DOKUZ EYLUL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

A HIGHLY EFFICIENT DOHERTY POWER AMPLIFIER BASED ON CLASS AB AND CLASS C AT 2.6 GHZ

by
Erhan KUŞ

October, 2010
İZMİR

A HIGHLY EFFICIENT DOHERTY POWER AMPLIFIER BASED ON CLASS AB AND CLASS C AT 2.6 GHZ

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **“A HIGHLY EFFICIENT DOHERTY POWER AMPLIFIER BASED ON CLASS AB AND CLASS C AT 2.6 GHZ”** completed by **ERHAN KUŞ** under supervision of **ASSOCIATE PROFESSOR YEŞİM ZORAL** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

This thesis presents a highly efficinet Doherty type high power amplifier appropriate for various WiMAX applications. The power amplifier consists of a Class AB type main amplifier which operates linearly and efficiently at low power levels and a Class C auxillary amplifier which starts to operate at high input power levels. The gain compression behaviour shown by Class AB type power amplifier is suppressed by the gain expansion behaviour of Class C type power amplifier at high power levels by adjusting the third order products of each amplifier outphased. Therefore, more linear power amplifier can be obtained even at high power levels.

First an unequal wilkinson power divider designed to divide power at 1:2 ratio for both amplification parts. That lets the whole amplifier transmit maximum output power at maximum input power. Then for the choosen LDMOS amplifier, optimum input and output matched amplification stage prototype designed carefully using loadpull simulations. Finally Doherty amplifier operating at 2.6GHz designed and simulated. Operated at 25V power supply, P_1dB is 46.6dBm and gain at this input power is nearly 9dB. The Power Added Efficiency (PAE) corresponding to P_1dB is 51.1% and at 6dB backoff is 40%.

Keywords: Doherty power amplifier, Wilkinson power splitter, WiMAX, efficiency, high power.

2,6 GHZ'DE YÜKSEK VERİMLİLİKLE ÇALIŞAN AB SINIFI VE C SINIFI TABANLI DOHERTY GÜÇ YÜKSELTİCİSİ

ÖZ

Bu tezde çeşitli WiMAX uygulamaları için uygun bir Doherty güç yükselticisi sunulmaktadır. Güç yükselticisi düşük güçlerde lineer ve verimli şekilde çalışan AB sınıfı ana güç yükselticisi ve yüksek giriş güçlerinde çalışmaya başlayan C sınıfı yardımcı güç yükselticisinden oluşmaktadır. Yüksek güçlerdeki AB sınıfı güç yükselticinin kazanç sıkışması davranışı, C sınıfı çalışan yükselticinin kazanç genleşmesi davranışıyla üçüncü derece harmoniklerinin üst üste getirilmesi ile bastırılmaktadır. Bu sayede yüksek güç seviyelerinde de lineer bir güç yükselticisi elde edilmektedir.

Öncelikle gücü iki yükseltici kat için 1:2 oranında bölecek eş olmayan bölümlü Wilkinson güç yükselticisi tasarlanmıştır. Bu tüm yükselticinin maksimum giriş gücünde maksimum çıkış gücünü üretmesini sağlar. Daha sonra seçilmiş olan LDMOS yükseltici için yük çekme simülasyonları yapılarak giriş ve çıkışı optimum olarak eşleştirilmiş yükseltici katı protatip olarak üretilmiştir. Son olarak da 2,6 GHz de çalışan Doherty güç yükselticisi tasarlanmış ve simülasyonları yapılmıştır. 25V besleme gerilimi uygulanırken P_1dB 46,6dBm ve bu güçteki kazanç 9dB olarak elde edilmiştir. P_1dB ye ait güç katan verimliliği %51.1 ve bunun 6dBm gerisindeki verimlilik ise %40 olarak elde edilmiştir.

Anahtar Kelimeler: Doherty güç yükselticisi, Wilkinson güç bölücü, WiMAX, verim, yüksek güç.

CONTENTS

CHAPTER ONE

INTRODUCTION

1.1 Introduction

Mobile communication solutions have became inevitable parts of our daily life. In order to offer data transfer like wireless multimedia, internet and voice; wireless data infrastructures are deployed into public zones. The battle to extend the operation and stand by time of radio frequency devices never ends, even increases each day. Accordingly the progress in wireless communication has also been pushing the evolution of the wireless communication systems and innovation of the Radio Frequency (RF) circuits, effectively Power Amplifiers (PA).

Wireless standarts using constant envelope modulation scheme such as Global Systems for Mobile Communications (GSM), could utilize nonlinear PA's as they generally offer higher efficiency than linear PA's. As the data transmitted within the allowed bandwidth is low, linearity is not a big concern. However, modern wireless communication systems generally use modulation schemes which modulates both amplitude and phase for the efficient use of frequency bandwidth. Such systems need high data-rate so their one of the most power thursty element, power amplifier, starts consuming inefficient power. Because high data-rate of modulated signals leads to high Peak to Average Power Ratio (PAR) and forces the PA to operate at large Back off Power (BOP) (Lee Y., Lee M., & Jeong, 2008a). The increase between the peak power and average power level compose high linearity requirement. Unfortunately, classic linear PA's only operate efficiently close to saturation (high) power levels. From the RF PA design point of view, achieving both high efficiency and linearity is a challenging problem because to acquire linearity, most of the DC supply power is sacrificed.

In order to overcome efficiency issues of the PA's, several efficiency enhancement teqhniques have been introduced such as Doherty structure, envelope elemination and restoration, Chirex’s outphasing and bias adaptation. In this dissertation Doherty type efficiency enhancement technique is approached as the operation area of the amplifier is decided to be for possible applications like Worldwide Interoperability for Microwave Access (WiMAX) which require high efficiency at BOP and good linearity even at high power levels.

1.2 Efficiency Issue of Power Amplifiers at Back off Power

RF PA is a circuit which converts DC power into significant amount of RF output power. Efficiency of the PA can be evaluated as its DC to RF conversion capability. The PA is the last active and also mostly the leading power consuming block in a transmitter chain. It amplifies the modulated RF signal to required power level enough to be sensed by the reciever antenna. Regarding to its high power relation, PA’s DC power requirement dominates the overall power consumption of the transceiver. Hence, the efficiency of the PA which is defined as the ratio of the output power to the DC power consumption has a major impact on the overall efficiency of the system. For example the PA of a cellular handset can consume up to 70% of the battery supply power during data transmission (Nagle, Burton, Heaney, & McGrath, 2001).

Power amplifiers operate at maximum efficiency when they are close to their saturation point. At low power levels away from the saturation, their efficiency drastically drops. Figure 1.1 shows representative Code Division Multiple Access (CDMA) Probability Density Function (PDF) and PAE data of a class AB amplifier. As seen in the figure PDF the amplifier operates mostly pretty far below of the maximum efficiency power. Maximum efficiency is above 40% while the efficiency at average power level is less than 5%. That means more than 90% of the DC power is wasted as heat (Yhao, 2006). A lot of energy waste under backed off operation oftenly occur in modern communication systems. In order to decrease current drawn from the DC supply and save energy, the efficiency at backed off power levels need

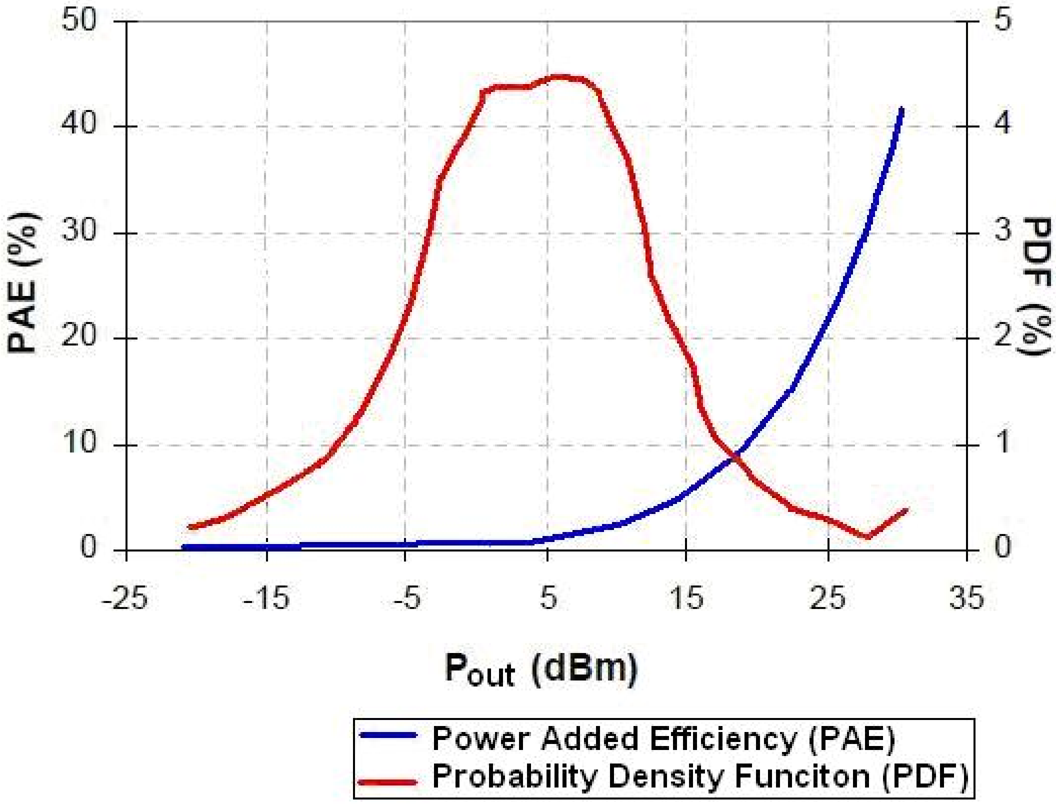


Figure 1.1 Representative PDF and PAE of a class AB PA

to be improved in such systems. Besides saving power, efficiency enhancement also decreases the wasted heat and its cooling expense. Additional advantage is to deal with more simple, cheap and also less space covering cooling mechanism.

1.3 WiMAX

WiMAX is an Institute of Electrical and Electronics Engineers (IEEE) standard known as broadband wireless access alternative to cable modem service and Digital Subscriber Line (DSL) service. It is a recently and fast developing exciting technology that gets its popularity from the mobile broadband internet access service. Firstly the frequency spectrum of WiMAX is designed to be between 10 to 66GHz. Then with IEEE 802.16a standart, 2 to 11GHz frequency band is also attached. Currently, focus is given to frequency bands between 2 to 6GHz portions of the spectrum (Fujitsu Microelectronics America, 2004). WiMAX presents various applications as but not limited to Voice over Internet Protocol (VoIP), Internet

Protocol Television (IPTV), mobile telephone service, mobile data TV, T1/E1 substitute for business, mobile emergency response services. WiMAX provides fixed or mobile non-line-of sight service from a base station to a subscriber station. It promises a radious of 6 miles range with one base station allowing approximately 40Mbps data applications (What is WiMAX, n.d.). All these features makes rapid increase in WiMAX base stations and its applications all over the world. Utilizing Orthogonal Frequency-Division Multiplexing (OFDM) based communication protocol, WiMAX base stations could also suffer from back off power efficiency issues and need improvement.

1.4 Research Goals

The main objective of this research is to design a high power, linear and highly efficient PA. Main focus is to provide high efficiency both at maximum and average power levels comparing to classic PA’s. Hence, various problems in high efficiency linear amplifier design will be addressed and attempted to be solved. To fullfill these high efficiency and linearty simultaneously, practical design issues of the Doherty PA is to be analyzed. By carefully investigating the characteristics of the Doherty PA simulations, optimum efficiency and linearity is to be obtained.

1.5 Organization

The rest of this dissertation is organized as follows. In Chapter 2, firstly basics of RF PA’s are briefly described. Then design characteristics of a PA are issued in a more detailed manner. Furthermore the classes of operation in RF PAs are explained. Finally in this chapter design process of RF PA is mentioned beginnig with the transistor selection. Chapter 3 covers the theoritical Doherty PA concept. To begin with, a brief introduction to Doherty structure is presented. After that the theory of Doherty PA is inspected elaborately. In Chapter 4, with the help of the theory, proposed Doherty PA design is examined. The theoretical simulation and experimental results are presented. At last in Chapter 5, the obtained consequences of the design are presented.

CHAPTER TWO
RF POWER AMPLIFIER FUNDAMENTALS

2.1 RF Power Amplifier Basics

Radio frequency PA is a key element of a wireless communication system. It is used in trancievers for wide variety of purposes and mainly used to amplify low power signal into larger signal of significant power that holds the information we need to deliver. The required level of output power is determined by the communication system such that the reciever can sense the signal adequately. The required power levels vary from hunderds of watts (eg. in satellite systems) to ten miliwatts (eg. in home RF) as it is adjusted to application necessity. Generally the PA dominates the power consumption of the tranciever. Therefore, the efficiency of the amplifier plays critical role overall the entire system. The simple block diagram of RF power amplifier can be seen in Figure 2.1 (Kazimierczuk, 2008).

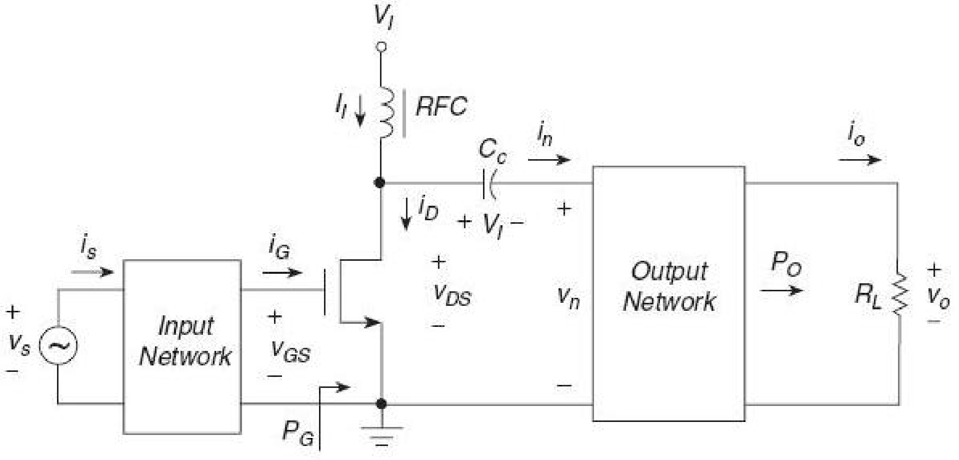


Figure 2.1 Block Diagram of RF Power Amplifier

2.2 Design Characteristics of RF Power Amplifiers

RF Power Amplifier design characteristics can be ordered as their output power, efficiency, linearity, stability and gain.

2.2.1 Output Power

The output power is a key charachteristic of an RF power amplifier as the amplifier must meet the power requirements of the connection system. The output power (P_{out}) is generally defined in watts or dBm. P_{1dB} is the point where P_{out} is 1dB less than its linearly projected value. $P_{\max}$ is the maximum output power and also the saturation point of the amplifier. $P_{\max}$ is roughly 2-3dB higher than P_{1dB} .

2.2.2 Efficiency

Usually the RF power amplifier is the most power thursty element of the entire transceiver. For instance cellular handsets PA can consume more than %70 of the DC battery power during transmit period (Nagle, Burton, Heaney, & McGrath, 2001). Power saving demand for wireless systems are ever-growing and efficiency of RF power amplifiers is remarkably important. In mobile systems, efficiency enhancement shows its primary benefit on the increase of the battery life while in high power applications like base station transmitters it minimizes the cooling expense as dissipated power is generally in the form of heat.

The main purpose of the PA is to deliver approprate output power to the following block in the transmitter which is generally the antenna. This significant amount of output power is obtained by using the DC power and converting it to amplify the input RF power. Here, the ability of the amplifier to convert DC power to RF power is named as its efficiency (η) and defined as

$$\eta = \frac{P_{out}}{P_{DC}} \tag{2.1}$$

where P_{out} is the output RF power delivered to the load and P_{DC} is the DC power drawn from the power supply. If MOS transistor is used as the amplifier and P_{DC} is evaluated as only the PA supply power, then the efficiency is called drain efficiency (η_D). If bipolar transistor is used, it is named as collector efficiency.

Drain efficiency can't fulfill enough to express the power conversion ability of the PA. Because drain efficiency doesn't take into account the power required to drive the PA input. The metric that is commonly used to include the effect of the input drive power is PAE, which is defined as

$$PAE = \frac{P_{out} - P_{in}}{P_{DC}} \tag{2.2}$$

where P_{in} is the input drive signal power.

2.2.3 Linearity

The trancievers must have a good linearity in order to preserve the information in both the amplitude and phase as modern communication systems widely use modulation schemes of nonconstant envelope signals. They usually have high peak to average ratio and linearity is critical to preserve the variation in the carrier (Gilmore, & Besser, 2003). To minimize interference and spectral re-growth, trancievers must be linear (Kazimierczuk, 2008). Nonlinearities at PA can lead to corrupted information signal at the output and break the reliability of the communication system. A simple way to explain linearity is to define it as the derivative of the gain, where it is perfect when equal to zero. If the derivative deviates from zero at high power levels, gain expansion or compression occurs and nonlinearities increases. However this definition is acceptable only for amplitude to amplitude (AM - AM) analysis. AM – AM shows relation between amplitude of the input signal and amplitude of the output signal while AM – PM (amplitude modulation to phase modulation) shows amplitude of the input signal and phase of the output signal. Bandwith, phase shift… etc. are also other linearity concerns. Linearity of the AM – AM characteristic is expressed with P_{1dB} as it is the output power point where the gain is compressed 1 dB. And phase change with different input signal amplitudes in AM – PM systems shows their linearity (Wongkomet, 2006).

Some metrics which specifies linearity are IMD3 (3rd order intermodulation distortion), ACLR (adjacent channel leakage ratio) or ACPR (adjacent channel power ratio) and EVM (error vector magnitude). When two input signals are applied to an amplifier simultaneously the odd order intermodulation products are close to the fundamental tone frequencies. IMD3 is the difference between fundamental output power and 3rd order intermodulation product power which has the most nonlinear effect on the amplifier. Those intermodulation products causes the spectrum to have a stepped view and these steps are named as regrowth sidebands or Adjacent Channel Power (ACP) (Cripps, 1999). You can see those sidebands on Figure 2.2. Ratio of the total power in the band and the power adjacent band of interest is the ACPR. Some communication standarts restrict the ACPR for each of the intermodulation products below some power level while some explicitly do not. EVM is a measure of error vector length to the distance from the actual transmit data point to the ideal data point as shown in Figure 2.3.

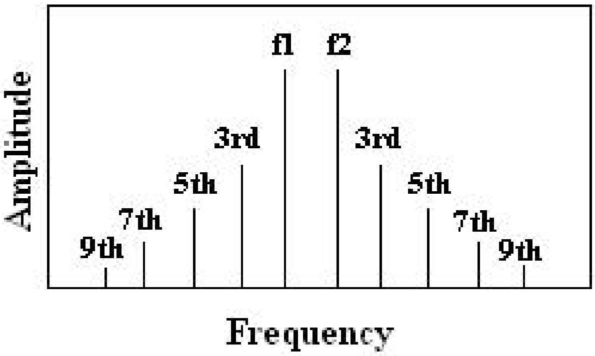


Figure 2.2 Two tone fundamental inputs and intermodulation products

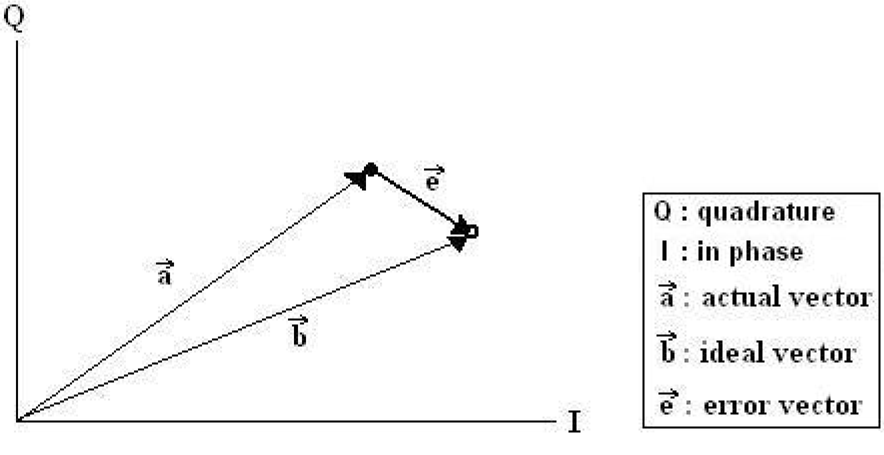


Figure 2.3 Error Vector

Most nonlinearities of the amplifier could be prevented by proper input and output matching, effective filtering and isolation. However some systems need linearity more then usual. Further linearization techniques like feedback, feedforward, predistortion, postdistortion could be used in such systems.

2.2.4 Stability

Stability at interested frequency is one of the most important requirements that an RF power amplifier must meet. Figure 2.4 shows the source, load, input and output reflection coefficients seen on general transistor amplifier circuit.

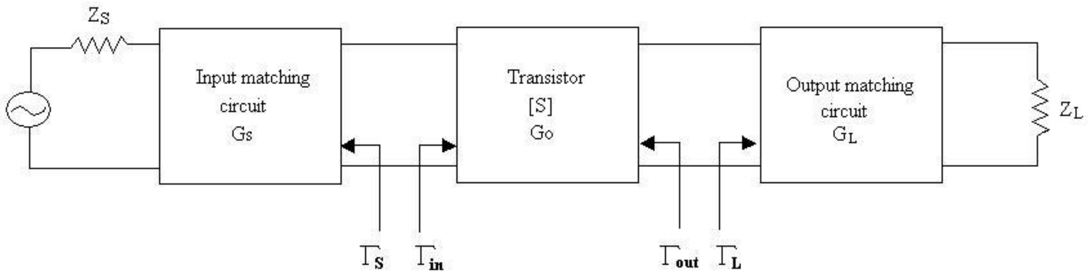


Figure 2.4 General transistor amplifier circuit

An amplifier could oscillate if either the input or output port impedance has negative real part. That implies $|\Gamma_{in}| > 1$ or $|\Gamma_{out}| > 1$ which means positive feedback. Γ_{in} and Γ_{out} depend on the source and load matching networks as

$$|\Gamma_{in}| = \left|\frac{S_{11} - \Gamma_L \Delta}{1 - S_{22}\Gamma_L}\right| \tag{2.3}$$

$$|\Gamma_{out}| = \left|\frac{S_{22} - \Gamma_S \Delta}{1 - S_{11}\Gamma_S}\right| \tag{2.4}$$

Here Δ is the determinant matrix of s-parameters which is defined as $\Delta = S_{11}S_{22} - S_{12}S_{21}$. While the s-parameters are fixed for operating frequency the stability of the amplifier depends on Γ_S and Γ_L as presented by the matching networks (Pozar, 1998), (Ludwig, & Bretchko, 2000).

2.2.4.1 Unconditional Stability

Unconditional stability is the situation where an RF PA is stable throughout the entire domain of the Smith chart at selected bias and frequency condition. An RF PA circuit system must satisify the requirements of $|\Gamma_{in}| < 1$ and $|\Gamma_{out}| < 1$ for all passive source and load impedances to be unconditionally stable. If the device is unilateral ($S_{12} = 0$) then $|S_{11}| < 1$ and $|S_{22}| < 1$ are sufficient for being unconditionally stable. Alternatively, the device will be unconditionally stable if Rollet factor (k stability factor) satisifies

$$k = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}S_{21}|} > 1 \tag{2.5}$$

and determinant matrix must be $|\Delta| < 1$.

2.2.4.2 Conditional Stability

An RF PA circuit system is conditionally stable if $|\Gamma_{in}| < 1$ and $|\Gamma_{out}| < 1$ for only a certain range of passive source and load impedances and also referred to as potentially stable. This range of Γ_S and Γ_L could be found by using Smith chart and drawing input and output stability circles.

Output stability circle equations could be derived from (2.4) for $|\Gamma_{out}| < 1$ and using some algebra gives

$$r_{out} = \frac{|S_{12}S_{21}|}{||S_{22}|^2 - |\Delta|^2|} \tag{2.6}$$

$$C_{out} = \frac{(S_{22} - S_{11}^{*}\Delta)^{*}}{|S_{22}|^2 - |\Delta|^2} \tag{2.7}$$

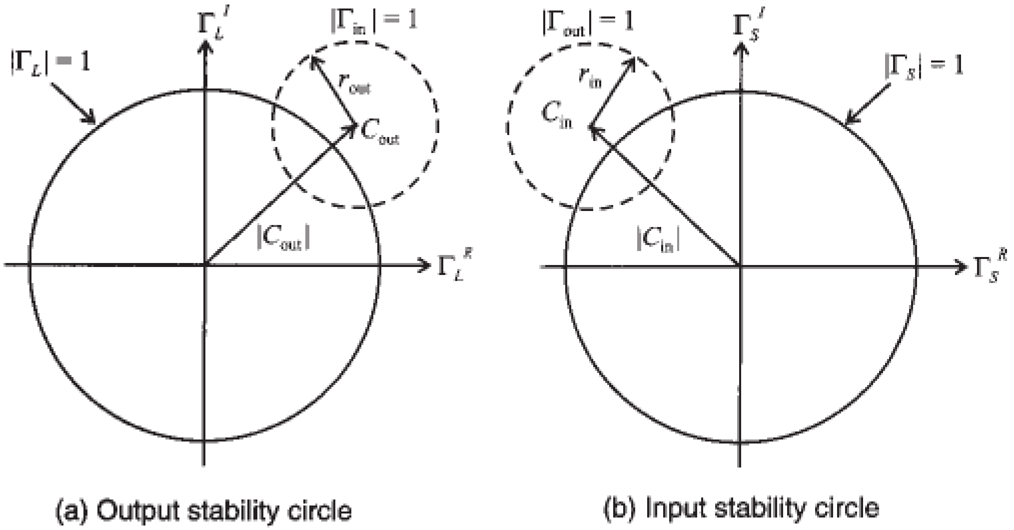
where r_{out} is the radious and C_{out} is the center of the output stability circle.

Input stability circle equations could be derived from (2.3) for $|\Gamma_{in}| < 1$ and using some algebra gives

$$r_{in} = \frac{|S_{12}S_{21}|}{||S_{11}|^2 - |\Delta|^2|} \tag{2.8}$$

$$C_{in} = \frac{(S_{11} - S_{22}^*\Delta)^*}{|S_{11}|^2 - |\Delta|^2} \tag{2.9}$$

where r_{in} is the radious and C_{in} is the center of the input stability circle. Figure 2.5 shows sample stability circles of Γ_L and Γ_S (Ludwig, & Bretchko, 2000).



(a) Output stability circle

(b) Input stability circle

Figure 2.5 Sample stability circles of Γ_L and Γ_S

We can draw input and output stability circles of the device if we know its s-parameters. In order to decide in which part of the Smith chart the device is stable, we can use the following technique:

For output stability circle if we set $Z_L = Z_0$ then $\Gamma_L = 0$ and (2.3) shows that $|\Gamma_{in}| = |S_{11}|$. Now if $|S_{11}| < 1$ then $|\Gamma_{in}| < 1$ so $\Gamma_L = 0$ must be in a stable region. That means all the Smith chart exterior to the stability circle defines stable range of Γ_L. However, if $|S_{11}| > 1$ then $|\Gamma_{in}| > 1$ so $\Gamma_L = 0$ and center of the Smith chart must be in unstable region. In this case stable region of Γ_L is the intersection region of Smith chart with the output stability circle. Similar results could be applied to the input stability circle (Pozar, 1998), (Ludwig, & Bretchko, 2000).

2.2.5 Gain

When we talk about gain in RF power amplifiers, it is the measure of the ability of the PA circuit to increase the power of a signal from the input to its output. In two port networks there are three important power gains which are power gain, available power gain and transducer power gain.

2.2.5.1 Power Gain

Power Gain (G) is the ratio of power dissipated in the load to the power delivered to the input of the network. This gain is independent of source impedance but strongly dependent in the amplifier circuit (Pozar, 1998). G can be written as;

$$G = \frac{P_L}{P_{in}} \tag{2.10}$$

2.2.5.2 Available Power Gain

Available Gain (G_A) is the ratio of the maximum average power available from the network to the maximum power available from the source (Pozar, 1998). Available gain can be written as;

$$G_A = \frac{P_{Load,\max}}{P_{Source,\max}} \tag{2.11}$$

2.2.5.3 Transducer Power Gain

Transducer power gain quantifies the gain of an amplifier. Transducer power gain of a two port network shown in Figure 2.2 can be written as

$$G_T = \frac{\text{Power delivered to the load}}{\text{Power available from matched source}} = \frac{P_L}{P_{AVS}}$$

$$= \frac{(1-|\Gamma_S|^2)|S_{21}|^2(1-|\Gamma_L|^2)}{|(1-S_{11}\Gamma_S)(1-S_{22}\Gamma_L)-S_{12}S_{21}\Gamma_S\Gamma_L|^2} \tag{2.12}$$

However the physical interpretation of (2.12) is hard to find. Thus we can use

$$G_T = \frac{1-|\Gamma_S|^2}{|1-\Gamma_{IN}\Gamma_S|^2}|S_{21}|^2\frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2} \tag{2.13}$$

or

$$G_T = \frac{1-|\Gamma_S|^2}{|1-S_{11}\Gamma_S|^2}|S_{21}|^2\frac{1-|\Gamma_L|^2}{|1-\Gamma_{OUT}\Gamma_L|^2} \tag{2.14}$$

where these two equations express the transducer gain in means of arbitrary source and load termination and basic gain of the amplifier. Finding transducer power gain requires the knowledge of s-parameters and source and load terminations connected to the input and output port. A special case often employed to approximately find the transducer power gain occurs when $S_{12} = 0$ or neglectable. This is called unilateral transducer power gain and shown as

$$G_{TU} = \frac{(1-|\Gamma_L|^2)|S_{21}|^2(1-|\Gamma_S|^2)}{|1-\Gamma_L S_{22}|^2|1-S_{11}\Gamma_S|^2} \tag{2.15}$$

Transducer power gain expression can also be greately simplified with a few assumptions. If we assume the source and the load are perfectly matched to the system characteristic impedance Z_0, this implies $\Gamma_S = \Gamma_L = 0$, therefore

$$G_T = |S_{21}|^2 \tag{2.16}$$

This expression can be described in decibels as

$$G_T(db) = 20\log|S_{21}| \tag{2.17}$$

2.3 Categories of Power Amplifiers

Two different categories of power amplifiers are involved in this section. Those include their classes of operation and them on switching mode.

2.3.1 Classes of Operation of Power Amplifiers

Power amplifiers can simply be classified into their classes of operation. This classification is based upon the conduction angle of the drain (collector) current where biasing condition (operating point) of the transistor determines this angle (Kazimierczuk, 2008).

2.3.1.1 Class A Power Amplifiers

This type of amplifiers are biased such that the active device stays in its conducting (linear) region all of the time. The operating point is selected between the cut-off and the saturation point carefully thus drain (collector) current flows during the complete cycle ($\theta = 360^o$) of the input signal. That provides a familiar output of the input signal where its amplitude is magnified. Operation point of the class A amplifier is seen in Figure 2.6 and input output signals can be seen in Figure 2.7;

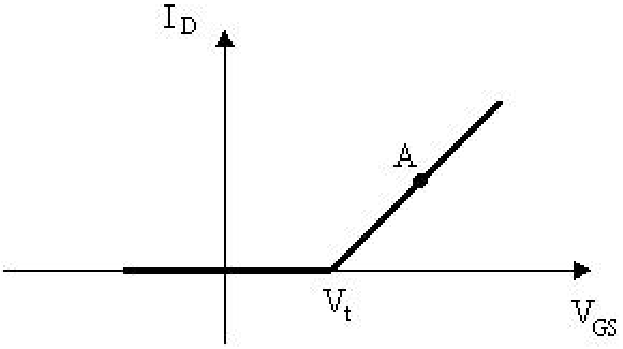


Figure 2.6 Operation point of class A power amplifier

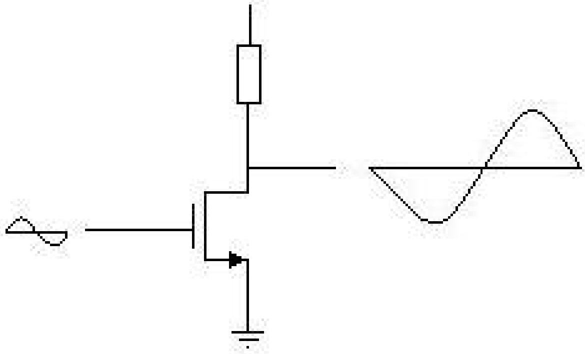


Figure 2.7 Input and output signals at class A power amplifier

Class A PA's yields low harmonic distortion and low intermodulation distortion. There are no nonlinearities of signal clipping since the device is turned on all the time (Kazimierczuk, 2008). Therefore, class A type PA's are considered to be the most linear of all. Besides its linearity advantage, class A PA's have insufficient efficiency. Theoretical maximum efficiency is 50% while obtainable efficiency rarely exceeds 30-40% due to the nonlinear effects of the transistor and finite quality factors of passive components (Gilmore, & Besser, 2003).

2.3.1.2 Class B Power Amplifiers

In class B power amplifiers current flows only half of the cycle, corresponding to its $\theta = 180^{o}$ conduction angle. This is achieved by choosing the operation point right at the boundry (threshold voltage) between the cut-off and active regions of the transistor (Kazimierczuk, 2008), (Gilmore, & Besser, 2003). During one half, the transistor is in the cut-off region and no current flows. While the current flows half of the time, output current is simply half-wave rectified sinusoid (Gilmore, & Besser, 2003). Assuming the transconductance of the transistor is constant and nonlinearities occured by passive elements are neglectible, theoretical maximum gain is 78.5% (Ludwig, & Bretchko, 2000). But when all these nonlinearities taken into account, obtainable efficiency is lesser. Operation point of the class B amplifier is seen in Figure 2.8 and input output signals can be seen in Figure 2.9;

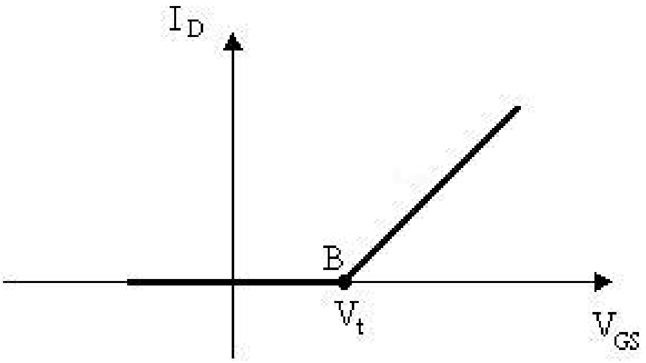


Figure 2.8 Operation point of class B power amplifier

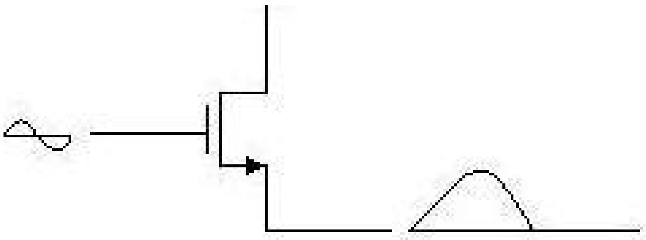


Figure 2.9 Input and output signals at class B power amplifier

Besides their high efficiency class B power amplifiers can’t perform good linearity as the signal distorts greatly because of half wave conduction. In order to acquire a full sine wave at the output, class B amplifiers are generally used in push pull structure. N type and P type transistors operate at different half of the cycle and compose a full wave at the output as depicted in Figure 2.10. However, there occurs a nonlinearity at the union section which is called notch distortion. Class B type power amplifiers are prefered in RF applications where the linearity of the signal is not very important.

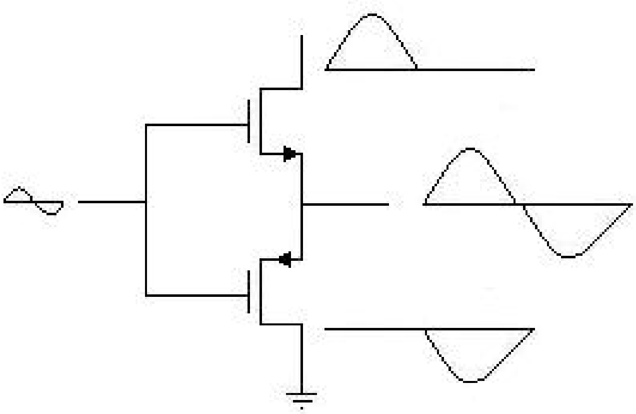


Figure 2.10 Input and output signals at class B push pull power amplifier

2.3.1.3 Class AB Power Amplifiers

Class AB amplifiers combines the properties of class A and class B power amplifiers and are better choice for the trade-off between the efficiency and linearity. They are biased carefully above the threshold voltage in order to satisify both linearity and efficiency needs. The conduction angle varies between 180^o-360^o hence the theoretical maximum efficiency is located between 50-78.5 %. Class AB power amplifiers are also usually employed in push pull structure. As the transistors operates in the active region more than half cycle, notch distortion at the union point gets smaller. Therefore more linear and efficient transistor is achieved with this structure.

2.3.1.4 Class C Power Amplifiers

In class C power amplifiers we have drain (collector) current less then half of the cycle. That provides us to have more efficient amplifier than class B where theoretical efficiency can reach up to 100 % (Kraus, Bosian, & Raab, 1980). Conduction angle is between 0^o-180^o and efficiency increases while conduction angle is choosen smaller (Kazimierczuk, 2008). Operation point of the class C amplifier is seen in Figure 2.11 and conduction angle efficiency relation of classical PAs can be seen in Figure 2.12;

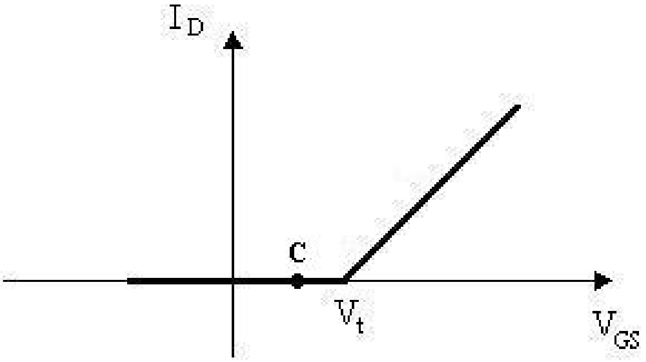


Figure 2.11 Operation point of class C power amplifier

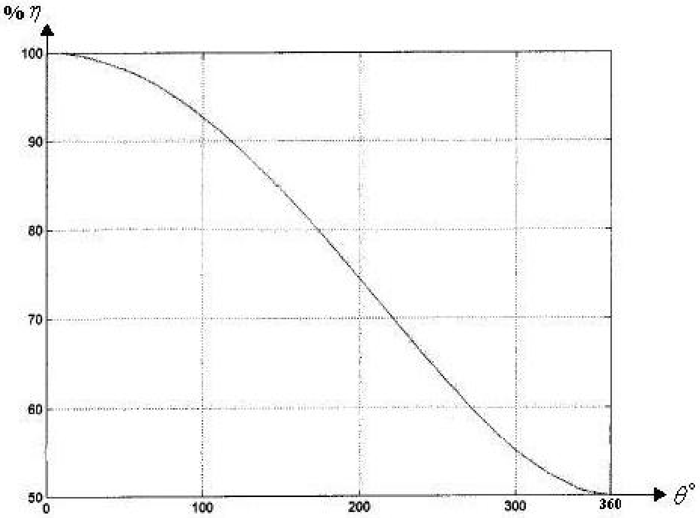


Figure 2.12 Efficiency versus conduction angle

As transistor is biased below the threshold voltage and active less then half of the input drive cycle, there exists a very high distortion at the output wave. However, class C power amplifier is considered as linear, because amplitude of the drain (collector) current is proportional to the amplitude of the gate to source voltage (Kazimierczuk, 2008). Sinusoidal input and output signals of class C amplifier is seen in Figure 2.13;

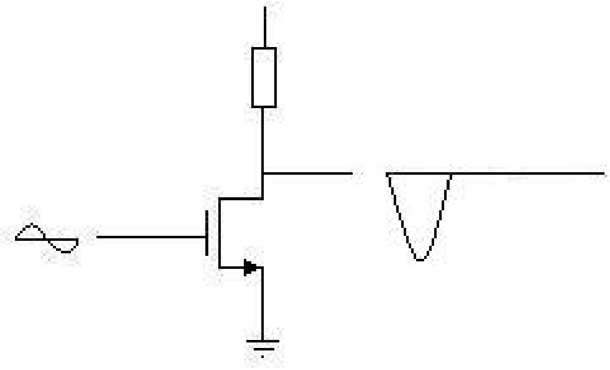


Figure 2.13 Input and output signals at class C power amplifier

In order to obtain output signal with highly efficient background, there should be a high input drive power. So it is impossible to have both high efficiency and high power in class C power amplifiers. This type of amplifiers are usually used in nonlinear applications where the information is carried on the phase of the signal.

2.3.2 Switching Mode Power Amplifiers

Switching mode amplifiers attain their name from the operating condition of the transistor as it works like a switch rather than a voltage dependent current source. The transistor is driven like a switch between two discrete idealized states on and off (Gilmore, & Besser, 2003). Ideally, in on state transistor is assumed to behave like a short circuit, in off state like open circuit and should switch between these two states instantaneously (Cripps, 1999). Switched mode amplifiers ideally 100 % efficient but inherently nonlinear as they exhibit constant envelope outputs (David, 2001). In this section Class D, E and F amplifiers will be held in a brief interest.

2.3.2.1 Class D Power Amplifiers

Class D power amplifiers use the same technique as an ideal switch as the switch current and switch voltage don't have any overlapping non-zero instance. Hence there is no loss in the switch (Wongkomet, 2006). The amplifier is used in push pull configuration and differential signal is applied to each transistors so that they operate $\theta = 180^o$ out of phase (Gilmore, & Besser, 2003). If we assume there is no parasitic capacitance and other passive componets of the amplifier are also lossless, theoretical 100 % efficiency could be achieved. Capacitive loss could be significantly reduced by using series LC tank, thus practical efficiency could be increased (Yhao, 2006). However class D power amplifiers are not prefered much in RF applications because of substantial loss from the output capacitance at high switching speed (Cui, 2007).

2.3.2.2 Class E Power Amplifiers

Transistors operated on class E amplifiers are also used in switching mode and applied with a passive load network. This network contains series resonant circuit and a capacitor parallel to the transistor (Cui, 2007). Class E power amplifiers are the most efficient amplifiers knows so far and can theoretically reach up to 100 % efficiency (Kazimierczuk, 2008). This is achieved by choosing resonant circuitry components properly so as to turn on the switch at zero voltage. The current and voltage waveforms of the switch are displaced with respect to time and don't overlap during the switching time intervals, as a consequence there occurs no switching loss (Kazimierczuk, 2008). However the performance of class E amplifier strictly dependent to the load impedance and output shunt susceptance (Bui, 2008). The high peak voltages of class E amplifiers are their most known drawbacks as it forces the reliability of the transistor (Wongkomet, 2006). It is also difficult to realize a CMOS transistor to follow sharp change requirements in the time domain (Yhao, 2006).

2.3.2.3 Class F Power Amplifiers

In class F power amplifiers, output harmonics are tuned reactively in order to prevent power loss at harmonic frequencies. This ensures low transistor voltage even at high current values and enhances efficiency which is theoretically 100% (Gilmore, & Besser, 2003). Although they seperate at load tuning technique, class E and class F amplifiers are considered closely related. These type of amplifiers are difficult to design due to their complex output matching networks.

2.4 RF Power Amplifier Design Process

RF power amplifiers have wide variety of uses as they occupy significant place in daily communication life. Some of the applications they are inavitably employed are low noise, broadband, high gain and high power amplifiers. Each application specific amplifiers have their own priority at design process.

2.4.1 Transistor Selection

A wide wariety of active device technologies are currently available in RF power amplifiers such as BJT, MOSFET, LDMOS, JFET, GaAs and SiGe MESFET, HFET and HEMT, HBT, MMIC and these devices are available in packaged, die, grown-to-order forms (Raab, Asbeck, Cripps, Kenington, Popovic, Pothecary, et. al., 2003). These technologies and forms provide different dominant specialities to the active devices. The designer should evaluate the device properties devoted to his application needs. Silicon bipolar transistors are capable of higher gain, lower 1/f noise, lower thermal resistance and higher power capacity at low frequencies while GaAs FETs have better noise performance and can operate at much higher frequencies (Pozar, 1998), (Gilmore, & Besser, 2003). MOSFETs perform good at thermal runaway and are appropriate for switching mode operation with reactive loads. LDMOS is easy to bias and has robust thermal stability. GaAs MESFETs have high mobility thus have the capability to operate efficiently at higher frequencies while linearity is a certain drawback. HFET nad HEMT devices are high technology devices and have high prices. HBTs operate well at milimeter wave regions (30GHz – 300GHz) and can carry high currents (Bui, 2008). MMICs are matched and coupled in package and could be used from 300MHz up to 300 GHz.

Whenever the suitable transistor form and technology decided, the designer should investigate the device datasheet unless he doesn’t design the transistor itself. The properties like maximum power, maximum gain, ACPR, output capacitance, drain efficiency etc., shuold be evaluated at operating frequency satisfying for the application requirements.

2.4.2 Biasing Network

Biasing network is essential in order to guarantee the transistor operate reliably at appropriate condition. There are two type of biasing circuits which are passive and active. Passive networks are simple and easy to implement. These networks are composed of passive components which provide the appropriate voltage and currents for the RF transistor as shown in Figure 2.14. Besides their simplicity, these type of networks are sensitive to device parameter and thermal change so additional precautions should be taken.

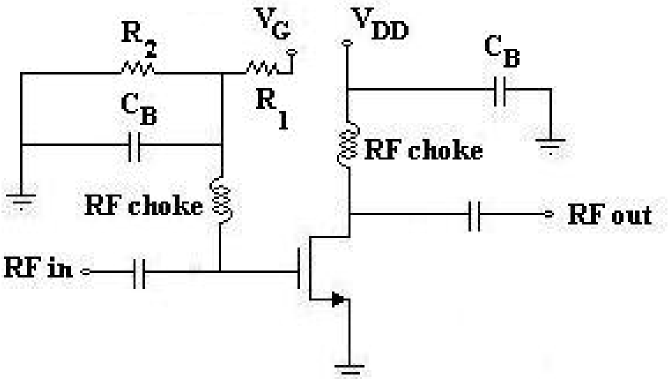


Figure 2.14 An example of simple passive biasing network

Biasing network is configured such that to set the queiscent point of the transistor in an appropriate point. Additionally, it is used to isolate the RF signal and DC power using RF chokes and DC blocking capacitors. RF chokes are usually accomplished by quarter wave transmission lines at high frequencies.

Active biasing circuits are also used often. They are complicated but have better performance compared to passive biasing network drawbacks. Active biasing circuit could be composed of a special function circuit or another low frequency transistor that controls the dc bias voltage (Gilmore, & Besser, 2003). An isolation circuit is also used in order to prevent RF losses on bias transistor. An example active biasing network can be seen in Figure 2.15;

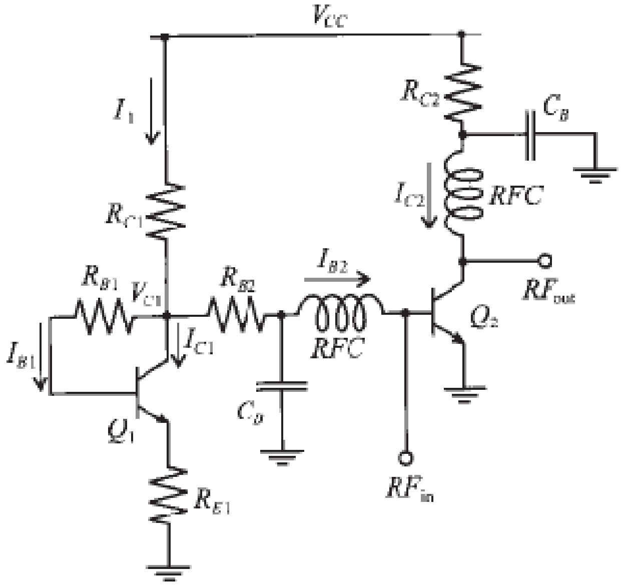


Figure 2.15 Active biasing network example for BJT (Ludwig, & Bretchko, 2000).

2.4.3 Matching the Input and Output of the Transistor

In a PA, how much power delivered to the load and how much gain and noise are produced in the process are mainly controlled by the input and output matching network. The aim is to match the load which is usually antenna and source (generator) impedances to the optimum input and output impedances of the transistor. There are several matching methods available like L sections, T and Pi type matching networks using discrete elements. At high frequencies (above 1 GHz) almost all matching is done using distributed elements which are transmission lines.

Increasing frequency and corresponding reduced wavelength forces the designer to have better control of the parasitics. As discrete components have their own parasitic effects, microstrip and striplines should be preffered as much as possible at high frequencies (Ludwig, & Bretchko, 2000). Moreover, discrete elements are fabricated only for certain values. With the availability of high quality passive components, wireless communication bands also allow hybrid matching techniques using both transmission lines and lumped elements (Cripps, 1999).

The maximum power transferred from the input generator with an output of $Z_S = R_S + jX_S$ to the load impedance $Z_L = R_L + jX_L$ could be achieved when the load impedance is equal to the complex conjugate of the output source impedance (Pozar, 1998). Here the load impedance is the input terminal of the transistor (gate or base). As the generator output impedance is usually 50Ω the complex gate (base) impedance of the transistor should be matched to this impedance level. The same principle is also valid for the output impedance of the transistor (drain or emmitter) and the load. However, input - output match will show different optima for maximum gain, maximum efficiency, gain at wider bandwith and best linearity situations so careful optimization is necessary subjected to the application requirements. Optimum impedance level at the output of the transistor could be revealed by the load pull analysis. Lowpass multisection networks could be designed in order to increase bandwidth and linearity. All shunt capacitors and series inductors could be replaced by series low impedance and series high impedance lines respectively. Alternatively single stub and double stub short or open circuits could be used to obtain any susceptance or reactance value.

2.4.4 Harmonic Tuning

All microwave circuits generate distortion as a result of nonlinear behavior. To investigate the generation of harmonics let us assume the input signal as a single tone sinusoidal voltage;

$$V_i(t) = A\cos(\omega_C t) \tag{2.18}$$

Neglecting other distortions and nonlinearities, the output voltage could be expressed as a Fourier series with harmonic components at multiples of input carrier frequency ω_C

$$V_{OUT}(t) = a_0 + a_1 A\cos(\omega_C t) + a_2 A^2 \cos^2(\omega_C t) + a_3 A^3 \cos^3(\omega_C t) + ... \qquad (2.19)$$

$$V_{OUT}(t) = a_0 + \frac{a_2 A^2}{2} + (a_1 A + \frac{3a_3 A^3}{4})\cos(\omega_C t) + \frac{a_2 A^2}{2}\cos(2\omega_C t) +$$

$$\frac{a_3 A^3}{4}\cos(3\omega_C t) + ...$$

(2.20)

The amplitude of the n^{th} harmonic is proportional to A^n and must be filtered out to an acceptable level (typically -46dBc or lower) in order not to interfere with other communication channels or with the fundamental frequency components when two or more tone signal is applied (Kazimierczuk, 2008). Short circuiting at harmonic frequencies will help to suppress those unwanted harmonics while will not influence fundamental matching circuit much. Simplest application of short circuiting is quarter wave short circuit shunt stub. It is advantageous because of showing open circuit at the fundamental frequency and presents short circuit at successive even harmonics (Cripps, 1999).

CHAPTER THREE
DOHERTY POWER AMPLIFIER

3.1 Introduction

Modern wireless communication systems such as CDMA-2000, Wideband CDMA (WCDMA), OFDM and so on use high PAR, thus need to operate at a large back off power in order to provide linearity requirements (Lee Y., Lee M., & Jeong, 2008b). Neverthless, classical power amplifiers show poor efficiency at large BOP from the saturation point. Doherty power amplifier architecture overcomes this deficiency as it also promises high efficincy and good linearity at large BOP levels.

Doherty power amplifier was first introduced by William H. Doherty at 1936. He suggested a new high efficiency power amplifier for modulated waves with his work at Bell laboratories (Doherty, 1936). Low average efficiency in AM modulation resulted in high power consumption and high expense on cooling systems. Doherty proposed his work as an improvement on these deficiencies where his system was on basis of power combination architecture and provided high efficiency at average power levels for AM modulated signals. That architecture somewhat lost its popularity while mobile phones utilized constant envelope modulation scheme like Gaussian Minimum-shift Keying (GMSK) instead of AM modulated schemes. However, modern communication systems use not only voice but also image and multimedia information where high data rate is necessary. So complex AM modulation schemes like OFDM, CDMA etc., are developed and the difficulties William H. Doherty tried to deal have gained its significancy back. Doherty power amplifier yet found a popular place in the agenda after the invention of modern transistors which consume much less power and also the extended need in the efficiency (Kazimierczuk, 2008).

3.2 Operational Theory of Doherty Power Amplifier

Doherty power amplifier consists of two active devices which are named as main (carrier) and auxiliary (peaking) amplifiers. Typically main amplifier is biased as class AB and auxiliary amplifier is as class C to balance the linearity and efficiency performance. Main amplifier operates at all power levels while auxiliary amplifier starts operating at medium or high power levels. A passive impedance inverter is placed at the output of the main amplifier to efficiently combine the outputs of the both amplifiers. In order to neglect 90 degree phase shift caused by this impedance inverter line, a phase compensation line has to be added before the auxiliary amplifier. A common block diagram of Doherty power amplifier could be seen in Figure 3.1;

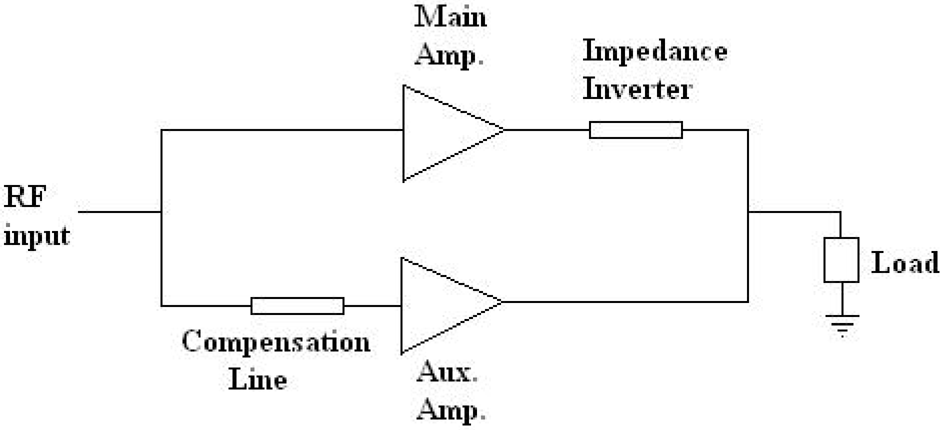


Figure 3.1 Typical block diagram of Doherty power amplifier

Doherty power amplifier utilizes the benefit of active load pulling technique to achieve high efficiency over a wide output power range. At low power levels, current is drawn only from the main amplifier while auxiliary amplifier is off and drains no current. When power increases and the main amplifier gets into saturation, the auxiliary amplifier starts operating and drains current. Both amplifiers operate as dependent current sources. At the main amplifier saturation point Doherty power amplifier reaches a peak high efficiency point. This is also the point where high efficiency back off power is expected. Current drawn from the auxiliary amplifier increases rapidly with the input power increase and reaches the same current as current drawn from the main amplifier when the both amplifiers are in saturation.

This point is the maximum and also second peak high efficiency point of Doherty power amplifier. At low power levels, class AB amplifier works linearly very well. However, with the increase of the input power, it reaches saturation region and suffers from gain compression which degrades the linearity. At this point taking the advantage of gain expansion behaviour of the class C amplifier and combining these gain compression and expansion also helps improving the linearity at high power levels.

3.3 Passive Impedance Inverter

Impedance inverter is a device or a circuit which has an input impedance inversely proportional to the load impedance. In Doherty structure simply a passive transmission line which has a length of λ/4 is used to achieve this task.

$$\frac{Z_{in}}{Z_o} = \frac{Z_o}{Z_L} \tag{3.1}$$

We can make the following definitions:

$$z_{in} = \frac{Z_{in}}{Z_o} \tag{3.2}$$

as normalized input impedance and

$$\frac{Z_o}{Z_L} = \frac{1}{z_L} = y_L \tag{3.3}$$

as normalized load admittance. Then we can write in the compact form;

$$z_{in} = \frac{1}{z_L} \tag{3.4}$$

which is also the definition of impedance inverter.

Lumped element equivalent network could also be used as an alternate way of impedance inverter. This network is more complex but occupies less area thus usefull when integration problems occur. Additionally, precise and high Q lumped elements are required for this type network at RF frequencies. Various examples of lumped element impedance inverters are shown in Figure 3.2;

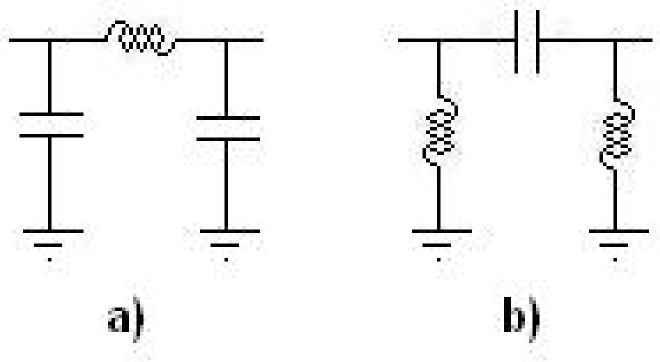


Figure 3.2 Lumped element impedance inverters

3.4 Active Load Pulling

The load impedance of a current source can be modified by applying current from another current source (Kazimierczuk, 2008). We may assume the current drawn from the main amplifier as I_m and the current drawn from auxiliary amplifier as I_{aux}. And we may adjust characteristic impedance of the impedance inverter at the output of the main amplifier as $Z_o = 2R_L$ while system load impedance is R_L. Figure 3.3 shows simple impedance modulation concept. At low power levels the auxiliary amplifier is off and should draw no current. Thus, the impedance Z_{aux} seen at the output of the auxiliary amplifier is ideally open and shows infinite impedance. In this case, only the main amplifier operates and the impedance Z_m at the output of the main amplifier could be simply evaluated from λ/4 transformer formula

$$Z_m = \frac{(2R_L)^2}{R_L} = 4R_L \tag{3.5}$$

That result shows that Doherty power amplifier sees four times higher load impedance when we compare it to class AB power amplifier and achieves saturation at

$$P_{out} = \frac{(V_{dd})^2}{2x4(R_L)} = \frac{(V_{dd})^2}{8R_L} \tag{3.6}$$

power level. This is the highly efficient typically 6dB back off power level.

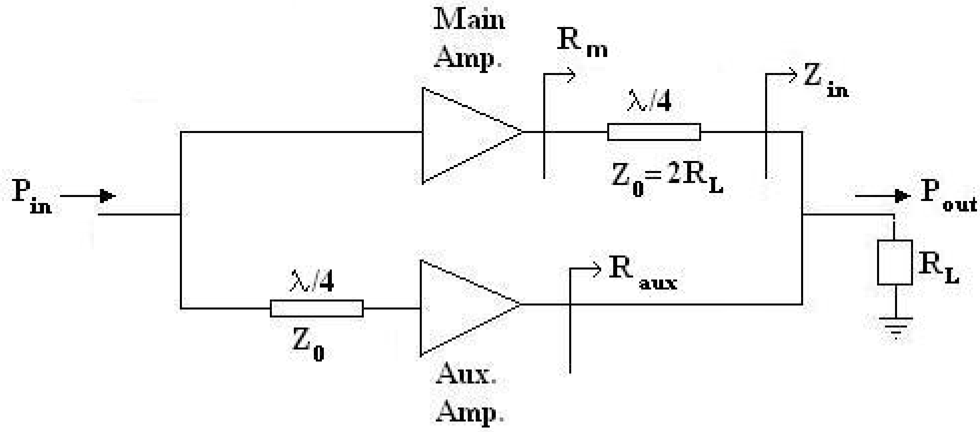


Figure 3.3 Impedance modulation consept on Doherty power amplifier

When the input power increases to higher power levels, the auxiliary amplifier starts draining current and contributes to the total output power. Current I_{aux} and I_m flown from each branch are inphased and adjusted to be equal at maximum power level. That maximum power point is also the saturation point of the auxiliary amplifier. As the current supplied by the auxiliary amplifier increases, load pull effect raises the effective impedance value Z_{in} at the output. That also leads to decrease at the output impedace of the main amplifier due to the impedance inverter. This load pulling effect allows the main amplifier to deliver more current to the load while it is saturated, and thus maintains higher efficiency over an extended power range (Gilmore, & Besser 2003). The output impedance Z_{in} when both amplifiers are operational is

$$Z_{in} = R_L\left(1+\frac{I_{aux}}{I_m}\right) \tag{3.7}$$

At maximum power, $I_{aux}=I_m$, $Z_{in}=Z_{aux}=2R_L$. That yields the maximum power obtained from auxiliary amplifier as,

$$P_{aux} = \frac{(V_{dd})^2}{2x2R_L} = \frac{(V_{dd})^2}{4R_L} \tag{3.8}$$

The load-pull effect seen on main amplifier is

$$Z_m = \frac{(2R_L)^2}{2R_L} = 2R_L \tag{3.9}$$

and power obtained from main amplifier is

$$P_m = \frac{(V_{dd})^2}{2x2R_L} = \frac{(V_{dd})^2}{4R_L} \tag{3.10}$$

Therefore the total maximum power obtained from the Doherty power amplifier is

$$P_{out} = P_m + P_{aux} = \frac{(V_{dd})^2}{4R_L} + \frac{(V_{dd})^2}{4R_L} = \frac{(V_{dd})^2}{2R_L} \tag{3.11}$$

Figure 3.4 shows the impedance change at the main and auxiliary amplifier output with respect to the input drive power;

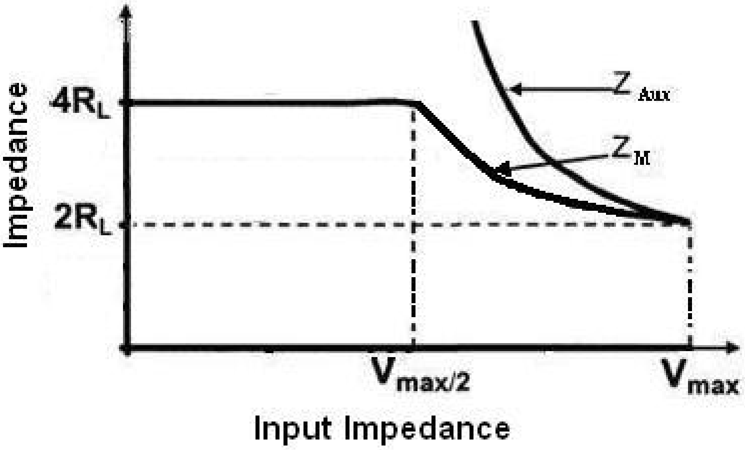
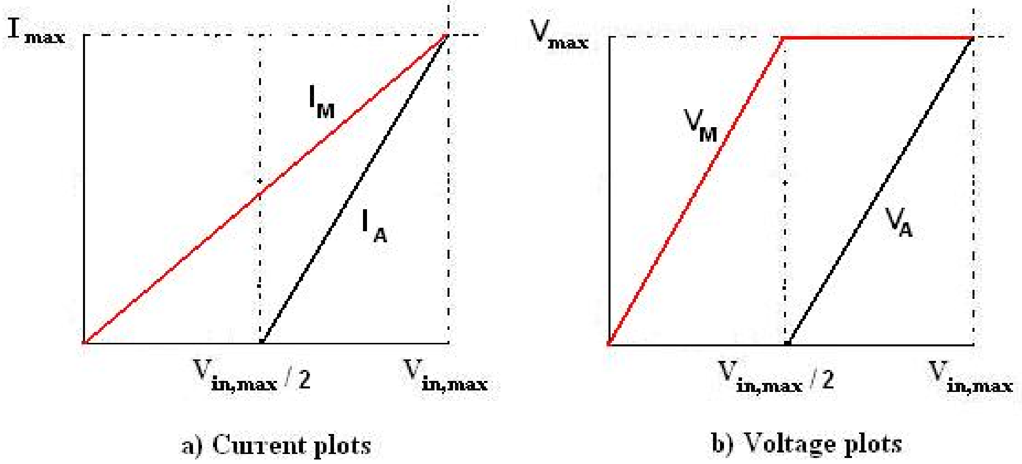


Figure 3.4 Main and auxiliary amplifier output impedances vs input drive

The main amplifier drains current all over the input power range and its current increases linearly with the input power increase. The auxiliary amplifier starts operating at 6dB back off power level and starts draining current. At the maximum power level both amplifiers should see equal current level so more power is delivered to the auxiliary amplifier by splitting the power at the input of the Doherty power amplifier. The current and voltage plots of both amplifiers can be seen in Figure 3.5;



a) Current plots

b) Voltage plots

Figure 3.5 Sample current and voltage plots of the main and auxiliary amplifiers.

3.5 Linearity of Doherty Power Amplifier

Doherty power amplifier is a highly efficient high power amplifier. That highly efficient high power points are achieved at transistor saturation points. It is a main concern to obtain good linearity at saturation point for power amplifiers because linearity of power amplifiers dramatically degrade when they operate close to the saturation points (Bui, 2008). Nevertheless, modern communication systems use both amplitude and phase modulated signals where good linearity is required.

At low power regions the linearity of the Doherty PA entirely determined by the main amplifier. Therefore, class AB biased amplifier shows high linearity for its carefully optimized load impedance. Main amplifier shows gain compression impact at high power levels as it is biased at class AB. Conversely, class C biased auxiliary amplifier shows gain expansion impact at high power levels. If these compression and expansion effects are combined carefully, Doherty power amplifier also exhibits good linearity at high power levels as seen in Figure 3.6;

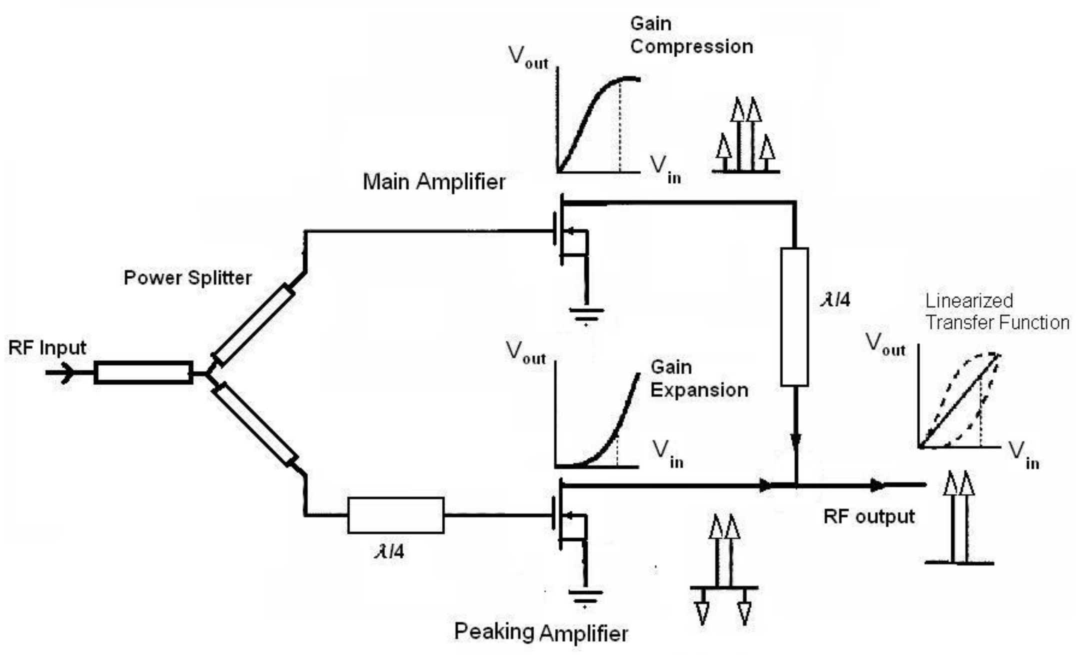


Figure 3.6 Linearization concept on Doherty PA configuration

In even power drive mode the fundamental current component of the auxiliary amplifier is insufficient to reach full load modulation. That leads to entering into saturation region for both of the amplifiers without producing full power as they both see load impedances larger than the optimum values. As a result, both linearity, power level and efficiency is degraded. However, uneven power division is a very usefull and easy method to obtain good linearity, carefully combine gain expansion and gain compression effects of main and auxiliary amplifiers, in Doherty power amplifier structure. It propose applying more power to the auxiliary amplifier thus can open the auxiliary amplifier fully and modulate the load impedances properly to the optimum values (Yang, Cha, Shin, & Kim 2003). Beacuse of the main amplifier's gain compression behaviour, it exhibits increased third order intermodulation (IM3) level while phase of the IM3 decreases. On the other hand, when the gain of the auxiliary amplifier is expanded by the uneven power drive, both IM3 level and its phase are increased. To cancel out IM3 components, both amplifiers must have same amplitude and 180 degree out of phased IM3s (Chen, Guo, & Shi 2008).

3.6 Power and Efficiency

The total power from both the main and the auxiliary amplifiers will maintain a linear relationship over the entire power range as the main current is a function of the input drive over that range. Maximum power of the Doherty PA will be much higher than the both individual amplifier powers. We can see the main and auxiliary amplifier currents and voltage amplitudes in Figure 3.5. It is obvious that main amplifier will exhibit maximum power efficiency over the upper 6dB power range. However the RF voltage swing at the output of the auxiliary amplifier reaches its peak only at the total peak power. Therefore the auxiliary amplifier can’t operate at maximum efficient condition over this range, but it contributes the overall efficiency as a function of amount of power it delivers. Assuming the efficiency of both amplifiers are $\pi/4$ at full RF voltage swing, v_{in} is the input voltage swing, at low power condition where only main amplifier is operational (assuming main amplifier operates in class B), the efficiency is (Cripps, 1999);

$$\eta = \frac{2v_{in}}{V_{\max}} \frac{\pi}{4}, \quad 0 < v_{in} < \frac{V_{\max}}{2} \tag{3.12}$$

As $I_{\max}$ is the maximum linear current swing for the devices. The RF output power at high power level is;

$$P_{out} = \frac{I_{\max}}{2} \left(\frac{v_{in}}{V_{\max}}\right)^2 V_{dc} \tag{3.13}$$

and overall efficiency η as a function of input drive can be written as;

$$\eta = \frac{\pi}{2} \frac{\left(\frac{v_{in}}{V_{\max}}\right)^2}{3\left(\frac{v_{in}}{V_{\max}}\right) - 1}, \quad \frac{V_{\max}}{2} < v_{in} < V_{\max} \tag{3.14}$$

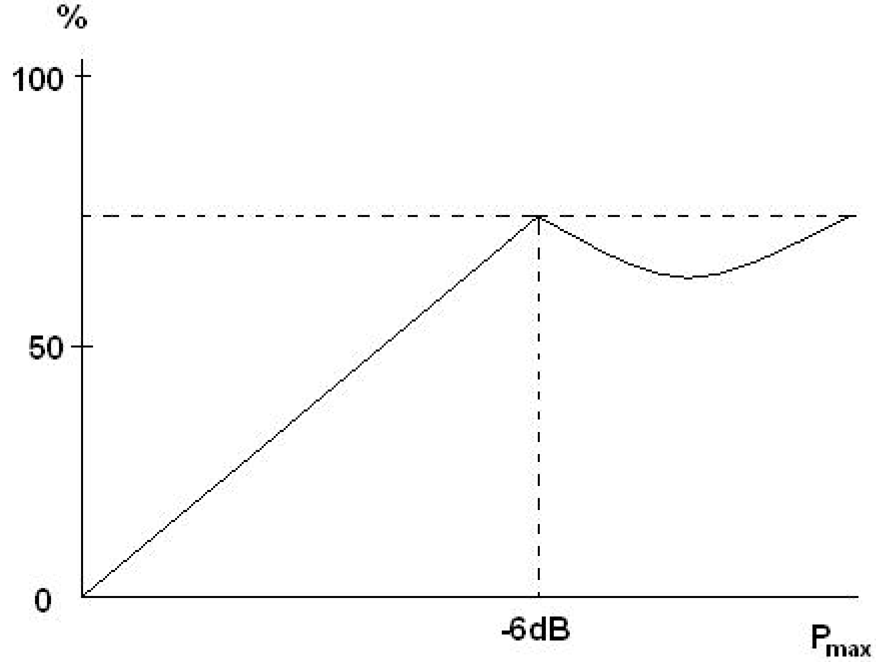


Figure 3.7 Typical efficiency vs power relation of Doherty PA

As seen in Figure 3.7, the efficiency acts linearly with respect to the input power at low power levels. In this range only main amplifier operates and efficiency plot of the Doherty PA is similar as class B efficiency graph. The main amplifier reaches its saturation so its most efficient region at 6dB back of the total peak power level and keeps its high efficiency all over that 6dB region. However, auxiliary amplifier just starts operating at 6dB back off point and reaches its maximum efficiency at total peak power level. The efficiency contribution of the class C biased auxiliary amplifier could be estimated by its output power level and conduction angle. Total peak power is combination of class AB and class C amplifier efficiencies.

CHAPTER FOUR
THE DESIGNED DOHERTY POWER AMPLIFIER

4.1 Introduction

In this study, Doherty power amplifier for various WiMAX applications is designed and simulated in order to demonstrate its applicability and advantage over classical amplifiers. Moreover, the power splitter and the main amplifier blocks of the Doherty PA are fabricated and measured. Due to the lack of high power sources in the labarotuary, the measurement on the entire design can not be performed. Therefore, only the simulation results are presented for the complete design.

Same type LDMOS transistors are used as the main and the auxiliary amplifiers and the PA is designed fundamentally to operate in the 2.6GHz frequency band. The specifications of the LDMOS transistor can be found in Freescale Semiconductor MRF6S27015N Technical data. Fabricated parts of the amplifier are printed on Taconic RF-35 substrate which is highly stable and specific for RF applications. Impedance matching, impedance inverter, harmonic termination, lowpass filter elements are designed in microstrip form as much as possible. Agilent’s Advanced Design System (ADS ®) is used as the simulation platform.

4.2 Load Pull Analysis

Load pull analysis is a usefull method to find optimum load impedance to have maximum output power with best efficiency. Load pull simulation principle comes out of varying the load reflection coefficient presented to the active device. The large signal load impedance is changed from a small value to a large value and the power delivered to these loads are calculated. Then a series of contours are plotted on Smith Chart representing the load reflection coefficients with similar output power level. Similarly, PAE contours are also plotted. Both contour outputs could be seen in Figure 4.2. The contours inside represents higher power and efficiency points. The schematic view of load pull analysis could be seen in Figure 4.1. Desired fundamental load tuner coverage is done using the s_{11} rho where s11_rho is the radious and s11_center is the center of the simulated reflection coefficients simulated on the Smith chart.

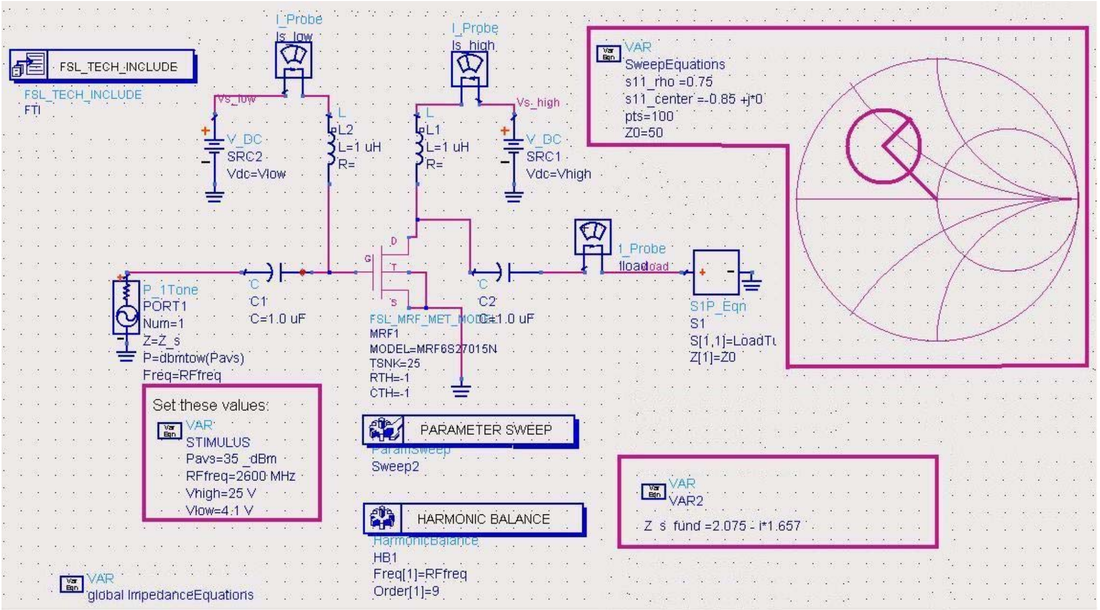
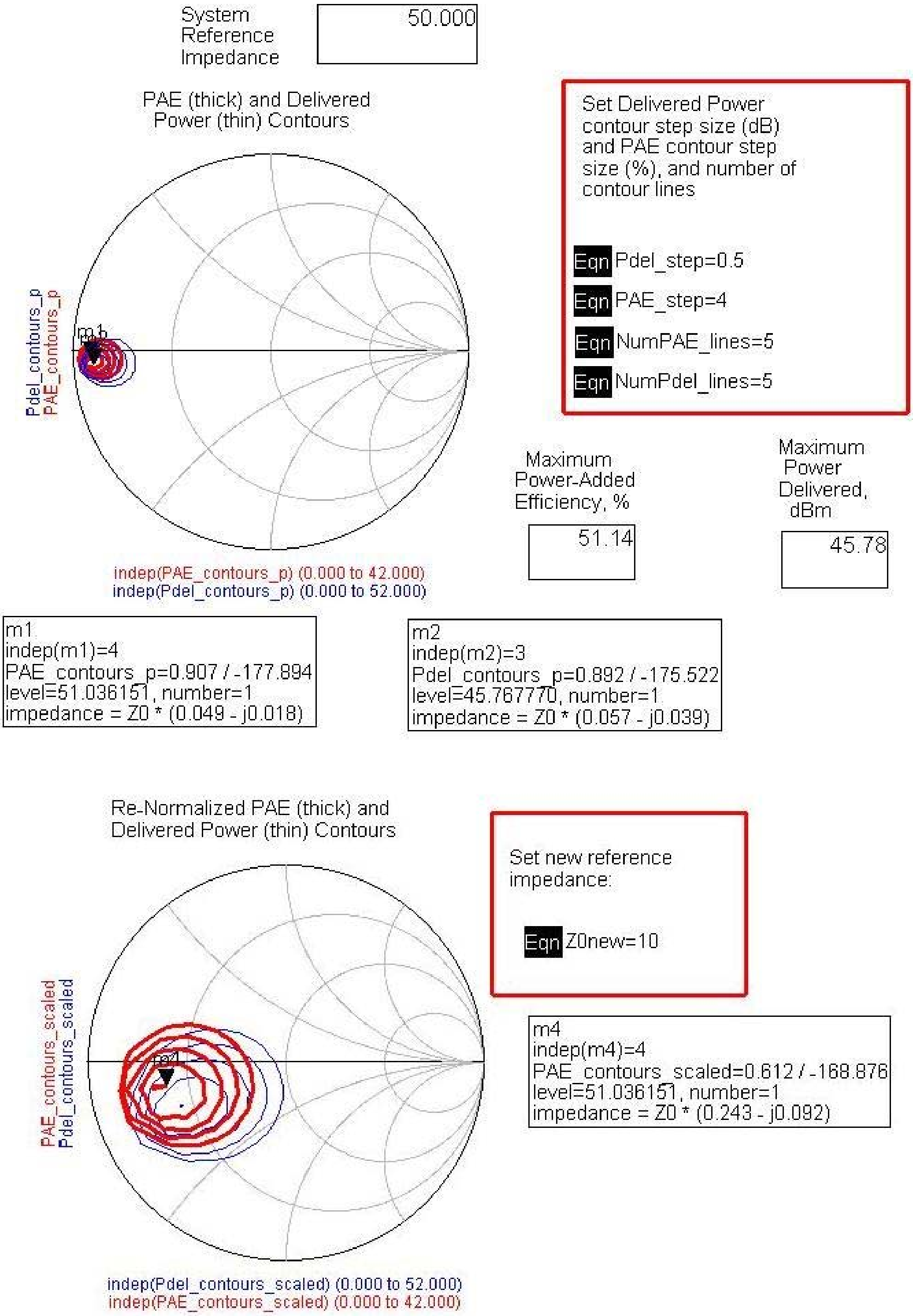


Figure 4.1 One tone load pull simulation schematic

Simulation results seen in Figure 4.2 shows that single amplifier can deliver maximum of 45.78dBm output power with 51.14% PAE. Contours seen in blue show the power delivered to the load and red contours show the PAE while maximum of each could be reached at the center of the contours. A good power amplifier should have a large power contour area which implies the delivered power to the load is not strictly sensitive to the load. That can also be explained as power amplifier can deliver considerably high power to wide range of load impedances. It is usually difficult to fullfill that feature though. Figure 4.2 exhibits reasonable results. Analyzing the Smith chart with various reflection coefficients orientates a well approximated load impedance of 2.5–j1 ohm to have maximum power and efficiency.



System Reference Impedance: 50.000

Set Delivered Power contour step size (dB) and PAE contour step size (%), and number of contour lines

Eqn Pdel_step=0.5
Eqn PAE_step=4
Eqn NumPAE_lines=5
Eqn NumPdel_lines=5

Maximum Power-Added Efficiency, %: 51.14

Maximum Power Delivered, dBm: 45.78

m1
indep(m1)=4
PAE_contours_p=0.907 / -177.894
level=51.036151, number=1
impedance = Z0 * (0.049 - j0.018)

m2
indep(m2)=3
Pdel_contours_p=0.892 / -175.522
level=45.767770, number=1
impedance = Z0 * (0.057 - j0.039)

Set new reference impedance:

Eqn Z0new=10

m4
indep(m4)=4
PAE_contours_scaled=0.612 / -168.876
level=51.036151, number=1
impedance = Z0 * (0.243 - j0.092)

Figure 4.2 Load pull simulation result

4.3 Input – Output Matching Circuits

The input and the output matching circuits main function at power amplifiers is to match the input signal source and output antenna impedance to desired appropriate levels. The transistors input and output impedances decreases with the increase in the operating frequency which further complicates the design of the matching networks. Matching networks will show different optima for maximum gain, highest efficiency and best linearity. The design should be configured to optimum levels corresponding to the system requirements.

From the load pull simulation, optimum load impedance is determined as 2.5–j1 ohm. For the classical Doherty PA operation the main and auxiliary amplifiers should have the same devices and matching network. Same impedances should be seen at the output of the both amplifiers at maximum output power level to obtain the optimum performance. In order to acquire wide bandwidth the matching circuit should have low loaded quality factor (Q). Constant Q curves are eye shaped on Smith chart and curves occupy larger area with the increase in their value. Example constant Q curves can be seen in Figure 4.3 (Froelich, n.d.). And Figure 4.4 shows various quality factors of matching networks. It can be obviously seen that matching network which has $Q_0 = 1$ operates well in wider range of frequency than $Q_0 = 3$.

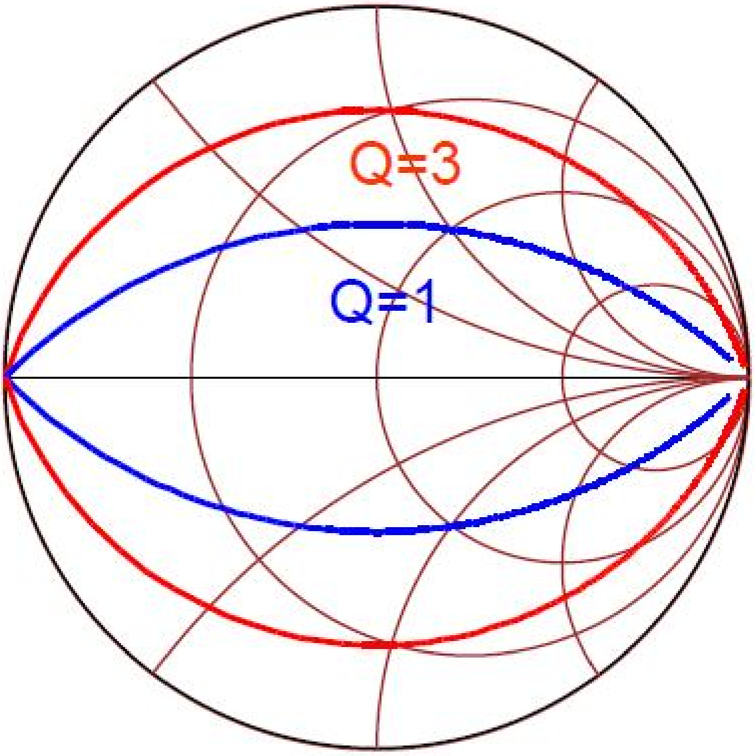


Figure 4.3 Locus of constant Q curves on Smith chart

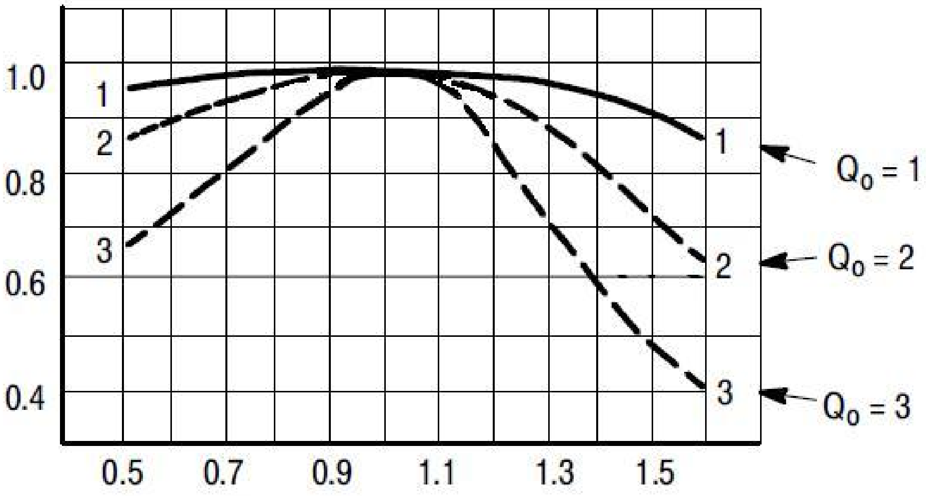


Figure 4.4 Sample normalized quality factors vs frequency for the L-section

In this work both the input and the output matching circuits are designed using multiple stage matching network in order to utilize low loaded quality factor thus to have wider bandwith. The test circuit in the datasheet of the transistor became a beneficial source to setup the multiple stage matching. Figure 4.5 shows one step and designed multiple stage microstrip line output networks.

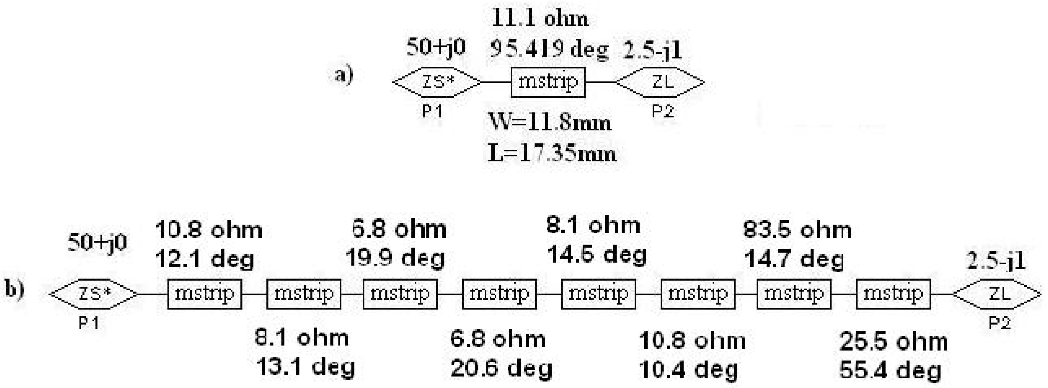


Figure 4.5 a) One step output matching b) Multiple stage output matching

In Figure 4.6 you can see corresponding one step output matching in bold curve and designed multiple stage output matching in black. The both matchings are done using microstrip lines. We can see the both matchings reach the desired load impedances but bold curve move away from real axis on Smith chart more than the black one which causes it to have larger Q.

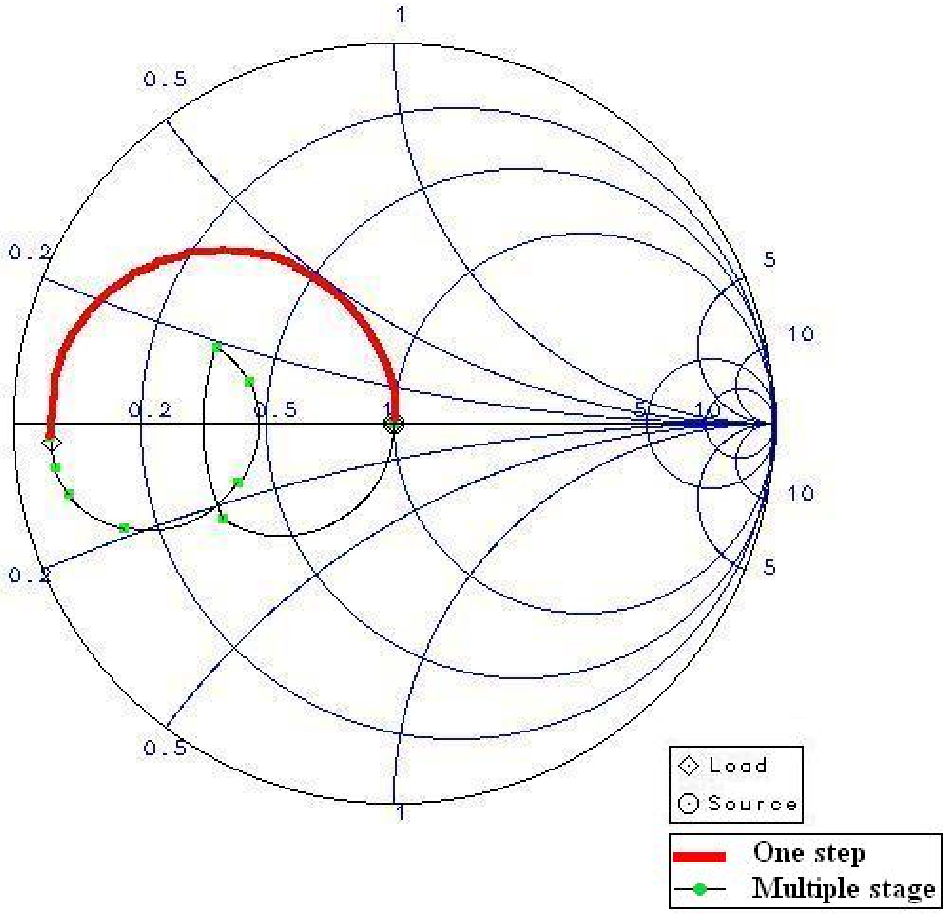


Figure 4.6 One step vs multiple stage output matching curves

Large signal input impedance is determined after deciding the output load impedance in order to keep the gain at maximum. The simulation results for large signal input impedance can be seen in Figure 4.7. P_{in} is the input power, real and imaginary curves show real and imaginary parts of the input impedance, respectively. 1.5+j3.5 ohm input impedance is matched to 50 ohm source impedance. The input matching circuit is also done using multiple microstrip lines on account of wider bandwith and suppress harmonic issues as mentioned in the previous chapter.

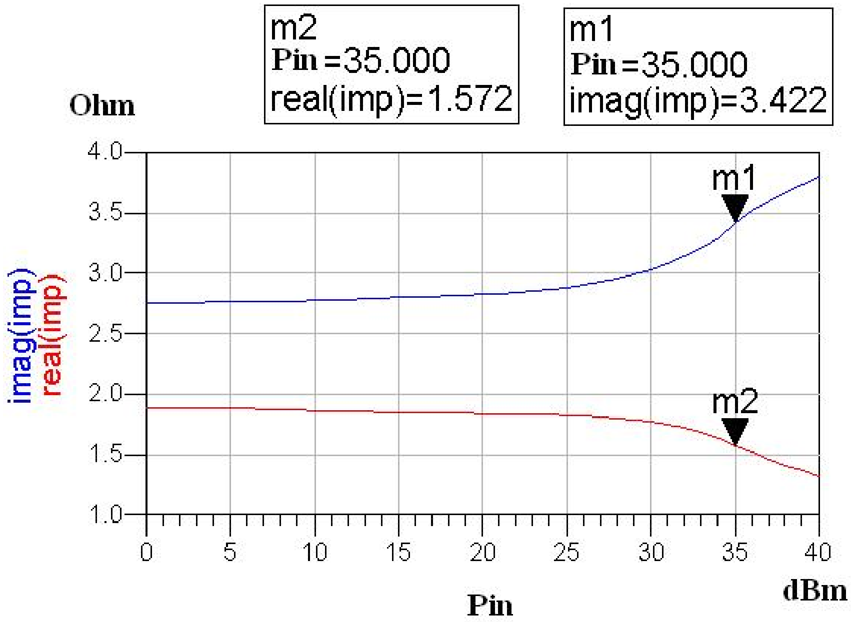


Figure 4.7 Simulation results for large signal input impedance

Simulation of one step and multiple stage designs show multiple stage input – output matching circuits have considerably wider bandwith as seen in Figure 4.8;

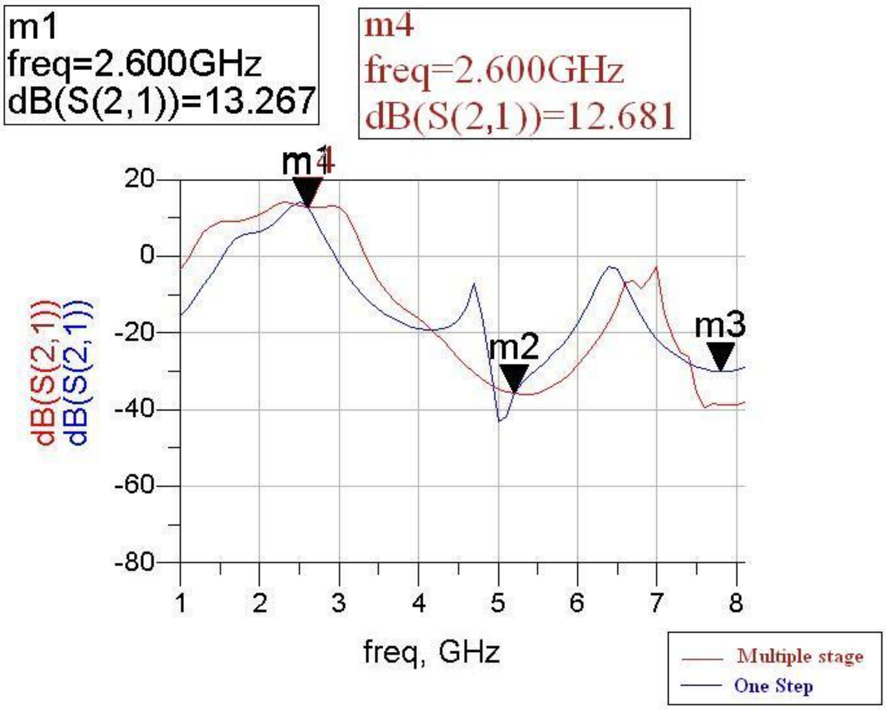


Figure 4.8 S-parameter simulations of one step and multiple stage matching networks

Multiple stage matching network also designed to have low pass filter characteristic. It helps to suppress the harmonic components of the fundamental frequency. The $\lambda/4$ transmission lines at drain and gate biasing paths are open circuit at fundamental frequency so have no effect on the input – output matching. However, these paths are short circuit at even harmonic frequencies so helps to suppress the even harmonics. Markers m2 and m3 at Figure 4.8 points the harmonic frequencies and they are effectively suppressed. It keeps more space while using multiple microstrips. The multiple stage matching network has a total of 52.4 mm length while one step matching has 32.5 mm.

4.4 The Main Amplifier Prototype

Doherty power amplifier combines the powers of the main and the auxiliary amplifiers. Main amplifier is operational at whole low and high power levels. In this work the single stage main amplifier prototype is fabricated and measured. The schematic view of the design can be seen in Figure 4.9. The measurements are restricted to maximum 13.9dBm input power level which is the maximum available power provided by the signal generator at 2.6GHz fundamental frequency. The maximum achievable input power level provided by the laboratory devices presents in the low power region of this design, so high power performance of the amplifier couldn’t be measured.

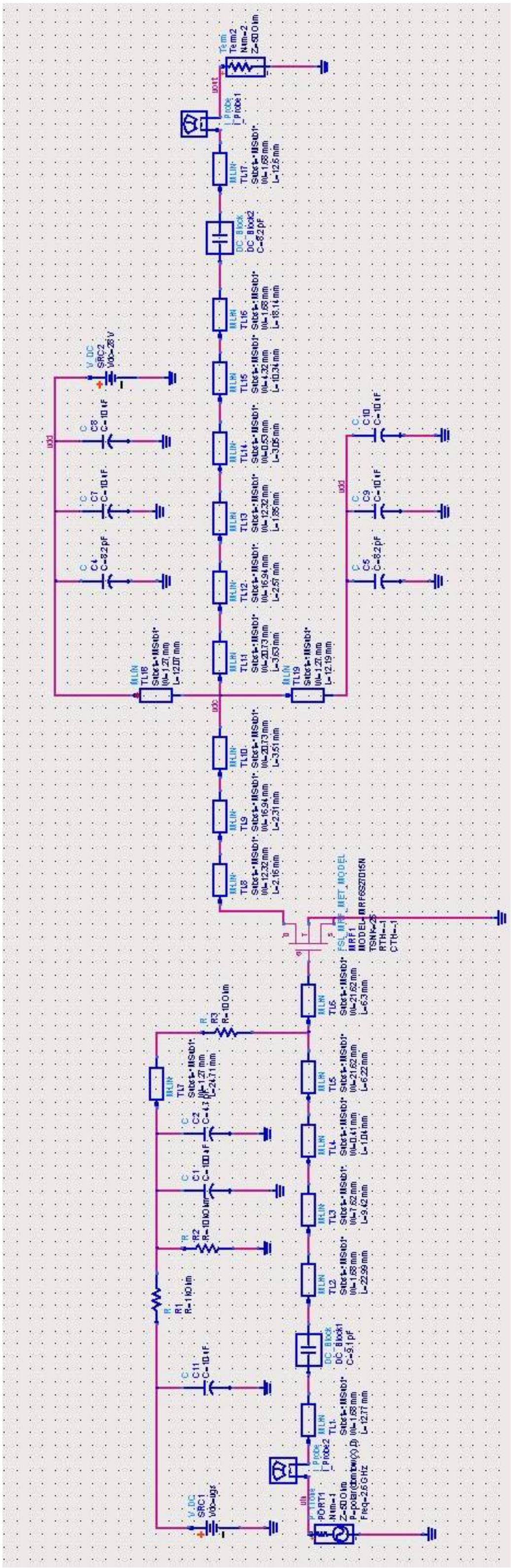


Figure 4.9 Schematic view of the main amplifier design

Taconic RF-35 substrate is used for the fabrication of the PCB (printed circuit board) which has a dielectric constant of 3.5 at the operating frequency. The height of the substrate is 0.762mm. The top and the bottom sides of the PCB are used while bottom layer fully designated to ground plane. Freescale's MRF6S27015N high frequency high power LDMOS transistor is used as the amplifier. Top view of the design can be seen in Figure 4.10;

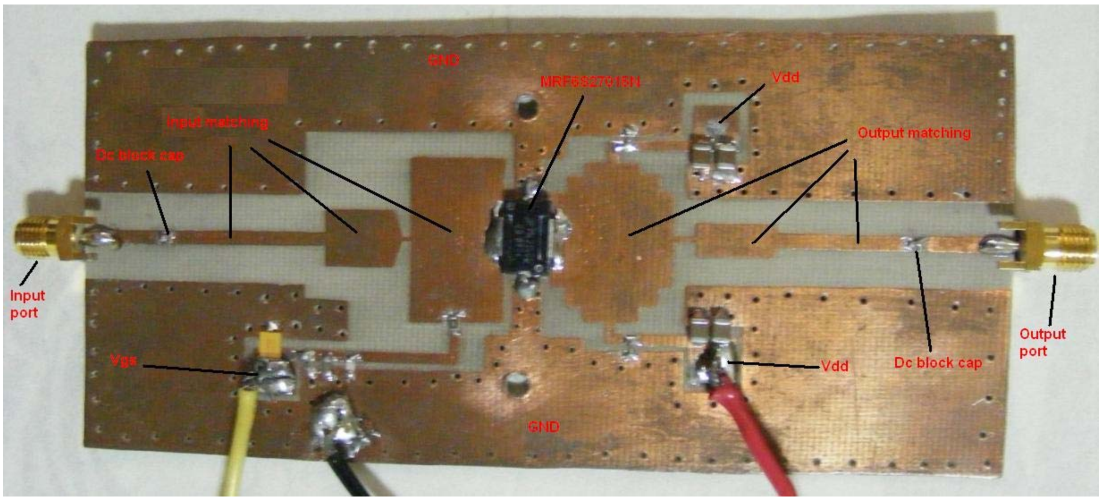


Figure 4.10 The main amplifier top layer layout

Figure 4.11 shows the simulation results of input (P_{in}) output (P_{out}) relation of the main amplifier. The main amplifier operates linearly up to 32dBm input power level as this is the 1dB gain compression point (input P_1dB).

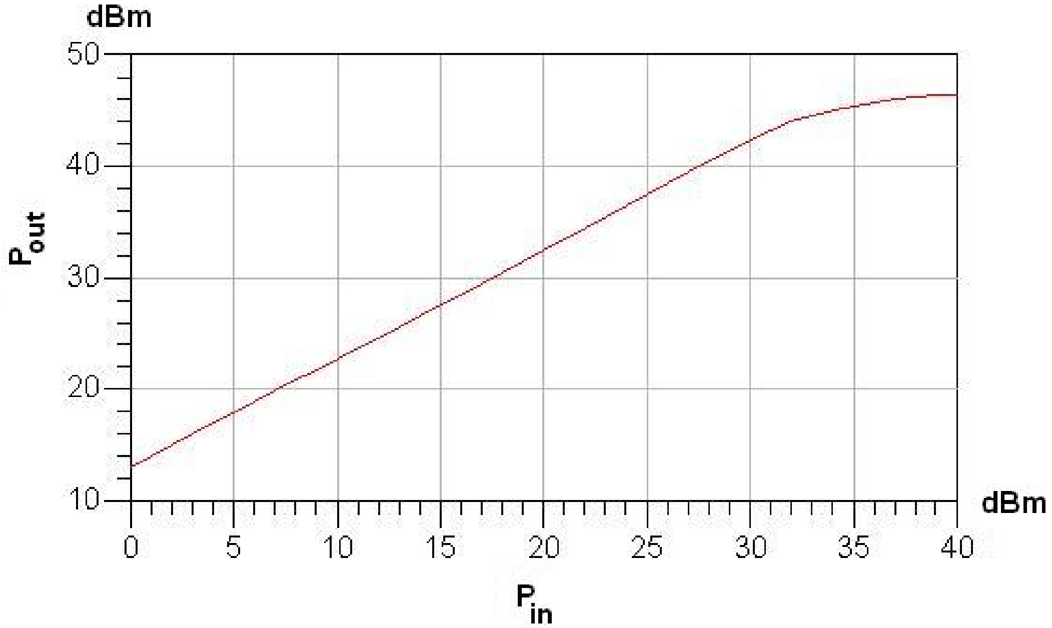


Figure 4.11 Simulation results for the main amplifier input vs output power

In the Figure 4.12 measurements of the main amplifier input vs output power relation can be clearly seen. The measurements and the simulation results are well-matched and the amplifier operates perfectly linear at low power levels.

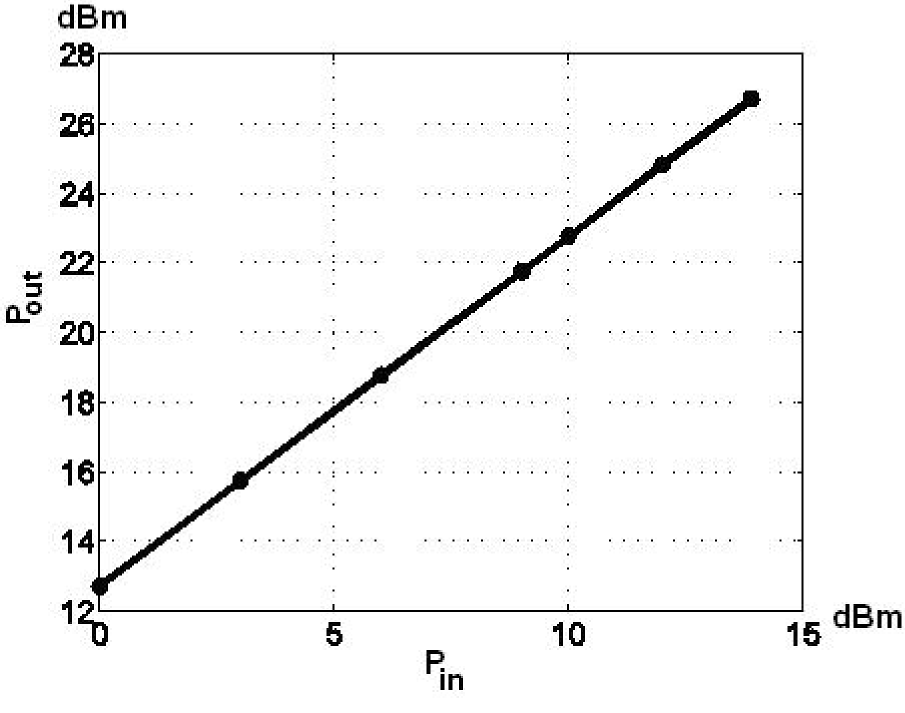


Figure 4.12 Measurement results for main amplifier P_{in} vs P_{out}

4.5 Unequal Wilkinson Power Divider

Wilkinson power dividers are often used for various RF applications in order to make desired power split or power combination (Lim, Lee, Jeong, Ahn, & Choi 2006). It has the advantage of being lossless when the output ports are matched but only reflected power is dissipated. The isolation of the splitted branches is done by applying proper resistance between them thus preventing crosstalk. A two way Wilkinson power divider can be seen in Figure 4.13;

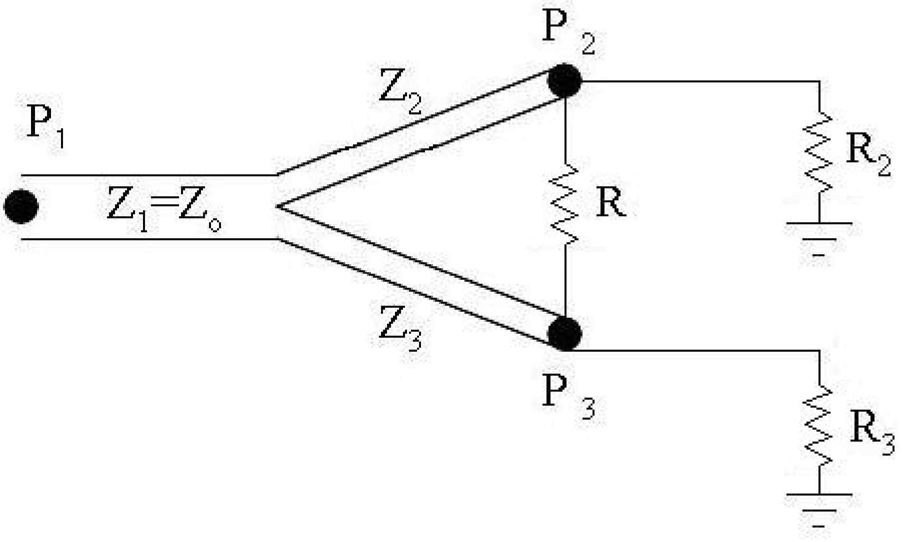


Figure 4.13 Two way microstrip Wilkinson power divider

Even – odd mode analysis of the equal split Wilkinson power divider extracts following s parameters (Pozar, 1998):

$S_{11} = 0$ since z_{in} at port 1 is equal to 1,

$S_{22} = S_{33} = 0$ since ports 2 and 3 are matched for both even odd modes,

$S_{12} = S_{21} = -j/\sqrt{2}$ symmetry due to reciprocity,

$S_{13} = S_{31} = -j/\sqrt{2}$ since ports 2 and 3 are symmetrical,

$S_{23} = S_{32} = 0$ due to short or opens at bisection point.

When the divider is driven from P_1 and also outputs are matched, no power is dissipated at the isolator resistor R. That means the divider is lossles when the outputs are matched. The isolator resistor absorbs only reflected power from port 2 and port 3. Since $S_{23} = S_{32} = 0$, ports 2 and 3 are isolated (Pozar, 1998).

In Doherty PA, current driven through main amplifier is increased with the increase of the input power. When we adjust the auxiliary amplifier to operate at half of the maximum output voltage, it is expected to drive the same current value as main amplifier at maximum output voltage. In order to satisify this condition, auxiliary amplifier must be supplied with two times as much power as main amplifier and this condition can be achieved by 1:2 unequal Wilkinson power divider.

When we can assume the power ratio between ports 2 and 3 as

$$K^2 = \frac{P_3}{P_2} \tag{3.13}$$

The following equations can be applied (Pozar, 1998):

$$R = Z_0(K + \frac{1}{K}) \tag{3.14}$$

$$Z_3 = Z_0\sqrt{\frac{1+K^2}{K^3}} \tag{3.15}$$

$$Z_2 = K^2 Z_3 = Z_0\sqrt{K(1+K^2)} \tag{3.16}$$

$$R_2 = Z_0 K \tag{3.17}$$

$$R_3 = \frac{Z_0}{K} \tag{3.18}$$

4.5.1 Simulation Results for the Unequal Wilkinson Power Divider

1:2 Wilkinson power divider is designed in microstrips. The input port is choosen as identical 50 ohms and the divider is matched to 50 ohms at the output ports by TL4 and TL5. The schematic view of the design is shown in Figure 4.14;

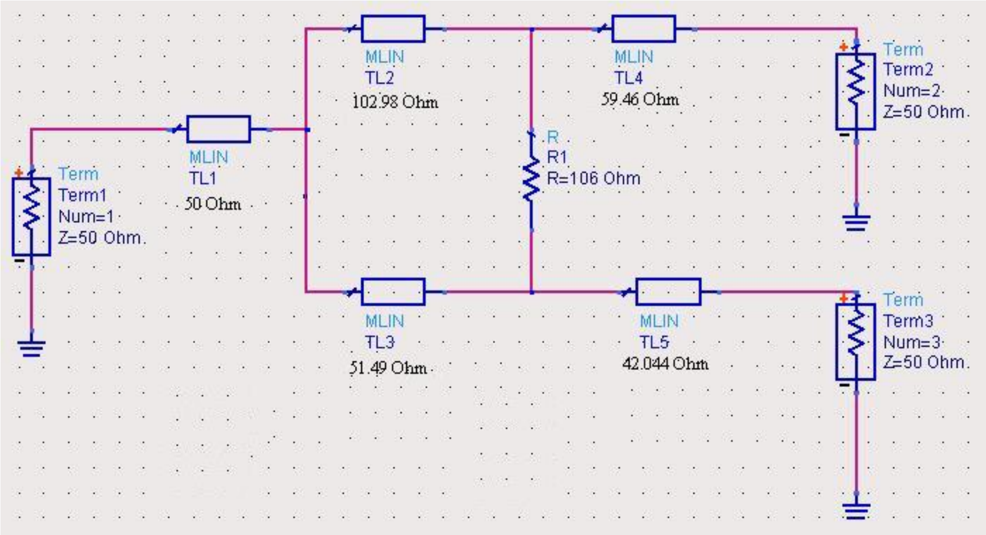


Figure 4.14 Schematic view of 1:2 Wilkinson power divider

2/3 of the whole power is departed to port 3 (S_{13}) as 10log(2/3)= -1.76 dB. And 1/3 of the total power is driven into port 2 (S_{12}) as 10log(1/3) = -4.77 dB. Other s-parameters show the reflection wave powers between 3 ports and each of them is below -50dB. That means the power reflected from each port is at least 10^5 times smaller than the power it transmits. S-parameter simulation results can be seen in Figure 4.15;

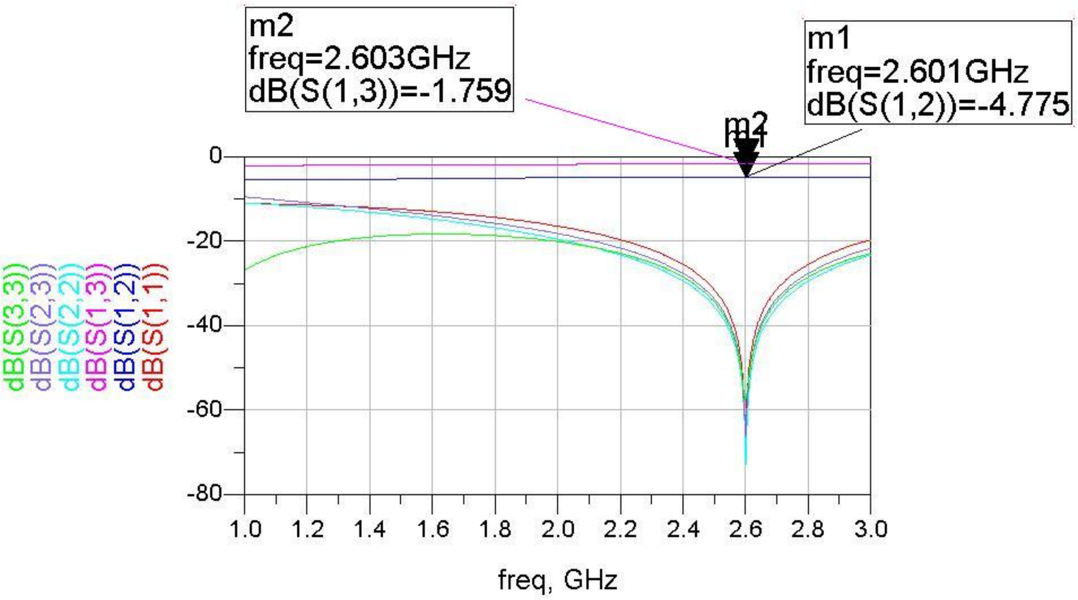


Figure 4.15 Simulated s-parameters of 1:2 Wilkinson power divider

4.5.2 Measurement results for the Unequal Wilkinson Power Divider

In order to split the input power properly and isolate the ports a 1:2 unequal Wilkinson power divider is fabricated and measured. Designed PCB can be seen in Figure 4.16. It is expected to have 3dBm difference between S_{12} and S_{13} which will exhibit the 1:2 power division. S_{12} and S_{13} measurements are done by connecting port 1 to the network analyzer input and port 2 or 3 respectively to the output of the network analyzer. (While port 2 or 3 is connected, other port is ended with 50 ohm) Measurements output -5.25dBm of S_{12} and -2.13dBm of S_{13} which will result in 3dBm power difference. Practical components are not ideal and also lossy, thus it is impossible to obtain zero reflection in real world. However measurement results shown in Figure 4.17 expose the reflection powers from and between all ports varies from -29dBm to -49dBm.

Figure 4.16 The 1:2 unequal Wilkinson power divider

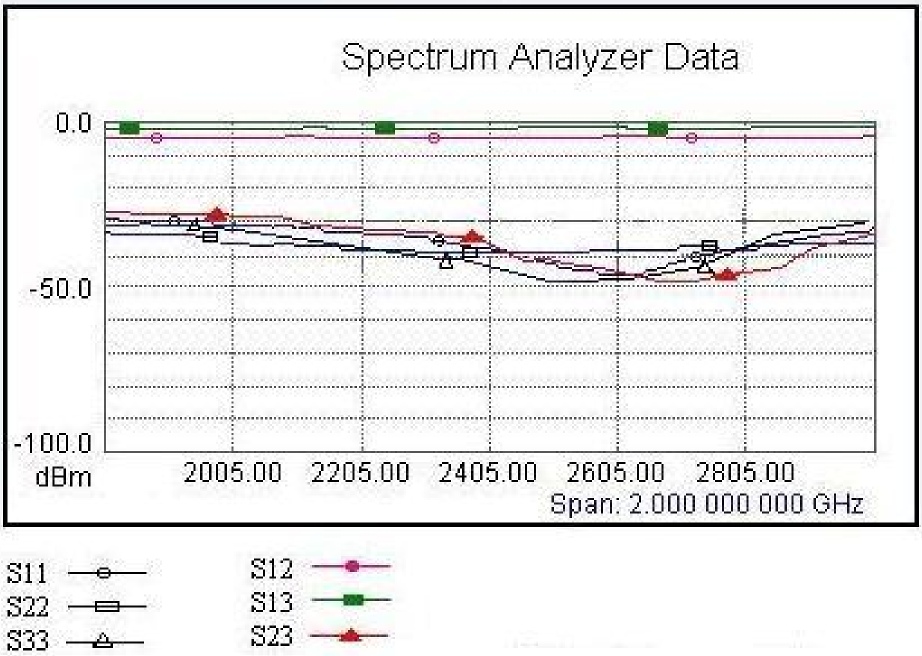


Figure 4.17 S-parameter measurements of 1:2 Wilkinson power divider

4.6 Proposed Doherty Power Amplifier Design

Doherty power amplifier is designed using ADS simulation tools. The schematic view of the design can be seen in Figure 4.18. The auxiliary amplifier maintains active load modulation effect on the main amplifier resulting in output impedance change at the main amplifier output. The load pull simulation results as seen in Figure 4.19 reveals the main amplifier output impedance values. At low power levels where the main amplifier operates alone, output impedance of the main amplifier should provide a highly efficient saturation point. When the auxiliary amplifier starts operating, the main amplifier output impedance should alter providing it to obtain more power comparing to its previous condition and also keeping its high efficiency stable. The impedance variation of the main and auxiliary amplifiers due to load modulation effect can be seen in Figure 4.19. It is obvious that the main amplifier impedance level has a significant change after the auxiliary amplifier starts operating.

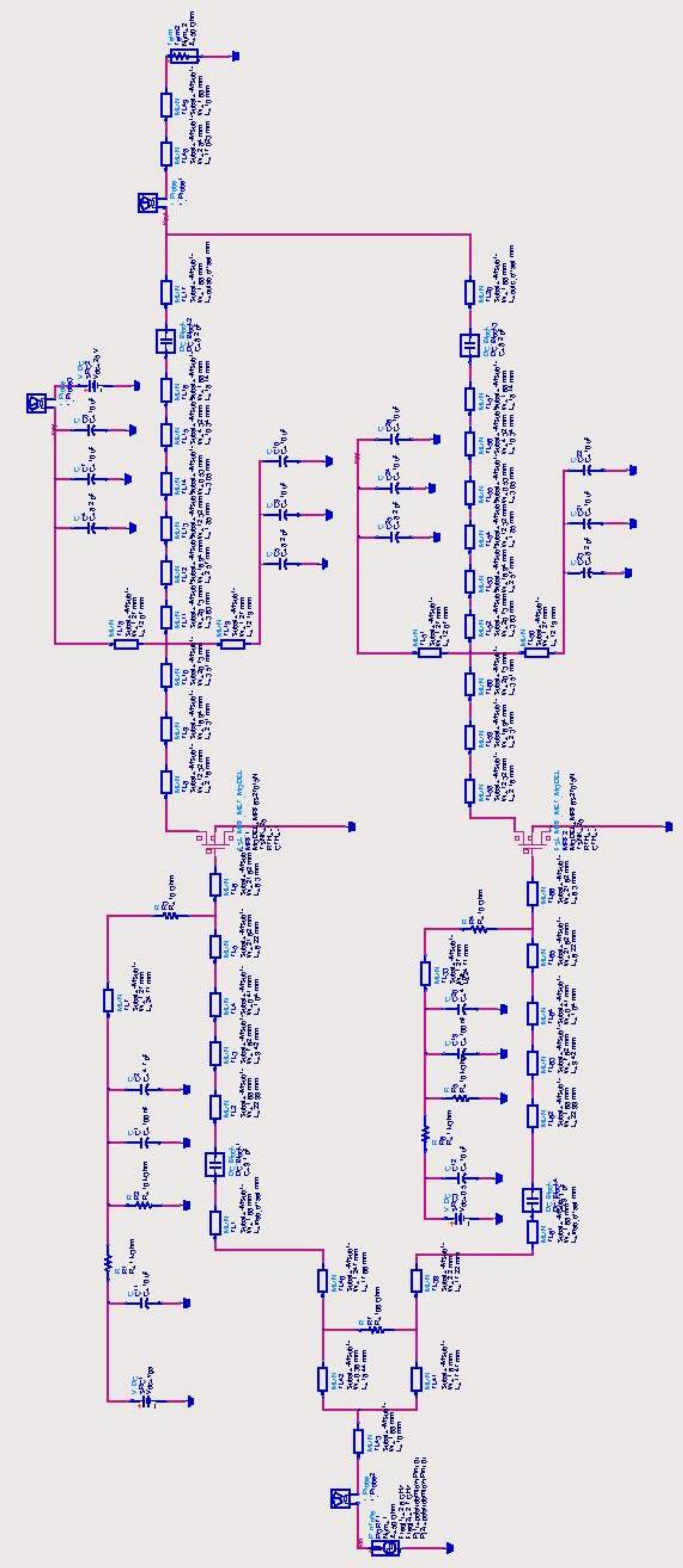


Figure 4.18 Schematic view of the Doherty PA

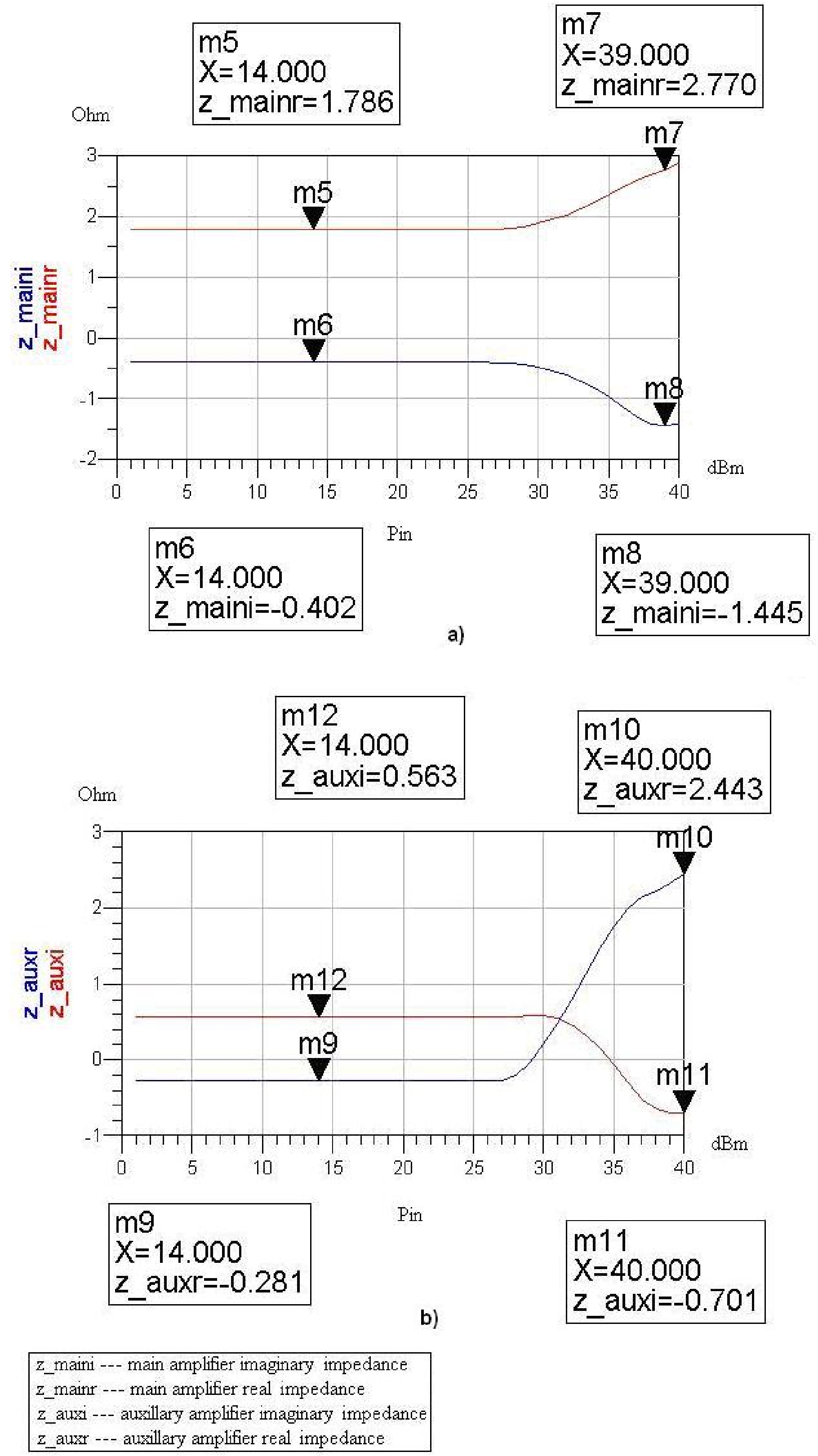


Figure 4.19 Impedance change due to load modulation a) main amplifier b) auxiliary amplifier

The impedance modulation of the main amplifier can be seen in Figure 4.20. The load impedance moves at the direction of black line, from outside contours to the center. After the start of the auxiliary amplifier operation, the main amplifier impedance changes letting it to saturate at higher power level. Point m4 shows the output impedance with only the main amplifier operation at saturation which is 43.4dBm. When the auxiliary amplifier is also in operation main amplifier can reach saturation point up to 45.8dBm power level which is marked as m6. The main amplifier operates highly efficient at all over its impedance track.

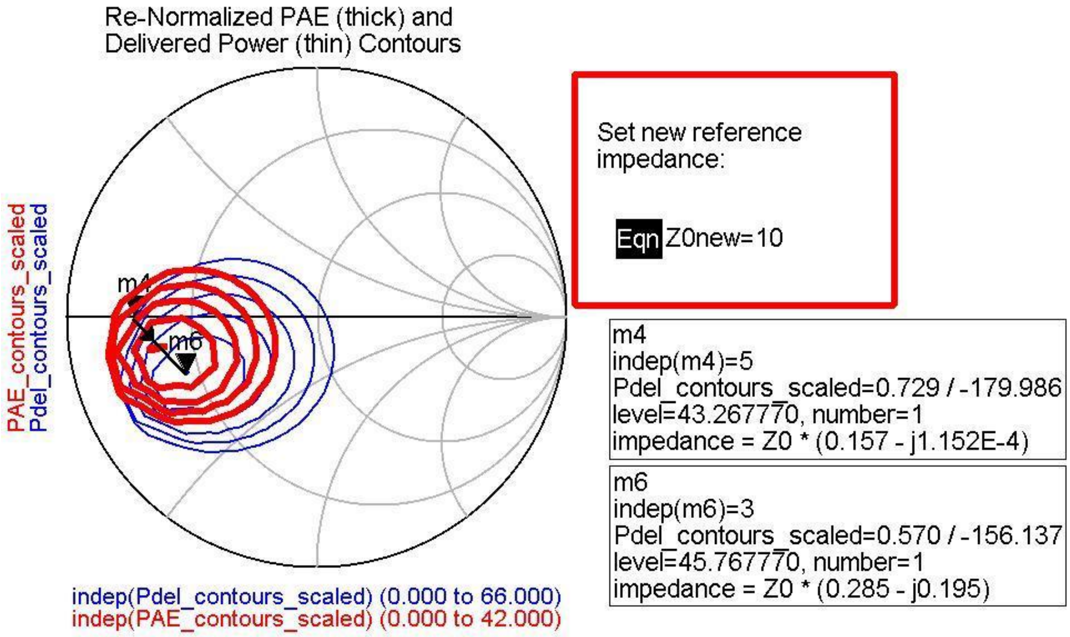
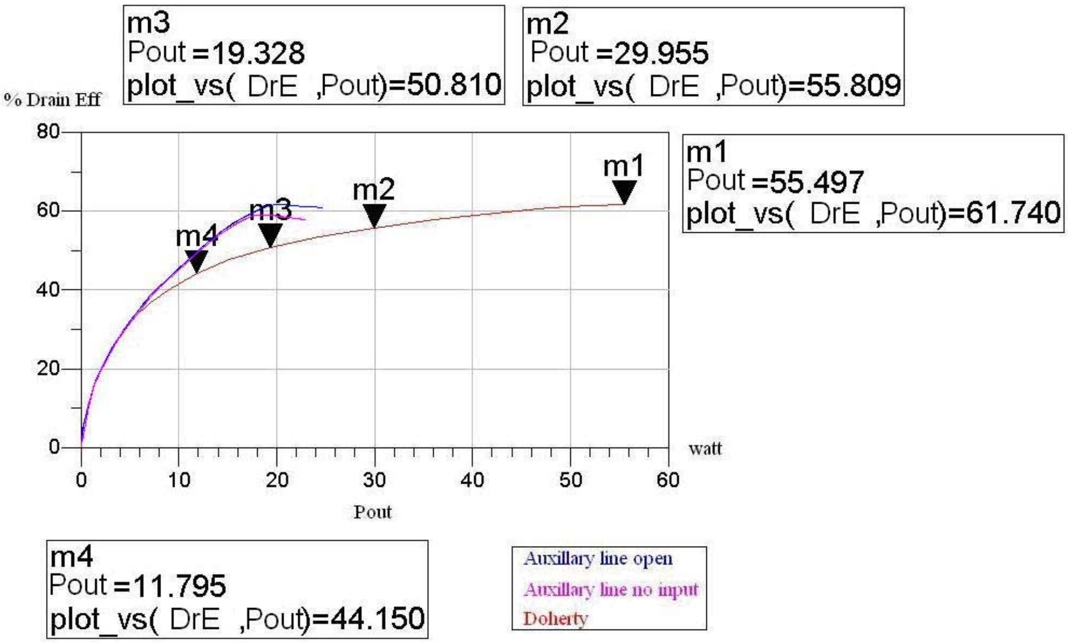


Figure 4.20 Load modulation effect on the main amplifier

The drain efficiency simulation reslults of the designed Doherty power amplifier can be seen in Figure 4.21. The blue curve represents the efficiency when the auxiliary amplifier stage is broken from the output line. That efficiency is the maximum achievable low power efficiency where the auxiliary stage is seen as completely open circuit from the output. The pink curve represents the efficiency when the auxiliary amplifier stage is broken from the input line. Corresponding efficiency brings in the performance when the auxiliary stage only have load effect at the output of the amplifier. The red curve represents the designed Doherty power amplifier drain efficiency and output power level. The biasing voltage of the auxiliary amplifier could be tuned to increase low power efficiency but loosing maximum available power.



4.21 Simulated efficiency plot of the Doherty PA

Designed Doherty PA operates linearly at both low and high power levels as seen in the simulation result in Figure 4.22. P_1 dB output point is nearly 46.7dBm.

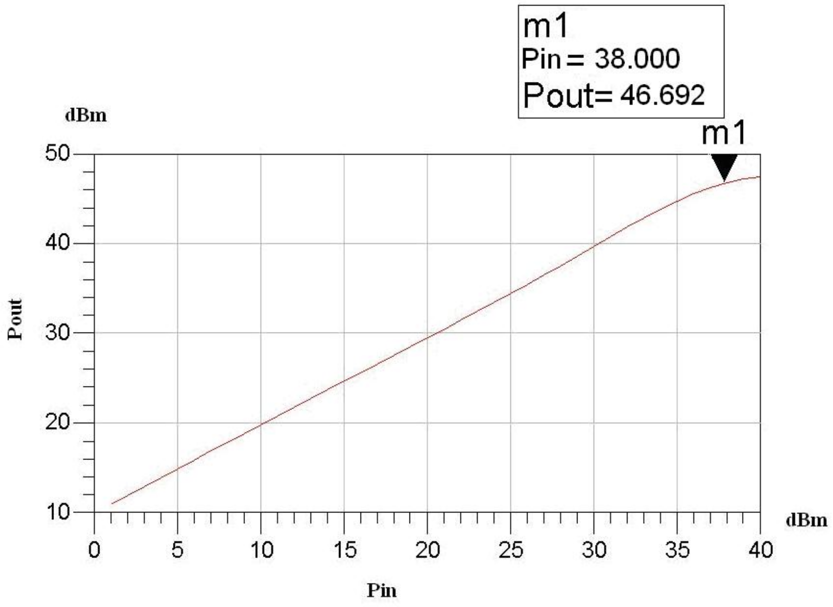


Figure 4.22 Input vs output power plot of the Doherty PA

Two tone simulation is an effective way to see the linearity of a PA. In order to see the 3rd order harmonic distortion levels two tone signals at 2.6 and 2.61GHz fundamental frequencies are applied. The output fundamental powers (2.6+2.61)GHz and 3rd order product powers (2.59+2.62)GHz are obtained in simulation as seen in Figure 4.23 a. The difference between the fundamental and IMD3 products can be seen in Figure 4.23 b. The 3rd order product power at 6dB back off power level is -42dBc .

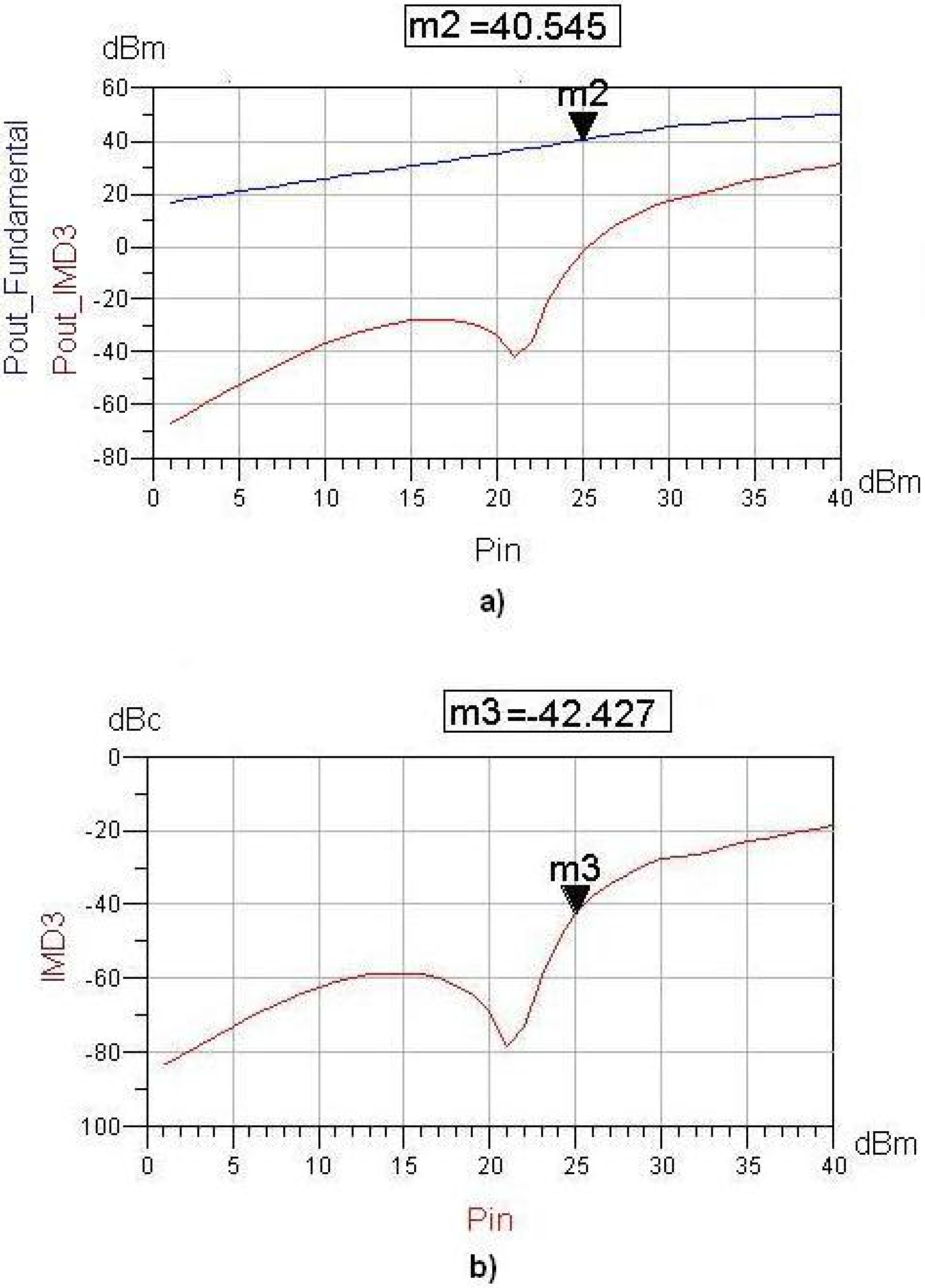


Figure 4.23 a) IMD3 and Funamental powers b) IMD3 in dBc

Noise figure of the amplifier represents its degradation in signal/noise ratio as the signal passes through (Agilent Technologies, 2010). It doesn’t directly effect power amplifier noise performance but it’s a factor on total output noise power, thus can be evaluated. In RF high power applications, IMD3 products have major impact on the reliability of the signal, nevertheless noise figure of the design can be examined. The

Doherty design contains of power splitter and amplifier stages, so the system can be evaluated as two cascaded stages while determining the noise performance. Noise figure of the cascaded system is (Pozar, 1998);

$$F_{cas} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \ldots + \frac{F_N - 1}{G_1 G_2 \ldots G_{N-1}} \qquad (4.1)$$

Noise figure of the cascaded systems are dominated by the first stage as the noise figure of the next stage is reduced by the gain of the first. The formula in (4.1) clearly shows that only first few stages have considerable effect on the noise figure of the entire system. Accordingly power amplifier noise figure don’t have crucial effect on overall noise figure as it is the last stage of the transmitter chain. Though, in the Doherty system the formula can be derived in the form;

Overall Noise Factor = Spliter Loss + (Amplifier Noise-1) x Spliter Loss (4.2)

Power delivered to the main amplifier is degraded 1/3 by the splitter. It has a loss of -4.7db which is also equal to 3. That results in splitter loss as an effective ratio of Doherty PA noise figure. The corresponding noise figure of the whole Doherty system can be seen in Figure 4.24. Noise figure of 9.188dB for this amplifier design

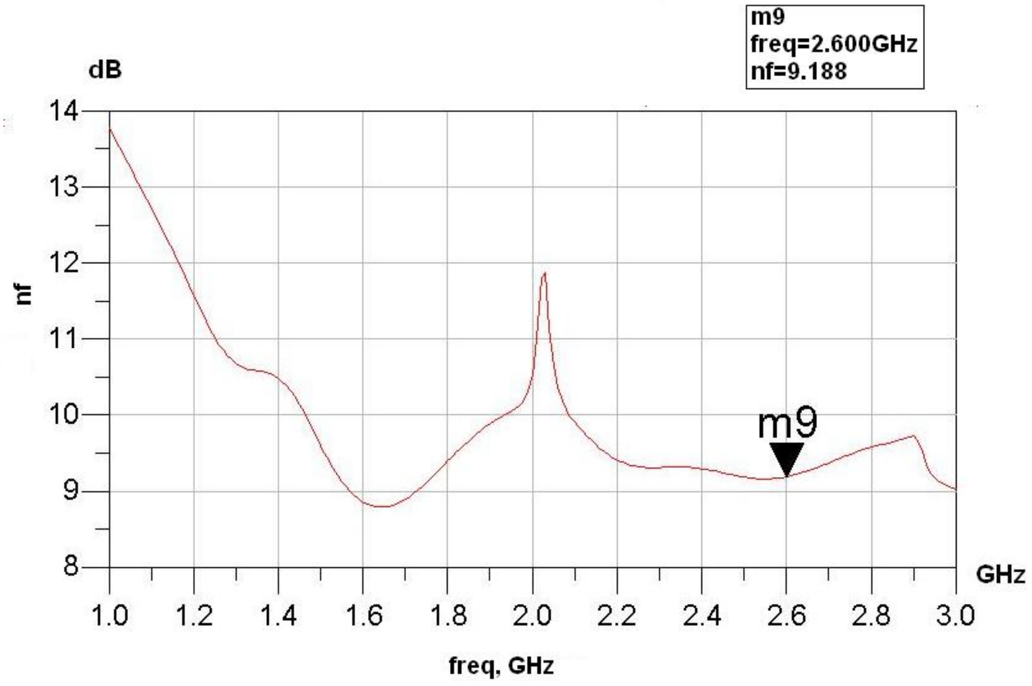


Figure 4.24. Noise Figure

is acceptably good. Though, the preamplifiers of the entire transmitter system should be designed carefully to have good noise performance. Manku (2007), has an expository article about the WCDMA based system noise figure limits and could be used to compare power amplifier noise figure performances.

CHAPTER FIVE
CONCLUSION

Harmoniously with the new technologic improvements, recent progress in wireless communication revealed more complex but highly spectrum efficient modulation schemes. These modulation schemes impose obligatory requirements on the power amplifiers, above all efficiency for mobile applications which require high battery life. Efficiency – linearity trade off in power amplifiers is a tough and common challenge, especially in the design of amplifiers that deal with those signals which require high data rate and thus PAR. The Doherty amplifier structure has attracted much research interest with the rapid increase in this mobile applications due to its high efficiency over an extended power range speciality.

In this dissertation, Doherty type efficiency and linearity enhancement technique, including its load impedances, uneven input power splitting, biasing of the stages and harmonic terminations, is investigated. Two identical active devices are used as the main and auxiliary amplifiers and practically implemented with Wilkinson power divider technique. Class C auxiliary amplifier bias point and related power division ratio carefully deduced. The presented design offers a simple and effective method to implement the Doherty amplifier.

Freescale's surface mounted LDMOS RF power transistor used as the identical amplifiers. The main aim in the amplifier design has been to improve linearity efficiency trade-off in basestation amplifiers. The design was considered for WiMAX applications at 2.6GHz. First main stage of the Doherty PA simulated, fabricated on Taconic RF-35 substrate and mesasured. After that whole design of the Doherty PA simulated. The simulations are carried out with reliable electronic design automation software ADS for RF applications. For this purpose, reliable RF high power ADS model design kit and model for the transistor has been delivered from the manufacturers own website. Both obtained measurement and simulation results were satisifying however measurements were limited to low power levels of this research because of the lack of high power measurement instruments in the laboratory. Hewled Packard (HP) 8592B Spectrum Analyzer and Anritsu MS2711D Spectrum Master is used as to measure the results and HP 8350B Sweep Oscillator with HP 83592B RF Plug-IN integrated used as signal generator.

Prior to the design of the Doherty amplifier, single stage linear PA has been designed as the main amplifier. Through the help of the main amplifier design, basic and contemporary RF power amplifier design issues have been examined and analyzed. Short circuited $\lambda/4$ lines, proper decoupling capacitors and multiple stage microstrip matching lines are used in order to suppress the harmonics and improve linearity. The designed main amplifier is biased in class AB and operated perfectly linear till 13.9dBm maximum available input power bringing in 26.72dBm measured output power. These results are also coherent with the simuation results. The main amplifier simulations show that it operates linearly till 32dBm input power level producing 43.9dBm output power where this is the P_1dB gain compression point. As a consequence these results lead to a conclusion that high linearity can be achieved through elaborate design of the matching and the biasing network together with bias point optimization. Multiple stage matching network also had major effect on bandwith of the system. The amplifier simulation seen at Figure 5.1 exhibits necessarily wide bandwith of 490MHz and about 10dB power gain at fundamental frequency.

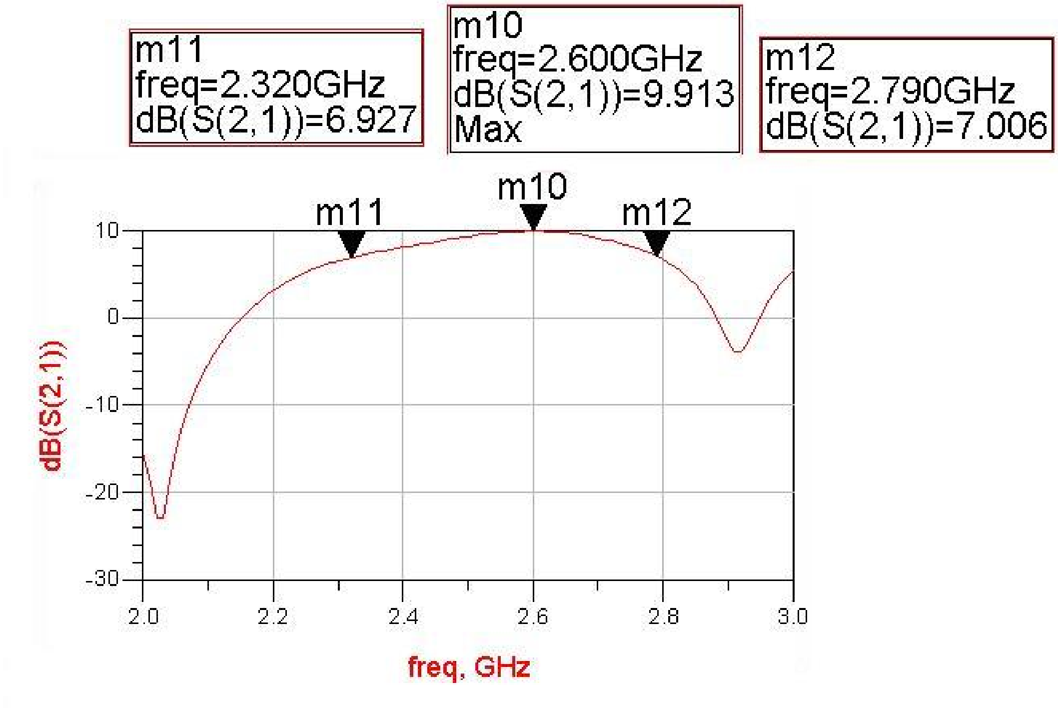


Figure 5.1 The Doherty power amplifier bandwidth

Doherty PA utilizes the gain compression and gain expansion behaviours of the class AB and the class C PA's by outphasing the third order products of each thus leading to increased linearity at higher power levels. Doherty PA output power simulation exhibits that amplifier reaches its P_1dB point at 38dBm input and 46.6dBm output power. That demostrates the extended linearity of the Doherty PA as seen in Figure 5.2.

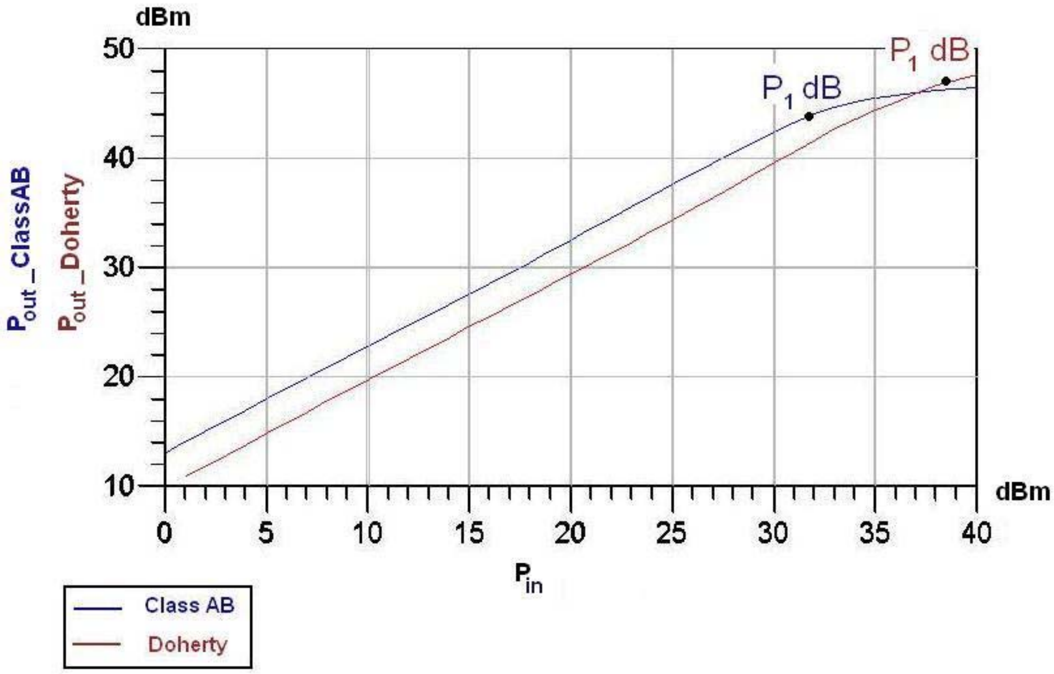


Figure 5.2 Linearities of the Doherty and class AB power amplifiers

The Doherty PA can amplify the input signal linearly with extended range as it can reach up to higher output power levels.

The single stage class AB amplifier produced high linearity but unfortunately low efficiency especially at average power levels. However, the designed Doherty PA has 51.1% PAE at operating frequency which is sufficient enough. Comparing the efficiency simulation results of the main amplifier and the Doherty amplifier as seen in Figure 5.3 expose that Doherty amplifier performs high drain efficiency at both maximum and average power levels. PEA of the class AB amplifier at 6db output back-off point is about 25% while the Doherty PA has 40%.

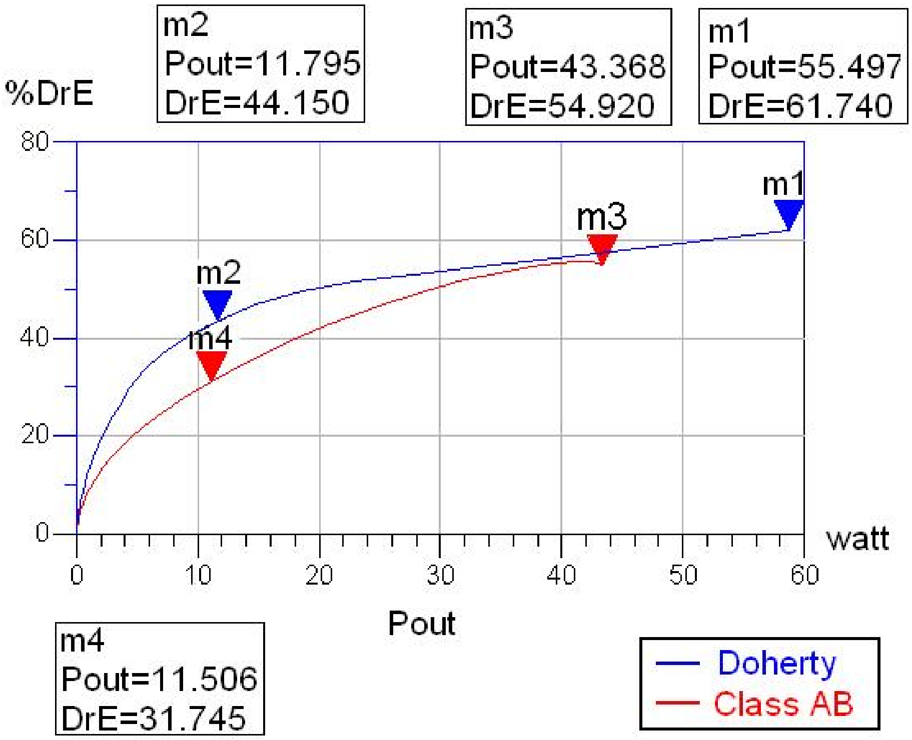


Figure 5.3 Drain efficiency vs output powers for the Doherty and class AB PA

The theory and the simulation results disclose that Doherty PA operates more linear and highly efficient at high power levels, additionally it has high efficiency at average power levels when comparing to classic PA's. That features of the Doherty PA makes it strongly feasible for the modern communication systems using CDMA, OFDM etc., which have high PAR. Although the design was considered for WiMAX applications, Doherty structure could also be an intriguing candidate for Wireless Local Area Network (WLAN), mobile handset, Wireless Broadband (WiBro), cellular base station applicaitons. The linearity, efficiency and IMD3 performances of the proposed Doherty amplifier design shows significant improvement and proves the success when implementing the technique on current mobile communication standarts.

The study described in this dissertation is adaptable to future researches and developments. To minimize the network space, instead of $\lambda/4$ lines the use of equivalent π or T networks are possible when accurate and high Q passive componets are available. Further enhancements techniques could be used in order to increase Doherty PA’s linearity and efficiency. These techniques include but are not limited to bias adaptation, power supply variation, cartesian feedback, digital adaptive predistortion however; they are out of the scope of this work. Moreover, multistage Doherty amplifier technique can also be implemented to increase efficiency. These techniques are well obvious important to acquire higher efficiency standarts but also most of them bring in increased complexity and cost.

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