Modulated Measurement and Engineering Systems for Microwave Power Transistors

Modulated Measurement and Engineering Systems for Microwave Power Transistors

Characterisation and Linearisation of Nonlinear Microwave Devices for Wireless Communication Systems

Muhammad Akmal Chaudhary, Ph.D.

BrownWalker Press
Irvine • Boca Raton

Modulated Measurement and Engineering Systems for Microwave Power Transistors: Characterisation and Linearisation of Nonlinear Microwave Devices for Wireless Communication Systems

BrownWalker Press / Universal Publishers, Inc.
Irvine • Boca Raton
USA • 2019
www.brownwalkerpress.com

ISBN: 978-1-62734-714-3 (pbk.)
ISBN: 978-1-62734-715-0 (ebk.)

Typeset by Medlar Publishing Solutions Pvt Ltd, India
Cover design by Ivan Popov

Publisher's Cataloging-in-Publication Data

Names: Chaudhary, Muhammad Akmal, author.
Title: Modulated measurement and engineering systems for microwave power transistors : characterisation and linearisation of nonlinear microwave devices for wireless communication systems / Muhammad Akmal Chaudhary.
Description: Irvine, CA : BrownWalker, 2019. | Includes bibliographical references and index.
Identifiers: LCCN 2018965302 | ISBN 978-1-62734-714-3 (paperback) | ISBN 978-1-62734-715-0 (ebook)
Subjects: LCSH: Wireless communication systems. | Electric circuits, Nonlinear. | Microwave circuits. | Power amplifiers--Design and construction. | Electric distortion. | Modulation (Electronics) | BISAC: TECHNOLOGY & ENGINEERING / Mobile & Wireless Communications. | TECHNOLOGY & ENGINEERING / Microwaves.
Classification: LCC TK5103.2 .C451 2019 (print) | LCC TK5103.2 (ebook) | DDC 621.384--dc23.

Dedicated to
my late parents for their prayers
and unprecedented love.

Table of Contents

Preface *xiii*

1 Introduction 1

- 1.1 Book Motivation 1
- 1.2 Power Amplifiers in Modern Wireless Applications 3
- 1.3 Challenges in Power Amplifier Design 4
- 1.4 Objective of Book 5
- 1.5 Primary Contributions 6
- 1.6 Book Synopsis 9
- 1.7 References 12

2 Modulated Domain Measurement Systems 15

- 2.1 Introduction 15
- 2.2 Memory Effects in Power Amplifiers 16
  - 2.2.1 Identification of Memory Effects 17
  - 2.2.2 Sources of Memory Effects 18
  - 2.2.3 Types of Memory Effects 19
    - 2.2.3.1 Short Term Memory Effects 20
    - 2.2.3.2 Long Term Memory Effects 20
      - 2.2.3.2.1 Thermal and Trapping Memory Effects 21
      - 2.2.3.2.2 Electrical Memory Effects 22

- 2.3 Modulated Domain Measurements Systems 24
  - 2.3.1 Industrial Measurement Solutions 30
    - 2.3.1.1 The Spectrum Analyzer 30
    - 2.3.1.2 The Vector Network Analyzer 31
    - 2.3.1.3 The Vector Signal Analyzer 31
    - 2.3.1.4 Large Signal Network Analyzers 32
- 2.4 Previous Cardiff Modulated Measurement System 32
  - 2.4.1 Previous Modulated Measurement System Limitations 34
    - 2.4.1.1 Triggering for Modulated Measurements 35
    - 2.4.1.2 Post Measurement Averaging 36
    - 2.4.1.3 Active IF Load-pull Architecture 37
    - 2.4.1.4 Active RF Load-pull Architecture 37
- 2.5 Enhanced Modulated Measurement System 38
  - 2.5.1 Necessary Measurement System Enhancements 39
    - 2.5.1.1 Multi-tone Measurement Averaging 40
    - 2.5.1.2 Multi-tone Measurement Software 42
    - 2.5.1.3 Broadband Baseband Load-pull 44
    - 2.5.1.4 Why AWG for Modulated RF Load-pull? 47
    - 2.5.1.5 Broadband Modulated RF Load-pull 47
  - 2.5.2 Capabilities of Enhanced Measurement System 50
    - 2.5.2.1 Extended Dynamic Range 51
    - 2.5.2.2 Extension of Measurement Bandwidth 53
    - 2.5.2.3 Possible Measurement Options 54
    - 2.5.2.4 Stitching Problem Occurrence 55
- 2.6 System Calibration 56
  - 2.6.1 IF Calibration Verification 58
  - 2.6.2 Measurement Accuracy Enhancement 61
- 2.7 Demonstration of Multi-tone Measurement Capability 62
  - 2.7.1 Output Power Spectrum Comparison 64
- 2.8 Impedance Control Solution 67
  - 2.8.1 Demonstration of Baseband Load-pull Capability 68
  - 2.8.2 Demonstration of RF Load-pull Capability 73
  - 2.8.3 Why Out-of-Band Impedance Control is Necessary? 75
  - 2.8.4 Comprehensive Out-of-Band Impedance Control 78
- 2.9 Chapter Summary 79
- 2.10 References 80

3 Baseband Electrical Memory Investigations 85
3.1 Introduction 85
3.2 Memory Properties of Nonlinear System 86
  3.2.1 Characterization of Memory Effects 91
    3.2.1.1 Continuous Wave Characterization 92
    3.2.1.2 Two-Tone Characterization 94
    3.2.1.3 Multi-Tone Characterization 95
    3.2.1.4 Noise Power Ratio 96
  3.2.2 Envelope Domain Analysis 97
  3.2.3 Properties of Power Supply 99
3.3 Memory Effects Measurements and Investigations 100
  3.3.1 Theoretical Study of Nonlinear Circuit 101
  3.3.2 Effect of Drive Level on Output Envelopes Investigations 103
  3.3.3 Theoretical Study of Active IF Load-pull 107
  3.3.4 Application of Active IF Load-pull 110
  3.3.5 Delay Adjustment Estimation 112
  3.3.6 Effect of Baseband Impedance on 2nd Harmonic 114
3.4 Broadband Baseband Impedance Termination 115
  3.4.1 Dynamic Characteristics of Power Device 117
  3.4.2 Minimization of Baseband Electrical Memory 122
3.5 Chapter Summary 124
3.6 References 125

4 Envelope Tracking Focused Investigations 129
4.1 Introduction 129
4.2 Efficiency Enhancement Techniques 130
  4.2.1 Peak to Average Ratio 131
  4.2.2 Envelope Tracking 133
  4.2.3 Envelope Tracking Power Supply 135
  4.2.4 Auxiliary Envelope Tracking 136
4.3 Device Level Linearity of GaN HEMTS 137
  4.3.1 Continuous Wave Characterization of GaN HEMTs 137
  4.3.2 Enhancing Linearity at Back-off Regime 139
    4.3.2.1 Baseband Signal Injection Technique 140
    4.3.2.2 Mathematical Analysis of Baseband Signal Injection 141

4.3.2.3 Linearity Investigations and Analysis 142
4.3.2.4 Emulation of Auxiliary Envelope Tracking Environment 147
4.4 Enhancing Linearity at Compressed Drive Level 152
4.4.1 Optimized Device Linearity Performance 160
4.4.2 Optimized Device Efficiency Performance 161
4.4.3 Mathematical Analysis on 2nd Harmonic Termination 163
4.4.4 Emulation of Class-J Mode of Power Amplifier 164
4.4.5 Repeatability of Baseband and RF Load Emulation 167
4.5 Chapter Summary 168
4.6 References 169

5 Multi-Sine Measurements and Linearization 171
5.1 Introduction 171
5.2 Properties of Multi-Tone Excitations 173
5.2.1 Correlation Between IMR and ACPR 174
5.2.2 Multi-Tone Signals 176
5.3 Multi-Tone Excitation and Characterisation 178
5.3.1 Multi-Tone Investigations of Memory Effects 181
5.4 Linearity Enhancements under Complex Excitation 187
5.4.1 Effect of Carrier Phase Distribution on Linearity 191
5.4.2 Optimum for IMR and ACPR Reduction 196
5.5 Chapter Summary 197
5.6 References 198

6 Sampling Issues of Digital Oscilloscope 201
6.1 Introduction 201
6.2 Sampling Circuitry of Digital Oscilloscope 202
6.3 Folded Sampling Technique 204
6.3.1 Application Issues of Folded Sampling 210
6.3.1.1 Error on Trigger Re-arm Time 211
6.3.1.2 Moving to Higher Clock Frequencies 212
6.3.1.3 Limited Tone Spacing Grid 212
6.3.1.4 Software Averaging 216
6.4 Measurements Using Folded Sampling 219
6.4.1 Uniqueness of Envelope Domain 223
6.5 Chapter Summary 226
6.6 References 227

7 **Phase Coherent Impedance Engineering** **229**
7.1 Introduction 229
7.2 Baseband Envelope Injection 232
7.2.1 Baseband Impedance Engineering 233
7.2.2 Input Port Baseband Injection 234
7.2.2.1 Baseband Predistortion Linearization Techniques 235
7.2.2.2 Signal Injection Linearization Techniques 239
7.2.2.3 Baseband Envelope Linearization Technique 241
7.2.2.4 Formulation for Baseband Envelope Linearization 245
7.2.2.5 Experimental Demonstration of Mathematical Formulation 246
7.3 Phase Coherent Impedance Control for Linearization 250
7.3.1 Demonstration of Phase Coherent Impedance Control 253
7.4 Chapter Summary 258
7.5 References 259

8 **Notes on Multiple Measurement Concepts** **263**
8.1 Introduction 263
8.2 Advanced Measurement Concepts 267
8.2.1 Improving Measurement Capability 268
8.2.1.1 Automated Baseband Load-pull 268
8.2.1.2 Automated Modulated RF Load-pull 269
8.2.1.3 Load-pull Capability for Digitally Modulated Stimuli 269
8.2.2 Supplementary DUT Investigations 270
8.2.2.1 Effect of 2nd Harmonic on Linearity 270
8.2.2.2 Combined LUT Predistortion and Baseband Injection 271
8.2.2.3 Modelling Memory Effects 271
8.2.2.4 Envelope Square Injection for Linearity Enhancement 272
8.2.2.5 Linearity Investigations of Continuous Modes 273
8.3 Conclusive Remarks 273
8.4 References 273

Appendix A Calibration Interpolation *275*
Appendix B IF Test-Set Calibration and Validation *279*
Appendix C Tektronix Scope Setting *289*
Appendix D Modulated Waveform Measurements *293*
Appendix E Multi-Sine Stimuli *297*
Appendix F Complementary Cumulative Distribution Function (CCDF) *299*
Appendix G Tektronix AWG Control *301*
Appendix H 10 W, RF Power GaN HEMT *303*
List of Acronyms *319*
Index *323*
About the Author *327*

Preface

The book entails comprehensively searing discussion on modulated measurement and engineering systems for microwave power transistors. The microwave devices and circuits need to be characterized prior to being employed in the design of systems and components. Unfortunately the measurement systems required to characterize the microwave devices and circuits have not kept pace with the emerging telecommunication technologies demands. This has resulted into a situation where either the circuits being employed in the components are unoptimized or the yield and turn-around of optimized circuits are slow. One of the contributing factors of such situations is the limitations of the existing measurement systems to scale up in performance to fulfil the necessary requirements. This book presents an enhanced multi-tone, time-domain waveform measurement and engineering system. The presented measurement and engineering system allows for a more considered, and scientific process to be adopted in the characterisation and measurement of microwave power devices for modern day communications systems. The main contributions documented in this book come in two areas; firstly developments that allow for accurate time domain measurement of complex modulated signals using commercially available equipment; and secondly in the area of active impedance control, where significant developments were made allowing active control of impedance across a modulated bandwidth.

The first issue pertaining to microwave device characterisation and measurements addressed is the fundamental difficulty in sampling multi-tone waveforms, where the main achievements have been the realisation of a high quality trigger clock for the sampling oscilloscope and a "Time Domain Partitioning" approach to measure and average multi-tone waveforms on-board. This approach allows the efficient collection of high quality vectoral information for all significant distortion terms, for all bands of interest.

The second area has investigated suitable impedance control architectures to comprehensively investigate out-of-band impedance effects on the linearity performance of a device. The ultimate aim was to simultaneously present independent, baseband impedances to all the significant baseband (IF) frequency components and to 2nd harmonic that result from a multi-tone excitation. The main achievement in this area was the ability of the enhanced measurement system to present the broadband impedance. At baseband this has been achieved in the time domain using a single arbitrary waveform generator (AWG) to synthesise the necessary waveforms to allow a specific IF impedance environment to be maintained across a wide IF bandwidth. To engineer the RF out-of-band load terminations at RF frequencies and to emulate specific power amplifier modes, a Tektronix AWG7000 Arbitrary Waveform Generator was used to deliver the desired impedances, practically fulfilling the wideband application requirements for reliable device characterisation under complex modulated excitations. The multi-harmonic phase-coherent multi-tone RF output signals constructed from Tektronix AWG7000 Arbitrary Waveform Generator were perfectly synchronized at both IF and RF frequencies. These signals were then used to both excite the microwave power transistors as well as for presenting various active harmonic load-pull impedances necessary to provide the static, high stability, high dynamic range RF impedances for comprehensive phase coherent out-of-band impedance control for characterization of microwave power transistors and for emulation of various modes of power amplifiers under complex modulated excitations.

Muhammad Akmal Chaudhary, PhD
Department of Electrical Engineering
College of Engineering
Ajman University

CHAPTER 1

Introduction

1.1 Book Motivation

The advent of fifth generation (5G) and existing fourth generation (4G) wireless systems, namely Long Term Evolution (LTE) and mobile WiMAX, has significantly increased the demand on Power Amplifier (PA) designers for multi-carrier capability; broadband for high data rate; high linearity to meet the adjacent channel power ratio (ACPR) requirements; multi-band; and multi-standards, so that the mobile systems can be used everywhere. The third generation (3G) comes under the umbrella of the International Mobile Telecommunications programme (IMT-2000) which employs wideband code division multiple access (WCDMA), achieving a transmission rate of 2 Mbit/s with a 5-MHz frequency bandwidth. The third generation of mobile communication systems is designed for applications such as Internet services, e-mail, database retrieval, video telephony, interactive video and sound. Despite the enhanced features of 3G systems, they are still severely constrained by the bandwidth particularly when handling full-motion videos [1].

With the growing demand for higher data rates and ever increasing users on the 3G network linearity specifications have become acute in accomplishing the needed bandwidth. In this regard, the basestation power amplifier must be able to accommodate large peaks, which means that the power amplifier is usually operating well below its peak efficiency point. For instance, the Universal Mobile Telecommunication System (UMTS) power amplifier requirements according to 3G partnership project (3GPP) specifications are to have frequency band (FDD, downlink) from 2.11 GHz to 2.17 GHz, with ACPR of –45 dBc at ±5 MHz and –50 dBc at ±10 MHz carrier offset [1, 2]. Moreover, since the UMTS basestation power amplifiers are subjected to wideband code division multiple access (WCDMA) signals, a peak-to-average ratio (PAR) ranging from 3 dB upto 12 dB must be sustained. The proposed 3G UMTS interface would employ orthogonal frequency division multiplexing (OFDM) for downlink with scalable bandwidths ranging from 1.25 MHz to 20 MHz [3]. This continuing developments in 3G radio interface towards broadband 4th generation capabilities targeting up to 100 Mb/s and 1 Gbit/s speeds is forcing rapid system enhancements.

The linear operation in conventional power amplifiers is achieved by reducing the RF input to a level sufficiently low to avoid saturation of the active devices [4]. When a high degree of linearity is required, back-off mode of operation inevitably degrades overall efficiency and output power. Consequently, as indicated in Figure 1.1, in modern RF power amplifier applications, fulfilling linearity for preserving fidelity of the signal together with power amplifier efficiency, impose two conflicting design requirements.

PA efficiency enhancement attempts to improve the efficiency of a linear but inefficient PA. Linearization takes a different approach by attempting to improve the linearity of a nonlinear but efficient PA.

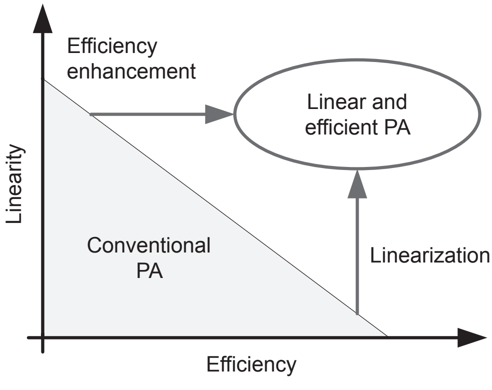

Figure 1.1 Linearity-efficiency trade-off in power amplifier design [5, 6].

By resorting to highly efficient power amplifier architectures, however, memory effects can cause a bottleneck when implementing conventional linearization techniques. Memory effects manifest as an asymmetric behaviour between lower and upper intermodulation distortion (IMD) sidebands, which vary with the signal bandwidth. Such problematic effects can lead to significant difficulty in achieving PA performance that meets the required linearity specifications. Indeed, if the intermodulation distortion becomes strongly asymmetrical, then this can necessitate the need to employ different digital pre-distortion compensation requirements for lower and upper IMD sideband signals, which itself can be problematic. As a result, some common linearization techniques can be rendered ineffective because their success rely upon constant and equal intermodulation levels over the signal bandwidth [5]. Thus, it is of prime importance to understand the sources of this asymmetry. This book focuses on the role of baseband impedance variations with the aim being to improve the power amplifier linearity for future wireless communication systems.

1.2 Power Amplifiers in Modern Wireless Applications

In typical wireless transceivers, the PA is the last active building block in the transmitter chain. The foremost function of a PA is to amplify the signal to a level high enough that it can travel through the air to the intended receiver. Often, the PA dominates the power consumption of the entire transceiver; therefore, improving the PA's power efficiency, defined as the ratio of the output power to the DC power consumption, usually translates to longer battery life in the wireless device. In some wireless standards such as GSM, where the modulated signal has constant envelope, a nonlinear PA can be used. A nonlinear PA generally has higher efficiency than a linear PA, despite their higher efficiency; the data rates that these transceivers can transmit within a given bandwidth are low. In order to increase the data rate without increasing the bandwidth, a more spectrally efficient modulation scheme must be used. This makes the modulated signal's envelope non-constant and therefore requires a linear PA to faithfully amplify the signal. Specifically this means that the design of a linear amplifier may not be achieved without compromising the efficiency. These requirements are inter-related which makes the design difficult to deal with independently. On the other hand the highest average efficiency is critical to maintain the low DC power consumption within the signal dynamic range accounting for PAR characteristics of the signal to be amplified. Hence, design solutions are under intensive investigation to improve the average efficiency as well as the linearity of the amplifier involved in the transmitter unit [7].

1.3 Challenges in Power Amplifier Design

To meet the requirements of the future generation of wireless communication systems, power amplifiers with high output power, high linearity, and broad bandwidth with high average efficiency are required. The basestation in the UMTS standard requires WCDMA modulation with 5 MHz bandwidth and adjacent power ratio of –45 dBc at the offset frequency of 5 MHz with a signal of PAR 7 dB to 10 dB [8]. The basestation PA needs to satisfy these stringent requirements as higher PAR values are expected for future standards like LTE and 5G [9].

The primary requirement in the basestation PA is to fulfil the linearity specifications. To satisfy the linearity requirements PA are typically operated at large back-off from the peak output power due to the high PAR of the signal, which leads to device operation at low average power and efficiency. The linearity of the amplifier can be improved through additional linearization but for the linearization method to be effective, the amplifier is also expected to have bandwidth independent linearity, for instance, minimum memory effects [9]. Consequently, the modern basestation PA should be designed to have high linearity, high output power, high average efficiency and a broad bandwidth. These multiple design challenges can be met with the following proposed solutions:

- Basestation amplifiers with high output power (>100 W) can be realized using new wide bandgap device technologies such as GaN HEMTs. The GaN HEMT devices provide architectural benefits and unique features to produce high output power [10, 11].
- The linearity at device level can be improved through the optimization of the baseband impedance environment. In this regard,

the use of a two-tone test signal to analyze the device properties in terms of minimizing the intermodulation distortion is the pertinent possibility [12, 13].

- High peak efficiency can be achieved using single stage design architecture such as class B, harmonic tuning and switched mode amplifiers [14]. These power amplifiers typically have either low average efficiency, if operated at large back-off level, or high non-linearity. The efficiency of these power amplifiers can be enhanced at back-off using enhancement techniques such as envelope elimination and restoration (EER), and envelope tracking (ET) which are still under intensive investigations [15].

The design of power amplifiers for future wireless communication systems should consider all these aspects to meet the requirements. A part of the problem will be embarked upon in this book whilst considering the high power device operating under the realistic modulation excitations to characterize the memory effects as well as the effects of envelope injection on the overall linearity of the device.

1.4 Objective of Book

The main objective of this book is to help future generation of students develop a modulated waveform measurement system that is capable of measuring and engineering both the low frequency and RF signal components, hence is suitable for the characterisation and performance evaluation of high power microwave devices and power amplifier modes under multi-tone excitations. The work documented in this book can be divided into two significant parts. The first focuses on further refinement to a state-of-art active IF and RF load-pull measurement system to allow the precise independent control of all significant baseband components generated as a result of the multi-tone excitation used.

The previously developed Cardiff modulated waveform measurement system that incorporated an IF measurement capability was unfortunately only able to present the impedance to the two most significant baseband components (IF1 and IF2) generated as a result of 2-tone excitation and had no RF load-pull capability. The IF active load-pull was achieved by combining two, phase coherent arbitrary waveform generators (AWGs) whilst the device was driven at a relatively backed-off level, at 1 dB below the 1 dB compression point. However, when the device is driven more deeply into compression, significantly more mixing terms are generated, and in order to achieve a sufficiently broadband IF termination, significant modification of the baseband load-pull measurement system was required in order to accurately account for higher baseband harmonics. The RF architecture of the measurement system was modified to allow synthesise of RF loads for the robust characterisation of microwave devices in specific impedance environments. This was achieved in the time domain through dual channel Tektronix AWG7000 Arbitrary Waveform Generator to synthesize the excitation and constant, frequency independent RF loads around the fundamental and 2nd harmonic tones.

The second part focuses on improving the triggering of Tektronix CSA 8000, so that it could capture and average the more complex modulated waveforms directly. Through extensive testing it was found that the most robust solution to this problem was achieved by using a high quality trigger signal. This was provided through 120 MHz Agilent arbitrary waveform generator (AWG). The measurement system was then demonstrated to capture consistent, repeatable, multi-tone waveforms without phase jitter, regardless of device behaviour.

1.5 Primary Contributions

The rigorous work documented in this book is the result of the need to improve the linearity of RF power amplifiers in wireless communication systems, in order to increase power efficiency and reduce undesired emissions at the same time. This book makes available the following primary contributions, not found in the literature, to the field of modulated measurement capability, memory effect characterization and envelope injection linearization in power amplifiers.

- To achieve a sufficiently broad baseband termination, significant modification of the baseband load-pull measurement system was required in order to accurately control the higher baseband components. The baseband active load-pull measurement system was thus modified to synthesise the necessary waveforms to allow a constant and specific baseband impedance environment to be maintained across a wide bandwidth. This was achieved in the time domain, using a single 80 MHz arbitrary waveform generator (AWG).

- The role played by higher baseband impedances in determining baseband electrical memory effects observed in power transistors under two-carrier excitation was rigorously quantified. These effects typically appear not only as asymmetrical distortion terms in the frequency domain, but also more reliably as a recognizable hysteresis in the dynamic transfer characteristics extracted from measured input voltage and output current envelopes of a power device. The investigations were carried out thoroughly to identify the relationship between the IMD asymmetries caused by the baseband impedance variations and the hysteresis that appears in the dynamic transfer characteristics.
- An additional feature of the modulated measurement system was identified and deemed usable in conjunction to improve the efficiency and linearity. In an envelope tracking (ET) architecture, the power amplifier supply voltage is dynamically adjusted to the most efficient level for the instantaneous output power level. This allows the power amplifier to operate near the maximum efficiency. The envelope tracking (ET) focused measurements with non-optimal load (50 Ω) showed that efficiency as well as linearity can be improved at reduced drain supply voltages: for V_{dc}=20 V, the average drain efficiency was improved by approximately 5% together with an improvement of 10 dBc in IM3 when compared to the static V_{dc}, where short circuit impedance was maintained for all four baseband components.
- One noteworthy issue when employing the sampling-oscilloscope to average the multi-tone signals was an inability to 'freeze' the display of the sampling-oscilloscope. Consequently, software post-processing was mandatory to accurately time align the collected waveforms in order to allow averaging that is necessary to improve the overall quality of the measurements to an acceptable level. This slowed down the process of measurement due to the post measurement averaging and this technique was only applicable for two tone and three tone modulated measurements, as it was very difficult to align the vectoral information for more tones. Therefore, it was

necessary to engineer an external clock to trigger measurements on the CSA 8000. The high quality trigger clock was successfully engineered thus allowing for on-board averaging of the oscilloscope.

- New modulated waveform measurement software was developed in conjunction to improve the measurement speed as well as allowing the multi-tone measurements. The successive time windows were used to capture all of the relevant information and stitched together as the oscilloscope coherently sampled across the selected time window, when the end of the time window was reached the data was stored, processed and displayed. The number of time windows was computed based on the number of points which the oscilloscope can sample in one time window which means that consecutive time windows were required to capture one complete modulation cycle of waveforms in conjunction with the lower modulation frequencies (≤1 MHz). Subsequently, this “Time Domain Partitioning” approach allowed measuring the broad bandwidth modulated signals very close to the noise floor with greater accuracy and enhanced the measurement speed in connection with the CW measurement in an example case when modulation frequencies are chosen such that total number of points to sample fit in one time window.
- The RF architecture of the modulated waveform measurement system was modified to synthesize the RF loads. The Tektronix AWG7000 Arbitrary Waveform Generator was used as an RF synthesizer, and is used to synthesize both fundamental excitation and harmonic load-pull signals simultaneously, in the time domain. Using two independent yet coherent channels, this waveform measurement system is capable of maintaining independent and constant impedance control for each individual tone across the RF impedance environment, and over a wider modulation bandwidth. This modified architecture was then used to demonstrate the emulation of a modulated class-J power amplifier, through the application of modulated RF active load-pull.

The work described in this book has the potential to be used to characterise and reduce bandwidth dependent non-linear distortion in microwave devices under realistic stimulus relevant for future wireless communication systems. This is possible because it can now quantify, comprehensively, the out-of-band impedance on the performance of microwave devices and to emulate the specific PA modes under modulated excitations.

1.6 Book Synopsis

To accommodate the various aspects of modulated waveform measurement and Engineering system and its application to the device characterisation and measurements the book is sectioned into eight chapters. Each chapter starts with the introduction and discusses the motivation and purpose of that particular chapter and concludes with the brief summary of the chapter.

Chapter 2 gives an overview of the modulated domain measurement solutions used for device characterisation at microwave frequencies in order to address the contemporary problems in power amplifier design, most importantly memory effects. Most of the commonly known measurement solutions are discussed, with their pros and cons. The modulated measurement system developed at Cardiff University is then discussed in two sections; the first highlights the limitations of the previous measurement system in its load-pull capability and then introduces a refinement to state-of-art active IF and RF load-pull measurement system that allows the precise independent control of all significant baseband and RF components generated as a result of the multi-tone excitation used. The second section addresses the limitations of the previous measurement technique implemented for the device characterisation under modulated excitations and demonstrates the new measurement algorithms required to allow the capture of multi-tone information using a standard sampling oscilloscope. The final section of this chapter demonstrates the measurement system capabilities through the practical device measurements.

Chapter 3 explains an investigation into the relationship between the intermodulation distortion (IMD) asymmetries caused by the baseband impedance variations and the hysteresis or looping that sometimes appear in the dynamic transfer characteristics of microwave power devices when subjected to the modulated excitation using the enhanced modulated waveform measurement system. The role played by higher baseband impedances in determining baseband electrical memory effects observed in power transistors under two-carrier excitation is rigorously quantified through the application of an active IF load-pull to present specific baseband impedance environments, allowing the sensitivity of IMD symmetry to baseband impedance variations to be investigated. The baseband impedances are controlled over a significant bandwidth; in this case at least eight times the modulating frequency.

Chapter 4 reports an additional feature of the modulated waveform measurement system, which is emulating appropriate negative impedances lying outside of the Smith chart. When this feature is considered alongside the Envelope Tracking (ET) power amplifier (PA) architecture, this raises the interesting possibility of significantly improving PA linearity using the very mechanisms that are employed to improve PA efficiency. The architecture and detailed operation of linearity and efficiency enhancement are discussed. An investigation into the effect of variable supply voltage at the drain of the device under test (DUT) and the baseband impedance on the RF output performance, including output power, efficiency and linearity, is performed revealing an improvement in power efficiency and linearity when compared with using a fixed voltage power supply. Finally this chapter includes a comprehensive discussion on the evaluation and effectiveness of the envelope injection technique highlighting the advantages and short comings of this in applications, when applied to the realistic power amplifier architecture and modes.

Chapter 5 along with the fundamentals focuses on the multi-tone characterisation and linearization for the elimination of adjacent channel distortion products when the power device is subjected to multi-tone excitation. It describes the multi-tone characterization of baseband electrical memory effects and their reduction. It emphasizes on the envelope injection technique to reduce the non-linear distortion generated by the power device. The measurements performed evaluating the envelope injection technique, which is a promising candidate to achieve high linearity from the power device, realized through an external envelope signal that is simply generated by an arbitrary waveform generator (AWG), are discussed. The envelope signal contains all of the baseband frequency components generated by the power device and is then properly injected at the output of the power device where it actively modifies the impedance environment seen by the power device. The results highlight that this linearizing and efficiency enhancing technique could be extended to more complex multi-tone excitations.

Chapter 6 documents sampling issues pertaining to digital sampling oscilloscope. A refined sampling method is employed that ensures the waveforms are captured in the most efficient manner using digital sampling oscilloscope. The captured time domain data can be manipulated to uncover all of the information usually provided by frequency domain or in-band linearity measurement architectures, but can also uncover additional relevant information necessary to identify the origin of the non-linearity. Until recently waveform measurement concepts have largely ignored the importance of measurement, analysis and engineering of in-band and out-of-band distortion components, the aim of the refined sampling technique when employed in a measurement system is therefore to extend the design role of waveform measurement and engineering to include not only optimization of output power and efficiency, but also directly linearity and electrical memory. The extraction of envelopes from time domain measurements suggested the presence of time varying anomalous effects.

Chapter 7 details baseband envelope injection linearization techniques for microwave power transistors. The envelope baseband linearization is demonstrated using developed system which is configured to automatically engineer specific baseband voltage waveforms using a mathematical formulation, generalized in the envelope domain, to describe the required baseband injection voltage. The chapter further introduces a phase-coherent impedance engineering for out-of-band impedance optimization. To investigate this method, a derivative of class J power amplifier termed BJ is emulated, which effectively lies between class J and class B along the reactive routes on the Smith chart. The mode helps explore baseband linearization approach and its suitability when using continuous mode architectures. This further extends a view to look at how well the emulated mode linearizes at a set of BJ contour points along the way. The method uses multiple modulated signal sources, phase synchronized at both radio frequency (RF) and intermediate frequency (IF) to provide a complete multi-harmonic broadband loadpull capability controlled by a single local oscillator and allows complete impedance control at the DUT current generator plane.