HIGH EFFICIENCY pHEMT BALANCED POWER AMPLIFIER DESIGN USING LOAD PULL TECHNIQUE

by

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DECLARATION

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged.

17th June 2010 LOKESH ANAND VIJAYAKUMARAN

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Dedications to my beloved parents

LIST OF ABBREVIATIONS

ACPR	Adjacent Channel Power Ratio
RF	Radio Frequency
IC	Integrated Circuit
PA	Power Amplifier
E-pHEMT	Enhanced mode Pseudomorphic High Electron Mobility Transistor
PAE	Power Added Efficiency
VSWR	Voltage Standing Wave Ratio
MMIC	Monolithic Microwave Integrated Circuit
InP	Indium Phosphate
InGaAs	Indium Galium Arsenide
HBT	Heterojunction Bipolar Transistor
LAN	Local Area Network
TWT	Travelling Wave Tube
MESFET	Metal Semiconductor Field Effect Transistor
CAD	Computer Aided Design
CPW	Coplanar Waveguide
NF	Noise Figure
TEM	Transverse Electromagnetic Mode
IMD	Intermodulation Distortion
ECM	Electronic Counter Measure

LIST OF PUBLICATIONS

M. F. Ain, Lokesh Anand, Narendra Kumar Sangaran Pragash, S. I. S.Hassan. "*5-Watt High Efficiency UHF class E RF Power Amplifier with stub load network*". Proceedings of MUCET2008 Malaysian Technical Universities Conference on Engineering and Technology March 8-10, 2008, Putra Palace, Perlis, Malaysia

M. F. Ain, Lokesh Anand, Narendra Kumar Sangaran Pragash, S. I. S.Hassan. *"Efficiency Enhancement With Stage Bypassing Concept For High Power RF Power Amplifier".* Proceedings of MUCET2008 Malaysian Technical Universities Conference on Engineering and Technology March 8-10, 2008, Putra Palace, Perlis, Malaysia

Kumar Narendra, Lokesh Anand, Sangaran Pragash, M. F. Ain, S.I.S.Hassan. *"Constant Efficiency Achievement with Switched Gain Stage and Drain Supply Adjustment Method for UHF RF Power Amplifier".* Microwave Journal,
Vol.51, no.4, pp.126-130, August 2008

Lokesh Anand, Kumar Narendra, Sangaran Pragash, M. F. Ain, S.I.S.Hassan. *"High Efficiency 600-mW pHEMT Balance Amplifier Design with Load Pull Technique"* International RF and Microwave Conference (RFM 2008)

HIGH EFFICIENCY pHEMT BALANCED POWER AMPLIFIER DESIGN USING LOAD PULL TECHNIQUE

ABSTRACT

A rapid increase in transmission capacity is required to meet the needs of the multimedia society. In broadband power amplifier design, a key element is maintaining flat gain across band while providing good efficiency and high output power. Commonly this is addressed using the single stage amplifier design. But in reality, to achieve high efficiency while maintaining good output power usually not practical with a single stage amplifier design. Alternatively, few stages of amplifier can achieve this and this is the point where balanced amplifier design comes into picture. Implementation of the push pull configuration using uniplanar technology is very desirable for microwave as it can create a high performance low cost compact amplifier. This thesis provides suitable design method to achieve high efficiency of single balanced amplifier based on load pull technique. The device technology is using pseudomorphic High Mobility Electron Transistor (pHEMT) having gate-width of 6400-μm. Wideband baluns were used to achieve balance to unbalanced characteristics. A test board with FR-4 material having dielectric of 4.5 and thickness of 14 mils was fabricated. Power-aided-efficiency (PAE) of more than 50 %, output power of 1 W and gain of 14 dB for the entire range 1-1.5 GHz is achieved at measurement level. These results show the feasibility of the balanced pHEMT amplifier configuration using load pull technique for microwave applications. This high efficiency design is favorable candidate for two way portable radios where the radio is required to operate over a large number of channels for long period from a small size battery.

REKABENTUK PENGUAT KUASA SEIMBANG pHEMT BERKECEKAPAN TINGGI DENGAN TEKNIK BEBAN TARIK

ABSTRAK

Peningkatan pesat dalam kapasiti penghantaran diperlukan bagi memenuhi keperluan pengguna multimedia. Dalam rekabentuk penguat kuasa jalur lebar, elemen kuncinya adalah untuk mempunyai gandaan yang rata pada jalur frekuensi sambil memberikan kecekapan dan kuasa output yang tinggi. Pada umumnya hal ini ditujukan dengan menggunakan rekabentuk penguat kuasa tunggal. Namun demikian, untuk mencapai kecekapan yang tinggi sementara mengekalkan kuasa output yang baik biasanya tidak praktikal dengan penguat kuasa tunggal. Beberapa tahap penguat kuasa diperlukan dan penguat kuasa seimbang merupakan antara rekabentuk yang mempunyai beberapa tahap. Pelaksanaan tatarajah "push pull" menggunakan teknologi uniplanar sangat diperlukan bagi gelombang mikro kerana dapat mencipta penguat kuasa berpretasi tinggi pada kos yang rendah. Tesis ini memberi kaedah rekabentuk yang berpadanan untuk mencapai penguat kuasa yang mempunyai kecekapan yang tinggi berdasarkan teknik beban tarik. Teknologi peranti yang mengunakan elektron berkelajuan tinggi (pHEMT) yang mempunyai lebar get 6.400 μm digunakan untuk mencapai keseimbangan ciri yang seimbang. Papan uji dengan FR-4 bahan mempunyai dielektrik 4.5 dan ketebalan 14 mils telah difabrikasi. Kecekapan (PAE) lebih dari 50%, kuasa output 1 W dan gandaan sebanyak 14 dB bagi jalur frekuensi 1-1.5 GHz dicapai melalui pengukuran. Rekabentuk ini dapat diaplikasikan dalam pengunaan radio mudah alih dua arah di mana radio diperlukan untuk mengendalikan lebih daripada sejumlah besar saluran untuk tempoh yang lama dari bateri yang bersaiz kecil.

CHAPTER 1

INTRODUCTION

1.0 Overview

A logical starting point for a thesis on RF power amplifier design would be a definition on what a power amplifier or better known as PA; actually is. If a technical definition is taken into account, obviously PA is an amplifier which is designed to deliver the maximum power output for a given selection of active device. Such a definition is essential in that it emphasizes technique described in this thesis that will be of interest to large signal amplifier design. For an instance, the problem of designing high efficiency and high output power amplifier used in wireless transceiver could be considered to be a PA design problem, and the technique described here in this thesis would be applicable. The demand for power amplifiers has been continually increasing over the last decade. The requirements include aspects of high power level, high efficiency, high linearity and high operating frequency and the relative importance of each of these features is application specific [Moore, 1997]. One major trend is the continuous demand for more power and efficiency over a wide bandwidth.

Any practical power amplifier will be a subassembly consisting of several driver and gain stages and the final power stage itself will probably use some form of power combining network. The thesis addresses several topics which arise in designing complete amplifier assemblies. These topics include balanced configuration, power combining, biasing and matching network. The interest in balanced amplifier design based on Enhanced mode Pseudomorphic High Electron Mobility Transistor (E-pHEMT) necessitates the development of accurate large signal models that can predict maximum output power level, achievable power added efficiency (PAE) and other nonlinear phenomena over the whole operating frequency range, using harmonic balance simulation.

This thesis addresses suitable design method to achieve high efficiency while maintaining promising high output power based on load pull technique. Balanced configuration with aid of coupled line balun is used for high efficiency operation. E-pHEMT having gate width of 6400-µm with low supply voltage (4.4V) is being utilized in this work. A design template to determine optimum source and load impedances simultaneously has been developed for efficient optimization. Detail explanations of load pull technique, balun design as well as circuit analysis will be considered in later sections.

1.1 Objectives

The proposed research is carried out in effort of realizing high efficiency balanced amplifier design with load pull technique. The idea came into picture as single stage amplifier design have some limitations in term of performance as follows:

- The ideal single stage microwave amplifier would have constant gain and good input matching over the desired bandwidth. From the examples that are known, conjugate matching will give maximum gain only over a relatively narrow bandwidth, while designing for less than maximum gain will improve the gain bandwidth, but the input and output ports of the amplifier will be poorly matched.
- In some system requirements, high efficiency and output power as well as broader bandwidth would be the major requirements which need to fulfill. Obviously such

specifications cannot be achieved using a single amplifier design because of the device limitations.

- Microwave transistors typically are not well matched to 50 Ω, large impedance mismatches and parasitic capacitances of the device.

Consequently, special considerations must be given to the problem of designing broadband amplifiers. Some of the common approaches to overcome these problems would be balanced amplifiers, distributed amplifiers, resistive matching networks and negative feedback. It should be noted that an improvement in bandwidth and efficiency is achieved only at certain expense of gain, complexity or similar factors. This work addresses the design of balanced amplifier design to improve efficiency over bandwidth (1000 -1500MHz) using load pull technique.

1.2 Design goal

As mentioned earlier, the objective of this thesis is to design high performance balanced amplifier across frequency (1000-1500MHz). The performances are basically referred to high efficiency and high output power with comparable gain. These 3 parameter would be the major considerations besides stability, intermodulation distortion, 1dB compression point and thermal dissipation.

As a requirement of good power amplifier design, it is necessary to design an amplifier with good thermal dissipation and stability performance across temperature and voltage characteristics. Thermal dissipation will keep the design reliable due to high drain current nature of power amplifier. Stability performance of the power amplifier must immune to impedance load angle of 6:1 VSWR.

The design goal is set as in Table 1.1 in order to get a better picture on design goals of this thesis.

Table 1.1: Design goal of pHEMT balanced amplifier

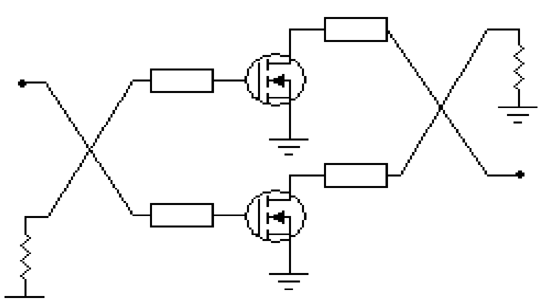
Parameter	Value
Center frequency	1300 MHz
Operating frequency	1000-1500 MHz
Bandwidth	500 MHz
Output power	30 dBm
Efficiency	50-60%
Gain	13 dB
1dB compression point	30 dBm
IMD at output power of 30dBm	32 dBc

The goals listed in table above would be a backbone for the whole balanced amplifier design and will be evaluated at both simulation and measurement level. To implement the hardware, fabrication process has to be done accordingly with correct procedure. The simulations and measurements will be highlighted in later chapters

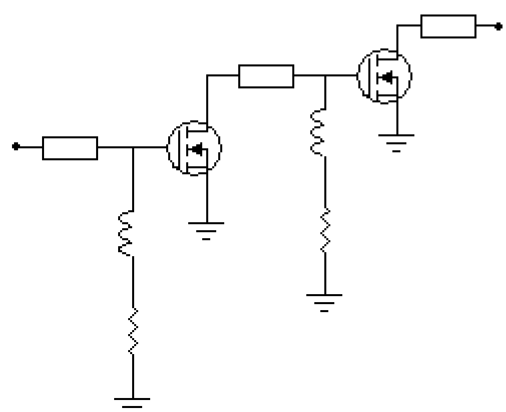
1.3 Scope of the project

Where there are wireless communications, there are transmitters and wherever transmitters exist, there are RF power amplifiers. The underlying principles in the power amplifier (PA) design are much more the same in all wireless communications. The PA specification and design will, in each and every case, be a subject of critical observation. In broadband power amplifier design, a key element is maintaining a flat gain over the band while also providing a good efficiency as well as output power.

Commonly this is addressed using the balanced amplifier approach Figure 1.1(a), whereby the input is reactively match for better efficiency and output power when two identical amplifiers is placed between them. The efficiency decides the battery life time as PA is the main consumer of dc power from battery in radio transmitters and handset. Output power affects the communication distance. This thesis emphasizes on balanced amplifier design eventhough there are many approaches such as lossy match network Figure 1.1(b), distributed amplifier Figure 1.1(c) and feedback amplifier Figure 1(d). Balanced configuration has its own unique advantages which will be discussed in later section.



(a)

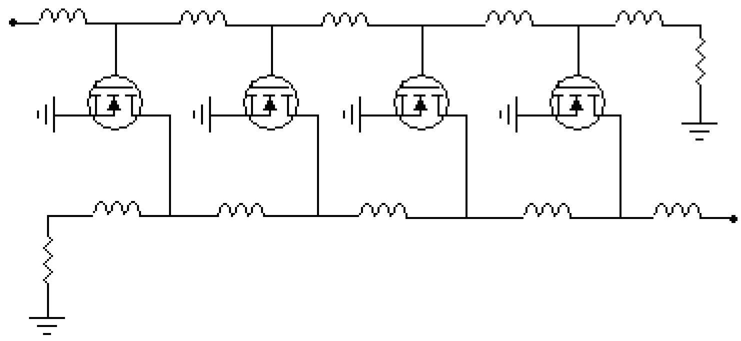


(b)

Figure 1.1: Broadband power amplifier approaches

(a) Balanced amplifier

(b) Lossy match



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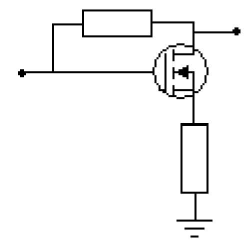


(d)

Figure 1.1: Broadband power amplifier approaches (continuation)

(c) Distributed amplifier

(d) Feedback amplifier

1.4 Thesis Outline

This thesis is organized in 6 chapters. Each of the chapter was written according to the progress of the report. Chapter 1 is the introduction part of the project which covers the objective of the project. In order to get a better view of the project, the research's scope and the design goals are also included.

Chapter 2 revisits some basic theory and fundamentals of balance amplifier design which is generally a complicated procedure to design an effective impedance matching depending on technical requirement and operation conditions, stability in operation, efficiency, output power, gain and ease in practical implementation. Therefore, at the beginning of some sections, the key definitions of technical terms are included as well. Chapter 2 takes the attempt to study on load pull technique which is indeed a backbone of this thesis.

The detailed circuit design and analysis of balanced amplifier with load pull technique are described in Chapter 3. This chapter covers the design schematic and step by step procedure to achieve high efficiency balanced amplifier using balun as power combiner and splitter. Design procedures using load pull technique to obtain optimum input and output impedance of a pHEMT single balanced amplifier are well established in this section. Optimum input and output impedance contour under large signal operation are derived for design step. In the design example that is presented, coupled line matching topology for the input and output RF matching circuits are used.

Chapter 4 takes up the theme of hardware fabrication. Chapter 5 is basically a compilation of simulation and measurement results. Prototype board is tested at Motorola Technology for design verification and the measurement results covers output power, gain, efficiency, stability and intermodulation distortion performance as well as case temperature analysis. The conclusions and future work recommendation are presented in Chapter 6.

CHAPTER 2

BALANCED AMPLIFIER DESIGN FUNDAMENTALS

2.0 Introduction

In broadband power amplifier design, a key element is maintaining a flat gain over band while also providing a good input VSWR. Commonly this is addressed by multi stages designs which include balanced, distributed, feedback and lossy match amplifiers. (Arell,1993). Any practical power amplifier will be subassembly consisting of several driver and gain stages and the final power amplifier stage itself will probably use some form of power combining network.

This work addresses several of the specific topics which arise in designing complete balanced amplifier design assemblies which includes load pull technique, power combining, biasing and matching network.

The balanced amplifier concept has dominated solid state amplifier design for nearly two decades (Rumelhard *et al*. 1986). While it is expected to continue its dominating role, the microwave balanced amplifier would be an attractive way for many system applications because of it advantages which includes

- better power added efficiency
- easier matching since two smaller gate devices are used in series
- minimizes even order distortion products

2.1 Literature survey

The balanced amplifier configuration was initially reported in 1965 and possesses many advantages such as a good input and output matching, a high degree of stability as well as better efficiency and output power. K.W. Kobayashi reported an InAlAs/InGaAs-InP based HBT MMIC linear amplifier which combines a double balanced design topology which achieves 15.4 dB of gain, 28.3 dBm of IP3 and saturation power of 16.2 dBm at 44 GHz using "current re-use" bias scheme (Kobayashi, 1998). Shuoqi Chen has demonstrated a compact MMIC balanced amplifier operating at Ka-band using pHEMT technology. This balanced three stage power amplifier achieves 32.8 dBm of output power and 18 dB of gain at 30GHz (Shuoqi, 2003).

In another work done by Min Han, balanced medium power amplifiers for 60 GHz wireless LAN application were designed and fabricated. The single-ended and the balanced medium power amplifier on MMIC technology were designed using 0.1μm Γ- gate GaAs p-HEMT and CPW library. From measurement, the design shows S_{21} gains of 13.14 dB and 1-dB compression point of 5.9 dBm (Min, 2005). On the other hand, Tomasz Cegielski demonstrated design of medium power C-Band balanced amplifier which performs output power up to 35.5 dBm (saturated power) and gain of 20 ± 0.5 dB. Devices are based on GaAs InGaP power amplifier MMIC. Different couplers and power divider circuits were used to achieve balanced amplifier with a microstrip line structure (Tomasz ,2005).

In the work done by Giuseppe Berretta, a MMIC SiGe HBT balanced amplifier for CDMA2000 is proposed where the configuration delivers 28.5 dBm linear output power, PAE of 35% and gain of 30dB (Giuseppe, 2006). Research by W.R. Deal presents MMIC low noise amplifiers using dual-gate GaAs HEMT devices in a balanced configuration which is targeted for the frequency bands of 5-9 GHz, 9-18GHz and 20-40 GHz. Additionally, noise performance is excellent with less than 1.75 dB NF, 2.75 dB NF and 2.5 dB NF for the respective frequency bands (Deal, 2006). Jeng-Han Tsai constructed a balanced amplifier with two broadband amplifier and two broadside couplers using standard 90-nm CMOS technology. The MMIC demonstrates a measured gain of 14.5 dB, 8% of PAE and 10.6 dBm of output power (Jeng, 2007).

Thomas Chong describes the design and realization of a balanced low-noise amplifier module in the 2 GHz band. In a balanced amplifier application with 3 dB hybrids, the design exhibits a noise figure of 0.9 dB, coupled with a high OIP3 of 46 dBm at 31 dB gain with a 5 V supply. The MMIC design leverages 0.5 micron e-pHEMT technology (Thomas, 2007).

A fully integrated balanced amplifier was realized in standard 0.18-μm CMOS technology by Jun-De Jin (Jun, 2008). From the S-parameters, a gain up to 21.5 dB was achieved at 45.4 GHz under supply voltage of 1 V and power consumption of 89 mW.

In the work reported by Jongsik, at class AB biasing, efficiency of 36% can be achieved with the proposed method. Reflected power is injected to an auxiliary and its out power is combined with the output power of balanced amplifier resulting higher power and efficiency (Jongsik, 2009). Hamid demonstrated a novel structure of balanced amplifier using six port power divider. Using this six port power divider as 3dB power divider and combiner, broadband properties and complete symmetric structure can be achieved. In contrary of conventional 3dB couplers, zero phase and gain unbalances of the proposed circuitry gives nearly unity input and output VSWR (Hamid, 2010)

2.2 Balanced amplifier

2.2.1 Introduction

No discussion on broadband microwave power amplifiers would be complete or even fair without paying due respect to the traveling wave tube (TWT). This venerable device has changed remarkably to perform microwave power amplification task that are still beyond any conceivable solid state device.

The impact of newly available GaAs MESFET devices in late 1970's and early 1980's was mainly to replace much low power TWTs used for electronic countermeasure (ECM) receiver front ends (Cripps,2002). Such applications required high gain over octave bandwidths but at power levels lower than 10 dBm. As MESFET power devices became available the power was gradually increased up to about 30 dBm level (Cripps,2002).Generally this power level was used to drive the output of TWT. But in all cases, a different approach to circuit design and matching techniques was required. These techniques can be explained under two headings which are balance amplifiers and network synthesis. In this thesis, only balanced amplifier design utilizing load pull technique will be covered.

2.2.2 Theory of operation

Generally, if it is necessary to increase the overall output power and efficiency, several active devices can be used in parallel or balanced configurations (push pull). In parallel configuration, the active devices are not isolated from each other. This requires a very good circuit symmetry and the output impedances will become too small in the case of high output power. (Grebennikov,2007). Balanced configuration leads to eliminations of drawback in parallel set up. For a case of same output power level, input impedance Z_{in} and output impedance

Z_{out} under balanced mode are approximately four times as high as a parallel connection of the active devices. Loaded quality factors of the input and output matching circuits remains unchanged because the real and reactive parts of these impedances are increased by the factor of four. (Grebennikov,2007)

Although the push pull configuration may be considered to be balanced in the more generic sense, in the microwave amplifier world “balanced” amplifier is something quite different and is shown graphically in Figure 2.1 below.

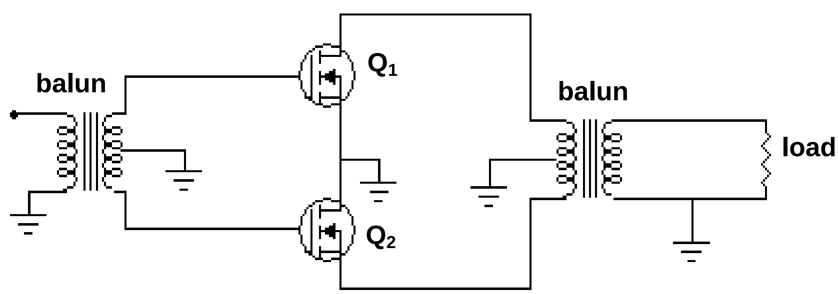


Figure 2.1: Basic balanced amplifier configuration

Figure 2.1 above shows balanced configuration pair of pHEMT device and two baluns. The input signal, fed to the balun, is split into two signals with equal amplitude but 180° out of phase to the gates of the pHEMT. The output signals from the drains of the pHEMT which are equal in magnitude but differ in phase by 180°, are combined via output of balun. The input voltages applied to the gates can be described in the forms

$V_{i1} = V_m \cos\omega t$ and $V_{i2} = -V_m \cos\omega t$. On the other hand, the output voltages, V_{o1} and V_{o2} of these pHEMT’s can be expressed as power series expansions of V_{i1} and V_{i2} which then yield

$$V_{o1} = Ao + A_1 \cos\omega t + A_2 \cos 2\omega t + A_3 \cos 3\omega t + \ldots. \quad (2.1)$$

$$V_{o2} = Ao - A_1 \cos\omega t + A_2 \cos 2\omega t - A_3 \cos 3\omega t + \ldots. \quad (2.2)$$

where the *A* are constant

The total output voltage (V_{Total}) is proportional to the difference between the two voltages V_{o1} and V_{o2}. So only odd order term remains as shown in Equation 2.3 below.

$$V_{Total} = 2A_1 \cos\omega t + 2A_3 \cos 3\omega t + 2A_5 \cos 5\omega t + \ldots \quad (2.3)$$

Equation 2.3 shows that balanced configuration will balance out all even harmonics in the output and will leave the third harmonic onwards term as the principal source of distortion, thus possessing inherent spurious signal rejection of even orders and less distortion.

Since no even order harmonics are present in the output, such configuration can give more output power per transistor for a given amount of distortion. In addition to the fact that output voltage contains no even order harmonics, it is fair to say that balanced configuration possesses “half wave” or “mirror” symmetry, which implies that the bottom half of the amplifier, when shifted 180° along axis, will be the mirror image of the top half. This results in a virtual ground along the axis, which can act as the RF ground and which eliminates the need of using external elements to connect the transistors to the ground. If perfect balanced is maintained on both sides of the circuit, the difference between the signal magnitudes becomes equal to zero in each mid point of the circuit as shown in Figure 2.2 below. This effect is called as virtual grounding and the midpoint line is referred to as virtual ground.

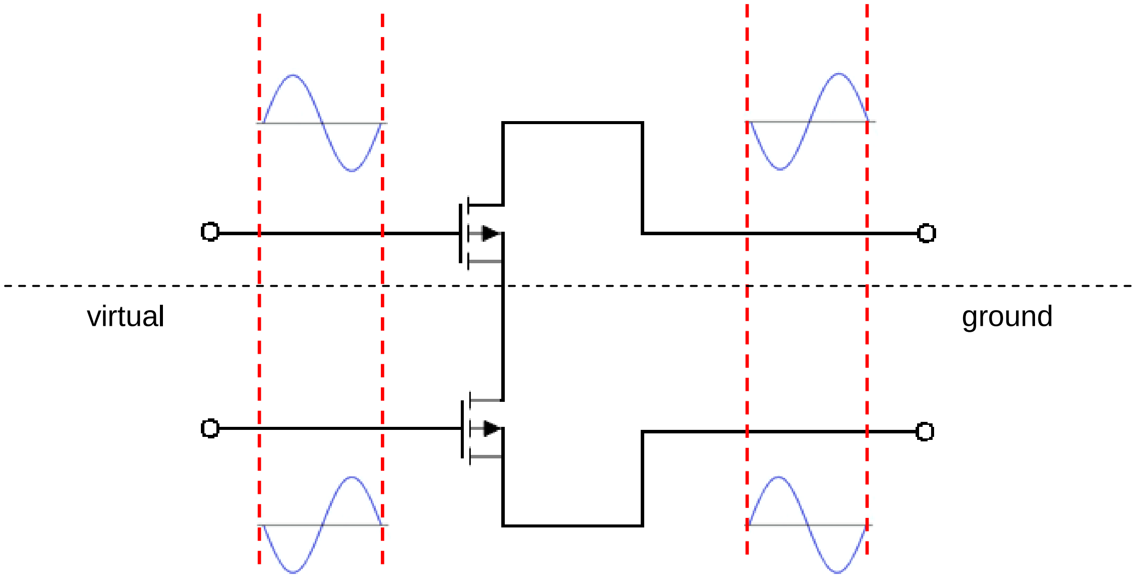


Figure 2.2: Virtual grounding concept of balanced configuration

For a balanced configuration, it is necessary to provide the unbalanced to balanced transformation referenced to the ground both at the input and the output of the power amplifier. The most suitable approach to solve this problem at high frequencies and microwaves is to use transmission line transformers (T_1 and T_2) as shown in Figure 2.3. If the characteristics impedance Z_o of the transmission line is equal to the input impedance at the unbalanced end of the transformer, the total impedance from the both devices seen at the balanced end of the transformer will be equal to the input impedance (Grebennikov,2007). Such a transmission line transformer can be used as 1:1 unbalanced to balanced transformer.

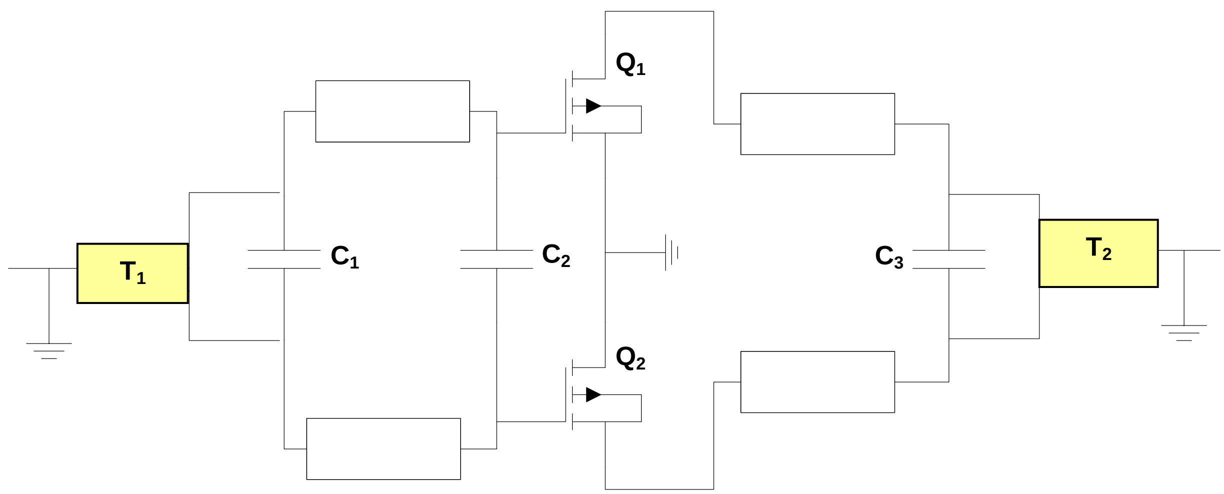


Figure 2.3: Balanced to unabalanced transformation of balanced amplifier

If Zo = 50 Ω, for the standard input impedance of 50 Ω, the impedance seen at each balanced part is equal to 25 Ω, which then is necessary to match with the appropriate input impedance of each part of a balanced transistor. The input and output matching circuits can easily be realized by using the series microstrip lines with parallel capacitors.

2.3 Load Pull for Power Device

2.3.1 Introduction

In PA design, the term “load pull” is used to describe an empirical process by which the matching requirements of a PA device are determined, using some form of variable impedance tuning device. In general, load pull can be sub divided into 3 types; load pull, harmonic load pull and source pull.

Load pull is a process of varying the impedance seen by the output of an active device to other than 50 Ω in order to measure performance parameters, in the simplest case, gain. (Microwave Encyclopedia,2009)

Harmonic load pull is a process of varying the impedance at the output of a device, with separate control of the impedances at f_o, $2f_o$, $3f_o$ and so on. Source pull is a process of varying the impedance seen by the input of an active device to other than 50 ohms in order to measure performance parameters. (Microwave Encyclopedia, 2009).

2.3.2 Load pull technique

The performance of an active device is a function of many things which are frequency of operation, temperature, bias point of the device, load and source impedance at fundamental frequency as well as power level. (Microwave Encyclopedia,2009)

When the active devices are measured using a network analyzer, the measurements are referring to small signal response in a 50 Ω system, as a function of frequency and bias point. But using linear CAD software, the small-signal response can be predicted accurately even if the impedances seen by the device is not 50Ω.

On the other hand, it's more difficult to predict performance under large-signal conditions. Perhaps a large signal model of the power device can be obtained, or use Steve Cripps method for predicting saturated power performance (Crips, 2002). But there are limitations to each of these methods; large-signal models are inaccurate. This is when the load pull comes in where it can be employed to empirically gather all of data needed to design a power amplifier and predict its large-signal responses, including, efficiency, harmonics, compression characteristics and intermodulation products.

To view large signal data, most of the plots that are of interest will be on Smith charts. By plotting contours of constant output power, efficiency and gain, typically data corresponds to one frequency at a time is examined. Load pull enables plenty of measurements at a single frequency, then move on to another frequency. Input power, source and load match as well as different bias point can be tried.

2.4 Power combiner and splitter

2.4.1 Introduction

Different eras do see technology improvements which would ultimately results in multiple power combined modules being gradually replaced by a single package solution. A critical issue in power combining applications is the insertion loss of such structures, especially if realized in the cheapest and most convenient manner, using open microstrips line.

Since the most common power combiner requirements are to combine two or most four, individual devices or single stage amplifiers, it would be appropriate at this point to review the relative merits of combiners as well as splitters. As power combiners came into picture, the candidates would be T-Junction power divider, Wilkinson power divider, directional couplers and baluns.

Such combiners have been described extensively in plenty of literature and this thesis will concentrate on use of balun as combiner and splitter.

2.4.2 Theory of balun

Multiway power combiners at lower microwave frequencies should, in principle, be easy to build with low loss, low cost and precision. It is critical, particularly at higher frequencies, that special types of combiner and divider are used to avoid insufficient power performance of the individual active devices. The method of configuration for combiners and dividers differs depending on the operating frequency, frequency bandwidth, output power and size requirements (Grebennikov, 2007)

In a balanced circuit, the identical sides carry 180º out of phase signal which have equal magnitudes. If a perfect balance has been considered, on both sides of the circuit, there is a mid point where the magnitude of the signal is zero. For absolutely identical circuits in each balanced side, the difference between signal magnitudes becomes zero at each midpoint. An ideal balanced amplifier can cancel the internally generated products and preserve the signal quality.

Figure 2.4 presents the simplified topology of balance amplifier. The two doted-lined rectangles represent the input and output of balun functions.

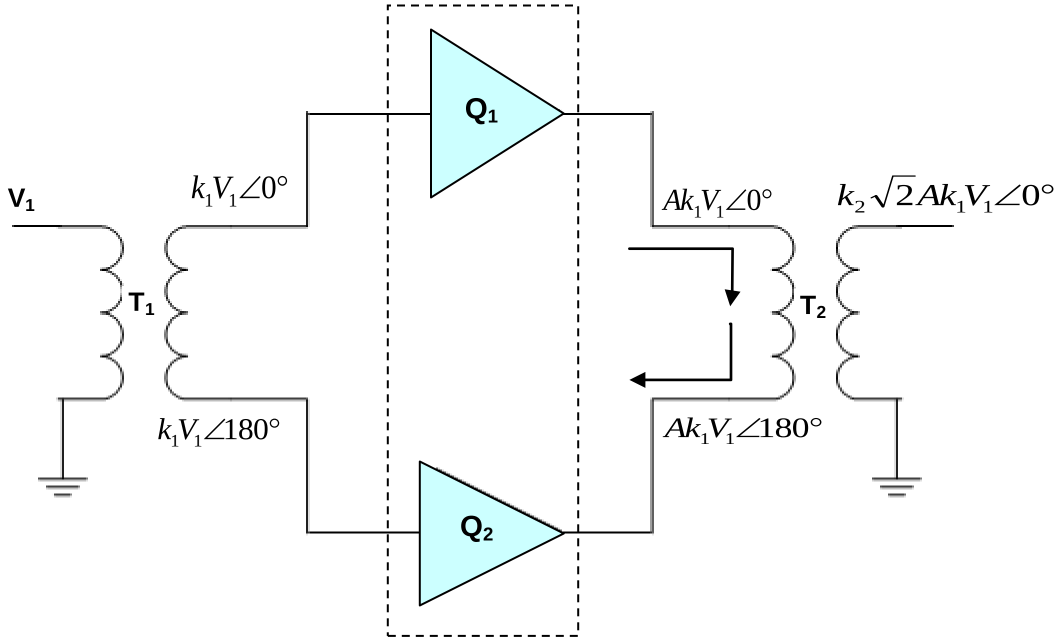


Figure 2.4: Simplified topology of balance amplifier with balun functions

The input balun splits the RF signal into two, creates 180º phase shift between two signals, thus decreasing the transformation ratio between the generator (50Ω) and the transistor terminal. The output balun has an opposite role where it combines the two signals while outphasing them and can also provide broadband matching structure. The two transistors amplify in phase opposition.

Referring back to Figure 2.4, the schematic consists two baluns and two identical amplifiers. When a signal of amplitude V_1 is applied to the input of the first balun (Balun 1), the output signal from the same balun consists of two out-of-phase signals as follows:

$$k_1V_1\angle 0 \tag{2.4}$$

and

$$k_1V_1\angle 180 \tag{2.5}$$

Factor k_1 represents the loss of the signals due to division and insertion loss. These two equal amplitude, out-of phase signals are applied to the input of two identical amplifiers. The amplified signals at the output of two amplifiers are equal in amplitude but are out-of-phase as follows:

$$Ak_1V_1\angle 0 \tag{2.6}$$

$$Ak_1V_1\angle 180 \tag{2.7}$$

A is the amplification factor of the amplifiers. These signals are applied to the two ends of the output balun (Balun 2).

The combined signal appears at the output of the balun 2 as:

$$k_2\sqrt{2}Ak_1V_1 \tag{2.8}$$

where k_2 represents the loss of signal in balun 2 and $\sqrt{2}$ is due to the voltage division. If baluns are ideal, k_1 and k_2 are as follows

$$k_1 = \frac{1}{\sqrt{2}} \tag{2.9}$$

$$k_2 = 1 \tag{2.10}$$

Hence the amplitude of the output signal is

$$AV_1\angle 0 \tag{2.11}$$

Consequently, the gain of the balance amplifier is the same as that individual amplifier, where the output power is twice that of an individual amplifier. Thus, balance amplifiers are frequently used for combining power of individual amplifiers. However, there is more to these amplifiers than combining power. This topology of amplifiers helps to improve power added efficiency (PAE), cancel even harmonics and intermodulations and improves the even-order intermodulation product. Design analysis of coupled line baluns will be discussed in Chapter 3.

2.5 Transmission line

2.5.1 Introduction

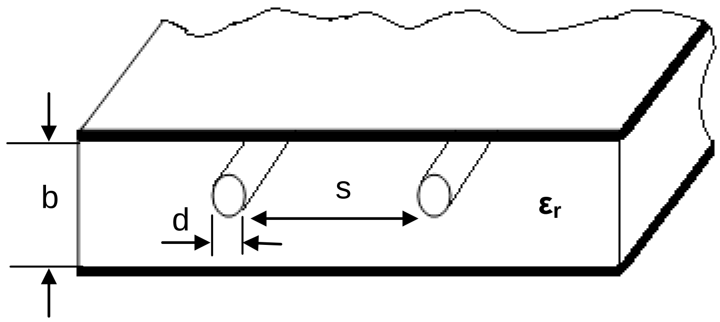
In a microstrip transmission line the dielectric material does not completely surround the conducting strip and consequently the fundamental mode of propagation is not a pure transverse electromagnetic mode (TEM). At low frequencies, typically below a few gigahertz for practical microstrip lines, the mode is a quasi-TEM mode. In the frequency range up to a gigahertz or somewhat higher, the microstrip transmission line can be characterized in terms of its distributed capacitance and inductance.

Passive elements in conventional microwave circuits consists of distributed structure and employ transmission line sections in order to achieve the desired functionality as well as meeting the design specifications. This functionality is largely achieved by the use of coupled transmission lines.

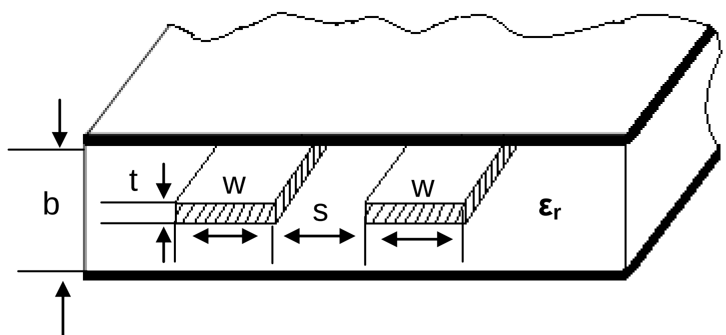
2.5.2 Coupled Structures

When two unshielded transmission lines are placed closely to each other, a fraction of the power present on the main line is coupled to the secondary line. The power coupled is a function of the physical function dimensions of the structure, mode of propagation (TEM or non-TEM), frequency of operation and the direction of propagation of the primary power. In these structures, there is a continuous coupling between electromagnetic filed between the two lines. These parallel coupled lines are known as edge coupled structures.

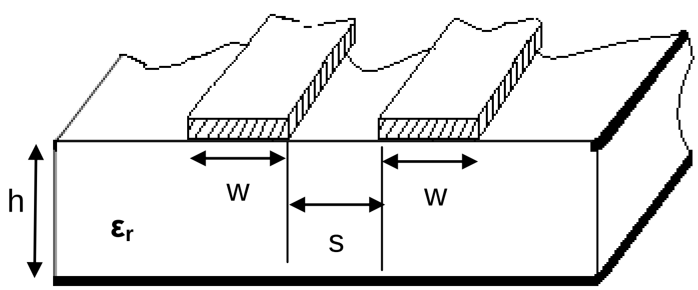
The coupled line structures are shown in Figure 2.5 below.



(a)



(b)



(c)

Figure 2.5: Coupled transmission lines: a) coaxial lines, b)striplines, c) microstrip lines (Mongia, 1999)

2.5.3 Types of coupled structure

Coupled line structures are available for all types of transmission lines including striplines, microstrip lines, coplanar waveguides and image guides. The configurations shown in Figure 2.5, use equal widths and constant spacing between the both conductors. These structures are therefore called symmetric and uniformly coupled.

Figure 2.6 represents an asymmetrical coupled microstrip line configuration with constant spacing between lines of unequal widths called uniformly coupled asymmetric line. The structure shown in Figure 2.7 is known as nonuniformly coupled symmetric line where it has a symmetric coupled line with variable spacing between microstrip lines.

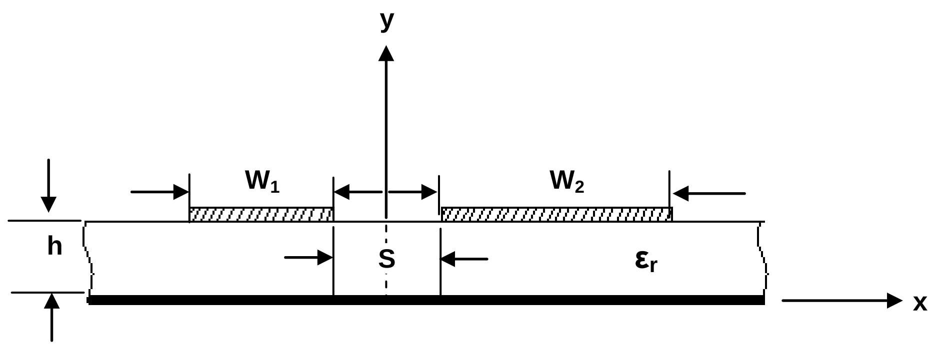


Figure 2.6: Coupled microstrip lines with unequal impedances (asymmetric lines)

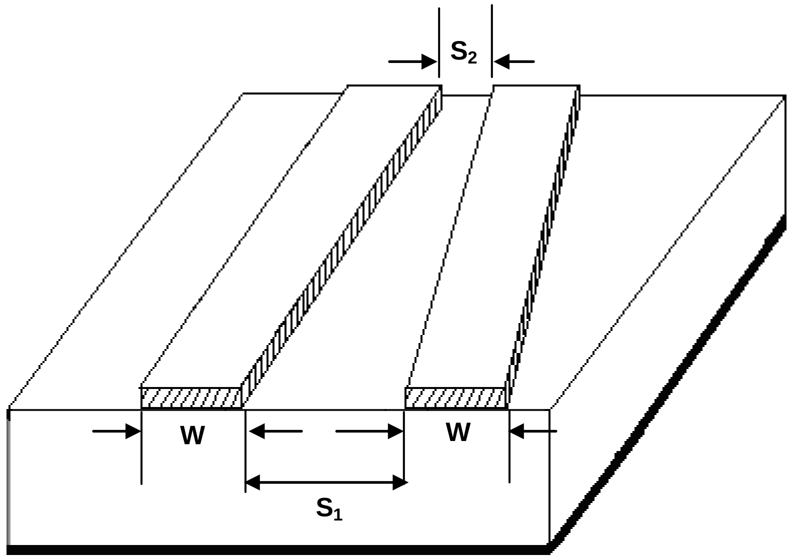


Figure 2.7: Nonuniformly coupled symmetric lines

2.5.4 Coupling mechanism

The symmetric coupled line structures support two modes which are even and mode. The interaction between these two modes induces coupling between the two transmission lines. In even mode excitation, both microstrip conductors have same potential while the odd mode delineates equal but opposite polarity potentials.

The even and odd modes have different characteristics impedances and their values are equal when the separation between them is significantly larger where the lines are said to be uncoupled. The even mode characteristics impedance, Z_{0e} is the impedance from one line to the ground when both lines are driven in phase from equal sources of equal impedances and voltages. The odd mode characteristics impedance, Z_{0o} is the impedance from one line to the ground when both lines are driven in out of phase from equal sources of equal impedances and voltages.

CHAPTER 3

pHEMT BALANCED AMPLIFIER DESIGN WITH LOAD PULL TECHNIQUE

3.0 Overview

The interest in microwave techniques for communication systems has grown immensely over recent years and the performance of microwave active and passive circuits for wireless systems technology has become extremely advanced. One of the most critical active circuits employed in systems applications is the microwave amplifier. Since it is a highly versatile circuit function, it has always been the first to benefit from developments in the device and semiconductor technologies. Amplifiers with extremely wide bandwidths with good performance have been successfully realized in the past two decades in hybrid and monolithic technologies. Hence the subject of amplifiers has been firmly established in the fields of optical communication, microwave and electronic warfare (EW).

Communication systems were severely limited due to the shortage of technology and sources of invention approximately in the late nineteenth century to as early as 1930. During this spell, triode electronic valve was used to develop amplifier modules that were associated with very limited applications. Many researches were carried out ; among them was A. G. Clavier, who successfully set up a radio link across the channel between England and France in 1931 (Mekonen, 1999).

Since then, the amplifier became the arena of active research carried out by many researchers where the primary aim was to improve the performance of its gain, bandwidth, efficiency and output power. Unfortunately these were not possible because the technology was limited at that time by the electronic valve.