DIRECT INTEGRATION OF PUSH-PULL AMPLIFIER
AND APERTURE COUPLED ANTENNA

BY

FARID ZUBIR

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School of Electronic, Electrical & Systems Engineering
University of Birmingham
Edgbaston, B15 2TT
Birmingham
United Kingdom
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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.
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>IC</td>
<td>Integrated Circuit</td>
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<tr>
<td>T/R SW</td>
<td>Transmit/Receive Switch</td>
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<tr>
<td>LNA</td>
<td>Low Noise Amplifier</td>
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<tr>
<td>PA</td>
<td>Power Amplifier</td>
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<tr>
<td>RX</td>
<td>Receiver</td>
</tr>
<tr>
<td>TX</td>
<td>Transmitter</td>
</tr>
<tr>
<td>GND</td>
<td>Ground</td>
</tr>
<tr>
<td>SRD</td>
<td>Short Range Device</td>
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<tr>
<td>InP</td>
<td>Indium Phosphide</td>
</tr>
<tr>
<td>SiGe</td>
<td>Silicon Germanium</td>
</tr>
<tr>
<td>GaN</td>
<td>Gallium Nitride</td>
</tr>
<tr>
<td>GaAs</td>
<td>Gallium Arsenide</td>
</tr>
<tr>
<td>MMIC</td>
<td>Monolithic Microwave Integrated Circuit</td>
</tr>
<tr>
<td>EM</td>
<td>Electromagnetic</td>
</tr>
<tr>
<td>SWR</td>
<td>Standing Wave Ratio</td>
</tr>
<tr>
<td>VCCS</td>
<td>Voltage Control Current Source</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
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<tr>
<td>AC</td>
<td>Alternative Current</td>
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<tr>
<td>PAE</td>
<td>Power Added Efficiency</td>
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<tr>
<td>IMD</td>
<td>Intermodulation Distortion</td>
</tr>
<tr>
<td>FET</td>
<td>Field-Effect Transistor</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>--------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>MESFET</td>
<td>Metal-Semiconductor Field-Effect Transistor</td>
</tr>
<tr>
<td>IF</td>
<td>Intermediate Frequency</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
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<tr>
<td>FDTD</td>
<td>Finite Difference Time Domain</td>
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<tr>
<td>MoM</td>
<td>Method of Moment</td>
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<tr>
<td>PT</td>
<td>Total Power</td>
</tr>
<tr>
<td>AWRDE</td>
<td>Applied Wave Research Design Environment Microwave Office</td>
</tr>
<tr>
<td>MWO</td>
<td></td>
</tr>
<tr>
<td>CST MWS</td>
<td>Computer Simulation Technology Microwave Studio</td>
</tr>
<tr>
<td>BSF</td>
<td>Bandstop Filter</td>
</tr>
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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 focused 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.

![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])](image-url)
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.

\[
\text{Amplitude Imbalance} = |S_{21}|(dB) - |S_{31}|(dB)
\]  

\[
\text{Phase Imbalance} = 180^\circ - |\angle(S_{21}) - \angle(S_{31})|\]

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


[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”.