DIRECT INTEGRATION OF PUSH-PULL AMPLIFIER AND APERTURE COUPLED ANTENNA

BY

FARID ZUBIR

A Thesis submitted to the
College of Engineering and Physical Sciences
University of Birmingham
For the Degree of
DOCTOR OF PHILOSOPHY

School of Electronic, Electrical & Systems Engineering
University of Birmingham
Edgbaston, B15 2TT
Birmingham
United Kingdom
May 2015

ABSTRACT

The work described in this thesis concerns the integration of push-pull class B amplifier and antenna modules. Push-pull class B is well-known with its fruitful advantages of using differential feeding technique, resulting in low distortion, reasonably high efficiency and high output power. Meanwhile, the antenna module in this work is adapted from the aperture-coupled antenna structure due to its degree of freedom to control the variables which provide the best possible topology that could be realised in system on chip or system in package. More generally, the variables allow good coverage of the Smith Chart so that a wide range of odd-mode matching requirements could be met, for different devices and bias condition of a given transistor. The approach also offers additional filtering up to 3rd harmonic in that it comprises identical harmonic traps on both sides of the aperture using resonant stubs to form bandstop filters, which reduce the ripples at the output waveforms, giving them a significant advantage of neat and tight integration of a push-pull transmitting amplifier.

ACKNOWLEDGMENTS

First of all, thanks to ALLAH S.W.T. for His continuous blessings and for giving me the strength and chances in completing this work. Deepest gratitude to my supervisor, Dr Peter Gardner, for his valuable guidance, advice, motivations, excellent supports as well as constructive comments in every aspect to accomplish this work. It has been an honour for me to be supervised by people with such wide knowledge and top notch ideas.

I owe my loving and sincere thanks to my parents Zubir Elias and Hasnah Hussein, my parents in-law Zualkafly Ahmad and Kamisah Abd Karim, my lovely wife Umi Hanum Zualkafly, my little ones Muhammad Fahym and Umyra Fayha. My special gratitude and loving thanks are also due to my brothers Azrin Zubir, Azmi Zubir, Amir Zubir and Mohd Fazli Zubir. These people deserve my special mention for their constant prayers, support, encouragement, understanding and sacrifices have helped as well as motivated me a lot throughout the entire time I worked out on my research work. Their roles of being such supportive are the driving force and pushing factor towards the success of my study.

I would also like to thank the wonderful members of Communication Group especially to technical support staff Mr Alan Yates who have been extremely kind and helpful throughout my study. “We don’t remember days, but we remember moments” and I had a great time and moments during my study in here.

My sincere appreciation also goes to everyone whom I may not have mentioned above; who have helped directly or indirectly in the completion of my work. A million thanks for all.

PUBLICATIONS

1. F. Zubir, P. Gardner, "A New Power Combiner Using Aperture Coupling Technique for Push-pull Class B Power Amplifier", IET 4th Annual Passive RF and Microwave Components Seminar, 18th March 2013, Birmingham, United Kingdom.
2. F. Zubir, P. Gardner, "Multilayer Antennas with Harmonic Filtering for Differentially Fed Power Amplifier Integration", ICEAA – IEEE APWC – EMS 2013, 9th – 13th September 2013, Torino, Italy.
3. F. Zubir, P. Gardner, "Differentially Fed Multilayer Antennas with Harmonic Filtering for Push-pull Class B Power Amplifier Integration", The 43rd European Microwave Conference (EuMC), 8th – 10th October 2013, Nuremberg, Germany.
4. F. Zubir, P. Gardner, "Design of Optimum Matching Networks for Push-Pull Amplifier – Antenna Modules", IET Colloquium on Antennas, Wireless and Electromagnetics, 27th May 2014, Ofcom, Riverside House, 2a Southwark Bridge Road, London.
5. F. Zubir, P. Gardner, M. K. A. Rahim, "New Technique to Comply with Impedance Requirement of Transistor for Push-Pull Amplifier", Radio Frequency and Microwave Conference 2015, RFM 2015. IEEE International.

ABBREVIATIONS

RF - Radio Frequency

IC - Integrated Circuit

T/R SW - Transmit/Receive Switch

LNA - Low Noise Amplifier

PA - Power Amplifier

RX - Receiver

TX - Transmitter

GND - Ground

SRD - Short Range Device

InP - Indium Phosphide

SiGe - Silicon Germanium

GaN - Gallium Nitride

GaAs - Gallium Arsenide

MMIC - Monolithic Microwave Integrated Circuit

EM - Electromagnetic

SWR - Standing Wave Ratio

VCCS - Voltage Control Current Source

DC - Direct Current

AC - Alternative Current

PAE - Power Added Efficiency

IMD - Intermodulation Distortion

FET - Field-Effect Transistor

MESFET	-	Metal-Semiconductor Field-Effect Transistor
IF	-	Intermediate Frequency
FEM	-	Finite Element Method
FDTD	-	Finite Difference Time Domain
MoM	-	Method of Moment
PT	-	Total Power
AWRDE MWO	-	Applied Wave Research Design Environment Microwave Office
CST MWS	-	Computer Simulation Technology Microwave Studio
BSF	-	Bandstop Filter

TABLE OF CONTENT

CHAPTER 3: DESIGN OF PUSH-PULL CLASS B POWER AMPLIFIER

CHAPTER 4: DIFFERENTIALLY FED APERTURE COUPLED ANTENNA

CHAPTER 5: FULLY INTEGRATED AMPLIFIER–ANTENNA SIMULATIONS AND MEASUREMENTS

CHAPTER 6: SUMMARY, CONCLUSION AND FUTURE WORK

CHAPTER 1

INTRODUCTION

1.1 Overview of Wireless Communications

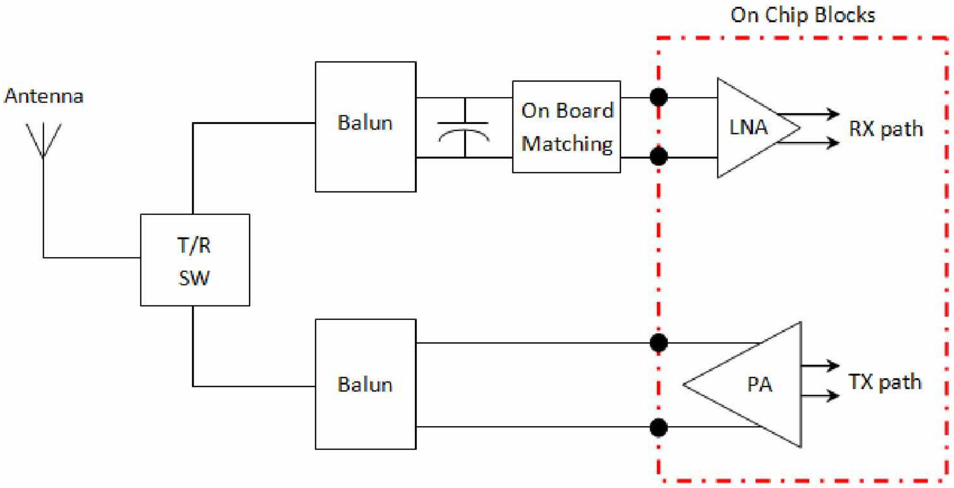
Wireless communications systems represent a branch of technology concerned with the communication engineering industry, which is taking place around the globe and is still developing rapidly. This explosive growth industry has created a mass market based on the media and consumers. For instance, the projected growth of the number of mobile phone users to billions worldwide indicates potential development in wireless communication technologies including mass-market consumer products. Billions of subscribers and a growing market for handheld devices over the years, demanding enhanced wireless communication services, lead operators to invest billions of dollars in spectrum for 3rd Generation (3G) systems, such as UMTS and most recently 4th Generation (4G) systems like LTE. The revolution of such systems is focussed towards larger capacity, better quality, more bandwidth, wider coverage, lower power consumption, high efficiency, mobility and more services. However, with an explosion of wireless mobile devices and services, there are still some challenges that cannot be accommodated by 4G, such as the spectrum crisis and high energy consumption. Wireless system designers have been facing the continuously increasing demand for high data rates and mobility required by new wireless applications and therefore have started research on fifth generation

(5G) that are expected to be deployed beyond 2020. There is an expectation that everyone will be permanently connected to the internet, no matter where they are. People are expecting that more information of a higher quality is delivered immediately and therefore newer services require higher data volumes and transfer rates. The aim is to connect the entire world and achieve seamless and ubiquitous communications between anybody (people to people), anything (people to machine, machine to machine), wherever they are (anywhere), whenever they need (anytime), by whatever electronic devices/services/networks they wish (anyhow). This means that 5G technologies should be able at least to support communications for some requirements which are not supported by 4G systems like relatively low power consumptions, higher efficiency, higher capacity, wider bandwidth and better coverage. This development remains a technical challenge with many issues still to be resolved in order to deliver the desired performance by taking into consideration the fact that is necessary to bear all or part of the weight of emerging applications. In this thesis, we propose a transmitter architecture based on a direct integration technique between power amplifier and antenna that can minimise the losses and thereby improve the whole system efficiency. This promising solution could be potentially adopted in 5G systems in order to deliver some of the aforementioned targeted requirements.

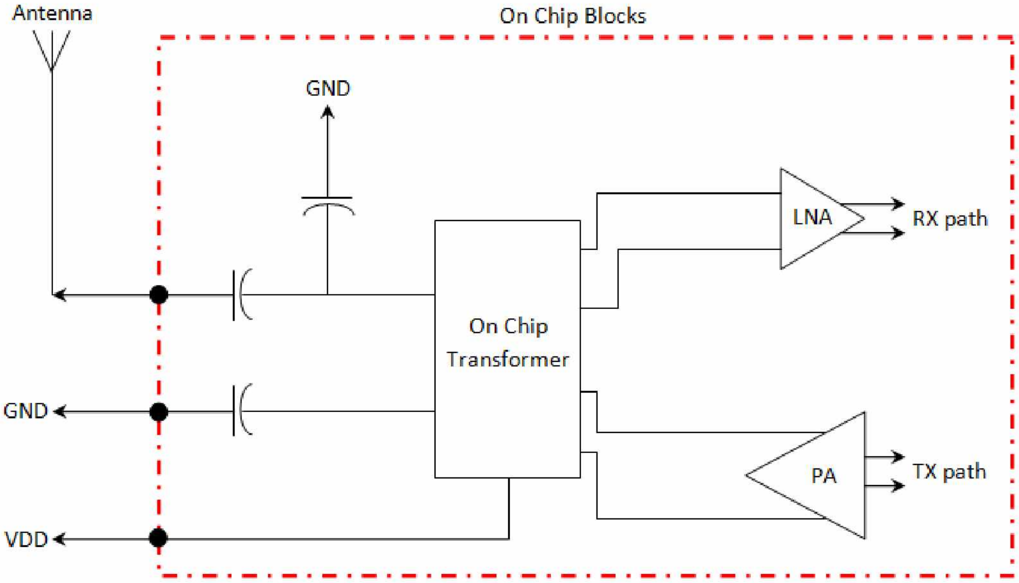
1.2 Motivation and Objectives

In recent years, intense development and fierce competition in the wireless communications industry has generated ambitious requirements for 4G LTE and most recently is 5G on radio frequency (RF) and microwave systems. The increasing demands are becoming more stringent and very difficult to achieve. Consumers demand for handy and compact devices drives the technology to integrate all necessary components and features neatly into a small space which is able to perform better in terms of energy efficient, coverage and wider bandwidth or at least has the same function as its larger version of circuit of discrete components. Furthermore, more people crave faster internet access and advanced multimedia capabilities on the move, trendier mobiles and in general, instant communication with others or access to information. In other words, the trends towards small, handy devices dictate a compact and low cost fully integrated RF and microwave front-end.

RF and microwave transceivers with the quality of being functional in the integrated circuit (IC) form have become more popular [1]. Nowadays, nearly all of the transceiver functionality could be realised in system on chip. Bhatti et al [2] has sufficient evidence through demonstration about the feasibility of establishing the integration of the balun into the combined radio transmitter and receiver. It is shown in Fig. 1.1.



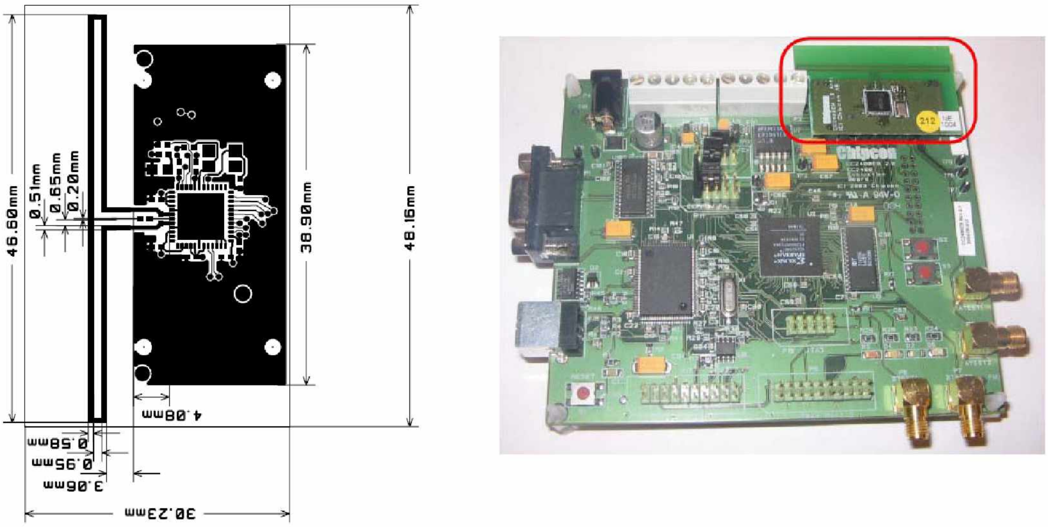
(a) Conventional transceiver with some important sub-circuits are externally incorporated with the chip block.



(b) Transceiver with all discrete components lie within the chip block making it compact and handy.

Fig. 1.1: Transceiver front-end architectures.

As shown in Fig. 1.1(a), the conventional front-end transceiver architecture had some externally built discrete components like switch, baluns, antenna as well as matching circuits which are incorporated with the on-chip blocks/modules which comprise the most power consuming active devices such as low noise amplifier (LNA) and power amplifier (PA). As can be seen in Fig. 1.1(b), other than the antenna, all discrete components within the transceiver front-end architecture could now be integrated as well as realised in system-on-chip blocks/modules. Simultaneously, this new architecture has impressively reduced the usage of discrete components, resulting in production of low cost RF and microwave front-end wireless devices. As reported by Bhatti et al in [2], there is still a need to accept responsibility for negative outcomes even though most of the discrete components have been made in system-on-chip blocks/modules. This is because on-chip transformer placement within the architecture still has an insertion loss of about 2.5 dB.



(a) **(b)**

Fig. 1.2: (a) Layout of folded dipole on a single-chip transceiver. (b) Evaluation board with folded dipole on a single-chip transceiver. (reprinted from [2])

Fig. 1.2 shows a further example of reasonably small off-chip electrically short folded dipole antenna with the evaluation board. This folded dipole antenna has been specifically designed to be incorporated with a true single-chip general purpose transceiver at 2.4 GHz short range device (SRD) band for data rates up to 1 Mbps [3]. As this folded dipole behaves like a balanced antenna, it fits well with the differential interface that is shared by the PA and LNA during transmission and reception respectively.

The integration of an absolute transceiver front-end into a true single-chip solution requires a great amount of effort. The work to integrate a whole set of functions in the integrated package would be favourable and beneficial. The advantage of integrating the entire wireless communication system in one package has given encouragement and motivation for researchers around the world to study and investigate on several semiconductor dielectric substrate using fabrication technologies such as Indium Phosphide (InP), Silicon Germanium (SiGe), Gallium Nitride (GaN) and Gallium Arsenide (GaAs) [4 – 6]. Fig. 1.3 shows relative merits of the commercially available RF and microwave low noise transistor examples. This data has been taken from commercial datasheet for NEC 2SC5761 (SiGe BJT), Bipolarics B12V114 (Si BJT) and Avago VMMK-1225 (PHEMT). On the other hand, Fig. 1.4 shows another relative merits of power transistor technologies which have been derived by Aaron Oki et al [7]. The choice of devices and device technologies used in this work is taken from the range of power transistors that using GaN fabrication technology. The selection of device technologies is based on its potential of very high output power, and efficient operation almost up to 100 GHz.

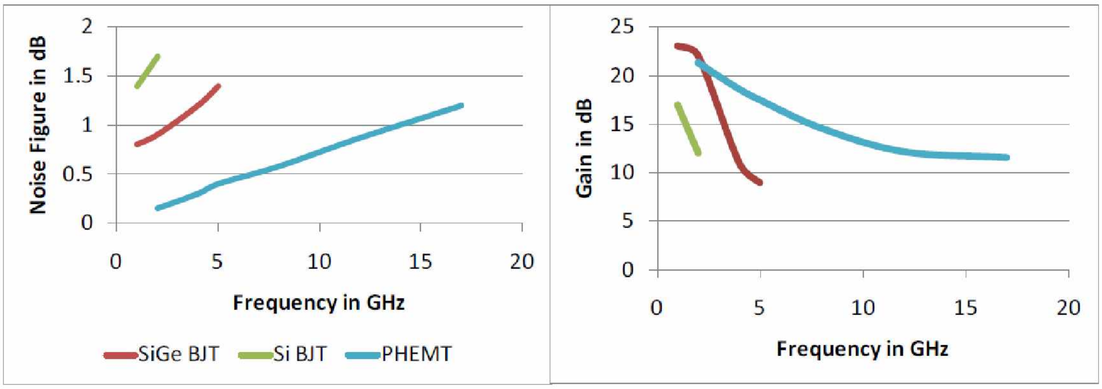


Fig. 1.3: Relative merits of the commercially available low noise transistors.

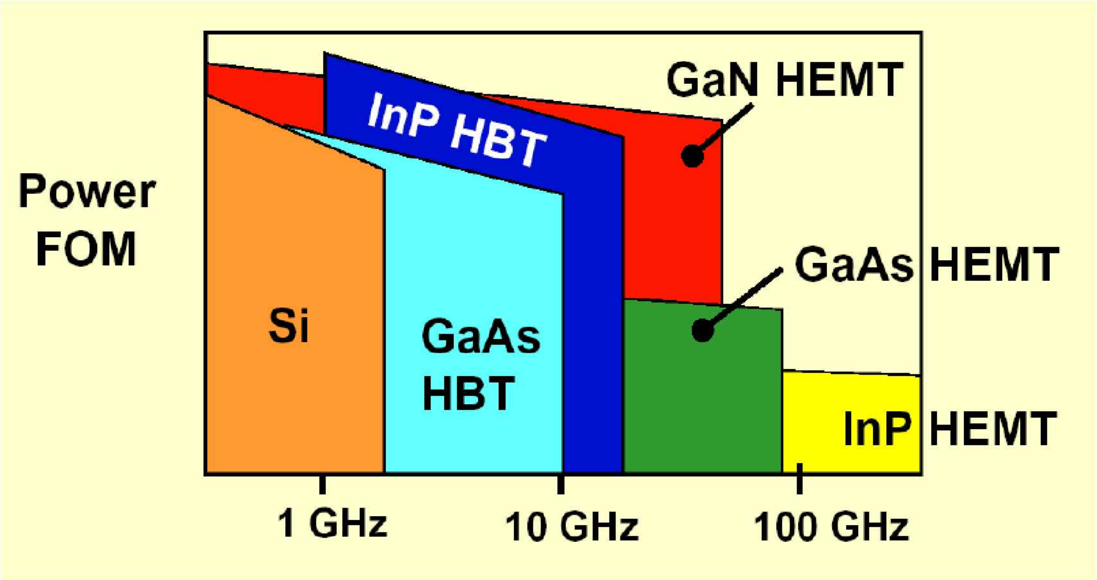


Fig. 1.4: Relative merits of power transistors technologies [7].

Due to this, antenna designers are determined to develop antennas that are physically compatible and fit within a given limited space where electrically small antennas are required to be a constituent part within handheld wireless devices. As a consequence to this, modern integrated circuit (IC) devices that are made from a single dielectric slab of semiconductor, called Monolithic Microwave Integrated Circuits (MMIC) have been developed [7]. The works on cascading of sub-circuits within MMIC does not require an external matching networks and hence, making this technology easier to use. However, the ideas on compactness using MMIC technologies for such high level integration have been realised with much higher cost and there is always a trade-off for the overall system performance. This is a typical drawback when integrating an electrically small antenna into a system on-chip; it will suffer from poor gain, efficiency and bandwidth due to its relatively small radiation aperture size [8]. Therefore, a reasonably small off-chip or externally built antenna as proposed by Chan et al [9] is a viable option to be fed differentially and without having direct electrical connection using bond wires or vias through an MMIC.

Song et al [10] proposed to fix the antenna position on the chip carrier, and this has slightly improved the antenna performance. The overall systems performance was still inferior standard during low operating frequencies. The concept proposed by Song et al [10] was to electromagnetically couple the energy from the chip through the parasitic patch to the antenna. However, the chip carrier where the antenna was to be situated is usually designed based on the chip's size which is quite small. This has caused the overall systems to suffer from the poor performance especially at lower microwave frequency band. Neglecting the chip's size, a larger chip carrier space should be reserved for the antenna to reside in a particular state and this will increase the total cost to build one within a package. For this reason, a feasible technique that has a potential to overcome this limitation was proposed by Chan et al [9]. A greater advantage arises from the compatibility with a differential feeding technique to generate two signals to feed the two-port networks made up of exactly similar parts facing each other. In addition, this kind of feeding technique is more desirable and suitable for IC realisation as seen in the Figs. 1.1 and 1.2, unlike most traditional antenna architectures which are generally one-port networks. This technique will create a null reaction to the crosstalk over common bias lines resulting from the two signals that flow in the opposite direction along the differential lines [11]. Simultaneously, it can enhance the circuit attributes in terms of immunity towards common mode interference.

Furthermore, differentially fed antenna designs will no longer require a balun such as hybrid coupler or impedance transformer within the front-end architecture as differential signals are preferable and can be directly fed into an IC [2]. In other words, this type of antenna not only radiates signal but it also behaves like a good matching circuit and a lossless coupler [3, 12]. However, there are always restrictions when employing new techniques into a system. For example, the physical geometry of a differentially fed antenna configuration should be in a symmetrical form. Besides, optimisations are still required within the circuit configurations such as additional open-circuit stubs etc.

In contrast, a traditional one-port antenna uses a balun as a platform for converting an unbalanced signal into an equivalent of balance signal before feeding into an IC [13-14]. The Balun is actually an electrical device that can cause a problem in the system performance. As shown in Fig. 2.4 (page 21), the balanced signals which are coming out from the balanced ports (Port 2 & 3) ideally are equal in their amplitudes and 180° out-of-phase. For a real balun, numerous reasons can cause a deviation from ideal conditions, and the balanced signals from a balun will not be perfectly differential. This deviation is known as the balun's imbalance which is quantified as follows.

$$Amplitude\ Imbalance = |S_{21}|(dB) - |S_{31}|(dB) \tag{1.1}$$

$$Phase\ Imbalance = 180° - |\angle(S_{21}) - \angle(S_{31})| \tag{1.2}$$

The balun's imbalance will increase the total system loss as this will cause even the symmetrical balanced ports become imbalanced which renders this device unusable within our push-pull PA configuration. Therefore, when it is still being used within the circuit configuration, it will result in poor efficiency. Moreover, the system using a balun within the configuration is not suitable for IC realisation and does not comply with the requirement of fully integrated solutions anyway.

Therefore, a novel technique for the direct integration of power amplifiers and antennas is to be investigated. Since the push-pull amplifier configuration uses the differential feeding technique, an EM structure like a typical two-port aperture coupled microstrip antenna is designed and it will be differentially fed at both ports so that it can be incorporated at the output stage within a push-pull amplifier architecture. Consequently, it can offer advantages of tight, neat and high level integration of a push-pull transmitting amplifier. Besides, an objective of this research is to minimise the losses by eliminating lossy devices like baluns or hybrid couplers within the existing configurations as can be seen in Fig. 1.1. Besides, incorporating an optimum matching network in the front-end circuit to ensure the maximum power transfer and minimise signal reflection from the load, is another goal of this research work. In the case of an amplifier that is part of a subsystem circuit, the mode of operation is one of the important considerations in order to generate differential signals. Thus, the main objectives of this research work are the following:

- To investigate the feasibility of integrating the power transistor output matching network into the differential feed network of an aperture coupled antenna.
- To establish a novel technique for direct integration of push-pull power amplifiers and antennas by removing the lossy output balun within the configuration.
- To demonstrate the feasibility of this novel technique by applying it to fully integrated antenna–amplifier front-end solutions.

1.3 Thesis Organisation

A brief overview of wireless communications and an insight into the motivation behind this thesis has been presented in chapter 1. Chapter 2 presents the background and overview on microwave theory, conventional power amplifier classes and early innovations and developments that include the evolution of integrated circuit antennas, passive antennas and their feeding techniques. The most important part is about push-pull integrated antenna front-end in which differential feeding technique is employed on an unbalanced antenna so that the unbalanced antenna will behave like a balanced fed one.

Chapter 3 explains in brief, the history of push-pull amplifiers as well as their design architecture. Besides, two research design flow charts are included that will cover two different designs, which are: push-pull Class B power amplifier and EM structure; and aperture coupled patch antenna. An investigation into the effect of higher order harmonic filtering in a push-pull configuration is also presented in this chapter.

Chapter 4 presents in detail the differential aperture coupling technique for a push-pull transmitting amplifier. It starts with the concept of a single fed aperture coupled antenna to show how maximum current is effectively being created and electromagnetically coupled to a microstrip patch antenna through a slot/aperture. This is followed by descriptions of the two types of differentially fed aperture coupled passive antennas named Structure A and Structure B respectively. The chapter includes some simulated and measured results to support the proposed design theory. Furthermore, the parametric studies on the available design variables for two different slot/aperture designs are presented in this chapter as well.

Chapter 5 describes the direct integration of a push-pull amplifier and an aperture coupled antenna. It starts with the simulation of a push-pull transmitting amplifier, followed by its transformation into a fully integrated version using real lossy components such as optimised biasing and decoupling circuits and a Wilkinson power divider. Comparison of waveforms of the two versions has been achieved through simulation. The difference in the measured received power from both passive and active structures is also presented in this chapter.

Chapter 6 summarizes the work which has been carried out in this thesis. It concludes that the proposed technique is very useful for direct integration of amplifiers and antennas by effectively incorporating the output matching functions and power combiner of a push-pull amplifier into the two-port antenna structure.

REFERENCES

[1] R. Ahola; et al, "A Single Chip CMOS Transceiver for 802.11a/b/g Wireless LANs". IEEE Journal of Solid-State Circuits, Vol. 39, No. 12, Dec. 2004, pp. 2250 – 2258.

[2] I. Bhatti; R. Roufoogaran; J. Castaneda, "A Fully Transformer-based front-end Architecture for Wireless Transceiver". Microwave Engineering Europe, April 2005, pp. 19 – 22.

[3] "Folded Dipole Antenna for CC2400, CC2420, CC2430 and CC2431". Application Note AN040, Chipcon Products from Texas Instruments.

[4] D. Mirshekar-Syahkal; D. Wake, "Bow-tie Antennas on High Dielectric Substrates for MMIC and OEIC Applications at Millimeter-wave Frequencies". Electronics Letters, Vol. 31, Issue 24, pp. 2060 – 2061, Nov. 1995.

[5] D. Sanchez-Hernandez; Q. H. Wang; A. A. Rezazadeh; I. D. Robertson, "Millimeter-wave Dual-band Microstrip Patch Antennas Using Multilayer GaAs Technology". IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-44, Issue 9, Sept. 1996, pp. 1590 – 1593.

[6] P. Russer, "Si and SiGe Millimeter-wave Intergrated Circuits". IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-46, Issue 5, Part 2, May 1998, pp. 590 – 603.

[7] D. Singh; C. Kalialakis; P. Gardner; P. S. Hall, "Small H-shaped Antennas for MMIC Applications". IEEE Transactions on Antennas and Propagation, Vol. APS-48, Issue 7, July 2000, pp. 1134 – 1141.

[8] J – J Lin; et al, “Integrated Antennas on Silicon Substrates for Communication over Free Space”. IEEE Electron Device Letters, Vol. 25, Issue 4, April 2004, pp. 196 – 198.

[9] K. M. Chan; E. Lee; P. Gardner; P. S. Hall; T. E. Dodgson, “Antenna System”. British Patent No. GB 0513053.9.

[10] C. T. P. Song; P. S. Hall; H. Ghafouri-Shiraz, “Novel RF Front-end Antenna Package”. IEE Proc. Microwave Ant. Propagat., Vol. 150, Issue 4, Aug. 2003, pp. 290 – 294.

[11] P. E. Fornberg; M. Kanda; C. Lasek; M. Piket-May; S. H. Hall, “The Impact of Non-ideal Return Path on Differential Signal Integrity”. IEEE Trans on Electromagnetic Compatibility, Vol. 44, Issue 1, Feb. 2002, pp. 11 – 15.

[12] W. R. Deal; V. Radisic; Yongxi Qian; T. Itoh, “Integrated-antenna Push-pull Power Amplifiers”. IEEE Transaction on Microwave Theory and Techniques, Vol. MTT-47, Issue 8, Aug. 1999, pp. 1418 – 1425.

[13] K. Y. Ho; M. Ismail, “A Fully Integrated CMOS RF Front-end for WiFi and Bluetooth”. The 2nd Annual IEEE Northeast Workshop on Circuits and Systems NEWCAS 2004, 20 – 23 June 2004, pp. 357 – 360.

[14] J. Ryynanen; et al, “A Dual-band RF Front-end for WCDMA and GSM Applications”. Custom Integrated Circuits Conference, 2000. CICC. Proceedings of the IEEE 2000, 21 – 24 May 2000, pp. 175 – 178.

[15] D. M. Pozar; “Microwave Engineering”. Wiley, 2011.

[16] P. Laplante; “Comprehensive Dictionary of Electrical Engineering”. Second Edition, Taylor & Francis, 2005.

[17] Ayman Jundi; “60 Watts Broadband Push-pull RF Power Amplifier Using LTCC Technology”. Thesis of Master of Applied Science in Electrical and Computer Engineering, University of Waterloo, Ontario, Canada, 2013.

[18] J. McLean; “Balancing Networks for Symmetric Antennas: Classification and Fundamental Operation”. IEEE Trans on Electromagnetic Compatibility, Vol. 44, No. 4, pp. 503 – 514, 2002.

[19] Steve C. Cripps; “RF Power Amplifier for Wireless Communications”. Boston, MA: Artech House, 2nd Edition, 2006.

[20] J. R. Copeland; W. J. Robertson; R. G. Verstraete, “Antennafier Arrays”. IEEE Trans on Antennas and Propagation, Vol. APS-12, March 1964, pp. 277 – 283.

[21] D. M. Pozar, “Considerations for millimetric wave printed antennas”. IEEE Trans on Antennas and Propagation, Vol. APS-3, Sept. 1983, pp. 740 – 747.

[22] J. R. James; et al, Handbook of Microstrip Antennas. Peter Peregrinus, London, UK, 1989.

[23] J. Lin; T. Itoh, “Active integrated antennas”. IEEE Trans on Antennas and Propogation, Vol. APS-42, No. 12, Dec. 1994, pp. 2186 – 2194.

[24] L. A. Navarro; K. Chang, “Integrated Active Antennas and Spatial Power Combining”. Wiley, New York, 1996.

[25] R. A. York; Z. B. Popovic, “Active and Quasi-optical Arrays for Solid State Power Combining”. Wiley, New York, 1996.

[26] L. Roy, “30GHz GaAs monolithic low noise amplifier–antennas”. IEEE MTT-S International Symposium, Denver, June 1997, pp. 967 – 970.

[27] M. Singer; K. M. Strohm; L. –R. Luy; E. M. Beibl, “Active SIMMWC–antenna for automotive applications”. IEEE MTT-S International Symposium, Denver, June 1997, pp.1265 – 1268.

[28] H. An; B. Nauwelaers; A. Van De Capelle, “Broadband active microstrip array elements”. Electronics Letters, Vol. 27, pp. 2378 – 2379, Dec. 1991.

[29] B. Robert; T. Razban; A. Papiernik, “Compact amplifier integration in square patch antenna”. Electronics Letters, Vol. 28, pp.1808 – 1810, Sept. 2002.

[30] G. A. Ellis; S. Liw, “Active Planar Inverted-F Antennas for wireless applications”. IEEE Trans on Antennas and Propagation, Vol. APS-51, No. 10, Oct. 2003, pp. 2899 – 2906.

[31] H. Kim; I. J. Yoon; Y. J. Yoon, “A novel fully integrated transmitter front-end with high power added efficiency”. IEEE Trans on Microwave Theory and Techniques, Vol. MTT-53, No. 10, Oct. 2005, pp. 3206 – 3214.

[32] S. Gao; Y. Qin; A. Sambell, “Broadband circularly polarised high efficiency active antenna”. Electronics Letters, Vol. 42, No. 5, pp. 258 – 259, March 2006.

[33] K. Chang; C. Sun, “Millimeter-wave Power-combining Techniques”. IEEE Trans on Microwave Theory and Techniques, Vol. MTT-83, No.2, Feb. 1983, pp. 91 – 107.

[34] D. Staiman; M. Breese; W. Patton, “New Technique for combining solid-state sources”. IEEE Journal of Solid-State Circuits, Vol. 3, No. 3, Sept. 1968, pp. 238 – 243.

[35] K. Chang; K. A. Hummer; G. K. Gopalakrishnan, “Active radiating element using FET source integrated with microstrip patch antenna”. Electronics Letters, Vol. 24, pp. 1347 – 1348, Oct. 1988.

[36] J. Birkeland; T. Itoh, "FET-based planar circuits for quasi-optical sources and transceivers". IEEE Trans on Microwave Theory and Techniques, Vol. MTT-37, Sept. 1989, pp. 1452 – 1459.

[37] X. D. Wu; K. Chang, "Dual FET active patch elements for spatial power combiners". IEEE Trans on Microwave Theory and Techniques, Vol. MTT-43, Jan. 1995, pp. 26 – 30.

[38] X. D. Wu; K. Chang, "Novel active FET circulator patch antenna arrays for quasi-optical power combining". IEEE Trans on Microwave Theory and Techniques, Vol. MTT-42, May 1994, pp. 766 – 771.

[39] S. Kawasaki; T. Itoh, "2x2 Quasi-optical combiner array at 20GHz". IEEE Trans on Microwave Theory and Techniques, Vol. MTT-41, No. 4, April 1993, pp. 717 – 719.

[40] W. K. Leverich; X. D. Wu; K. Chang, "New FET active notch antenna". Electronics Letters, Vol. 28, pp. 2239 – 2240, Nov. 1992.

[41] R. A. York; R. C. Compton, "Quasi-optical power combining using mutually synchronized oscillator arrays". IEEE Trans on Microwave Theory and Techniques, Vol. MTT-39, No. 6, 1991, pp. 1000 – 1009.

[42] V. F. Fusco; S. Drew, "Active antenna phase modulator performance". 23rd European Microwave Conference Proceedings, 1993, pp. 248 – 251.

[43] A. Zarrouge; P. S. Hall; M. J. Cryan, "Active antenna phase control using subharmonic locking". Electronics Letters, Vol. 31, pp. 842 – 843, May 1995.

[44] M. J. Cryan; P. S. Hall, "Analysis of harmonic radiation from an active integrated antenna". Electronics Letters, Vol. 33, pp. 1998 – 1999, Nov. 1997.

[45] P. Bhartia; I. Bahl, "A frequency agile microstrip antenna". Antennas & Propagation Society International Symposium, Vol. 20, May 1982, pp. 304 – 307.

[46] P. M. Haskins; P. S. Hall; J. S. Dahele, "Active patch antenna element with diode tuning". Electronics Letters, Vol. 27, pp. 1846 – 1847, Sept. 1991.

[47] P. M. Haskins; J. S. Dahele, "Varactor-diode loaded passive polarisation-agile patch antenna". Electronics Letters, Vol. 30, pp. 1074 – 1075, June 1994.

[48] K. D. Stephan; N. Camilleri; T. Itoh, "A quasi-optical polarisation duplexed balanced mixer for millimetre wave applications". IEEE Trans on Microwave Theory and Techniques, Vol. MTT-31, Feb. 1983, pp. 164 – 170.

[49] D. Singh; P. Gardner; P. S. Hall, "Integrated push-pull frequency doubling active microstrip transponder". Electronics Letters, Vol. 33, No. 6, pp. 505 – 506, March 1997.

[50] P. A. Linden; V. F. Fusco, "A frequency doubling active patch antenna". Microwave and RF Conference, London, 1996, pp. 344 – 348.

[51] M. J. Cryan; P. S. Hall, "Integrated active antenna with simultaneous transmit-receive operation". Electronics Letters, Vol. 32, No. 4, pp. 286 – 287, Feb. 1996.

[52] M. J. Cryan; P. S. Hall, "An integrated active circulator antenna". IEEE Microwave and Guided Wave Letters, Vol. 7, No. 7, July 1997, pp. 190 – 191.

[53] G. Ma; P. S. Hall; P. Gardner; M. Hajian, "Zero-IF detection active antenna". Electronics Letters, Vol. 37, No. 1, pp. 3 – 4, Jan. 2001.

[54] G. A. Deschamps, “Microstrip Microwave Antennas”. 3rd USAF Symposium on Antennas, 1953.

[55] H. Gutton; G. Baissinot, “Flat Aeriel for Ultra High Frequencies”. French Patent No. 70313, 1955.

[56] J. Q. Howell, “Microstrip Antennas”. IEEE AP-S Int. Symp. Digest, 1972, pp. 177 – 180.

[57] R. E. Munson, “Conformal Microstrip Antennas and Microstrip Phased Arrays”. IEEE Trans on Antennas and Propagation, Vol. AP-22, 1974, pp. 74 – 78.

[58] I. J. Bahl; P. Bahartia, “Microstrip Antennas”. Artech House, Dedham, MA, 1980.

[59] J. R. James; P. S. Hall; C. Wood, “Microstrip Antennas: Theory and Design”. Peter Peregrinus, London, UK, 1981.

[60] P. Bhartia; K. V. S. Rao; R. S. Tomar, “Millimeter-Wave Microstrip and Printed Circuit Antennas. Artech House, Norwood, MA, 1991.

[61] D. M. Pozar; D. H. Schaubert (Eds), “The Analysis and Design of Microstrip Antennas and Arrays”. IEEE Press, New York, 1996.

[62] J. F. Zurcher; F. E. Gardiol, “Broadband Patch Antennas”. Artech House, Norwood, MA, 1995.

[63] R. A. Sainati, “CAD of Microstrip Antennas for Wireless Applications”. Artech House, Norwood, MA, 1996.

[64] D. M. Pozar, “Microstrip Antennas”. Proc. IEEE, Vol. 80, 1992, pp. 79 – 91.

[65] J. P. Daniel et al, “Research on Planar Antennas and Arrays: Structures Rayonnantes”. IEEE Antennas Propagation Magazine, Vol. 35, 1993, pp. 66 – 76.

[66] C. A. Balanis, "Antenna Theory: Analysis and Design". 2nd Edition, Artech House, Norwood, MA, 1996.

[67] J. T. Abrele; D. M. Pozar, "Analysis of infinite arrays of probe-fed rectangular microstrip antennas using a rigorous feed model". Proc. IEE, Pt. H, Vol. 136, 1989, pp. 110 – 119.

[68] J. P. Damiano; A. Papiernik, "Survey of analytical and numerical model for probe-fed microstrip antennas". IEE Proc., Microwave Antenna Propagation, Vol. 141, 1994, pp. 15 – 22.

[69] C. Wu; et al, "Accurate characterisation of planar printed antennas using finite-difference time-domain method". IEEE Trans. On Antennas and Propagation, Vol. AP-40, 1992, pp. 526 – 534.

[70] S. C. Wu; et. al, "Feeding Structure Contribution to Radiation by Patch Antennas With Rectangular Boundaries". IEEE Trans. on Antennas and Propagation, Vol. AP-40, 1992, pp. 1245 – 1249.

[71] D. M. Pozar, "A Microstrip Antenna Aperture Coupled to a Microstrip Line". Electronics Letters, Vol. 21, pp. 49 – 50, January 17, 1985.

[72] D. M. Pozar; S. D. Targonski, "Improved Coupling for Aperture Coupled Microstrip Antennas". Electronics Letters, Vol. 27, pp. 1129 – 1131, June 20, 1991.

[73] V. Rathi; et al, "Improved Coupling for Aperture Coupled Microstrip Antennas". IEEE Trans. on Antennas and Propagation, Vol. AP-44, Issue 8, 1996, pp. 1196 – 1198.

[74] G. Gronau; I. Wolff, "Aperture Coupling of a Rectangular Microstrip Resonator". Electronics Letters, Vol. 22, pp. 554 – 556, 1986.

[75] P. L. Sullivan; D. H. Schaubert, “Analysis of an Aperture Coupled Microstrip Antenna”. IEEE Trans. on Antennas and Propagation, Vol. AP-34, 1986, pp. 977 – 984.

[76] M. Himdi; et al, “Analysis of Aperture Coupled Microstrip Antenna using Cavity Method”. Electronics Letters, Vol. 25, pp. 391 – 392, 1989.

[77] M. Himdi; et al, “Transmission Line Analysis of Aperture Coupled Microstrip Antenna”. Electronics Letters, Vol. 25, pp. 1229 – 1230, 1989.

[78] H. G. Booker, “Slot Aerials and Their Relation to Complimentary Wire Aerials”. JIEEE, pt. IIIA, London, No. 4, 1946.

[79] J. D. Kraus; et al, “Antennas”. Mcgraw Hill, 3rd Edition, Singapore, 2002.

[80] Y. Yoshimura, “A Microstrip Line Slot Antenna”. IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-20, 1972, pp. 760 – 762.

[81] D. M. Pozar, “Reciprocity Method of Analysis for Printed Slot and Slot-Coupled Microstrip Antennas”. IEEE Trans. on Antennas and Propagation, Vol. AP-34, 1986, pp. 1439 – 1446.

[82] A. Axelrod, M. Kisliuk, J. Maoz, “Broadband Microstrip-Fed Slot Radiator”. Microwave Journal, Vol. 32, June 1989, pp. 81, 82, 84 (4 ff.).

[83] M. Himdi, J. P. Daniel, “Analysis of Printed Linear Slot Antenna using Lossy Transmission Line Model”. Electronics Letters, Vol. 28, pp. 598 – 601, 1992.

[84] J. P. Kim, W. S. Park, “Network Modelling of an Inclined and Off-center Microstrip-fed Slot Antenna”. IEEE Trans. on Antenna and Propagation, Vol. AP-46, pp. 1182 – 1188, 1998.

[85] H. G. Akhavan, D. Mirshekar-Syahkal, “Approximate Model for Microstrip Fed Slot Antenna”. Eletronics Letters, Vol. 30, pp. 1902 – 1903, 1994.

[86] D. Sasaki; S. Hayashida; K. Imamura; H. Morishita; M. Usami, “A Planar Folded Dipole Antenna for Handset”. IEEE International Workshop on Antenna Technology: Small Antennas and Novel Metamaterials, 7 – 9 March 2005, pp. 133 – 136.

[87] P.-C. Hsu; C. Nguyen; M. Kintis, “Uniplanar broad-band push-pull FET amplifiers”. IEEE Trans. on Microwave Theory and Technique, Vol. 45, Issue 12, December 1997, pp. 2150 – 2152.

[88] Y. X. Qian; T. Itoh, “Active integrated antennas using planar quasi-yagi radiators”. 2nd International Conference on Microwave and Millimeter Wave Technology, ICMMT 2000, 14 – 16 September 2000, pp. P1 – P4.

[89] S.A. Cripps, “A theory for the prediction of GaAs FET load-pull power contours,” Microwave Symposium Digest, vol. 83, no. 1, pp. 221-223, May 1983.

[90] US Patent 549,477 Local Transmitter Circuit for Telephones., W. W. Dean

[91] Donald Monroe McNicol, “Radios' Conquest of Space: The Experimental Rise in Radio Communication”. Taylor & Francis, 1946, page 348.

[92] Gregory Malanowski, “The Race for Wireless: How Radio Was Invented (or Discovered?)”. AuthorHouse, Aug. 2011, ISBN-10 1463437501 pages 66-67.

[93] Tian He, “Design of Radio Frequency Power Amplifiers for High Efficiency and High Linearity”. Thesis of Master of Science of Electrical and Computer Engineering, Electronic Engineering Option, California State University, Chico, 2009.

[94] R. Ludwig; P. Bretchko, “RF Circuit Design – Theory and Applications”. Prentice Hall, New Jersey, 2000.

[95] Lee, E., Chan, K.M., Gardner, P., Dodgson, T.E.: 'Active Integrated Antenna Design Using a Contact-Less, Proximity Coupled, Differentially Fed Technique', IEEE Transactions on Antennaas and Propagation, Vol. 55, No. 2, February 2007.

[96] Chan, K.M., Lee, E., Lee, T.Y., Gardner, P., Dodgson, T.E.: 'Aperture-coupled, differentially-fed planar inverted F antenna', ELECTRONICS LETTERS 25th May 2006 Vol. 42 No. 11.

[97] The H-183-4-N from MACOM, "180 Degree Hybrid Coupler with Frequency 30 MHz to 3 GHz, Average Power 5 W, Frequency Sensitivity 4.5 dB, Amplitude Balance ± 4 dB, Insertion Loss 1.2 to 1.5 dB".