MODELING AND DESIGN TECHNIQUES FOR RF POWER AMPLIFIERS

Arvind Raghavan
Intel Corporation
Hudson, MA

Nuttapong Srirattana
RF Micro Devices
Greensboro, NC

Joy Laskar
Georgia Institute of Technology
Atlanta, GA

IEEE PRESS

WILEY-INTERSCIENCE
A John Wiley & Sons, Inc., Publication

This Page Intentionally Left Blank

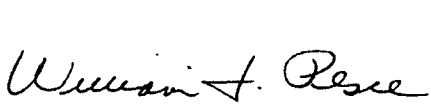
MODELING AND DESIGN TECHNIQUES FOR RF POWER AMPLIFIERS

THE WILEY BICENTENNIAL–KNOWLEDGE FOR GENERATIONS

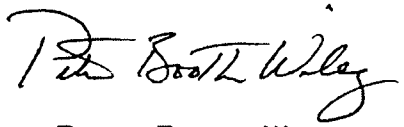
Each generation has its unique needs and aspirations. When Charles Wiley first opened his small printing shop in lower Manhattan in 1807, it was a generation of boundless potential searching for an identity. And we were there, helping to define a new American literary tradition. Over half a century later, in the midst of the Second Industrial Revolution, it was a generation focused on building the future. Once again, we were there, supplying the critical scientific, technical, and engineering knowledge that helped frame the world. Throughout the 20th Century, and into the new millennium, nations began to reach out beyond their own borders and a new international community was born. Wiley was there, expanding its operations around the world to enable a global exchange of ideas, opinions, and know-how.

For 200 years, Wiley has been an integral part of each generation's journey, enabling the flow of information and understanding necessary to meet their needs and fulfill their aspirations. Today, bold new technologies are changing the way we live and learn. Wiley will be there, providing you the must-have knowledge you need to imagine new worlds, new possibilities, and new opportunities.

Generations come and go, but you can always count on Wiley to provide you the knowledge you need, when and where you need it!



WILLIAM J. PESCE
PRESIDENT AND CHIEF EXECUTIVE OFFICER



PETER BOOTH WILEY
CHAIRMAN OF THE BOARD

MODELING AND DESIGN TECHNIQUES FOR RF POWER AMPLIFIERS

Arvind Raghavan
Intel Corporation
Hudson, MA

Nuttapong Srirattana
RF Micro Devices
Greensboro, NC

Joy Laskar
Georgia Institute of Technology
Atlanta, GA

IEEE PRESS

WILEY-INTERSCIENCE
A John Wiley & Sons, Inc., Publication

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

Wiley Bicentennial Logo: Richard J. Pacifico

Library of Congress Cataloging-in-Publication Data:

Raghavan, Arvind.
Modeling and design techniques for RF power amplifiers / by Arvind Raghavan, Nuttapong Srirattana, Joy Laskar.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-471-71746-1 (cloth)
1. Power amplifiers—Design and construction. 2. Amplifiers, Radio frequency.
I. Srirattana, Nuttapong. II. Laskar, Joy. III. Title.
TK7871.58.P6R34 2007
621.384'12—dc22 2007027547

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

CONTENTS

This Page Intentionally Left Blank

PREFACE

Wireless communication is ubiquitous in today's world. The advancement of wireless communication technology in the quest for better performance at lower cost has resulted in increasingly stringent demands on the integrated circuits (ICs) that constitute the building blocks of wireless systems. The radiofrequency (RF) power amplifier, an important component of any wireless transmitter, is often the villain of the piece, since it is a limiting factor in achieving better performance and reliability, and lowering cost. Thus, RF power amplifier design is a topic of immense interest and import in wireless communications.

This book discusses different aspects of RF power amplifier design. RF power amplifier design is multidisciplinary, and requires the designer to be cognizant of the several factors that have an impact on the performance of the power amplifier IC: the choice of semiconductor technology, accuracy of the transistor device models, packaging and thermal management, and circuit and architectural design techniques. Most textbooks on RF power amplifiers discuss only circuit design and architecture. The scope of this book extends beyond that, and a discussion of device models and device physics concepts, knowledge of which is of great value to the power amplifier designer, is included. RF power amplifier design is also an area of active research. An objective of this book is to acquaint the reader with the latest advances in power amplifier design. For each topic dealt with in this book, a discussion of the fundamental concepts is followed by a description of recent developments.

For a long time, power amplifier design, especially for mobile applications, remained the domain of III–V semiconductor technologies. This has changed recently, with SiGe HBT technology becoming an option for building RF power amplifiers. Power amplifier design in standard silicon-based complementary metal oxide semiconductor (SiCMOS) technology is the subject of much current research. Silicon-based power amplifiers create interesting possibilities for higher integration and lower cost. However, power amplifier design in silicon, especially in CMOS, poses considerable challenges. This book treats the important topic of power amplifier design in silicon, and includes a discussion of state-of-the-art design techniques in this area.

Another trend that has emerged in recent wireless communication standards is the use of modulation schemes with significant amplitude modulation, to achieve higher spectral efficiency. This has the effect of increasing the power amplifier linearity requirement, which conflicts with the desire for higher efficiency, an important criterion in mobile handsets, since it directly affects talk time. Thus, architectural techniques to enhance the efficiency of linear power amplifiers, a topic discussed in this text, have become very important in modern RF power amplifier design.

Accurate transistor device modeling is important in today's competitive IC design world, with increasing emphasis on fast design cycles and first-pass design success. This is particularly true for RF power amplifier design, since the power amplifier usually operates at the limit of the capability of the semiconductor device technology. Traditional device models typically prove inadequate to the task of accurately predicting power amplifier performance. New device models and enhancements to existing models have been proposed in recent years, to overcome the deficiencies of older models. An understanding of the formulation, features, and shortcomings of various device models, and the underlying device physics, enables the power amplifier designer to make more informed decisions about the choice of device technology and appropriate model to be used for a particular circuit design. It also provides the designer with an understanding of the expected accuracy of the predicted circuit performance. This book describes various bipolar transistor and metal oxide semiconductor field effect transistor (MOSFET) device models, and discusses advanced modeling techniques pertaining to RF IC design.

The book is organized as follows. Chapter 1 introduces RF power amplifier design concepts. An overview of considerations related to various topics of interest to the power amplifier designer, such as semiconductor technologies, simulation tools, and modulation schemes, to name a few, is provided. Chapter 2 discusses bipolar transistor and MOSFET device physics and device models. Chapter 3 describes an empirical modeling technique applicable to a wide variety of bipolar transistors. The goal of this technique is to simplify model parameter extraction while retaining sufficient accuracy for RF circuit design. Chapter 4 discusses enhancements to a standard MOSFET model, BSIM3v3, to model the RF characteristics more accurately. This includes a scalable model with substrate network. Chapter 5 covers power amplifier IC design concepts. This chapter includes discussions of power amplifier design methodology, classes of operation, and power amplifier performance metrics. Chapter 6 is concerned with silicon-based power amplifier design. Design techniques are illustrated using practical design examples. A SiGe heterojunction bipolar (HBT)-based high-efficiency power amplifier module is presented. This design demonstrates the integration of power amplifier IC and novel board-level design techniques using a high-performance LTCC substrate, to improve the overall performance of the power amplifier. This chapter also discusses RF power amplifier design in CMOS. A novel device periphery adjustment technique to improve the efficiency of power amplifiers at low output power levels is described. Chapter 7 deals with efficiency enhancement architectures, the focus being on the multistage Doherty amplifier technique.

This text compiles discussions of some of the most important topics related to RF power amplifier design in one concise volume. It is envisioned to serve the purposes of a wide range of readers, from beginning designers to advanced researchers. The discussion of the fundamental concepts of a range of topics pertaining to power amplifier design makes this book suitable for use as a textbook or reference for graduate or advanced undergraduate courses in RF IC design. The inclusion of recent developments serves to introduce beginners to more advanced topics, and is also particularly useful to researchers in this area. The description of state-of-the-art techniques, without sacrificing breadth of coverage of topics, is intended to make this book a valuable and handy reference to practicing engineers.

This book was made possible by assistance from many individuals and organizations. The material covered in this book evolved over several years of research and teaching at the Georgia Institute of Technology. We would like to acknowledge our colleagues, past and present, at the Georgia Institute of Technology, particularly Prof. Phillip Allen, Prof. John Cressler, Dr. Deukhyoun Heo, Dr. Kyutae Lim, Dr. Stephane Pinel, Dr. Moonkyun Maeng, Dr. Albert Sutono, Dr. Sebastien Nuttinck, Dr. Ramana Murty, Dr. Emery Chen, Dr. Chang-Ho Lee, Dr. Sudipto Chakraborty, Dr. Bhaskar Banerjee, Sunitha Venkataraman, and Anand Raghavan. Special thanks are due to Patrick O'Farrell, Andy McLean, and Arlo Aude of National Semiconductor. We are grateful to the staff at John Wiley & Sons, Inc., especially Whitney Lesch, for their assistance. Most importantly, we thank our respective families for their patience and support, especially Vasantha Raghavan, Bashyam Raghavan, Noppawan Srirattana, Chongrak Srirattana, Nuttapan Srirattana, Thidarat Tosukhowong, Devi Laskar, Anjini Laskar, Ellora Laskar, and Devrani Laskar.

Arvind Raghavan
Nuttapong Srirattana
Joy Laskar

This Page Intentionally Left Blank

1

INTRODUCTION

The radiofrequency (RF) power amplifier is one of the most important components of a wireless communication system. It plays a significant part in determining the overall performance, cost, and reliability of the wireless system. In fact, the increasing use of modulation schemes with amplitude modulation of the carrier signal, to achieve higher spectral efficiency, is only expected to enhance this significance. The RF power amplifier is also one of the most challenging components of the wireless system front end to design, analyze, and model for, as it generally operates at the limits of the capability of the semiconductor device technology. This situation is exacerbated by the current trend toward migration of the radio front-end to silicon-based technologies, which are considerably less suitable for RF power amplifier design than are the traditional III–V-based technologies. RF power amplifier design encompasses, and is impacted by, several areas: semiconductor technology, which provides the active and passive devices used in power amplifier design and determines the performance and reliability of the power amplifier to a large extent; transistor device modeling, which makes it possible to design and predict the behavior of the power amplifier; RF measurement and characterization techniques; integrated circuit (IC) design; architectural techniques, which help improve the performance of the power amplifier; behavioral "blackbox" modeling, which enables analysis of the impact of the characteristics of the power amplifier on the performance of the wireless system; and IC packaging and thermal management technology.