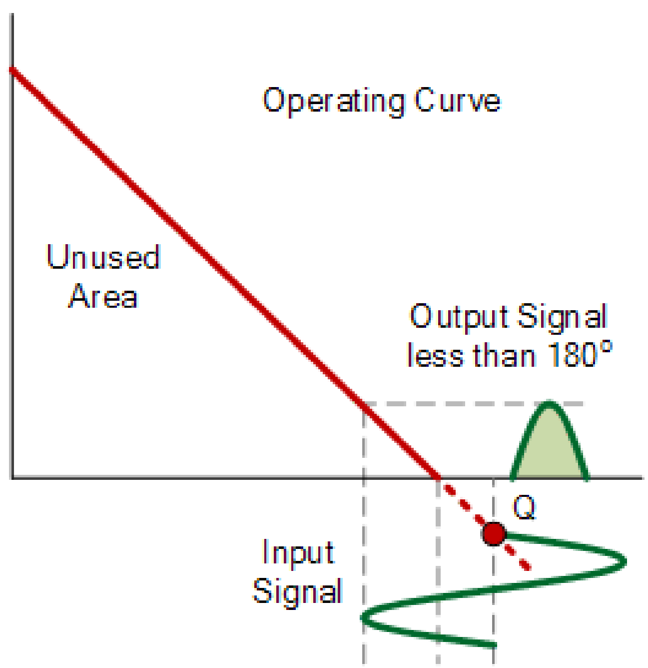



Figure 16: operating curve of class C amplifier

### 3.2.5 Class AB Amplifier

Another class of amplifier, Class AB, conceived with the aim to mitigate drawbacks of Class A amplifier while combining advantages of both Class A and Class B. Due to its popularity and versatility, Class AB amplifier is presently the most common classes among all kinds. Class AB amplifier is actually removes the drawback of class B by eliminating the crossover distortion issue.

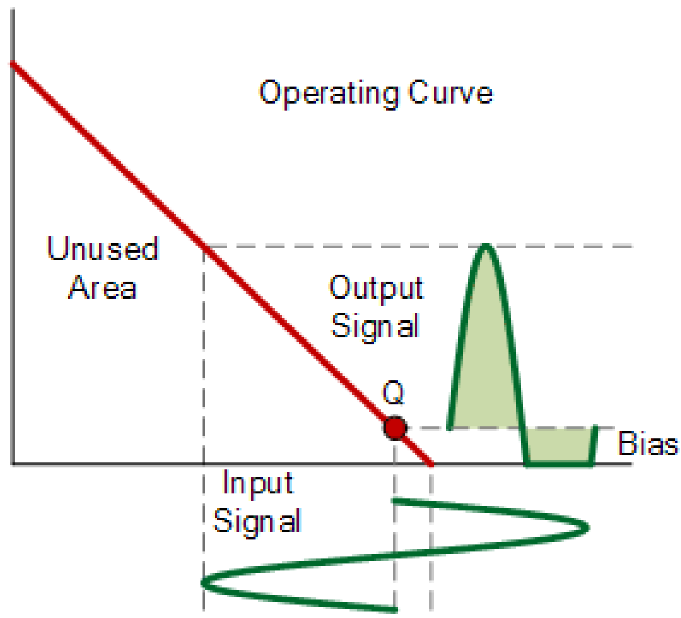



Figure 17: operating curve of class AB amplifier

Main improvement of insignificant bias voltage is to reduce crossover distortion. This is reduced without disturbing efficiency. As a result of this, class AB is considered a good compromise between class A and class B in terms linearity and of efficiency almost around 50% to 60%.

#### 3.2.5.1 Class AB Advantages

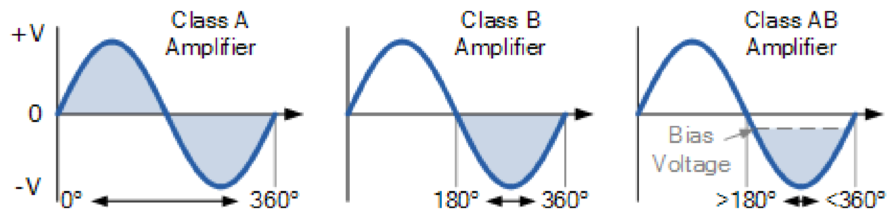
1. Up to kilowatt output achievable
2. Superior efficiency and good linearity
3. Compactness
4. Low distortion and large bandwidth
5. Relatively Cool Operation

#### 3.2.5.2 *Applications*

1. ECM/EW Jammers
2. Booster Amplifiers
3. Transmitters
4. RFI/EMI Testing

### 3.2.6 Comparison of different amplifier's classes

Following diagram depicts comparison between discussed classes of amplifiers. Table below also summarizes important parameters for each common amplifier classes.



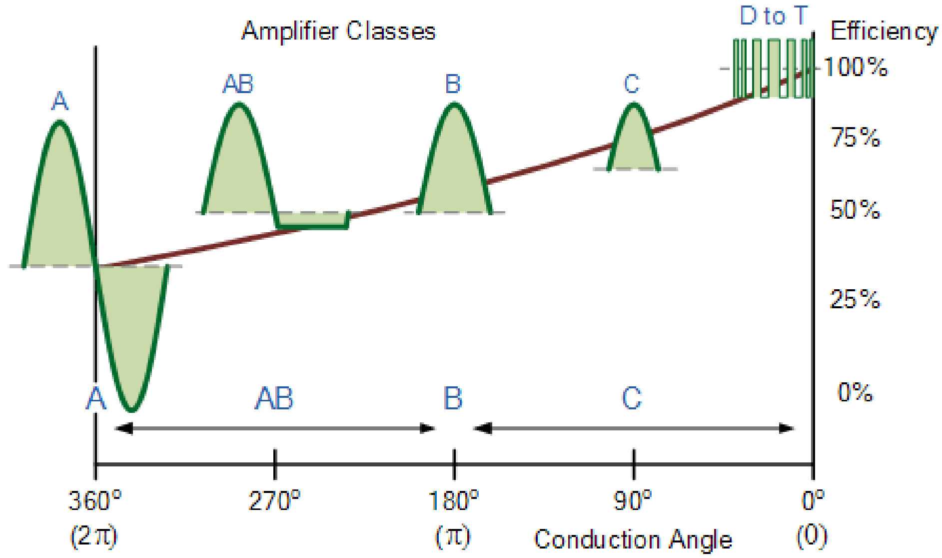




**Table III: Comparison of PA classes**

| Class | Mode | Conduction Angle | Max Efficiency |
|---|---|---|---|
| A | Current Source | 100% | 50% |
| AB | | B<(Angle)<A | A<(Efficiency)<B |
| B | | 50% | 78.5% |
| C | | <50% | 100% |
| D | Switch | 50% | 100% |
| E | | 50% | 100% |
| F | | 50% | 100% |

## 3.3 Ideal Assumptions for PA Design

To examine the effectiveness and output power potential of amplifiers in dissimilar modes, other than the device current, it is essential to be familiar with the drain voltage. A common amplifier structure is explained as follows:

1. Reactance at required frequency of RF choke infinite having no series resistance.

2. Considering main concern of the drain voltage, the input circuit is symbolized by a voltage source.
3. RF choke permits DC current resolute by the biasing circuit.
4. $C_{block}$ blocks DC short for AC signal. It is obligatory that impedance of the capacitance is insignificant at the preferred RF frequency.

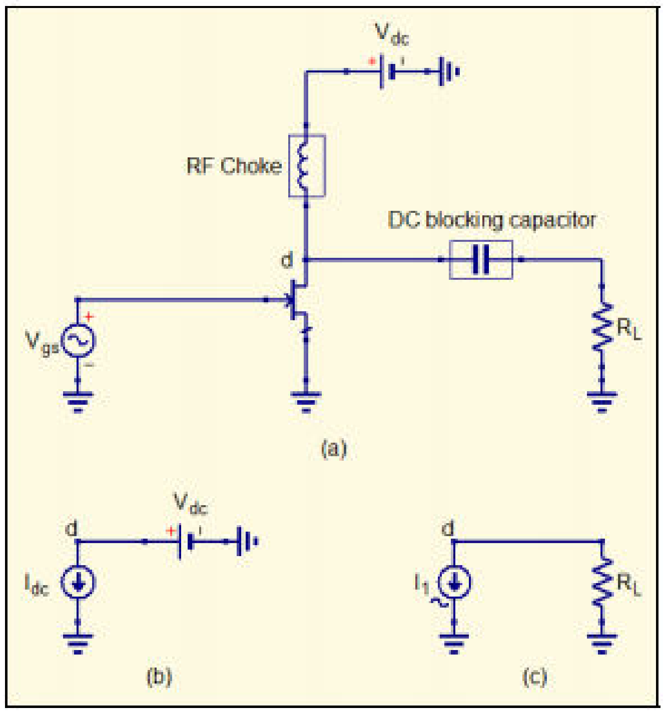



Figure 18: Drain voltage calculation using superposition principle

As observed, all components are linear other than transistor; therefore, drain voltage $V_d$ can be calculated using superposition principle. Applying superposition principle is depicted in figure above. DC bias $V_{dc}$ represents DC component of the drain voltage. From basic analysis, it seems that there is no limit on $V_1$ as long as $R_L$ is greater which is contrary to the fact since the transistor drain has a knee voltage $V_{knee}$. for given $V_{knee}$, VCCS model becomes invalid and thus whole analysis. To avoid this, the maximum $V_1$ should be $V_{dc} – V_{knee}$ as shown in Figure below.

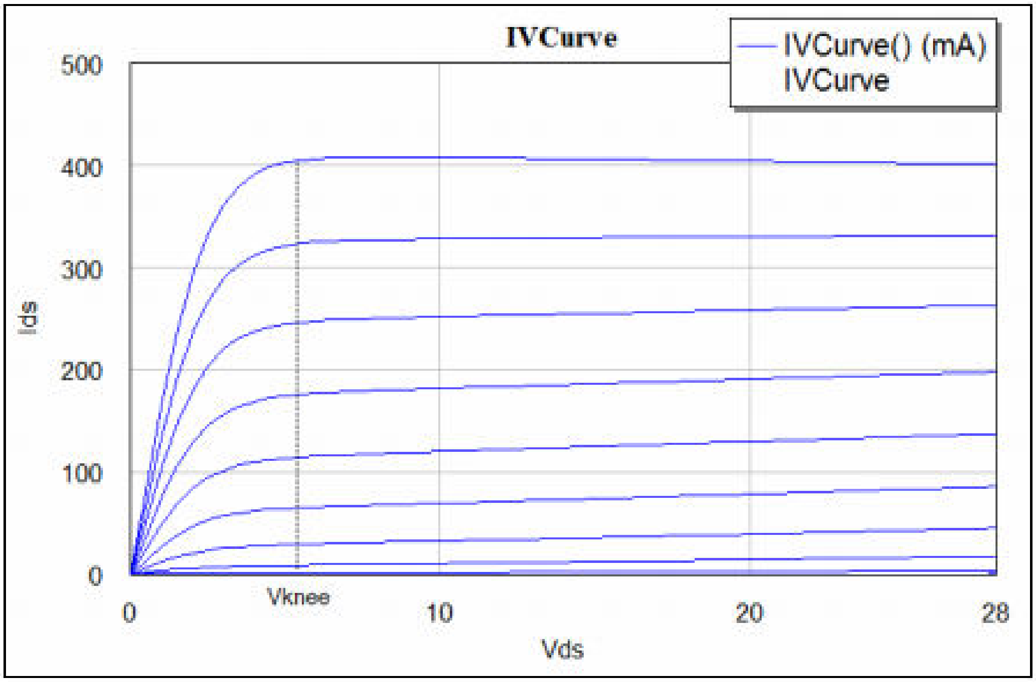



Figure 19: IV Curve highlighting knee voltage

Fundamental output power could be expressed as;

$$P_1 = \frac{V_1}{\sqrt{2}}\frac{I_1}{\sqrt{2}} = \frac{I_1 V_1}{2}$$

While DC power is:

$$P_{dc} = V_{dc} I_{dc}$$

Drain efficiency is defined as:

$$\rho = \frac{P_1}{P_{dc}} = \frac{I_1 V_1}{2 I_{dc} V_{dc}}$$

## 3.4 Power Amplifier Design

Fundamental functions of PAs to boost signals, RF or audio, by changing DC power into a considerable RF or audio power. PAs are classified as per mode of operation, implementation and architecture as discussed earlier in this chapter. For specific application, PAs are designed to meet particular requirements like efficiency, gain, linearity, bandwidth, output power or any combinations of basic parameters.

In today's communication systems, the most significant factors are Linearity and efficiency. Linearity concerns the signal reliability and efficiency defines the energy utilization of the system. The design of highly linear as well as efficient PA is design challenge and need thorough analysis to meet both requirements simultaneously. This can be explained by looking at the input-output power characteristics of a PA as shown in figure below.

As depicted in figure, the output power ideally consists in the linear region. It means that only the fundamental frequency, gain in the linear region is fixed. The theoretical efficiency is about 50% and 78.5% at Peak Envelope Power (PEP) for class A and class B respectively. On the other hand, the efficiency is improved by generating more efficient current and voltage (I-V) waveforms at the cost of a degraded linearity if power amplifier operates in compression region.

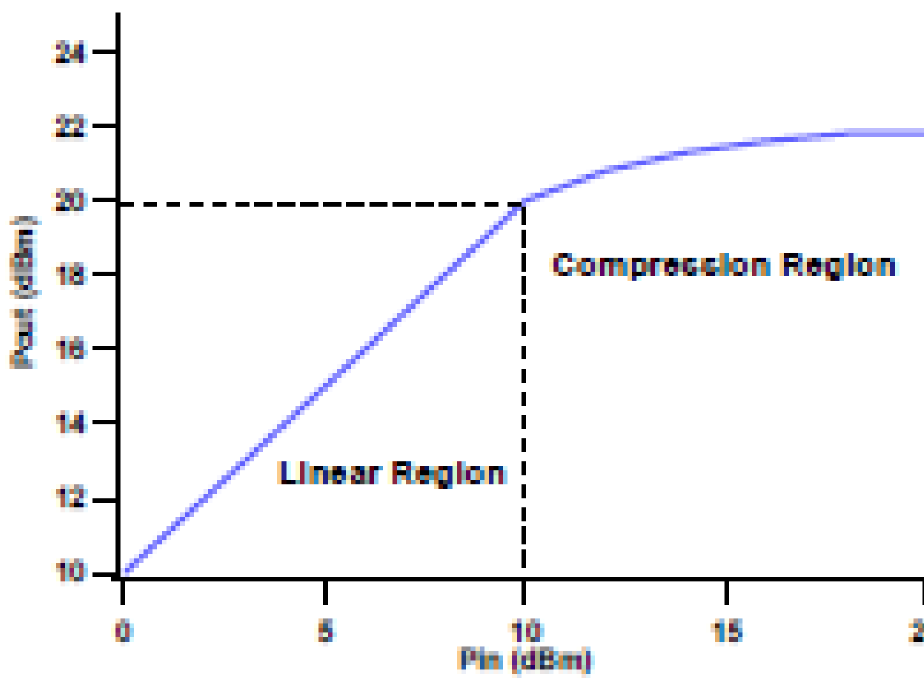



Figure 20: Different regions of power amplifier

In order to meet design requirements, there must be a trade-off between linearity and gain, the two critical factors in PA design. For instance, in constant envelope purposes, there is a very useful trade-off between efficiency enhancement and linearity. the linearity can be traded for efficiency and RF output power for modulation schemes like FSK (Frequency Shift Keying) and BPSK (Binary Phase Shift Keying) that can tolerate significant amount of amplitude and phase distortion [11]. This enhancement is accomplished by driving the active device into the compression region and also by appropriate harmonic terminations to attain elevated efficient current and voltage waveforms. For case in point, a class F amplifier achieved elevated efficiency by converting voltage waveform at the output of the active device from a sine wave to a square wave. [12]

## 3.5 GaN Transistors in PA

AlGaN/GaN HEMT technology has become widely popular for advanced wireless PA applications and has gained research pace as compared to research conducted in during last few decades. It has been extensively utilized for radars and traditional military applications because of following main reasons:

1. High speed of electron (more than107 cm/s),
2. elevated break potential (above 50 V for 50 GHz),
3. wide bandgap (3.4 eV) and
4. Carrier concentration (>1013 $cm^{-2}$).

As a result of unconventional electrical properties of GaN devices and likelihood to utilize available SiC substrate representative elevated heat conductivity of 3.5 W/cm.K, power concentration as increased as 30,000 W/m calculated at frequency of 4 GHz [21] in addition to output of 500 W calculated at 1.5 GHz [22] has been accomplished.

The GaN device technology is extensively intended for PA purposes. Importance of GaN technology based PA devices are evident in mobile base stations as reported by scientists that GaN based devices have improved output power and densities along with efficiencies [24]–[25]. Class E amplifiers operating at nominal 13 MHz with an elevated-potential as the key switching apparatus is established to indicate opportunity of utilizing GaN HEMTs in elevated frequency power switching purposes. Recently introduced 380 V/1.9 GaN based HEMT device suitable for elevated potential power electronics purposes.

## 3.6 PA Design Issues

Following are the main design issues that need to be considered while designing RF power amplifiers.

1. Power reflection occurs because of elevated VSWR between PA and its load. It can destroy transistor for good.
2. Higher power dissipation produces more heat and transistor may perform in undesirable mode.
3. DC bias voltage efficiency would be lower if choke has higher resistance.

4. Always select capacitor of low-ESR since they can supply the needed current without delay to the amplifier stage.
5. When transistor working in saturation mode, linearity are most affected by the reflections of its own harmonics. These reflections generally arise by the next stage that include either terminating antenna or another stage, as in our case.
6. RF amplifiers are more instable and require much attention in almost every frequency to avoid oscillations. This oscillation can also damage GaN transistor. Such oscillations, called as spurious oscillations, will occur at precise or very wide ranging, frequency or frequencies, and over specific bias, temperature, drive level, or output load impedance. Such oscillations are further classified into Bias oscillations and RF oscillations. Proper considerations need to be taken for each of these kinds.
7. Major reason for uncontrollable instability in a PA is the presence of segmented ground plane.

**PA Design Flow**

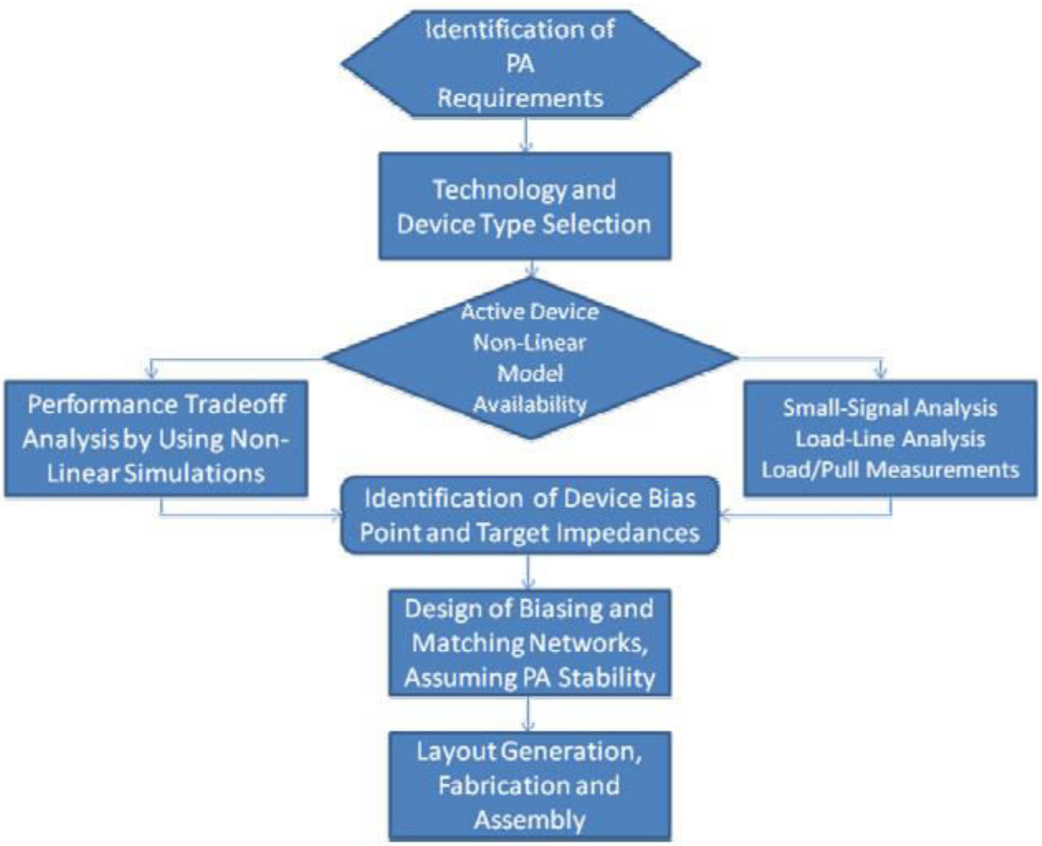



Figure 21: PA Design Flow

## 3.7 Design Consideration for Multistage Amplifier

When designing more than one stage PA for high power applications, there have been many associated challenges that need to be considered. Main consideration is the selection of appropriate transistor that fabricated on required substrate and fully support required frequency operation. This thesis discussed simulation and design technique for two stage power amplifier for s-band applications, followed following guidelines to demonstrate robust amplifier for intended applications.

1. The pre-driver need to be biased Class-A for getting reliable working for negligible consequence on device linearity as a result of small variations in bias supply. Efficiency is not major concern for pre-driver stage since it will be compensated in coming stage of amplifier design.
2. The driver and the output stage is class AB for getting appropriate tradeoff between linearity and efficiency of the amplifier.
3. General approach for finding linearity is to measure inter-modulation distortion (IMD) with two tones spaced for 20 MHz
4. Must consider transistor characteristic like IMD for lower output power whenever main transistors when considerably backed-off from peak power value.
5. There must be large positive slope for IMD vs. Pout (drive-up) graph.
6. The transistor operated in the driver stage has comparable linearity needs as the output stage.
7. Main parameters that identify efficiency of the elevated transistor for application in wide band environment flatness of amplifier gain. Hence, gain must remain flat across the band for its use in multiple channel amplifiers. Amplifier gain with no variation for desired is highly sought parameter. It significantly makes things easier for design of linearization approach.

### 3.7.1 Design of Multistage PA

For multistage PA, each stage requires driver that need to be properly tuned for particular frequency, gain and linearity in order to achieve overall efficiency. It is essential to identify required power for driver, linearity and any other specific requirements as per frequency band and desired final output, any particular case requires. Driver linearity issues are ignored if PA is designed to operate in saturation region. In actual design practice, on the other hand, it is almost natural to opt for linear designs for developing high gain multistage PA that be extended further up to 40 dB or larger at last stage. This is because of the comparatively little impact of driver effectiveness specified a PA stage with larger than 10 dB power gain, plus the increased gain available from linear stages. Almost certainly the only stage which may still assistance from improved efficiency mode operation would be the driver itself; following pre driver stages might additionally be built for maximum linear gain at suitable power levels.

Driver chains for multistage amplifier design are the engineering design challenge for maintaining overall linearity. Major problem is to manage the production of nonlinear spurious products in the driver stages, while preserving efficiency and power supply conditions. It appears to be simple task to achieve but require much engineering to maintain gain for each coming stage.

### 3.7.2 PA Identical Network Design

After pre-driver and choice of suitable amplifier class AB for s-band high power amplifier and the best possible load impedance of AlGaN/GaN HEMT conditional on the HPA conditions, similar networks, whether passive or active, must be designed at input and output ports of each active stage incorporating DC supply path. The design of an amplifier implies an appropriate production of passive networks design for PA stage matching, completing stability and design necessities problems [21].

In order to understand the circuit design, dispersion parameters are inured to make clear the shared power waves as it is common in elevated-frequency schemes. The definition of S-parameters is evidently specified, e.g. in [19], and consequently will not explain here in more detail.

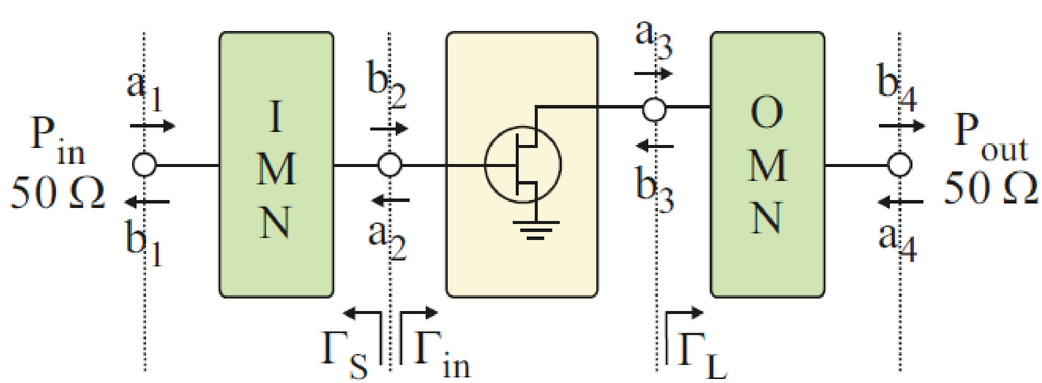



**Figure 22: Representation of single stage RF power amplifier**

The block diagram shown above depicts circuit in most simple form for a basic single stage amplifier. The circuit comprises of independent active unit for amplification purposes, input matching network (IMN) and output matching network (OMN) . These IMN and OMN include DC biasing network without precise termination networks for harmonics. In case of two stage amplifier, as in case of this thesis work, an extra inter-stage matching network, referred to as ISMN, is required between amplifier stages.

Derived from the transistor device models available in ADS format including circuit schematics, simulation was completed in ADS (Advanced Design System), software tool of Agilent Technologies.

Autonomous of the kind of matching network, the basic functions of all passive matching networks are similar. They all comprises of:

1. dividing or merge system for more than a few equivalent operated FET parts unified in the transistor-stages.
2. bias voltage supply path(s) between Gate/drain and gates/drains
3. Least inclusion loss based impedance translation system and
4. Additional stability elements to maintain stability.

Chapter 4

# 4 HPA DESIGN AND SIMULATIONS IN ADS

## 4.1 Introduction

Good PA design need to incorporate all design requirements discussed in previous chapter and additional real world design constraints in order to produce usable and robust PA device. Major design constrain is stability that need to be maintained along with linearity, gain and efficiency. Stability for RF amplifier is its resistance to producing false oscillations. Two kinds of stability for RF amplifiers are of great debate:

1. Conditional stability and
2. Unconditional stability.

Stable RF amplifiers are steady when input and output ports are appropriately terminated. A much improved outcome is categorical stability that illustrates that stable amplifier despite the consequences of input output impedances. Following conditions decides whether the condition is stable or not;

$$|\Gamma_{\text{in}}| = S_{11} + \frac{S_{12}S_{21}\Gamma_{\text{L}}}{1 - S_{22}\Gamma_{\text{L}}}$$

&

$$|\Gamma_{\text{out}}| = S_{22} + \frac{S_{12}S_{21}\Gamma_{\text{s}}}{1 - S_{11}\Gamma_{\text{s}}}$$

To make possible the purpose of this main parameter, we desired to first set up that in our circuit the flow of RF signal is merely in onward direction or, homogeneously, $S_{12}$ (conduction of power from port 2 to port 1) is zero. In case if one-sided condition is fulfilled, evaluations essential for absolute steadiness calculation becomes greatly simple, fulfilling only following two requirements:

$$|S_{11}| < 1$$

&

$$|S_{22}| < 1$$

To deduce the PA stability, we required inspecting the level of input and output reflection coefficients for many factors of PA was customized to locate undesirable circumstances. Following simulation setup demonstrates stability measurement.

Considering prevalent modelling approaches discussed in [17], physical and empirical approaches have gained much popularity in PA design for high power applications. First approach, physical modeling, is mainly focus on device technology parameters, physical architecture and also consider material in device manufacturing and production of particular application. Second model type, empirical modeling, focus inherent characteristics obtained from S-parameters and also pulsed I (V) measurements taken into consideration for device efficiency.

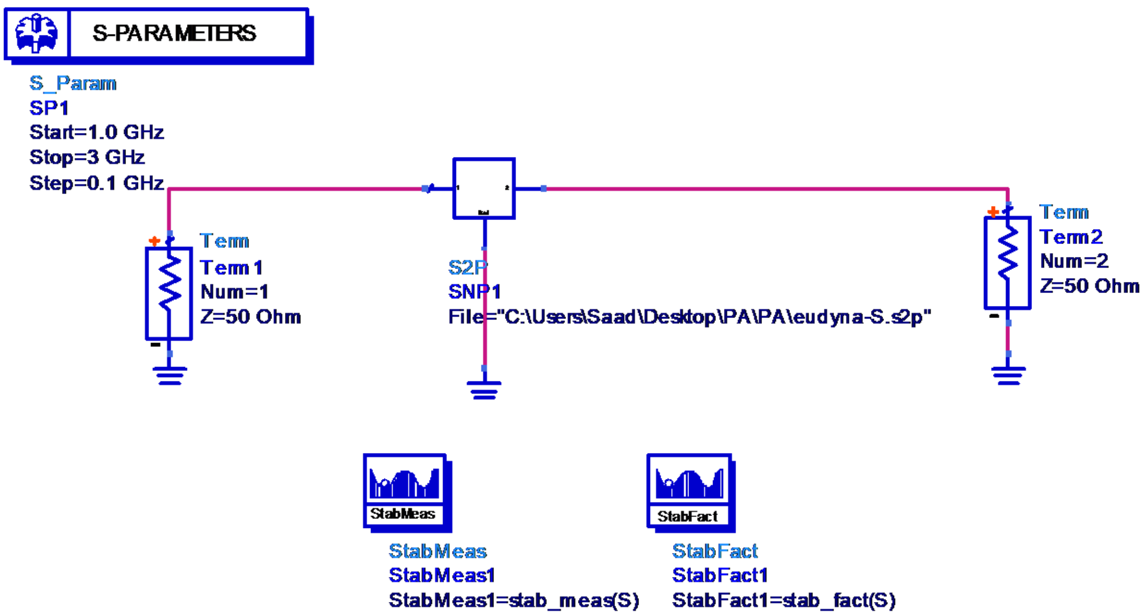



Figure 23: Stability measurement

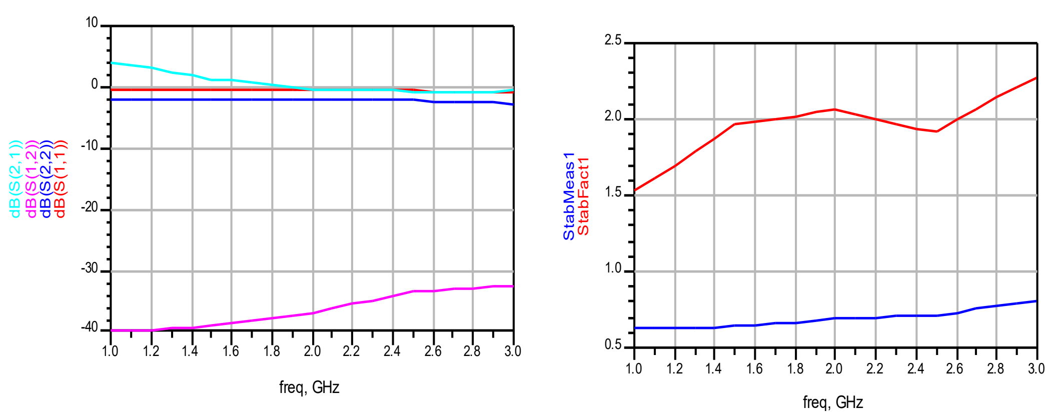



Figure 24: Results of S-parameter simulation and stability factor

### 4.1.1 Computing Stability Factor (k) and Measure (b)

In order to evaluate stability of a transistor at broadband level, parameter k (Rollett Stability Factor) and b (Stability Measure) are evaluated. The unrestricted steadiness requirements are to be properly addressed, i.e., k>1 and b>0, where b and k are calculated by formula:

$$\boldsymbol{K} = \frac{\mathbf{1} - |\boldsymbol{S_{11}}|^2 - |\boldsymbol{S_{22}}|^2 + |\Delta|^2}{\mathbf{2}|\boldsymbol{S_{21}}||\boldsymbol{S_{12}}|}$$

&

$$\boldsymbol{b} = \mathbf{1} + |\boldsymbol{S_{11}}|^2 - |\boldsymbol{S_{22}}|^2 + |\Delta|^2$$

The S – parameters details were acquired from FLL-120MK FET datasheet. Additionally, the simulation tools like StabMs and StabFct were also incorporated into the diagram as presented in figure below.

It can be inferred that the discussed design has stability factor (k > 1) and stability measure (b > 0) within limits for operating frequency. Hence, designed PA is considered stable between desired frequencies ranges. The ultimate 2 – ports MESFET amplifier is ended into 50 Ω terminations as shown below. Different investigation tools like L_StabCircle, S_StabCircle, SmGamma2 and SmGamma1 were also added to the schematic. For 2-port network, following observations are reported;

1. SmGamma1 returns the instantaneous input-reflection coefficient match,
2. S_StabCircle and L_StabCircle explain the area of constancy for PA device and
3. SmGamma2 returns the instantaneous output-reflection coefficient match

Desirable parameter is reflection coefficients for concurrent matching of conjugates for the circuit under considerations.

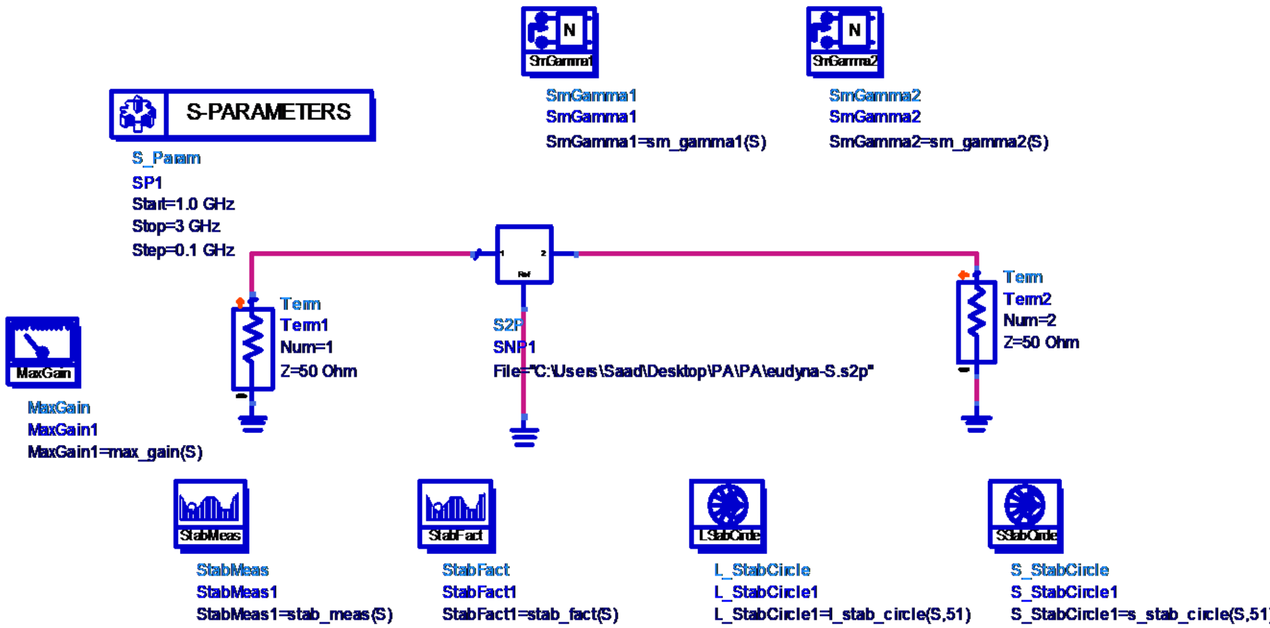



**Figure 25: PA Conjugate matching through S-parameters**

AS depicted in above conjugate matching plot, it monitors that in the region of 4 GHz, $S_{11}$ and $S_{22}$ levels are smaller as compared to $S_{21}$ which is plentiful as compared to $S_{12}$. It was also monitors that $S_{11}$ is reasonably of good quality in the region of 5 GHz – this is for the reason that there exist inherent matching to PA input.

### 4.1.2 Capacitance Values

**Table IV: Nominal Capacitance Values for input and output impedances**

| freq | SmZ1 | SmZ2 |
|---|---|---|
| 1.000 GHz | 2.885 / 58.510 | 8.041 / 25.939 |
| 1.050 GHz | 2.735 / 55.655 | 8.112 / 23.522 |
| 1.100 GHz | 2.590 / 52.547 | 8.174 / 21.172 |
| 1.150 GHz | 2.451 / 49.151 | 8.229 / 18.884 |
| 1.200 GHz | 2.319 / 45.431 | 8.276 / 16.654 |
| 1.250 GHz | 2.196 / 41.352 | 8.315 / 14.481 |
| 1.300 GHz | 2.082 / 36.883 | 8.346 / 12.362 |
| 1.350 GHz | 1.980 / 32.002 | 8.368 / 10.295 |
| 1.400 GHz | 1.892 / 26.702 | 8.383 / 8.281 |
| 1.450 GHz | 1.818 / 21.001 | 8.390 / 6.319 |
| 1.500 GHz | 1.761 / 14.948 | 8.389 / 4.408 |
| 1.550 GHz | 1.740 / 9.178 | 8.533 / 2.994 |
| 1.600 GHz | 1.736 / 3.311 | 8.673 / 1.581 |
| 1.650 GHz | 1.748 / -2.542 | 8.809 / 0.172 |
| 1.700 GHz | 1.776 / -8.274 | 8.940 / -1.232 |
| 1.750 GHz | 1.820 / -13.791 | 9.068 / -2.628 |
| 1.800 GHz | 1.879 / -19.019 | 9.190 / -4.015 |
| 1.850 GHz | 1.950 / -23.912 | 9.307 / -5.391 |
| 1.900 GHz | 2.034 / -28.445 | 9.419 / -6.754 |
| 1.950 GHz | 2.127 / -32.613 | 9.525 / -8.102 |
| 2.000 GHz | 2.230 / -36.427 | 9.626 / -9.433 |
| 2.050 GHz | 2.399 / -39.779 | 9.777 / -10.594 |
| 2.100 GHz | 2.575 / -42.717 | 9.927 / -11.755 |
| 2.150 GHz | 2.757 / -45.305 | 10.073 / -12.9... |
| 2.200 GHz | 2.944 / -47.596 | 10.218 / -14.0... |
| 2.250 GHz | 3.136 / -49.638 | 10.360 / -15.2... |
| 2.300 GHz | 3.332 / -51.466 | 10.501 / -16.3... |
| 2.350 GHz | 3.531 / -53.114 | 10.639 / -17.4... |
| 2.400 GHz | 3.733 / -54.606 | 10.776 / -18.6... |
| 2.450 GHz | 3.937 / -55.964 | 10.911 / -19.7... |

Table below depicts Input Impedance **SmZ1** and Output Impedance **SmZ2**:

**Table V: Measurements of input-output impedances**

| Simultaneous mismatch-Input Impedance SmZ1 | Simultaneous mismatch-Output Impedance SmZ2 |
|---|---|
| **2.03-j2.39** | **9.99-j2.72** |

The stability regions of the amplifier were analyzed differentiate stable and unstable regions of PA through stability plots as shown below. From mentioned plots, it is cleared that the design is potentially unstable only below 500 MHz

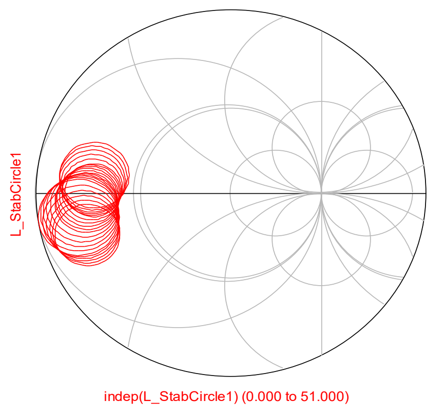



Figure 26: L stability circle

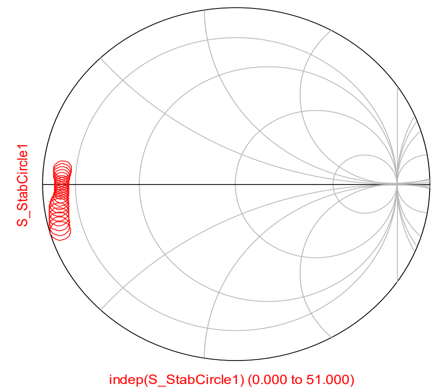



Figure 27: S stability circle

After identifying unstable regions through plots, it is necessary to incorporate in the designs necessary actions to avoid such regions where PA becomes unstable.

### 4.1.3 Conjugate Matching for Input and Output Impedances

Conjugate matching of PA is utilized to convert the highest power level transfer from source to 1st stage PA and again from 2nd stage PA to the load. Mathematically, conjugate matching for input and output network can be written as:

$$\Gamma_s = \Gamma_{in}^* = S_{11}^*$$

Figure below explains the network and its equivalent Thevenin's part utilized for extreme power transfer in PA evaluated from source with *d-length* of transmission line to load as soon as the load is appropriately matched to source.

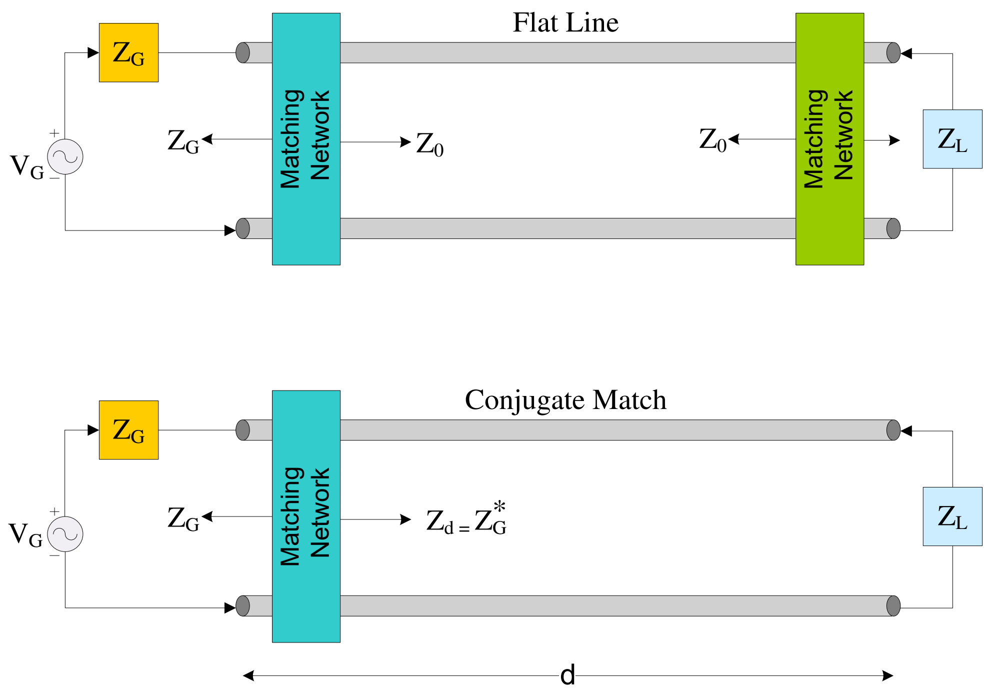



Figure 28: Conjugate matching setup

### 4.1.4 Load Pull Setup

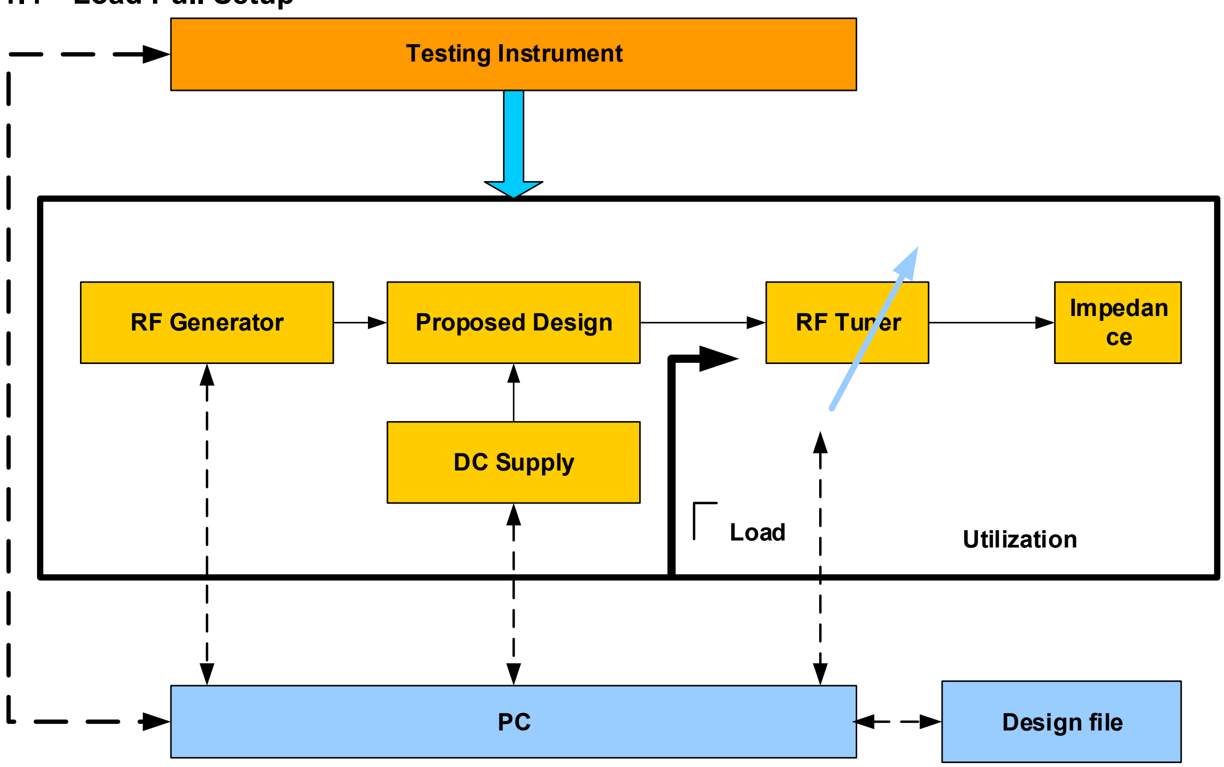



Figure 29: Load pull setup

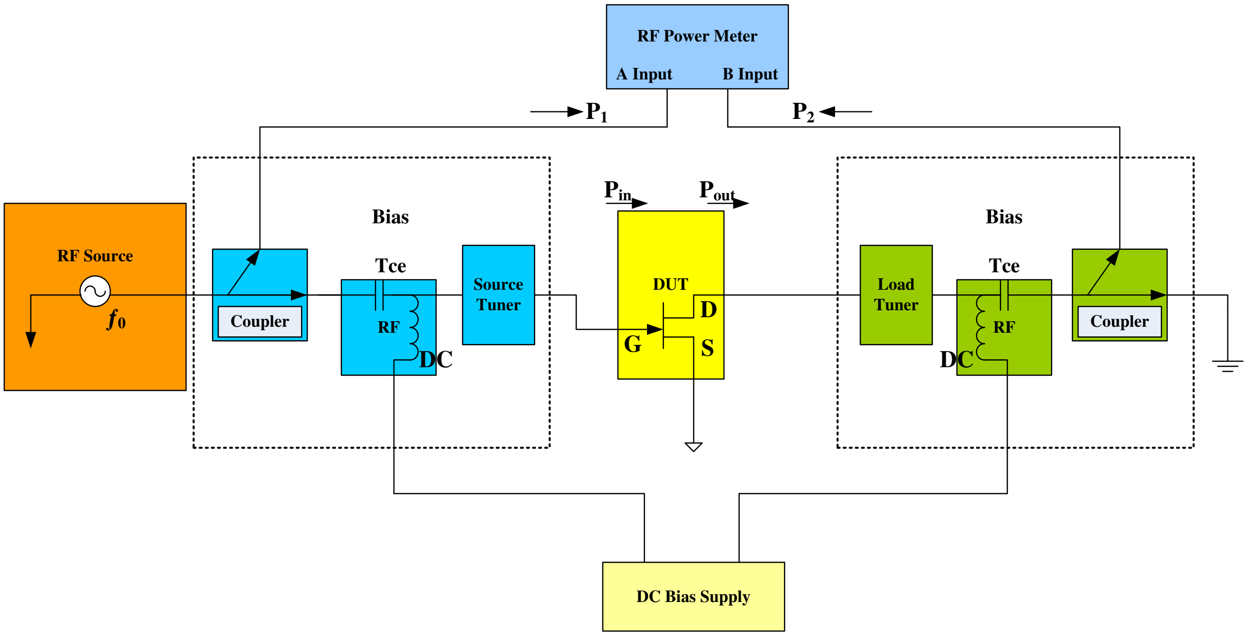



Figure 30: Setup for Design under Test

#### *4.1.4.1 Construction of RF choke*

The choke designed by many different ways. One technique is to utilize a ferrite Toroid core with fine wire wound around one-half of the Toroid. That device has moderately elevated inductance and is enough for many low frequency applications.

One more way is to utilize a small air-core choke. These devices have also small inductance but are enough for small bandwidth applications.

Another way is to utilize a tiny inductor with a magnetic core. These devices have greater inductance, but suitable at very much smaller frequencies.

In general, RF chokes normally have miniature air-core inductors with turns depending on the nominated operating frequency band. These RF chokes have finest wire and have somewhat small stray capacitance to ground plane as of little considerable dimension. These RF chokes have comparatively good response on given frequency band,

In order to improve frequency band, coil biasing can be comprehensive with two or more coils in series. In series coil, first coil is slighter to offer towering frequency partition. Second coil is progressively bigger to offer lower frequency separation. The discussed method causes abrupt changes in uniqueness that originates impedance irregularity in S parameters. The said technique may not be viable in responsive frequency method for the reason that wavering in the electrical parameters.

Another method to rise RF band sensitivity is to utilize resistance wire for the inductor. The resistance wire is extremely difficult to wind and use. The substance is also mismatched with bonding techniques

#### 4.1.4.2 *GaN Justification as PA for S-band Application*

In today's communication systems, demands for high bandwidth and high data rate constantly increasing that need devices having;

- Higher breakdown potential,
- Higher charge velocity and
- Better heat conductivity.

For such application, PA able to perform in wideband like GaN and SiC are appropriate option. The greatest current passed through PA when higher field is applied is restricted through the drift velocity of concentrated electron (VSAT) by discouraging charge flux. Greater VSAT value will permit more transfer of electron and thus consequently higher power. When compared GaN and SiC with conventional semiconductor materials, they have twice higher value than Si and GaAs. At higher power/unit, width of gate is significant in microwave devices, since the PA must be tiny in contrast operating wavelength function so as to shun spreading that would or else degrade efficiency and gain of the device. On the other hand, charge mobility of GaN and SiC are lower than conventional Si and GaAs that lowers efficiency.

## 4.2 Design of Two Stage S-band HPA

Main work of this thesis is to design and develop two stage s-band HPA for wireless applications. Working of GaN based HPA is as follows:

### 4.2.1 First Stage

In 1st stage, Cree Model Unmatched transistor CGH40006P takes input of 10dBm from signal source and step up power of about 29dBm at its output.

### 4.2.2 Second Stage

First stage's power is fed into another Cree Model unmatched transistor 40010F through attenuator so as to prevent any damage to the system and also isolates 2 stages. Final stage gives output of 40dBm or 10W.

## 4.3 CGH40006P

Cree's CGH40006P, utilized in first stage of s-band HPA, and is a GaN HEMT. It offers high gain, high efficiency, and wide bandwidth ability making the CGH40006P perfect for linear and compressed amplifier designs.

Wide band CGH40006P operate from DC through 6 GHz frequency range. This transistor is perfect for our proposed application. Additionally, it can be utilized in low-noise amplifier (LNA) usage since GaN reduce number of components in the design by removing unnecessary protection components, typically essential in GaAs MESFET LNAs.

### 4.3.1 Features of CGH40006P

- 28 V Operation
- Up to 6 GHz Operation
- 8 W typical at PIN = 32 dBm
- Small Signal Gain 13 dB at 2 GHz
- Small Signal Gain 11 dB at 6 GHz
- 65 % Efficiency at PIN = 32 dBm

## 4.4 CGH40010F

Cree's CGH40010, utilized in $2^{nd}$ stage of our s-band HPA, is an unmatched, GaN HEMT. Like CGH40006P, it also offers high gain, high efficiency and wide bandwidth abilities making the CGH40010 ideal for linear and compressed amplifier circuits.

### 4.4.1 Features of CGH40010F

- 28 V Operation
- Up to 6 GHz Operation
- 13 W typical PSAT
- 65 % Efficiency at PSAT
- Small Signal Gain 16 dB at 2.0 GHz
- Small Signal Gain 14 dB at 4.0 GHz

**CGH 40010F Schematic**

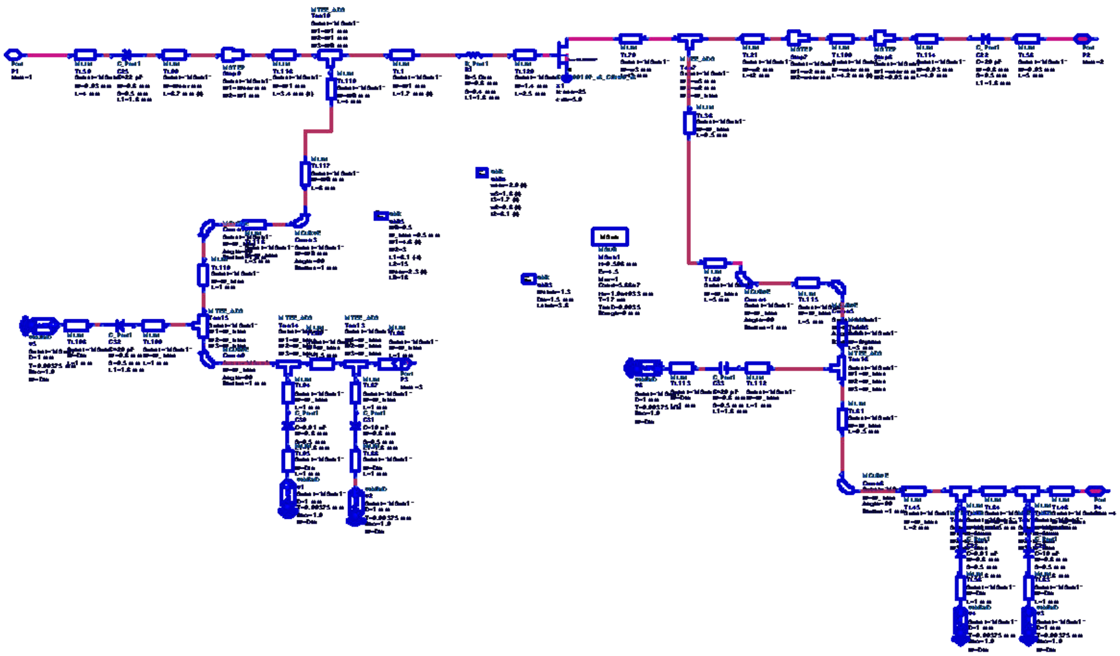


Figure 31: Schematic of 40010F

The Schematic shown above is for CGH 40010F made from micro strip components in ADS 2009. Main purpose to design a circuit is to calculate length and width of the tracks accordingly to make circuitry on desired substrate.

## 4.5 CGH 40006P Schematic

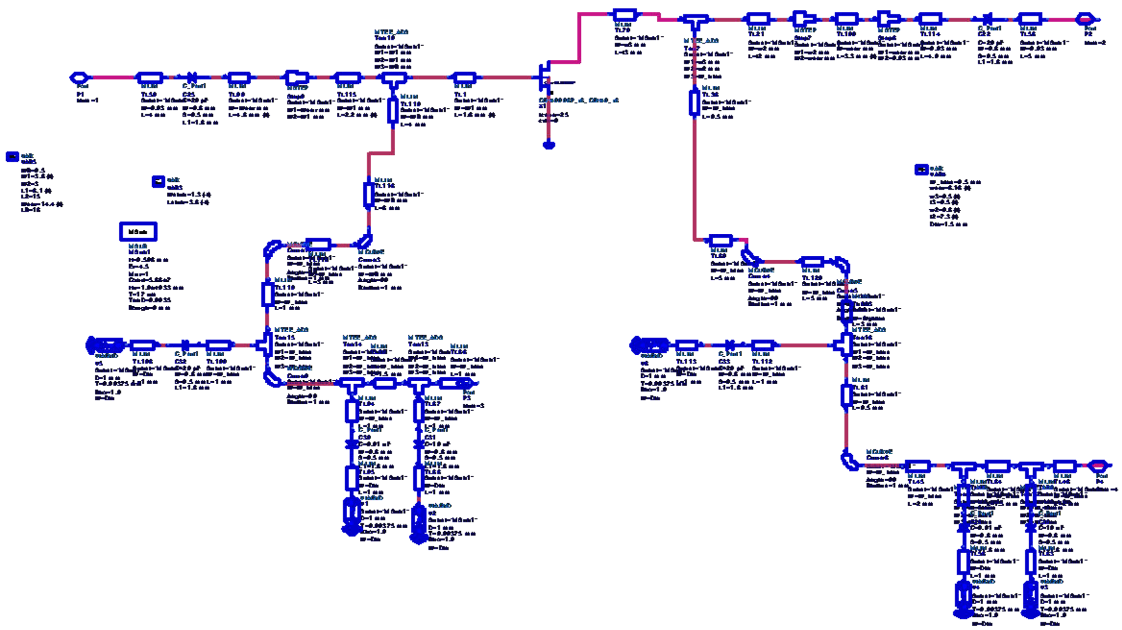


**Figure 32: Schematic of 40006P**

The Schematic shown above is for CGH 40006P made from micro strip components in ADS 2009. Main purpose to design a circuit is to calculate length and width of the tracks accordingly to make circuitry on desired substrate.

## 4.6 Schematic for Stability of CGH 40010F

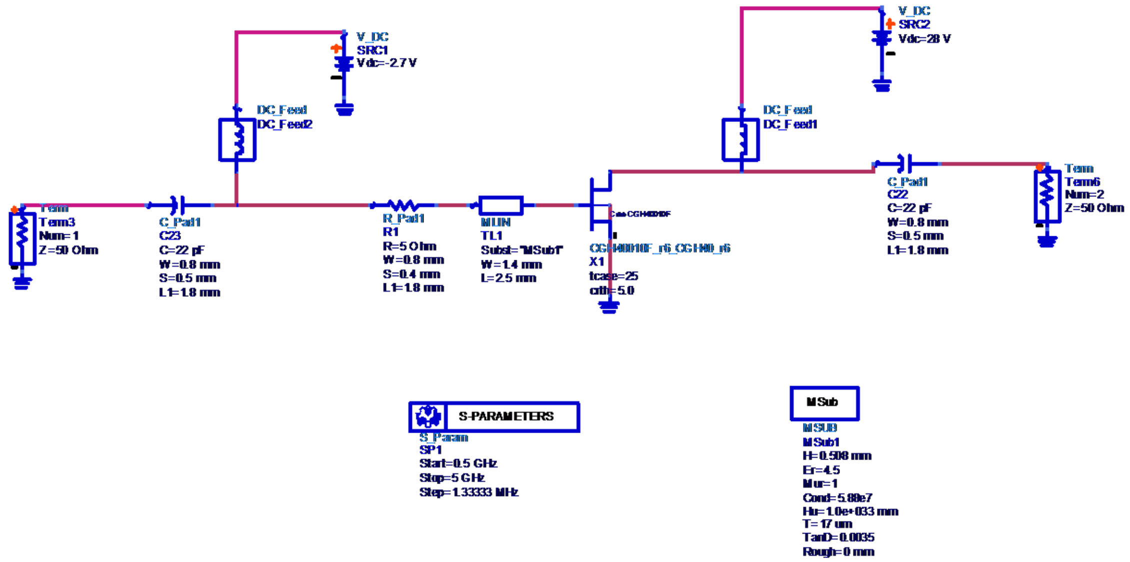



**Figure 33: Stability Schematic of 40010F**

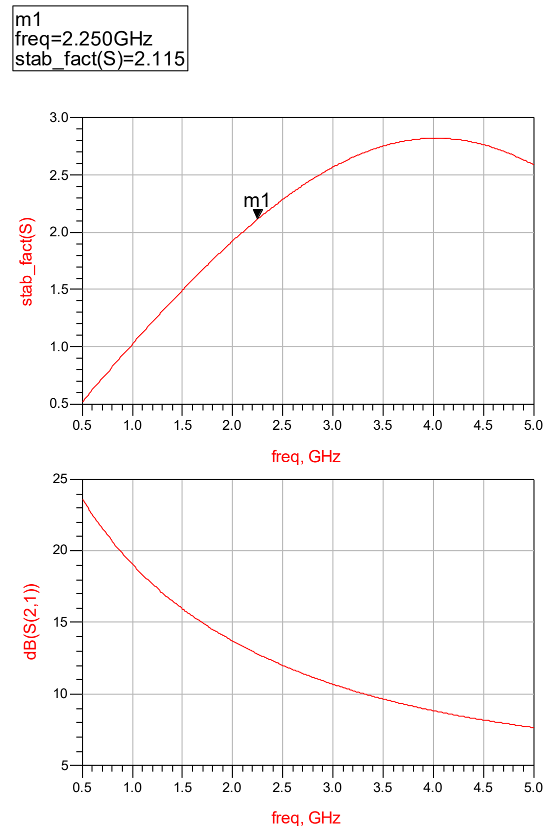



**Figure 34: Stability graph**

The graphs shown above are used to check or calculate stability for CGH 40010F. Stability factor is calculated to check whether the stable is stable or not in our desired frequency (2-2.3 GHz). From the graph it is depicted that our device is not stable in that particular frequency range.

## 4.7 Schematic for Calculation of S-Parameters of CGH 40010F

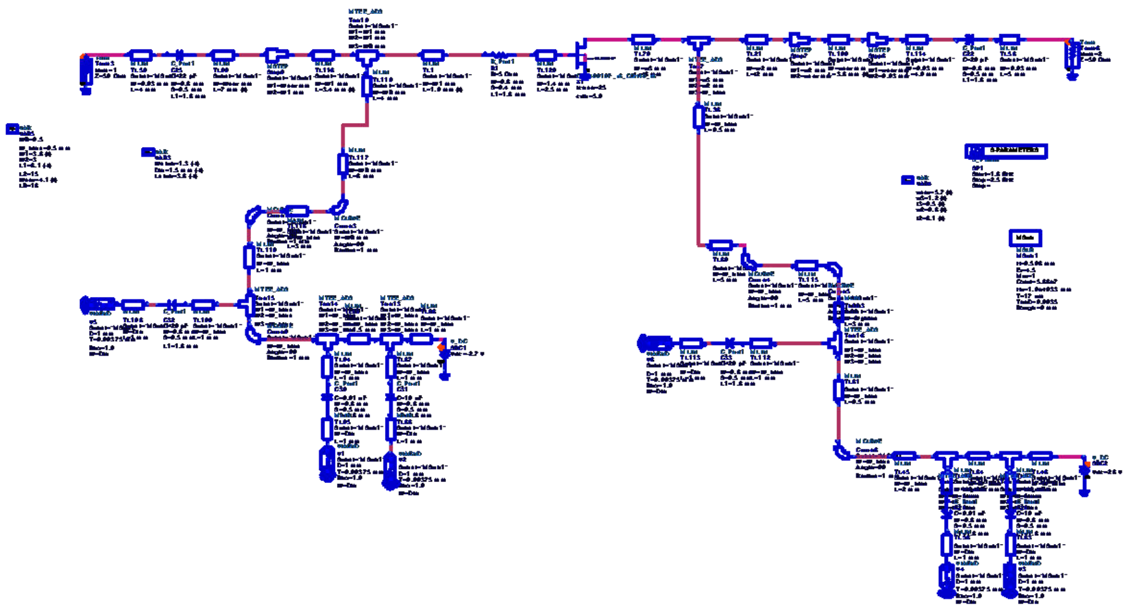


**Figure 35: S-parameters schematic for 40010F**

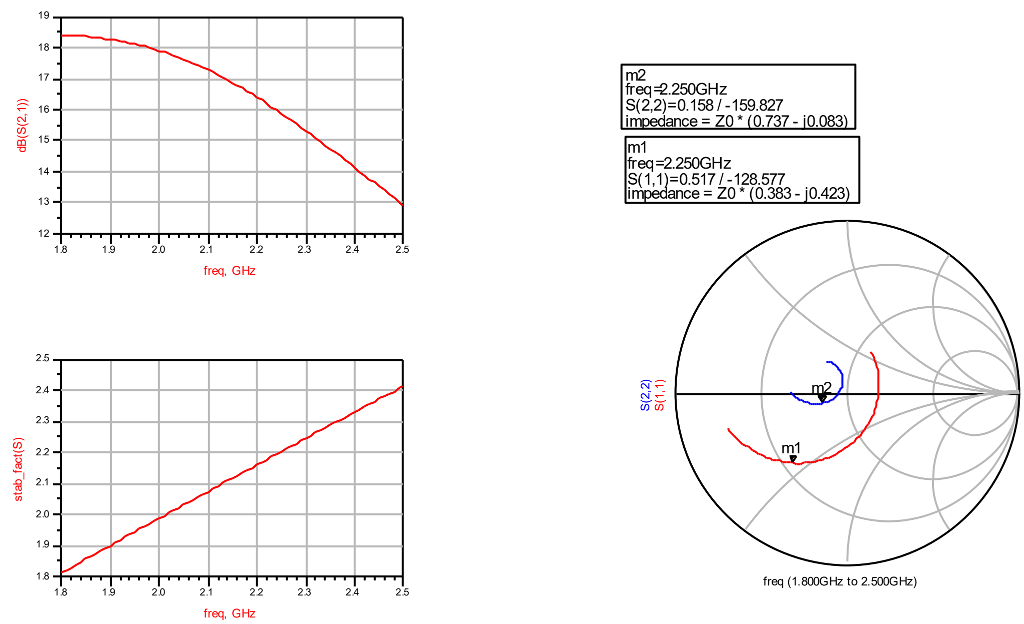



**Figure 36: S-parameters results for 40010F**

The graphs shown above are used to calculate S-parameters for CGH 40010F. Stability factor is calculated to check whether the stable is stable or not in our desired frequency (2-2.3 GHz). From the graph it is depicted that our device is not stable in that particular frequency range. From smith it can be seen that markers are not at the center which shows our device is neither matched nor stable.

## 4.8 Schematic for Calculation of S-Parameters of CGH 40006P

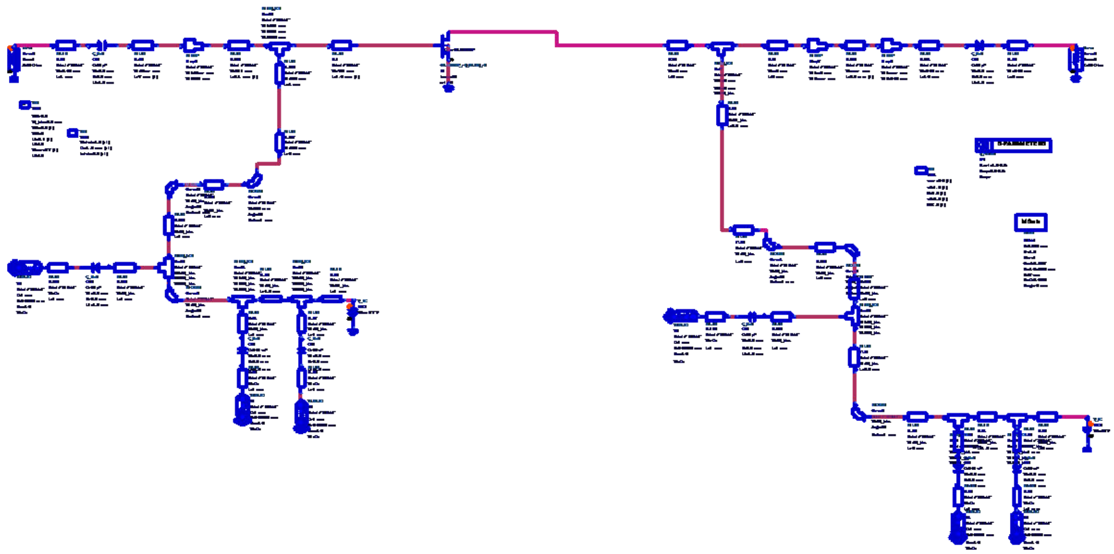


Figure 37: S-parameters schematic for 40006P

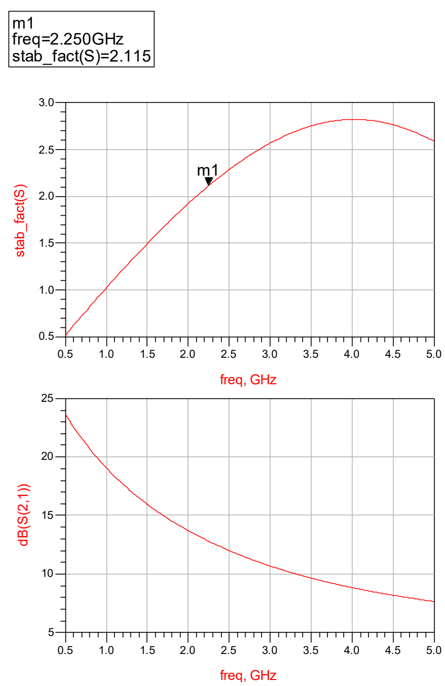



Figure 38: S-parameters results for 40006P

The graphs shown above are used to calculate S-parameters for CGH 40006P. Stability factor is calculated to check whether the stable is stable or not in our desired frequency (2-2.3 GHz). From the graph it is depicted that our device is not stable in that particular frequency range.

## Schematic of Source Pull for CGH 40010F

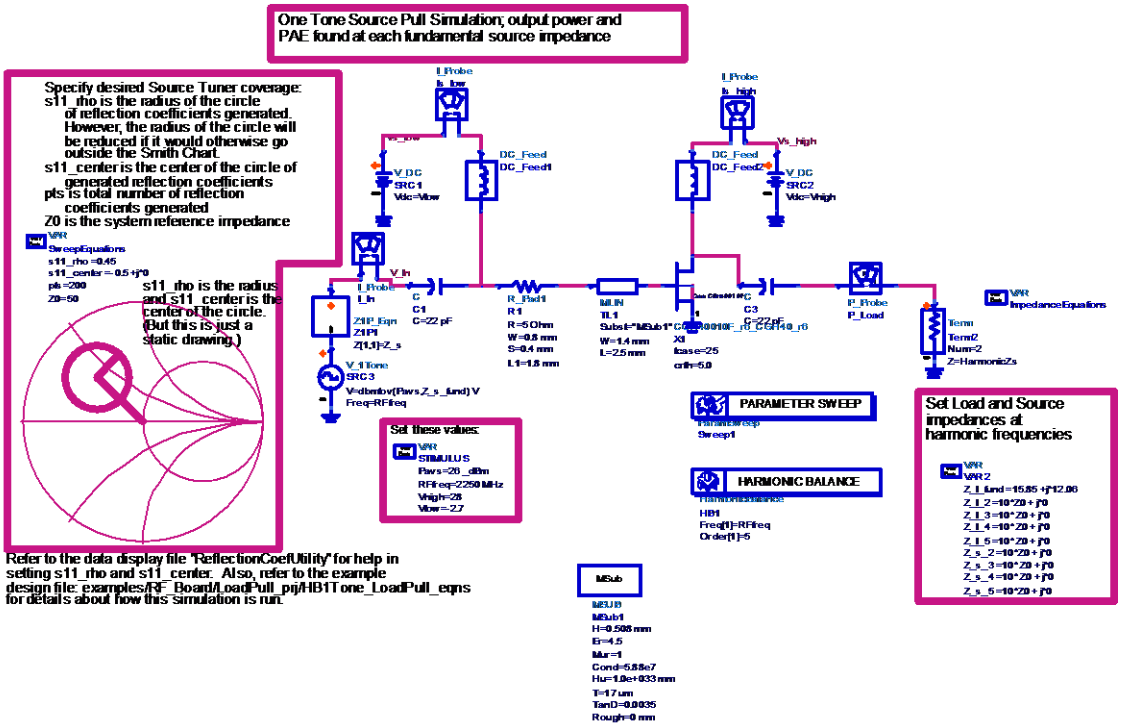



**Figure 39: Source Pull schematic for CGH 40010F**

## 4.9 Graphs of Source Pull for CGH 40010F

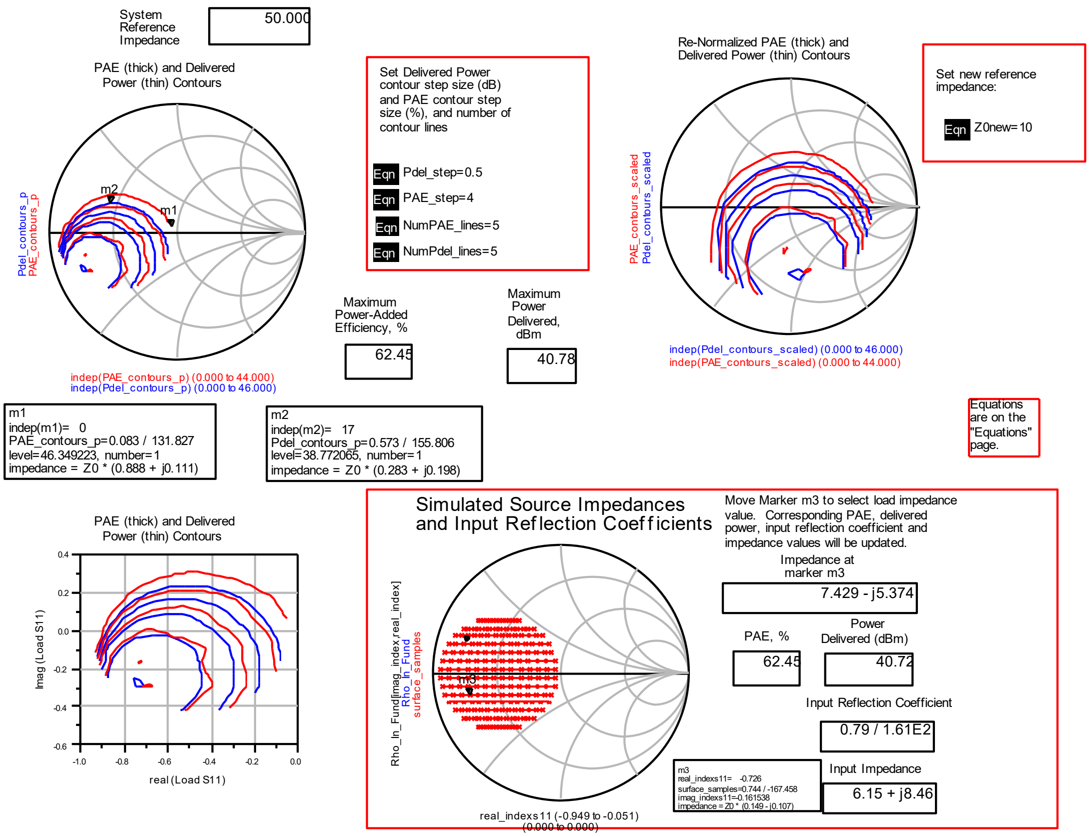



**Figure 40: Source Pull results for CGH 40010F**

Source Pull is done at the source side to properly match the signal with the system to avoid any type of reflections at the input side. From source pull we calculate Impedances. This Source Pull setup is for CGH 40010F. Power Delivered by the system, input reflection coefficient, input impedance are calculated from source pull setup.

## 4.10 Schematic of Source Pull for CGH 40006P

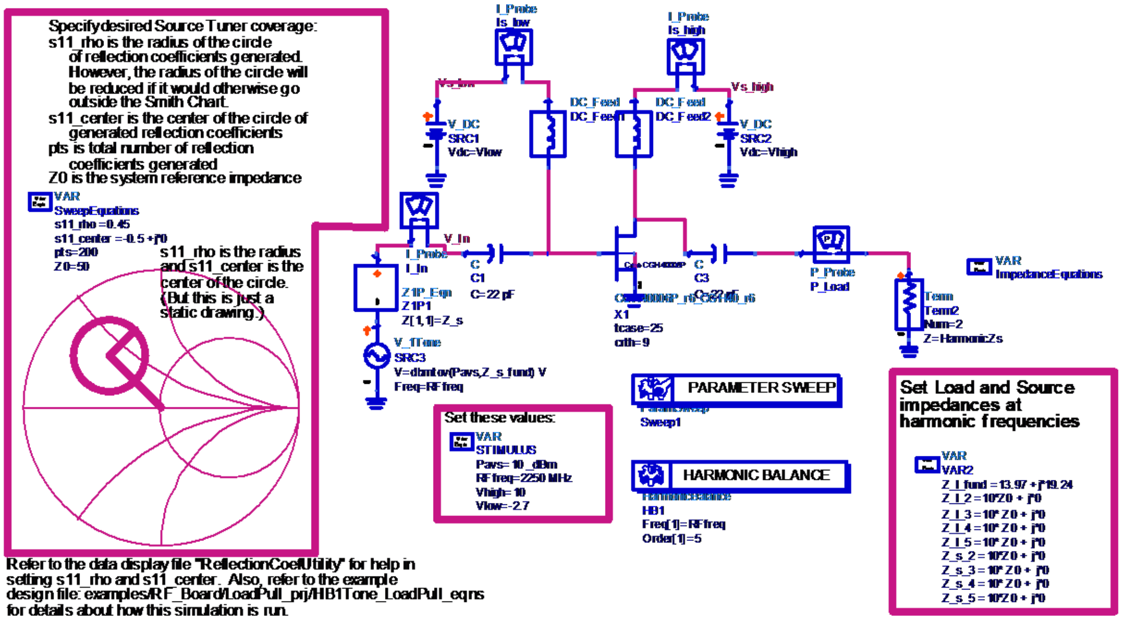



**Figure 41: Source Pull schematic for CGH 40006P**

# 4.11 Graphs of Source Pull for CGH 40006P

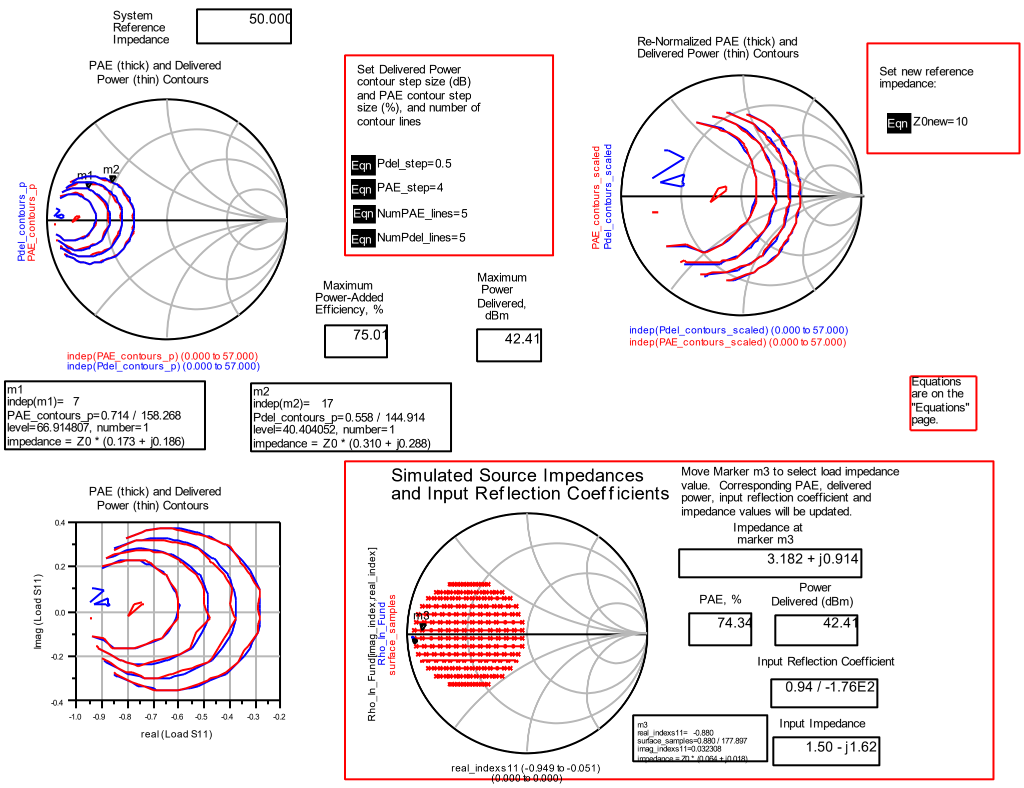



**Figure 42: Source Pull results for CGH 40006P**

Source Pull is done at the source side to properly match the signal with the system to avoid any type of reflections at the input side. From source pull we calculate Impedances. This Source Pull setup is for CGH 40006P. Power Delivered by the system, input reflection coefficient, input impedance are calculated from source pull setup.

## 4.12 Schematic of Input Matching for CGH 40006P

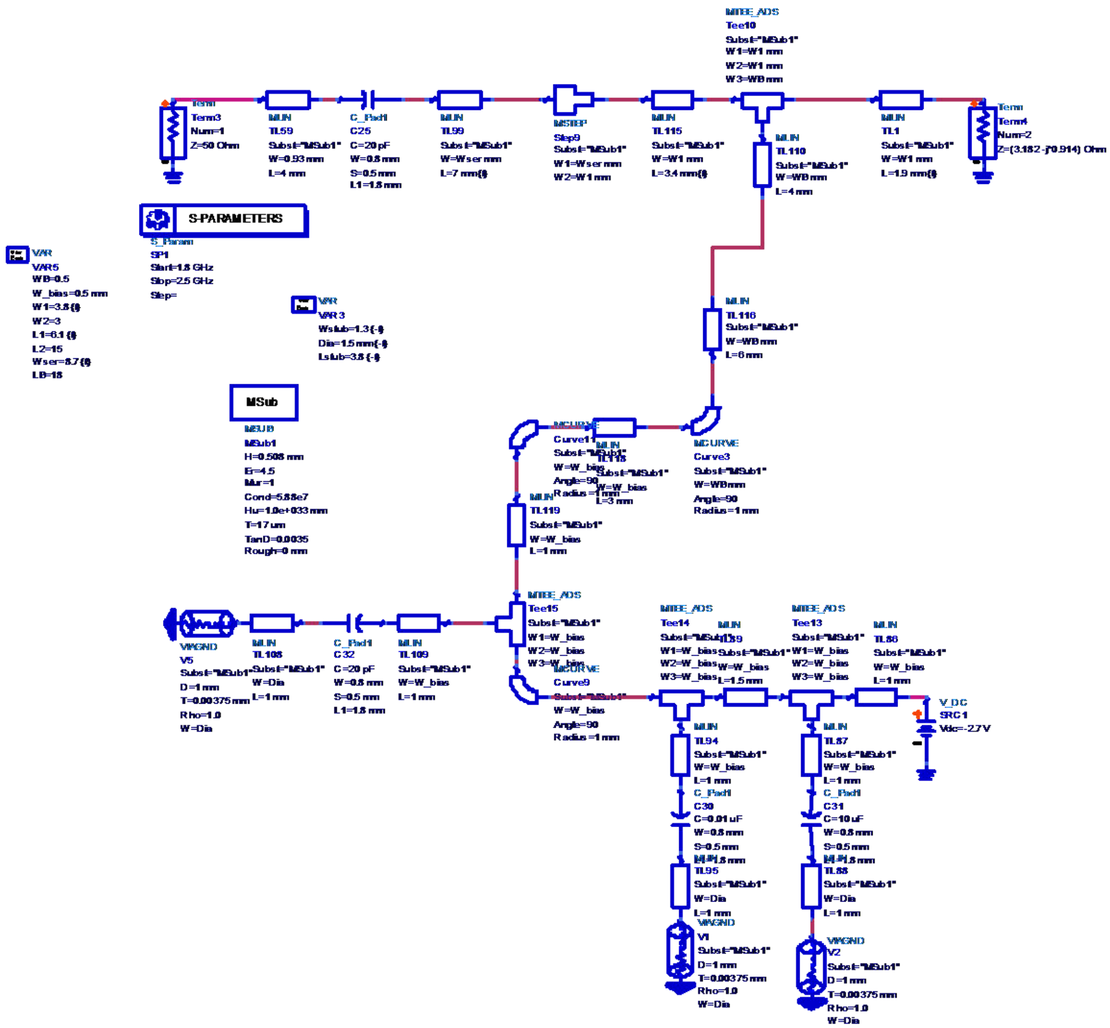



**Figure 43: Input Matching schematic for CGH 40006P**

## 4.13 Graphs of Input Matching for CGH 40006P

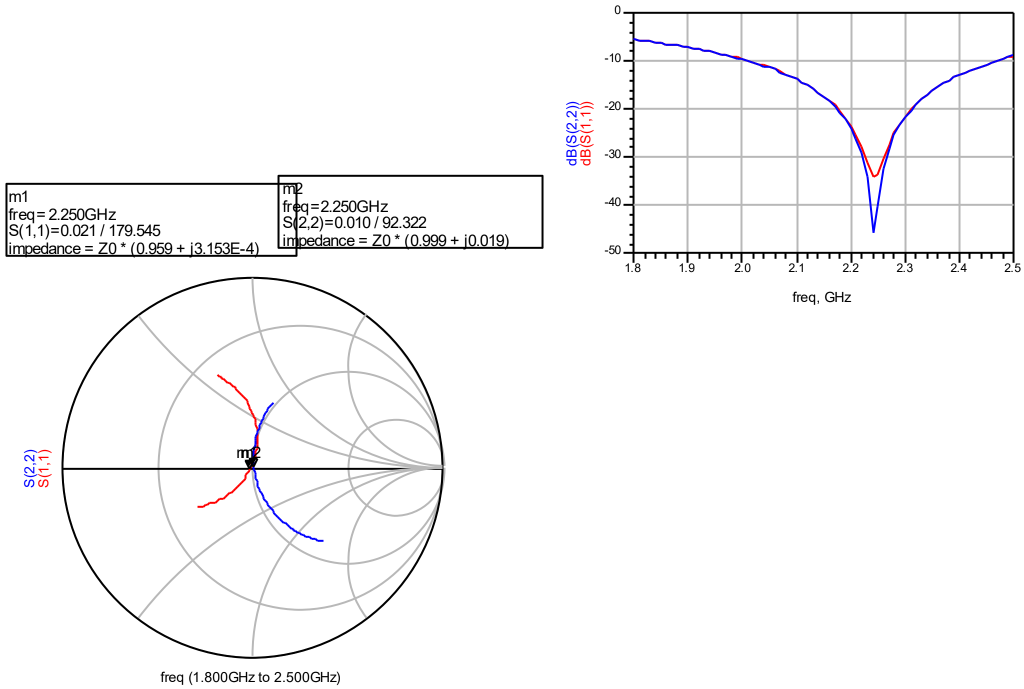



**Figure 44: Input Matching result for CGH 40006P**

The Diagram shows Output matching of CGH 40006P. The marker point at the center shows that device is properly matched in the desired frequency range (2-2.3 GHz) at the input side by using 50 Ohm terminator to avoid any reflections at the source so as to isolate the system from reflections. The Graph shows that the device is stable in the desired frequency range.

## 4.14 Schematic of Input Matching for CGH 40010F

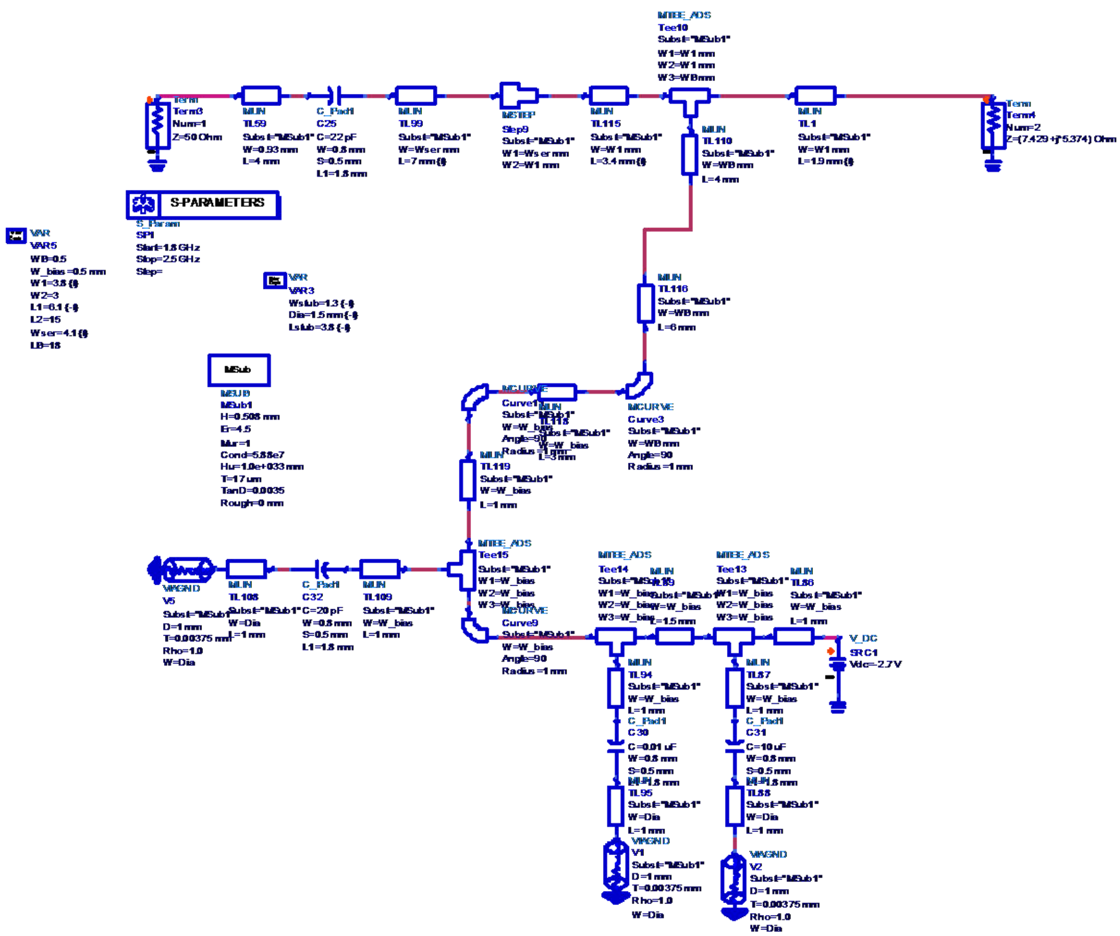



Figure 45: Input schematic for CGH 40010F

## 4.15 Graphs of Input for CGH 40010F

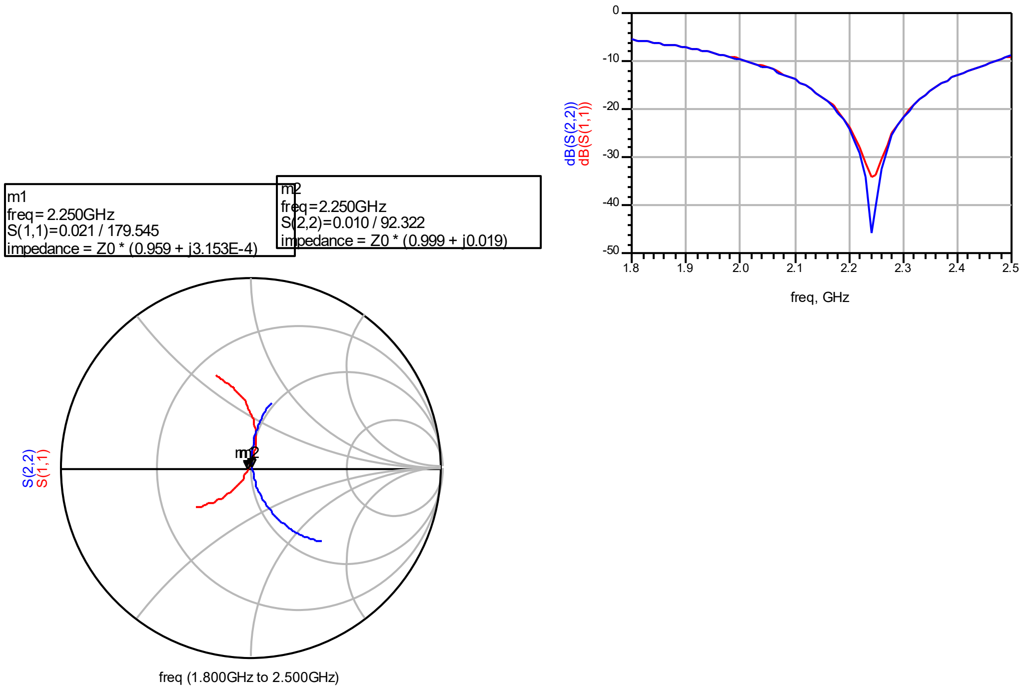



**Figure 46: Input result for CGH 40010F**

The Diagram shows Input matching of CGH 40010F. The marker point at the center shows that device is properly matched in the desired frequency range (2-2.3 GHz) at the input side by using 50 Ohm terminator to avoid any reflections at the source so as to isolate the system from reflections. The Graph shows that the device is stable in the desired frequency range.

## 4.16 Schematic of Output Matching for CGH 40006P

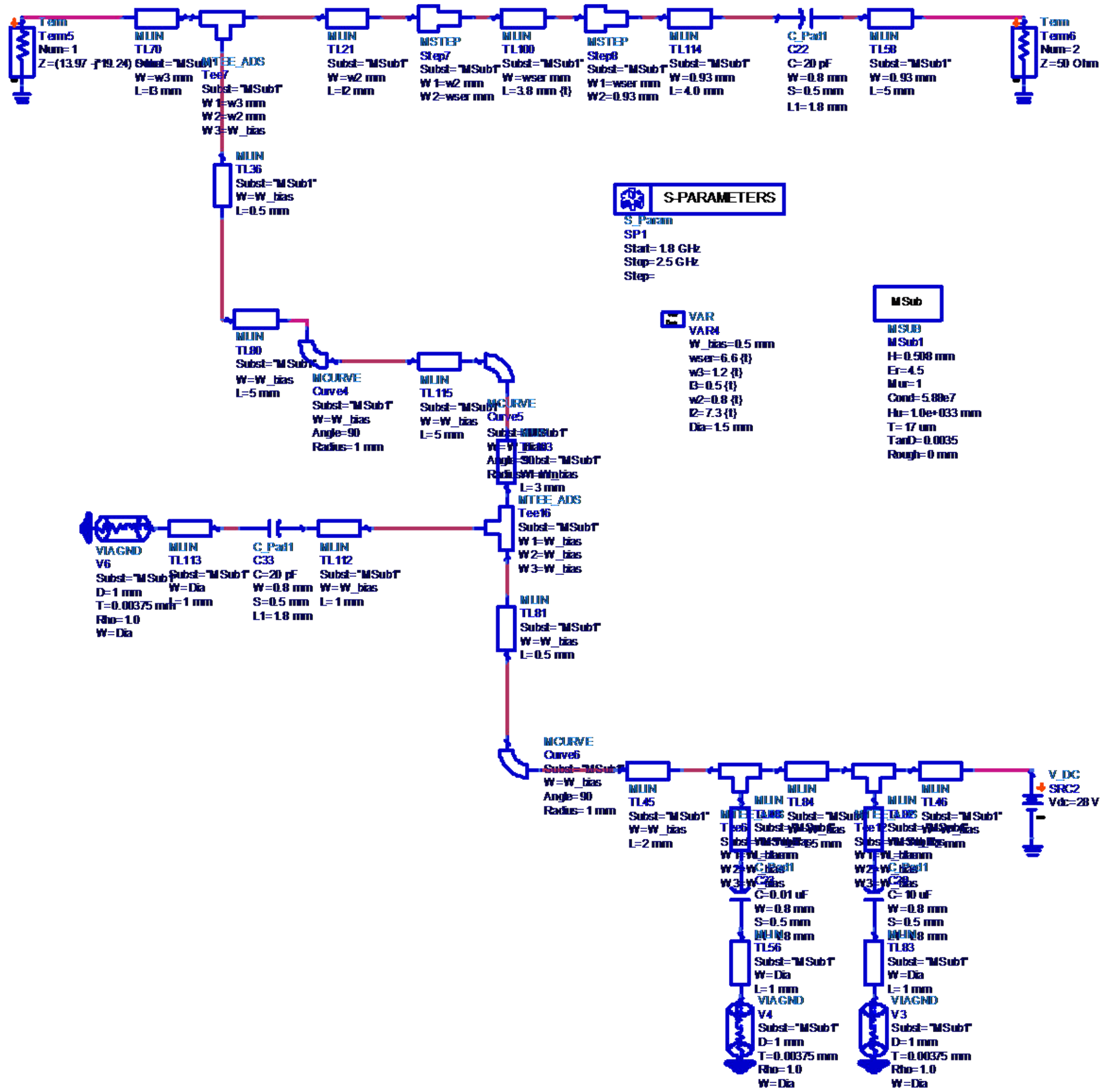



**Figure 47: Output Matching schematic for CGH 40006P**

## 4.17 Graphs of Output Matching for CGH 40006P

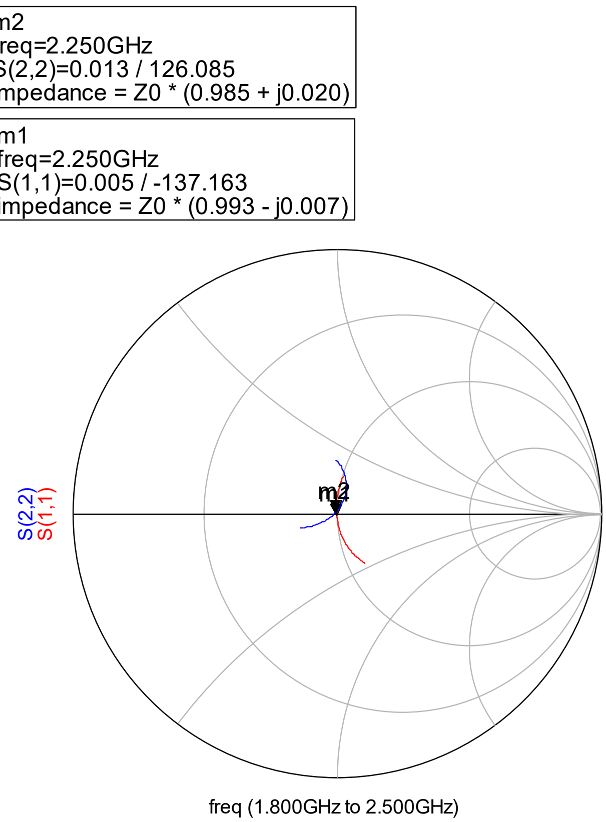



**Figure 48: Output Matching result for CGH 40006P**

The Diagram shows Output matching of CGH 40006P. The marker point at the center shows that device is properly matched in the desired frequency range (2-2.3 GHz) at the output side by using 50 Ohm terminator to avoid any reflections at the load so as to isolate the system from reflections.

## 4.18 Schematic of Output Matching for CGH 40010F

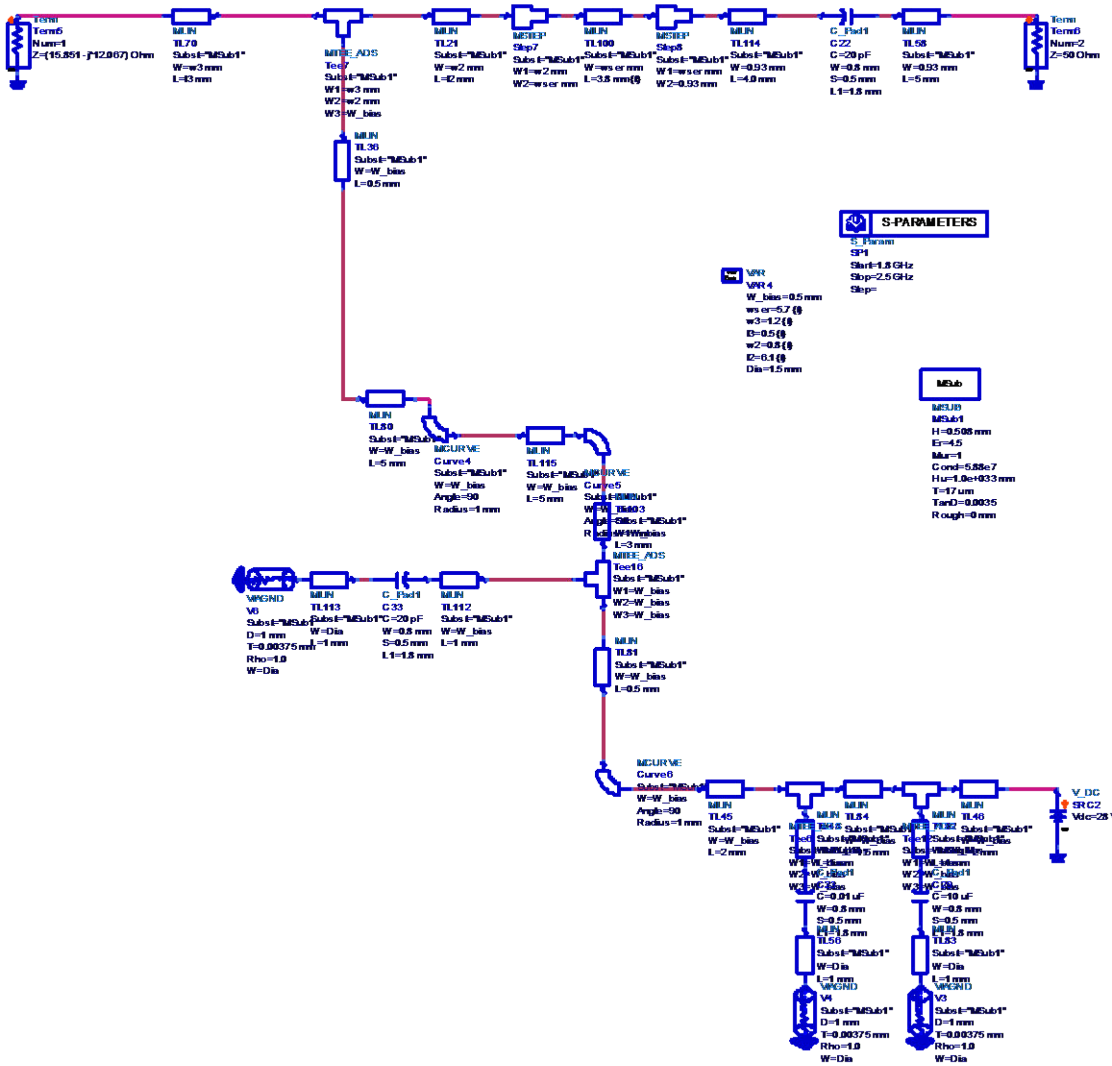



**Figure 49: Output Matching schematic for CGH 40010F**

## 4.19 Graphs of Output Matching for CGH 40010F

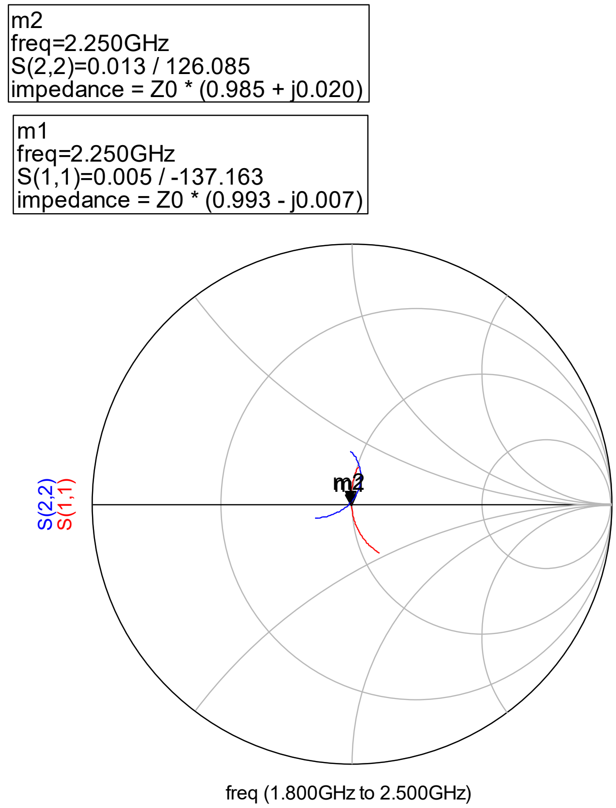



**Figure 50: Output Matching results for CGH 40010F**

The Diagram shows Output matching of CGH 40010F. The marker point at the center shows that device is properly matched in the desired frequency range (2-2.3 GHz) at the output side by using 50 Ohm terminator to avoid any reflections at the load so as to isolate the system from reflections.

## 4.20 Schematic of Load Pull for CGH 40006P

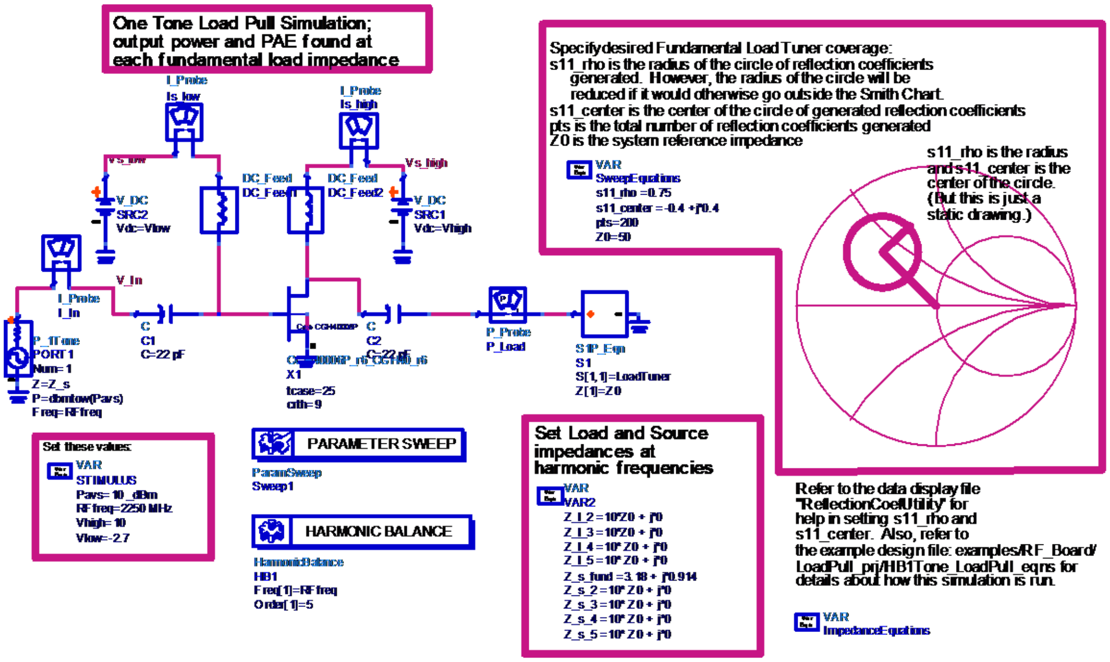



**Figure 51: Load Pull schematic for CGH 40006P**

## 4.21 Graphs of Load Pull for CGH 40006P

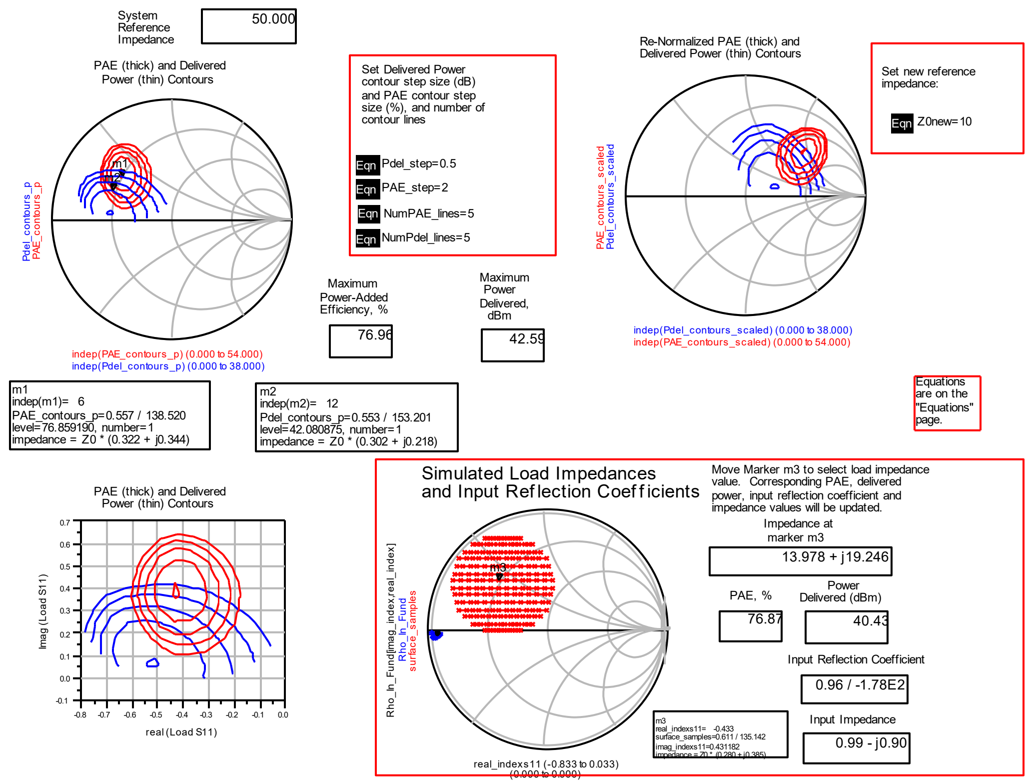



**Figure 52: Load Pull results for CGH 40006P**

Load Pull is done in order to terminate the Signal Properly to avoid any reflections at the load side. From load pull we calculate Impedances. This Load Pull setup is for CGH 40006P. Power Delivered by the system, input reflection coefficient, input impedance are calculated from load pull setup.

## 4.22 Schematic of Load Pull for CGH 40010F

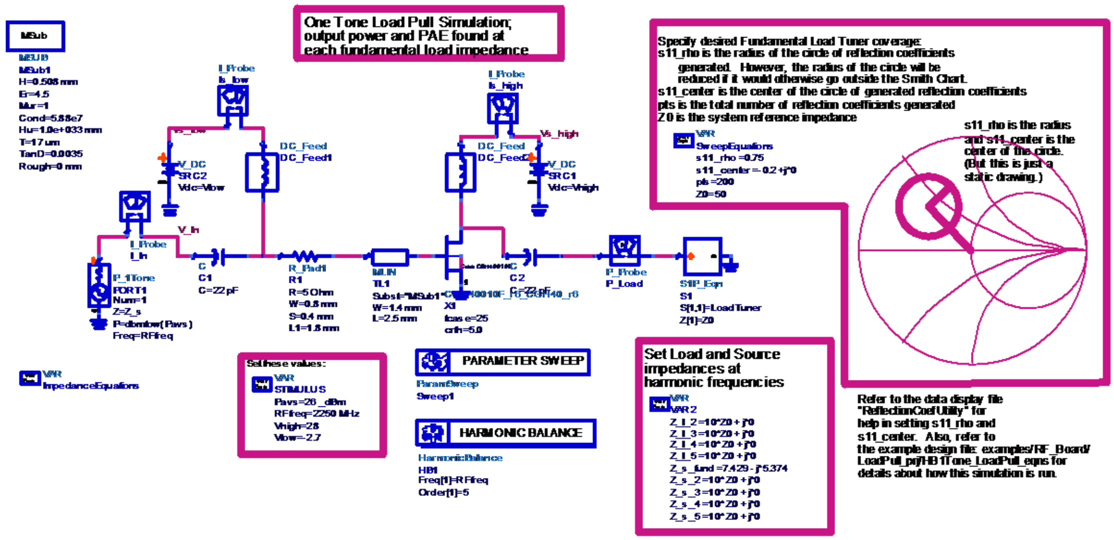



**Figure 53: Load Pull schematic for CGH 40010F**

## 4.23 Graphs of Load Pull for CGH 40010F

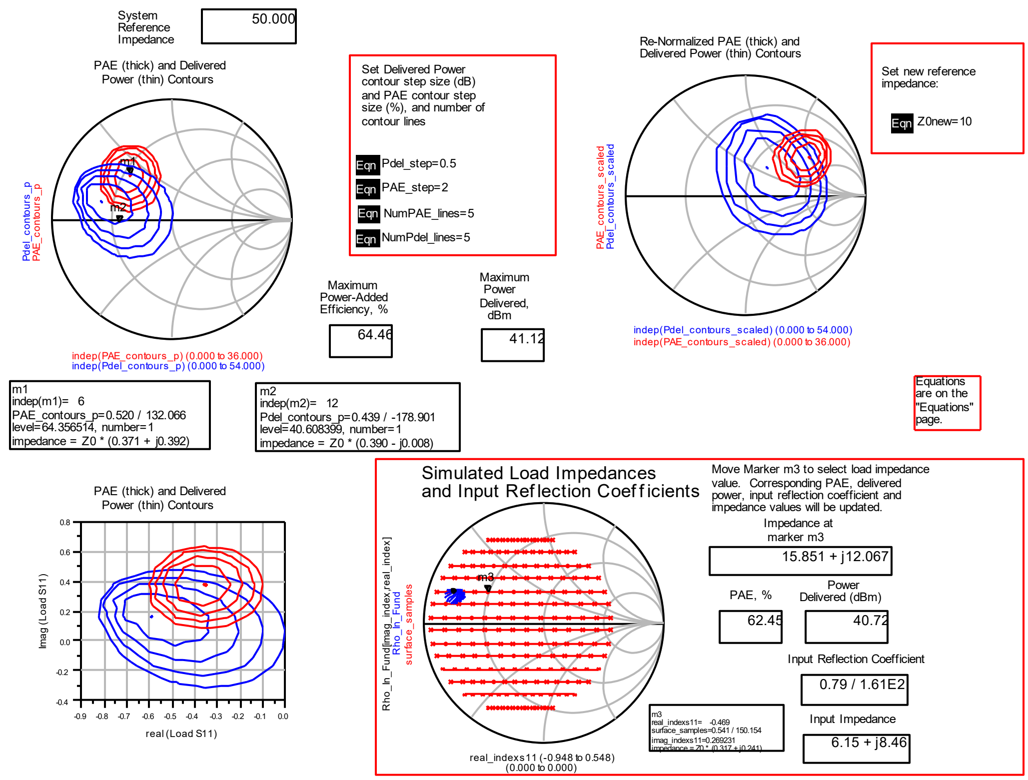



**Figure 54: Load Pull results for CGH 40010F**

Load Pull is done in order to terminate the Signal Properly to avoid any reflections at the load side. From load pull we calculate Impedances. This Load Pull setup is for CGH 40010F. Power Delivered by the system, input reflection coefficient, input impedance are calculated from load pull setup.

## 4.24 Schematic of Harmonic Balance Simulation for Power Added Efficiency (PAE) of CGH 40010F

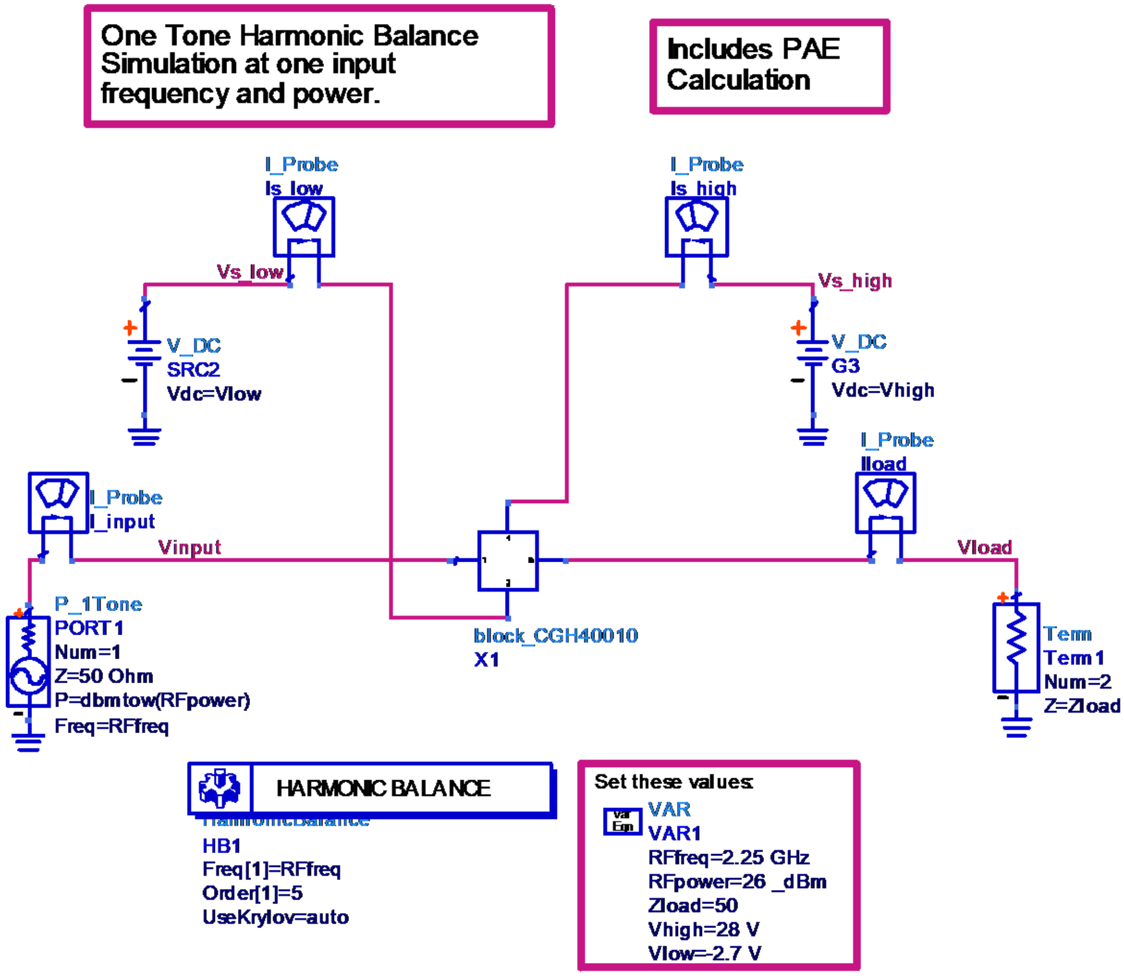



**Figure 55: Harmonic Balance Simulation for Power Added Efficiency (PAE) of CGH 40010F**

## 4.25 Graphs for Harmonic Balance for CGH 40010F

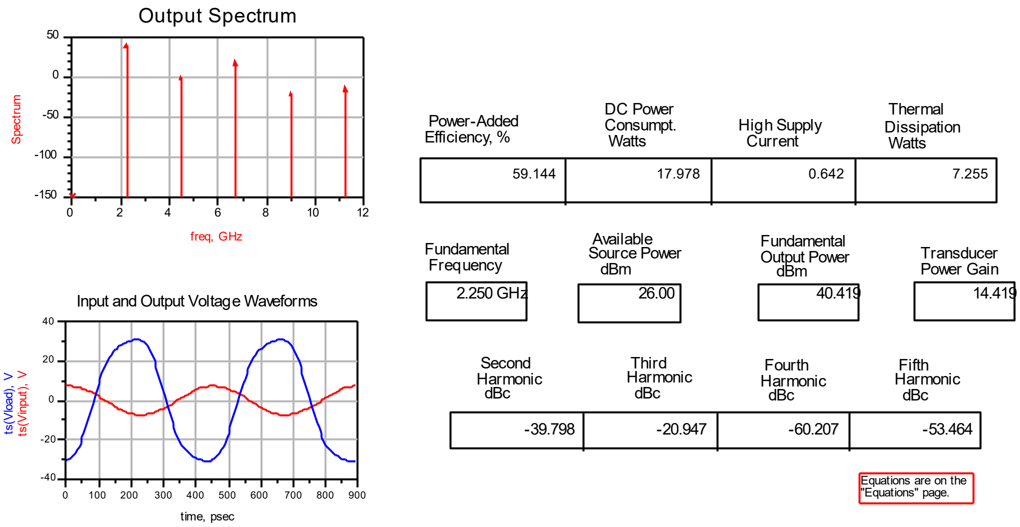



**Figure 56: Harmonic Balance results for CGH 40010F**

These results are from CGH 40010F (2nd Stage) taking 26dbm input power and giving 40dbm output power. Also Power Added Efficiency and Transducer Power Gain is 59.14% and 14.41 respectively. Graphs shows One Tone Testing and Input/output waveforms of RF Signals for CGH 40010F.

## 4.26 Schematic of Harmonic Balance Simulation for Power Added Efficiency (PAE) of CGH 40006P

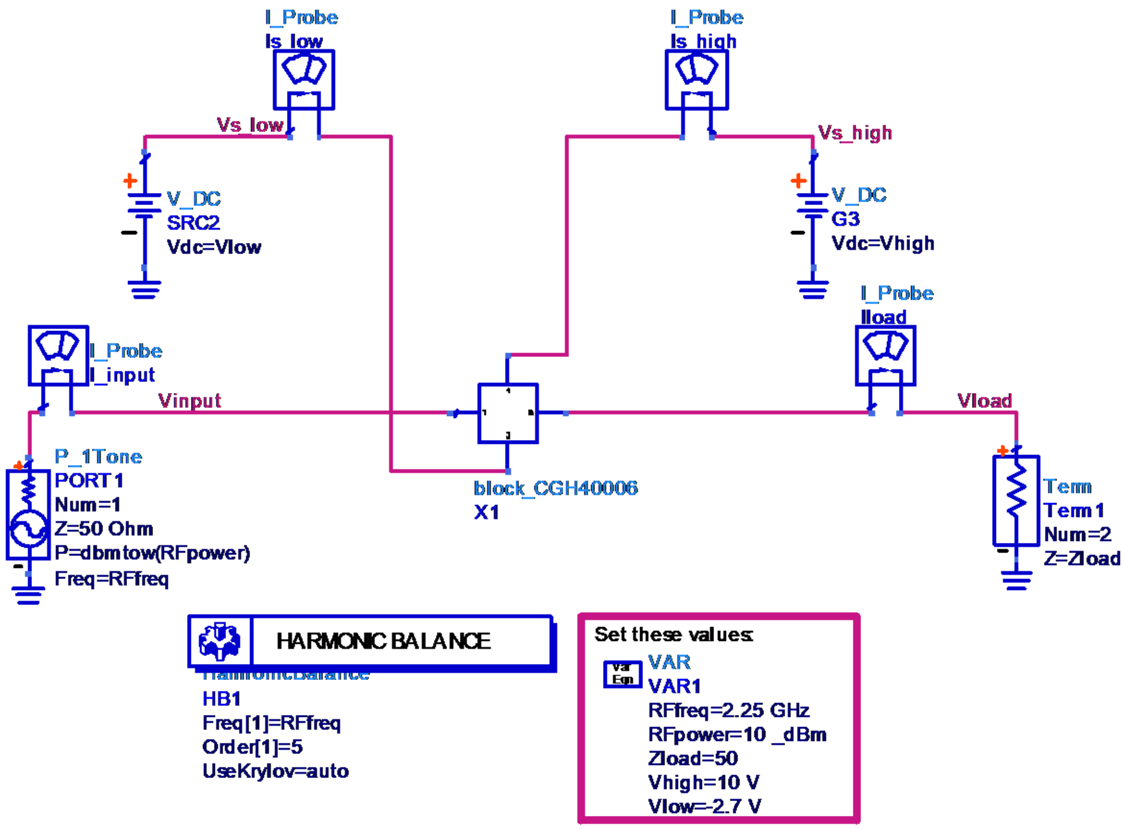



Figure 57: Harmonic Balance Simulation for Power Added Efficiency (PAE) of CGH 40006P

## 4.27 Graphs for Harmonic Balance of CGH 40006P

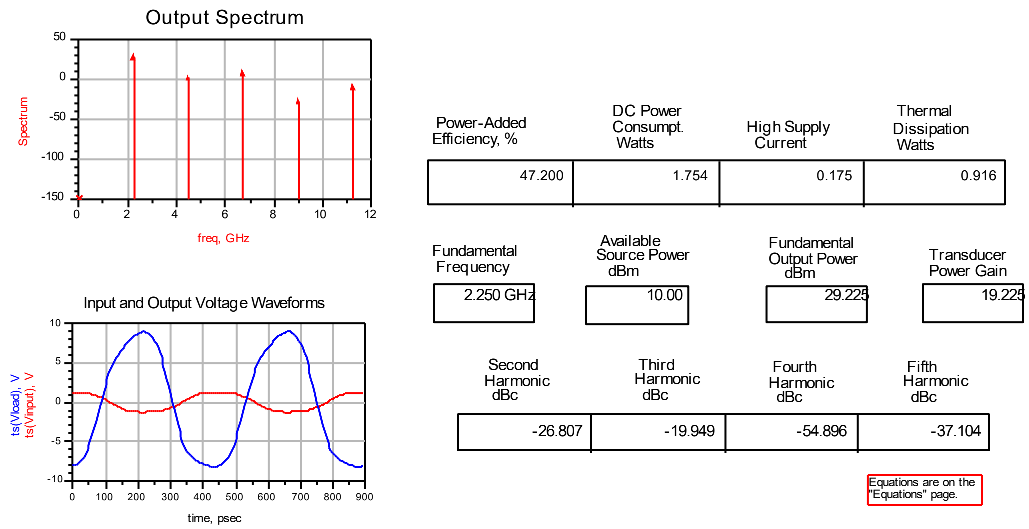



**Figure 58: Harmonic Balance of CGH 40006P**

These results are from CGH 40006P (1st Stage) taking 10dbm input power and giving 29dbm output power. This power is then fed to the CGH 40010F (2nd Stage). Also Power Added Efficiency and Transducer Power Gain is 47.20% and 19.22 respectively. Graphs shows One Tone Testing and Input/output waveforms of RF Signals for CGH 40006P.

## 4.28 Schematic of Harmonic Balance for Power Added Efficiency (PAE) of Cascaded System (40006P and 40010F)

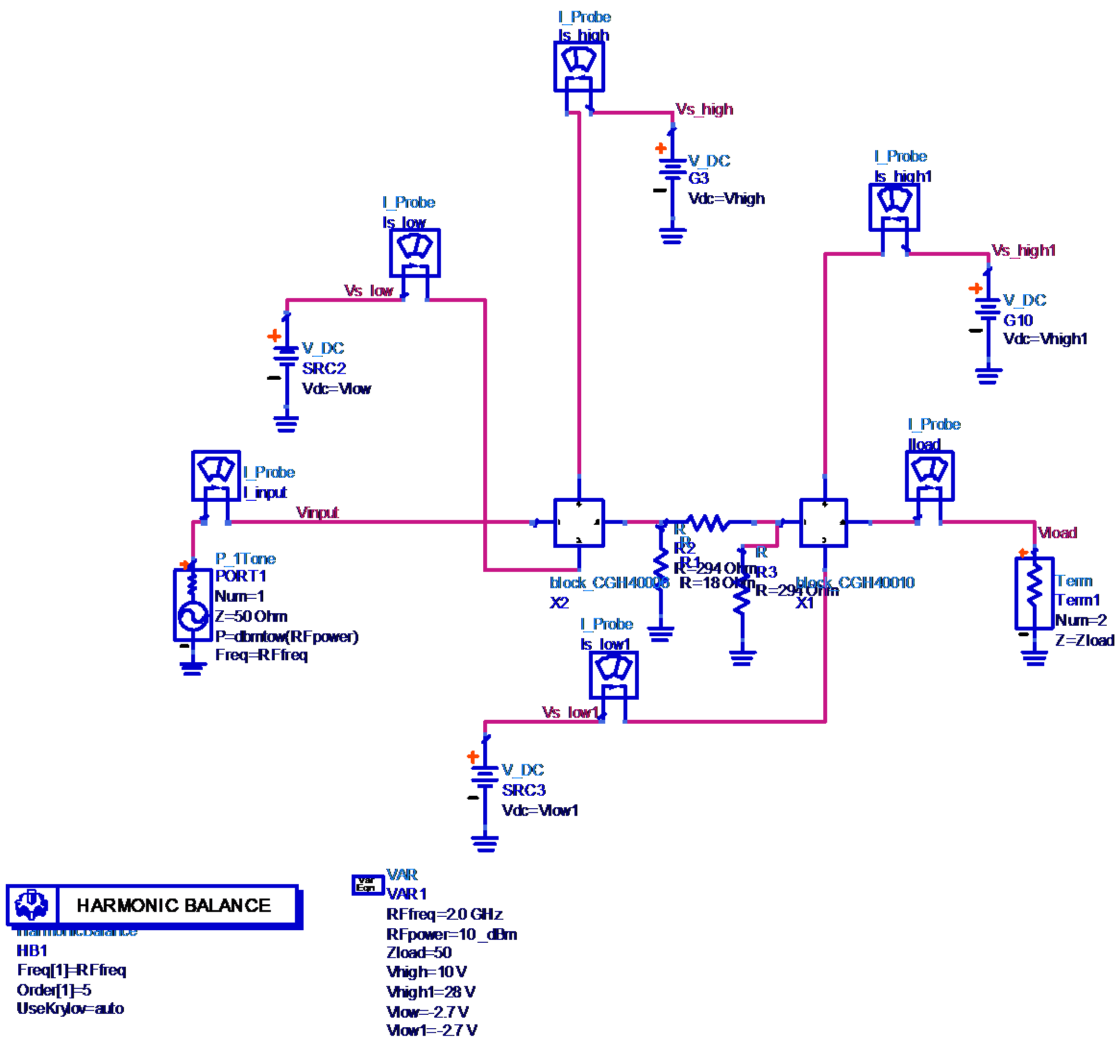



**Figure 59: Cascaded Schematic of Harmonic Balance for PAE**

## 4.29 Graphs for Harmonic Balance for Cascaded System (40006P and 40010F)

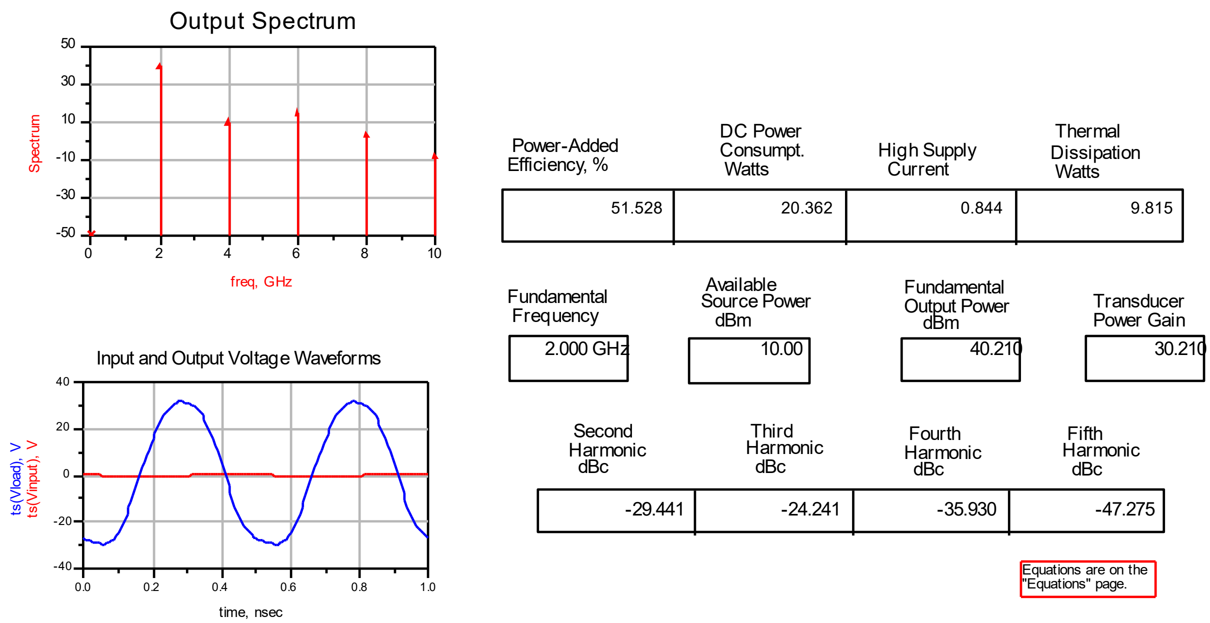



**Figure 60: Results of Cascaded System**

These Results are from cascaded system shows that our device is giving 40dbm output power which is 10W by taking 10dbm or 10mW which was our task. Also Power Added Efficiency of the device is 51.52% and Transducer Power Gain is 30.21. The Graphs shows One Tone Testing results of the device and Input/output waveforms the RF Signals.

## 4.30 Graphs of Co-Simulation of CGH 40006P

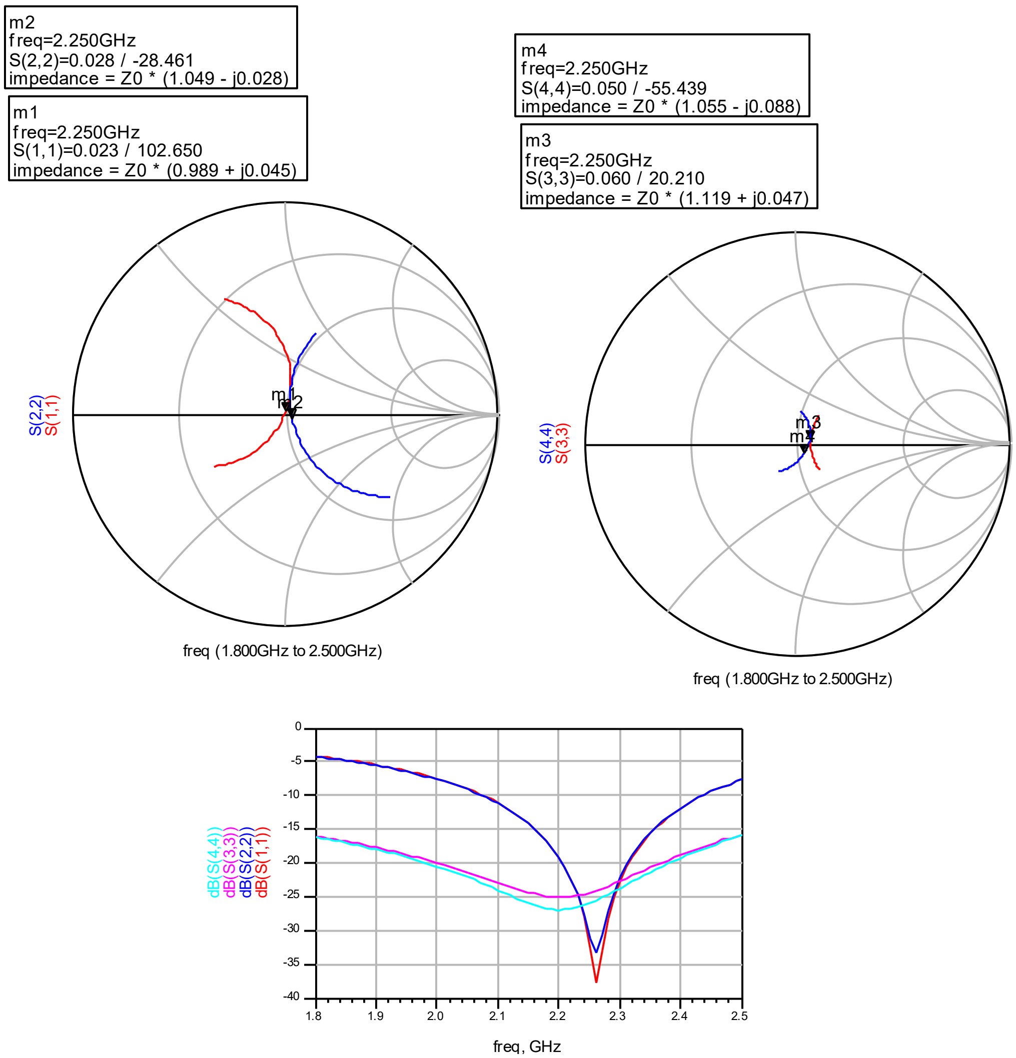



**Figure 61: Co-simulation results of CGH40006P**

The Graphs shown above depicts that our device is our device is stable or matched in the desired frequency range (2-2.3 GHz). The markers on the smith chart at center shows that the device is properly matched.

## 4.31 Co-Simulation of CGH 40006P

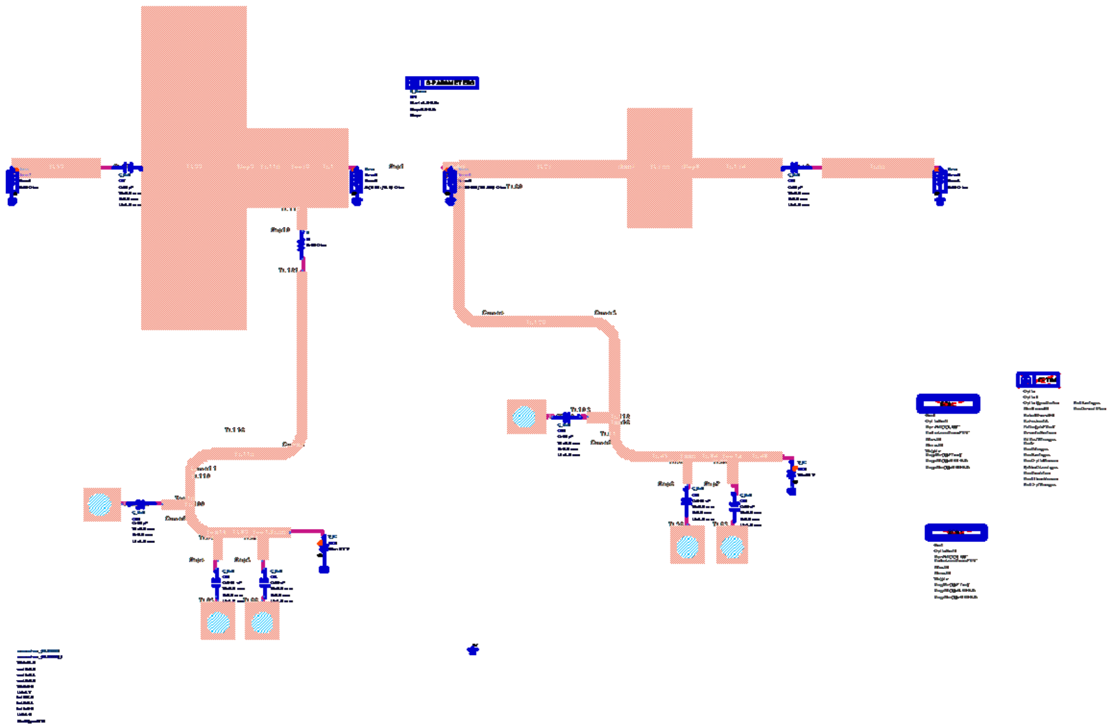


**Figure 62: Co-simulation of CGH40006P**

The Diagram shown above is the final part after which Gerber file is generated for fabrication purpose for the substrate.

Chapter 5

# 5 Fabrication and Performance Measurements

## 5.1 Fabrication of HPA

S-band PA was developed and tested to verify its efficiency under given condition. Figure of developed PA for s-band applications is depicted below.

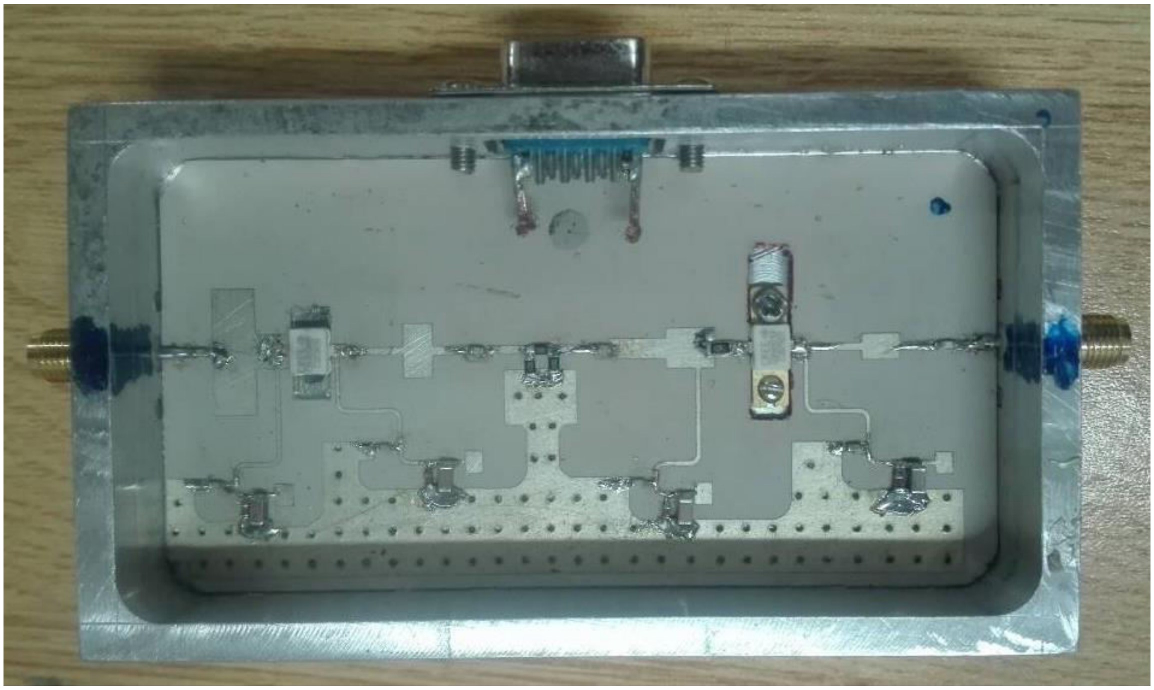


Figure 63: HPA for s-band applications

## 5.2 HPA On/Off Procedures

Following steps are followed to turn on and turn off HPA

**Turn-on procedure:**

1. Initially, every test device, relevant instruments being used along with device operator must be appropriately grounded
2. All input and output of the HPA must be at 50-ohm load.
3. Throughout testing, regulated power supplies are suggested.
4. During procedure, there may be voltage spike therefore both bias lines must have some protection mechanism to deal with it.
5. Initially, adjust 0 V on the gate terminal, i.e. $V_{gs}$=0 V, and also on the drain, i.e. $V_{ds}$=0 V.

6. Reduce gate-source voltage up to pinch off voltage of the HPA.
7. Gradually raise drain to source voltage up to the suggested drain to source voltage.
8. Raise gate to source voltage up to the suggested quiescent drain current, $I_{dsq}$.
9. Finally, turn-on HPA drives.

**Turn-off procedure**
Following steps are followed to properly turn-off HPA

1. Stop the HPA drive.
2. Reduce $V_{gs}$ up to $V_{pMin}$, around –4 to –0.5 V as per HPA device under consideration.
3. Reduce $V_{ds}$ up to $V_{ds}$=0 V.
4. Finally, raise $V_{gs}$ up to $V_{gs}$=0 V.

## 5.3 Performance Testing of Fabricated HPA

Discussed HPA is fabricated and tested soon after satisfied simulation results. Following test equipment's have been utilized to check performance of fabricated HPA.

Figure 1: SMBV100A

Figure 2: FSC

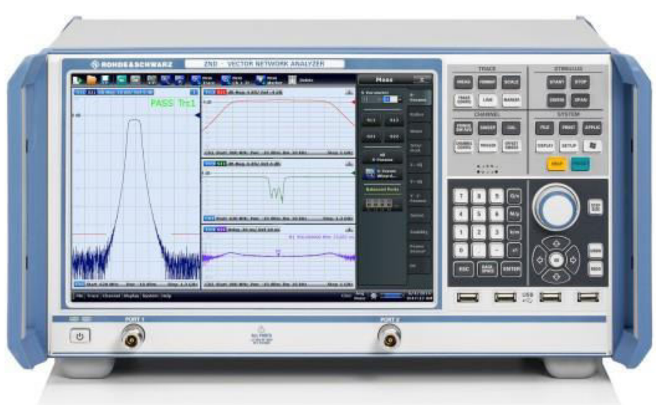


Figure 3: ZND

## 5.4 Performance results

Performance parameters of HPA like S11, S12 and S21 parameters are measured through test equipment's and depicted in following graphs.

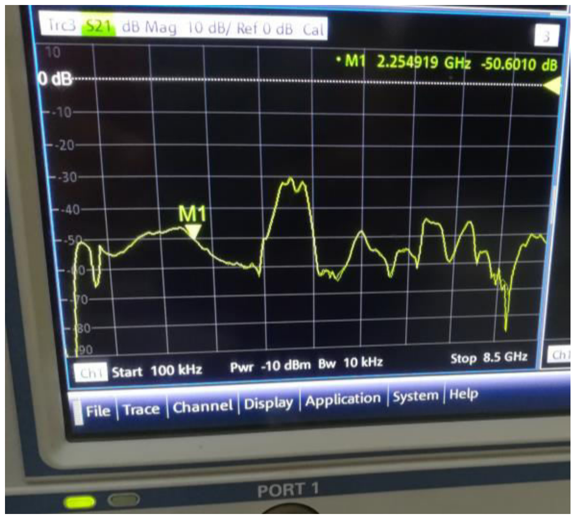



**Figure 4: S21 parameters**


**Figure 5: Marking of S12 parameter**

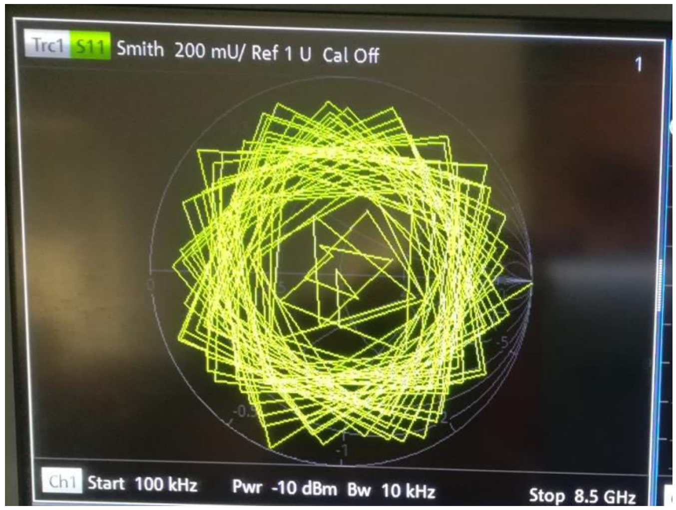



Figure 6: S11 eye-diagram

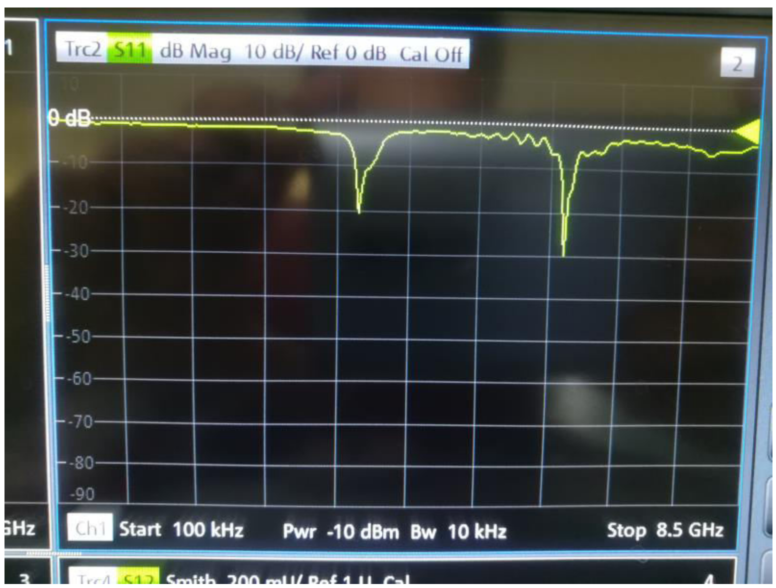



Figure 7: S11 parameter

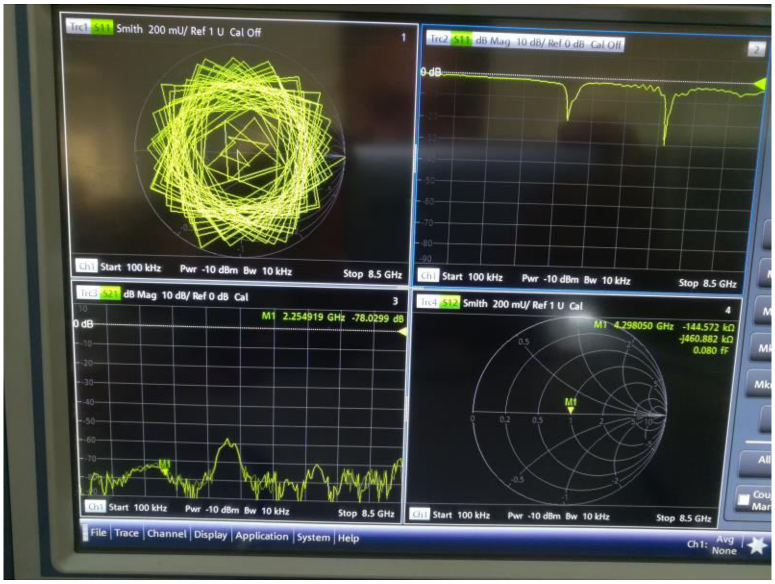



Figure 8: All parameters

## 5.5 HPA band

Designed HPA was analyzed on spectrum to verify HPA band and noise floor. Following figures identify desired results.

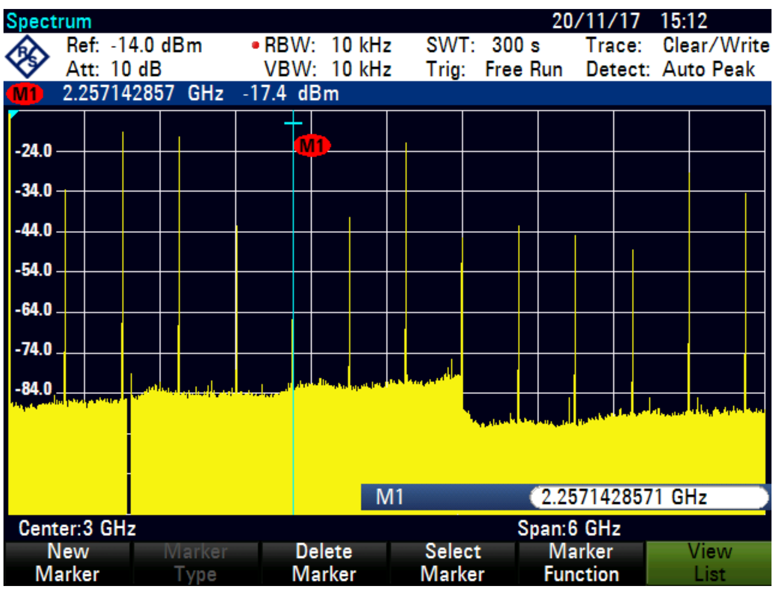



Figure 9: Marker at 2.25 GHz

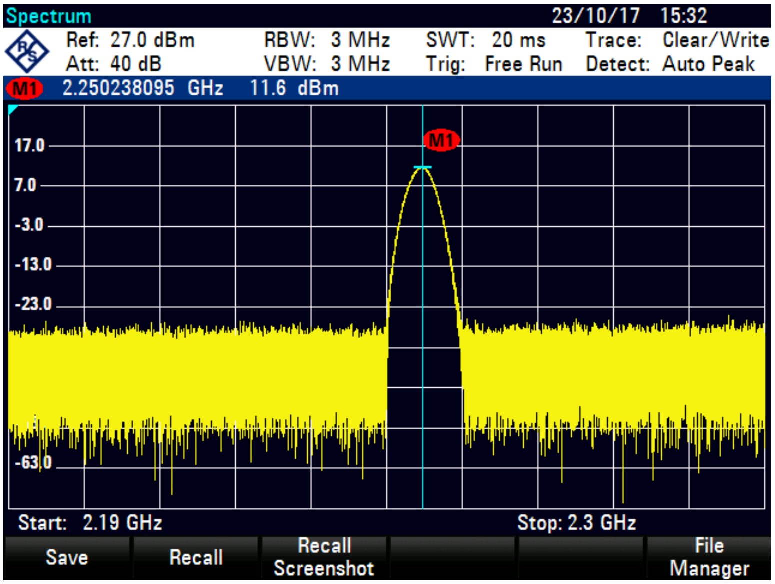



Figure 10: Spectrum at 2.2.5 GHz

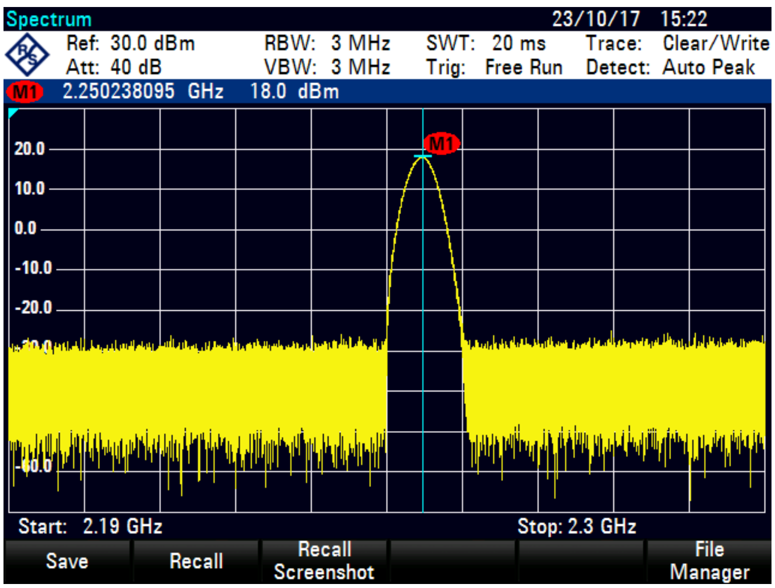



Figure 11: Spectrum at 2.2.5 GHz

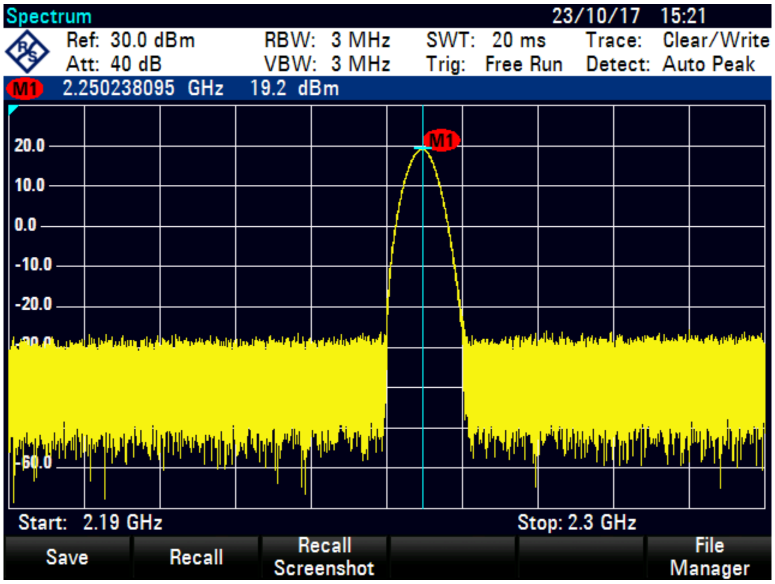



Figure 12: Spectrum at 2.2.5 GHz

## 5.6 Gain performance

Gain performance of HPA was measured and depicted in following graph.

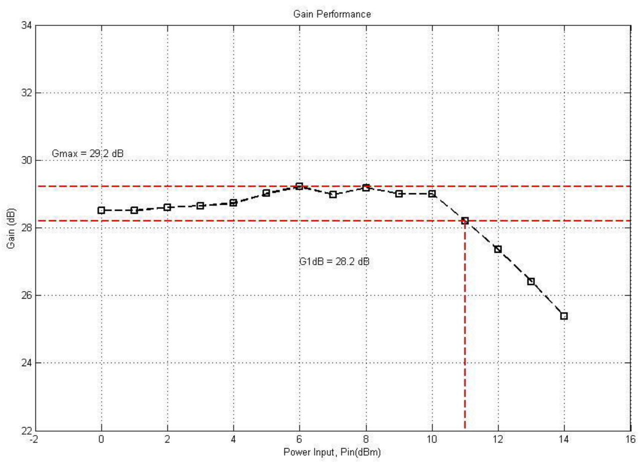



Figure 13: Gain performance

## 5.7 Output power performance

Output power performance of HPA was measured and depicted in following graph.

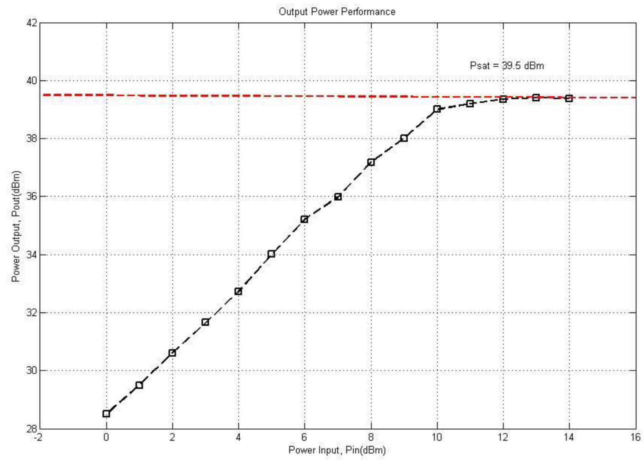



**Figure 14: output power performance**

## 5.8 Comparison of measured and simulated results

Finally, comparison was performed between simulated and measured results to justify the design of HPA.

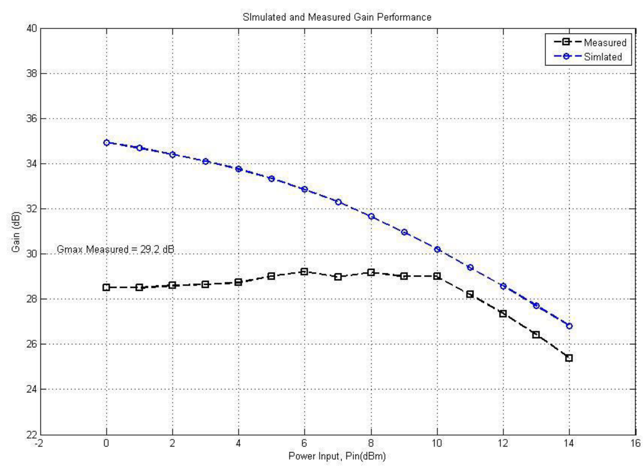



**Figure 15: Comparison of measured and simulation results**

Chapter 6

# 6 CONCLUSION AND FUTURE WORK

## 6.1 Conclusion

In this thesis, we demonstrated design, fabrication and testing of GaN based HPA operating at center frequency of 2.25 GHz. The device test results make it suitable for s-band applications. In 1st stage, Cree Model Unmatched transistor CGH40006P takes input of 10dBm from signal source and step up power of about 29dBm at its output. This power is fed into another Cree Model unmatched transistor 40010F through attenuator so as to prevent any damage to the system and also isolates 2 stages. Final stage gives output of 40dBm or 10W.

Available model is customized for use in S-band HPA circuits. This was done in order to estimate and utilize GaN HEMT devices in the circuits. The devices and their models were established by the design, fabrication, and testing for class AB HPA.

Good HPA design need to incorporate all design requirements discussed in previous chapter and additional real world design constraints in order to produce usable and robust PA device. Major design constrain is stability that need to be maintained along with linearity, gain and efficiency. This thesis has demonstrated stability of proposed design.

## 6.2 Future Work

Regardless of the enormous development in efficiency attain during the last few years, GaN high electron mobility transistors (HEMTs) still have more than a few vital issues to be resolved for millimeter-wave (30 ~ 300 GHz) purposes. One of the main issues is to develop high frequency characteristics. To make best use of $f_{max}$, parasitic components in the device (Ri, R, $R_g$, $C_{gd}$, and $g_o$).

Considering discussed simplified approach to model and design GaN based PA, model accuracy can be optimized since the work discussed above have potential to be optimized in order to reduce discrepancies between model and fabricated PA circuit.

Observed disadvantages include long delays and material cost for required for in house PA fabrication. In order to quickly perform iteration, recommended approach to tune PA model is to measurement setup of harmonic load/source pull.

Furthermore, presented PA design could be evaluated for higher frequencies considering basic design principles discussed in initial chapters. This approach would lead to more complex design based on guidelines discussed in chapter 2 of this thesis. Maximum benefits of the design work are only achieved through mass fabrication of PA for wider applications.

Moreover, the use of GaN based technology is expected to cover wider areas in future including machine to machine (M2M) communication and in cloud based networking for transporting various sensing functions. The field has promising future in biotechnology and structural analysis due to high sensitivity characteristics of GaN HEMT. Smart connected communities, food industry, logistics, and agriculture, environmental and educational systems are some examples where this technology is expected to make remarkable contribution.

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