ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

UHF RF POWER AMPLIFIER DESIGN AND IMPLEMENTATION FOR SMALL SATELLITES

M.Sc. THESIS

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Electronics and Communication Engineering Department

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JUNE 2013

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

KÜÇÜK BOYUTTA UYDULAR İÇİN UHF BANDINDA ÇALIŞAN RF GÜÇ KUVVETLENDİRİCİ TASARIMI VE GERÇEKLENMESİ

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HAZİRAN 2013

Mehmet DUMAN, a M.Sc. Student of ITU **Institute of Science and Technology/Graduate School of Istanbul Technical University** student ID 504111208, successfully defended the **thesis** entitled **"UHF RF Power Amplifier Design and Implementation for Small Satellites"**, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my family,

FOREWORD

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Mehmet DUMAN
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ABBREVIATIONS

AC	: Alternating Current
ACPR	: Adjacent Channel Power Ratio
BJT	: Bipolar Junction Transistor
BW	: Bandwidth
CATV	: Cable Television
CDMA	: Code Division Multiple Access
CMOS	: Complementary Metal Oxide Semiconductor
D	: Dimension
DA	: Distributed Amplifier
DC	: Direct Current
EHF	: Extremely High Frequency
ESD	: Electrostatic Discharge
EVM	: Error Vector Magnitude
FET	: Field Effect Transistor
FR	: Flame Retardant
GaAs	: Gallium Arsenide
GaN	: Gallium Nitride
GaP	: Gallium Phosphide
GaSb	: Gallium Antimonide
GHz	: Gigahertz
G_A	: Available Power Gain
GMSK	: Gaussian Minimum Shift Keying
G_P	: Operating Power Gain
g_{rev}	: Reverse Gain
G_T	: Transducer Power Gain
HBT	: Heterojunction Bipolar Technologies
IMC	: Input Matching Circuit
IMD	: Intermodulation Distortion
ISM	: Industrial, Scientific and Medical
kHz	: kilohertz
MHz	: Megahertz
MMIC	: Monolithic Microwave Integrated Circuit
OIP_3	: Output Intercept Point Third
OMC	: Output Matching Circuit
PA	: Power Amplifier
PAE	: Power Added Efficiency
PCB	: Printed Circuit Board
RF	: Radio Frequency
RFC	: Radio Frequency Choke
RFMD	: Radio Frequency Micro Devices
RL	: Return Loss
RMS	: Root Mean Square

SHF : Super High Frequency
SiGe : Silicon Germanium
SMA : Sub Miniature Version A
SMD : Surface Mount Device
THD : Total Harmonic Distortion
TL : Transmission Line
TPO : Transmitter Power Output
UHF **:** Ultra High Frequency
VHF : Very High Frequency
VSWR : Voltage Standing Wave Ratio

LIST OF SYMBOLS

w	: Width
l	: Length
$\mathbf{Z_0}$	: Characteristic Impedance
$\mathbf{Z_{in}}$	: Input Impedance
$\mathbf{Z_{out}}$	: Output Impedance
$\mathbf{Z_L}$	: Load Impedance
$\mathbf{Z_S}$	: Source Impedance
K	: Stability Factor
B1	: Stability Factor
I	: Current
P	: Power
Eff	: Efficiency
λ	: Wavelength
f	: Frequency
$\mathbf{f_0}$	: Center Frequency
V	: Voltage
W	: Watt
π	: Pi
Q	: Quiescent
Γ	: Reflection Coefficient
T	: Thickness
dB	: Decibel
Ω	: Ohm
ρ	: Voltage Reflection Coefficient
G	: Gain Constant
η	: Efficiency
$\mathbf{P_{ldB}}$	: l dB Compression Point
$\mathbf{IP_{3rd}}$	: Third Order Intercept Point
ω_0	: Resonance Frequency

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UHF RF POWER AMPLIFIER DESIGN AND IMPLEMENTATION FOR SMALL SATELLITES

SUMMARY

In this thesis, the radio frequency power amplifier which can be used for small satellites is designed. The RF power amplifier has 23 dB gain and 0.6 Watt output power theoretically. It is designed in Microwave Office AWR (Applied Wave Research) program. The power amplifier center frequency is 435.250 MHz which is the standard frequency of small satellites. The bandwidth is about 7 MHz and the gain is flat around the center frequency.

In the thesis, there are five chapters and the chapter one covers an introduction part which gives preliminary information about the thesis. The second chapter tells about the power amplifier basics which are given with four subtitles. One of the subtitles includes gain, output power, efficiency, linearity, stability, distortion, etc. The other subtitle gives information about S parameters and S parameters specifications. Later, the classes of power amplifiers and amplifier design fundamentals are given in the other subtitles. In the third chapter, the experiments are written in detail. The materials and the equipment are also given in this chapter. Experiments which are done in Microwave Office AWR program and in the real world are given in the third chapter too. The forth chapter shows the results and discussion about the experiments done in program and in real. There are also comparisons in this chapter. Finally, the last chapter which has conclusion part is given.

As a start point of this work, the literature was researched very deeply among the M.Sc. theses, RF power amplifier books, IEEE publications, the articles and B.Sc. theses which were analyzed well. Later, it was decided that the power amplifier could be designed with SGA9289z medium discrete power transistor which is taken from RFMD (RF Micro Devices).

The bias circuit for the transistor was designed according to the circuit specifications. The input and output circuit of the transistor were designed and impedance matching circuits were added. The optimum circuit was reached with controlling the S parameters, VSWR (voltage standing wave ratio), stability, etc. All of the components which were used in the circuit were SMD (surface mount device) product and they were very small, as a result, the power amplifier circuit dimensions were 2,5cm × 3.3cm. The components used in the amplifier circuit were explained in detail in the thesis.

The circuit layout is drawn in the same program that is Microwave Office AWR. Later, it is printed out to the PCB (printed circuit board) and all of the components are soldered to the PCB. The SMA (subminiature version A) connectors are soldered to the input and output of the circuit to measure characteristics of the power amplifier. Finally, graphic results which are gain, output power, S_{11}, S_{12}, S_{21}, S_{22}

values and efficiency are obtained with using spectrum analyzer, oscilloscope, signal generator and the other equipment which are given in the third chapter.

In the conclusion chapter of the thesis, it is given that why this thesis is important in the literature and why it can be used for small satellites. There is also information about the other works that can be done after this thesis work. Finally, there are appendix sections at the end of the thesis; some of the knowledge is given in this part.

KÜÇÜK BOYUTTA UYDULAR İÇİN UHF BANDINDA ÇALIŞAN RF GÜÇ KUVVETLENDİRİCİ TASARIMI VE GERÇEKLENMESİ

ÖZET

Küçük boyutta uydular için üretilen güç kuvvetlendiricilerinde kullanılması şart olan standart bir merkez frekans değeri belirlenmiştir. Bu tezde, belirlenen standart değer olan 435.250 MHz merkez frekanslı olarak çalışan ve bant genişliği yaklaşık olarak 7 MHz olan radyo frekansı güç kuvvetlendiricisi tasarımı yapılmıştır. Üretilen güç kuvvetlendiricisinin teorik olarak hesaplanan kazanç değeri 23 dB ve çıkış güç değeri 0.6 Watt değerindedir. Üretilecek olan devrenin bütün çizimleri ve bilgisayar ortamındaki simulasyonları Microwave Office AWR programı ile yapılmıştır.

Bu tez beş bölümden oluşmaktadır. Bölüm bir, tez hakkında kısa bilgiler veren ve tez konusunun neden seçildiğini belirten ön bilgilerden oluşmaktadır. Bu bölüm içinde genel olarak teze giriş yapılmıştır.

Kendi içinde dört alt başlığa ayrılan ikinci bölüm, radyo frekansı güç kuvvetlendircilerinin temellerini konu almaktadır. Bu bölümdeki alt başlıklardan ilkinde kazanç, çıkış gücü, verimlilik, doğrusallık, kararlılık, bozulmalar vs. hakkında literatür bilgileri verilmiştir. Ayrıca tez için oluşturulan grafik ve devre şematikleri bu alt başlıkta yer almıştır. İkinci bölümün bir diğer alt başlığında S parametrelerine geniş bir giriş yapılmış ve S parametrelerinin çeşitleri ile voltaj durağan dalga oranı hakkında bilgiler verilmiştir. Üçüncü alt başlıkta güç kuvvetlendirici sınıfları üzerinde durulmuş ve doğrusal olarak çalışan A sınıfı, B sınıfı, AB sınıfı ve C sınıfı detaylı olarak incelenmiştir. Tez için oluşturulan güç kuvvetlendiricisi A sınıfı olduğu için bu sınıf derinlemesine incelenmiştir. İkinci bölümün son alt başlığında güç kuvvetlendiricisi tasarım temelleri aktarılmıştır.

Tezin üçüncü bölümünde bilgisayar ortamında Microwave Office AWR programıyla yapılan deneylere ve gerçek ortamda baskı devrenin spectrum analizörü, osiloskop vb. ölçüm aletleri ile yapılan deneylerine yer verilmiştir. Bilgisayar ortamında ve gerçek ortamda yapılan deneyler iki ayrı alt başlık altında yer almaktadır. Her bir ölçüm detaylı olarak tezde anlatılmıştır. Tez için üretilen güç kuvvetlendiricisi devresinde kullanılan malzemelere ve devrenin ölçüm aşaması için gerekli olan cihazlara da bu bölüm içinde iki ayrı alt başlık verilmiştir. Bu alt başlıklarda malzemeler ve cihazlar tanıtılmıştır.

Dördüncü bölümde bilgisayar ortamında ve gerçek ortamda yapılan deneylerin sonuçları karşılaştırılmış ve elde edilen bulgular hakkında yorumlar yapılmıştır. Tezin bütün bölümlerinde olmakla birlikte özellikle dördüncü bölümde önemli karşılaştırmalar yapılmış ve bu karşılaştırmalar tablolar halinde aktarılmıştır. Bu bölümde ayrıca; güç kuvvetlendiriciler konusu üzerine daha önceden yapılan bazı yüksek lisans tez çalışmaları hakkında bilgiler verilmiştir. Üzerinde çalışılan tezin daha önceden yapılan tezler ile karşılaştırılması yapılmış ve aralarındaki farklar özetle anlatılmıştır.

Son bölüm olan beşinci bölümde, üzerinde çalışılan tezin neden seçildiği anlatılmış ve literatürde neden önemli olduğuna dair bilgiler verilmiştir. Küçük boyutta uydular için neden kullanıldığı tekrarlanmış ve tezin önemli sonuçları üzerinde tekrar durulmuştur. Ayrıca bu tezden sonra, tezin devamı için doktora aşamasında yapılabilecek çalışmalar aktarılmıştır.

Son bölümden sonra, ayrı olarak, tezin bölümlerinde anlatılmayan bazı bilgiler ek kısmında aktarılmıştır. Tezin yazım aşamasında elde edilen bütün sonuçlar detaylı olarak paylaşılmış ve devre şematikleri, grafikler özenle teze eklenmiştir.

Teze başlama aşamasında literatür çalışmaları iyi bir şekilde araştırılmış ve yüksek lisans tezleri, radyo frekansı güç kuvvetlendirici kitapları, IEEE yayınları, makaleler, bildiriler ve lisans tezleri detaylıca incelenmiştir. Daha sonra tez çalışmasının RFMD'nin üretmiş olduğu SGA9289z güç kuvvetlendiricisi ile yapılması danışman ve tez öğrencisi tarafından uygun görülmüştür.

Transistor için tasarımı yapılacak olan kutuplama devresi, A sınıfı güç kuvvetlendirici devresinin çalışma prensibine uygun olarak dizayn edilmiştir. Kutuplama devresinde kullanılan direnç değerlerine analitik hesaplamalara göre ve transistorun veri sayfasından elde edilen bilgilere göre karar verilmiştir. Transistorun çalıştığı gerilim değerleri ve kutuplama akımı da veri sayfasındaki bilgiler esas alınarak oluşturulmuştur.

Kutuplama devresinin tasarımından sonra devrenin giriş kısmına ve çıkış kısmına istenilen bant genişliği, kazanç değeri ve S parametrelerini verecek giriş ve çıkış devreleri eklenmiştir. Empedans uyumuna dikkat edilerek giriş ve çıkış devreleri güncellenmiş ve bilgisayar ortamında yapılan simulasyonlara devam edilmiştir. Empedans uyumunun gerçekleştirilmesi sırasında Microwave Office AWR programının iFilter özelliğinin yanı sıra; S_{11}, S_{12}, S_{21} ve S_{22} değerlerinin standart bir güç kuvvetlendirici devrede olması gereken değerleri de dikkate alınmıştır. Kararlılık analizlerine ve voltaj durağan dalga oranına göre güç kuvvetlendiricisinin çalışmasına en uygun görülen devre şematiği oluşturulmuştur.

Elde edilen devre şemasının baskı devre işlemine geçmesi için bakır plaka üzerine yerleşim planının çıkarılması gerekmektedir. Microwave Office AWR programı ile baskı devre yerleşim planı çıkartılmıştır. Bu aşamada devrenin boyutunun yeterince küçük olmasına özen gösterilmiştir. Devrede kullanılacak olan bütün elemanların SMD eleman olması istenmiştir. Bu sayede devrenin olabildiğince küçük olması sağlanmıştır. Devredeki 24mm uzunluğundaki hat gibi bazı hatların uzun olmasından dolayı bu hatlar kıvrılmış bir şekilde baskı devreye çizilmiştir. MWO AWR programının bu özelliği sayesinde devrenin boyutu önemli ölçüde küçülmüştür.

Sonuç olarak bilgisayar programında baskı devreye hazır hale getirilen devrenin boyutu 2,5cm en ve 3,3cm boy oranındadır. Üretilen baskı devrede kullanılan elemanların özellikleri hakkında ve baskı devrenin karakteristik özellikleri hakkında detaylı bilgilere tezde yer verilmiştir.

Devredeki toprak bağlantılarının yeterince çok olması radyo frekansı güç kuvvetlendirici devreleri için gerekli bir durumdur. Bu durumun sağlanması için devrenin üst yüzeyinde toprak için yeterince büyük bir alan ayrılmıştır. Devrenin alt kısmı tamamen toprak olarak basılmıştır. Üst yüzeydeki toprak bağlantılarını alt yüzeydeki toprağa bağlamak için devrenin birçok yerinde hole olarak adlandırdığımız delikler açılmıştır. Bu sayede devrenin toprak bağlantısı istenilen ölçütlere ulaşmış olacaktır.

Bilgisayar ortamında üretilen baskı devre gerçek ortamda üretilmiş ve devredeki kapasite, indüktans, direnç ve transistorlar devreye lehimlenmiştir. Son olarak devrenin giriş ve çıkışına SMA konnektörler lehimlenmiş ve devre gerçek ortamda deney ölçümlerine hazır hale getirilmiştir. Bilgisayar ortamında çizilen devre ve gerçek ortamda bakır levha üzerine basılan devre resimlerine tezde yer verilmiştir.

Üretilen baskı devrenin kazanç değeri, S parametreleri, çıkış gücü ve verimi sinyal jeneratörü, osiloskop ve spectrum analizörü vb. ölçüm aletleri sayesinde ölçülmüş ve gerçek ortamda yapılan deney ile bilgisayar ortamında yapılan deneyler karşılaştırılmıştır. Sonuçlar ve karşılaştırmalar tezde başlıklar halinde detaylı olarak incelenmiştir.

Sonuç olarak, küçük boyutta uydular için kullanılmaya elverişli bir radyo frekansı güç kuvvetlendirici devresi tasarlanmış ve gerçekleştirilmiştir.

1. INTRODUCTION

In the last few years, there have been a remarkable amount of growth in the electrical and electronics engineering areas. Consequently, the demand for optimizing the circuits involved in radio frequency devices has increased drastically. Not only has the demand for the circuits increased drastically, but also the amount of research done in this area has grown as well. This growth also spread to amplifier circuits. Power is the most important and primary cause for this spread. As the amplifier circuits takes important place in everyday life, an optimized design of power amplifiers (PA) becomes a necessity. Since in radio frequency devices, all circuits are drawing power from a small battery, it seems clear that one of the most important aspects of the circuits that need to be optimized is the power consumption. Additionally, the cost of the circuits must be lowered as well, because these devices must be used in a low cost product.

There are some bands defined to make the systems compatible for amplifier circuits. UHF (ultra high frequency) Band is one of them. Its operating frequency band is between 421 MHz and 470 MHz, sometimes UHF operating band frequency is given within 300 MHz and 3 GHz. In this thesis, 435.250 MHz center frequency band is chosen and the requirements are fixed according to UHF Band definitions. 435.250MHz frequency is chosen specifically because this frequency has been used for small satellites. The other bands are VHF, SHF, EHF, etc.

There are many power amplifier implementation techniques for designing an amplifier. In a Monolithic Microwave Integrated Circuit (MMIC), high efficient power amplifiers such as Class E, Class F, or Class S can be preferred but in this thesis, it is decided that the linearity and stability are more important and hence Class A power amplifier is designed. This class of operation also gives higher output power by implementing some of the power techniques. High power and highly linear amplification cannot be easily achieved at the same time. The power amplifier classes are explained elaborately in this thesis.

Although GaAs (Gallium Arsenide) and some other technologies are commonly used in the integrated power amplifiers, SiGe (Silicon Germanium) technology also finds a wide implementation area for amplifier designs. Devices in SiGe HBT (Heterojunction Bipolar Technologies) medium power discrete technology can operate at between 50MHz and 3000MHz. It can be said that SiGe technology is easy to implement rather than III-V compound semiconductor technologies which are GaAs, GaSb (Gallium Antimonide), GaP (Gallium Phosphide), GaN (Gallium Nitride), etc. Also it is cheaper than the other technologies so it is an advantage while implementing. Therefore, it is decided to design the amplifier with SiGe HBT technology because of these several advantages.

In this thesis, a power amplifier is designed using SGA9289Z Medium Power Discrete SiGe transistor. In general, capacitors, resistors and transmission lines are used. Most of the inductors are implemented by transmission lines. As explained above, the amplifier is designed according to UHF Band. The center frequency is 435.250MHz and the band width is about 6.8MHz. Gain is about 23 dB and output power is about 27 dBm theoretically.

All the simulations are performed in Microwave Office Advancing the Wireless Revolution (or Applied Wave Research) Design Environment (MWOAWRDE). First of all, the center frequency and band width are performed with band pass filters which are located base of the transistor and collector of the transistor. Gain is also considered in this stage according to the transistor datasheet. Emitter of the transistor is connected to the ground which is explained in detail in the thesis. The operating bias values are found for a single-stage Class-A power amplifier and for transistor. Later desired input and output impedances are found. Matching circuits are created according to these analyses and final performance of a single-stage amplifier is obtained. It is also considered that gain value at the center frequency should be flat throughout about 300 kHz. As a result, there will be flat gain at the top of the gain figure. S Parameters have been very important while implementation.

The ideal and real models of passive components are compared in this amplifier. Firstly, the power amplifier is designed according to the ideal components; secondly, the real AWR library models are used in the design. Finally, layout is created according to final design and layout simulations are done. All simulation results are compared as a conclusion.

Later in the thesis, general information about the power amplifier design theory is given. Architecture of an RF system is explained in detail. Then, some basic characteristics of a power amplifier is explained and defined. Biasing and linear classes of power amplifier are introduced especially. These linear classes are A, B, AB, and C operating classes for power amplifier. The other power amplifier classes are also introduced in the thesis. Later, power amplifier is designed. The improvement of a power amplifier can be seen stage by stage. As a last step, the layout of the power amplifier is created in MOAWRDE. The simulations are repeated with this layout and the most realistic behavior of the circuit is derived. The circuit is printed to PCB (printed circuit board) and the graphs have been analyzed in the real world. The comparison is done in the fourth chapter between simulations and the reality. Finally, the conclusion chapter is given.

2. POWER AMPLIFIER BASICS

An electronic amplifier is an electronic device used for increasing the power of a signal. The amplifier takes energy from power supply and controls the output to match the input signal shape but with a larger amplitude. As a result, an amplifier can be considered as modulating the output of the power supply. There are several amplifiers such as power amplifiers, vacuum-tube amplifiers, operational amplifiers, fully differential amplifiers etc. [Url-6]

Today, power amplifiers are being used in a wide variety of applications including Wireless Communication, TV transmissions, Radar, and RF heating, etc. Power amplifiers are the last stage of the transmitter chain where highest RF power is generated and highest DC (direct current) power is consumed. The term power amplifier is a relative term with respect to the amount of power delivered to the load and/or sourced by the supply circuit (Bowick, C., Blyler, J., Ajluni, C., RF Circuit Design 2008).

Power amplifiers may be separated application by application. Audio power amplifiers, RF power amplifiers, servo motor controlling amplifiers, piezoelectric audio amplifiers and so on. In this thesis, generally RF power amplifiers are explained. A schematic of a basic RF power amplifier is given in Fig. 2.1.

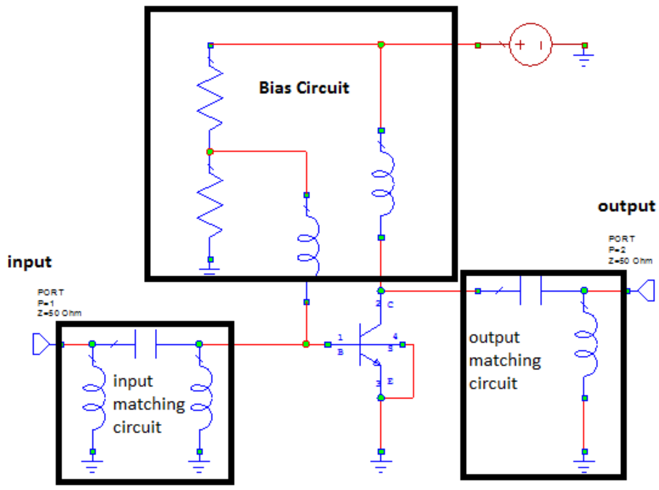

Figure 2.1: Schematic view of a basic RF amplifier.

In Fig.2.1, Port 1 is the input and Port 2 is the output terminals. There is a bias circuit connected to the base and collector of transistor. There are also RF Chokes on the base and collector. PA transistor can be seen in the middle of the Fig. 2.1. This schematic can also be seen like in Fig. 2.2. Here, instead of ports input and output impedances can be seen.

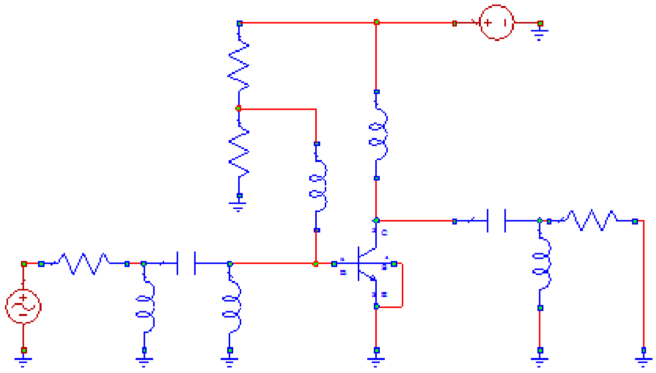

Figure 2.2 : Schematic view of a basic RF power amplifier with input and output impedances.

The power amplifier consists of DC biasing circuit, RFC (radio frequency choke), RF transistor, input and output matching circuits and 50Ω source and load impedances in most of the devices (Cripps, S.C., Advanced Techniques in RF Power Amplifier Design, 2002).

2.1 Power Amplifier Performance Parameters

Most important parameters that define an RF Power Amplifier are gain, output power, linearity, stability, DC supply voltage, efficiency, ruggedness, etc. The requirements of the PA vary depending on application. When linearity is important for some of the PA, efficiency may be important for the others. According to the application, both of them can be important sometimes. In this chapter, power amplifier parameters will be explained; then power amplifier classes will be mentioned.

2.1.1 Gain

In electronics, gain is a measure of the ability of a circuit (often an amplifier) to increase the power or amplitude of a signal from the input to the output, by adding energy to the signal converted from power supply. It may also be defined on a logarithmic scale, in terms of the decimal logarithm of the same ratio ("dB gain").

A gain greater than one (zero dB), that is, amplification, is the defining property of an active component or circuit, while a passive circuit will have a gain of less than one. An amplifier's gain may imply that either the voltage, current or the power gain. Most often this will mean a voltage gain for audio and general purpose amplifiers, especially operational amplifiers, but a power gain for radio frequency amplifiers. The small signal power gain can be described by three definitions such as transducer power gain (G_T), operating power gain (G_P) and available power gain (G_A) [Url-19]. In Fig.2.3 the G_T, G_P and G_A values can be seen:

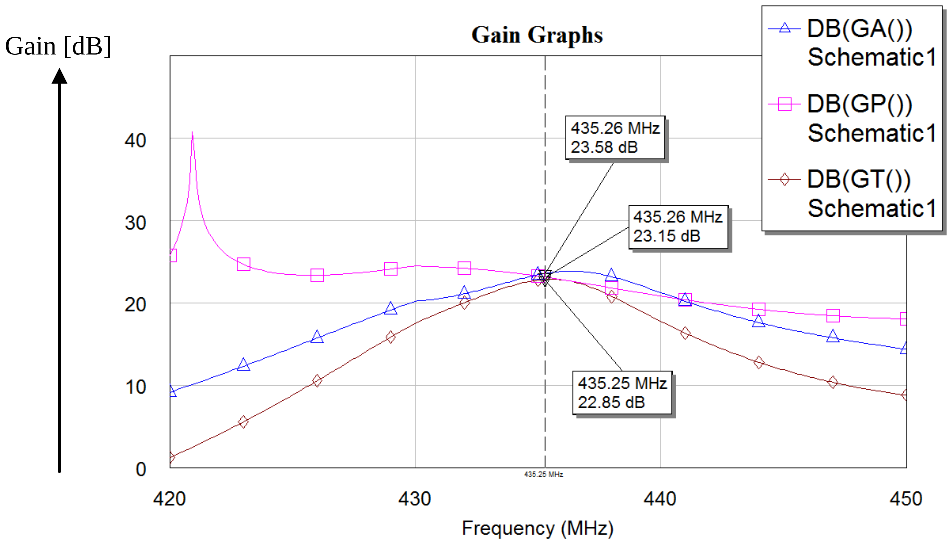

Figure 2.3 : G_T, G_P and G_A values.

In this thesis, the RF power amplifier is designed for 435.250 center frequency, as a result, the values in the graph shows at the center frequency values. Transducer power gain is the ratio of power delivered to the load to the source's available power. This is simply a measure of how much power from the source gets to the load. The transducer power gain is the most widely used gain definition for PA.

Transducer power gain is defined by:

$$G_T = \frac{Power_{Load}}{Power_{Source,max}} \tag{2.1}$$

where

- P_{Load} is the average power delivered to the load
- P_{Source} is the maximum available average power at the source

The G_T can be given with scattering parameters as:

$$G_T[dB] = 10\log|S_{21}|^2 \quad \textbf{(2.2)}$$

Operating power gain is defined by:

$$G_P = \frac{Power_{Load}}{Power_{Input}} \quad \textbf{(2.3)}$$

where

- P_{load} is the maximum time averaged power delivered to the load
- P_{input} is the time averaged power entering the network

The operating power gain is defined as the ratio of the power delivered to the load from the power input of the amplifier. The power input to the amplifier is considered instead of power available from source.

Available power gain is defined by:

$$G_A = \frac{Power_{Load,max}}{Power_{Source,max}} \quad \textbf{(2.4)}$$

The available gain is the ratio of available load power to available source power. The available power is defined as the maximum power capable of being delivered by a source to a load under conditions of conjugate matching and that available gain is only defined under conditions of conjugate matching.

In the conjugate matched conditions, all above the gain values are equal. On the other hand, it can be said that $G_P \geq G_T$ and $G_A \geq G_T$.

The saturated gain can be defined as:

$$G[dB] = P_{out}(sat)[dB] - P_{in}(sat)[dB] \quad \textbf{(2.5)}$$

It is so important that the gain of the amplifier is required to be flat over the operating frequency band.

An example of gain graph which is drawn with Microwave Office AWR Design Environment is shown in Fig. 2.4.

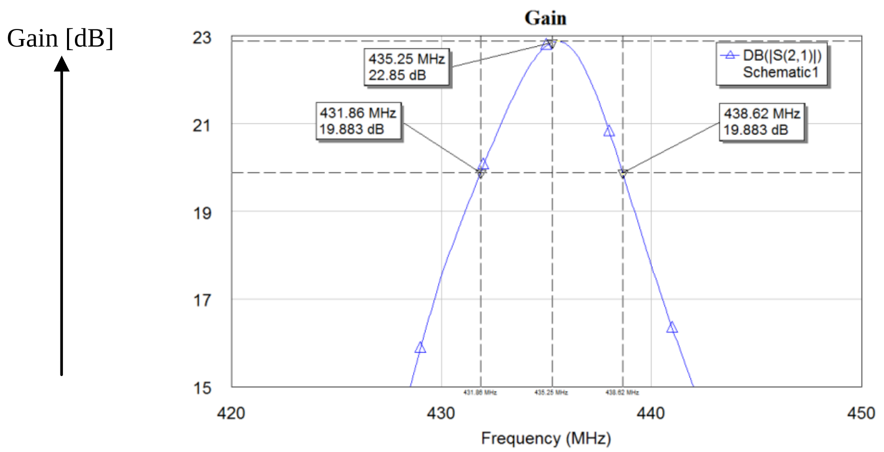

Figure 2.4 : Gain graph of a power amplifier.

2.1.2 Output power

In radio transmission, transmitter power output (TPO) is the actual amount of power (in watts) of radio frequency energy that a transmitter produces at its output. Power Amplifier's output power is the important design parameter for an amplifier. The power level is defined by the communication standards. In some of the countries, power amplifiers with extremely high output power may be illegal. Countries around the world also have different restrictions on maximum radiated power on the wireless bands so this is always worth checking with local regulatory body.

The RF power varies between manufacturers and is typically 13-30 dBm (approximately 20mW-1W). Some high power amplifiers are capable of supplying up to a few watts.

The formulas for calculating between dBm and miliwatts are shown as:

$$dBm = 10\log(mW) \qquad \textbf{(2.6)}$$

$$mW = 10^{dBm/10} \qquad \textbf{(2.7)}$$

2.1.3 Efficiency

One of the other consequential figure of merit is the efficiency for a power amplifier. Efficiency in general describes the extent to which time, effort or cost is well used for the intended task or purpose. It is often used with the specific purpose of relaying the capability of a specific application of effort to produce a specific outcome effectively with a minimum amount or quantity of waste, expense, or unnecessary effort. "Efficiency" has widely varying meanings in different disciplines. Power amplifiers are the most power consuming system. Because of consuming most of the power, the overall efficiency is determined by efficiency of power amplifier. Overall efficiency can be described simply as:

$$Overall\ efficiency = \frac{what\ you\ get}{what\ you\ pay\ for} \quad \textbf{(2.8)}$$

Drain efficiency, power added efficiency and total efficiency are the most important efficiency terms of a PA [Url-9].

2.1.3.1 Drain efficiency

Drain (or collector) efficiency is the ratio of output RF power to input DC power, both measured at the chip level (de-embedding bond wire or other terminal DC resistance). Generally drain efficiency is slightly better than overall efficiency, and is used to characterize the transistor at chip/die level.

Drain efficiency is the ratio of output power to DC power consumption:

$$Eff_{drain} = \frac{P_{out}}{P_{DC}} \quad \textbf{(2.9)}$$

Drain efficiency is a measure of how much DC power is converted to the RF power. Drain efficiency doesn't take into account the incident RF power that goes into a device. In the case of a single-stage RF amplifier, the RF input power can be substantial, because the gain is low.

2.1.3.2 Power added efficiency

The power added efficiency is defined in Eq. 2.10

$$PAE = \frac{P_{out} - P_{in}}{P_{DC}} \quad \textbf{(2.10)}$$

Power added efficiency (PAE) is similar to drain efficiency, but it takes into account the RF power that is added to the device at its input, in the numerator. The ratio of the RF power added by the power amplifier to the DC power consumption gives PAE. In the theory, the power amplifier with infinite gain will have PAE which equals to drain efficiency. For real, PAE will always be less than the drain efficiency. The difference between these efficiency terms extends as the gain of the amplifier increases. The maximum possible power added efficiency of a device always decreases with frequency. Natural tendency for maximum gain of an active device decreases with frequency too.

2.1.3.3 Total efficiency

Total efficiency, sometimes called overall efficiency as explained in the efficiency main title, gives a complete picture of the ratio of output power to both types of input power (DC and RF).

$$Eff_{Total} = \frac{P_{out}}{P_{DC}+P_{in}} \tag{2.11}$$

2.1.4 Linearity

In electronics, the linear operating region of a device, for example a transistor, is where a dependent variable (such as the transistor collector current) is directly proportional to an independent variable (such as the base current). This ensures that an analog output is an accurate representation of an input, typically with higher amplitude (amplified). A typical example of linear equipment is a high fidelity audio amplifier, which must amplify a signal without changing its waveform. For a given frequency the gain is constant in the linear region of a power amplifier. Linearity measures that how much power can be delivered to the load.

2.1.4.1 1 dB compression point

Output power is only a fixed part of the input power for a linear device such as most passive devices, connectors, cable, waveguides, etc. Nonlinear devices exhibit complex behavior when input power is compared to output power. However, most of the nonlinear devices tend to lose more with increasing input power. The gain response of device will become reduced by a specific amount at some power level. This power level is the compression point. Microwave engineers often refer to the 1-dB compression point, but 2 or 3 dB compression points are often important in PA chains. Thus we refer to the quantities P_{1dB}, P_{2dB}, P_{3dB} [Url-10].

1 dB compression point is defined as the power level for which the gain of the power amplifier drops down 1 dB with respect to the linear gain for a specific frequency. After the 1 dB compression point for an amplifier the linear operation ends. P_{1dB} (1 dB compression point) can be seen in Fig. 2.5. 1 dB compression point can be found by intersecting the actual gain easily.

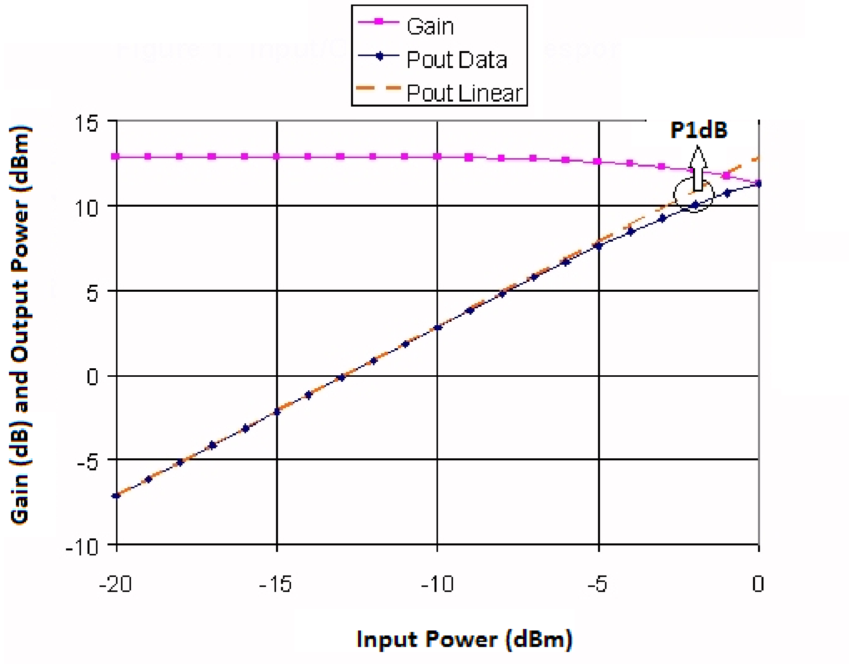

Figure 2.5 : 1 dB compression point characteristics [Url-14].

In the Fig. 2.6, P_{1dB} point can be found in another way easily. Here gain compression, normalized to small signal gain, is plotted against input power. 0.25 dB compression point may be found too. Unfortunately, P_{2dB} and P_{3dB} are out of range for this measurement.

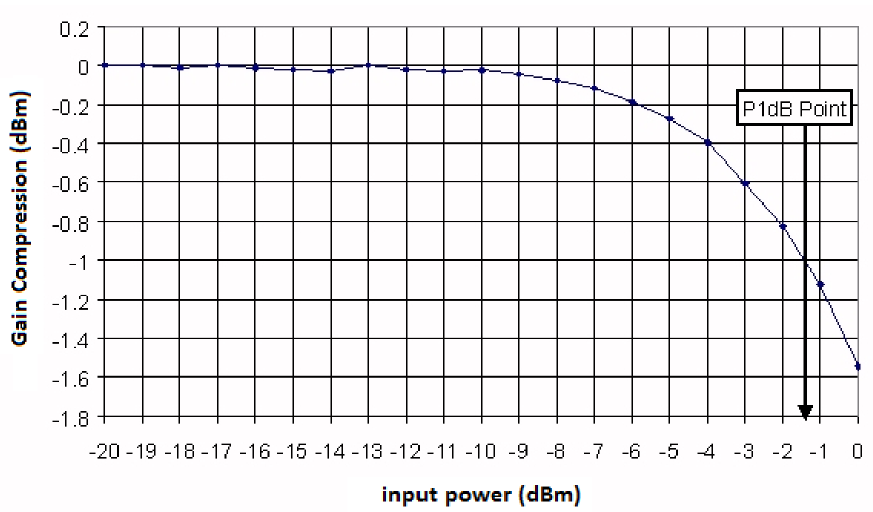

Figure 2.6 : Alternative technique for 1 dB compression point [Url-14].

2.1.4.2 Third order intercept point

Third order intercept point (IP_3) is a measure for nonlinear systems and devices, such as receivers, linear amplifiers and mixers in telecommunications. The device nonlinearity can be modeled using a low order polynomial, derived by means of Taylor series expansion. The IP_3 relates nonlinear products caused by the third order nonlinear term to the linearly amplified signal, in contrast to the second order intercept point that uses second order terms. The intercept point is mathematical concept, and does not correspond to a practically occurring physical power level.

The intercept point is obtained by plotting the output power versus the input power on logarithmic scales. Both curves are drawn; one for the linearly amplified signal at an input tone frequency, one for a nonlinear product. On a logarithmic scale, the function x^n translates into a straight line with slope of n. As a result, the linearly amplified signal will bode a slope of 1. A third order nonlinear product will increase by 3 dB in power when the input power is raised by 1 dB.

Both curves are extended with straight lines of slope 1 and 3. The intercept point is curves intersect point. It can be read off from the input or output power axis, leading to input or output intercept point. In Fig. 2.7 IP_3 can be seen.

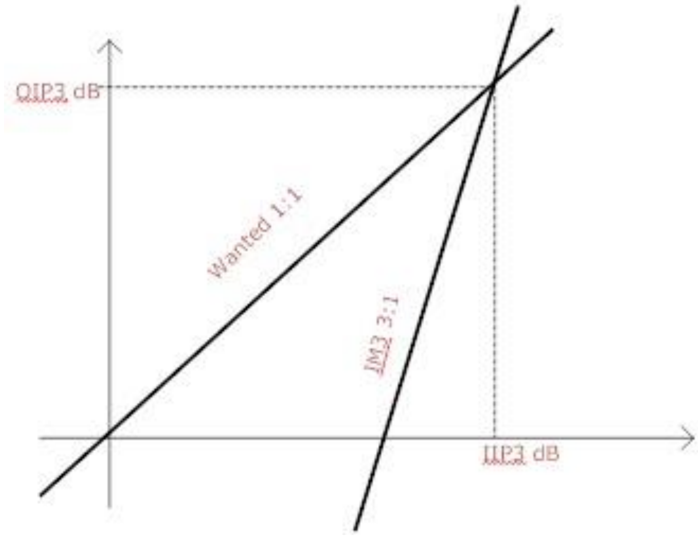

Figure 2.7 : Third order intercept point.

The IP_3 can be found by guessing the fundamental term and third order intermodulation term as given in Fig. 2.8 and the output referred third order intercept point can be given as Eq. 2.12.

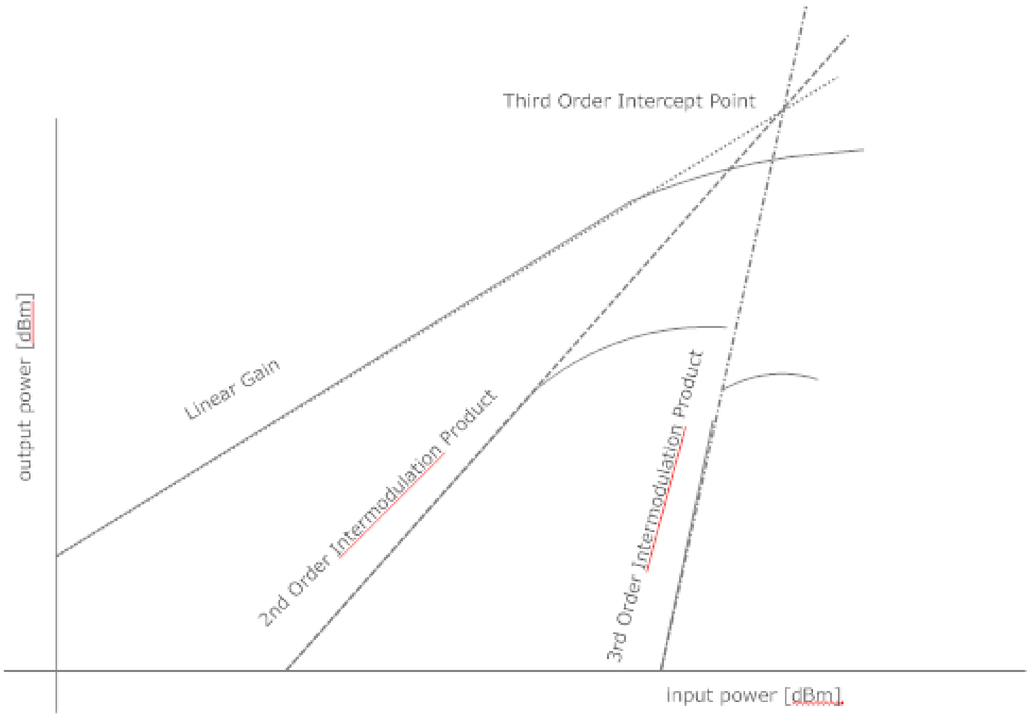

Figure 2.8 : Linear gain, second and third order intercept points.

$$OutputIP3[dBm] = P(f_1) + \frac{P(f_1) - P(IMP_3)}{2} \quad \textbf{(2.12)}$$

2.1.5 Stability

Stability is an important figure of merit to design an amplifier especially power amplifier. Oscillations in the system can be bound to happen if stability is not considered because of high gain. K factor is the most commodious stability factor to measure stability. If K factor is greater than 1, the power amplifier is stable. In this situation, input and output impedances are not important because amplifier is unconditionally stable. Some of the amplifier is conditionally stable which means the input and output impedances should be 50Ω. If the impedances values do not tuned 50Ω, the system could be unstable (Kesik, E.P. UHF Güç Kuvvetlendirici Tasarımı ve Gerçeklenimi). In Eq. 2.13, the K factor formula is given:

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{21}S_{12}|} \quad \textbf{(2.13)}$$

$$|\Delta| = |S_{11}S_{22} - S_{12}S_{21}| \quad \textbf{(2.14)}$$

K factor graph is shown in Fig. 2.9.

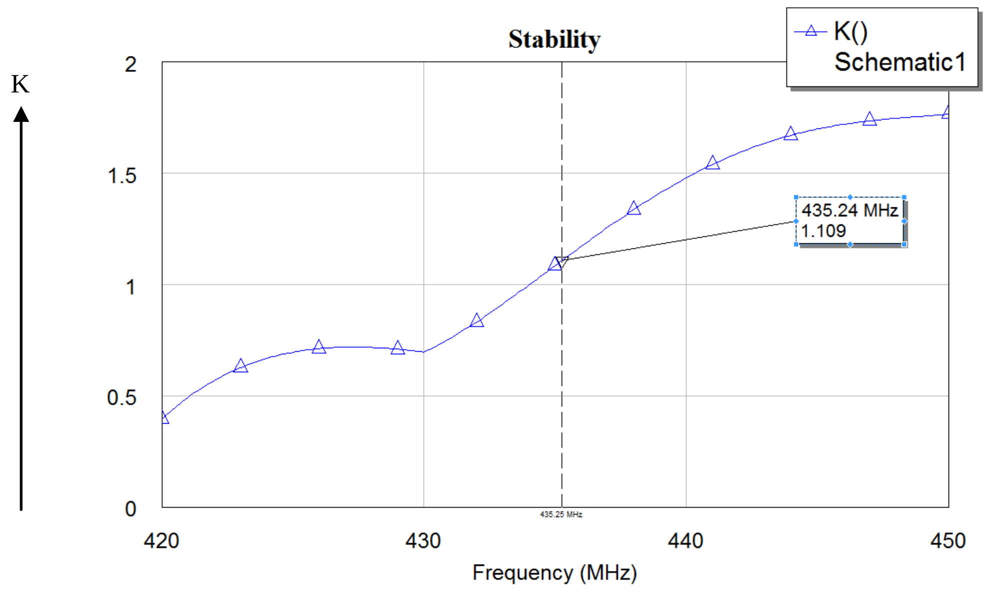

Figure 2.9 : K factor for stability analysis.

Another measure of stability is B1 factor. Microwave Office AWR Design Environment is also measure B1 factor like K factor. B1 factor should be greater than 0. B1 factor graph is shown in Fig. 2.10.

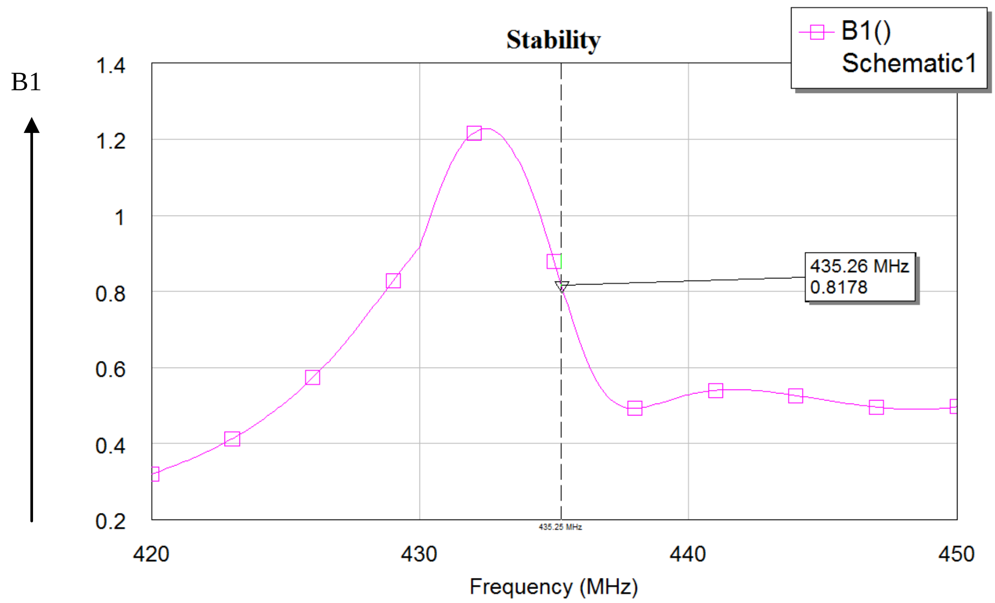

Figure 2.10 : B1 factor for stability analysis.

With stability circles which are drawn in the Smith chart is also a measure of stability. This measurement is mostly used for conditionally stable power amplifiers. The amplifier will be stable in the area between circle and the rest of the Smith chart on the side which contains the center of the Smith chart. The input stability circles and the output stability circles is shown in the Fig. 2.11 and Fig. 2.12 respectively. The Smith chart graphs are drawn between 434 MHz and 436 MHz with 0.5 MHz intervals (Kesik, E.P. UHF Güç Kuvvetlendirici Tasarımı ve Gerçeklenimi).

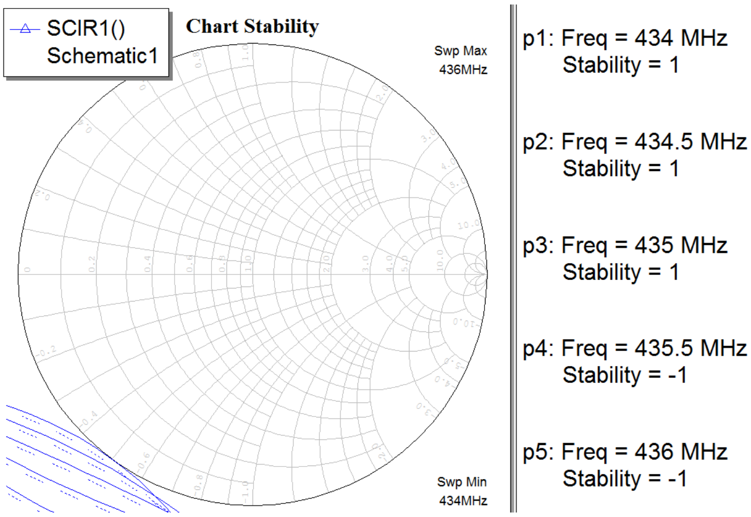

Figure 2.11 : The input stability circles.

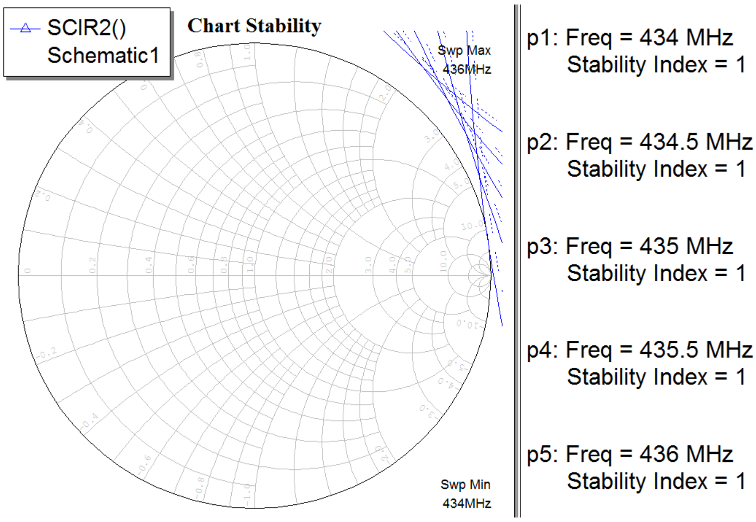

Figure 2.12 : The output stability circles.

2.1.6 DC supply voltage

DC Supply voltage is another important substance to design an amplifier. The higher supply voltage is being, the higher the cost of the system gets. It should be tuned according to the power amplifier needs especially transistors. DC supply voltage which is 5V can be seen in Fig. 2.13.

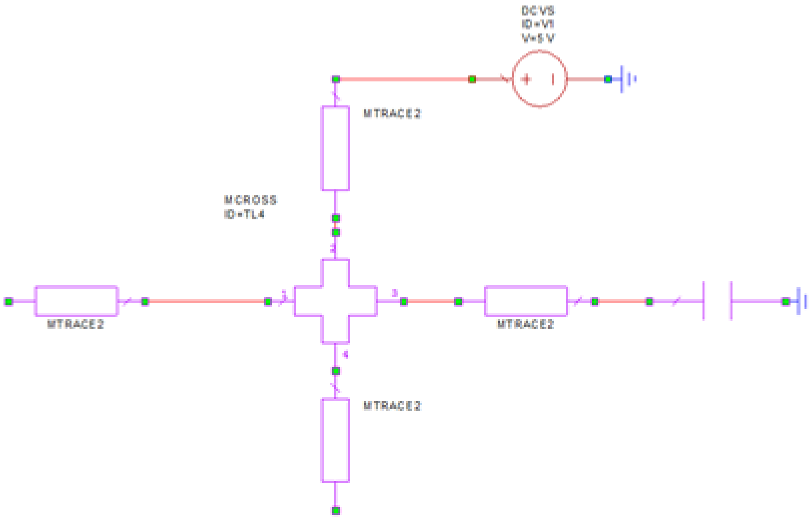

Figure 2.13 : DC supply voltage.

2.1.7 Ruggedness

Ruggedness is a cardinal metric in high power radio frequency amplifier designs. Not only providing great performance characteristics about gain, output power and efficiency, but also sustaining that performance for more than 10 years in the area is expected by radio frequency power amplifiers. Generally, designers have built amplifiers using components fabricated in cost-effective silicon-based technologies while these technologies can operate at high voltages; they suffer from low ruggedness ratings.

The ability of the RF power transistor to stand load mismatch conditions under high output power conditions can be referred as ruggedness. Under this mismatched load conditions, a lot of power can be fed back into the active device where it is dissipated in the semiconductor. The ability to handle this large power dissipation internally in the active area without altering the performance of system shows that PA is reliable device. The ruggedness of a specific transistor is typically a function of the magnitude and phase of the mismatch, the output power level conditions, and the thermal dissipation properties of the power amplifier.

2.1.8 Error vector magnitude

The error vector magnitude (EVM) is a measure which can be used to quantify the performance of digital radio transmitter or receiver. A signal sent by an ideal transmitter or received by a receiver would have all constellation points precisely at the ideal locations; however various imperfections in the implementation cause the actual constellation points to deviate from the ideal locations. Informally, EVM is a measure of how far the points are from the ideal locations. In other words, it is the difference between actual received symbols and ideal symbols. The error vector magnitude (EVM) is equal to the ratio of the power of the error vector (in RMS) to power of the reference (in RMS).

$$EVM(dB) = 10\log\left(\frac{P_{error}}{P_{reference}}\right) \quad \textbf{(2.15)}$$

In Fig. 2.14 error vector magnitude is shown.

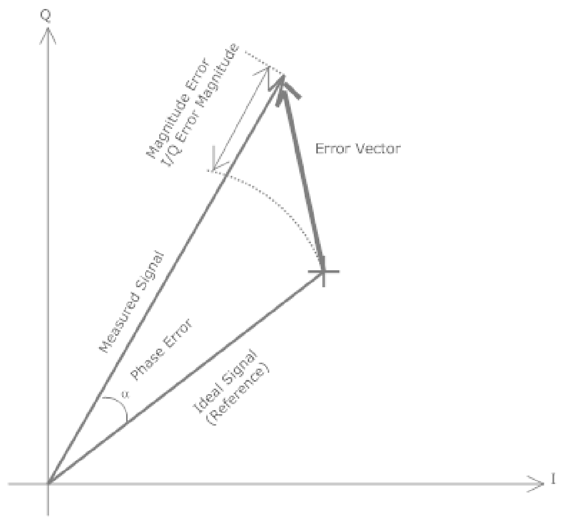

Figure 2.14 : Error vector magnitude.

The nonlinear PA cause deterioration in digital modulation systems and it can also produce distortion in phase and amplitude, consequently, a distorted constellation diagram occurs.

2.1.9 Adjacent channel power ratio

Adjacent Channel Power Ratio (ACPR) is a measurement of the amount of interference, or power, in the adjacent frequency channel. ACPR is usually defined as the ratio of the average power in the adjacent frequency channel to the average power in the transmitted frequency channel. It is a critical measurement for code division multiple access (CDMA) transmitters and their components. ACPR describes the amount of distortion generated due to nonlinearities in RF components. In the other words, the adjacent channel power ratio is between the total power adjacent channel (intermodulation signal) to the main channel's power (useful signal) [Url-12].

2.1.10 Distortion

To operate correctly without any distortion to the output signal for a signal amplifier, it requires some form of DC bias on its base or gate terminal; as a result, it can amplify the input signal over its entire cycle with the bias "Q-point (quiescent point)" set as near to the middle of the load line [Url-13].

The power, voltage or current gain amplification provided by the amplifier is the ratio of the peak output value to its peak input value. However, if we incorrectly design our amplifier circuit and set the biasing Q-point at the wrong position on the load line or apply too large an input signal to the amplifier, the resultant output signal may not be an exact reproduction of the original input signal waveform. In other words the amplifier will suffer from distortion. The common emitter amplifier circuit distortion is shown in the Fig. 2.15. (Intermodulation Distortion, *Aeroflex Application Note, Issue 2*, 2004)

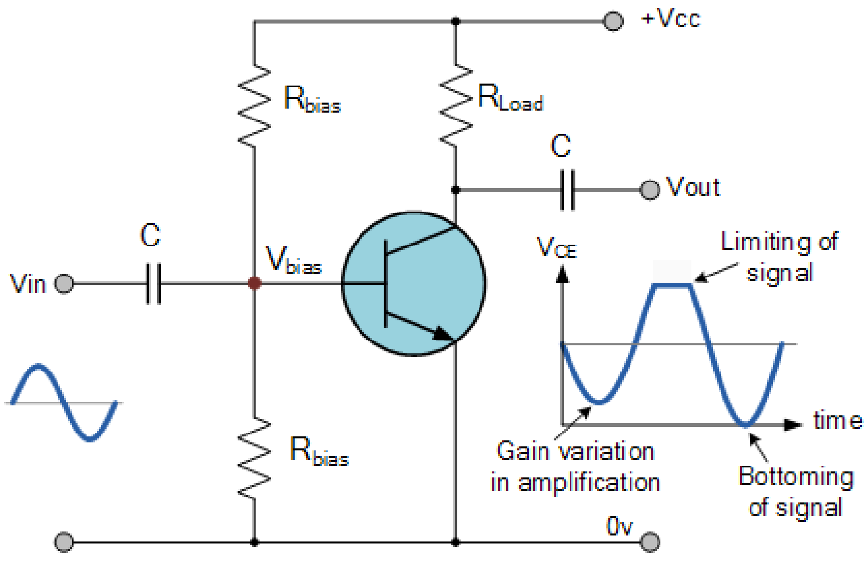

Figure 2.15 : Amplifier circuit distortion [Url-6].

The reason of the distortion of the output signal is:

- Amplification may not be taking place over the all signal cycle due to incorrect biasing.
- The input signal may be too large, causing the amplifier to be limited by the supply voltage.

- The amplification may not be linear over the entire frequency range of inputs.

All of these explanations mean some form of amplifier distortion has occurred.

2.1.10.1 Amplitude distortion

Amplitude distortion occurs when the peak values of the frequency waveform are attenuated causing distortion due to a shift in the Q-point and amplification may not take place over the whole signal cycle. This non-linearity of the output waveform is shown in Fig. 2.16:

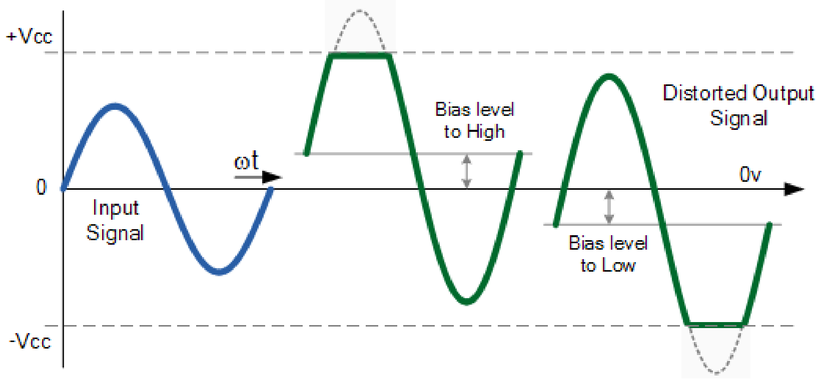

Figure 2.16 : Amplitude distortion due to incorrect biasing [Url-6].

2.1.10.2 Frequency distortion

Frequency Distortion occurs in a power amplifier when the level of amplification varies with frequency. The input signals that an amplifier will amplify consist of the required signal waveform called the "fundamental frequency" plus a number of different frequencies called "harmonics". Normally, the amplitude of these harmonics are a fraction of the fundamental amplitude and therefore have very little or no effect on the output waveform. However, the output waveform can become distorted if these harmonic frequencies increase in amplitude with regards to the fundamental frequency [Url-13]. For example, Fig 2.17:

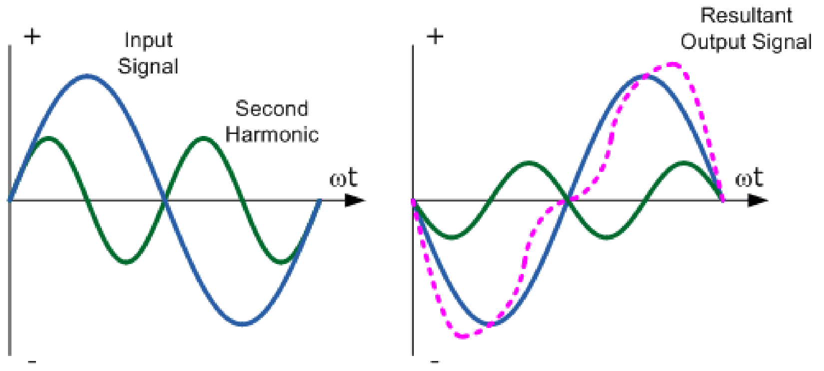

Figure 2.17 : Frequency distortion due to harmonics [Url-6].

2.1.10.3 Phase distortion

Phase Distortion occurs in a nonlinear power amplifier if there is a time delay between the input signal and its appearance at the output. This time delay will depend on the construction of the PA and will increase progressively with frequency within the BW (bandwidth) of the PA. For example, Fig.2.18:

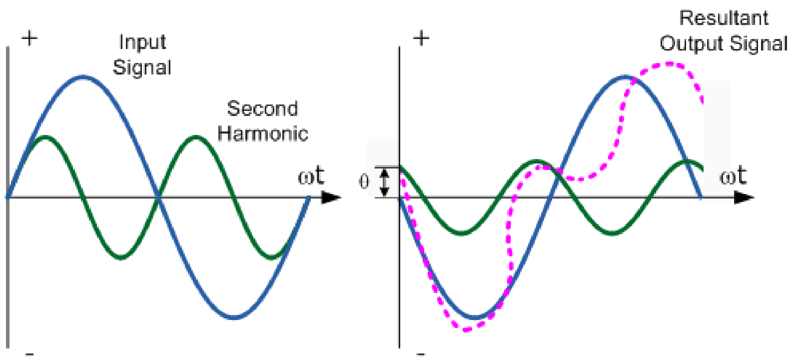

Figure 2.18 : Phase distortion due to delay [Url-6].

2.1.10.4 Intermodulation distortion

Intermodulation distortion (IMD) is a common problem in a variety of areas of electronics. In RF communications, it represents a difficult challenge to designers who face tougher requirements on component and sub system linearity. IMD is the result of two or more signals interacting in a nonlinear device to produce additional unwanted signals. These additional signals occur mainly in devices such as amplifiers and mixers, they also occur in passive devices. For example, RF connectors on transmission feeds may become corroded over time resulting in them behaving as nonlinear diode junctions. In Fig.2.19 the higher order intermodulation products are shown:

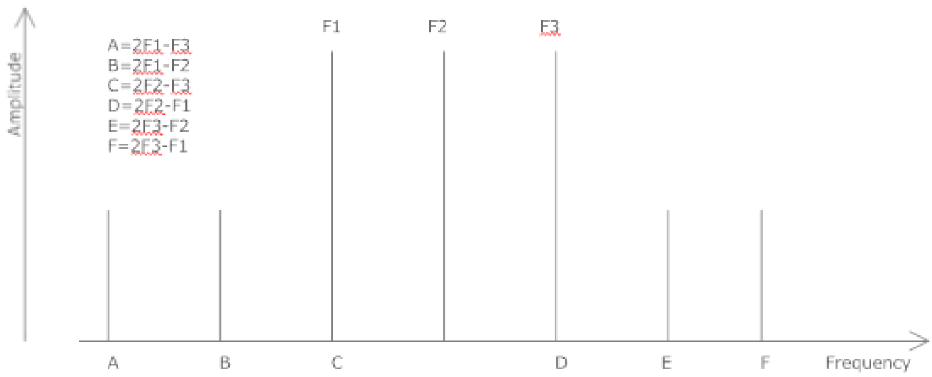

Figure 2.19 : Three tone intermodulation products.

In Fig.2.20 two tone intermodulation products are shown. Here the third order intermodulation products ($2f_1 - f_2$ *and* $2f_2 - f_1$) are really critical products because they are the closest products to the fundamental products (f_1 *and* f_2). It is very hard to eliminate them from the pass band.

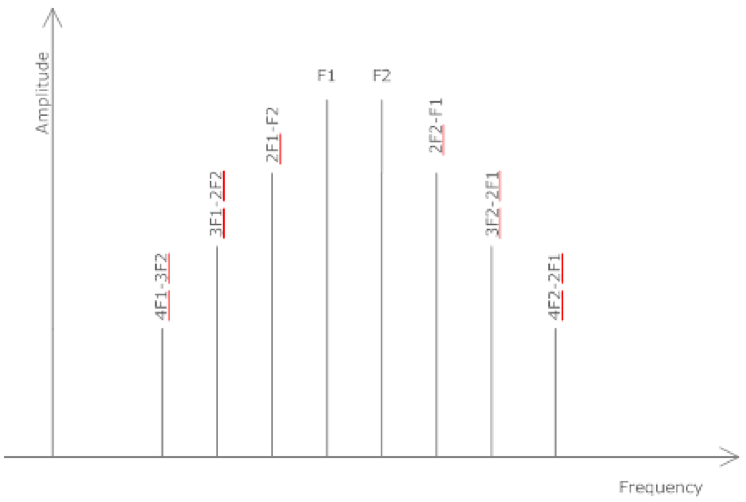

Figure 2.20 : Two tone intermodulation products.

2.1.10.5 Total harmonic distortion

The total harmonic distortion (THD) is defined as the ratio of the sum of whole harmonic components powers to power of the fundamental.

$$THD = \frac{\sum P_{total\ harmonic}}{P_{fundamental\ frequency}} = \frac{P_2+P_3+\cdots+P_n}{P_1} \quad \textbf{(2.16)}$$

The total harmonic distortion is generally expressed in dB or in percent. It is used for distortion attenuation or distortion factor, respectively.

2.2 S Parameters

S-parameters refer to the scattering matrix. The scattering matrix is a mathematical construct that quantifies how RF energy propagates through a multi-port network. A multi-port network can be seen in Fig. 2.21.

For an RF signal incident on one port, some fraction of the signal bounces back out of that port, some of it scatters and exits other ports and some of it disappears as heat or even electromagnetic radiation [Url-14].

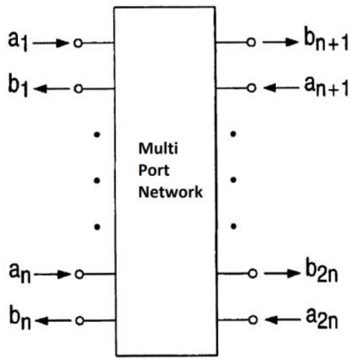

Figure 2.21 : A multi-port network.

S-parameters are complex and have magnitude and angle because both the magnitude and phase of the input signal are changed by the network. Most of the time, magnitude is main consideration. The important topic in here is that how much the gain loss than can be achieved. S-parameters are defined for a given frequency and system impedance, and vary as a function of frequency for any non-ideal network.

For the S-parameter subscripts “ij”, j is the input port, and “i” is the output port. Thus S_{11} refers to the ratio of signal that reflects from port 1 for a signal incident on port 1. Parameters along the diagonal of the S-matrix are referred to as reflection coefficients because they only refer to what happens at a single port, while off-diagonal S-parameters are referred to as transmission coefficients, because they refer to what happens from one port to another. In Fig. 2.22 two port network is shown as:

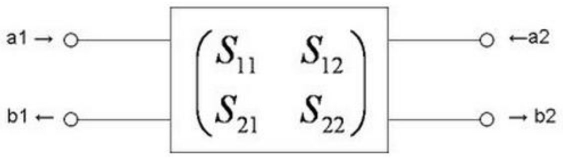

Figure 2.22 : Two port network.

The following gives the S-matrices for one, two and three-port networks:

$(S_{11}) \longrightarrow$ for one port network

$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \longrightarrow$ for two port network

$\begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \longrightarrow$ for three port network

S-parameters describe the response of an n-port network to voltage signals at each port. If we assume that each port is terminated in impedance Z_0, we can define the four S-parameters of the 2-port as:

$$S_{11} = \frac{b_1}{a_1} \quad \textbf{(2.17)}$$

$$S_{12} = \frac{b_1}{a_2} \quad \textbf{(2.18)}$$

$$S_{21} = \frac{b_2}{a_1} \quad \textbf{(2.19)}$$

$$S_{22} = \frac{b_2}{a_2} \quad \textbf{(2.20)}$$

S_{21} means the response at port 2 due to a signal at port 1. In Eq. 2.21, the matrix algebraic representation of 2-port S-parameters is shown:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \times \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \quad \textbf{(2.21)}$$

In order to measure S_{11}, a signal is given at port 1 and measure its reflected signal again port 1. In this case, no signal is given into port 2, so a_2=0. We only inject one signal at a time. In order to measure S_{21}, the signal is given at port 1, and measure the resulting signal exiting port 2. In order to measure S_{12}, the signal is given into port 2, and measure the signal leaving port 1, and for S_{22}, the signal is given at port 2 and measure its reflected signal at port 2 [Url-15].

The meanings of the S parameters:

- S_{11} is the input port voltage reflection coefficient.
- S_{12} is the reverse voltage gain.
- S_{21} is the forward voltage gain.
- S_{22} is the output port voltage reflection coefficient.

S parameters can also be measured in dB. Eq. 2.22 shows us how to convert magnitude to dB.

$$S_{ij}[dB] = 20\log S_{ij}[Magnitude] \quad \textbf{(2.22)}$$

The S-parameters are members of a family of similar parameters such as Y-parameters, Z-parameters, H-parameters, T-parameters or ABCD-parameters. Most commonly usage is on S-parameters. They differ from these, in the sense that S-parameters do not use open or short circuit conditions to characterize a linear electrical network; instead, matched loads which are much easier to use at high signal frequencies are used. Moreover, the quantities are measured in terms of power.

S-parameters can express most of the components electrical properties like inductors, capacitors, resistors, transistors, etc. These properties are gain, return loss, voltage standing wave ratio (VSWR), reflection coefficient and amplifier stability, etc. In Fig. 2.23 Gain is obtained with S-Parameters and Transducer power gain formula with Microwave Office AWR Design Environment.

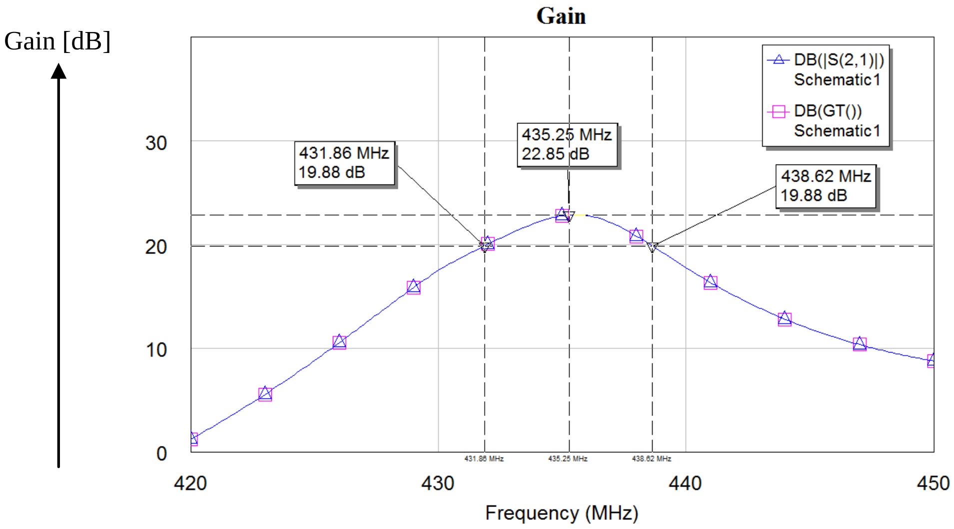

Figure 2.23 : Gain with G_T and S_{21}.

S-parameters are commonly used for network systems operating at RF and microwave frequencies where signal power and energy considerations are more easily quantified than currents and voltages. Because of changing with the measurement frequency, S-parameter measurements are different for each frequency, in addition to the characteristic impedance or system impedance.

The following information must be defined when specifying a set of S-parameters:

- The frequency
- The characteristic impedance (often 50Ω)
- The allocation of port numbers
- Conditions, such as temperature, control voltage, and bias current.

2.2.1 Types of S parameters

Small signal S-parameters are mostly used and nearly have same meaning with S parameters for electronics engineers. By small signal S-parameters, the signals have only linear effects on the network. Small signal S-parameters is enough for passive networks, because of acting linearly at any power level.

Large signal S-parameters are more complicated. In this case, the S- parameters will vary with input signal strength.

Mixed-mode S-parameters refer to a special case of analyzing balanced circuits. Pulsed S-parameters are measured on power devices; consequently, an accurate representation is captured before the device heats up.

2.2.2 Reciprocity

If the network is passive and it contains only reciprocal materials the network will be reciprocal such as attenuators, cables, splitters and combiners. For this situation, the S-parameter matrix will be equal to its transpose ($S_{ij} = S_{ji}$). Networks which include non-reciprocal materials such as those containing magnetically biased ferrite components or an amplifier will be non-reciprocal.

2.2.3 Lossless and lossy networks

If a network does not dissipate any power, it is called a lossless network. The sum of the incident powers at all ports is equal to the sum of the reflected powers at all ports.

$$\sum|a_n|^2 = \sum|b_n|^2 \tag{2.23}$$

Lossless networks are only in the simulation programs and cannot be realize in the real world.

$$\sum|a_n|^2 \neq \sum|b_n|^2 \tag{2.24}$$

A lossy passive network is one in which the sum of the incident powers at all ports is greater than the sum of the reflected powers at all ports.

$$\sum|a_n|^2 > \sum|b_n|^2 \tag{2.25}$$

2.2.4 Insertion loss

If the two measurement ports use the same reference impedance i.e. 50Ω, the insertion loss (IL) is the dB expression of the transmission coefficient. IL can be given by:

$$IL = -20\log|S_{21}|\,[dB] \quad \textbf{(2.26)}$$

The extra loss can be introduced by mismatch or intrinsic loss. In case of extra loss the insertion loss is defined to be positive.

2.2.5 Input return loss

Input return loss (RL_{input}) is a scalar measurement and expressed in logarithmic magnitude. It measures that closeness of actual input impedance of the network to the nominal system impedance.

$$RL_{input} = |20\log|S_{11}||[dB] \quad \textbf{(2.27)}$$

The lower input return loss provides the higher performance for the power amplifier system. If the S_{11} parameter is low, loss of the amplifier will be low. In Fig.2.24 the power amplifier's S_{11}graph is shown. According to the S_{11} value, RL_{input} can be calculated by the following:

$$RL_{input} = |20\log|-11.69||[dB] = 21.36[dB] \quad \textbf{(2.28)}$$

In this thesis the power amplifier is designed for 435.250 MHz, consequently, the value for 435.250 MHz is considered for the calculations.

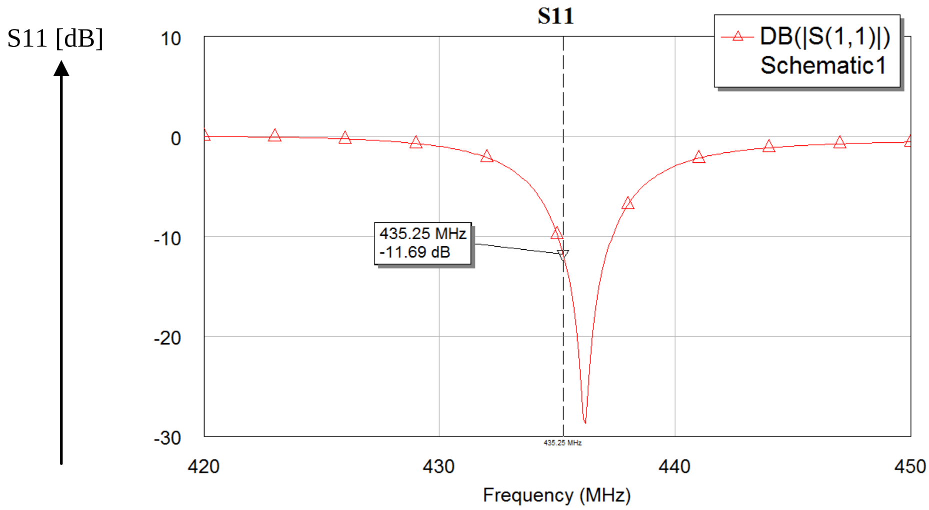

Figure 2.24 : The power amplifier's S_{11} graph.

For an RF power amplifier, if S_{11}value is under -8 dB, the amplifier has very small input return loss. In this design S_{11} is -11.69 dB.

2.2.6 Output return loss

The output return loss (RL_{output}) is a scalar measurement and expressed in logarithmic magnitude. RL_{output} is applied to the output port instead of the input port. It can be given by:

$$RL_{output} = |20\log|S_{22}||[dB] \qquad \textbf{(2.29)}$$

The lower output return loss provides the higher performance for the power amplifier system. If the S_{22} parameter is low, loss of the amplifier will be low. In Fig.2.25 the power amplifier's S_{22} graph is shown. According to the S_{22} value, RL_{output} can be calculated by the following:

$$RL_{output} = |20\log|-8.206||[dB] = 18.29[dB] \qquad \textbf{(2.30)}$$

In this thesis the power amplifier is designed for 435.250 MHz, consequently, the value for 435.250 MHz is considered for the calculations.

For an RF power amplifier, if S_{22}value is under -8 dB, the amplifier has very small output return loss. In this design S_{22} is -8.206 dB.

In Fig.2.26 the power amplifier's S_{11} and S_{22} graphs are shown together.

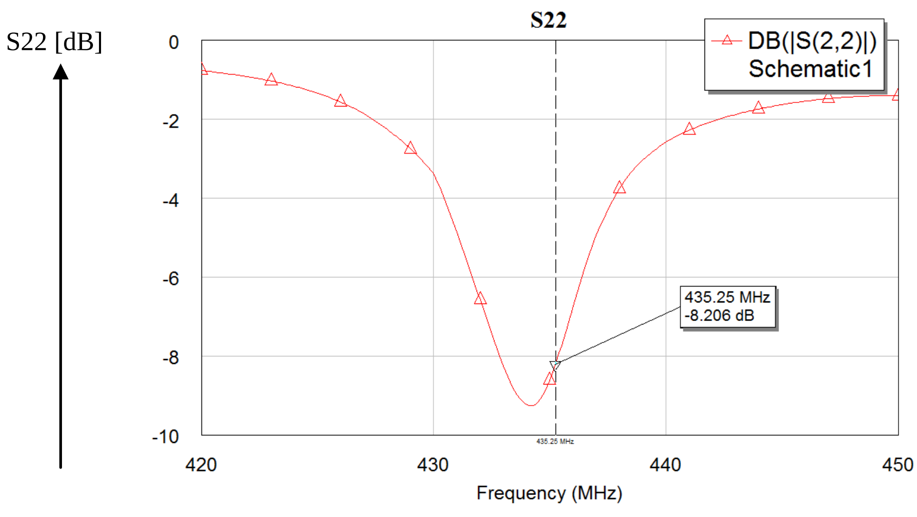

Figure 2.25 : The power amplifier's S_{22} graph.

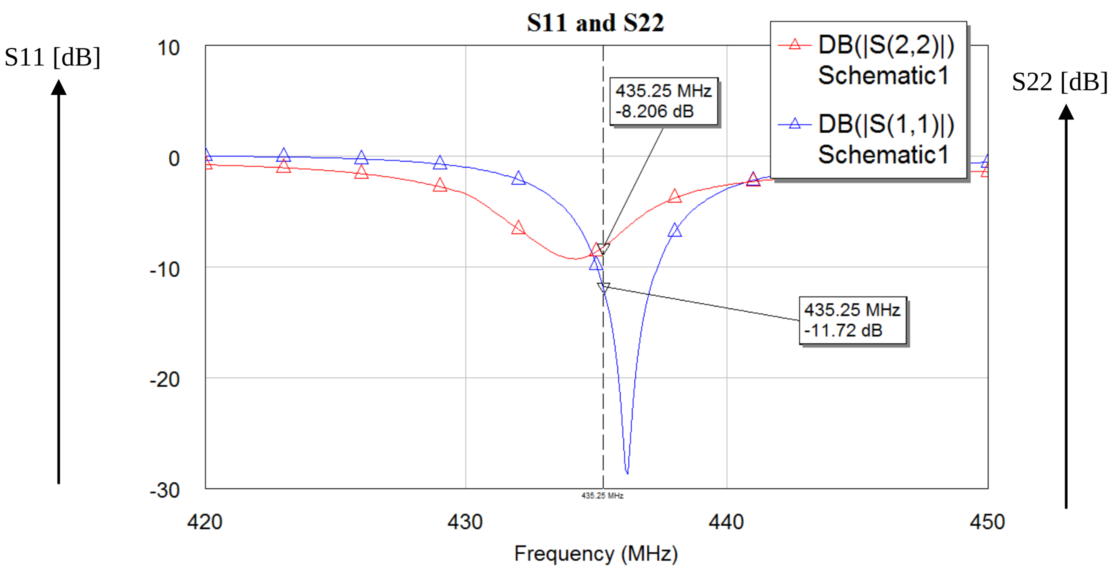

Figure 2.26 : The power amplifier's S_{11} and S_{22} graphs.

2.2.7 Reverse gain and reverse isolation

The reverse gain (g_{rev}) is a logarithmic measurement and expressed in dB. It is measured by S_{12}.

$$g_{rev} = 20\log|S_{12}|\ [dB] \tag{2.31}$$

The reverse gain is often given in magnitude version and it is called reverse isolation.

$$I_{rev} = |g_{rev}| = |20\log|S_{12}||[dB] \tag{2.32}$$

In Fig. 2.27 S_{12} is given:

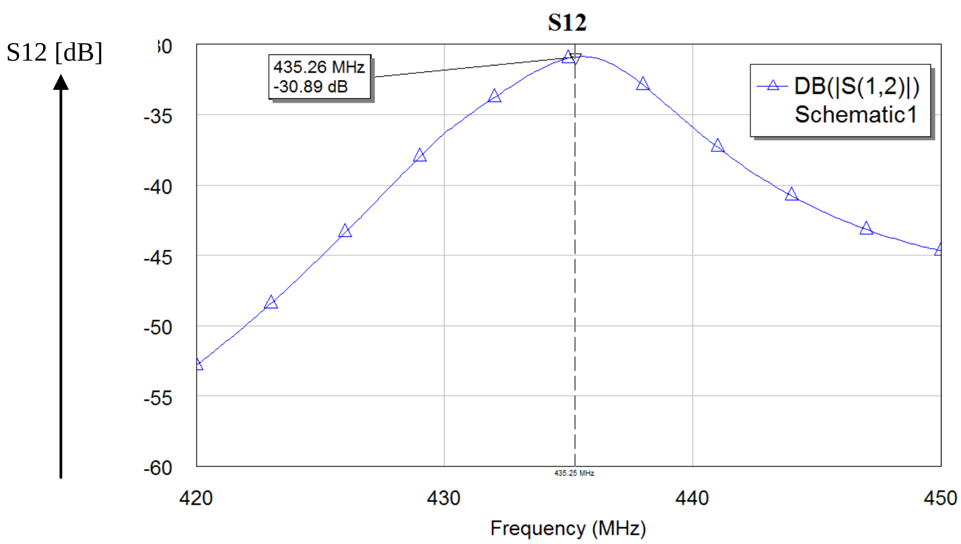

Figure 2.27 : The power amplifier's S_{12} graph.

According to Eq.2.31 and Eq.2.32: g_{rev} = 29.79 dB and I_{rev} = 29.79 dB, too.

$$I_{rev} = |g_{rev}| = |20\log|-30.89||[dB] = 29.79\ [dB] \quad \textbf{(2.33)}$$

In this thesis the power amplifier is designed for 435.250 MHz, consequently, the value for 435.250 MHz is considered for the calculations.

S_{12} is always the smallest one. As a result, reverse gain and reverse isolation are the smallest values in the system. Because there is no input signal in the port 2 and there is no output signal except the reflections in the port 1.

If the S_{12}value is under -30 dB, it will be a great design for an RF power amplifier. In this thesis, S_{12} is -30.89 dB so that the amplifier nearly has no reverse gain.

2.2.8 Reflection coefficient

The reflection coefficient is used in physics, electrical and electronics engineering while wave propagation in a medium containing discontinuities is considered. A reflection coefficient describes either the amplitude or the intensity of a reflected wave. The reflection coefficient is closely related to the transmission coefficient.

In electronics, the reflection coefficient (Γ) is the ratio of the amplitude of the reflected wave (E^-) to the amplitude of the incident wave (E^+) [Url-18].

$$\Gamma = \frac{E^-}{E^+} \quad \textbf{(2.34)}$$

According to the circuit properties reflection coefficients can be given in other terminations. If $Z_S$is the source impedance and $Z_L$is the load impedance, reflection coefficient can be given as Eq.2.35. Z_S and Z_L are showed in Fig.2.28.

$$\Gamma = \frac{Z_L - Z_S}{Z_L + Z_S} \quad \textbf{(2.35)}$$

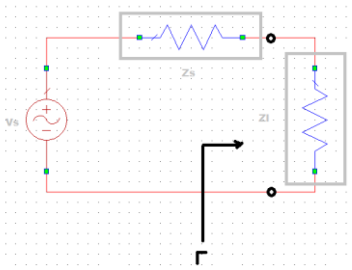

Figure 2.28 : Simple circuit configuration showing measurement location of reflection coefficient.

2.2.8.1 Voltage reflection coefficient

The voltage reflection coefficient is (ρ_{in}) at the input port and (ρ_{out}) at the output port. They are equivalent to $S_{11}\ and\ S_{22}$ and respectively. Voltage reflection coefficients are complex quantities and can be represented on polar diagrams or Smith Charts.

$$\rho_{in} = S_{11} \text{ and } \rho_{out} = S_{22} \tag{2.34}$$

2.2.9 Standing wave ratio

In electronics, standing wave ratio (SWR) is the ratio of the amplitude of a partial standing wave at a maximum node to the amplitude at a minimum node. Standing Wave Ratio is used for an efficiency measure for transmission lines (TL), electrical cables that conduct radio frequency signals, used for purposes such as connecting radio transmitters and receivers with their antennas, and distributing cable television signals.

The impedance mismatches in the cable tend to reflect the radio waves back toward the source end of the cable which is really great problem with TL. SWR measures the relative size of these reflections. An ideal transmission line would have an SWR of 1:1, with all the power reaching the destination and there is no reflected power. The SWR of a transmission line can be measured with an instrument called an SWR meter, and checking the SWR is a standard part of installing and maintaining transmission lines.

The absolute magnitude of the reflection coefficient can be calculated from the SWR.

$$|\Gamma| = \frac{SWR-1}{SWR+1} \tag{2.35}$$

2.2.9.1 Voltage standing wave ratio

The SWR is usually defined as a voltage ratio called the VSWR (voltage standing wave ratio). $|\Gamma|$ is enough to calculate the VSWR. Let's say, $\rho = |\Gamma|$.

$$\rho = \frac{SWR-1}{SWR+1} \tag{2.36}$$

$$VSWR = \frac{1+\rho}{1-\rho} \tag{2.37}$$

Γ can be -1, +1, 0 or between -1 and +1.

- $\Gamma = -1$: maximum negative reflection, when the line is short-circuited,
- $\Gamma = 0$: no reflection, when the line is perfectly matched,
- $\Gamma = +1$: maximum positive reflection, when the line is open-circuited.

According to Γ, ρ can be [0,1]. As a result, VSWR is always≥ 1. In Fig. 2.29 VSWR of the power amplifier is shown:

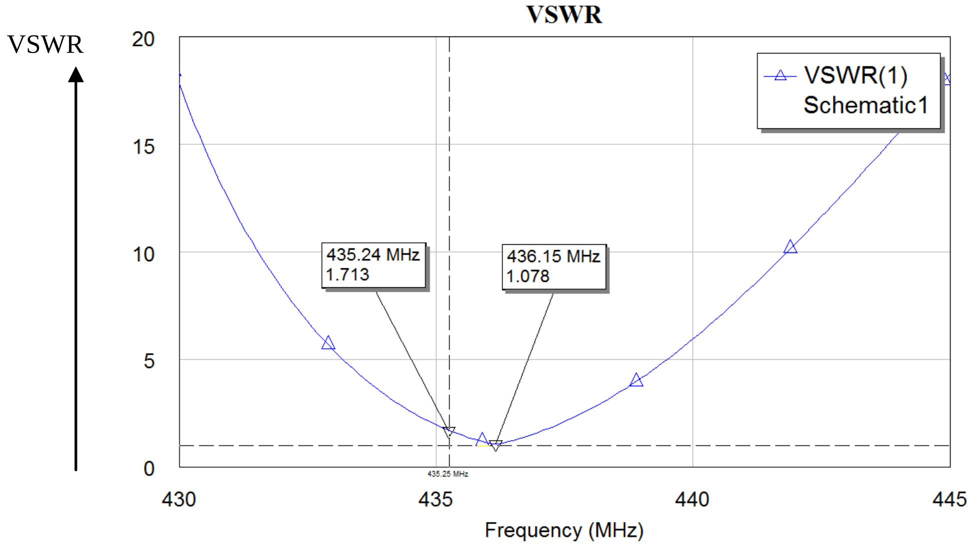

Figure 2.29 : VSWR of the power amplifier.

It is also possible to define the SWR in terms of current as ISWR (current standing wave ratio) or in terms of power as PSWR (power standing wave ratio) which is defined as the square of the VSWR.

2.2.10 S parameters values for RF power amplifier of the thesis

In Table 2.1, the S parameter values are given for the RF power amplifier:

Table 2.1 : The S parameter values for the RF power amplifier

S Parameter	Value [dB]
S_{11}	-11.69
S_{12}	-30.89
S_{21}	22.85
S_{22}	-8.206

In Fig. 2.30, the S parameters graph is shown together:

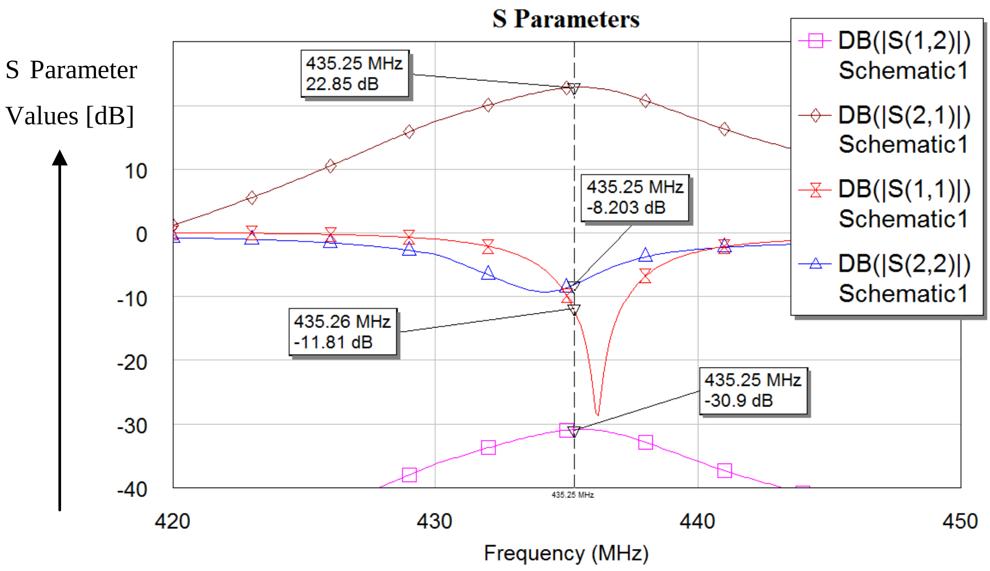

Figure 2.30 : The S parameters graph.

2.3 Classes of Power Amplifiers

There are so many power amplifier classes such as Class A, AB, B, C, D, E, F and Class G, etc. Some of the classes are used for linearity and some of them are used for efficiency. The designers choose the class that they would like to use according to wishes. If the linearity is important for an RF power amplifier, most of the time Class A power amplifier is chosen. On the other hand, if linearity is not so important but efficiency is very important, Class E power amplifier can be chosen. Linearity decreases and efficiency increases while going from Class A amplifier to Class F amplifier (Vendelin, G.D., Design of Amplifiers and Oscillators by the S-Parameter Method, 1982).

Power amplifier classes may be separated by their operating mode such as linear RF power amplifiers and non-linear RF power amplifiers as mentioned the previous paragraph. The non-linear RF power amplifiers can be called switching mode RF power amplifiers (Kenington, P.B., High Linearity RF Amplifier Design, 2000).

Class A, AB, B and C can be classified for linear amplifiers and they work in linear mode. The output signal is a linear multiplication of the input signal for this kind of power amplifier. The efficiency drops dramatically in this group of amplifier (Cripps, S.C., Advanced Techniques in RF Power Amplifier Design, 2002).

Class D, E and F are non-linear power amplifiers. The efficiency improves for this group of amplifier but the output signal is not the linear multiplication of the input signal because of nonlinearities.

The topology determines the class of amplifier. The bias conditions and the input signal is the important measure for choosing the class. If a designer wants to design an amplifier for modulated signals, he/she has to choose linear power amplifier classes. The designer can not choose switching mode power amplifier for this mission.

The bias points of an RF power amplifier may determine the level of performance as mentioned before with that PA. By comparing PA bias approaches, bias conditions can evaluate the tradeoffs for: output power, efficiency, linearity, etc.

The transistor’s active region (base biasing) is extremely important to decide the class. Base bias voltage added to the input signal allowed the transistor to reproduce the full input waveform at its output with lossless of signal. However, by altering the position of this base bias voltage, it is possible to operate the power amplifier in an amplification mode. With the introduction to the amplifier of a base bias voltage, different operating ranges and modes of operation can be obtained which are categorized according to their classification.

None class of the class operation is "better" or "worse" than any other class with the type of operation being determined by the use of the amplifying circuit.

In this thesis, the power amplifier is designed in Class A power amplifier. The other classes will be explained but Class A will be emphasized more than the other classes. The graphs and schematics will be given in the thesis in detail.

2.3.1 Class A power amplifier

Class A power amplifiers are used for linearity amplifications. They are usually biased like small signal amplifiers and they nearly have no distortion. The transistor(s) in the Class A power amplifier design is always biased on during the amplification (Kenington, P.B., High Linearity RF Amplifier Design, 2000).

Class A amplifier is the most linear power amplifier class in all PA classes. If linearity is important design parameter for the application, this class may be chosen. On the other hand, the efficiency is the lowest design parameter in this class.

The Class A power amplifier gives the constant multiply of input signal at the output as all linear amplifier.

$$V_{output} = A \, . V_{input} \quad \textbf{(2.38)}$$

In Eq.2.37, A is a constant gain of application.

As mentioned in the main heading which is "Classes of Power Amplifiers" before, the operating point decides the amplifier class. Here, for Class A, the operating point (bias condition) is in the linear region, as a result, the amplifier is linear.

Conduction angle is also a consequential figure of merit for RF power amplifiers. The conduction angle is 360^o (2π) for Class A power amplifier. The 360^o conduction angle means the transistor in the output stage conduct for the full cycle of the input signal. In Fig.2.31, output current of the amplifier is shown.

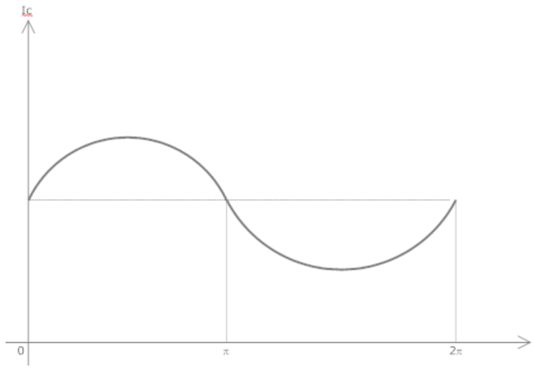

Figure 2.31 : The output current of the amplifier.

None of the transistor can be perfectly linear but the transistor that is used for Class A power amplifier is the most linear one.

The purpose of class A bias is to make the amplifier fairly free from distortion by keeping the signal waveform out of the region between 0V and about 0.7V where the transistor's input characteristic is nonlinear as shown in Fig.2.32.

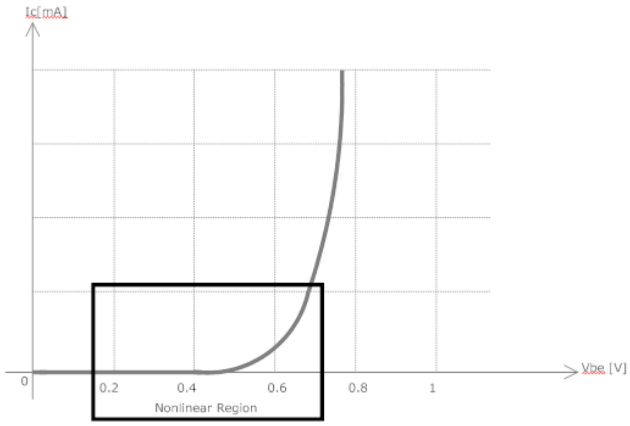

Figure 2.32 : Transistor's nonlinear region.

The Class A power amplifiers are good for linearity but their output power is not high. The output power is theoretically 50%, but practically only about 10 to 30%, compared with the DC power supply.

To achieve high linearity and gain, the amplifier's bias conditions should be chosen properly so that the amplifier operates in the linear region. Because of working in the linear region, the amplifier conducts at all times and it is conducting current all the time. Consequently, there is a continuous loss of power in the PA. This continuous loss of power makes the output power low.

$$P_{DC} = \frac{V_{CC}^2}{R} = V_{CC} \times I_{CQ} \tag{2.39}$$

In Eq.2.39, P_{DC} is the DC power consumption and I_{CQ} is the quiescent output current which is approximately half of the maximum output current. V_{CC} is the supply voltage.

The Class A amplification process is linear, hence increasing the quiescent current or decreasing the input signal level decreases intermodulation distortion and harmonic levels of the design. To have low harmonics, for Class A, nearly all of the transistor frequencies can be used to operate the amplifier during the design. If an application require low power, high linearity, high gain, broadband operation, or high-frequency operation the Class A power amplifier can be used.

In this thesis, the power amplifier is Class A and the small signal S parameters are used to design the amplifier. In Class A amplifiers small signal S parameters can be used in simulations even if the large signal amplifier is operating.

The quiescent current which is also called standing bias current (Fig.2.33), makes the collector voltage to drop to the half of the supply voltage. As a result, the power will be half of the $I_{CMAX} \times V_{CC}$ as mentioned in Eq.2.39 before.

To conduct the signal, whether there is signal, all the time makes power dissipate for transistors and amplifiers. But this situation is not a big problem for designers in Class A voltage amplifiers because the collector current is not big one but very small one. On the other hand, it is a big problem in Class A power amplifiers because output currents are huge currents considering input base current. So that efficient use of power is critical issue.

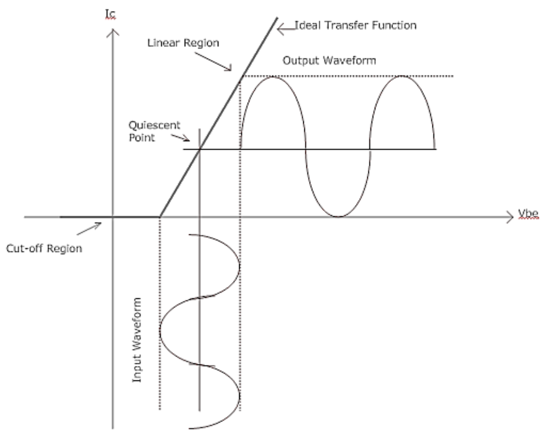

Figure 2.33 : Class A input and output wave form.

These types of amplifications run all the time, therefore, the PA is on and it heats easily. Heat dissipation is also high due to this 360^{o} conduction angle. Because of these factors, Class A amplifiers consume at least 4-5 watts as heat for every watt of output power. The transistors which are used in Class A power amplifier needs additional components for cooling and heat regulation.

Although, there are some disadvantages to use Class A power amplifier, there are also some big advantages to implement this class in the amplifier design such as linearity, low distortion and so on as mentioned before.

In Fig.2.34, the input waveform and the output wave form of an amplifier are showed in horizontal mode to see the linear amplification easily.

Class A power amplifier output stages are used in low to medium power output stages of 1 to 2 watt or below, such as domestic radio or TV receivers and headphone amplifiers. In this thesis, the transistor is chosen as medium discrete power transistor and the power amplifier which will be implemented in the following chapter will use for satellite systems, because linearity is so important in satellite systems to control and give command.

These classes of amplifications are also used for musical instruments, because the power amplifier reproduces all of the audio waveform without ever cutting off. Consequently, the musical instruments sound is cleaner, more linear and has low distortion.

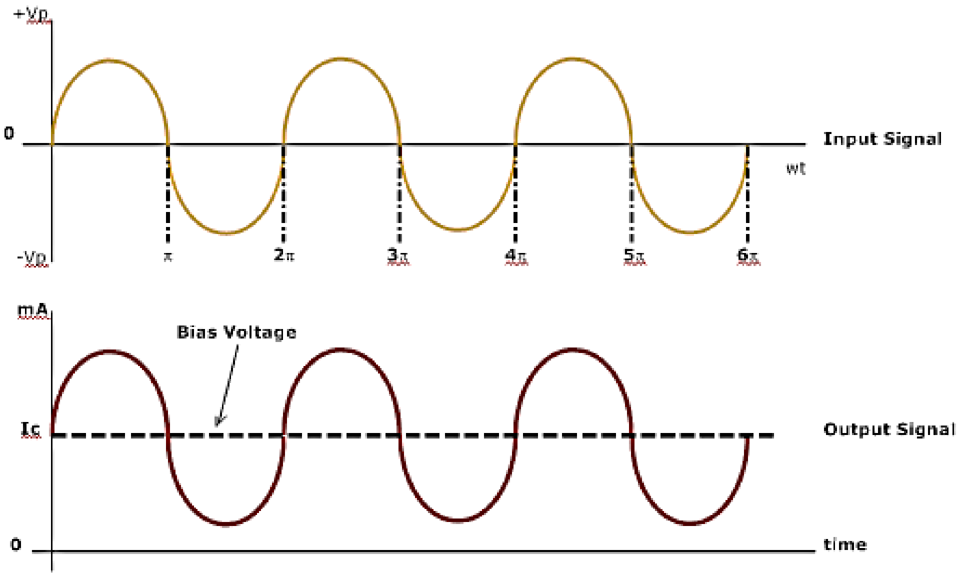

Figure 2.34 : Class A input and output wave form.

The basic schematic version of Class A is shown in the Fig.2.35. There is a load impedance in the right hand side of the schematic. The input impedance follows to the base of the transistor. Voltage divider is used to bias the base and collector of the transistor. There are RF choke connected both side of the transistor. The supply voltage provides the energy that circuit needs. Finally, the fourth leg of transistor is connected to the ground (Kenington, P.B., High Linearity RF Amplifier Design, 2000).

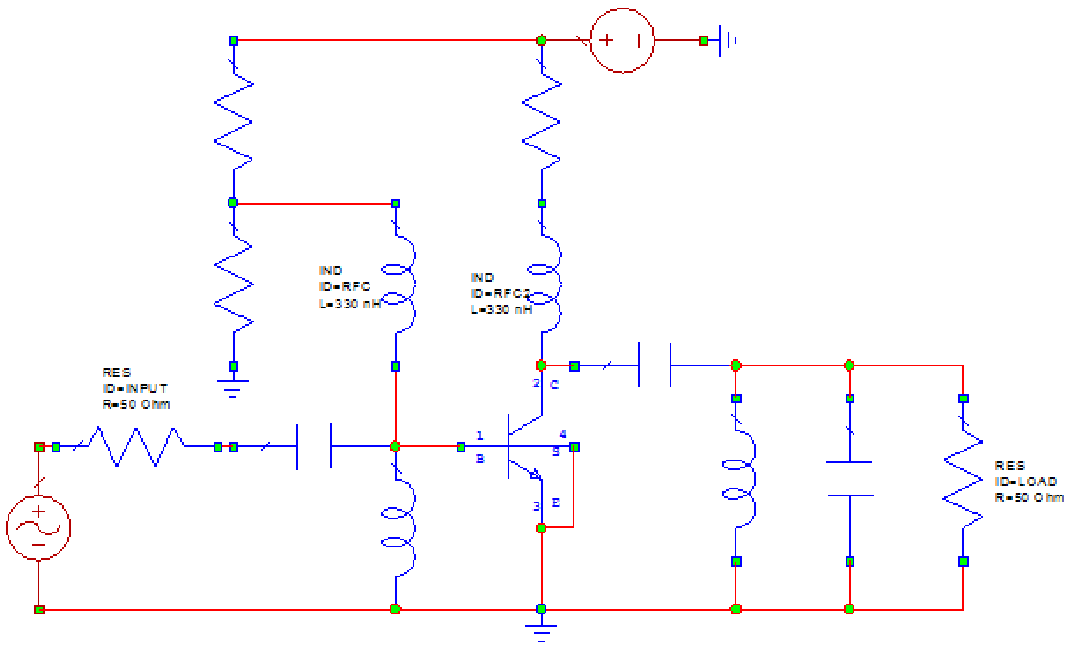

Figure 2.35 : The basic schematic version of Class A.

According to the figures and the explanations that mentioned before, these equations can be written:

$$I_C = I_{CQ} + I_{Peak} \cos wt \quad \textbf{(2.40)}$$

Here, I_{Peak} is the peak value of AC current.

$$I_{CQ} + I_{Peak} \leq I_{MAX} \quad \textbf{(2.41)}$$

$$I_{Peak} \leq I_{CQ} \quad \textbf{(2.42)}$$

According to Eq.2.41 and 2.42, we can give Eq.2.43:

$$I_{Peak} \leq I_{CQ} \leq I_{MAX} \quad \textbf{(2.43)}$$

The quiescent current can be chosen like in Eq.2.44, so that, the amplifier gives the maximum RF current swing where Eq.2.45.

$$I_{CQ} = \frac{I_{MAX}}{2} \quad \textbf{(2.44)}$$

$$I_{Peak} = \frac{I_{MAX}}{2} \quad \textbf{(2.45)}$$

The peak voltage can be given by the multiplication of peak current and the load resistor.

$$V_{Peak} = I_{Peak}\, R_{Load} \leq V_{CC} - V_{SAT} \quad \textbf{(2.46)}$$

The DC power was given in Eq.2.39. The output radio frequency power is:

$$P_{RF} = \frac{I_{Peak}^2 R_L}{2} \quad \textbf{(2.47)}$$

According to equations above, the efficiency can be represented as:

$$\eta = \frac{I_{Peak}^2 R_L}{2I_{CQ}V_{CC}} \quad \textbf{(2.48)}$$

The other form of Eq.2.48 is:

$$\eta = \frac{P_{RF}}{P_{DC}} \quad \textbf{(2.49)}$$

The maximum efficiency occurs when the current and voltage swings take on their maximum values. Notice that R_L is generally 50Ω and can not be changed. If I_{Peak} is taken equally with I_{CQ} and V_{Peak} is taken equal as $V_{CC} - V_{SAT}$, the Eq.2.50 can occur:

$$\eta = \frac{I_{CQ}^2 R_L}{2I_{CQ}V_{CC}} \quad \textbf{(2.50)}$$

Because of Eq.2.51:

$$I_{CQ} R_L = V_{Peak} \quad \textbf{(2.51)}$$

The maximum efficiency can be written as:

$$\eta_{Max} = \frac{V_{CC}-V_{SAT}}{2V_{CC}} \quad \textbf{(2.52)}$$

Theoretically, if the V_{SAT} is chosen "0", η_{Max} will be $1/_2$. That means Class A power amplifier has 50% efficiency theoretically.

2.3.1.1 Transformer Coupled Class A Power Amplifier

The efficiency of Class A power amplifier can be improved by adding a transformer at the output of the transistor. This transformer is replaced with the resistor which is connected between supply voltage and collector of the transistor. The transformer's primary winding side has high impedance (Z_{out}) at the audio frequencies. N_P is primary side turns of the transformer and N_S is the secondary side turns of the transformer. Z_{out} can be shown as:

$$Z_{out} = Z_{Loud} \left(\frac{N_P}{N_S}\right)^2 \quad \textbf{(2.53)}$$

Z_{out} (primary winding side impedance) will be equal with the Z_{Loud} multiplied by the square of the turns ratio. The transformer coupled Class A power amplifier can be shown in Fig.2.36:

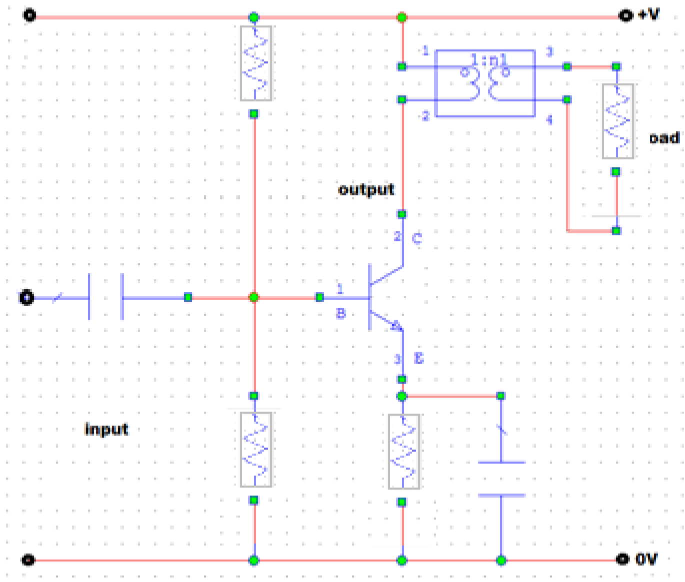

Figure 2.36 : The transformer coupled Class A power amplifier.

Although the Class A amplifier's efficiency improves when transformer is used in the output of the transistor, the transformer can itself produce additional distortion. This additional distortion can be minimized by limiting amplitude of the signal.

2.3.2 Class B power amplifier

For Class B power amplifier, bias of the transistor and output signal of the amplitude are only placed in positive half cycle of the input signal. When there is no signal (zero signal), the collector current is zero and there will be no biasing system in Class B power amplifiers.

The operating point is selected according to transistor's collector cutoff voltage. The negative half cycle is eliminated in this type of amplifier; as a result, the distortion can have high values.

If the Class A power amplifiers and Class B power amplifiers are compared, average current and power dissipation of Class B will be less. Consequently, overall efficiency is increased. Theoretically, efficiency in Class B is about 78.5% while it is only 50% in Class A amplifier.

The Class B amplifier operates usually and ideally at zero quiescent current, therefore, the DC power will be small. Class B power amplifier is less linear than Class A power amplifier.

The conduction angle is approximately 180^o for Class B amplifier. In Fig.2.37 the conduction angle graph can be seen.

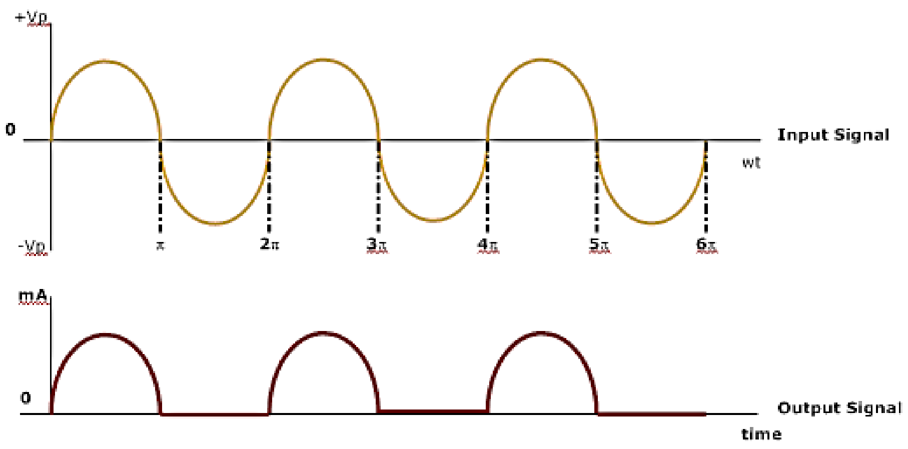

Figure 2.37 : The conduction angle for Class B power amplifier.

This class almost use no electricity, they only consume small electricity which are small signals. They need the base-emitter voltage (V_{be}) to be greater than the 0.7 V (approximately value) required for the BJT (bipolar junction transistor) to start conducting. There are two transistors in the amplifier, one transistor conducts during positive half cycles of the input signal and the second transistor conducts during the negative half cycle, Therefore, the all of the input signal is reproduced at the output. There is a distortion in small part of the output waveform at the zero voltage (crossover point). This distortion is called by crossover distortion. In Fig.2.38 the Class B push-pull power amplifier schematic is shown. The quiescent point is shown in Fig.2.39. There is also Class B PA which can be designed with one transistor but in this time a resonant circuit must be placed in the output network to reproduce the half of the input signal.

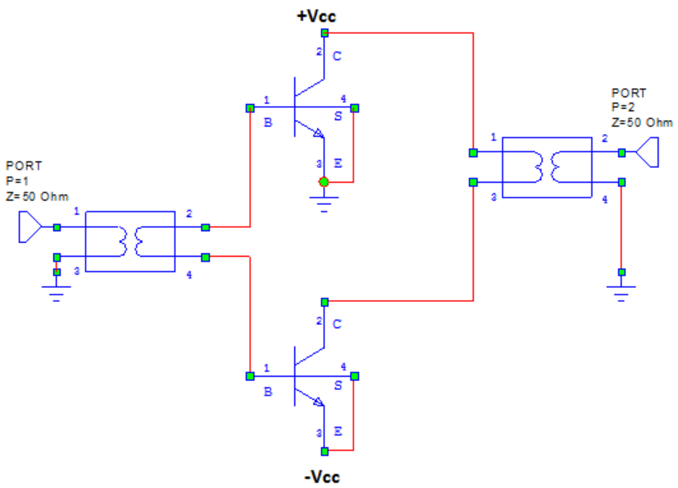

Figure 2.38 : The Class B push-pull power amplifier.

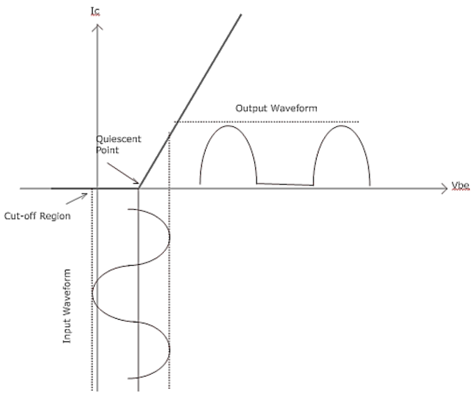

Figure 2.39 : The Class B power amplifier input and output signals.

2.3.3 Class AB power amplifier

The Class AB power amplifier can be classed between Class A and Class B PA. Its efficiency and linearity are also between these two amplifiers. The output bias is set, therefore, output current flows in a specific output device. The output current flows more than a half cycle but less than a full cycle. Only small amount of current is allowed to flow through both devices unlike the complete load current of Class A power amplifier. It is enough to keep each device operating so they respond instantly unlike Class B power amplifier.

According to these situations, efficiency increases and the amplifier is still linear. For a Class AB power amplifier, the conduction angle is between 180^o and 360^o. In Fig.2.40 the conduction angle can be seen and in Fig.2.41 the quiescent point of Class AB which is above than the zero point and lower than the Class A bias point is shown:

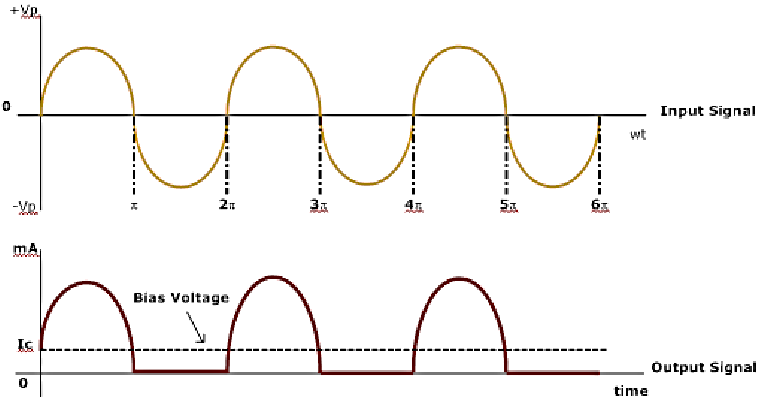

Figure 2.40 : The conduction angle of Class AB power amplifier.

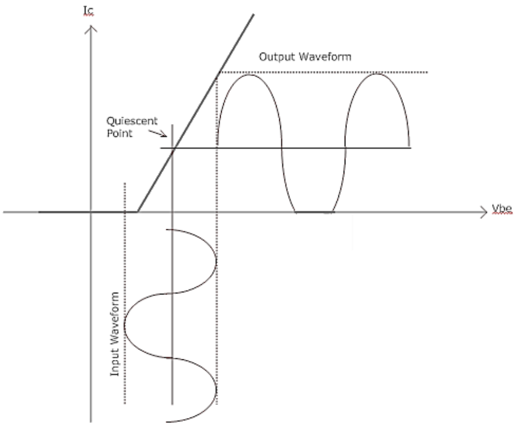

Figure 2.41 : The quiescent point of Class AB.

The Class AB schematic is shown in Fig.2.42:

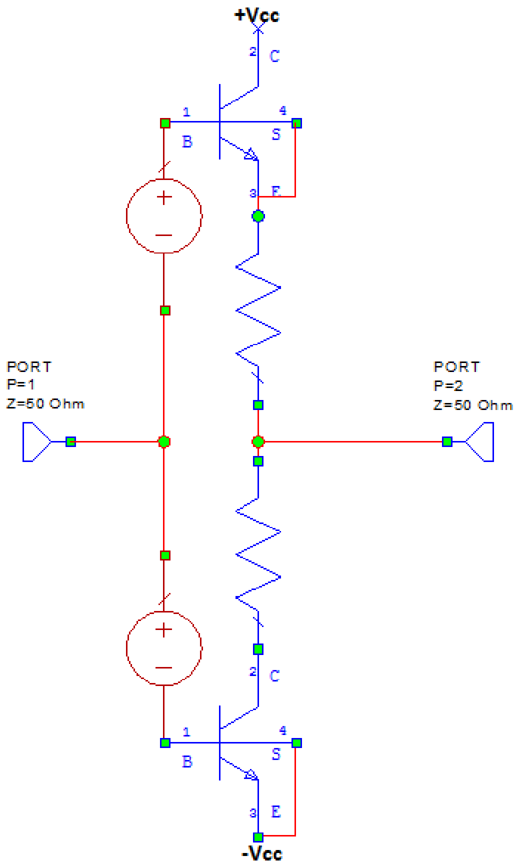

Figure 2.42 : The Class AB schematic.

2.3.4 Class C power amplifier

The conduction angle is less than 180^{o} for Class C power amplifier. This type of amplifier will operate only with a tuned or resonant circuit which provides a full cycle of operation. They are biased and the output current will be zero for more than one half of an input signal cycle.

The Class C power amplifiers can be used for radio and communications. They are restricted to the broadcast industry for radio frequency transmission.

The operation is worked by turning on one device at a time for less than a half cycle. Each output device is pulsed on for some percentage of the half cycle. Consequently, the Class C power amplifiers are more efficient Pas than Class A, B and AB.

A kind of Class C power amplifier schematic is shown in Fig.2.43. The inductor is an RF choke in the schematic.

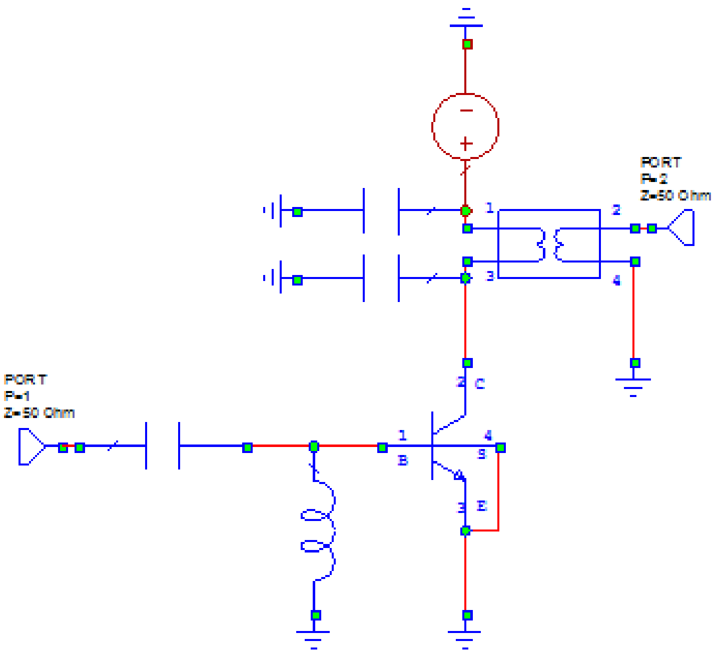

Figure 2.43 : The Class C power amplifier schematic.

Theoretically, the efficiency of the Class C PA can be reached to 85% that is better than Class A, B and AB Pas. They have low average output power because the transistor conducts only for short periods. The conduction angle and quiescent point of the amplifier is shown in Fig.2.44 and 2.45, respectively.

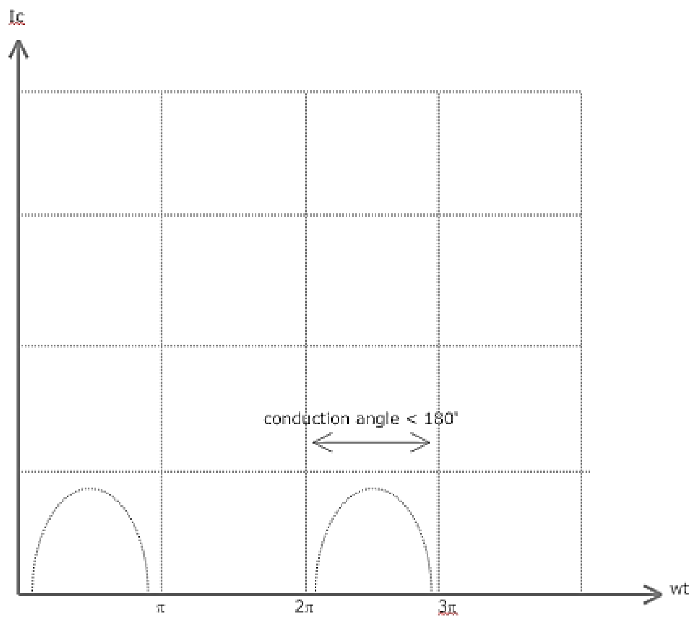

Figure 2.44 : The Class C power amplifier conduction angle.

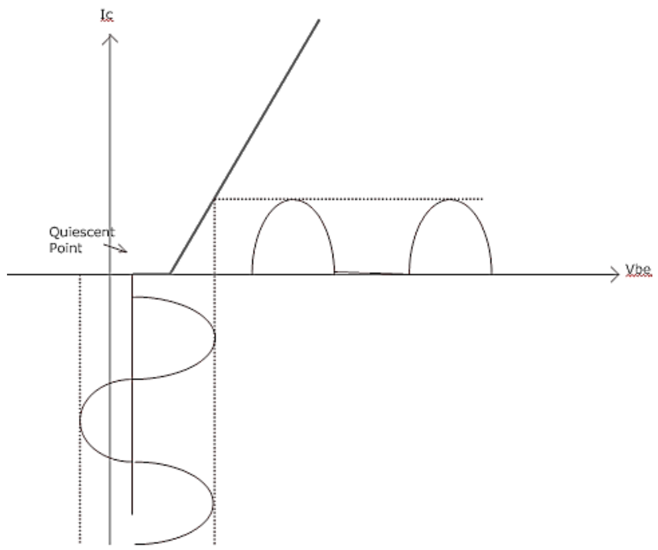

Figure 2.45 : The Class C power amplifier quiescent point.

In the Table 2.2 The conduction angle, position of the quiescent point, overall efficiency and distortion are given for Class A, B, AB and C power amplifiers.

Table 2.2 : The comparison of the Class A, B, AB and C power amplifiers

Class	**A**	**B**	**AB**	**C**
Conduction Angle	360^{o}	180^{o}	180^{o} to 360^{o}	≤180^{o}
Position of Quiescent Point	Centre Point of the Load Line	On the X axis	Between the X axis and the Centre Load Line	Below the X axis
Overall Efficiency	25 to 30%	Better, 70 to 80%	Better than A but less than B 50 to 70%	Higher than 80%
Distortion	None if Correctly Biased	At the X axis Crossover Point	Small Amounts	Large Amounts

2.3.5 Class D power amplifier

The Class D power amplifier is a switching mode amplifier like Class E power amplifier. The transistor works as a switch and it has “on” state where amplifier acts as a short circuit and “off” state where amplifier acts as an open circuit.

Theoretically, Class D PA has 100% efficiency. The amplifier does not have analog state, so that the analog changes in the input signal will disappear.

The Class D power amplifiers can be used in frequency modulation, pulse width modulation and Gaussian minimum shift keying (GMSK) modulation but cannot be usually used for amplitude modulation.

Class D power amplifiers use two or more transistors and most of the time these transistors will be field effect transistors. These types of amplifiers are difficult to realize at high frequencies. The device parasitic and lead inductance lead the power loss in each cycle. On the other hand, the main advantage of Class D amplifier is the amplifier is on only for short intervals.

Class D power amplifiers are designed to operate with digital or pulse type signals. Digital techniques make it possible to have a signal that varies over the entire cycle to recreate the output from many pieces of input signal.

In this thesis, a linear power amplifier which is Class A power amplifier is used, therefore, linear power amplifiers are explained in detail. The other power amplifiers as Class D, E, F, G and H etc. will be given in basic form.

2.3.6 Class E power amplifier

The Class E power amplifier's operation involves amplifiers designed for rectangular input pulses instead of sinusoidal input waveforms. It operates with a single transistor as a switch.

The efficiency is ideally 100%. Class E power amplifiers are offering more complex output filtering design. They are including some additional wave shaping of the pulse width modulation signal to prevent distortion.

In the ideal Class E PA, the shunt capacitor does not loss any power unlike Class D PA. Class E amplifier will exhibit an upper limit on its frequency of operation biased on the output capacitance. The RFC is large, so that only DC current flows through it.

Because of the quiescent point is high enough, the output current and output voltage consist of only fundamental part. As a result, all harmonics will be eliminated.

2.3.7 Class F power amplifier

The Class F power amplifier is similar to Class D power amplifier. It is including some additional wave shaping of the pulse width modulation signal to prevent distortion. This amplifier is the one of the highest efficiency amplifier, because of having harmonic resonator. In example, this amplifier may have some circuits (resonators) to prevent third harmonic signals. Also the output resonator is used to eliminate the harmonic and only keep the fundamental frequency output signal.

In Class F power amplifiers, lumped element traps are used at low frequencies and transmission lines can be used at microwave frequencies.

The Class F power amplifier is quite difficult because of having complex output circuit. If output matching network is implemented in the design, the harmonics can be eliminated. If matching network provides high impedance like open circuit, odd harmonics are eliminated and if matching network provides low impedance like short circuit, even harmonics are eliminated.

A $\lambda/_4$ transmission line transforms an open circuit into a short circuit or vice versa.

In Table 2.3 the power amplifier classification can be seen from Class A to Class F.

Table 2.3 : The comparison of the power amplifiers from Class A to Class F

Class	Mode	Efficiency	Linearity
A	Trans-conductance	50%	Good
B		78.5%	Moderate
C		100%	Lower than B
D	Switch	100%	Poor
E		100%	Poor
F		100%	Poor

2.3.8 Class G power amplifier

The Class G power amplifier can be used for large output signals with changing the power supply voltage level. The simple Class G power amplifier involve with Class

AB PA output stage which is connected to two power supply rails by a diode or transistor switch.

This type of amplifier can also be implemented by using two Class AB amplifier each has a different power supply. Its efficiency improves if this implementation is realized.

Class G may be used in pro audio designs and musical program material. It has satisfied the need for narrow band tuned amplifiers and high efficiency.

2.3.9 Class H power amplifier

The Class H power amplifier improves on Class G PA by continually varying the power supply voltage. It modulates the higher power supply voltage by the input signal, therefore, the power supply tracks the audio input and provide enough voltage for optimum operation.

Both of the Classes G and H require more complex power supplies, as a result it costs too much to implement.

2.3.10 Class J power amplifier

The Class J power amplifier provides a solution for the adverse effects of switch mode amplification; as a result, potentially high efficiency, linearity and wideband behavior can be seen simultaneously.

2.3.11 Class S power amplifier

The Class S power amplifier is a switching mode PA which has 100% efficiency. It is used for amplification of low frequency signals. This amplifier requires pulse width modulated signal.

2.4 Amplifier Design Fundamentals

In this part general power amplifier design fundamentals will be explained. The bias point and impedance matching will be discussed in detail. The DC operating point is very important figure of merit for the amplifier design. This point can also determine class of the amplifier. Each transistor has its own bias point, as a result, it should be chosen carefully for the amplifier. The matching network is also an important figure of merit. If the simulation results do not meet the requirements, the design of the amplifier and the matching networks should be changed (Bowick, C., Blyler, J., Ajluni**, C.,** RF Circuit Design, 2008).

2.4.1 The bias point

The operating point of a device, also known as bias point, quiescent point, or Q point can be found by biasing the circuit. Biasing is the method of establishing predetermined voltages or currents at various points of an electronic circuit for the purpose of establishing proper operating conditions in electronic components. Many electronic devices whose function is signal processing time-varying (AC) signals also require a steady (DC) current or voltage to operate correctly. The Q point is chosen to keep the transistor operating in the active mode, using a variety of circuit techniques, establishing the Q point DC voltage and current for BJT.

In Fig.2.46, a generic power amplifier circuit for optimum transistor analysis for each class is shown. The capacitors on the base and collector are the by-pass capacitors and RF chokes are used for biasing. In Fig.2.47, the bias circuit which is used for this thesis is shown:

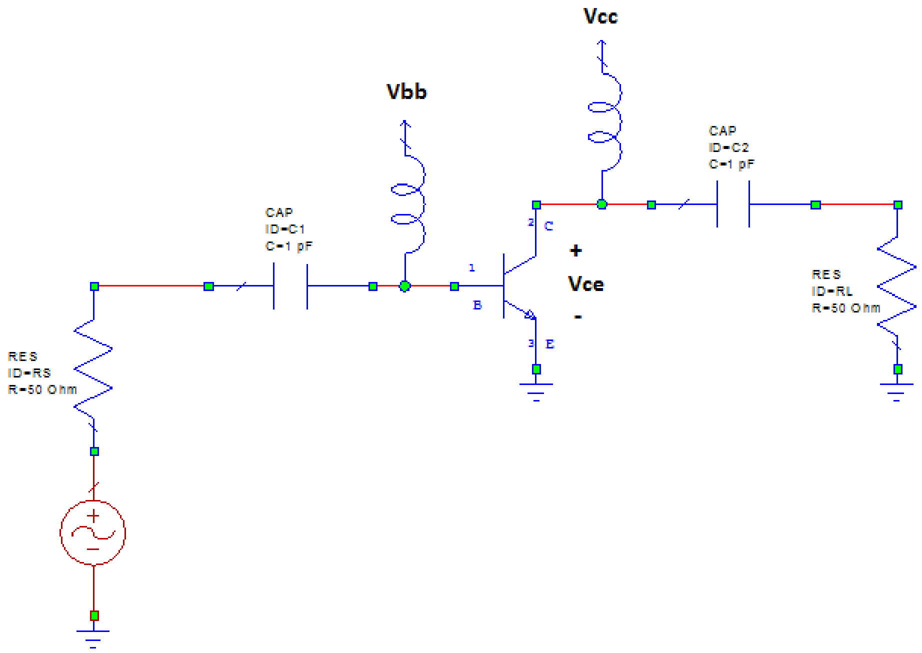

Figure 2.46 : A generic power amplifier circuit.

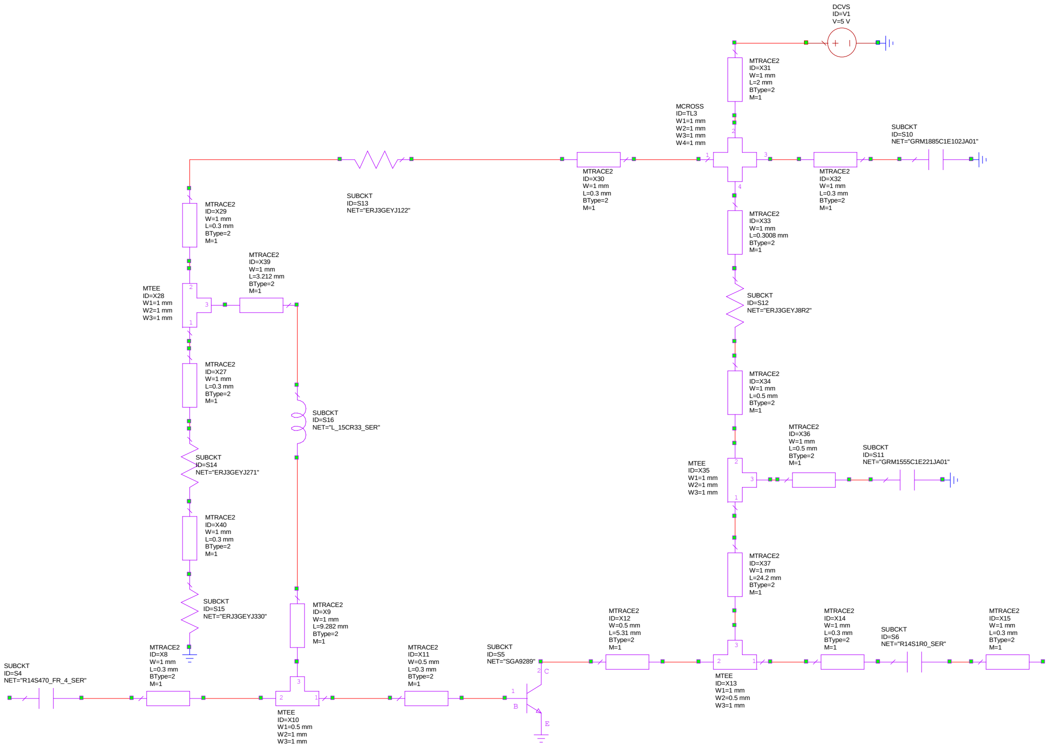

Figure 2.47 : The bias circuit.

There are resistors to divide the voltage which is supplied by V_{CC}. There is also an RF choke as mentioned above.

Transmission lines are used for each of the connections to see the solder effects. As a result, we can know that what the solders change in PA design. Instead of inductance, transmission lines can be used in an RF power amplifier too. The circuit properties will be mentioned later in the third chapter.

To find the bias point circuit components, current source is connected to the base of transistor. This source is increased volume by volume. When the I_{CEQ} current value equals to 280mA which is the datasheet value of transistor the base current will be obtained. According to the I_{CEQ} current value bias circuit elements value will be obtained too. In Fig.2.48, the base current graph is given:

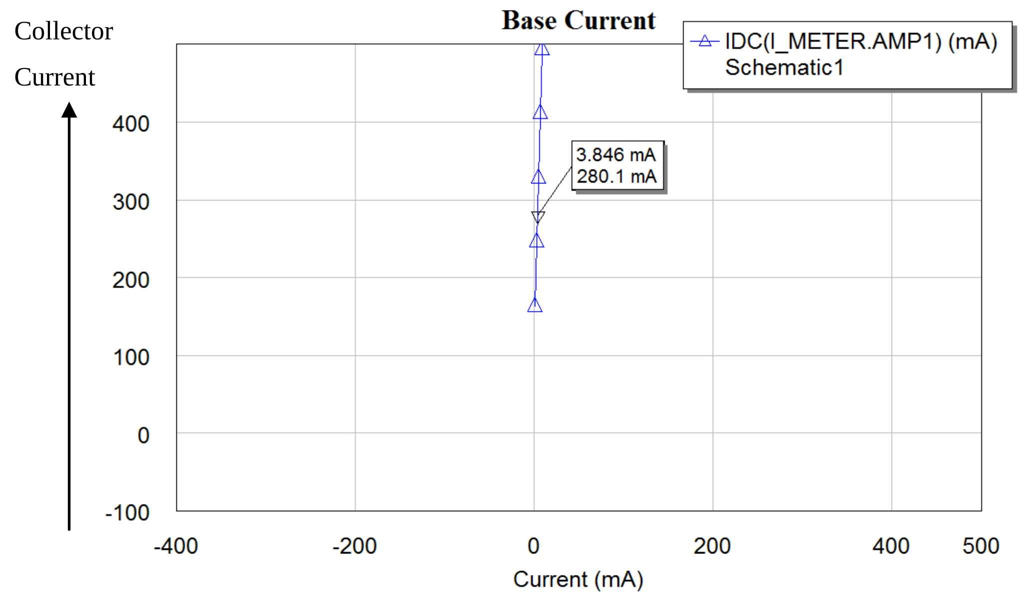

Figure 2.48 : The base current graph.

According to the Fig.2.48 the base current is 3.846mA for the 280.1mA collector current of transistor. To obtain 3.846mA base current R_2 (ID=S13 in Fig.2.47) is chosen 1200Ω and R_3 (ID=S14 in Fig.2.47) is chosen 300Ω. Not to have 300Ω for realization, R_3 is taken 270Ω and another resistor is added series to R_3, and its value is 33Ω (ID=S15 in Fig.2.47).

V_{CEQ} should be between 0V and 5V according to transistor datasheet. To obtain 0-5V 0.07V is given from the port 1. The 0.07V value is obtained by sweeping. Later, it is proved by Fig.2.49. V_{CEQ} graph can be seen in Fig.2.50. V_{out} is also shown in the same graph.

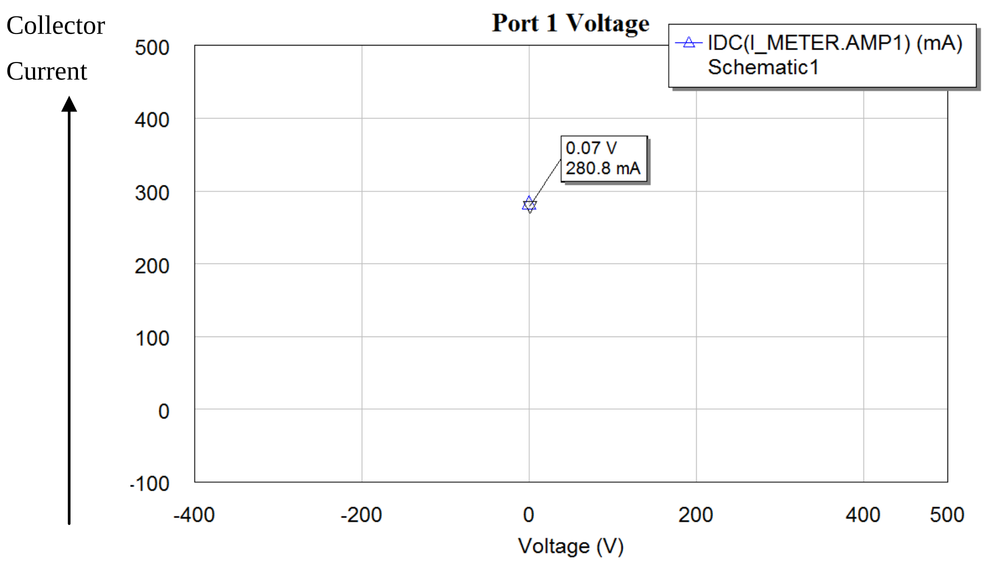

Figure 2.49 : The port 1 voltage.

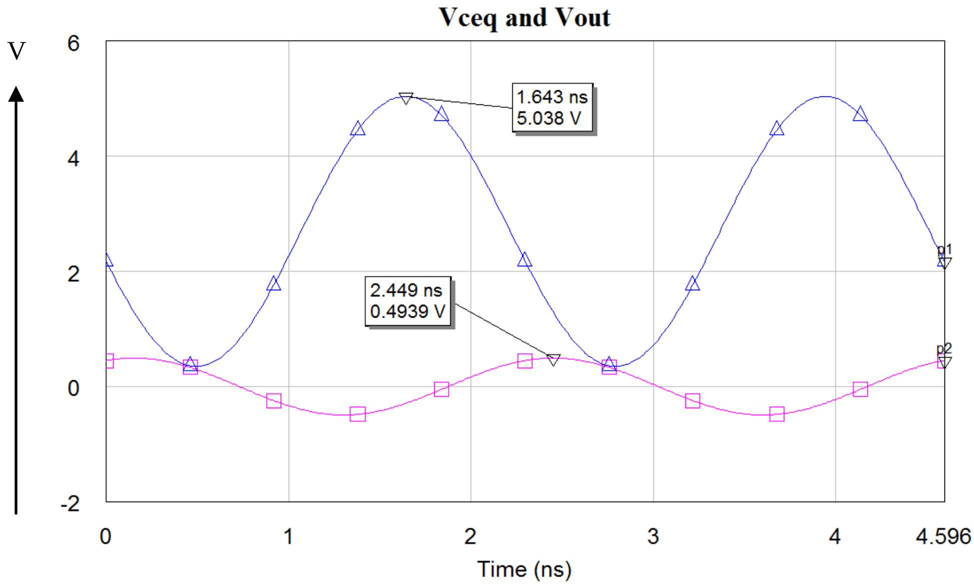

Figure 2.50 : The V_{CEQ} and V_{out} graph.

The last bias circuit element R_3 (S_{12} in Fig.2.47) is obtained by calculation:

$$R_3 = \frac{\frac{Vcc}{2}}{Icq} = \frac{\frac{5}{2}}{280m} = 8.93\Omega \qquad \textbf{(2.54)}$$

This value can be approximated to 9Ω but for realization we have 8.2Ω, as a result, R_3 is chosen 8.2Ω.

The circuit elements will be explained in detail in chapter 3.

2.4.2 Impedance matching

In electronics, impedance matching is the practice of designing the input impedance of a load (or the output impedance of its corresponding signal source) to maximize the power transfer or minimize reflections from the load. The input and output impedances must be matched to the source and the load impedances to prohibit reflections and to maximize power transference (Kesik, E.P., UHF Güç Kuvvetlendirici Tasarımı ve Gerçeklenimi).

In the case of a complex source impedance Z_S and load impedance Z_L, maximum power transfer is obtained when:

$$Z_S = Z_L^* \qquad \textbf{(2.55)}$$

In Fig.2.51, the source and load impedance can be seen:

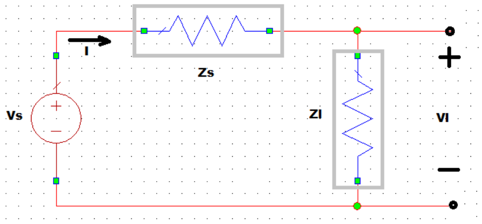

Figure 2.51 : The source and load impedance.

In RF power amplifier systems, the impedance matching is a bit different from the normal circuits. The transistor is used to amplify the system; as a result, two impedance matching circuit should be used. One of them is before the transistor and the other one is after the transistor. It means the matching circuits are located before the base of the transistor and after collector of the transistor.

Most of the discrete components are designed for 50Ω in an RF amplifier. Consequently, there is not any reflection between them. The input impedance (Z_{in}) and the output impedance (Z_{out}) should be 50Ω for this reason. Therefore the optimum load (Z_L) and source (Z_S) impedance should be transformed to 50Ω. An amplifier schematic represents Z_{in}, Z_{out}, Z_L and Z_S is shown in Fig.2.52:

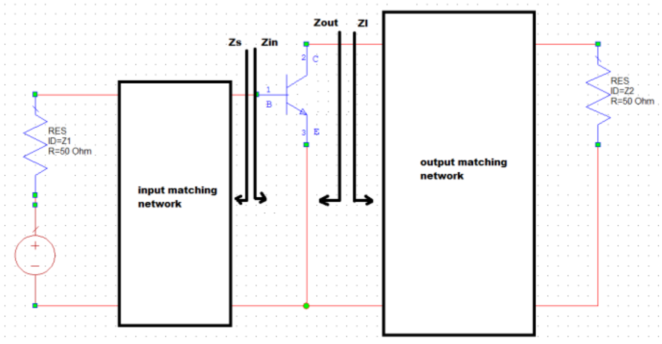

Figure 2.52 : An amplifier schematic showing Zin, Zout, ZL and ZS.

The impedance matching circuit can be implemented by L type network, T type network, pi type network or with transmission lines. Capacitances and inductance are used for matching. In this thesis, capacitances and transmission lines are used for matching. In order to implement the inductances into the circuit is difficult, the transmission lines is used.

The MWOAWR program has impedance matching circuit wizard which is named with iFilter Wizard. In this thesis, firstly, iFilter Wizard is used; secondly, according to the gain and S parameters characteristics, the impedance circuits are designed again.

In Fig. 2.53 the single-stage PA with matching circuits is shown and in Fig.2.54 the input matching circuit and in Fig.2.55 the output matching circuit which are used in this thesis are shown. In Fig.A.3, Fig.A.4 and Fig. A.5, the input, output and RF circuits are shown respectively.

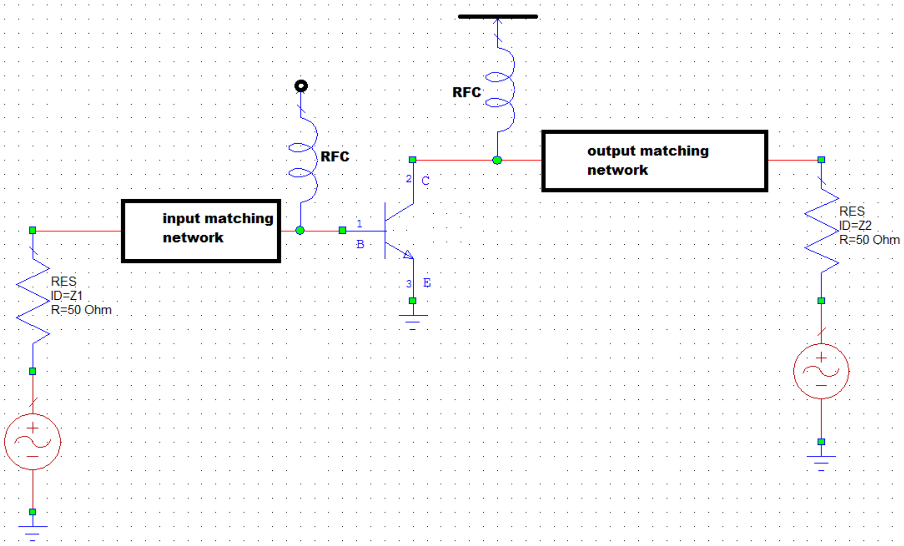

Figure 2.53 : The single-stage PA with matching circuits.

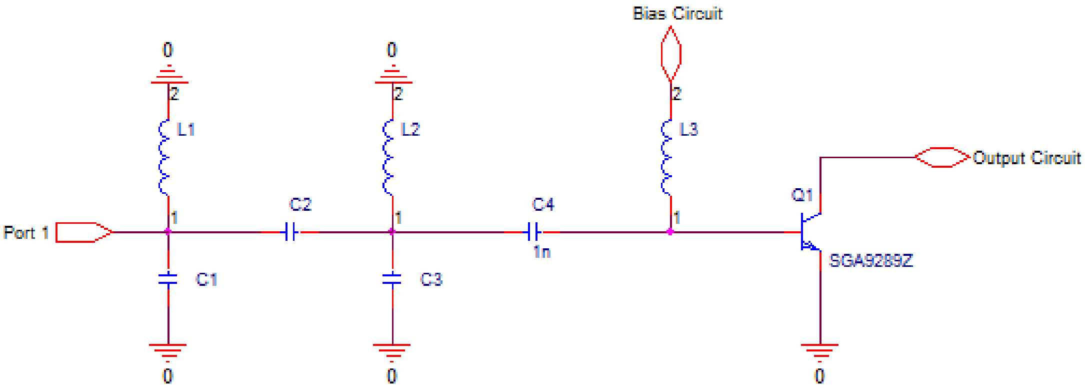

Figure 2.54 : The input matching circuit.

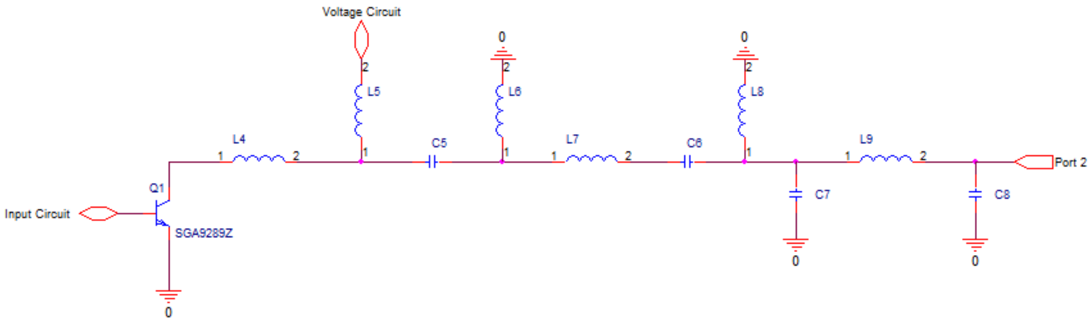

Figure 2.55 : The output matching circuit.

3. EXPERIMENTAL

In this chapter, the experiments done in MWOAWR program with computer and the experiments done in real world are explained in detail. The circuit schematics and the result graphs will be shown clearly. From the basic schematic to the realization of the last schematic will be given step by step.

Firstly, the materials and the equipment will be introduced in upcoming titles. Secondly, experiments in the computer program and lastly, experiments in the realization will be illustrated.

3.1 Materials

3.1.1 Capacitances

Capacitance is the ability of a body to store an electrical charge. Due to store electrical charge it can provide stability of voltage. There are four capacitances at the input side and again four capacitances at the output side of the circuit used in this thesis. There are also bias capacitances in the circuit schematic. In Table 3.1, the capacitances values are shown:

Table 3.1 : The capacitances values

C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
3.6pF	82pF	1pF	47pF	1pF	7.5pF	5.1pF	68pF	1000pF	220pF

Generally, Johanson's 603 body SMD FR4 base capacitances will be used in this thesis. In MWO program, firstly, ideal components are used, later in order to realize the circuit in the real world, the real AWR capacitances values are used. It is interesting that the ideal 220pF capacitance equals to 82pF Johanson's 603 body FR4 (flame resistant 4) base real capacitance and the ideal 100pF capacitance equals to 68pF. While using the real AWR capacitances the gain characteristics of the circuit is considered. When the gain graph changed, the changes are removed by the transmission lines.

3.1.2 Inductances

It is difficult to implement the inductances to the circuit so that there is only one inductance used in the circuit. This inductance is used for RF Choke that is explained in the following title. In RF line, the inductances are exchanged to the transmission lines which are explained in the "Transmission Line" title. The band pass circuits and impedance matching circuits are designed by capacitances and transmission lines instead of inductances.

3.1.3 RF choke

The RFC (radio frequency choke) is an inductance that can be used in the bias circuit. In this thesis, 330nH Johanson Monolitic 805 body RFC is used. It raises the power in the power amplifier. Meanly, it is a bar for reflecting power from the transistor.

An RF choke is a coil of insulated wire and it is often wound on a magnetic core, used as a passive inductor which blocks higher-frequency alternating current in an electrical circuit while passing signals of much lower frequency and direct. Chokes are typically used as the inductive components in electronic filters.

3.1.4 Transmission line

A transmission line is a specialized cable which is designed to carry alternating current of RF, the currents with a frequency high enough that their wave nature must be taken into account.

A transmission line can be used for inductances or capacitances. In order to implement inductances in the circuit is difficult, transmission lines are used most of the time instead of inductances. In this thesis, some of the inductances are exchanged to the transmission lines when realization of the circuit.

Transmission lines are used for purposes such as connecting radio transmitters and receivers with their antennas, distributing cable TV signals and computer network connections.

In this thesis, generally, transmission lines have 1mm width are used. Their length is between 0.3mm and 22.75mm. In example in the Fig.3.1 the transmission line length is 1.637mm.

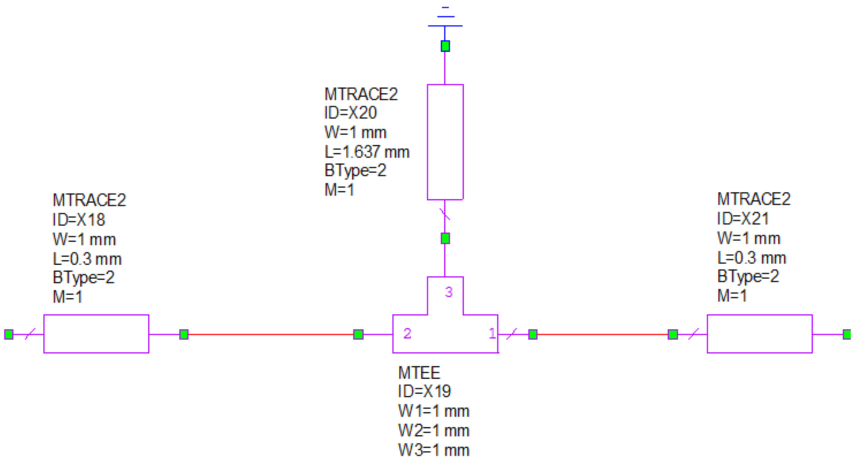

Figure 3.1 : The transmission lines.

There are “T” lines between three lines and there are “+” lines between four lines which is shown in Fig.3.2. These “T” and “+” lines are drawn in order to see the effect of solders. Their width is also 1mm except the “T” lines which are connected to the transistor. Their one of three line is 0.5mm because of transistors pin.

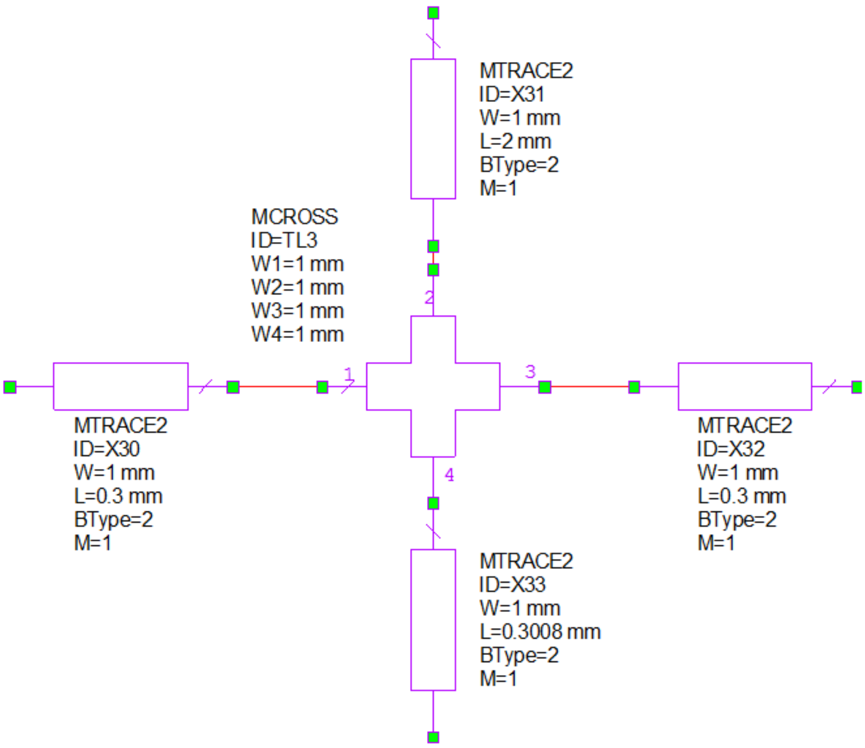

Figure 3.2 : The “+” transmission line.

The transmission lines that are used in this thesis will be shown in the following chapters as layout and the real printed circuit board (PCB) pictures.

3.1.5 Transistor

In this thesis, RFMD's SGA9289z medium power discrete SiGe transistor is used. This transistor is a high performance transistor designed for operation to 50 MHz to 3000 MHz. Our design is operated for 435.250 MHz. SGA9289z transistor has about 27.5 dBm P_{1dB}. It is cost-effective for applications requiring high linearity even at moderate biasing levels. It is well suited for operation at 5 V. It can be used in wireless infrastructure driver amplifiers, CATV (cable TV) amplifiers, wireless data and power amplifiers. The gain, P_{1dB} and OIP3 graph is shown in Fig. 3.3:

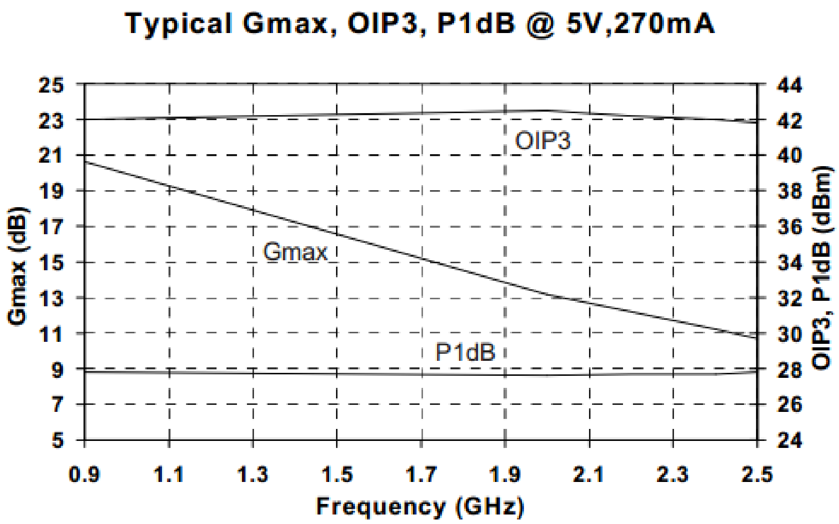

Figure 3.3 : The gain, P1dB and OIP3 graph (SGA9289Z Medium Power Discrete SiGe Transistor Datasheet, 2006).

The other specifications of SGA9289z transistor will be examined in Appendix A.1. There are also other transistors that are examined for the realization of thesis. These transistors are listed in Appendix A.2. SGA9289Z is the most suitable transistor for this thesis.

The modules are also examined but it is decided that if the modules were used for power amplifier it could be too easy for a M.Sc. thesis. So, the transistor was chosen to amplify the circuit.

3.1.6 Resistors

The resistors are used in bias circuit as a voltage divider. As mentioned before in the bias point section (2.4.1), there are four resistors used in the circuit. Their values are 1200Ω, 300Ω, 33Ω and 8.2Ω. In Equation (2.54), the 8.2Ω was explained in detail.

3.1.7 Voltage source

The 5V DC voltage source is used for the power amplifier. The whole circuit including voltage source can be seen in Fig.3.4. The voltage source will be the power supply when realization of the circuit.

3.1.8 FR4 PCB

FR4 is a type of printed circuit board. FR4 is the primary insulating backbone upon which the vast majority of rigid printed circuit boards (PCBs) are produced. A thin layer of copper foil is laminated to one, or both sides of an FR4 glass epoxy panel. These are commonly referred to as “copper clad laminates.” In this thesis, 1.6mm FR4 is used with 35um copper width.

3.1.9 Connectors

There will be two connectors connected to the port one and port two. They can be SMA connectors and they may turn 90^o. The connectors and FR4 with all components in the PCB will be shown in the following chapters.

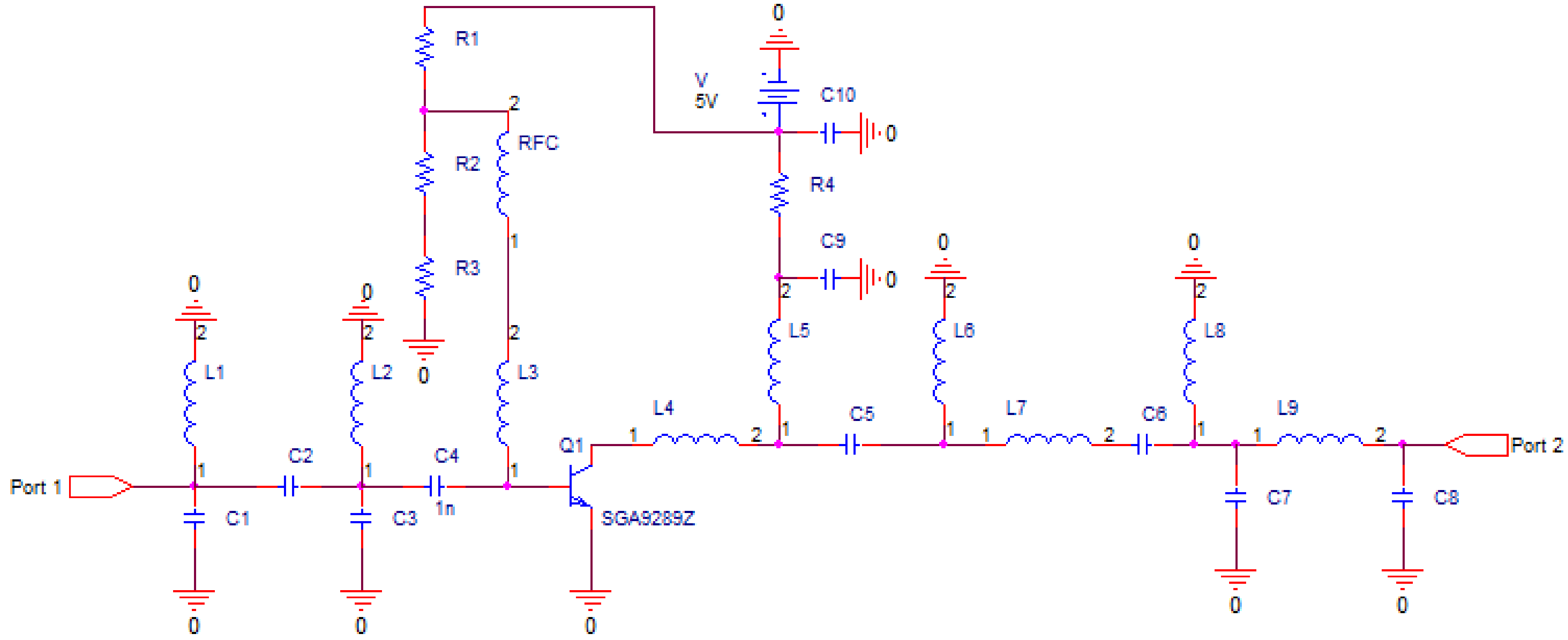

Figure 3.4 : The circuit schematic.

3.2 Equipment

3.2.1 Power supply

It is a device which supplies electric power to an electric load. A regulated power supply is one that controls the output voltage or current to a specific value; the controlled value is held nearly constant despite variations in either load current or the voltage supplied by the power supply’s energy source. In this thesis, 5V power supply is used.

3.2.2 Multimeter

It is an electronic measuring instrument that combines several measurement functions in one unit.

3.2.3 Oscilloscope

It is a type of electronic test instrument which allows observation of constantly varying signal voltages. It is usually as a two dimensional graph of one or more electrical potential differences using the vertical and horizontal axis.

3.2.4 Spectrum analyzer

It measures the magnitude of an input signal versus frequency within the full frequency range of the instrument. The major use is to measure the power of the spectrum of known and unknown signals.

Dominant frequency, power, distortion, harmonics, bandwidth and other spectral components of a signal can be observed by analyzing the spectra of electrical signals.

3.2.5 Signal generator

It can also be called function generator or RF and microwave signal generator. It is an electronic device which generates repeating or nonrepeating electronic analog or digital signals. It is usually used in designing, testing, troubleshooting and repairing electronic devices.

3.2.6 Soldering machine

It is used to implement the components to the printed circuit board.

3.3 Experiments in MWO Program

Most of the experiments are done in MWO Design Environment Program on computer. The tenth version of this program is used. According to the transistor specifications, S Parameters and result charts of the power amplifier schematic, the circuit is completed.

3.3.1 Transistor characterization

The transistor is characterized in MWO program with S Parameters. Transistor's emitter is connected to the ground directly in order to reduce lead inductance. Firstly, project >>> add data file >>> new data file >>> touchstone data file is chosen and transistor parameters are added to the MWO Program. Later, add subcircuit element is chosen and transistor is added to the circuit. As mentioned before, its emitter is connected to the ground. Transistor specifications are mentioned in the 3.1.5 chapter and will be mentioned in the Appendix A.1.

3.3.2 Filters

After adding the transistor in the circuit, the band pass filters are added to the circuit. In the beginning, there is one band pass filter in the input of the circuit and there is one band pass filter in the output of the circuit. Each band pass filter is formed with one low pass filter and one high pass filter.

To use these filters the 435.250 MHz center frequency is wanted to be created. MWO program has “Tune” and “Optimize” option. These options are used to create the center frequency. While creating the center frequency, the bandwidth and the other characteristics are observed in detail. Gain is also a figure of merit to design a power amplifier, so that, the gain is observed too.

Sometimes, the capacitances and inductances values can be huge values. To fix this problem, another band pass filter is added to the circuit. Gain at the center frequency should be flat, as a result, adding another band pass filter is necessary too.

After adding new band pass filters to the circuit, the “Tune” and “Optimize” options are used to determine new capacitance and inductance values. Sometimes, the series inductance values can be very small. In this situation, the series inductance can be removed from the circuit.

3.3.3 Bandwidth

The bandwidth is also an important figure of merit for amplifiers. In the Power Amplifier Performance Parameters (2.1), gain is explained (2.1.1). The bandwidth can be determined with gain graph (Fig.2.4). The bandwidth of this power amplifier should be 6 MHz approximately. In order to tune the bandwidth to this value, the capacitances and inductances values should be changed again. While these values are changed, the gain and the gain flatness at the center frequency should be the same.

The bandwidth is determined according to the top of the gain value. When this value is dropped to 3 dB below for each of side, the frequency that shows these 3 dB below is noted. These two frequency values are subtracted from each other.

$$438.62 - 431.86 = 6.76\,MHz \tag{3.1}$$

3.3.4 Transmission line changes

The inductance element is difficult to imply in an electronic circuit, as a result, the inductances in the circuit are changed with transmission line. Each transmission line has inductance value. While changing the inductances, the characteristics that obtained before should not be changed.

This changing process is done with "TXLine" option which is in MWO Program (Fig.3.5). The "Tune" and "Optimize" options are also used for optimizing the transmission line width and length values. These transmission line values and other properties are mentioned in 3.1.4 section.

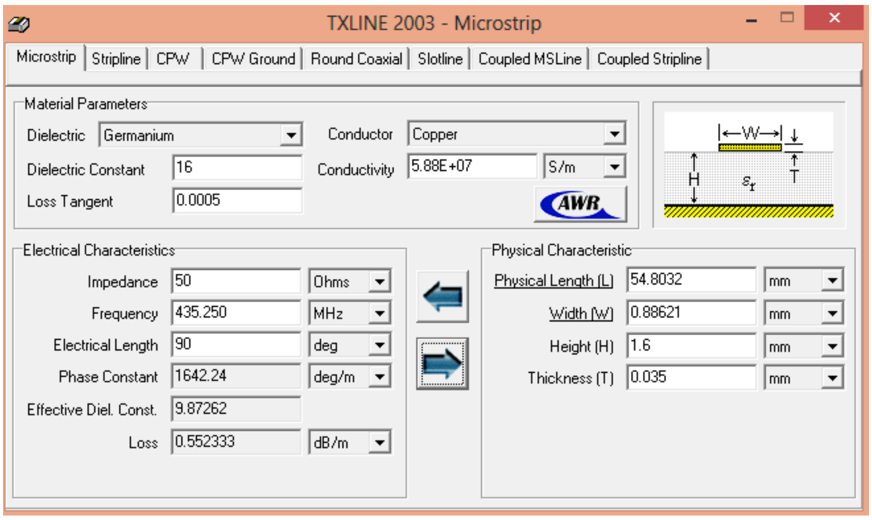

Figure 3.5 : TXLine.

3.3.5 Transmission line for solder effects

In order to implement the components in the circuit for layout and in order to see the solder effects in the amplifier the transmission lines should be added before and after for the all circuit components.

Firstly, the transmission line is only used for inductances because of difficulty to implement inductances in the circuit. After the transmission line is used only before and after the transistor because of importance of transistor in the circuit. The amplifier characterization can be totally changed according to transistor. Later, it is decided that transmission line should be used before and after for all of the components. In Fig.3.4, the transmission lines that are used for all components can be seen.

The "T" and "+" lines (Fig.3.1 and Fig.3.2) are also necessary to see the solder effects for all joint nodes.

3.3.6 Impedance matching for circuit

The impedance matching as mentioned in the previous sections is very important in order to block the power loss. While tuning the impedance to the 50Ω, the characterizations that obtained before should not be changed. The bandwidth and center frequency are very accurate for this situation.

If all the characterization like gain, S_{11}, S_{22}, S_{12}, and S_{21}, VSWR, stability etc. are suitable for amplifier, the impedance matching is suitable for amplifier most likely. In Fig.3.6 and Fig.3.7, the impedance values should be greater than 0Ω and near the 50Ω.

The impedance matching was discussed in detail in section 2.4.2.

3.3.7 Bias circuit

It is very important for an amplifier to operate in the right class. In this thesis, the amplifier is operated in Class A. Therefore, the bias circuit is designed in order to make the amplifier linear. The bias circuit of the amplifier was shown in Fig.2.47.

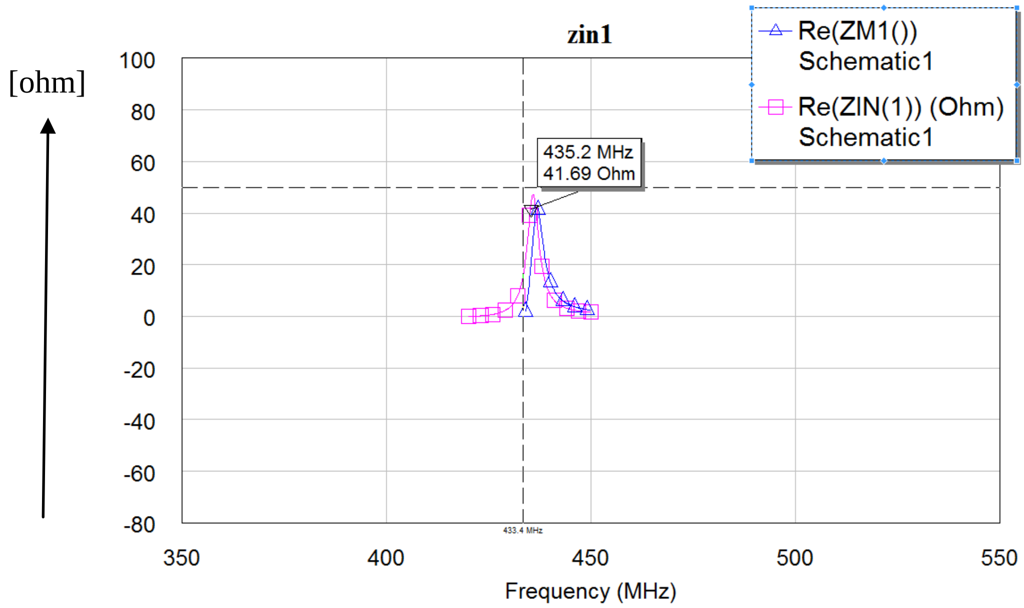

Figure 3.6 : Z_{in}.

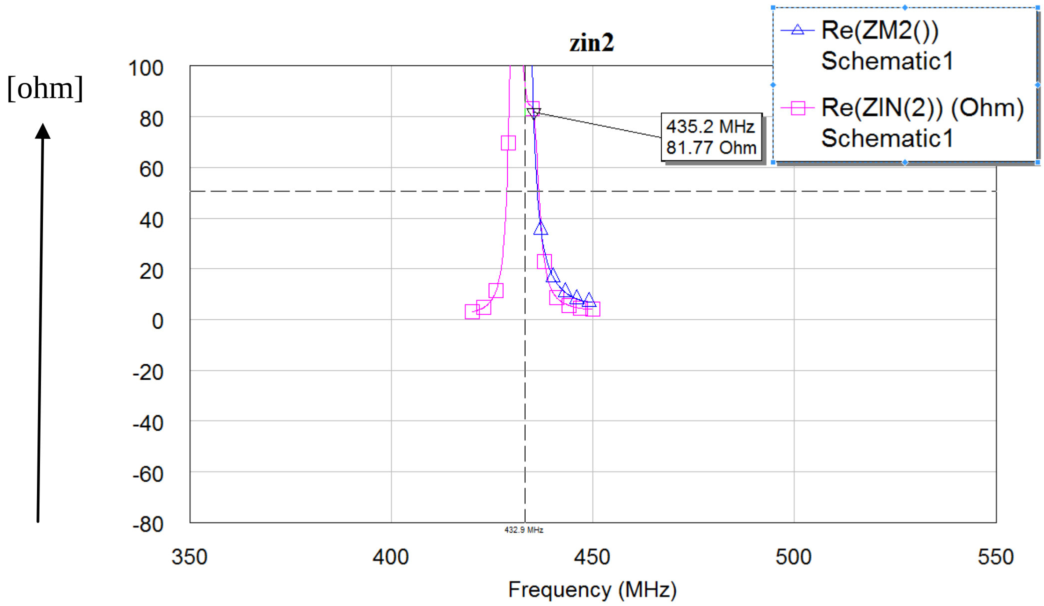

Figure 3.7 : Z_{out}.

3.3.8 The 2D layout

After the circuit is drawn in MWO Program, the 2D (two dimension) layout should be created. There is "View layout" button in the program. If this button is pressed the 2D layout is created but the components cannot connect to each other by themselves. They are connected by user. After connecting all of them, the "Select all" and "Snap together" function can be chosen from "Edit" menu. As a result, the right connection is created.

While doing this work, some of the lines can't be connected to each other so that they should be extended or shortened. If they are extended or shortened, the characterization of the circuit can be changed but it is undesirable situation. Consequently, the circuit can be redesigned.

Generally, if the bias circuit lines are changed, the circuit characterization does not change. After all these stages, the 2D layout is created. Now the via holes and copper for ground etc. are added to the 2D layout. The 2D layout is shown in Fig.3.8:

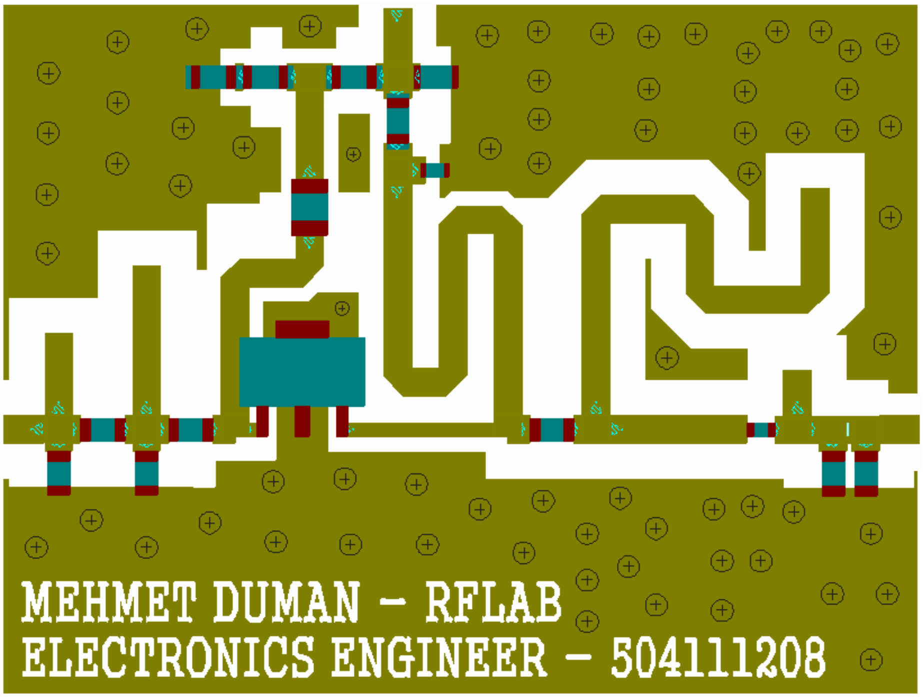

Figure 3.8 : The 2D Layout.

The 2D layout can also be created with Altium Designer Program but if it has been created with Altium Designer Program, the microwave and RF effect could not be seen by the designer. As a result, 2D and 3D (three dimension) are created with MWOAWR Design Environment Program.

3.3.9 The 3D layout

The 3D layout is very easy to create. After creating the 2D layout, by clicking the "View 3D layout" it can be seen (Fig.3.9):

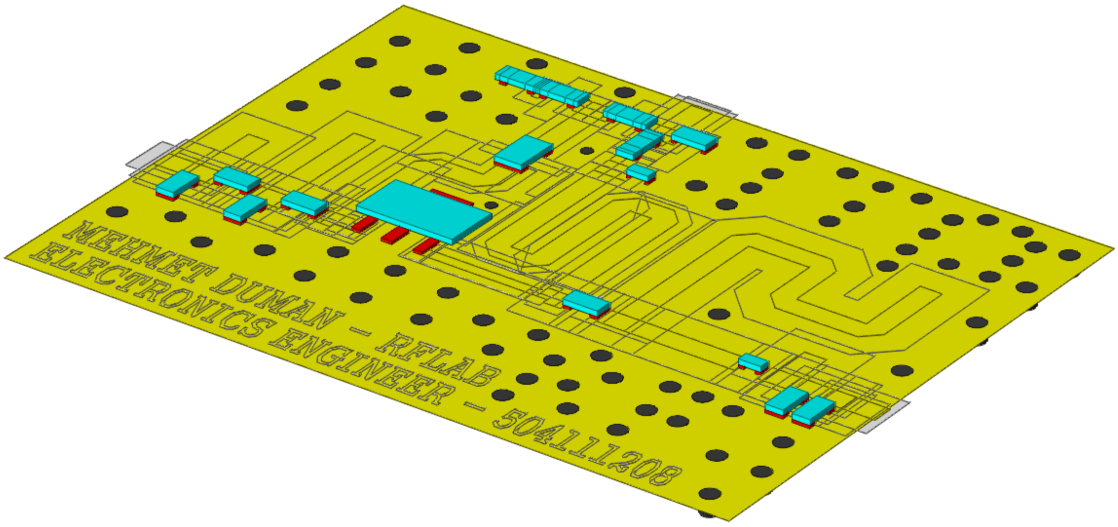

Figure 3.9 : The 3D Layout.

3.4 Experiments in Real World

The circuit is printed out to the FR4 PCB which has 1.6mm thickness and 35µm copper thickness. In Fig.3.10, the PCB is shown:

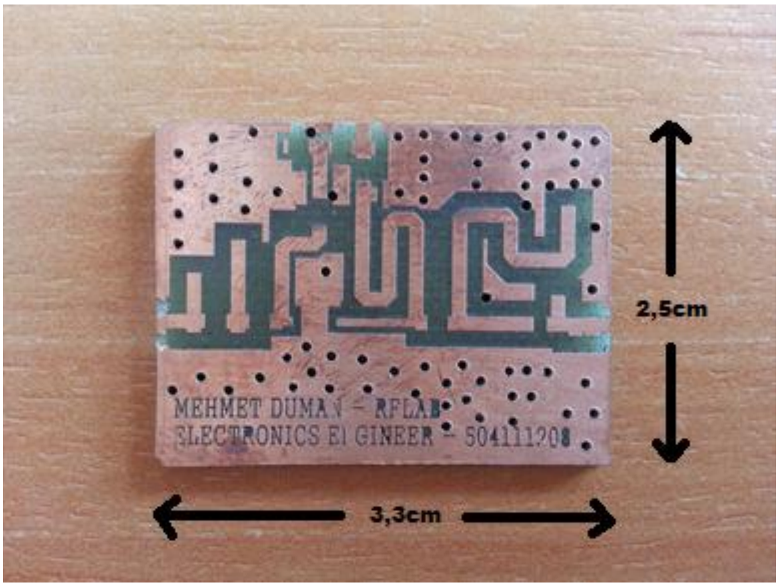

Figure 3.10 : The PCB.

3.4.1 Material class

In this thesis the SMD materials are used.

3.4.2 PCB with components

The PCB with all of its components and SMA connectors is shown in Fig. 3.11.

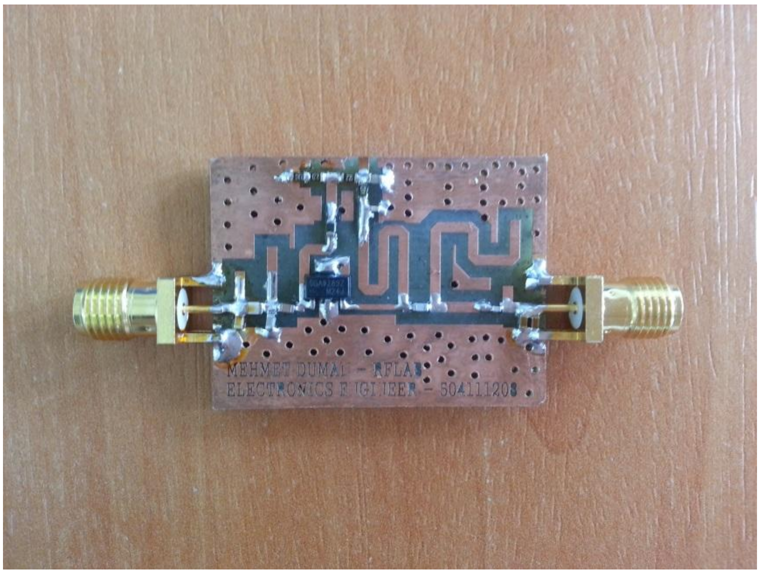

Figure 3.11 : PCB with Components.

3.4.3 Real experiments

In real experiments, the results have been obtained at 393 MHz center frequency. The S parameters are very close to the MWOAWR computer program tests. In the following figures the real S parameter values are shown:

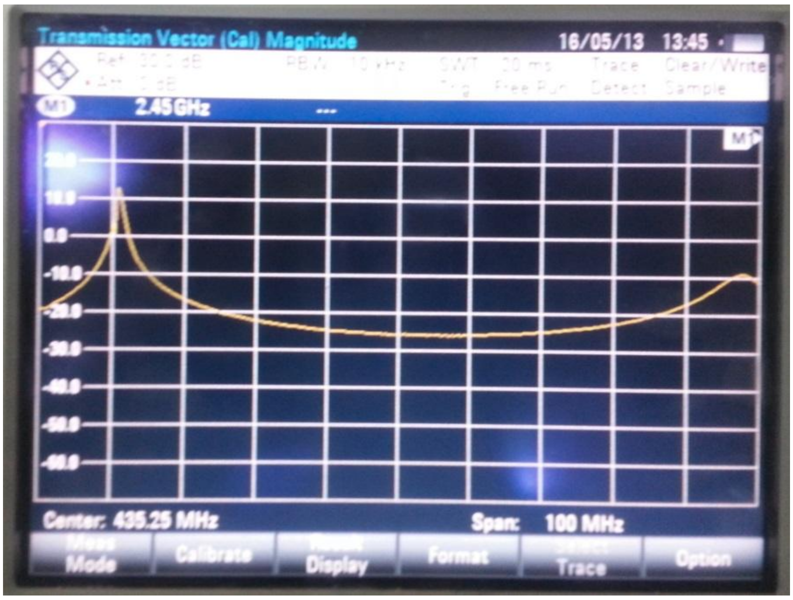

Figure 3.12 : Real S11 Figure.

In Fig. 3.12, the S11 parameter value is about -10 dB at the 393 MHz. The center frequency shifted 42 MHz approximately.

Figure 3.13 : Real S22 Figure.

In Fig. 3.13, the S22 parameter value is about -10 dB at the 393 MHz. The center frequency shifted 42 MHz too.

Figure 3.14 : Real S21 Figure.

In Fig. 3.14, the S21 parameter value is about 14 dB at the 393 MHz.

In real experiment, the collector current is 230mA, consequently, the power which is consumed is shown as:

$$(230mA)^2 \times 10 = 0.529\,Watt \qquad \textbf{(3.2)}$$

Here the resistor is implemented in the value of 10Ω. The output power is about 0.65 Watt.

In the Fig.3.15, the power amplifier circuit's final version is shown:

Figure 3.15 : Final version of the power amplifier.

4. RESULTS AND DISCUSSION

In this chapter, the comparison of experiments which are done in the Microwave Office AWR program and in the real world will be given and the results will be explained. There is also information about the theses which were done before.

4.1 The Comparison

In the Table 4.1, the real experiment values and the MWOAWR computer program values are comparised. The center frequency shifted about 42 MHz. It can be fixed with changing the microstrip lines. The real experiment values are very close to the MWOAWR computer program.

Table 4.1 : The comparison of the real experiment values and the MWOAWR computer program values

Experiments	Center Frequency (MHz)	S11	S22	S21	Collector Current
MWOAWR Values	435.250	-11.69dB	-8.206dB	22.85dB	280mA
Real Values	393	-10dB	-10dB	14dB	230mA

4.2 The Other Theses

There are some other M.Sc. theses and articles about RF power amplifier. One of them which name is “Design of Combined Power Amplifier Using 0.35 micron SiGe HBT Technology for IEEE 802.11.a Standart” works on 5 GHz for IEEE 802.11a wireless local area network and it is also operated in Class A biasing like this thesis. Its output power changes from 40mW to 800mW. The other thesis is “The Design of a High Efficiency RF Power Amplifier for an MCM Process”. It is designed for 2.3

GHz and it has 63.9% PAE. Its output power is 30 dBm. “High Efficiency Broadband Parallel-Circuit Class E RF Power Amplifier with Reactance-Compensation Technique” is the other article and it is about high efficiency. It is operated in Class E biasing. LDMOS (laterally diffused metal oxide semiconductor) is used in this article. The other article’s name is “0.1 – 10 GHz 0.5W High Efficiency Single Transistor GaAs pHEMT (pseudomorphic high-electron mobility transistor) Power Amplifier Design Using Load Pull Simulations”. It’s output power is greater than 0.5W and PAE is greater than 45%. The other M.Sc. thesis is about distributed amplifier and its gain is 8 dB. 0.35 micron transistor technology is used in that thesis. In “Reference” section the other theses and articles is given.

In this thesis, the power amplifier works on 435.250 MHz which is the specific frequency for small satellites. Its output power is about 0.6W and the gain is about 23 dB theoretically. The bandwidth is 6.8 MHz and SGA9289z power discrete power transistor is used.

5. CONCLUSION

In conclusion, a radio frequency power amplifier was designed in the computer program which name is Microwave Office AWR and it is realized in the RF laboratory. This thesis is written to explain this amplifier. The amplifier can be used for small satellites. It can provide 23 dB gain and 0.6 Watt output power. The lossy power of this RF power amplifier is not so much; as a result, it is useful for implementing to the satellites. The other properties of this power amplifier were given in the thesis in detail.

The power amplifier was designed very small as 3.3cm×2.5cm dimensions not to cover so much area and it can be operated 435.250 MHz center frequency which is the standard frequency of small satellites.

These types of power amplifiers are so important to design our own satellites; consequently, we do not have to buy these electronic circuits from the other countries. Thus, in ten years, our own satellites may be sent to the space with 100% inland produce.

Nowadays, homeland satellites are started to designed and sent to the space such as Göktürk-2 Satellite and TÜRKSAT-3USAT which is designed and realized in the radio frequency laboratory of Istanbul Technical University. The power amplifier that is designed by me can also be used in this satellite.

After the master of science, it is planned that, new researches about small satellites will be done and new RF power amplifiers will be designed in the Ph.D.

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APPENDICES

APPENDIX A.1 : The transistor specifications

APPENDIX A.2 : The other transistors

APPENDIX A.3 : Input, output and RF circuits

APPENDIX A.1

Table A.1 : SGA9289z absolute maximum ratings

Parameter	Rating	Unit
Max Base Current (IB)	10	mA
Max Device Current (ICE)	400	mA
Max Collector-Emitter Voltage (VCEO)	7	V
Max Collector-Base Voltage (VCBO)	20	V
Max Emitter-Base Voltage (VEBO)	4.8	V
Max Junction Temp (TJ)	+150	°C
Max Storage Temp	+150	Max Storage Temp

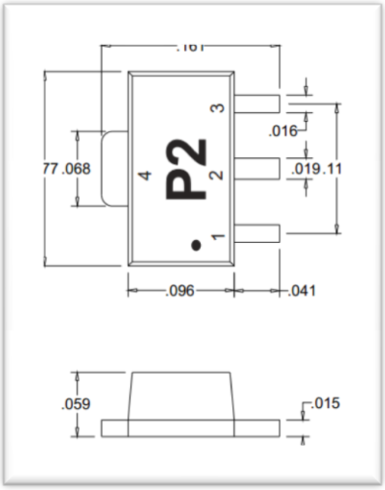

Figure A.1 : Transistor dimensions in inch.

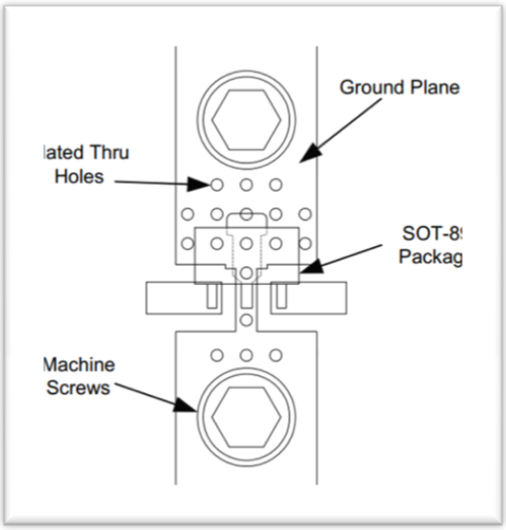

Figure A.2 : Recommended mounting configuration.

Table A.2 : SGA9289z datasheet specifications

Parameter	Specification			Unit	Condition
	Min.	***Typ.***	***Max.***		
Maximum Available Gain		20.5		dB	900 MHz, Z_S=Z_S*, Z_L=Z_L*
		13.1		dB	1960 MHz
Power Gain	16.2	17.7	19.2	dB	900 MHz [1], Z_S=Z_{SOPT}, Z_L=Z_{LOPT}
	11.0	12.0	13.0	dB	1960 MHz [2]
Output Power at 1dB Compression		28.0		dBm	900 MHz, Z_S=Z_{SOPT}, Z_L=Z_{LOPT}
	26.0	27.5		dBm	1960 MHz [2]
Output Third Order Intercept Point		42.0		dBm	900 MHz, Z_S=Z_{SOPT}, Z_L=Z_{LOPT}, P_{OUT}=+13dBm per tone
	40.0	42.5		dBm	1960 MHz [2]
Noise Figure		2.4		dB	900 MHz, Z_S=Z_{SOPT}, Z_L=Z_{LOPT}
		2.5		dB	1960 MHz
DC Current Gain	100	180	300		
Breakdown Voltage	7.5	8.5		V	collector - emitter
Thermal Resistance		32		ºC/W	junction - lead
Device Operating Voltage			5.5	V	collector - emitter
Operating Current	250	280	320	mA	

Test Conditions: VCE=5V, ICQ=280mA (unless otherwise noted), TL=25°C. [1] 100% Tested [2] Sample Tested

The other specifications of the transistor can be seen in the datasheet of SGA9289z medium power discrete SiGe HBT transistor. (SGA9289Z Medium Power Discrete SiGe Transistor Datasheet, 2006.)

APPENDIX A.2

These transistors are also examined for the thesis:

- TGF2960-SD from TriQuint
- T1G4005528-FS from TriQuint
- MAGX-000035-030000 from MACOM
- SGA8543ZDS from RFMD
- BLT50 from Philips
- BLT81 from Philips
- CLY2 from TriQuint
- CLY5 from TriQuint
- MRF321 from MACOM
- MRF327 from MACOM
- ms1649 from Advanced Power Technology RF
- NDS-023 from Nitronex
- NPTB00025 from Nitronex
- SGA9089ZDS from RFMD
- SGA9189ZDS from TriQuint
- T1G6000528 from TriQuint
- T1G6003028 from TriQuint
- umil3 from Advanced Power Technology RF
- utv005 from GHz Technology
- utv040 from GHz Technology

APPENDIX A.3

In Figure A.3, the input circuit is shown with using MWOAWR.

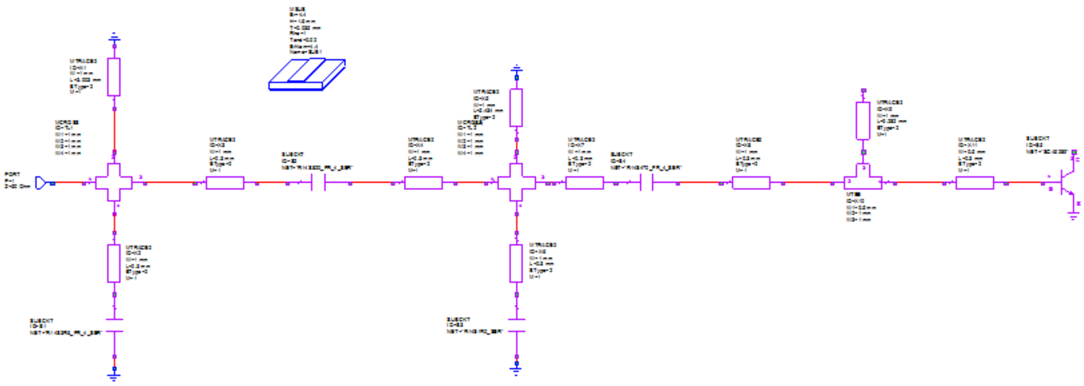

Figure A.3 : Input circuit schematic.

In Figure A.4, the output circuit is shown with using MWOAWR.

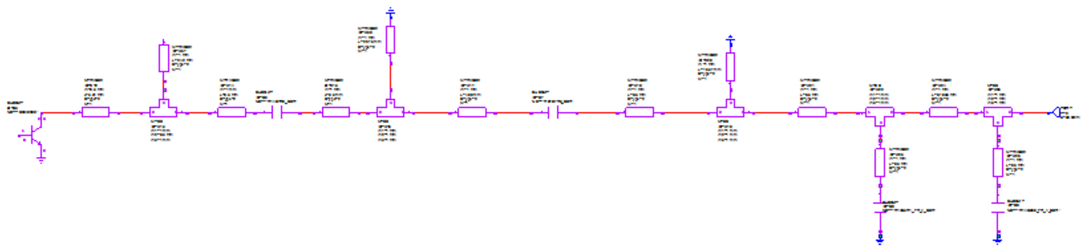

Figure A.4 : Output circuit schematic.

In Figure A.5, all of the RF circuit is shown with using MWOAWR.

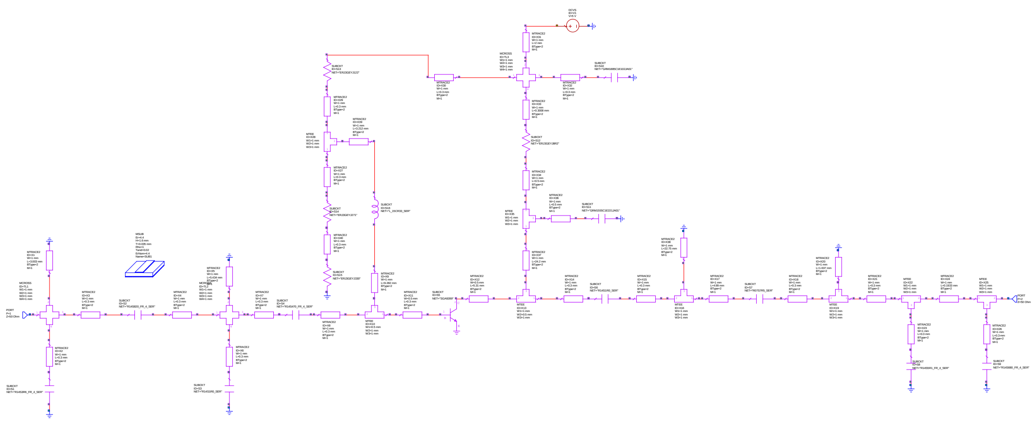

Figure A.5 : RF circuit schematic.

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