DESIGN OF GaN BASED S-BAND HIGH LINEARITY

POWER AMPLIFIER

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By

Furkan HÜRCAN

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05 June 2023

We certify that we have read this dissertation and that in our opinion it is fully adequate, in scope and in quality, as a dissertation for the degree of Master of Science.

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LIST OF SYMBOLS

Ω	: Resistance
λ	: Wavelength
°	: Degree
%	: Percentage
A	: Ampere
W	: Watt
V	: Volt
dB	: Decibel
dBm	: Decibel-milliwatts
F	: Farad
H	: Henry
Hz	: Hertz

ABBREVIATIONS

RF	: Radio Frequency
PA	: Power Amplifier
LNA	: Low Noise Amplifier
MPA	: Main Power Amplifier
PPA	: Peaking Power Amplifier
MHz	: Megahertz
GHz	: Gigahertz
BW	: Bandwidth
OBO	: Output Back Off
IBO	: Input Back Off
IMN	: Input-Matching Network
OMN	: Output-Matching Network
FET	: Field Effect Transistor
P1dB	: 1 dB Compression Point
OP1dB	: Output 1 dB Compression Point
IP1Db	: Input 1 dB Compression Point
DPA	: Doherty Power Amplifier
PAE	: Power Added Efficiency
DE	: Drain Efficiency
EM	: Electromagnetic
AC	: Alternating Current
DC	: Direct Current
GaN	: Gallium Nitride
SiC	: Silicon Carbide
GaAs	: Gallium Arsenide
4G	: Fourth Generation
5G	: Fifth Generation
BJT	: Bipolar Junction Transistor
MESFET	: Metal-Semiconductor Field Effect Transistor
HEMT	: High Electron Mobility Transistor
LTE	: Long Term Evolution
CW	: Continuous Wave
VNA	: Vector Network Analyzer
ADS	: Advanced Design System
AM	: Amplitude Modulated
PM	: Phase Modulation
QFN	: Quad Flat Package
PCB	: Printed Circuit Board
RADAR	: Radio Detection and Ranging
IP3	: Third Order Intercept Point
IMD	: Intermodulation Distortion

GaN TABANLI S-BAND YÜKSEK DOĞRUSALLIKLI GÜÇ AMPLİFİKATÖRÜ TASARIMI

ÖZET

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Bu tez haberleşme sistemlerinin vericilerinde kullanılmak üzere L ve S frekans bantlarındaki uygulamalar için yüksek doğrusallığı, verimliliği, 1dB sıkıştırma noktası (P1dB) ve kazanç seviyesi bakımından ön plana çıkan iki farklı güç amplifikatörü tasarımı içermektedir. İlk olarak 1-4 GHz arası çalışan yüksek güçlü GaN Sınıf AB güç yükselteci tasarlanıp deney sonuçları elde edilmiştir. İkinci olarak yüksek verimliliği ile ön plana çıkan 3.4-3.6 GHz arasında çalışan GaN Doherty Güç Yükselteci (DGY) tasarlanıp simülasyon sonuçları elde edilmiştir. 1-4 GHz arası çalışan yüksek güçlü GaN Sınıf AB güç yükseltici için seçilen transistör modelinin yük çekme simulasyonları sonucunda ideal yük ve kaynak empedans değerleri elde edildi. Bu değerlere göre dağıtılmış LC merdiven uyumlama yapısı kullanılarak giriş ve çıkış uyumlama devreleri kuruldu. Bu yapı sayesinde çalışma bant genişliği arttırıldı. Gate (-2.55 V) ve Drain voltaj (28 V) beslemeleri için öngerilim ağları kuruldu ve GaN Sınıf AB güç yükselteci için şematik ve anahat simülasyonları yapıldı. Bu simülasyonlarda doğrusallık, verimlilik, 1 dB sıkıştırma noktası, çıkış gücü ve kazanç değerleri elde edildi. Simülasyon sonuçları elde edildikten sonra GaN AB sınıfı güç yükseltecinin üretimi yapılıp ölçüm sonuçları alınmıştır. Ayrıca simülasyon sonuçları ve deney sonuçları karşılaştırılmıştır. Deney sonuçlarında 1 GHz de 18.7 dB, 2 GHz de 14.86 dB, 3 GHz de 11.06 dB ve 4 GHz de 4.6 dB kazanç elde edilmiştir. Güç Katma Verimliliği frekans bandı içinde 32.4-50.93% arasında elde edilmiştir ve 1 dB Compression point 37-39.8 dBm arasında elde edilmiştir. DC-20 GHz arasında yapılan small signal analizi sonucunda güç amplifikatörü koşulsuz kararlılık sağladığı görülmektedir. Bu tezin bir diğer çalışması olan 3.4-3.6 GHz frekans aralığında çalışan GaN DGY tasarımı yapılmıştır. Melez bir yapıya sahip olan DGY esas ve yardımcı amplifikatör olmak üzere iki amplifikatör içermektedir. Esas amplifikatör, genellikle AB sınıfı veya B sınıfa göre tasarlanır ve düşük güç seviyelerinde doğrusallık ve verimlilik sağlar. Yardımcı amplifikatör C sınıfına göre tasarlanır ve yüksek giriş gücü seviyelerinde çalışmaya başlar. Bu sayede yüksek verimliliği, doğrusallığı ve yüksek çıkış gücü paremetleri sağlanır. Giriş bağlantı noktasındaki sinyal iki amplifikatöre hibrit kuplör ile dağılır ve amplifikatörlerinin çıkışlarının birleştirilmesiyle çıkış sinyali elde edilir. Yük çekme simülasyon sonuçlarıyla elde edilen kaynak ve yük empedans değerlerine göre uygun uyumlaştırma devreleri sayesinde 3.4-3.6 GHz arası 200 MHz bant genişliğe sahip DPA tasarlandı ve elektromanyetik (EM) simülasyonları yapıldı. Simülasyonlar sonucunda frekans bandı içinde 10-12 dB arasında kazanç ve 40.8-41.5

dBm aralığında çıkış 1 dB sıkıştırma noktası (OP1dB) elde edilmiştir. Ayrıca DPA 77-84% arası verimliliğe sahiptir.

Anahtar sözcükler: GaN, Sınıf AB PA, Kazanç, Verimlilik, Doğrusallık, OP1dB, DGY

DESIGN of GaN BASED S-BAND HIGH LINEARITY POWER AMPLIFIER

ABSTRACT

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This thesis includes two different power amplifier designs that stand out in terms of linearity, efficiency, 1dB compression point (P1dB) and gain level for applications in L and S band frequencies to be used in transmitters of communication systems. First, a high-power GaN Class AB power amplifier operating at 1-4 GHz was designed and experimental results were obtained. Secondly, GaN Doherty Power amplifier (DPA) operating between 3.4-3.6 GHz, which stands out with its high efficiency, was designed and simulation results were obtained. Optimum load and source impedance values were obtained because of load pull simulations of the selected transistor model for the high power 1-4 GHz GaN Class AB Power Amplifier (PA). According to these values, input and output matching networks were established using the Distributed LC ladder matching network structure. Thanks to this structure, the working bandwidth has been increased. Bias networks were established for gate and drain Voltage (28 V) feeding. Schematic and layout simulations were made for GaN Class AB power amplifier. In these simulations, linearity, efficiency, 1 dB compression point, output power and gain results were obtained. After the simulation results, GaN Class AB power amplifier was produced, and experimental measurement results were taken. The simulation results and experimental results were compared. Experimental results show a gain of 18.7 dB at 1 GHz, 14.86 dB at 2 GHz, 11.06 dB at 3 GHz and 4.6 dB at 4 GHz. Power Added Efficiency (PAE) was achieved in the band between 32.4-50.93% and a 1 dB Compression point was achieved between 37-39.8 dBm. As a result of DC-20 GHz small signal analysis, the power amplifier provides unconditional stability. Another study of this thesis, GaN DPA working between 3.4-3.6 GHz has been designed. Having a hybrid structure, DPA includes two amplifiers. These are main (carrier) and peaking (auxiliary) amplifier. The main amplifier is usually designed to Class AB or B, ensuring linearity and efficiency at low power levels. The peaking amplifier is designed to Class C and starts up at high input power levels. In this way, it provides high efficiency, linearity, and high output power parameters. The input signal is distributed to the two amplifiers with a hybrid coupler and the output signal is obtained by combining the outputs of the amplifiers. EM simulations were made for DPA with operating frequency range of 3.4-3.6 GHz, thanks to optimum matching circuits established according to the source and load impedance values obtained with the load pull simulation results. As a result of the simulations, 10-12 dB gain and 40.8-41.5 dBm OP1dB were obtained in the frequency band. In addition, DPA has an efficiency of 77-84%.

Keywords: GaN, Class AB PA, DPA, Gain, PAE, Linearity, OP1dB

CHAPTER 1

1. INTRODUCTION

There are many wireless communication standards in wireless communication systems. These communication systems should use different frequency bands efficiently in the radio spectrum by taking different communication standards as a reference. Audio, video, and other data streams supported in wireless communication systems need to be cost-effective and fast to facilitate the rapidly developing human life. To meet these demands, RF transmitter systems must have multi-bands, high efficiency, and high linearity [1]. In wireless communication networks, power amplifiers are essential. It is quite challenging for power amplifiers to have high linearity and efficiency at the same time. Since linearity and efficiency are of critical importance in power amplifier (PA) design, linearity versus efficiency compensation is an important criterion in the design phase. In power amplifiers, the efficiency increases as the amplifier approaches saturation, but linearity begins to deteriorate. Linearity improves in the back-off region. Since both efficiency and linearity are important parameters in communication systems, it necessitates optimizing the efficiency-linearity tradeoff. For this reason, power amplifier design has grown in significance as a research area [2].

To distinguish characteristics and behavior of different PA circuits, Class A, AB, B, and C PA topologies are defined. Class A amplifiers stand out in terms of high linearity, while Class C amplifiers stand out in terms of high efficiency. For the power amplifier to deliver linearity and high efficiency simultaneously, William H. Doherty conducted research in Bell Telephone Laboratories Inc. in 1936 and Doherty Amplifier was invented. The Doherty Power Amplifier (DPA) has a great use in base station transmitters and RF designs for cellular communication systems. It has increased efficiency and provides cost savings in millions of base stations around the world. The Doherty power amplifier aims to provide high efficiency in linear operating mode [3].

Since efficiency has an important role in Amplitude Modulation (AM) transmitter circuits, Doherty structure is commonly used in these systems. In addition, linearity with traditional and newer modulation forms in 4G, 5G and other radio communication systems is of critical importance for minimizing data errors.

The DPA is structurally hybrid. There are two amplifier circuits in one structure, main (carrier) and peaking (auxiliary) amplifier. While the peaking amplifier is typically constructed as class C, the main amplifier is typically designed as class AB or B. Power divider circuit distributes the input signal to the two amplifiers, and the output signal is created by combining the amplifiers outputs. Due to the Class AB amplifier's superior gain, the system uses less power when low-level input signals are present because only the main amplifier is activated. Peaking amplifier is activated to supplement the main amplifier when high-level signals are received, resulting in simultaneous high efficiency, linearity, and output power [4].

CHAPTER 2

2. RF POWER AMPLIFIER DESIGN

2.1. Basics of RF Power Amplifiers

A power amplifier is a type of electrical circuit made to boost the power of a certain input signal. Long-distance modulated wave transmission is necessary for wireless transmissions. Antennas are used to transmit signals, and the signal power determines how far the signal may go. Therefore, PAs used in transmitting systems are used to increase the signal power level [5].

2.2. RF Power Amplifier Design Characteristics

Power amplifiers are used in transmitter designs to achieve the needed high-power signal levels by receiving low-power RF signals and using them as intermediate components. Important signal analysis factors including output power, gain, efficiency, linearity, and stability in RF power amplifiers are taken into consideration in this respect.

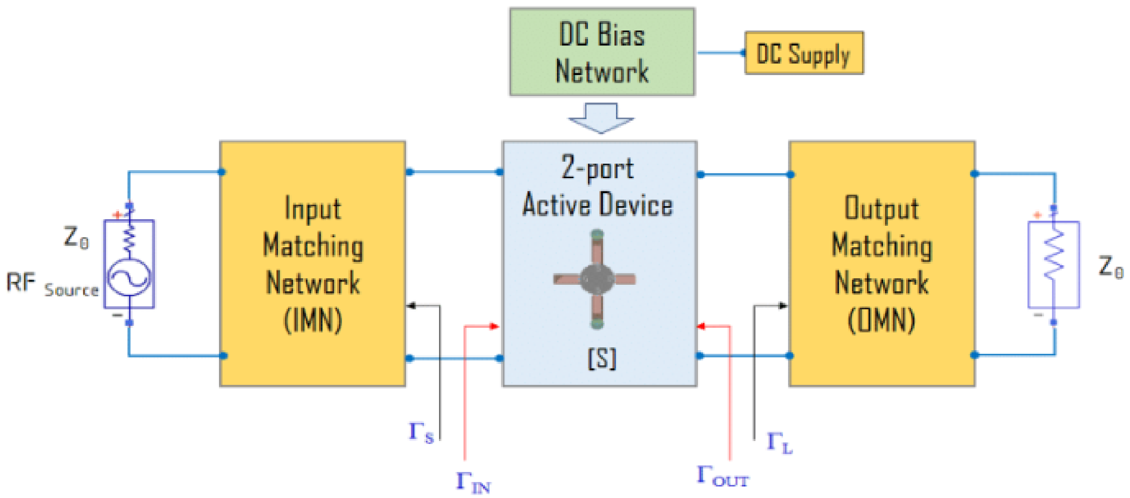

Figure 2. 1: Block Diagram of an RF Power Amplifier

2.2.1. Output Power

Transmitter circuits are used in wireless communication systems to send signals. Depending on the distance between it and the receiver, the objective of transmitters is to broadcast a signal with an output power above a particular threshold. On the transmitter side, a power amplifier is used to do this. Because of this, an essential factor in power amplifier design is the RF power amplifiers available output power. The output power (P_{out}) is defined in dBm or Watts [6]. In the linear region, the output power depends on the input power and gain of the amplifier.

$$\text{Output Power (dBm)} = \text{Input Power (dBm)} + \text{Gain (dB)} \qquad \mathbf{2.1}$$

$$P(W) = 1W \times \frac{10^{\frac{P(dBm)}{10}}}{1000} \qquad \mathbf{2.2}$$

As seen in **2.1**, the input power and gain value are added to get the output power, although this formula is only applicable in the linear working range. The output power does not increase as much as the gain value and achieves saturation when the input power is increased into the saturation zone, which we refer to as the nonlinear region. The output power level at which the gain drops by 1 dB from its constant value is known as the "1dB compression point," as shown in **Figure 2.6** [7].

2.2.2. Gain

An amplifier's function is to increase the signals power from its input to its output. Gain is the term for the variation in input and output signal levels. Multiple gain definitions are available at different stages of the design process that provide insight into the performance of the amplifier.

Using the parameters in **Figure 2.2**, the gain definitions can be examined in detail. P_{in} represents the input power transmitted from the signal source to the amplifier. P_{Ai}, shows the available input power at the source. Usually, $P_{in} \leq P_{Ai}$ is present due to possible losses but as seen in **Figure 2.2**, if M1 (Input Matching Network) provides conjugate matching with source when viewed from source, $P_{in} = P_{Ai}$ condition is met. Actual input power transmitted to the transistor is expressed by P_{inD}. If lossless matching network is performed on M1, the condition $P_{inD} = P_{in}$ is satisfied.

The available output power obtained at the output of the transistor is defined as P_{ADo}. The output power obtained from the amplifier circuit is defined as P_{Ao} and if M2 (Output Matching Network) is lossless, the condition $P_{Ao} = P_{ADo}$ is satisfied. Finally, the actual output power transmitted to the output, that is to the load, is expressed with P_L. If conjugate matching is provided between M2 and load, and M2 is lossless, $P_L = P_{Ao} = P_{ADo}$ condition is provided.

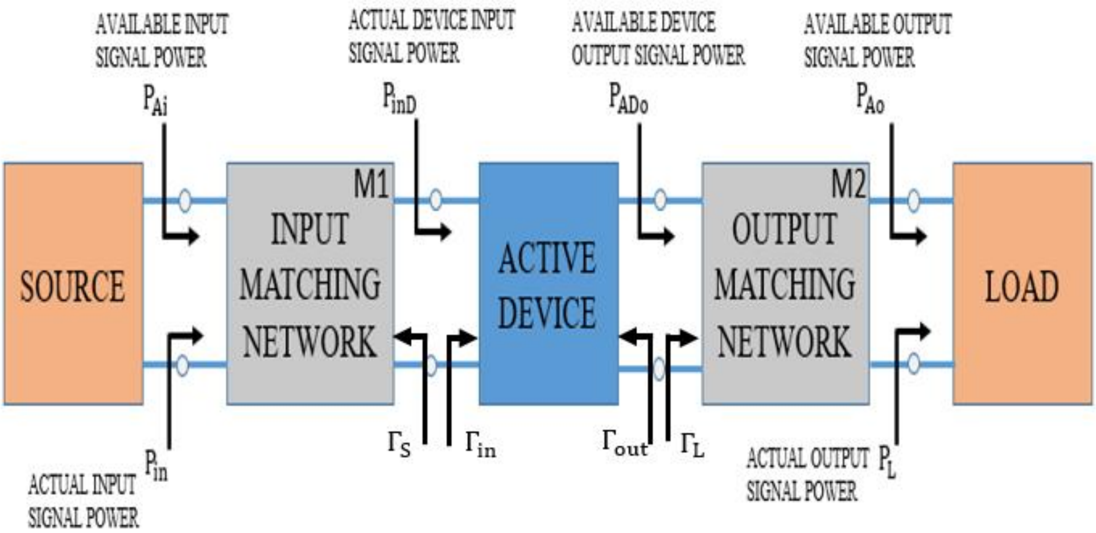

Figure 2. 2: Power Amplifier Gain Analysis

The final gain value of the amplifier is calculated by employing several power definitions at various phases of the amplifier's design. With this approach, the desired gain in the design can be analyzed and obtained with an easier method. Power Gain, Available Gain, and Transducer Gain are three distinct amplifier gain analysis definitions [8].

2.2.2.1. Power Gain

According to **2.3**, power gain is determined as the difference between the actual power ratio in the load and the power at the gain transistor's input. M1 is considered lossless in this equation.

$$G_P = \frac{P_L}{P_{in}} = \frac{|S_{21}|^2(1 - |\Gamma_L|^2)}{(1 - |\Gamma_{in}|^2)|1 - S_{22}\Gamma_L|^2} \qquad \mathbf{2.3}$$

2.2.2.2. Available Gain

According to **2.4**, available gain is determined by dividing the input power from the source by the load's output power. While calculating G_A, M1 and M2 are considered lossless. If M1 and M2 are lossless, maximum power transfer is achieved.

$$G_A = \frac{P_{Ao}}{P_{Ai}} = \frac{|S_{21}|^2(1-|\Gamma_S|^2)}{(1-|\Gamma_{out}|^2)|1-S_{11}\Gamma_S|^2} \qquad \mathbf{2.4}$$

2.2.2.3. Transducer Gain

The ratio created by dividing the power in the load by the power that is available from the source is known as the transducer gain, as seen in the **2.5**. This gain is often the preferred method for defining gain in amplifier designs. G_T was obtained by optimizing the M2 ($|S_{12}|=0$).

$$G_T = \frac{P_L}{P_{Ai}} = \frac{|S_{21}|^2(1-|\Gamma_S|^2)(1-|\Gamma_L|^2)}{|1-S_{22}\Gamma_L|^2|1-\Gamma_S\Gamma_{in}|^2} \qquad \mathbf{2.5}$$

2.2.3. Efficiency

Efficiency is an important parameter in power amplifiers and transceivers. Power amplifiers are one of the components that consume highest levels of power in wireless communication systems. Demand for power saving is constantly increasing as data speeds are continuously improved in Radio Communication systems [9]. However, efficiency has become extremely important as the required overall system performance is increasing rapidly. For example, in a recent research report, it was stated that an average of 12 kW of power is consumed in a typical 5G Base station, and an average of 7 kW in an LTE base station. This shows that there is a 5kW power consumption difference. This shows that the power amplifiers provide serious power consumption in wireless communication systems and hence the efficiency is quite important. With the increase in efficiency in mobile systems, the battery life is increased. In addition, the power dissipated from the amplifiers in the base stations generates heat. If a high efficiency amplifier is used, the amount of heat that will be generated is reduced and the cooling requirement is minimized [10].

Linearity and efficiency are interacting parameters in power amplifiers, and it's hard to keep both high at the same time. To be protected from nonlinear effects that may occur in power amplifiers, it is appropriate for the amplifiers to operate in the linear region, that is, at the bottom of the compression point. As a result, input, or output back-off (IBO and OBO) performance and power efficiency performance are trade-offs. Power efficiency varies depending on input and output pullbacks [11].

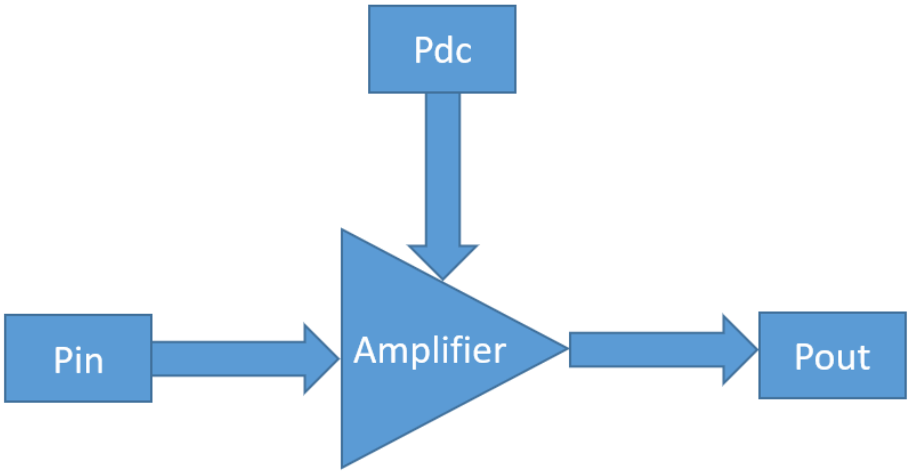

Figure 2. 3: Power Amplifier Efficiency Analysis

As seen in **Figure 2.3**, depending on the input power (P_{in}) and the supplied DC (P_{dc}), the power amplifier produces output power (P_{out}). The ratio of the difference between the amplifier's input and output power to the DC power is known as power added efficiency, or PAE, as specified in the **2.6**.

$$\mathrm{PAE} = \frac{P_{out} - P_{in}}{P_{dc}} \qquad 2.6$$

PAE indicates how effective the DC power is in amplification of the input signal. If all the input power is converted to output power, the efficiency reaches 100%, but practically this can’t be achieved. A certain amount of DC power is lost as heat to the environment during the power conversion process.

When we define the ratio of output power to DC power as shown in **2.7**, we discover Drain Efficiency (DE), which can be used to demonstrate how well DC power is converted to RF power.

$$DE\ (\eta) = \frac{P_{out}}{P_{dc}} \qquad 2.7$$

However, because Drain Efficiency does not consider how much power the amplifier uses, an amplifier can have very low gain even though it has high drain efficiency. This may be misleading during the design and evaluation phase [12].

2.2.4. Stability

RF amplifiers must be stable to avoid unwanted oscillations. The transistor, the two innermost ports housing the feedback networks, and the active devices unconditional stability are all necessary for the amplifier to be stable.

The amplifier may become unstable and oscillate. In general, this is a chaotic response rather than a constant oscillation of fixed amplitude and frequency. This indicates that the amplifier will be unstable. There are 2 different stabilities conditions as unconditional and conditional stability [13].

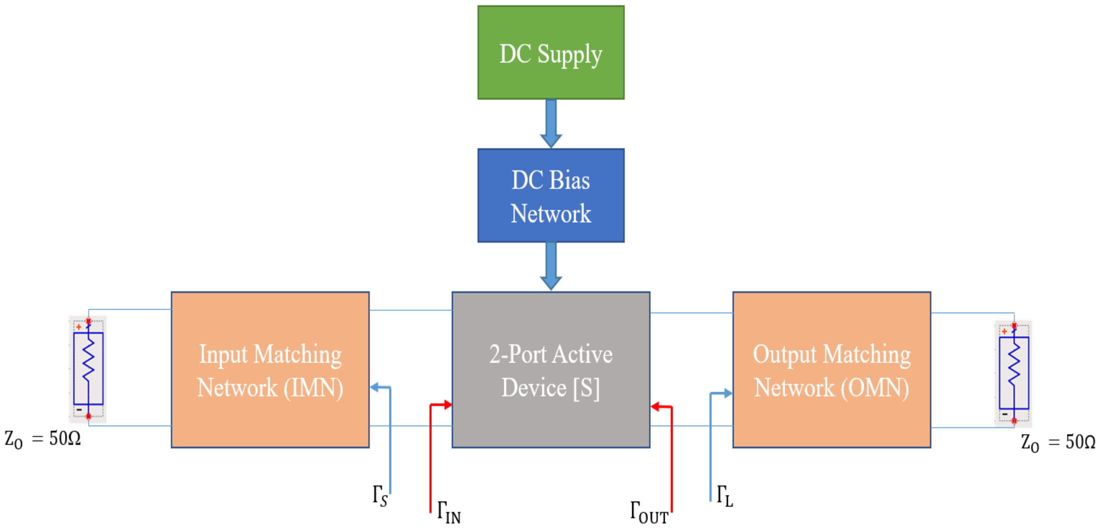

Figure 2. 4: 2-Port Network Stability Analysis

If all source and load impedances meet the conditions $|\Gamma_s|<1$ and $|\Gamma_L|<1$ and $|\Gamma_{\mathrm{IN}}|<1$ and $|\Gamma_{\mathrm{OUT}}|<1$, the network is unconditionally stable. However, if only $|\Gamma_{\mathrm{IN}}|<1$ and $|\Gamma_{\mathrm{OUT}}|<1$ at certain source and load impedances, it is called conditionally stable.

K-|Δ| test and stability circles are used to assess device stability in designs. The most practical and straightforward method to calculate unconditional stability analysis is the K-factor, commonly known as Rollet's stability criterion. K is defined as;

$$\mathrm{K} = \frac{1 - |\mathrm{S}_{11}|^2 - |\mathrm{S}_{22}|^2 + |\Delta|^2}{2|\mathrm{S}_{12}\mathrm{S}_{21}|} > 1 \qquad 2.8$$

$$|\Delta| = |\mathrm{S}_{11}\mathrm{S}_{22} - \mathrm{S}_{12}\mathrm{S}_{21}| < 1 \qquad 2.9$$

With respect to frequency and DC voltage level, the transistor's large signal S characteristics change in the amplifier. Therefore, Care is taken to ensure that the values of K and |Δ| are appropriate for stability. The amplifier is unconditionally stable if K> 1. However, the amplifier cannot be deemed unconditionally stable if K<1. Generally, instability is encountered at low frequencies, causing the amplifier to oscillate at low frequencies. This can damage devices due to sudden amplitude spikes. A resistance is typically applied to the transistor's gate to solve the instability in amplifiers. The Gate's resistance keeps the RF stability performance level high in all circumstances [14].

Generally, in practical designs, the traditional method of (ROLLER (K-|Δ|) test is used in stability analysis. Here, the large-signal S-parameters of the amplifier are used to assess the stability of the amplifier [15].

2.2.5. Linearity

The term linearity describes an amplifier's capacity to faithfully reproduce the input signal at the output. Following are descriptions of the three levels at which linearity solutions can be described: semiconductor device level, circuit design level, and system design level.

2.2.5.1. At the Semiconductor Device level

Semiconductor technology offers a device-level solution for the linearization of PAs. There are various semiconductor technologies such as GaAs MESFET, GaAs HFET, GaAs HBT, SiC MESFET, Si BJT, Si LDMOS FET, GaN HEMT, and devices in these semiconductor technologies have been commonly used in RF power amplifier designs. However, each technology was used with a different approach, especially with respect to the linearity and efficiency requirements of PAs. For example, GaAs MESFET stands out in semiconductor technology in terms of its high RF performance characteristics and ease of application. High Electron Mobility Transistor (HEMT) transistors offer a better noise and breakdown voltage (V_{br} = 84 V for CGH40006S) value compared to other device technologies but have higher f_T and f_{Max} values than other ordinary transistors. As a result, they are chosen in designs for low noise amplifiers (LNA) and power amplifiers (PA), mobile phones, satellite receivers, and radar systems [16].

GaN technology has become more prevalent in RF and microwave solutions because of the rising demand for high-power devices at high frequencies. As seen in **Figure 2.5**, GaN technology offers high power at high frequencies. Thermal conductivity, which is an important parameter in terms of the lifetime of the devices, is another feature that comes to the fore in GaN technology. The greater the thermal conductivity, the cooler the device will run, which will give the device a longer life. In addition, thermal conductivity ensures that the device operates at low temperatures and that the coolers used with the device are physically smaller. In addition, GaN technology overcomes the thermal dissipation problem that may occur in Silicon (Si) and Silicon Carbide (SiC) [17].

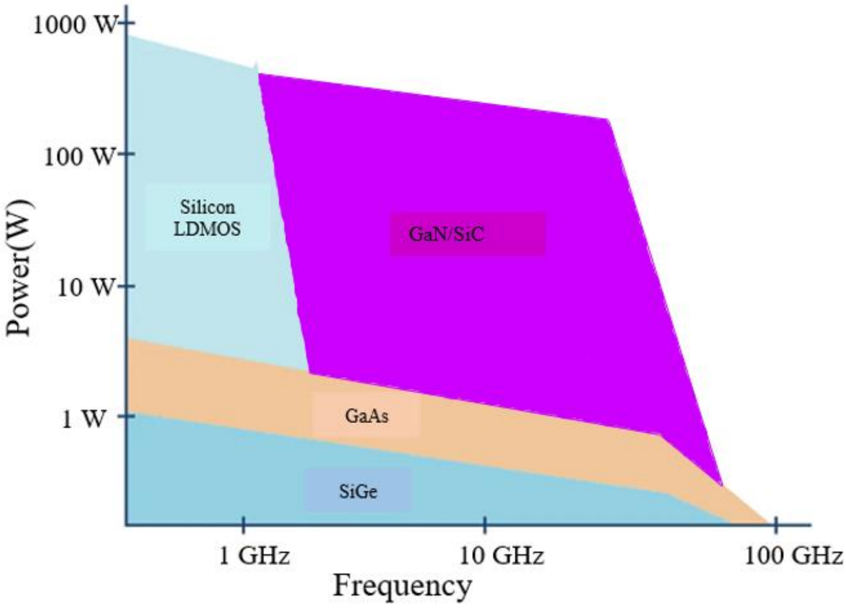

Figure 2. 5: Frequency vs Power Information of Semiconductors

2.2.5.2. At the circuit design level.

The classes of PAs (i.e., Class A, AB, B, and C) are important for linearity of the designs. Each class has a conductivity angle. The efficiency and linearity of the PA have an inverse connection with the conductivity angle, which represents the level of the signal passed from the amplifier's input to its output. As can be seen in Table 2.1, there is a potentially 360° transmission angle for Class A PA since the signal integrity is maintained and 100% of the signal is transported from the amplifier's input to its output. Between 180° and 360° is the conduction angle for Class AB Power Amplifiers, compared to 180° for Class B and 90° down for Class C. Efficiency declines as linearity rises because efficiency and linearity have an inverse relationship. As a result, Class C operates with great efficiency but providing poorer linearity than other classes. But with Class A, AB, and B, linear power amplifier design with lower efficiency can be realized [18].

Table 2. 1: Properties of RF Power Amplifier Classes

Class	Linearity	PAE	Gain	Power Capability	Conduction Angle
A	Excellent	25 to 50%	High	Low	360˚
B	Medium	70 to 80%	Medium/ High	High	180˚

AB	Good	50 to 70%	High	Medium/High	180-360˚
C	Poor	>80 %	Low	High	<90˚

2.2.5.3. System Design Level.

The linear relationship between input signal power and output signal power is known as amplifier linearity. Therefore, it is directly proportional to the gain of the amplifier. Technically the amplifier should have constant gain throughout its operating frequency range, but the gain decreases with increasing frequencies.

Modern communication systems commonly use modulation schemes of unstable envelope signals. Receivers need to have good linearity to preserve information in both amplitude and phase. The linearity of the RF power amplifiers is determined by considering the 1 dB compression point and the third order intercept IP3 point. These features allow us to evaluate performance in power amplifiers.

The output power of a signal is equal to the sum of its input power and gain; this level of output power is known as the 1dB compression point because the gain drops by 1 dB from its fixed value at this point. That is, as the input power level rises, the amplifier's output power does not rise as quickly as the gain value, starting to saturate and rise nonlinearly as a result. The region where the amplifier operates with constant gain is called the linear region and as seen in **Figure 2.6**, the slope of the line needs to be unity. When an amplifier reaches the P1dB compression point, it starts operating in the nonlinear region or compression region. It starts to produce distortion, harmonics, and intermodulation products in the nonlinear region. Since the amplifier runs linearly up to this point, P1dB is one of the most crucial parameters for power amplifiers.

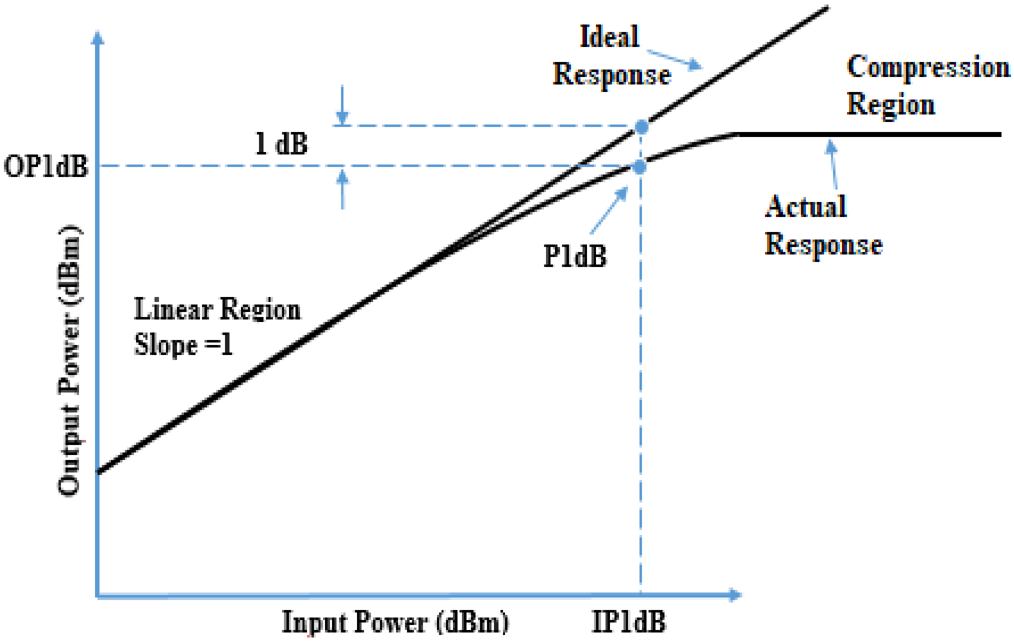

Figure 2. 6: P1dB Compression Point

AM-AM metric displays the relationship between the input signals and output signals amplitudes. For AM-AM analysis, the linearity definition that considers the input and output signals' amplitude levels is appropriate. In communication systems, apart from AM-AM metric, there is also AM-PM metric. The AM-PM analysis demonstrates the link between the input signal's amplitude and the output signal's phase information. While P1dB point shows linearity in AM-AM analysis, phase change with different input signal amplitudes is shown in AM-PM analysis.

The third-order intercept (IP3) point, as shown in **Figure 2.7**, is a crucial parameter for linearity and is a crucial component in device characterization. Under normal circumstances, we will never reach this point, as the amplifier will reach saturation before IP3 is reached.

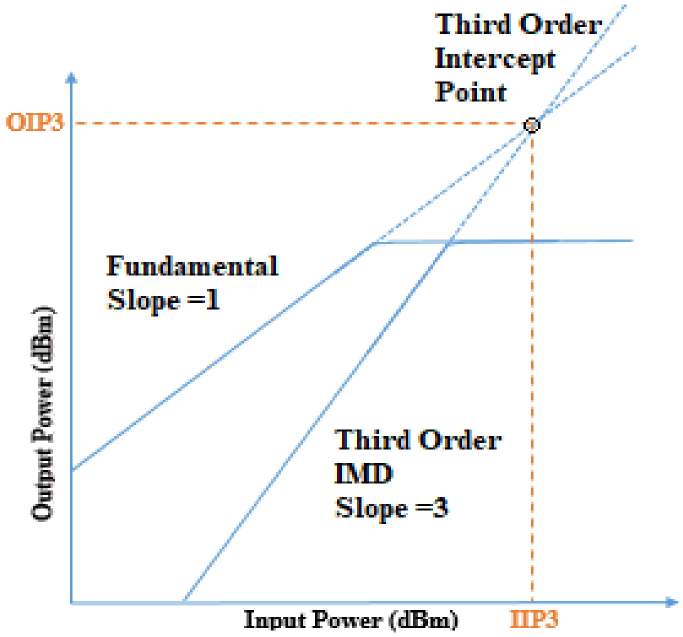

Figure 2. 7: IIP3 Compression Point

When the amplifier is non-linear, the amplified input signals begin to produce harmonics. The input signal amplified at frequency f1 creates second, third and other harmonics such as 2*f1, 3*f1. Harmonics are outside the bandwidth of the RF amplifier. Therefore, it is easy to filter. If there are 2 tones or more signals at the input in the nonlinear region and mixing is performed, shape distortions occur. Therefore, IP3 must be calculated to measure Intermodulation Distortion (IMD) and linearity of the device under test. This is a critical point for the RF Performance of the device. If the device has good linearity, it has a high IP3 rating. It means that in device with low IP3 rating, IMD products may interfere with the fundamental signal. As seen in **Figure 2.8**, f1 and f2 frequencies are formed within the bandwidth of the amplifier. In addition, due to distortion, new second order signals such as f1-f2 and f1+f2 were formed. These signals are mixed with each other to produce interfering signals in the pass band of the amplifier. The third order products are those that are most like the fundamental tone frequencies when two input signals are applied simultaneously to an amplifier. The most non-linear impact on the amplifier is the third-degree intermodulation power, or IMD3, which is different from the fundamental output power. Appropriate design steps must be taken to minimize the generation of these terms. In addition, non-linear products can be prevented by effective filtering and isolation [19], [20].

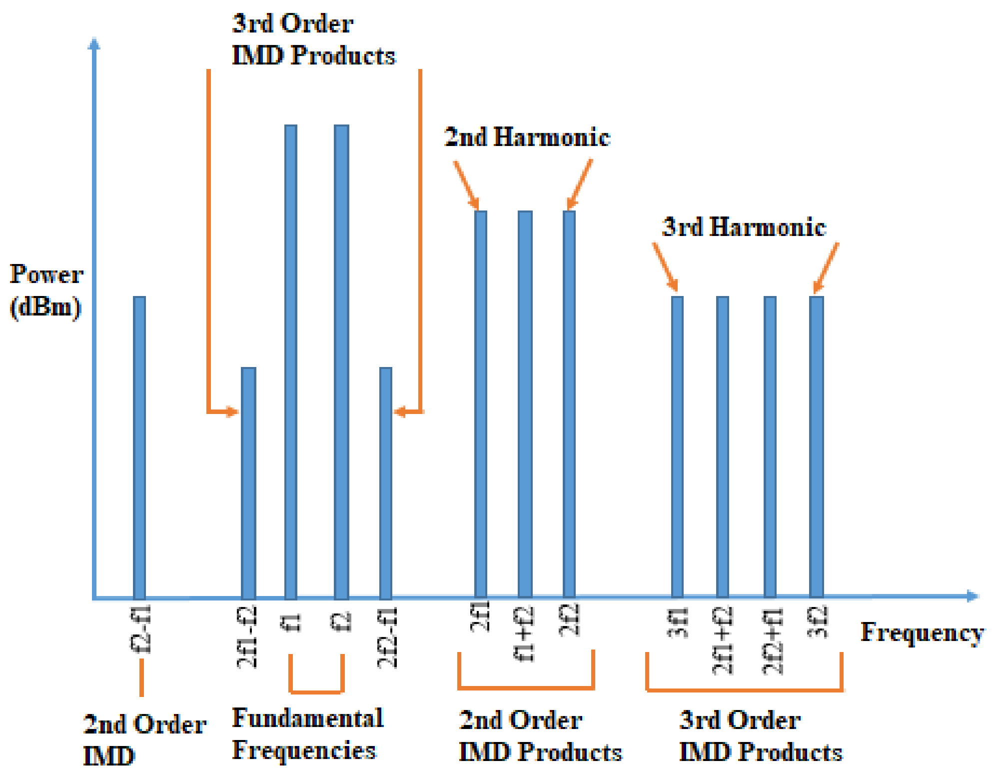

Figure 2. 8: Harmonics and IMD Products

2.3. RF Power Amplifier Categories

One of the essential components in communication technologies and wireless communication applications like radar are RF power amplifiers. These systems have a proportional relationship between efficiency and power consumption, range and linearity, output power, and gain level. As a result, depending on the needs of the system, different signal types have varied amplification requirements in terms of gain, output power, efficiency, linearity, and other performance criteria. For this reason, amplifier classes are classified according to the performance and characteristics of the amplifier. (A, B, AB, C etc.). These classes are the more common types of amplifiers for linear designs. There are also other amplifier classes that doesn't use analog approaches. These are various classes of amplifiers (Class D to T) that tend to be based on switching techniques.

In AM (Amplitude Modulated) or PM (Phase Modulated) communication systems, the amplitude and phase information of the input signal is important. The input signals together with the amplifier's gain generate output signals. The amplifier with good linearity maintains the AM and PM relationships in the continuously increasing input signals up to a certain output signal level. Multitone signals are used in AM and PM systems. If the amplifier is non-linear, it will cause unacceptable Intermodulation Distortion (IMD). Pulsed signals are used in radar systems. In such systems, amplifier efficiency, output power and gain are more important parameters than linearity. Radar applications may not need high linearity.

2.3.1. Class A Power Amplifier

Positive highs and negative lows make up the analog waveforms. Such signals are processed by preserving wave integrity while amplifying the signal from the source. The waveform's positive and negative components are both amplified while maintaining the original waveform as best as possible. Since Class A power amplifiers have substantially lower levels of signal distortion and a 360° transmission angle, they function better at higher frequencies. These classes of amplifiers have very high operating temperatures as they constantly draw a constant current with or without a signal at the input. For this reason, it is poor compared to other amplifier classes in terms of efficiency. They usually operate at 25%-50% efficiency levels. But they are the best amplifier class in terms of linearity and provide high gain. As seen in **Figure 2.9**, to establish the operational bias voltage values in a Class A power amplifier, the Quiescent Point (Q-Point) is chosen from the region shown on the DC I-V graph [21].

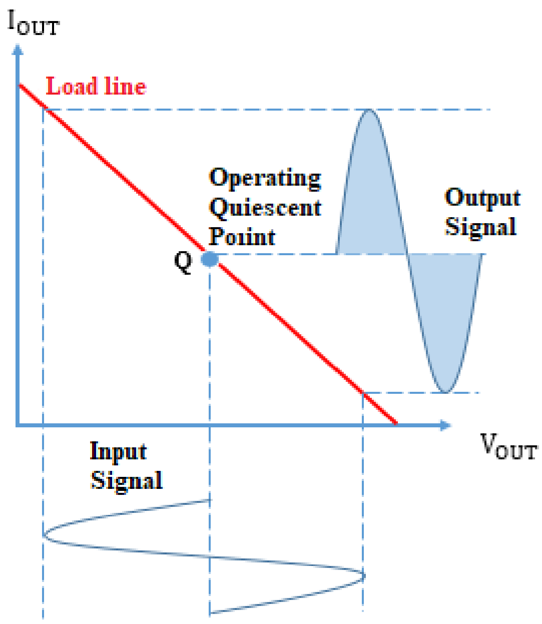

Figure 2. 9: Operating Quiescent Point of Class A Power Amplifier from DC I-V Curve

2.3.2. Class B Power Amplifier

Class A amplifiers have efficiency and overheating problems. Class B power amplifiers are designed to address these problems. The conduction angle in class B power amplifiers is 180 °. The theoretical maximum efficiency level is between 75 and 80%, hence its power capability is greater than Class A. Heat production is at low levels. Approximately 30% of the energy is converted into heat but in terms of linearity, Class B power amplifiers fall short of Class A amplifiers in performance. The level of gain that can be achieved is also lower than class A. As seen in **Figure 2.10**, The DC I-V Graph's Quiescent Point (Q-Point) is the reference point used to calculate the operational bias voltage values for a Class B power amplifier [22].

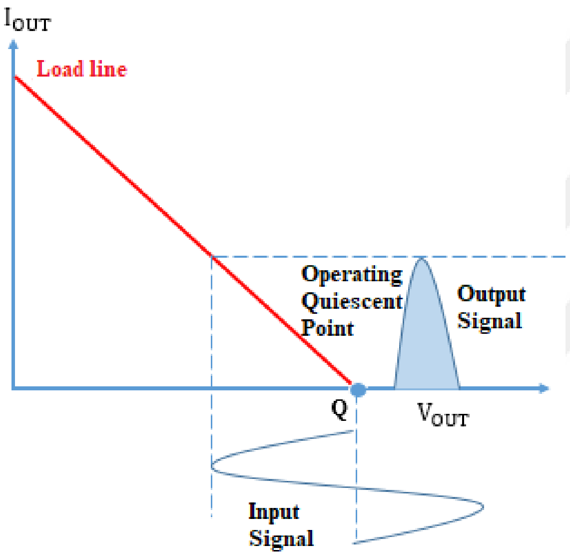

Figure 2. 10: Operating Quiescent Point of Class B Power Amplifier from DC I-V Curve

2.3.3. Class AB Power Amplifier

Designing a linear, efficient, and high gain power amplifier is the goal of class AB amplifiers. A combination of class A and class B amplifiers make up this kind of amplifier. Class AB amplifiers are created to lessen crossover signal distortion in class B amplifiers and efficiency issues with Class A amplifier. They continue to have good efficiency and a high frequency response, just as Class A amplifier. The transmission angle is in the range of 180˚- 360˚ and the efficiency level is in the range of 50-70%. Although they are more efficient than Class A, they are less efficient than Class B. As can be seen in **Figure 2.11**, the operating bias voltage values for a Class AB power amplifier are determined by the Quiescent Point (Q-Point), which is in the range shown on the DC I-V graph [23].

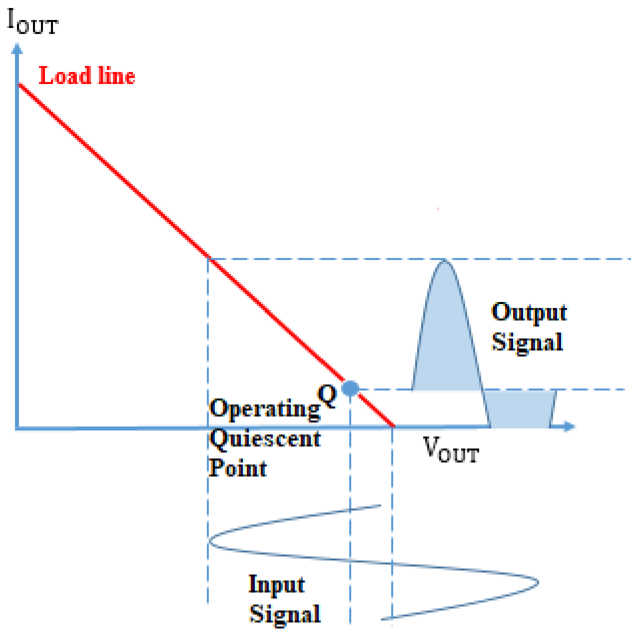

Figure 2. 11: Using the DC I-V Curve to Operate the Quiescent Point of a Class AB Power Amplifier

2.3.4. Class C Power Amplifier

The necessity for high efficiency amplifiers is addressed by class C amplifiers. The efficiency level is more than 80% and the transmission angle is below 90˚. Therefore, linearity and gain are worse than other types. In other words, amplification quality is sacrificed for increased efficiency. Less transmission angle means more signal degradation. For this reason, high frequency oscillators and nonlinear amplification of radio frequency signals are the two main applications for Class C amplifiers. As seen in **Figure 2.12**, the DC I-V Graph's Quiescent Point (Q-Point) is the reference point used to calculate the operational bias voltage values for a Class C power amplifier [24].

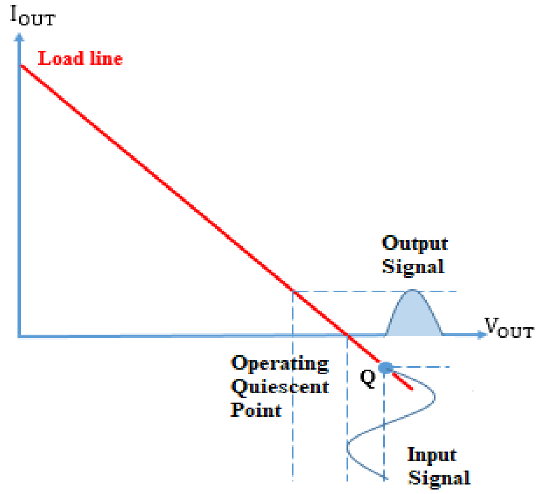

Figure 2. 12: Operating Quiescent Point of Class C Power Amplifier from DC I-V Curve

CHAPTER 3

3. GaN CLASS AB PA DESIGN BETWEEN 1 TO 4 GHz

This section explains the Class AB Power Amplifier design phase between 1-4 GHz. As explained in the previous sections, a combination of Class A and Class B amplifiers is known as a Class AB power amplifier. Class A amplifiers offer high gain and linearity, but low efficiency. Class B amplifiers, on the other hand, offer higher efficiency and less gain and linearity than class A. When all RF parameters are taken into consideration, Class AB Power amplifier design operating between 1 – 4 GHz frequencies has been carried out.

3.1. DC I-V Curve of 1-4 GHz Class AB PA

The Q-point is established when classifying the amplifier, as depicted in **Figure 3.1**. While V_{DS} = 28V in Class AB amplifier design, it is seen that V_{GS} = -2.7 V at the selected Q point and the drain current (I_{DS}) is 130 mA. In this way, bias values were found in Class AB amplifier design. The transmission angle at the selected operating point is between 180 and 360 ˚.

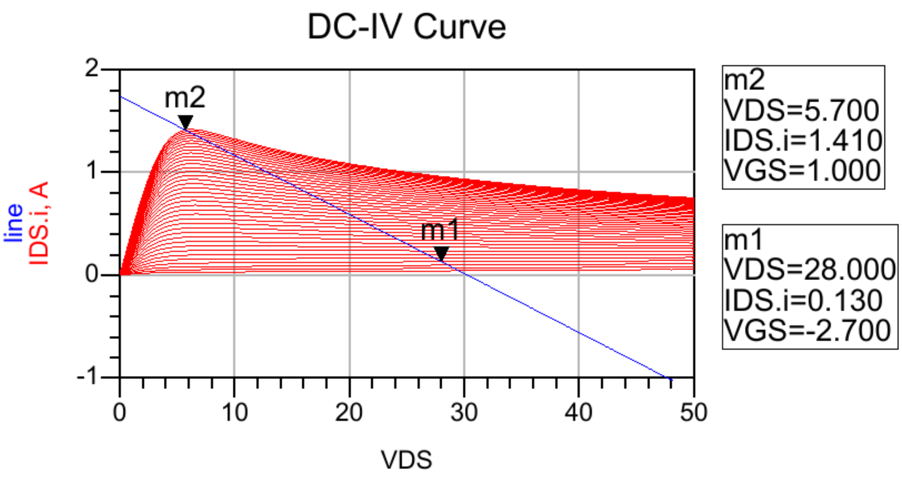

Figure 3. 1: DC I-V Curve Analysis and Q-Point of Cree CGH40006S Transistor

3.2. Schematic Design of 1 to 4 GHz GaN PA Design

Due to its high efficiency, high power density, and wide bandwidth, GaN-based RF Transistors have gained popularity in recent years. To design a Class AB class high efficiency broadband power amplifier that will operate between 1-4 GHz, Wolfspeed's CGH40006S is an unmatched gallium nitride (GaN) high electron mobility transistor (HEMT), which offers a broadband solution for RF and microwave applications. This transistor has the dimensions of 3x3 mm and has a plastic package.

The suggested PA was designed using Agilent's Advanced Design System (ADS) tool. Rogers 4003C with 0.508 mm thickness relative dielectric constant, er = 3.38 and 1 oz/sqft copper path and tangent loss, tand = 0.0027 up to 10 GHz was used for RF laminate. The transistor Wolfspeed CGH40006S has a maximum output power of 8W and can operate between DC and 6 GHz. During the design and simulation, the company's large signal model was used.

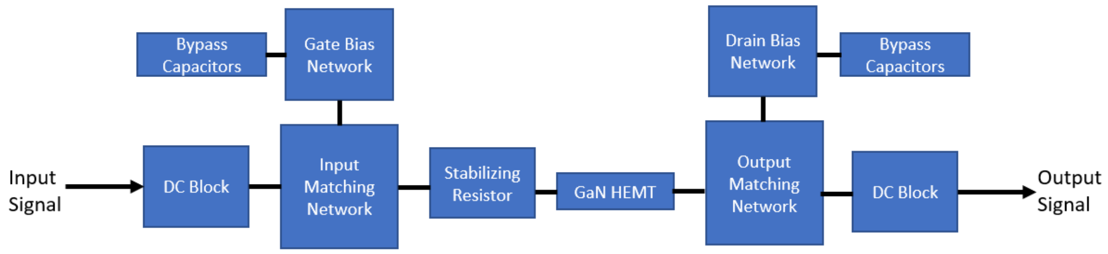

Figure 3. 2: Proposed GaN Class AB PA Block Diagram between 1 to 4 GHz

In **Figure 3.2**, a Class AB power amplifier operating between 1-4 GHz is depicted in block diagram form. The DC blocking capacitor in the block diagram has a value of 10 pF. Afterwards, the distributed lc ladder matching network structure was used as the input matching circuit for the source impedance values of 5.98 + j*6.81 Ω and 3.32 – j*2.89 Ω at 2000 MHz and 3000 MHz obtained from the datasheet. PA can operate between 1-4 GHz with this matching network. The series lines should have high impedance to act inductively, while the shunt stubs should have low impedance to serve as capacitors. Traditionally, broadband matching has been provided using computer-aided design (CAD) techniques. In this case, both the source and load impedance values must be chosen to begin the optimization in CAD tools. If a proper starting value is not selected in your operating frequency range, CAD tools may not find suitable values and will not offer the desired bandwidth.

The Gate Bias Network structure to feed the gate voltage to the transistor was created together with the bypass capacitors used to filter the AC noise that may be in the DC current. Quarter wavelength microstrip line was used before bypass capacitors. This way, the RF input sees high impedance and easily couples to the gate side of the transistor.

CGH40006S stabilizing resistor R_{stab} is used in series with the gate of the transistor, since stabilization is problematic at low frequencies. After R_{stab}, the connection between the gate pad of the transistor and the tapered line is done. A tapered line is used to connect the drain and output matching network in a similar manner.

As seen in **Table 3.1**, the output matching circuit was created using a distributed LC ladder matching network structure, as in the input matching circuit, to match to the load impedance values of 32.7 + j*32.9 Ω and 19.2 + j*29.8 Ω for 2000 MHz and 3000 MHz from the datasheet. The Drain Bias Network structure was developed along with the bypass capacitors used to filter any AC noise that might be present in the DC current and to feed the drain voltage to the transistor at the output section as well as at the input part of the PA.

Table 3. 1: Source and Load Impedances of CGH40006S Transistor Model

Frequency (MHz)	Z source (Ω)	Z lead (Ω)
2000	5.98 + j*6.81	32.7 + j*32.9
3000	3.32 – j*2.89	19.2 + j*29.8
4000	2.38 – j*9.45	15.2 + j*15.7

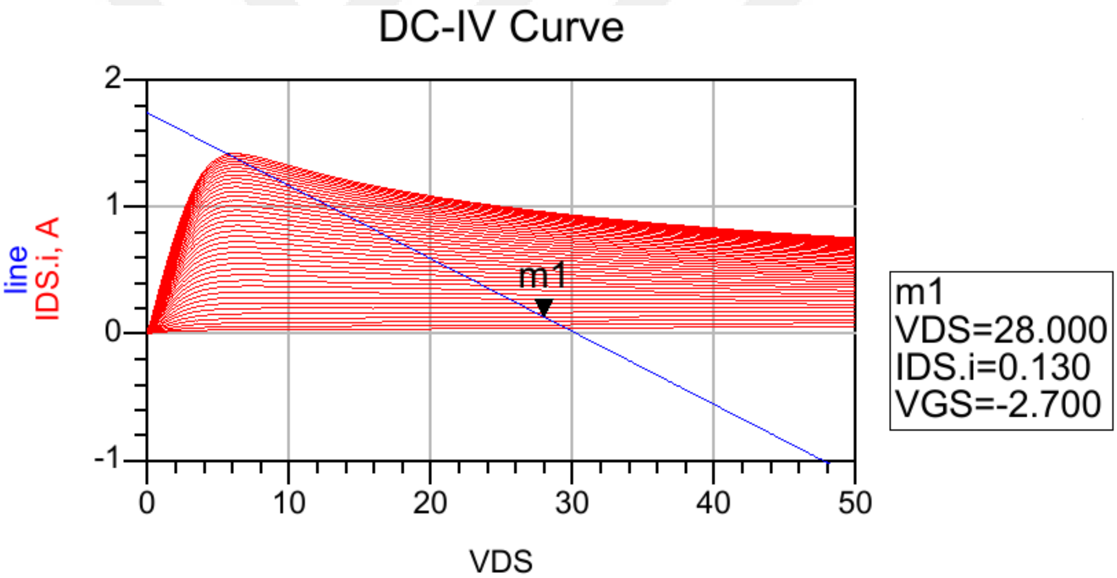

Figure 3. 3: DC I-V Characteristic Performance of CGH40006S used with Vgs = -3V to 1V and Vds = 0 V to 28 V

The PA Q-point allows the amplifier classification to be determined. For this reason, DC simulation was performed as seen in **Figure 3.3** to find the optimum gate and drain quiescent voltage (V_{GSQ} and V_{DSQ}) values. This transistor's I-V characteristic was obtained. Between the Class A and Class B operating points is the Class AB operating point. In Class A class drain to source current $I_{DS} = I_{MAX} / 2$ and in Class B class drain to source current $I_{DS} = I_{PINCHOFF}$ is selected. As seen in **Figure 3.4**, the operating point V_{GSQ}=-2.7V, V_{DSQ}=-2.7V and I_{DSQ}=130 mA was selected for the Class AB power amplifier, the schematic of which was designed in ADS and then the layout was created and manufactured.

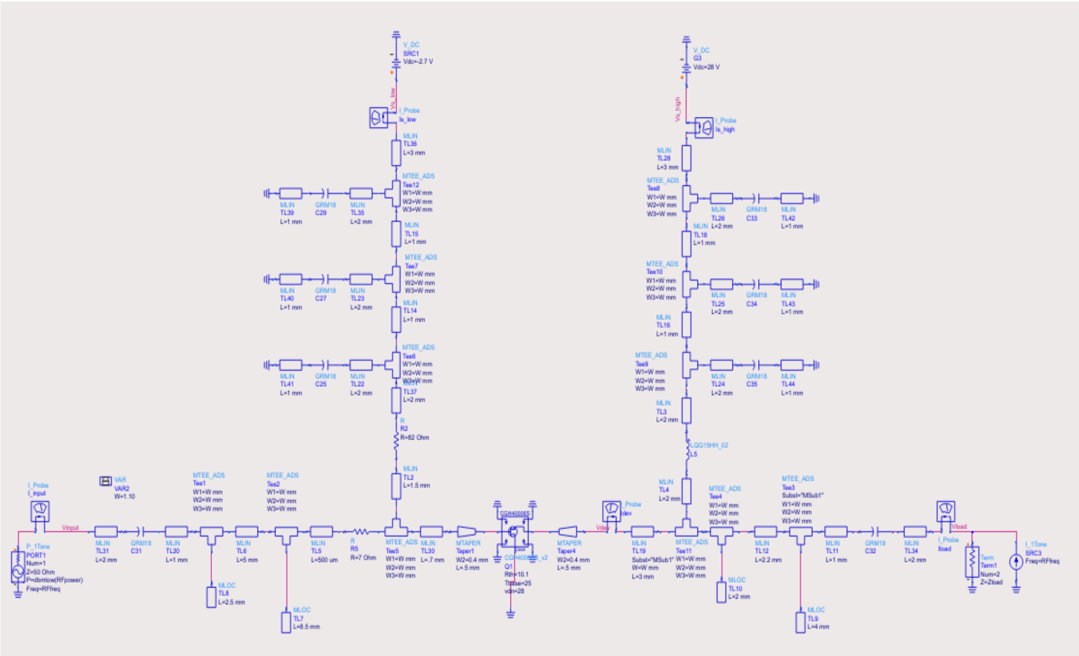

Figure 3. 4: Schematic of 1 to 4 GHz Class AB Power Amplifier

After selecting the DC operating point, GaN Class AB PA schematic was created as seen in **Figure 3.4**. Subsequently, small signal, stability and large signal analysis were performed on ADS. As seen in **Figure 3.5**, 18.7 dB gain (S_{21}) was obtained at 1.0 GHz and input-output return loss (S11-S22) was -3.3 dB and -11,4 dB. At 2.0 GHz, 15.1 dB gain (S21) was obtained, and input/output return loss (S_{11}/S_{22}) was -4.8 dB and -13.3 dB, respectively. At 3.0 GHz, 12.2 dB gain was obtained, and input-output return loss was -11.6 dB and -10.5 dB, respectively. At 4.0 GHz, 7.1 dB gain was obtained, and input/output return loss was -6.2 dB and -16.3 dB, respectively. In addition, as seen in **Figure 3.6**, stability analysis was performed between DC-10 GHz, and it is seen that the PA is unconditional stable.

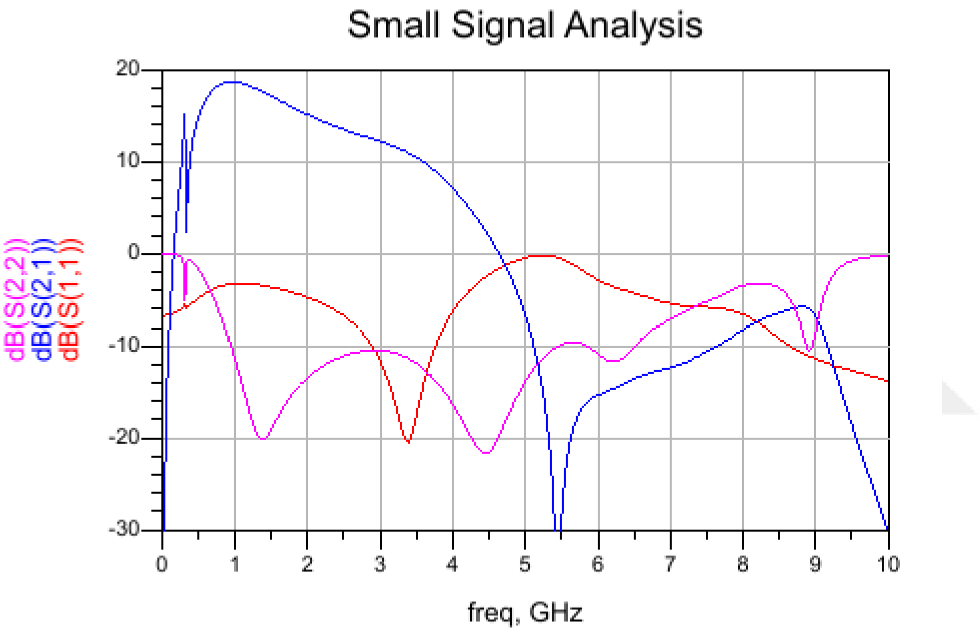

Figure 3. 5: Small Signal Analysis for Schematic of 1 to 4 GHz Class AB Power Amplifier

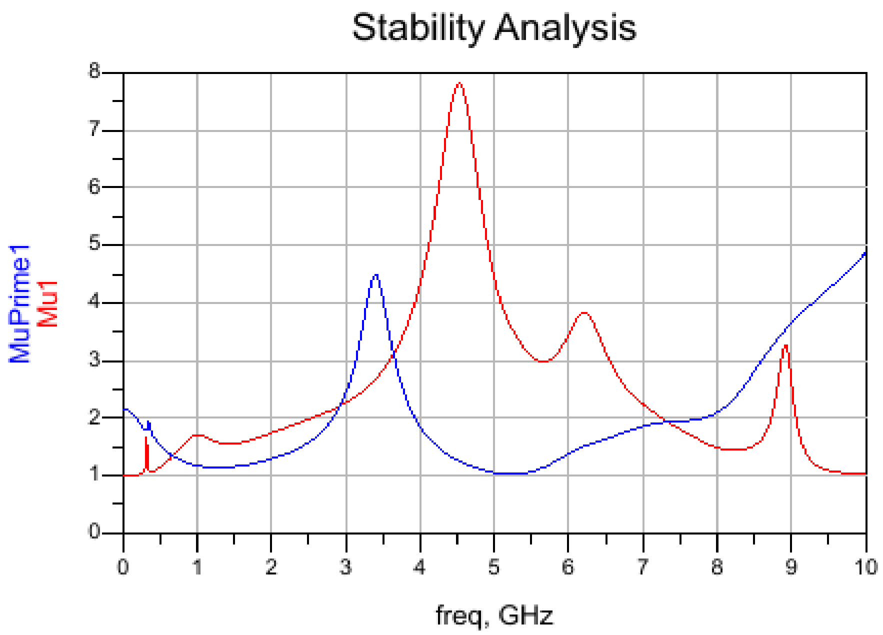

Figure 3. 6: Stability Analysis for Schematic of 1 to 4 GHz Class AB Power Amplifier

Along with small signal analysis, large signal analysis was performed by sweeping the input power between 10-35 dBM. In Table 3.2, together with the large signal analysis, OP1dB, output power, PAE and Gain measurements between 750 MHz and 4250 MHz are shown. In **Figure 3.7**, 500 MHz steps OP1dB graph is shown between 1000 MHz and 4000 MHz.

Table 3. 2: RF Parameter Simulation Results for Schematic of 1 to 4 GHz Class AB Power Amplifier

Frequency (MHz)	Gain Comp. (dB)	Output Power (dBm)	Transducer Gain (dB)	PAE%	DC Power Consump. (Watts)	High Supply Current (mA)	Thermal Dissipation (Watts)
750	1.010	36.81	17.24	29.21	16.24	578.7	11.29
1000	1.010	38.26	17.73	42.20	15.72	560.0	8.77
1250	1.009	38.61	17.11	46.06	15.61	555.9	8.07
1500	1.008	38.80	16.14	47.38	15.79	562.4	7.99
1750	1.008	38.96	15.12	47.75	16.19	576.6	8.16
2000	1.008	39.18	14.19	48.85	16.54	589.3	8.18
2250	1.007	39.43	13.37	50.05	16.93	603.3	8.21

2500	1.009	39.63	12.66	50.72	17.36	618.5	8.38
2750	1.009	39.57	12.00	48.50	17.69	630.3	9.01
3000	1.010	39.25	11.34	43.92	17.88	637.1	9.97
3250	1.008	39.32	10.58	43.62	17.93	638.9	10.08
3500	1.009	39.28	9.554	42.31	17.85	636.1	10.27
3750	1.008	39.24	8.105	40.91	17.63	628.1	10.38
4000	1.010	39.06	6.132	38.27	17.11	609.6	10.51
4250	1.009	38.60	3.691	33.34	16.30	580.6	10.74

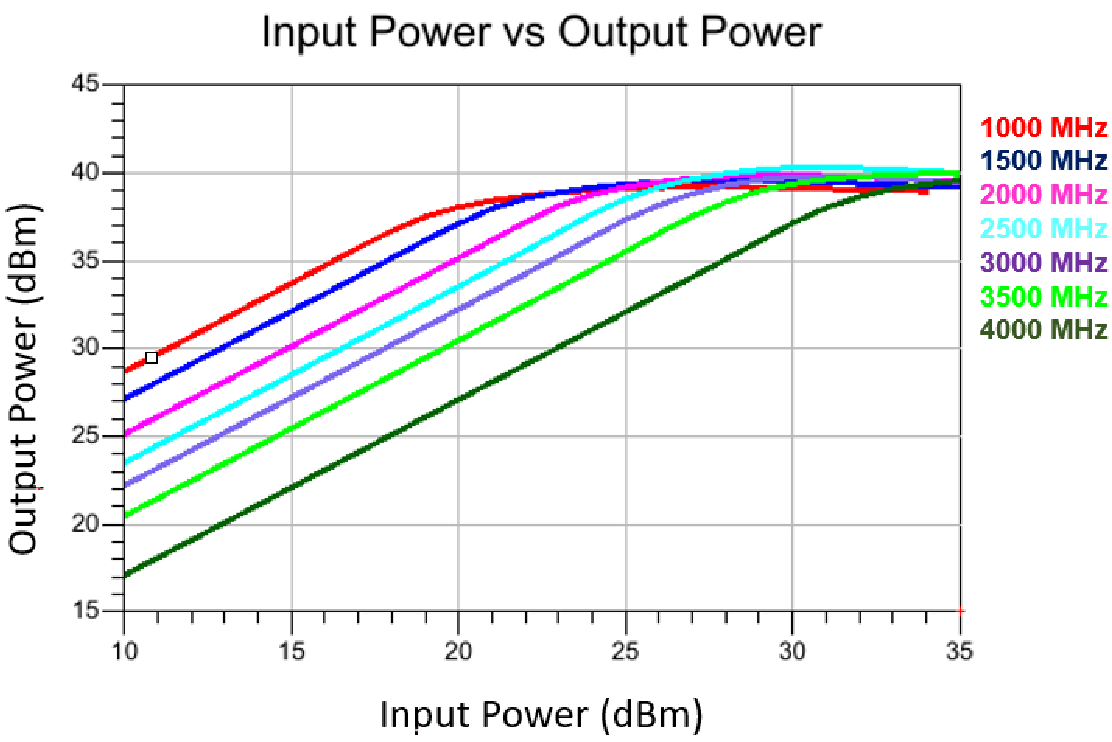

Figure 3. 7: PAE Simulations for a Schematic of a GaN Class AB Power Amplifier Operating at 1 to 4 GHz

3.3. 1 to 4 GHz GaN Class AB Power Amplifier Layout Design

After completing the schematic simulations, the PA layout was created as seen in **Figure 3.8** and EM simulations were done with port layouts. Small signal, stability and large signal analysis were performed with EM simulations. As seen in **Figure 3.9**, 18.4 dB gain (S_{21}) was obtained at 1.0 GHz and input/output return loss (S_{11}/S_{22}) were -4.0

dB and -14,813 dB, respectively. At 2.0 GHz, 15.306 dB gain (S_{21}) was obtained, and input/output return loss (S_{11}/S_{22}) were -5.2 dB and -11.9 dB, respectively. At 3.0 GHz, 12.3 dB gain (S_{21}) was obtained, and input-output return loss (S_{11}/S_{22}) were -9.6 dB and -19.8 dB, respectively. At 4.0 GHz, 8.4 dB gain (S_{21}) was obtained, and input-output return loss (S_{11}/S_{22}) were -7.8 dB and -12.00 dB, respectively. In addition, as seen in **Figure 3.10**, stability analysis was performed between DC-10 GHz, and it is seen that the PA is unconditionally stable.

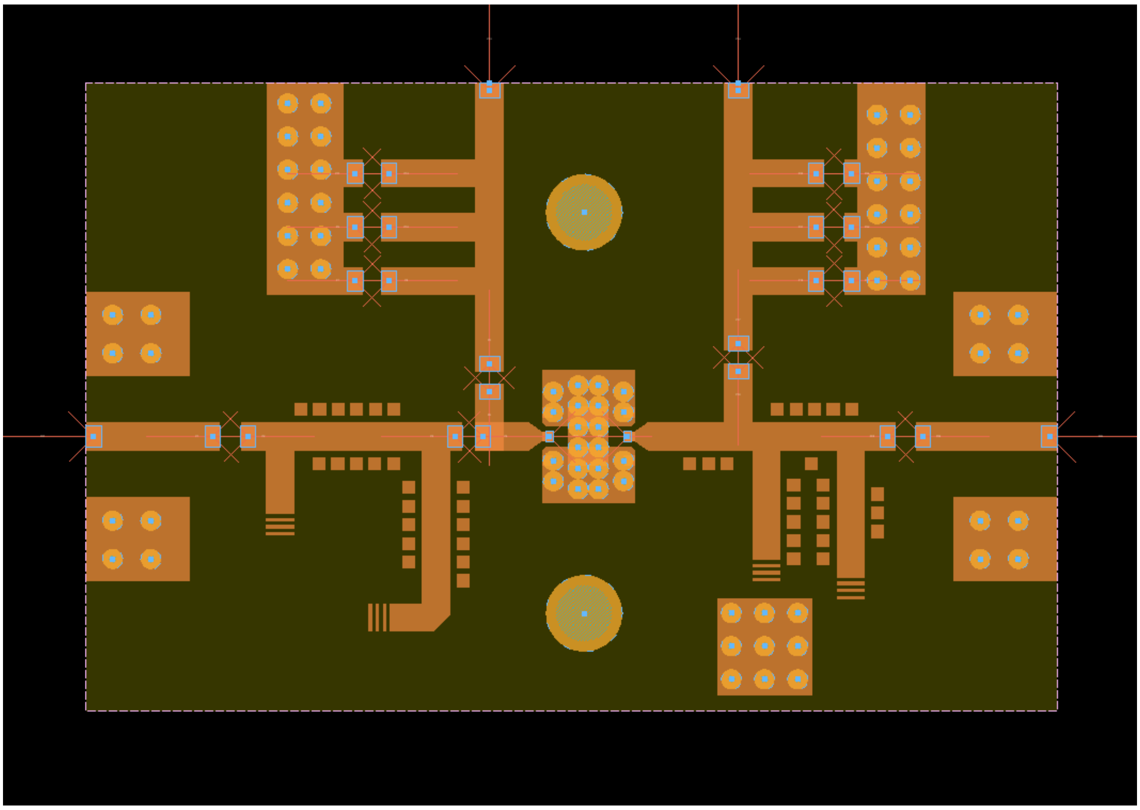

Figure 3. 8: Layout of 1 to 4 GHz GaN Class AB Power Amplifier

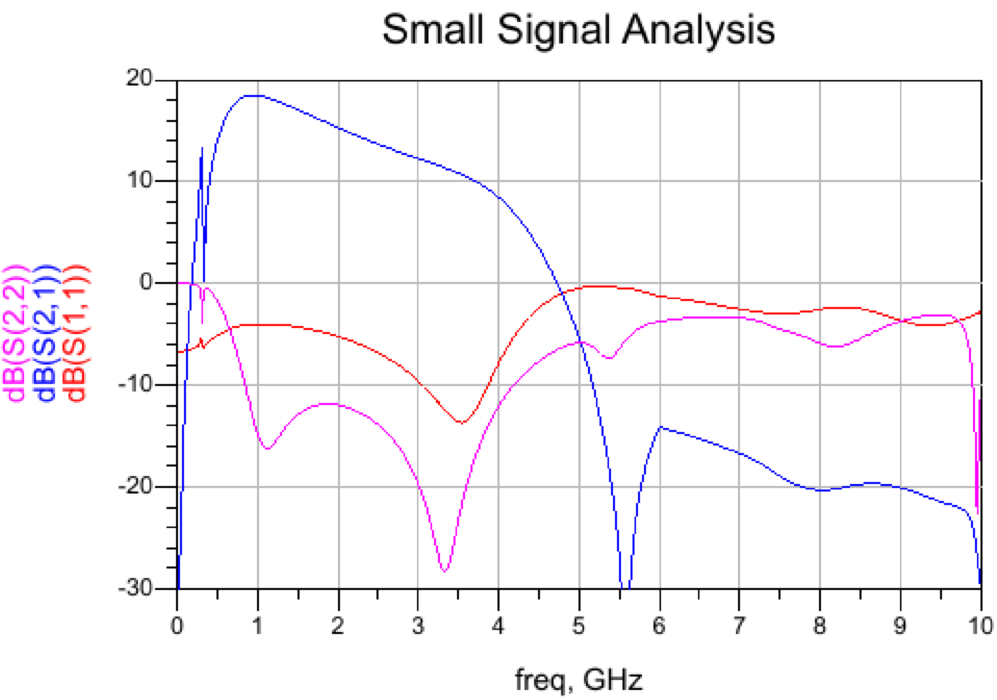

Figure 3. 9: Small Signal Analysis for Layout of 1 to 4 GHz Class AB Power Amplifier

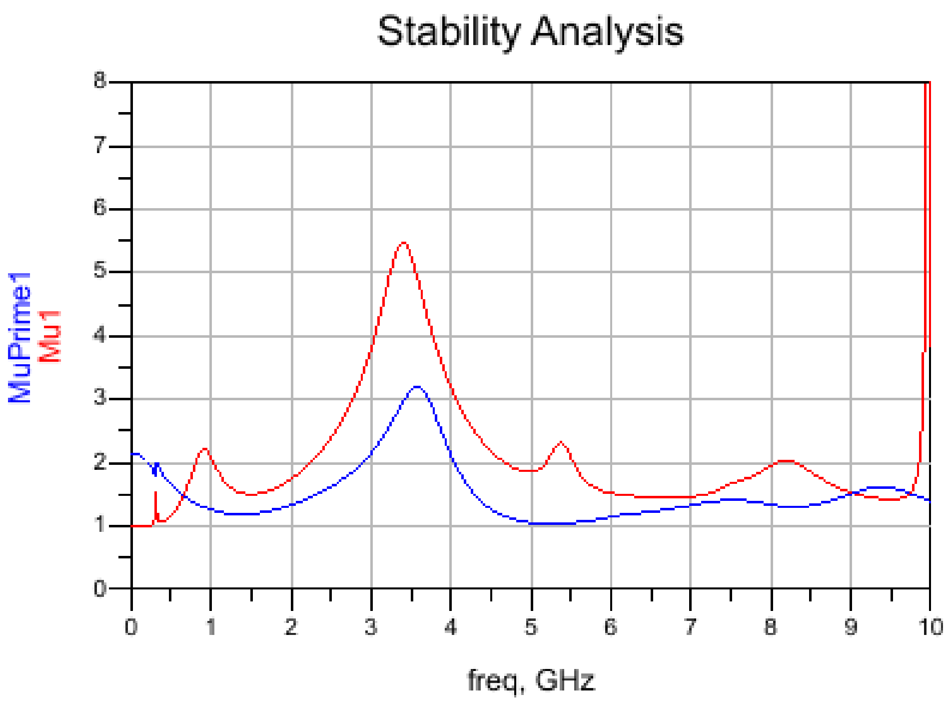

Figure 3. 10: Stability Analysis for Class AB Power Amplifier 1 to 4 GHz Layout

Table 3. 3: Results of RF Parameter Simulation for Class AB Power Amplifier Schematic from 1 to 4 GHz

Frequency (MHz)	**Gain Comp. (dB)**	**Output Power (dBm)**	**Transducer Gain (dB)**	**PAE (%)**	**DC Power Consump. (Watt)**	**High Supply Current (mA)**	**Thermal Dissipation (Watt)**
750	1.008	37.12	17.04	31.96	15.90	566.6	10.59
1000	1.008	38.35	17.50	42.77	15.83	564.0	8.78
1250	1.008	38.85	16.96	46.30	16.35	582.6	8.53
1500	1.007	39.16	16.19	47.85	16.97	604.7	8.65
1750	1.008	39.48	15.35	49.66	17.51	624.0	8.63
2000	1.008	39.72	14.52	50.95	17.94	639.2	8.63
2250	1.007	39.80	13.70	51.09	18.10	645.0	8.72
2500	1.001	39.79	12.91	50.93	17.96	640.2	8.71
2750	1.007	39.67	12.15	50.00	17.59	626.9	8.71
3000	1.008	39.47	11.4	48.59	17.05	607.5	8.65
3250	1.009	39.24	10.64	47.20	16.36	583.0	8.50
3500	1.009	38.83	9.823	44.17	15.56	554.3	8.54
3750	1.001	38.22	8.836	39.04	14.92	531.5	8.97
4000	1.008	37.44	7.419	32.39	14.55	518.2	9.73
4250	1.009	36.58	5.342	25.50	14.5	516.3	10.70

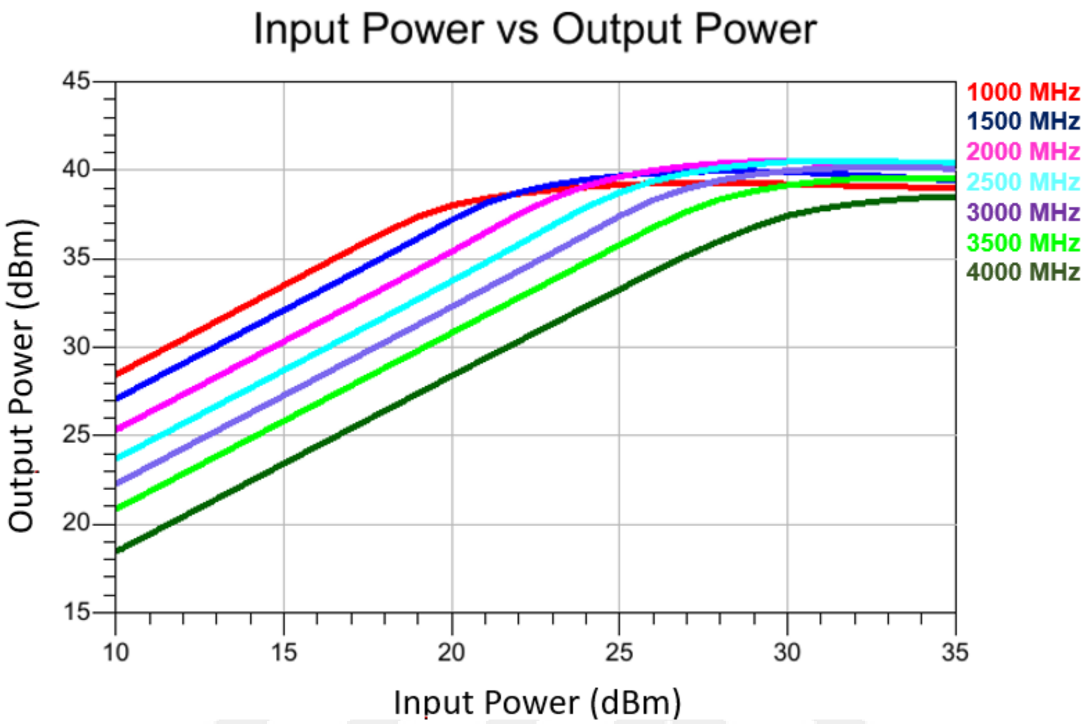

Figure 3. 11: PAE Simulations for the Layout of Class AB Power Amplifiers from 1 to 4 GHz

Along with the small signal analysis, a large signal analysis was performed by using 10-35 dBM input power sweep. In **Table 3.2**, OP1dB, output power, PAE and Gain measurements between 750 MHz and 4250 MHz are shown. In **Figure 3.11**, 500 MHz steps OP1dB graph is shown between 1000 MHz and 4000 MHz.

3.4. Measured 1 to 4 GHz Power Amplifier Design

After the schematic and EM simulations, the PA was manufactured, and the component placement was done as in **Figure 3.12**. After the PCB was completed, as seen in **Figure 3.13**, Rohde Schwarz ZVA40 Vector Network Analyzer (VNA) operating between 10 MHz - 40 GHz and Agilent Technologies' E3631A and E3632A DC supply equipment for Gate - Drain voltage supply was used for Small Signal measurements.

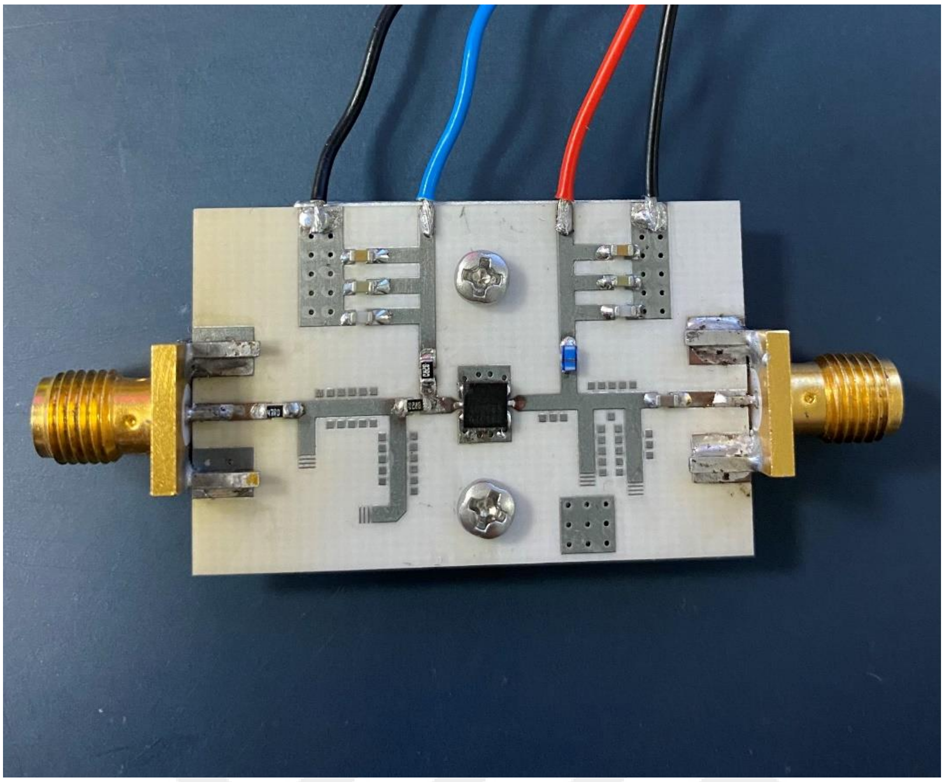

Figure 3. 12: Manufactured of 1-4 GHz Power Amplifier

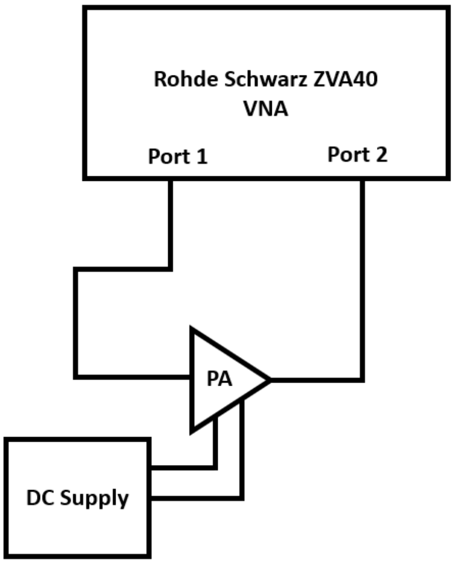

Figure 3. 13: Measurement Setup of 1-4 GHz Power Amplifier

As seen in **Figure 3.14**, using the produced PA for the measurements, 18,486 dB gain (S_{21}) and -5.4 dB and -18.7 dB input/output return loss (S_{11}/S_{22}) values were obtained at 1 GHz frequency. At 2 GHz frequency, 14.9 dB gain (S_{21}) and -8.9 dB and -8.9 dB input/output return loss (S_{11}/S_{22}) values were obtained. At 3 GHz frequency, 11.0 dB gain (S21) and -6.2 dB and -23.2 dB input - output return loss (S_{11}/S_{22}) values were obtained. 7.2 dB gain (S_{21}) and -3.0 dB and -11.168 dB input - output return loss (S_{11}/S_{22}) values were obtained at 4 GHz frequency. In addition, using the S-Parameter file obtained from the small signal measurements we did using Rohde Schwarz VNA, stability analysis was performed as seen in **Figure 3.15**. Unconditional stabilization was achieved between 100 MHz and 10 GHz.

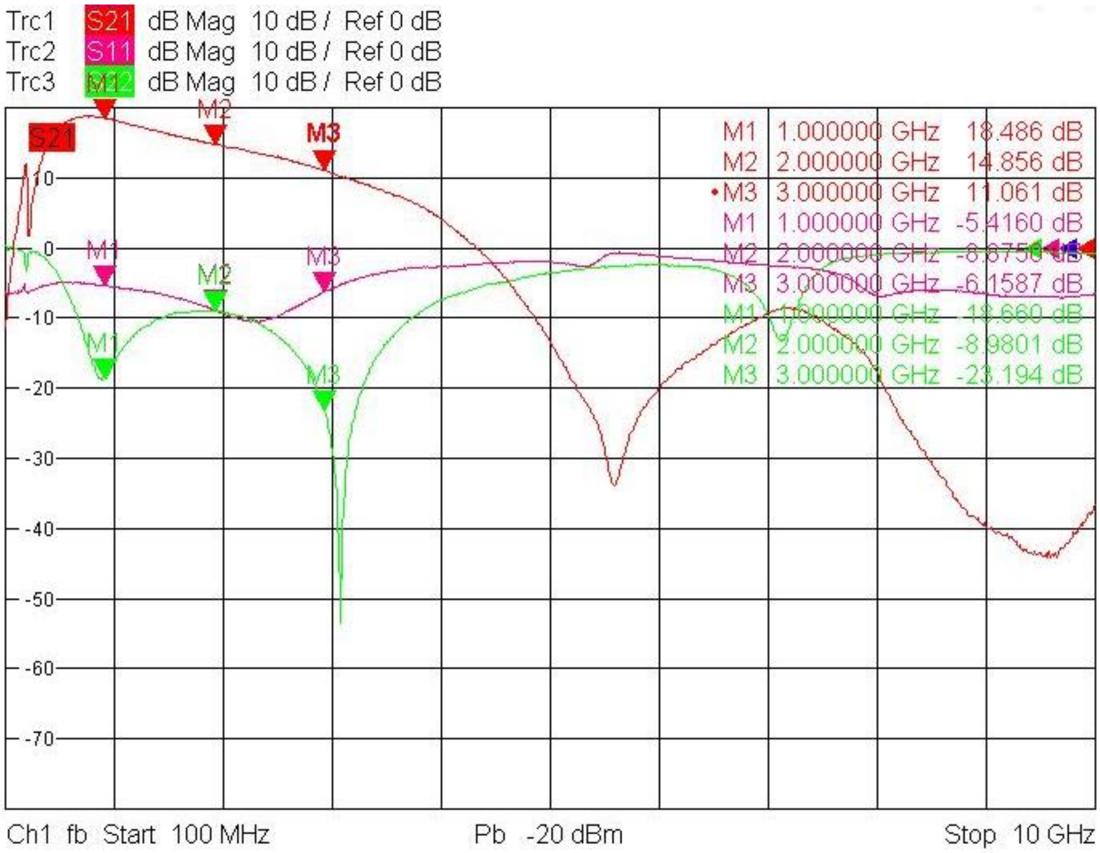

Figure 3. 14: Small Signal Analysis of Manufactured PA

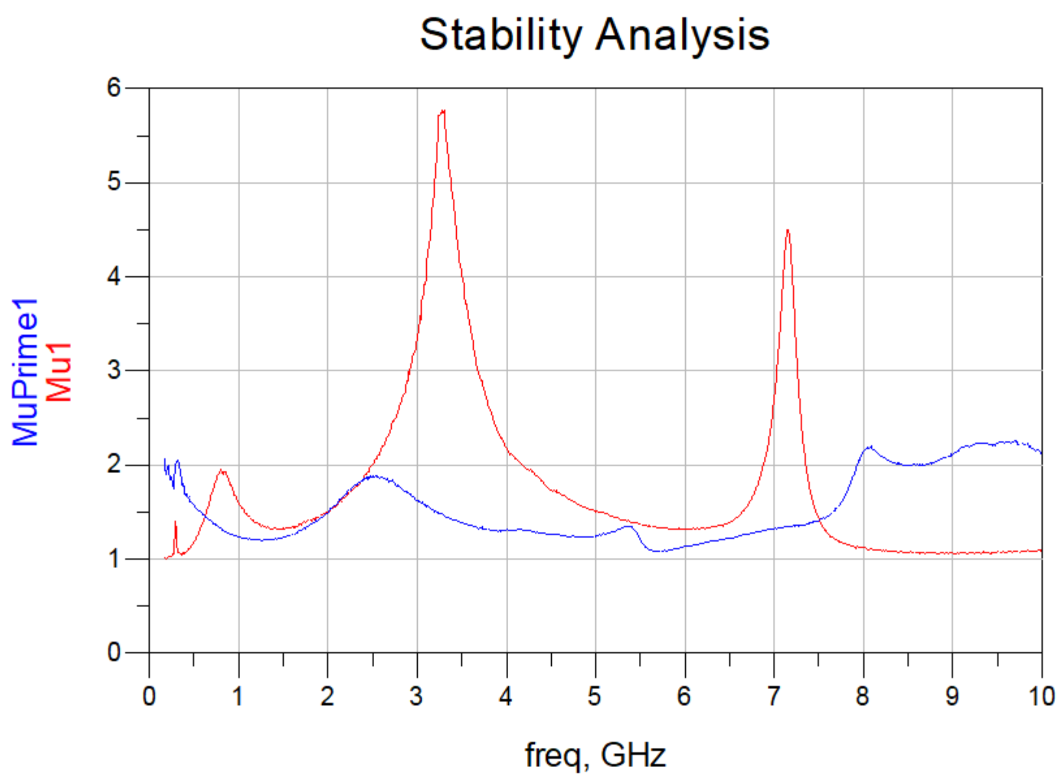

Figure 3. 15: Small Signal Analysis of Manufactured PA

Table 3. 4: Small Signal Simulation Comparison

Simulation Type	Frequency (GHz)	Gain (S_{21}) (dB)	Input Return Loss (S_{11}) (dB)	Output Return Loss (S_{22}) (dB)
Schematic	1	18.67	-3.30	-11.42
Layout	1	18.43	-4.03	-14.81
Manufactured	1	18.49	-5.42	-18.66
Schematic	2	15.13	-4.77	-13.29
Layout	2	15.30	-5.22	-11.96
Manufactured	2	14.86	-8.88	-8.98
Schematic	3	12.20	-11.66	-10.46
Layout	3	12.27	-9.59	-19.74
Manufactured	3	11.06	-6.16	-23.20

Schematic	4	7.09	-6.14	-16.33
Layout	4	8.43	-7.75	-16.33
Manufactured	4	4.59	-2.79	-7.85

After the small signal analysis, the block diagram shown in **Figure 3.16** was arranged in the lab for large signal measurements. **Figure 3.17** shows the set up for this experimental measurement. Rohde Schwarz SMF100A was used as signal generator in this measurement. GaN PA requires a signal power at the input of between 15 and 30 dBm, which is outside the capabilities of our apparatus. Therefore, the ZVE-3W-83+ amplifier operating at 2000-8000 MHz was used as a driver PA. Class AB GaN PA with a DC block is directly connected. Rohde Schwarz FSVA3044 Signal & Spectrum Analyzer was used to analyze the signal in this measurement. Due to the high signal level at the PA's output, BW-S10W20+ with 10 dB attenuation and BW-S20W20+ with 20 dB attenuation, which operate between DC-18000 MHz and can withstand up to 20W, are connected to each other in series before connecting to the Spectrum Analyzer. This way, a total of 30 dB attenuation is provided.

There are 4 cable connections between the modules. Mini-circuits 141-32SM+ cable is used for 1 No Cable. Mini-circuits 086-12SM+ cable is used for 2 No Cable. Huber+Suhner Minibend KR4 cable is used for 3 No Cable. Finally, Huber+Suhner LR24 cable was used for 4 No Cable.

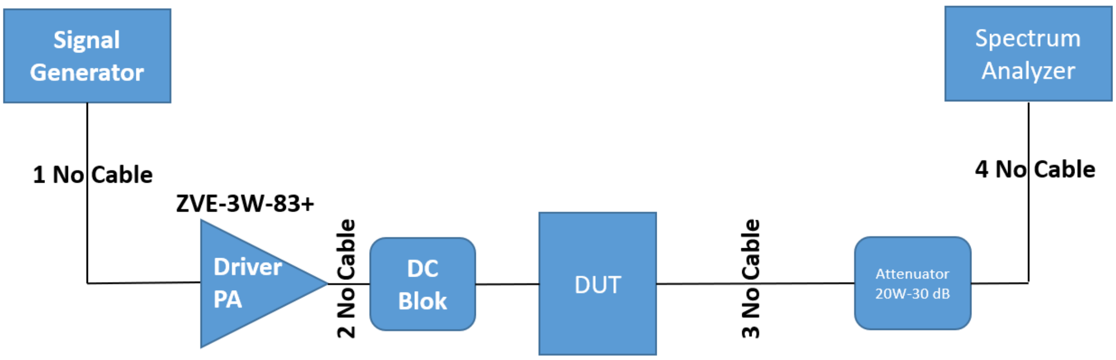

Figure 3. 16: GaN Class AB Large Signal Measurement Block Diagram

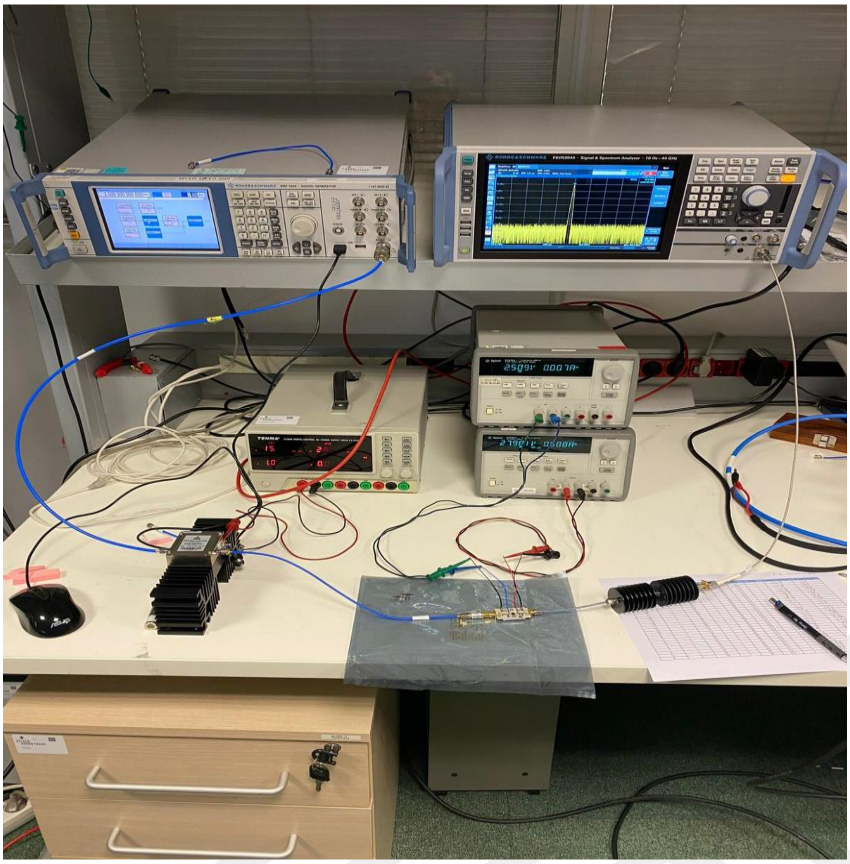

Figure 3. 17: Large Signal Measurement Setup of Manufactured GaN Class AB PA

P1dB measurement result is seen between 2000-3500 MHz in **Figure 3.18**. In addition, as seen in **Table 3.5**, OP1dB values were measured between 38.2-40.25 dBm.

Table 3. 5: RF Measurement Results of Manufactured GaN Class AB PA

Freq. (MHz)	OP1dB (dBm)	PAE (%)	DE (%)
2000	39.73	51.67	61.62
2250	39.79	46.45	55.85
2500	40.25	57.1	66.61
2750	39.95	55.8	66.11
3000	39.50	49.74	60.87
3250	39.1	54.55	67.89
3500	38.2	42.38	59.55

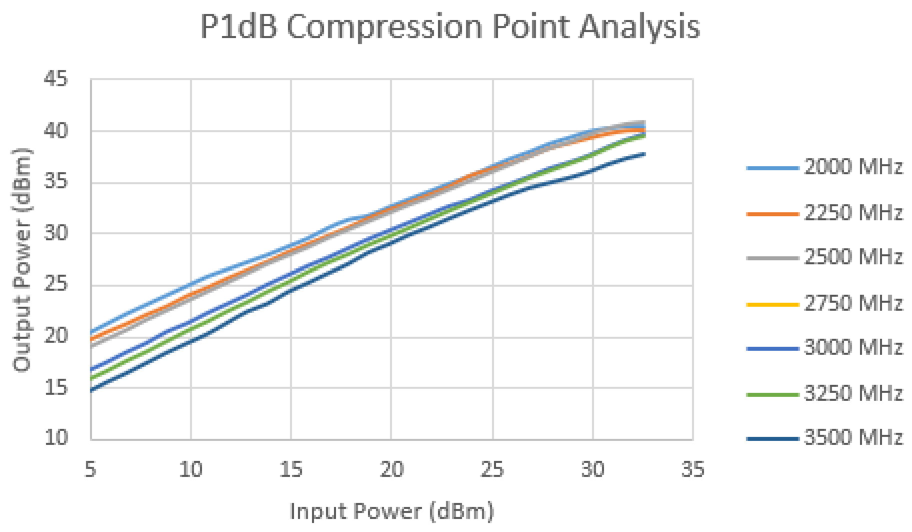

Figure 3. 18: P1dB Analysis of Manufactured GaN Class AB PA

As shown in **Figure 3.19** and **Figure 3.20**, the gain was measured in addition to the large signal measurements based on both the input power and the output power.

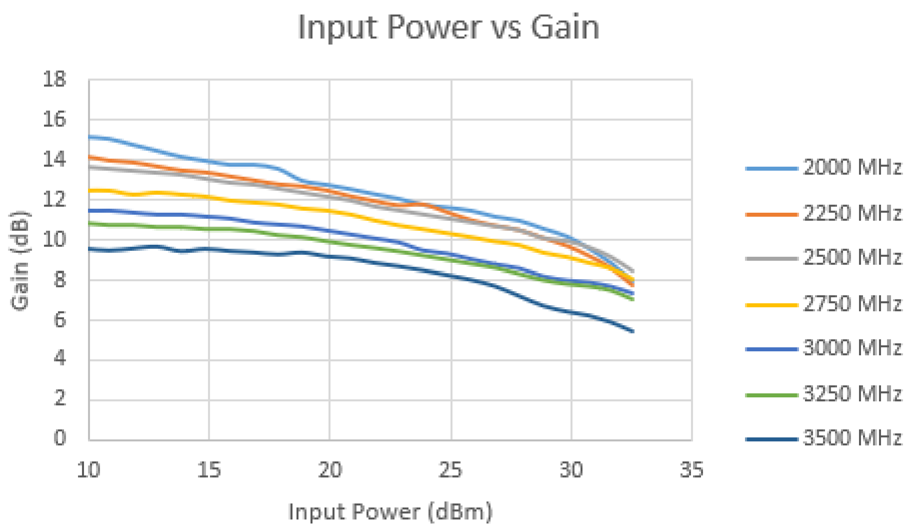

Figure 3. 19: Input Power vs Gain Analysis of Manufactured GaN Class AB PA

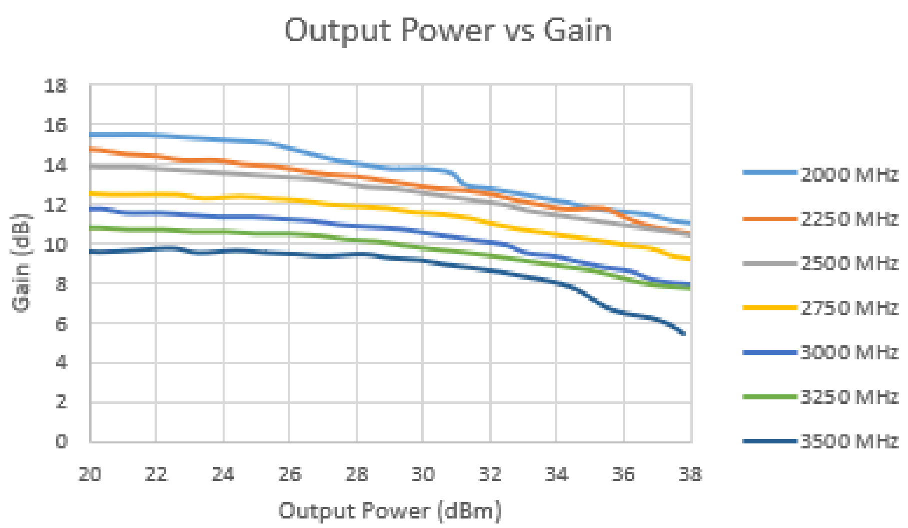

Figure 3. 20: Output Power vs Gain Analysis of Manufactured GaN Class AB PA

During the measurement, depending on the input power, output power and DC current in the drain bias network, PAE analysis was performed as seen in **Figure 3.21** and **3.22**. **Table 3.5** shows that the PAE between 2000-3500 MHz was obtained between 42.38 and 57.1%.

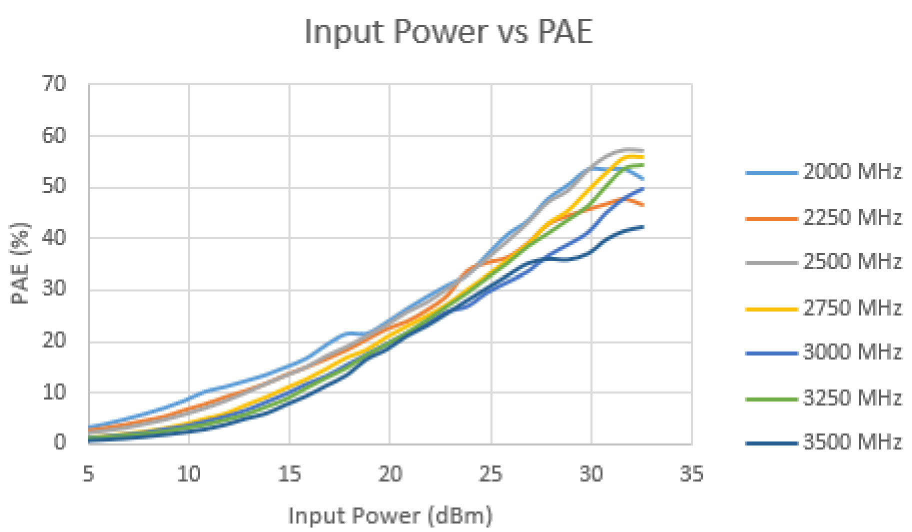

Figure 3. 21: PAE vs Input Power Analysis of Manufactured GaN Class AB PA

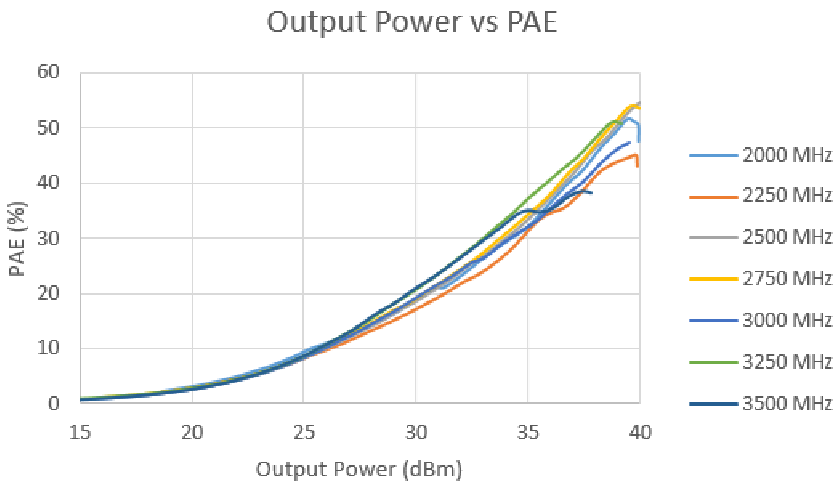

Figure 3. 22: PAE vs Output Power Analysis of Manufactured GaN Class AB PA

Drain Efficiency (DE), which is the analysis based solely on the output power and the DC current of the drain bias network of the PA, without depending on the input power, was performed during the efficiency study. This analysis is shown in **Figure 3.23** and **Figure 3.24**. As seen in **Table 3.5**, between the frequencies of 2000-3500 MHz 55.85-67.89% DE was obtained.

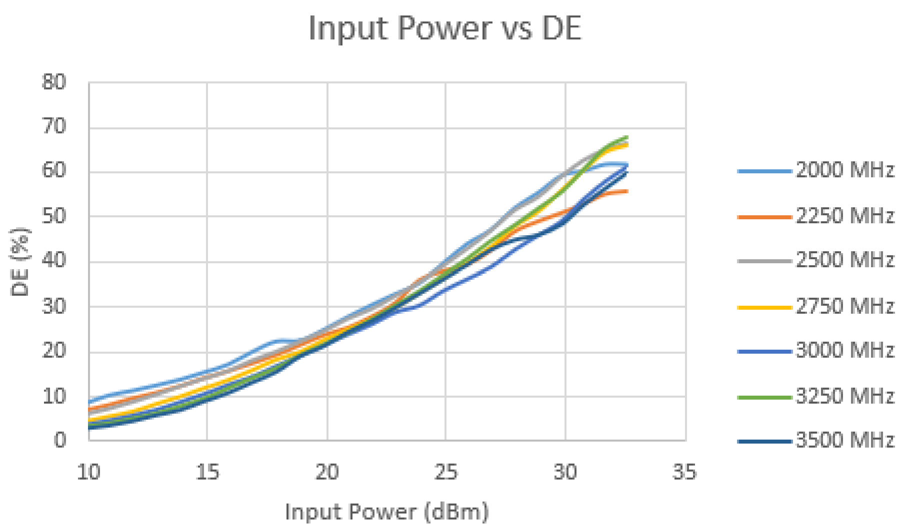

Figure 3. 23: DE vs Input Power Analysis of Manufactured GaN Class AB PA

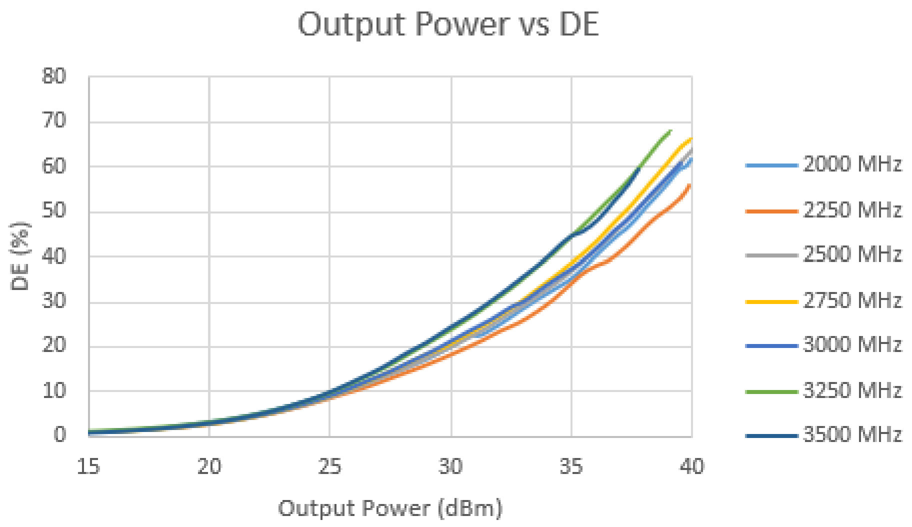

Figure 3. 24: DE vs Output Power Analysis of Manufactured GaN Class AB PA

CHAPTER 4

4. DOHERTY POWER AMPLIFIER

Since energy consumption is high in AM broadcast transmitters, efficiency comes to the fore. William H. Doherty designed a power amplifier in 1936 that kept efficiency and linearity at high levels simultaneously in high-power AM broadcast transmitters. Today, the search for better energy efficiency in 5G Systems continues and this search starts with the power amplifiers used in base stations. For this reason, when we examine RF power efficiency, Doherty Power Amplifier is a technique used to reduce energy consumption. Vacuum tube amplifiers, both of which are biased with class B, were the first RF circuit design that created the Doherty amplifier structure. This technique increased the efficiency of amplifiers from 30% to over 60%. While William Doherty used vacuum tubes while applying this technique, today the same approach is applied to many different semiconductor technologies (CMOS, GaAs, LDMOS, GaN) [25].

There are many base stations around the world, and increased efficiency will result in significant cost reductions. In base station transmitter designs for cellular telecommunications systems, the Doherty amplifier is frequently utilized. Since the Doherty power amplifier maintains linear working mode while increasing the amplifier efficiency, it can also be found in many other radio communication systems where higher power levels and high efficiency levels are required. For mobile or wireless communication systems, reducing power consumption and increasing overall efficiency is a key requirement [26].

In 4G/5G mobile communication and other radio communication systems, new modulation formats are used, and this causes an increase in peak/average power ratios (PAPR). According to **Figure 4.1**, PAPR is the ratio of a signal's peak power to its average power. Its unit is decibels (dB). Lower PAPR is required for efficient performance of a system. As seen in **Figure 4.1**, we can think that the signal operates in two regions, low power, and high power, in an amplifier. If the amplifier is built to perform well at peak power levels with strong linearity, it will perform significantly less well at average power levels [27].

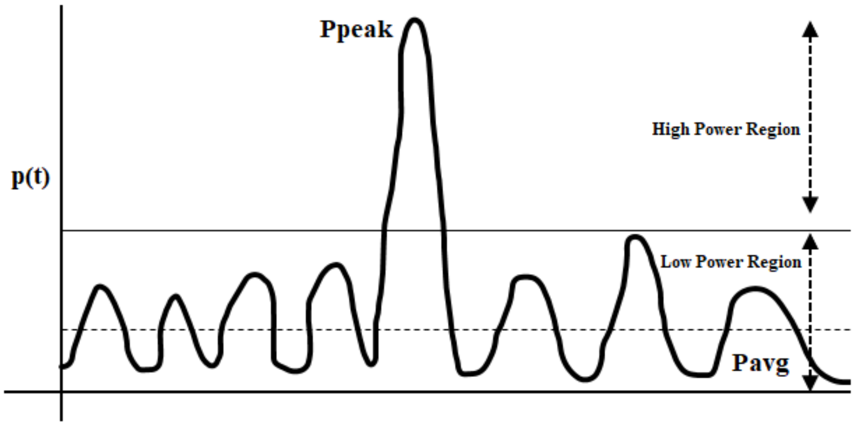

Figure 4. 1: Peak to Average Power Ration

Signals having high peak-to-average power ratios can be accommodated by Doherty power amplifiers while yet retaining a high level of power efficiency. Two parallel amplifiers are used in a single general RF amplifier to accomplish this. As seen in **Figure 4.2**, Peaking Amplifier functions in the high-power zone whereas Main Amplifier operates in the low power sector. This enhances the amplifier's overall performance. Additionally, many modulation schemes depend heavily on the linearity of the main and peaking amplifiers to maintain the amplitude and phase purity [28].

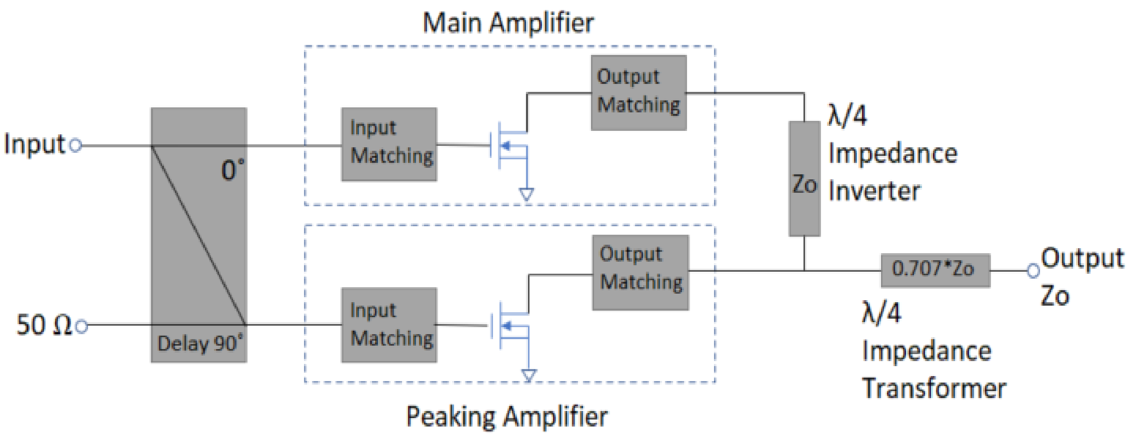

Figure 4. 2: Doherty Power Amplifier Block Diagram

4.1. Main (Carrier) Amplifier

The main amplifier's function is to transmit average amplitude signal levels when operating in the low power range. Class A or AB operation is used by the main amplifier. Here, linear operation of the amplifier in the low power range and high gain values are the goals.

4.2. Auxiliary (Peaking) Amplifier

The second amplifier in the system, the auxiliary (peaking) amplifier, is activated when the main amplifier approaches saturation (limits). Auxiliary amplifier works in class C. While class C amplifiers have high efficiency, they are poor in linearity. In order to maintain a high efficiency level at the highest achievable output power, the auxiliary amplifier employed in the DPA structure is built [29].

4.3. Hybrid (Quadrature) Coupler

Hybrid Couplers are 4-port passive devices that can combine and split signals, among other things. The hybrid coupler comes in two different shapes: 90° and 180°. Because a signal given to any input would produce two equal amplitude signals at opposite quadrants that are 90° phase-shifted from one another, the 90° are frequently referred to as quadrature hybrids. There is no power is isolated to port 4 (the coupled port). The scattering matrix form is as seen in **4.1**.

$$[S] = \frac{-1}{\sqrt{2}}\begin{bmatrix} 0 & j & 1 & 0 \\ j & 0 & 0 & 1 \\ 1 & 0 & 0 & j \\ 0 & 1 & j & 0 \end{bmatrix} \qquad \mathbf{4.1}$$

In the Doherty power amplifier structure, the input signal coming from the input port should be divided into two and go to the Main and Peaking amplifier. But here, when going to Peaking amplifier, 90˚ phase difference is required and 90˚ Hybrid coupler (Quadrature Coupler) is used for this [30].

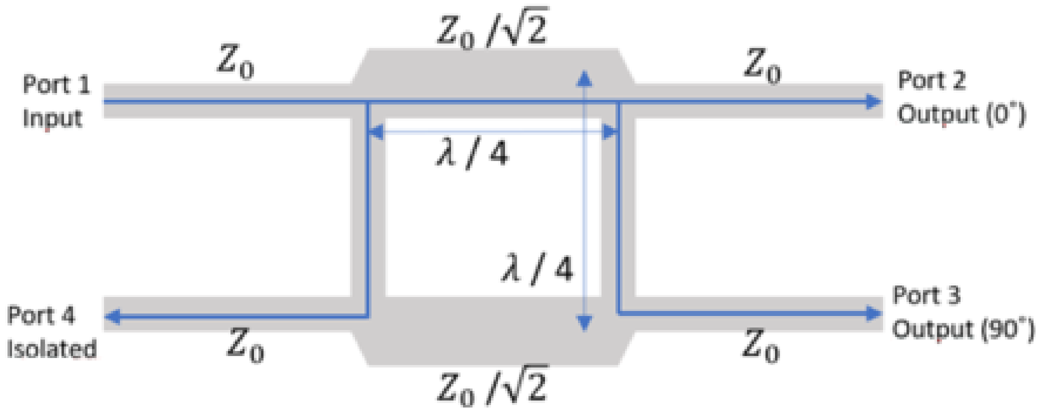

Figure 4. 3: Geometry of 90˚ Hybrid Coupler

$$\mathrm{L} = \frac{\lambda}{4} \tag{4.2}$$

$$\lambda = \frac{\mathrm{c}}{\mathrm{f}\sqrt{\varepsilon_r}} ==> \mathrm{L} = \frac{\mathrm{c}}{4 * \mathrm{f}\sqrt{\varepsilon_r}} \tag{4.3}$$

4.4. Quarter Wave Impedance Transformer

When impedance matching a transmission line to a load, simple impedance transformers known as quarter-wave transformers are typically employed to lessen the amount of energy reflected. The quarter-wave transformer uses a transmission line with a different characteristic impedance and one-quarter the guided-wavelength in length to match a line to a load.

The DPA structure uses a quarter wave impedance transformer to transmit energy as efficiently as possible. There is an inverse relationship between input impedance (Z_{in}) and output impedance (Z_L) [31].

$$\frac{\mathrm{Z_{in}}}{\mathrm{Zo}} = \frac{\mathrm{Zo}}{\mathrm{Z_L}} \tag{4.4}$$

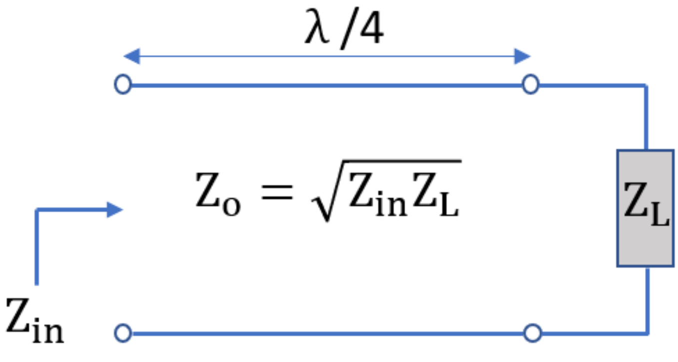

Figure 4. 4: Circuit Schematic of a Quarter Wave Transformer

CHAPTER 5

5. DOHERTY POWER AMPLIFIER DESIGN BETWEEN 3.4 to 3.6 GHz

Modern communication devices require high efficiency, good linearity, and high power at back-off power levels simultaneously. However, these criteria cannot be met at the same time in conventionally designed power amplifiers. For example, we can obtain high efficiency at back-off powers in the DPA structure, however when looking at the Class AB power amplifier design, it is known that the efficiency level to be achieved at back-off power levels is around 15-20%.

In this study, a Doherty power amplifier between 3.4 GHz and 3.6 GHz was designed and produced to be used in the N78 th band of base stations. EM simulation and production results were obtained. The Doherty Power Amplifier structure was used in this project, as efficiency comes to the fore in the power amplifiers used in the base stations. Main and peaking amplifiers make up its two-stage amplifier architecture. A Hybrid Coupler is designed to distribute power at the input port. Before the output port, 50Ω output is given with impedance matching lines.

The 6W GaN HEMT transistor model, the CGH4006S model of Wolfspeed/Cree, which stands out in RF power amplifier applications, was used. CGH4006S model transistor with 3x3 mm size is Surface Mount QFN sheathed. It offers good efficiency, gain, and wide bandwidth. 0.508 mm thick Rogers 4003C, which is suitable for RF applications, is used for the substrate. Matching circuits and impedance inverters are designed with microstrip lines. Passive components are used in bias circuits. The simulations were carried out in Agilent's ADS (Advanced Design System) simulator.

5.1. Load-Source Pull Analysis

The source and load impedance values must be determined before the design process even begins in power amplifier designs. Additionally, one of the keys aims in the design of an amplifier is to provide stability at the highest power level with the best efficiency. Finding the ideal stable load and source impedance values at this time can be done using the Load-Source Pull Analysis method. The goal of this research is to identify the ideal impedance match operating point that, under large signal working conditions, enables maximal power transfer between network stages. In the RF system, signal reflections are reduced in this way.

Figure 5.1 shows how load pull analysis is used to map a series of contours on the Smith Chart that show the maximum power output that can be obtained with a specific load. These contours provide a useful method for calculating the optimum load impedance value. It has been determined by load pull analysis that the optimum load impedance value is 9.84 + j*16.7Ω and the input impedance value is 2 + j*5.38Ω on the marker on the Smith Chart in **Figure 5.1**. The gain at this point is 10.2 dB, and the PAE value that can be attained is 60%.

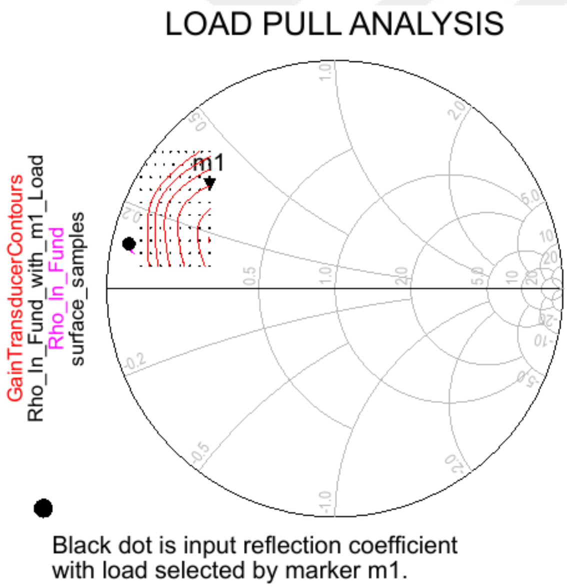

Figure 5. 1: Load Pull Analysis for Optimum Matching for DPA

5.2. DC-IV Curve Analysis

As previously explained, Doherty PA includes two types of amplifier structures, Main and Auxiliary amplifiers. The difference between these two amplifiers is that the bias circuits are designed in different classes. Class AB biasing is used in the Main

Amplifier. Class AB has higher efficiency than Class A amplifier and is preferred in PA designs to have higher gain than Class B amplifier. The point selected on the DC-IV curve for Class AB structure helps to determine the gate and drain voltage of the transistor. As seen in **Figure 5.2**, while V_{DS} is 28V in Class AB amplifier design, V_{GS} is set to -2.2 V at the selected Q point and the resulting drain current is 308mA. This way, bias values were found in the Main amplifier design. The transmission angle at the selected operating point is between 180 and 360˚. Class C amplifier biasing was used for the second amplifier, the Auxiliary amplifier. Since the efficiency level that can be obtained in Class C amplifiers is above 80%, it is used to meet the need for high efficiency amplifiers. The conduction angle is below 90˚ and therefore the selected V_{GS}= -3.2 V is below the $V_{pinchoff}$ (-3 V).

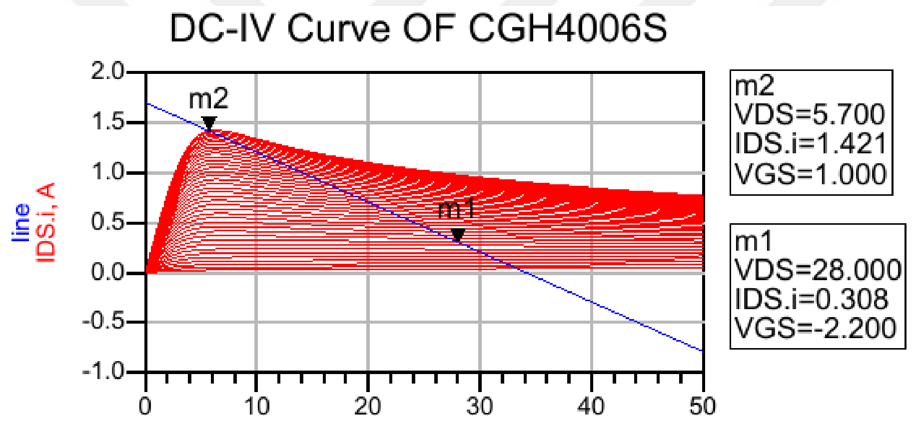

Figure 5. 2: Q-Point Selection from DC I-V Curve for Main Amplifier in the DPA

5.3. Input Output Matching Circuits

Impedance matching network is critical in power amplifiers to minimize signal reflection and ensure maximum power transfer. Here, the goal is to change the input and output impedances to a specific value. The matching circuit is heavily dependent on the input and output impedance values of the transistors at the operating frequency. Taking this into account, the power amplifier's input and output matching circuits are designed to maximize gain, linearity, and efficiency.

The load impedance value after completing the load pull analysis was 9.84+j*16.7Ω, while the source impedance value was found to be 2 + j*5.38Ω. As shown in **Figures 5.3** and **5.4**, input and output matching circuits in amplifiers are developed with microstrip lines using these values as a reference. The matching circuits and transistor model utilized in traditional DPA architectures are identical. Because of this, the Main and Auxiliary amplifiers are constructed to match the input/output matching circuits.

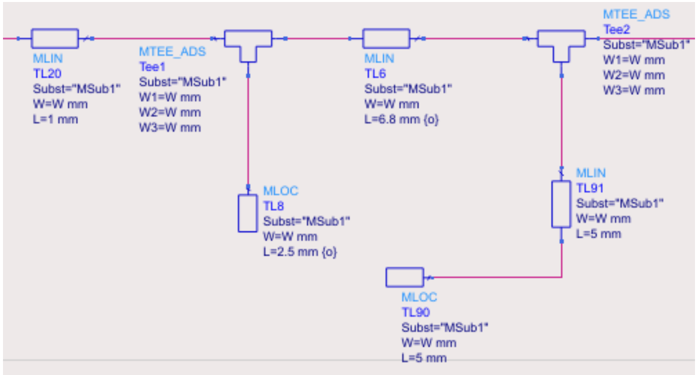

Figure 5. 3: Input Matching Network of Main/Auxiliary Amplifiers

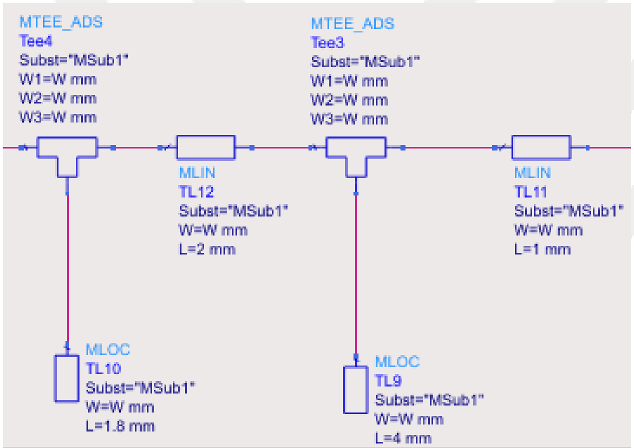

Figure 5. 4: Output Matching Network of Main/Auxiliary Amplifiers

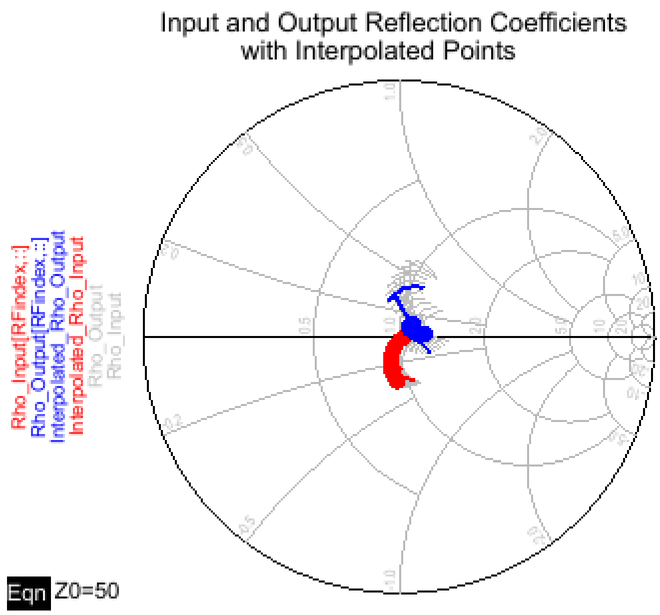

Figure 5. 5: DPA Matching Condition Representation on Smith Chart

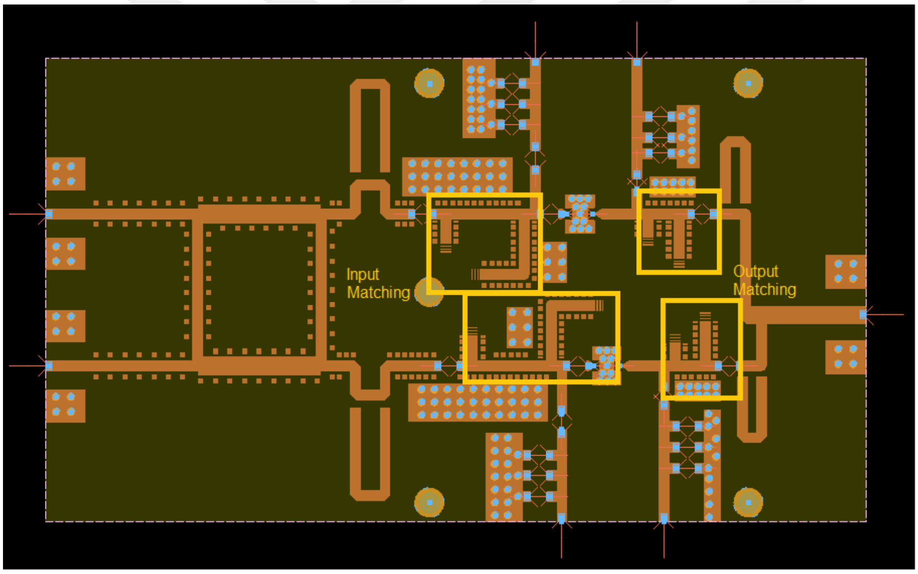

Figure 5. 6: Matching Network Representation on Layout for DPA

5.4. The Main Amplifier Design

The main and peaking power amplifiers in the DPA structure are parallel to one another and connected to the input power divider at the input. Gain and linearity parameters come to the fore in the main amplifier design. According to the impedance values acquired from the load pull simulation, input and output matching circuits were made.

The Class AB structure was used in the main amplifier design and V_{GS} = -2.2 V and V_{DS} = 28 V were selected. In this way, the conduction angle became 236°. By using bypass capacitors in the bias circuits, the amount of AC noise that may occur on the DC current is minimized. The stabilization of the power amplifier is achieved with a 4Ω resistor at the gate of the transistor. In addition, DC is rejected with coupling capacitors on the RF input and output microstrip lines.

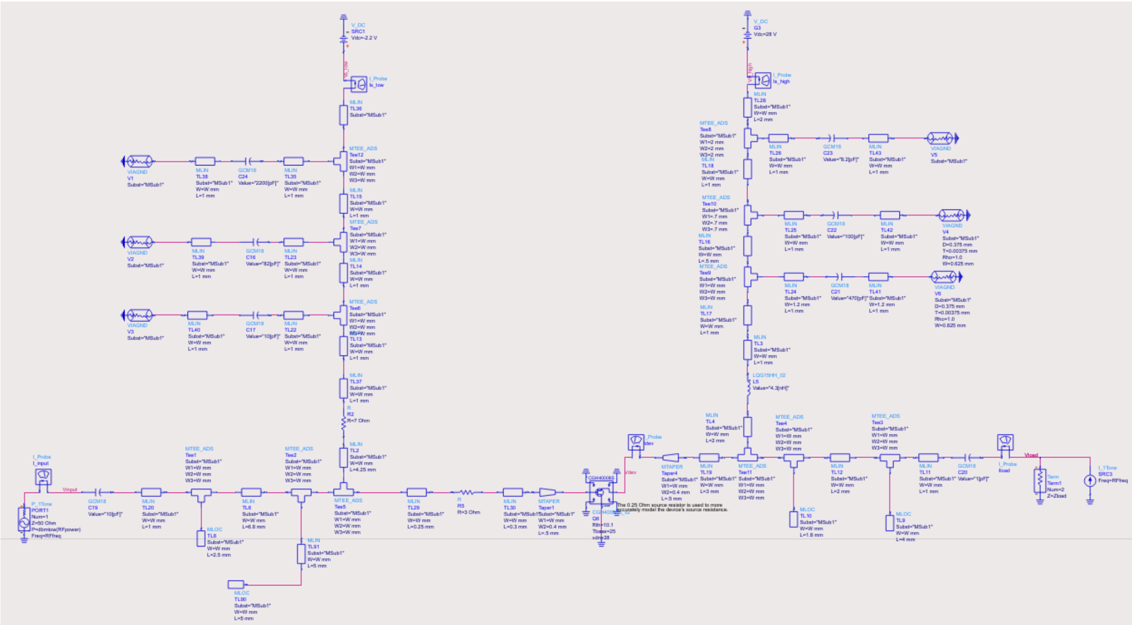

Figure 5. 7: Schematic of Main Amplifier in the DPA

5.5. The Peaking Amplifier Design

The second amplifier, the Auxiliary Amplifier, of the DPA is designed as Class C. This means that the V_G value is lower than the $V_{pinchoff}$. For this reason, the optimum V_{GS} obtained for the peaking amplifier because of the simulations is -3.2 V. Although Class C amplifiers are weak in terms of linearity and gain, they stand out in terms of efficiency. Together with the main amplifier, the auxiliary amplifier is designed to attain high efficiency levels at high output power. The Main and Auxiliary amplifiers in this design share the identical input and output matching circuits.

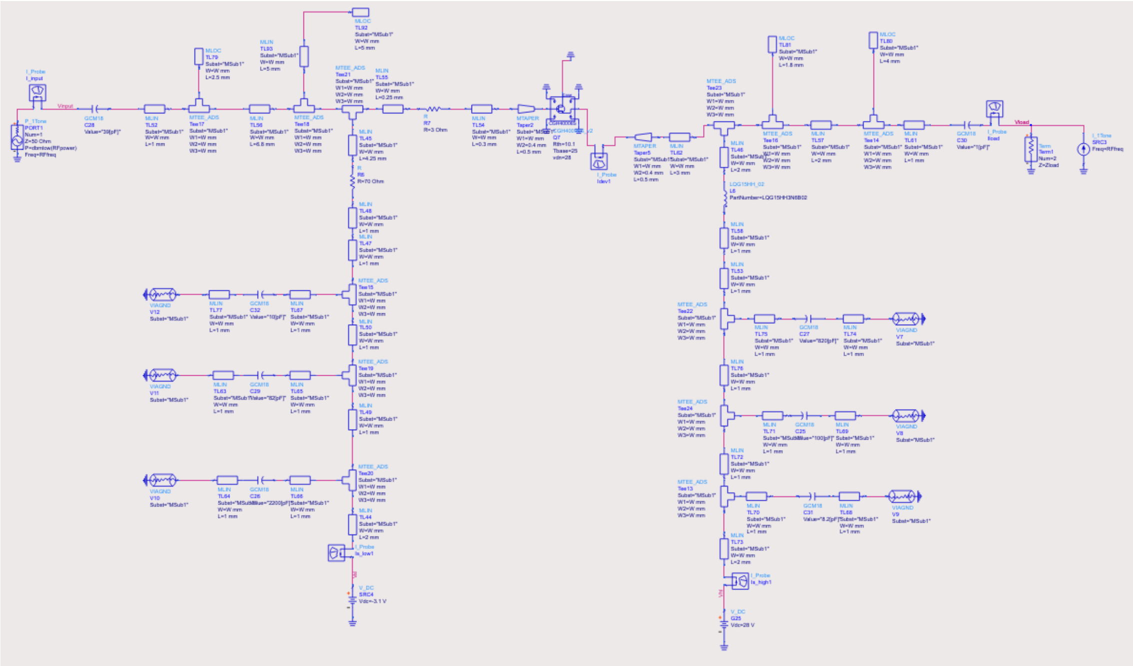

Figure 5. 8: Schematic of Auxiliary Amplifier in the DPA

5.6. Hybrid Coupler Design

As mentioned before, Hybrid Couplers are used for coupling the signal to both amplifiers of the DPA. The signal is attenuated by 3 dB at the output ports of this directional power divider, which divides the signal from the first port evenly between the second and third ports. Analysis reveals that the signals at the 2nd and 3rd port outputs have a 0° and 90° phase discrepancy. Direct transmission of DPA input with a phase difference of 90° is made to both the Main Amplifier and the Peaking Amplifier. For this reason, as seen in **Figure 4.2**, 90 ˚ Hybrid coupler is used in the DPA structure. Widths and lengths of microstrip lines forming hybrid coupler were calculated as seen in Formulas 4.1 and 4.2. The schematic and layout are shown in **Figures 5.9** and **5.10**. As seen in **Figure 5.11**, after EM simulation, S_{21} and S_{31} values at 3.5 GHz are -3.25 dB and -2.98 dB. In addition, S_{11} and S_{41} values were obtained as -33.16 dB and -32.56 dB, respectively.

Table 5. 1: Hybrid Coupler Design Parameters

No	Parameters	Values
1	Frequency	3.5 GHz
2	Substrate	Rogers4003C (ε_r=3.55)

3	Zo	50Ω
4	Zo / $\sqrt{2}$	35.35Ω
5	W1	1.2 mm
6	L1	15.3 mm
7	W2	1.9 mm
8	L2	12.4 mm

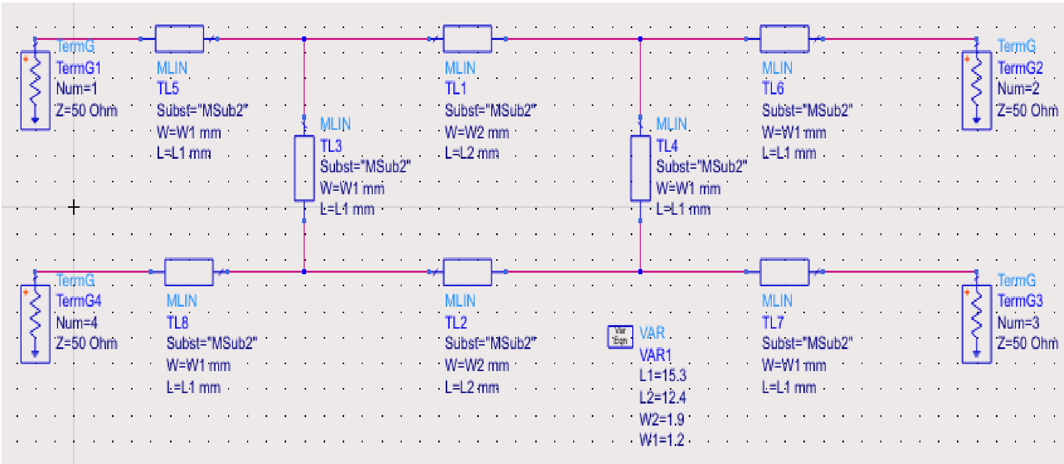

Figure 5. 9: Schematic of Hybrid Coupler

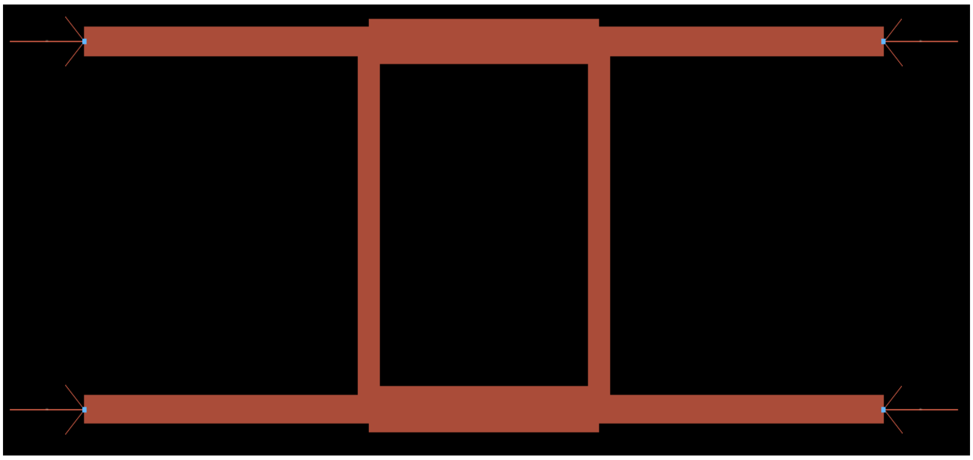

Figure 5. 10: Layout of Hybrid Coupler

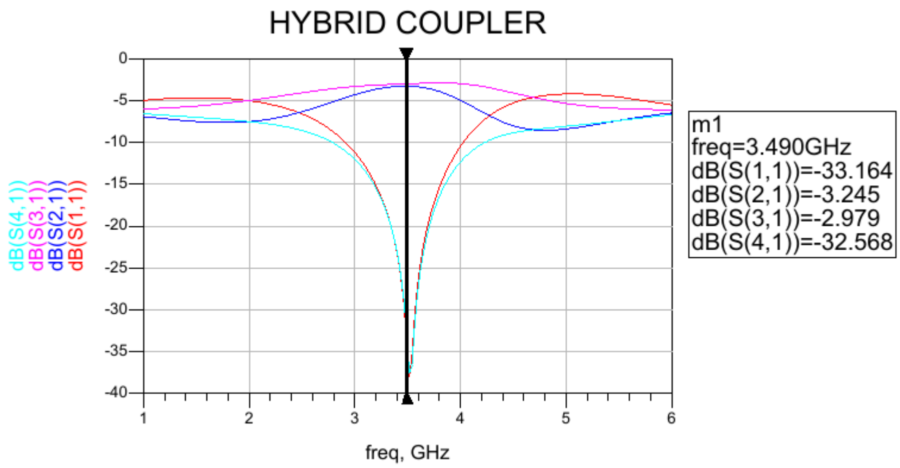

Figure 5. 11: EM Simulation Results of Hybrid Coupler

5.7. Design of the Proposed Doherty Power Amplifier

When evaluating the DPA, the power of the RF signal at the input is crucial. For this reason, as, the output current and impedance values of the amplifiers in the DPA seen in **Figure 5.12** are important.

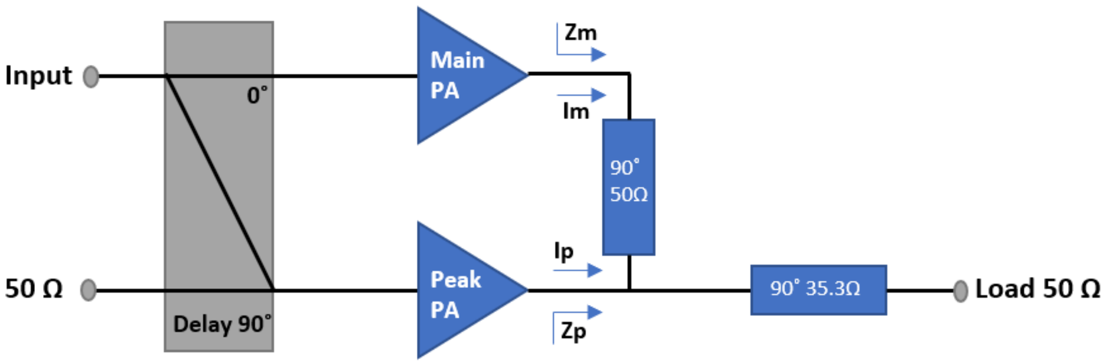

Figure 5. 12: DPA Current and Impedance Analysis

Low power and high-power regions can be distinguished in DPA operation. The main amplifier is ON, and the peaking amplifier is OFF when a low strength RF signal is received from the input. It is seen that when the signal level at the input is slowly increased, the current (I_m) at the output of the main amplifier increases and there is no current at the output of the peaking amplifier. In addition, 100Ω impedance value should be read at the output of the main amplifier. This is due to the peaking amplifier acting like an open circuit at low power levels and the output quarter wave lengths providing impedance fluctuation. The main amplifier becomes saturation when a high signal level enters the input, and the peaking amplifier switches to the ON state. Load modulation occurs as the current (I_p) at the peaking amplifier's output starts to rise and Z_m decreases from 100Ω to 50Ω. Quarter wavelength lines have a critical role in providing load modulation. As a result, the two PAs are saturated with 50Ω load.

After the DPA schematic design seen in **Figure 5.13**, the layout drawing was completed, and the ports were placed for EM simulation. After EM simulation and cosimulation, Small Signal results were obtained between DC-20 GHz as seen in **Figure 5.15**.

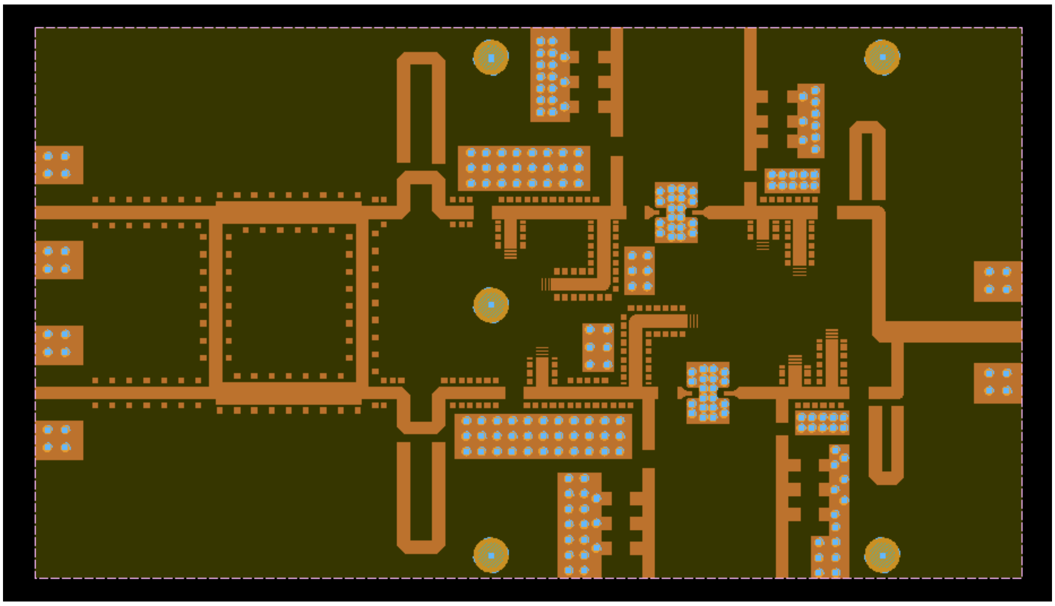

Figure 5. 13: EM Simulation Setup of DPA without Ports

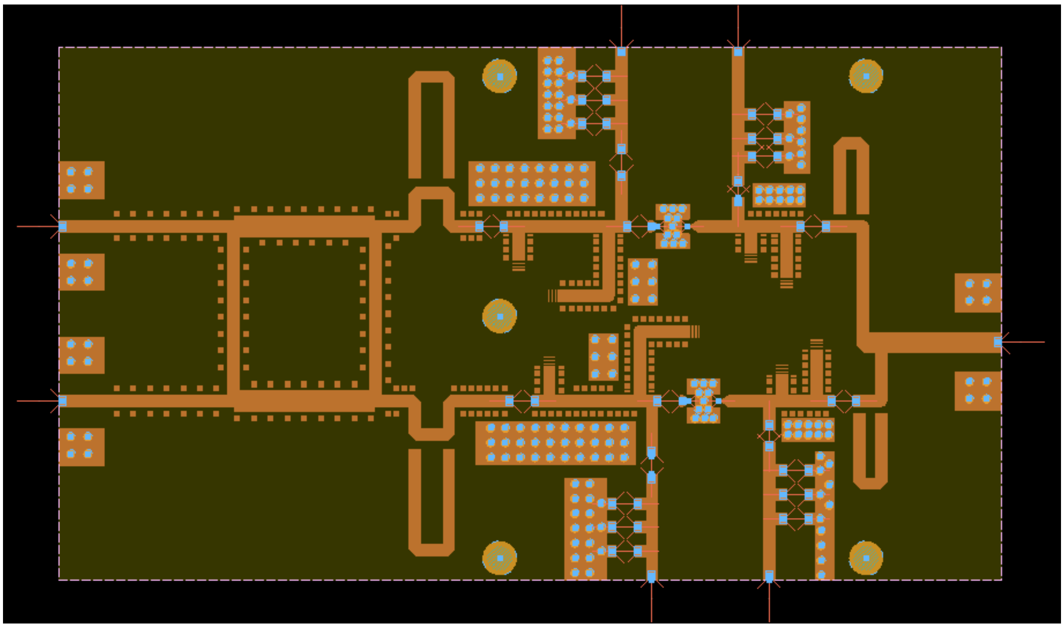

Figure 5. 14: EM Simulation Setup of DPA with defined Ports

Power amplifiers operate in two regions, linear and non-linear. For small signal analysis, linear behavior is described around an operating point in the linear region. When the intensity of the AC signal at the amplifier's RF input is low enough to prevent significant disruption of the DC operating point, the small signal analysis model is employed. The amplifier reaches the nonlinear area and becomes nonlinear if the amplitude of the AC signal at the RF input exceeds this threshold. The signal analysis performed in the nonlinear region is also called Large Signal Analyses.

As seen in **Figure 5.15**, Gain (S_{21}), Output Return Loss (S_{22}) and Input Return Loss (S_{11}) results were obtained by Small Signal Analysis method between DC-20 GHz. **Table 5.2** shows that 10.876 dB gain, -15.46 and -10.83 dB input and output return loss values were obtained at 3.5 GHz. At 3.6 GHz, 11.807 dB gain, -19.42 and -13.10 dB input and output return loss values were obtained.

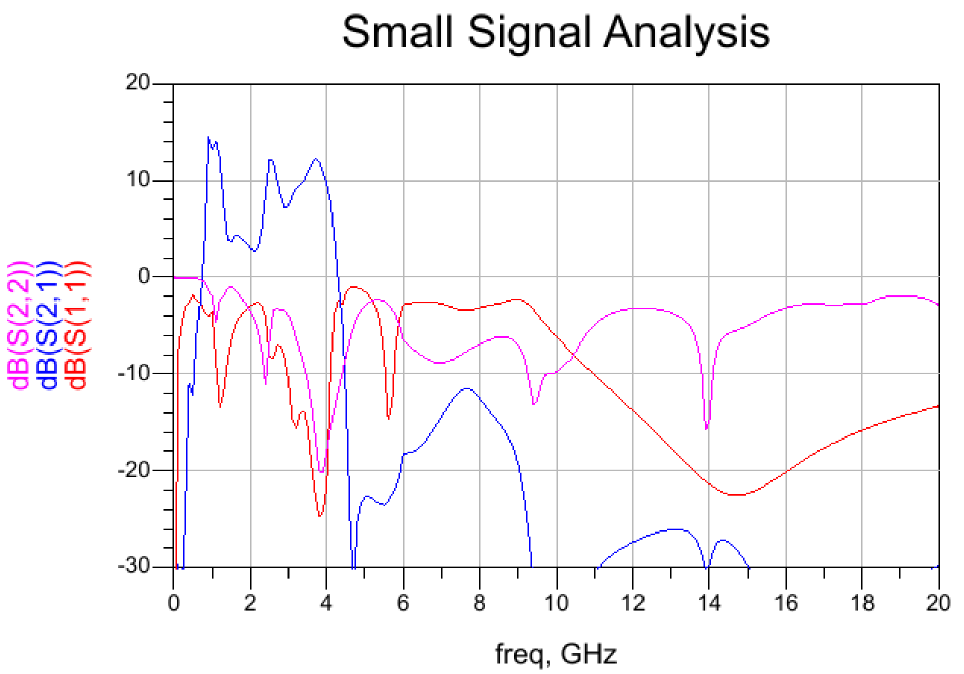

Figure 5. 15: Small Signal Analysis of DPA

Table 5. 2: Scattering Parameters of DPA

Frequency (GHz)	S21 (dB)	S11 (dB)	S22 (dB)
3.4	10.11	-13.72	-9.16
3.45	10.46	-14.33	-9.95

3.5	10.88	-15.46	-10.83
3.55	11.34	-17.20	-11.86
3.6	11.80	-19.42	-13.10
3.65	12.18	-21.40	-14.65
3.7	12.37	-22.54	-16.52
3.75	12.30	-23.57	-18.52
3.8	11.97	-24.74	-20.06
3.85	11.48	-24.94	-20.50
3.9	10.87	-24.19	-20.21

Wideband (DC-20 GHz) stability analysis is required in the design to avoid oscillations in RF amplifiers. As a result of the analysis made according to the Rollet's stability criterion, μ and μ^{I}> 1 is seen in **Figure 5.16**. This shows that the DPA is unconditionally stable.

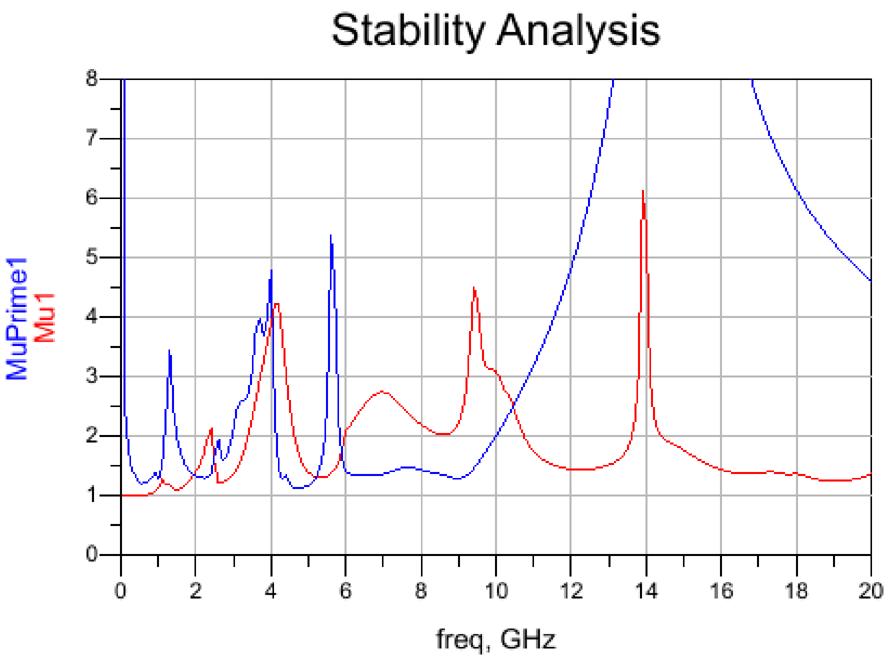

Figure 5. 16: Stability Analysis of DPA

Thanks to the Large Signal simulations (the AC signal with the rule of thumb being more than 1/5 of the DC operating point), we can access the PAE information of the DPA from the graph in **Figure 5.17**. It has 80% efficiency at 3.5 GHz and 41.2 dBm output power which is the OP1dB compression point. 51.67% PAE at 3 dB back off power and 33.5% PAE at 6 dB back off power were achieved.

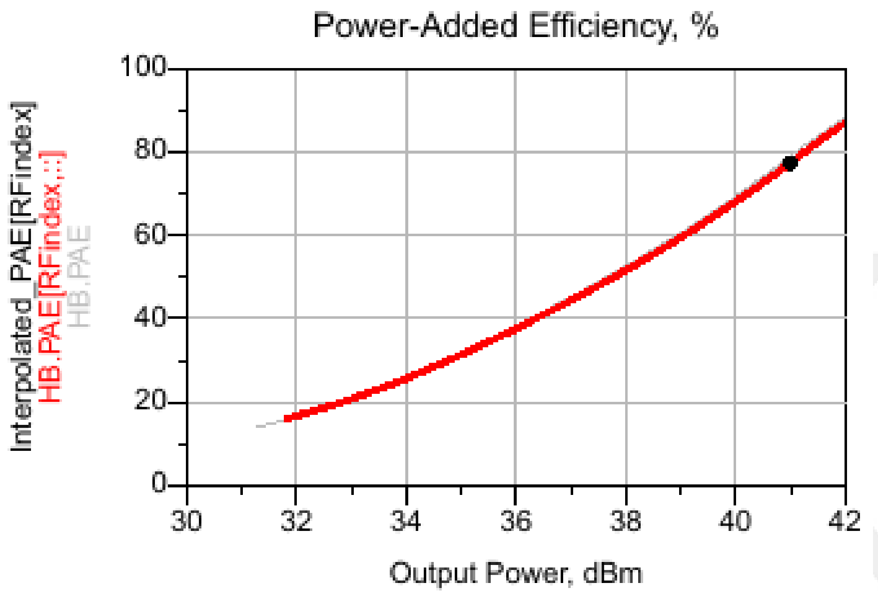

Figure 5. 17: Output Power vs PAE for DPA

Figure 5.18 is detailed representation of the transition between the linear and nonlinear regions and the 1 dB compression point demonstrates the DPA's linearity. In **Table 5.3**, the output power and PAE values obtained at 1dB compression points in simulation results between 3.4-3.6 GHz with 20 MHz steps are available. Additionally, **Figure 5.19** displays the gain and gain compression as a function of output power in increments of 20 MHz. The graph here shows the saturation region in detail.

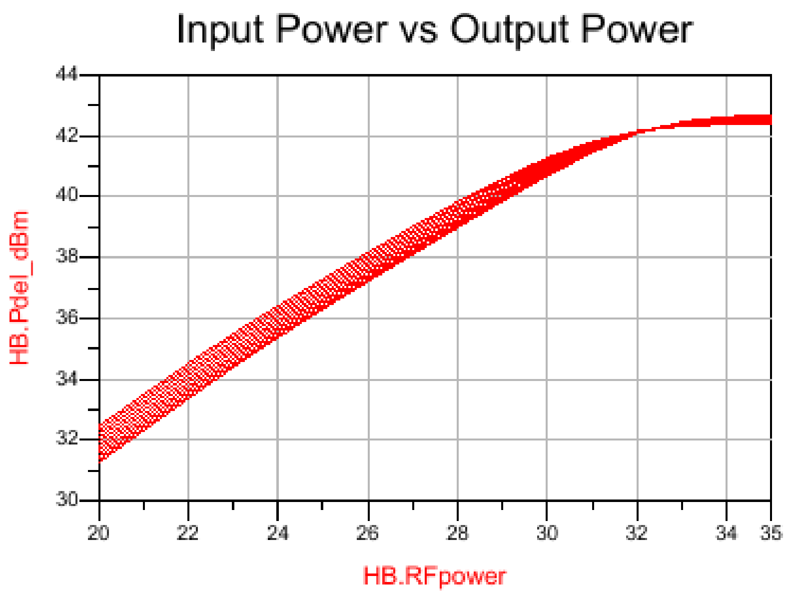

Figure 5. 18: Input Power vs Output Power between 3.4 GHz to 3.6 GHz with 20 MHz Steps

Table 5. 3: RF Performances at Compression Point of 1.0 dB

Frequency (GHz)	Output Power (dBm)	PAE (%)	Transducer Gain (dB)	DC Power Consumpt. (Watts)	High Supply Current (mA)
3.40	41.6	84.32	10.41	15.67	559.6
3.42	41.55	83.49	10.49	15.63	558.4
3.44	41.48	82.57	10.59	15.59	556.7
3.46	41.42	81.63	10.69	15.53	554.6
3.48	41.34	80.73	10.80	15.45	551.7
3.50	41.24	79.73	10.92	15.33	547.6
3.52	41.14	78.81	11.04	15.19	542.5
3.54	41.05	78.11	11.17	15.04	537.3
3.56	40.97	77.65	11.29	14.89	531.6
3.58	40.89	77.41	11.41	14.70	525.0
3.60	40.81	77.50	11.53	14.48	517.0

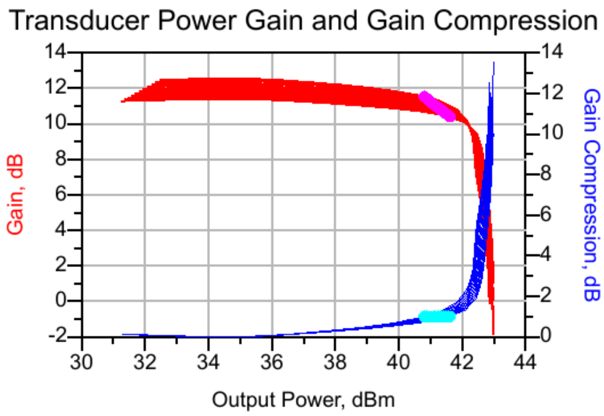

Figure 5. 19: Transducer Power Gain and Gain Compression with Output Power with 20 MHz Steps

Following the schematic and EM simulations, the Doherty Power Amplifier was manufactured, and the components were assembled on the board, as illustrated in **Figure 5.20**. On the VNA, a measuring setup has been built up for small signal analysis. DPA was powered when DC connections were established, however there was a stability issue. Stabilization was accomplished in this case by raising the value of the resistor I placed in front of the gate of the transistor. However, due to a lack of ESD (Electrostatic Discharge) conditions and a mistake during the power up sequence procedure, the transistors were damaged. As a result, the measurement could not be completed.

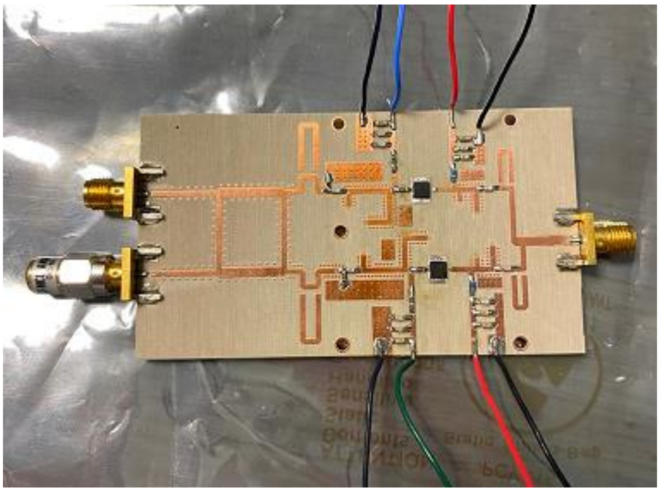

Figure 5. 20 Manufactured Doherty Power Amplifier

CHAPTER 6

6. RESULTS AND DISCUSSION

Two different power amplifiers with wide and narrow bandwidth were designed for applications in L and S band frequencies to be used in transmitters of communication systems. The power amplifiers stand out in terms of operating frequency, linearity, efficiency, 1dB compression point (P1dB) and gain level.

Firstly, the GaN Class AB PA design operating between 1-4 GHz was manufactured after the schematic and EM simulations were completed in ADS, and the components were populated on the PCB. Then, small signal measurements were performed using Rohde Schwarz ZVA40 VNA. Gains of 18.49 dB at 1 GHz, 15.31 dB at 2 GHz, 12.26 dB at 3 GHz and 4.86 dB at 4 GHz were obtained. In the EM Simulation results, on the other hand, gains of 18.43 dB at 1 GHz, 14.86 dB at 2 GHz, 11.06 dB at 3 GHz and 8.4 dB at 4 GHz were obtained. The modeling results and the measurement results are comparable considering these findings. Additionally, S11 and S22 measurements were carried out to determine the tiny signal input and output return loss values. The input return loss values of -5.42 dB at 1 GHz, -8.88 dB at 2 GHz, -6.16 dB at 3 GHz and -2.79 dB at 4 GHz were measured. In the EM simulation results, -4.03 dB at 1 GHz, -5.22 dB at 2 GHz, -9.60 dB at 3 GHz and -7.75 dB at 4 GHz were obtained. When we look at these results, it is seen that the measurement results up to 2 GHz is better than EM simulations. In addition, when we examined the output return loss value of the produced card, it was measured to be -18.66 dB at 1 GHz, -8.98 dB at 2 GHz, -23.19 dB at 3 GHz and -7.85 dB at 4 GHz. In the EM simulation results, -14.81 dB at 1 GHz, -11.96 dB at 2 GHz, -19.75 dB at 3GHz and -16.33 dB at 4 GHz were obtained. Looking at these results, it is seen that the measurement results at various frequencies are better than the EM simulation results. In addition, it was verified through small signal S-parameter file that GaN Class AB PA is unconditional stable between DC-20 GHz.

After Small Signal Analysis, the measurement setup seen in **Figure 3.16**, and **Figure 3.17**, were prepared. OP1dB, PAE and DE were measured at some frequencies within the operating frequency band. As seen in **Table 3.5**, OP1dB values between 38.2 and 40.25 dBm were obtained between 2000-3500 MHz from the produced card. As a result of EM simulations, OP1dB values between 38.83 and 39.79 dBm were obtained between 2000-3500 MHz. Considering these results, similar 1dB output compression points were obtained in the production and EM Simulation results. When we examined the efficiency, PAE between 2000-3500 MHz was obtained as 46.4-57.1 % for the produced card. In the same operational frequency range, PAE between 44.17 and 51.09% was achieved in EM simulations. It is seen that the production results are better than the EM simulation results. In addition, the produced card has DE values in the range of 55.85-67.89% in the same frequency band.

This thesis also included the design of a GaN DPA, which is notable for its efficiency and operates between 3.4 and 3.6 GHz. After the schematic simulations of DPA, the layout was created, and EM Simulations were made. As a result of these simulations, 10.10-11.80 dB gain was obtained between 3.4-3.6 GHz in small signal analysis. In addition, the input return loss is between -13.72 dB and -19.42 dB. Output return loss is achieved in the range of -9.16 dB and -13.17 dB. Besides, the design is unconditional stable between DC-20 GHz. Large signal analysis was performed after the small signal analysis as in the first PA. As a result of EM simulations, 40.81-41.6 dBm OP1dB was obtained in the 3.4-3.6 GHz frequency range. In addition, PAE in the range of 77.5-84.3% and gain in the range of 10.4-11.5 dB were obtained. It is seen that it has 80% PAE especially at 3.5 GHz. 51.67% PAE at 3 dB back off power and 33.5% PAE at 6 dB back off power.

CHAPTER 7

7. CONCLUSIONS AND FUTURE WORK

RF PA is essential to wireless transmitters used in RADAR and communication systems. In these applications, a radio frequency power amplifier is necessary to achieve an adequate output power at the antenna.

There are numerous topologies for PAs to suit these needs, and the output power, operating frequency, efficiency and power consumption, linearity, gain, and distortion are crucial aspects in RF PA design. Each circuit design has its own characteristics. According to the conduction angle, different configurations of linear amplifiers are categorized as Class A, AB, B, and C. Class A amplifiers are used for linear amplification of input signals due to their 360° transmission angle. It has a poor efficiency performance but a high gain and linearity performance. Class B Amplifiers have a transmission angle of 180° and have high efficiency. However, they offer less linearity and gain than Class A. Class AB amplifiers are hybrid amplifiers. Therefore, the conduction angle remains between 180° and 360°. They provide linearity performance that is superior to Class B and efficiency performance that is superior to Class A. Class C amplifiers have a conduction angle below 180°. Although this class of amplifiers has the best efficiency, it also has the lowest gain and linearity.

After selecting the class of the amplifier according to the PA requirements, the transistor model to be used is determined. In this thesis, Wolfspeed/Cree's CGH40006S (6W GaN HEMT) transistor model with DC-6GHz operating frequency range is used for two different designs. It is a surface mount transistor with a size of 3x3 mm and a QFN sheath. After the transistor selection, Rogers 4003C substrate with 0.508 mm thickness was used for PA design.

After the transistor selection, two different PA designs that can be used in the L and S frequency bands and in the N78 band of 5G base stations have been realized. In the beginning, a GaN Class AB amplifier working in the 1-4 GHz operating frequency range was designed. According to the ideal load and source impedances found in the load pull simulations and datasheet, input and output matching circuits were created. Afterwards, biasing networks were designed for gate and drain biasing of the transistor. The electronic design software Agilent ADS (Advanced Design System) was used for schematic and EM simulations. Linear and nonlinear ADS model design kits are supplied by the vendor of the transistors, so these models were used in design simulations. After reaching the desired results in schematic and EM simulation, the layout file was manufactured. After the PCB was produced, passive and active components were populated In Small Signal analysis, S-Parameters were obtained using Rohde Schwarz ZVA40 model VNA and gain, input/output return loss and stability analysis were performed. The simulation results and measurement results were close to each other.

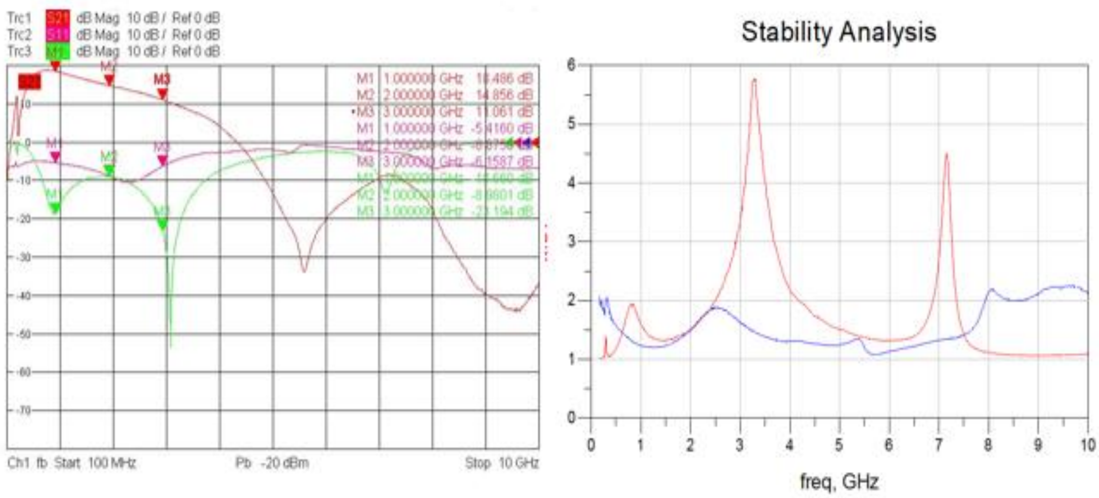

Figure 6. 1: Small Signal Performance of GaN Class AB PA

Rohde Schwarz SMF100A signal generator and Rohde Schwarz FSVA3044 Signal & Spectrum Analyzer devices were used for large signal measurements. In front of the GaN Class AB amplifier, Mini-circuits ZVE-3W-83+ amplifier was used to act as a driver amplifier. OP1dB (dBm) was measured between 38.2-40.25 dBm in the frequency band of interest. PAE values between 49.74-57.1% and DE values between 55.85-66.61% were achieved. When we compare the EM simulation results and the measurement results, they are in line with each other.

The second PA design, known as GaN DPA, operates between 3.4 and 3.6 GHz and is intended to have high power, linearity, and efficiency for usage in 4G and 5G base stations. A 90° hybrid coupler is used as an input power divider. This way, 90˚ phase difference is provided between the two separated signals. DPA includes amplifiers operating in two different classes in parallel, a main and a peaking amplifier. At the amplifiers' output, the phase difference is equalized using a 90° line. Consequently, when both amplifiers are operating, they have the same phase.

The main and peaking amplifiers have similar schematics, but the gate bias voltage (V_G) values are different from each other. The incoming signal is split into two halves by the hybrid coupler at the input. The Main amplifier is ON at low power levels, and the Peaking amplifier is ON at high power levels. Hence, OP1dB point is achieved at a higher power level and high efficiency is achieved. In the operating frequency range of 3.4 -3.6 GHz, a gain of 10.1–12 dB was attained in the results of the schematic and EM simulations. Input return loss is between -13.7 and -20 dB and output return loss is between -9.1 and -13.5 dB. As a result of large signal simulations, 78-80% PAE and 40.8-41.6 dBm OP1dB were obtained. 45-51.67% PAE at 3 dB back off power and 30-33.5% PAE at 6 dB back off power were obtained.

In two different structures, RF PAs with different operating frequencies and requirements were designed and the results were obtained. With the knowledge gained here, narrow, and wide band PAs can be designed depending on different RF requirements in the L, S, C, X, Ku, K and KA frequency bands in the RF frequency spectrum.

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