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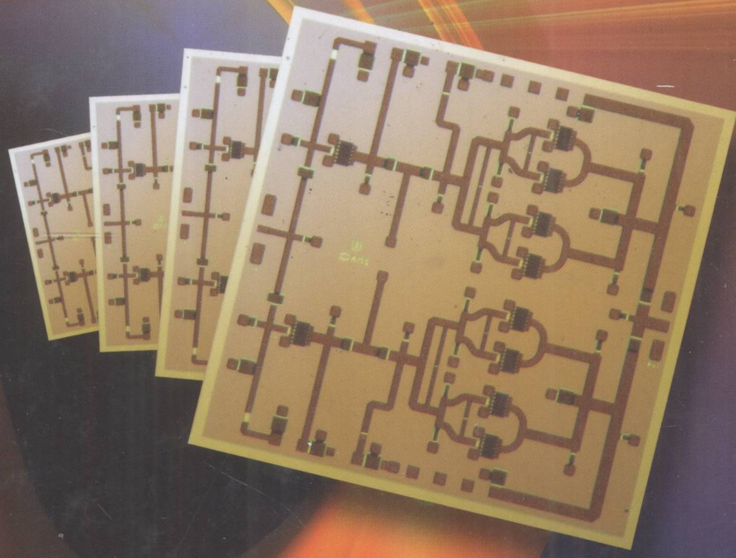

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High Efficiency RF and Microwave Solid State Power Amplifiers

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High Efficiency RF and Microwave Solid State Power Amplifiers

Preface

Research on microwave power amplifiers has gained a growing importance demanded by the many continuously developing applications which require such subsystem performance. A broad set of commercial and strategic systems in fact have their overall performance boosted by the power amplifier, the latter becoming an enabling component wherever its efficiency and output power actually allows functionalities and operating modes previously not possible. This is the case for the many wireless systems and battery-operated systems that form the substrate of everyday life, but also of high-performance satellite and dual-use systems.

Clearly, the major role of the power amplifier (PA) resides not only in the generation of an adequate output power to be transmitted, but above all in how efficiently the conversion of battery-stored power into such output is performed. The role of amplifier efficient power generation therefore becomes central, thus attracting the efforts of researchers and practitioners towards design methodologies that do not optimize challenging parameters, at the expense of the transmitted signal quality (i.e. preserving the amplifier's linearity).

The authors started their adventure in power amplifier high efficiency design methodologies at the beginning of the '90s, driven by the growing interest of the academic and industrial community in such challenging component. This book is the result of many years experience in the field of micro and millimetre PA design, and it aims to present a unified overview of high efficiency microwave solid state power amplifier (SSPA) design approaches and methodologies. Many valuable contributions have already been presented on the general topic of power amplifiers, but, at least in the authors' opinion, a gap still exists in high efficiency design techniques, above all if microwave and millimetre-wave applications are considered.

The main concepts involved in PA design are presented in this book, clarifying some classical misunderstandings or confusing topics (such as bias classes, or PA nomenclatures) as well as suggesting optimum design approaches, combining theoretical (or analytical) results and computer-aided design solutions. Thus, starting from the theoretical basis of SSPA design, examples are provided to clarify each discussed topic. Both hybrid and monolithic microwave integrated circuit (MMIC) approaches are addressed, highlighting design guidelines and criteria.

The techniques for high efficiency microwave power amplifier design, developed by the authors and published in world-wide diffused scientific journals, are presented and detailed, stressing the *pros* and *cons* as compared to different approaches, with practical examples. As a result, the book is meant to represent a reference text for designers as well as a textbook for researchers and scientists operating in this field. The topics treated in the book are introduced starting from simple considerations, useful from the practical viewpoint, extending to advanced topics for people already working in the field of SSPA design. Consequently, the book is composed of many sections that may be regarded as introductory, but also includes advanced material.

It is, however, self-consistent for post-doctorate researchers and wide portions may be used for senior undergraduate courses. Practitioners in the field with Masters degrees should not encounter any problems in picking up the relevant section dealing with their specific queries, together with the running examples provided.

The book is organised into three main parts.

The aim of the first one is to introduce the fundamental concepts related to PA design. Starting from the definition of the main figures of merit characterizing a PA in Chapter 1, in Chapter 2 a simplified approach is discussed to easily infer the power capabilities of a given active device. In this chapter, a step-by-step PA design example is discussed. Then, in Chapter 3 the non linear analysis issues intrinsically related with the design of a PA are outlined. This first portion of the book is finally completed by Chapter 4, focused on experimental methodologies adopted for PA design, i.e. load pull techniques.

The second part is the core of the entire book, and it is devoted to the description and detailed discussion of high efficiency design techniques for PAs. Moving from a general theory, discussed in Chapter 5, two main approaches are categorized, namely the switched-mode and the current-mode PA design approaches. In Chapter 6 the former design solution is described, mainly focused on Class E amplifiers. Starting from the low frequency theory, several topologies are discussed and the extension of the methodology to high RF and micro-millimetre wave frequency ranges is outlined. The chapter concludes with several design examples where theoretical concepts are applied and demonstrated. Then, in the following two chapters (7 and 8) the current mode harmonic tuned design approaches are detailed. In particular, Chapter 7 is devoted to Class F PA design solutions, while Chapter 8 covers the more general harmonic tuning strategies, based on both input and output network harmonic loading behaviour and design.

Finally, the third and last part of the book discusses advanced concepts in the design of solid state PAs. In chapter 9 the linearity issue of a power stage is focused on in more detail. In particular, the synthesis methodologies adopted to design PA stages with high linearity performance are described, simultaneously optimizing power conversion efficiency. Then, in Chapter 10 an overview of power combining techniques is provided. Finally, to account for new and challenging requirements of solid state PA, in Chapter 11 the Doherty amplifier is discussed. Starting from the theoretical analysis, the design relationships inferred are explained through several design examples for classical or harmonic tuned (Class F) Doherty stage. The chapter is completed with a discussion about multi-way and multi-stage Doherty architectures.

Paolo Colantonio
Franco Giannini
Ernesto Limiti

About the Authors

Paolo Colantonio was born in Rome on March 1969 and he received Electronic Engineering and Ph.D degrees in Microelectronics and Telecommunications from the University of Roma 'Tor Vergata' in 1994 and 2000 respectively, working on design criteria for high efficiency power amplifiers. In 1999 he became a research assistant at the Electronic Engineering Department of the University of Roma 'Tor Vergata' and since 2002 he has been a professor of microwave electronics at the same university.

His research activities are mainly focused on the field of microwave and millimetre-wave electronics, and in particular on design criteria for nonlinear microwave subsystems. This activity resulted in the development of innovative design criteria for high efficiency and high linear power amplifiers, oriented to the optimization of power performance making use of harmonic tuning classes of operation. The results of such activities have been presented in major conferences and published in international journals.

Paolo Colantonio has been responsible for the work package activity on 'power amplifier design overview' in the VI-FP European Network of Excellence TARGET (January 2004–June 2005) and general chairman of the international event 'First TARGET NoE Workshop on RF Power Amplifiers', held in Orvieto, Italy 2005.

He is author or co-author of more than 120 papers on PA design published in refereed journals or international conference proceedings and he has been awarded Best Poster Paper at GAAS 2000 (*IMD performances of harmonically tuned microwave power amplifiers*) and Best Paper at EuMIC 2007 (*A 6W Uneven Doherty Power Amplifier in GaN Technology*).

Franco Giannini was born in Galatina (LE), on November 9, 1944, and graduated in Electronics Engineering, *summa cum laude* in 1968, before getting the chair of Full Professor of Applied Electronics in 1980. In 2008 he was awarded the *Laurea Honoris Causa Scientiarum Technicarum* degree by the Warsaw University of Technology (WUT), Poland

Since 1981 he has been at the University of Roma 'Tor Vergata', where he has been serving as Head of Department, Vice President for International Affairs, Pro-Rector, and Dean of the Faculty of Electronics Engineering. He presently chairs the Microwave Engineering Centre for Space Applications (MECSA).

He has been working on modelling, characterization and design methodologies of active and passive microwave components and circuits, including MICs and MMICs for telecommunication and space applications, authoring or co-authoring more than 400 scientific contributions.

He chaired the theme MMICs of the national project MADESS I of the CNR and was a member of the Management Board of MADESS II, chairman of the theme MMICs of the National Project MICROELECTRONICS, and member of the Board of Directors of the Italian Space Agency (ASI).

He has also been active in many European Projects, and was the Italian representative in the 'European Working Group for GaAs Microelectronics'. He has been acting as consultant for various national and international organizations, including the ITU for the United Nations Development Program (UNDP), and the European Union for ESPRIT, LTR, ISTC projects. He has been chairman of various International Symposia on Microwave & Millimetre Wave Techniques and is a member of many committees of international scientific conferences.

In 1996 Professor Giannini was awarded the 'Irena Galewska Kielbasinski Prize' by the Technical University of Darmstadt, Germany, and an Honorary Professorship by WUT, Poland, in 2001.

Ernesto Limiti has been Full Professor of Electronics at the University of Roma 'Tor Vergata' since 2002, after being associate professor and researcher at the same university since 1991.

He teaches undergraduate courses in microwave electronics, namely Microwave Electronics (basic) and Microwave Instrumentation and Measurements, all of them at the *Laurea Magistrale* in the Electronic Engineering degree course (i.e. towards students with at least three years experience at the university). He also teaches MSc and PhD courses, both at the University of Roma 'Tor Vergata' and at other Italian universities.

His scientific interests encompass a broad range of topics, including microwave active device characterization and modelling, regarding both linear (small-signal and noise) and nonlinear regimes and microwave subsystems design methodologies. Regarding the latter, high efficiency power amplifier design methodologies have been his focus since 1992, oriented towards power performance optimization making use of harmonic tuning operating classes. This research topic has been investigated also in the frame of European research projects, e.g. Manpower, Edge, and others. The results on the work in high efficiency power amplifier design approaches have been presented in major conferences and published in international journals.

Ernesto Limiti is author or co-author of more than 200 papers appearing in refereed journals or international conference proceedings. He is a member of the Editorial Board of the International Journal of Microwave and Millimetre-Wave CAE (Wiley Interscience), serving also as a reviewer for various IEEE Transactions and IET Journals.

He has been general chairman and organizer of the 2004 international workshop on Integrated Nonlinear Microwave and Millimetre-wave Circuits (INMMiC 2004) as well as the 11^{th} International Symposium on Microwave and Optical Technology (ISMOT 2007).

The authors are experienced PA designers and gained such experience in over 16 years of research activities in this specific field. They developed new design criteria based on harmonic tuning for high efficiency and linear power amplifiers. Their experience has matured through the implementation of design criteria in both hybrid and monolithic solutions. The results of their research activities on high efficiency PA design strategies have been published in more than 50 refereed journal contributions and chapters of the Wiley Encyclopedia on Microwave Electronics entitled *Microwave Power Amplifier* and *Load-Pull Techniques* (with other co-authors).

In addition to their institutional duties, the authors also teach in postgraduate and PhD schools, including the International Travelling Summer School (http://itss.elka.pw.edu.pl/), International course for PhD students at Warsaw University of Technology (MiTraPAs) and the Short Course on 'Fundamentals of Microwave Power Amplifier Design' organized and held within the framework of the European Microwave Week.

Acknowledgments

This book contains the results of more than a decade of research activities performed in this frame by the authors.

In this context, the long interaction and discussion with colleagues and researchers working on the same or related topics has been very helpful to determine the most suitable organization and focus of the book. Many people deserve therefore our thanks for their direct help in useful discussion and a long list should be provided. Nevertheless, some of them have to be acknowledged for their effort, without which this work would not have been possible.

Among them, we acknowledge the support of all the members of the High Frequency Electronic group of University of Roma Tor Vergata, and in particular our young engineers and PhD students (R. Giofrè, L. Piazzon, E. Cipriani and M. Jankowski) whose work has been extremely useful in developing several PA designs and relative characterizations.

We would also like to thank our colleagues from Politecnico di Torino, Italy (G. Ghione, M. Pirola, V. Camarchia, A. Ferrero and V. Teppati), for their support and long cooperation in performing both active device load pull and PA characterizations.

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Finally, a special thanks to G. Magerl (Technology University of Vienna) for his encouragement, support and useful "general discussions".

Since writing a book typically implies a decrease in human interactions and duties, we hope that the latter effect has not been so dramatic in our case, apologizing to all those, including our families, who suffered from it: the promise is to jump back to normality as soon as possible!

As a final acknowledgement, the authors would like to express their sincere appreciation to all the Wiley staff involved in this project, for their cheerful professionalism and outstanding efforts.

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1

Power Amplifier Fundamentals

1.1 Introduction

A power amplifier (PA) is an essential component, playing a key role in the realization of many microwave and millimetre-wave systems. PA applications span a broad range of areas [1], among which telecommunications, radar [2–4], electronic warfare, heating [5, 6], and medical microwave imaging [7–12] represent just a few examples. Given such extremely diversified fields, PA specifications may greatly differ in operating, technological and design requirements. As a consequence, a wide variety of PA realizations results, from travelling-wave tube amplifiers in satellite payloads to solid-state amplifiers for personal wireless communication handsets, from microwave heating tubes to amplifiers composing hyperthermia apparatus.

Regardless of its physical realization, the task of a PA is to increase the power level of the signal at its input in a given frequency band, up to a predefined level at its output. As contrasted therefore to low-level (i.e. linear) amplifiers, often specified in term of small-signal gain, the absolute output power level, as well as the power gain, become the PA's primary performance.

The need for high output power levels is the main driver in the selection of the active devices composing the PA, on the basis of their output power capabilities. Moreover, to limit the power consumption, active devices are typically operated under large-signal regimes, so fully swinging their nonlinear characteristics. Otherwise, a sufficiently large active device could be adopted, resulting in an almost linear behaviour, while dissipating a large amount of DC power for voltage and current biasing.

A PA is therefore to be considered as a nonlinear system component, whose large-signal operating conditions often lead to detrimental effects on the output signal, resulting in a distorted replica of the input. On the other hand, the linear approximation underlying small-signal amplifier design techniques is no longer strictly valid, hence not allowing their direct application to PA design. Dedicated methodologies have to be exploited and adopted, even if preliminary and first guess approaches can be employed.

PA design is typically the result of a trade-off, trying to fulfil several conflicting requirements such as linearity *vs.* efficiency or high output power level *vs.* low distortion. The design approach to be selected depends on operating frequency and bandwidth, available device technology, application (fixed, mobile or satellite communications, modulated CW or pulsed signal, etc.) and many other factors [13].

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