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英文版

射频微电子（第二版）

RF Microelectronics, Second Edition

［美］ Behzad Razavi 著

電子工業出版社
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内 容 简 介

本书侧重系统级描述，综合了无线通信电路系统描述、器件特性及单元电路分析，讨论最新架构、电路和器件。第1章和第2章首先介绍射频电子学的基本概念和术语；第3章和第4章讨论通信系统层的建模、检测、多路存取等技术及无线标准；第5章讨论无线前端收发机的结构和集成电路的实现，第6章到第9章详细讨论了低噪声放大器和混频器、振荡器、频率综合器及功放器电路原理和分析方法。本书在改编过程中删除了英文原版中的少量习题。

本书既可作为高年级本科生或硕士研究生的双语教学教材，又可满足集成电路设计工作者进一步提高自身知识和设计技能的需求。

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导　读

*RF Microelectronics*一书的作者Behzad Razavi是美国加州大学洛杉矶分校终身教授，曾经在美国贝尔实验室和惠普实验室从事多年的射频电路设计工作，在射频电路领域有数十年的科研和教学经验。本书的第一版于1998年问世，经过不断的再版和翻译，成为射频电路设计领域的经典书籍。14年来，射频电路设计领域发生了巨大的变化，高集成度的无线设备和宽带的无线应用，促使科研人员在收发信机结构、电路形式及器件特性上，不断推陈出新。而且，新的电路分析方法及建模技术的成熟，使科研人员对射频电路的理解步入一个新的台阶。为反映这些变化，本书的第二版得以问世。

与旧版相比，新版在篇章结构与具体内容上都有显著变化，两者的内容重合度在10%左右。在新版著作中，作者通过大量的设计实例和问题讨论，帮助读者在学习射频电路整体分析方法的同时，了解射频电路设计中可能遇到的细节问题。同时，在新版著作中，作者也更加强调如何帮助读者掌握射频电路设计的基本方法，为此作者还特别增加了一章，用于指导读者如何一步一步地设计晶体管级的双频段WiFi收发机。

本书的具体内容可以概括如下。第2章介绍射频电路设计中的基本概念，其中增加了双端口网络S参数的定义和计算实例，为本书后续章节的分析打下基础。随后，第3章对无线通信的基本概念进行阐述，重点介绍数字调制方式及其相应的电路实现实例。第4章不仅介绍传统经典结构的各类收发信机，同时基于作者对射频电路最新发展趋势的跟踪，广受关注的新型收发信机结构也出现在新版著作中。值得一提的是，作者还通过问题讨论等方式，结合802.11a/g等具体无线通信标准，讲解了设计中需要注意的实际问题。本书的第5章至第12章，详尽介绍了无线收发信机中的各个子模块。与旧版相比，各子模块的分类方式有显著改进，作者也浓墨重彩地分析了各类新型模块技术，使读者能够及时地掌握射频电路设计的新趋势。新版还加入了无源器件的介绍与分析，使内容更趋完整。本书的第13章是收发信机设计实例，如前所述，本章内容是全书知识点的灵活运用，也是作者专注于设计方法传授的点睛之笔。

本书的内容体系基本涵盖了国内高校“通信基本电路”（亦称“高频电子线路”）专业基础课程的教学内容。但是，通过本人在上海交通大学电子工程系本科三年级的亲身教学实践（1学期64学时），发现本书与“通信基本电路”课程的教学大纲存在一定的不匹配之处。本书的内容相对于本科阶段的知识体系显得内容过于庞大，系统级的电路分析定性讲解有余，而单元电路的定量分析不足。因此，本书更适合作为理工类大专院校电子类专业研究生的课程教材。如果作为理工类大专院校通信、电子类本科生双语教学和全英文教学的教材，建议结合Thomas H. Lee的*Design of CMOS Radio-Frequency Integrated Circuits*（由电子工业出版社翻译出版），以便于学生掌握单元电路基础知识，为今后的科研打下扎实的基础。本书内容涵盖无线收发信机各个模块的介绍、分析和设计，并融入了Razavi教授数十年的电路设计经验，对从事射频电路设计的专业技术人员而言，更是一本不可多得的必备书籍。

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PREFACE TO THE SECOND EDITION

In the 14 years since the first edition of this book, RF IC design has experienced a dramatic metamorphosis. Innovations in transceiver architectures, circuit topologies, and device structures have led to highly-integrated "radios" that span a broad spectrum of applications. Moreover, new analytical and modeling techniques have considerably improved our understanding of RF circuits and their underlying principles. A new edition was therefore due.

The second edition differs from the first in several respects:

1. I realized at the outset — three-and-a-half years ago — that simply adding "patches" to the first edition would not reflect today's RF microelectronics. I thus closed the first edition and began with a clean slate. The two editions have about 10% overlap.
2. I wanted the second edition to contain greater pedagogy, helping the reader understand both the fundamentals and the subtleties. I have thus incorporated hundreds of examples and problems.
3. I also wanted to teach design in addition to analysis. I have thus included step-by-step design procedures and examples. Furthermore, I have dedicated Chapter 13 to the step-by-step transistor-level design of a dual-band WiFi transceiver.
4. With the tremendous advances in RF design, some of the chapters have inevitably become longer and some have been split into two or more chapters. As a result, the second edition is nearly three times as long as the first.

Suggestions for Instructors and Students

The material in this book is much more than can be covered in one quarter or semester. The following is a possible sequence of the chapters that can be taught in one term with reasonable depth. Depending on the students' background and the instructor's preference, other combinations of topics can also be covered in one quarter or semester.

Chapter 1: Introduction to RF and Wireless Technology

This chapter provides the big picture and should be covered in about half an hour.

Chapter 2: Basic Concepts in RF Design

The following sections should be covered: General Considerations, Effects of Nonlinearity (the section on AM/PM Conversion can be skipped), Noise, and Sensitivity and Dynamic Range. (The sections on Passive Impedance Transformation, Scattering Parameters, and Analysis of Nonlinear Dynamic Systems can be skipped.) This chapter takes about six hours of lecture.

Chapter 3: Communication Concepts

This chapter can be covered minimally in a quarter system — for example, Analog Modulation, Quadrature Modulation, GMSK Modulation, Multiple Access Techniques, and the IEEE802.11a/b/g Standard. In a semester system, the concept of signal constellations can be introduced and a few more modulation schemes and wireless standards can be taught. This chapter takes about two hours in a quarter system and three hours in a semester system.

Chapter 4: Transceiver Architectures

This chapter is relatively long and should be taught selectively. The following sections should be covered: General Considerations, Basic and Modern Heterodyne Receivers, Direct-Conversion Receivers, Image-Reject Receivers, and Direct-Conversion Transmitters. In a semester system, Low-IF Receivers and Heterodyne Transmitters can be covered as well. This chapter takes about eight hours in a quarter system and ten hours in a semester system.

Chapter 5: Low-Noise Amplifiers

The following sections should be covered: General Considerations, Problem of Input Matching, and LNA Topologies. A semester system can also include Gain Switching and Band Switching or High-IP_2 LNAs. This chapter takes about six hours in a quarter system and eight hours in a semester system.

Chapter 6: Mixers

The following sections should be covered: General Considerations, Passive Downconversion Mixers (the computation of noise and input impedance of voltage driven sampling mixers can be skipped), Active Downconversion Mixers, and Active Mixers with High IP_2. In a semester system, Active Mixers with Enhanced Transconductance, Active Mixers with Low Flicker Noise, and Upconversion Mixers can also be covered. This chapter takes about eight hours in a quarter system and ten hours in a semester system.

Chapter 7: Passive Devices

This chapter may not fit in a quarter system. In a semester system, about three hours can be spent on basic inductor structures and loss mechanisms and MOS varactors.

Chapter 8: Oscillators

This is a long chapter and should be taught selectively. The following sections should be covered: Basic Principles, Cross-Coupled Oscillator, Voltage-Controlled Oscillators, Low-Noise VCOs. In a quarter system, there is little time to cover phase noise. In a semester system, both approaches to phase noise analysis can be taught. This chapter takes about six hours in a quarter system and eight hours in a semester system.

Chapter 9: Phase–Locked Loops

This chapter forms the foundation for synthesizers. In fact, if taught carefully, this chapter naturally teaches integer-N synthesizers, allowing a quarter system to skip the next chapter. The following sections should be covered: Basic Concepts, Type-I PLLs, Type-II PLLs, and PFD/CP Nonidealities. A semester system can also include Phase Noise in PLLs and Design Procedure. This chapter takes about four hours in a quarter system and six hours in a semester system.

Chapter 10: Integer–N Synthesizers

This chapter is likely sacrificed in a quarter system. A semester system can spend about four hours on Spur Reduction Techniques and Divider Design.

Chapter 11: Fractional–N Synthesizers

This chapter is likely sacrificed in a quarter system. A semester system can spend about four hours on Randomization and Noise Shaping. The remaining sections may be skipped.

Chapter 12: Power Amplifiers

This is a long chapter and, unfortunately, is often sacrificed for other chapters. If coverage is desired, the following sections may be taught: General Considerations, Classification of Power Amplifiers, High-Efficiency Power Amplifiers, Cascode Output Stages, and Basic Linearization Techniques. These topics take about four hours of lecture. Another four hours can be spent on Doherty Power Amplifier, Polar Modulation, and Outphasing.

Chapter 13: Transceiver Design Example

This chapter provides a step-by-step design of a dual-band transceiver. It is possible to skip the state-of-the-art examples in Chapters 5, 6, and 8 to allow some time for this chapter. The system-level derivations may still need to be skipped. The RX, TX, and synthesizer transistor-level designs can be covered in about four hours.

A solutions manual is available for instructors via the Pearson Higher Education Instructor Resource Center web site: pearsonhighered.com/irc; and a set of Powerpoint slides is available for instructors at informit.com/razavi. Additional problems will be posted on the book's website (informit.com/razavi).①

— *Behzad Razavi*

July 2011

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① 登录华信教育资源网（http://www.hxedu.com.cn）可下载本书相关资源。采用本书作为教材的教师可获得本书配套教辅和习题解答（英文版）。详见书末所附“教学支持说明”。

PREFACE TO THE FIRST EDITION

The annual worldwide sales of cellular phones has exceeded \$2.5B. With 4.5 million customers, home satellite networks comprise a \$2.5B industry. The global positioning system is expected to become a \$5B market by the year 2000. In Europe, the sales of equipment and services for mobile communications will reach \$30B by 1998. The statistics are overwhelming.

The radio frequency (RF) and wireless market has suddenly expanded to unimaginable dimensions. Devices such as pagers, cellular and cordless phones, cable modems, and RF identification tags are rapidly penetrating all aspects of our lives, evolving from luxury items to indispensable tools. Semiconductor and system companies, small and large, analog and digital, have seen the statistics and are striving to capture their own market share by introducing various RF products.

RF design is unique in that it draws upon many disciplines unrelated to integrated circuits (ICs). The RF knowledge base has grown for almost a century, creating a seemingly endless body of literature for the novice.

This book deals with the analysis and design of RF integrated circuits and systems. Providing a systematic treatment of RF electronics in a tutorial language, the book begins with the necessary background knowledge from microwave and communication theory and leads the reader to the design of RF transceivers and circuits. The text emphasizes both architecture and circuit level issues with respect to monolithic implementation in VLSI technologies. The primary focus is on bipolar and CMOS design, but most of the concepts can be applied to other technologies as well. The reader is assumed to have a basic understanding of analog IC design and the theory of signals and systems.

The book consists of nine chapters. Chapter 1 gives a general introduction, posing questions and providing motivation for subsequent chapters. Chapter 2 describes basic concepts in RF and microwave design, emphasizing the effects of nonlinearity and noise.

Chapters 3 and 4 take the reader to the communication system level, giving an overview of modulation, detection, multiple access techniques, and wireless standards. While initially appearing to be unnecessary, this material is in fact essential to the concurrent design of RF circuits and systems.

Chapter 5 deals with transceiver architectures, presenting various receiver and transmitter topologies along with their merits and drawbacks. This chapter also includes a number of case studies that exemplify the approaches taken in actual RF products.

Chapters 6 through 9 address the design of RF building blocks: low-noise amplifiers and mixers, oscillators, frequency synthesizers, and power amplifiers, with particular attention to minimizing the number of off-chip components. An important goal of these chapters is to demonstrate how the system requirements define the parameters of the circuits and how the performance of each circuit impacts that of the overall transceiver.

I have taught approximately 80% of the material in this book in a 4-unit graduate course at UCLA. Chapters 3, 4, 8, and 9 had to be shortened in a ten-week quarter, but in a semester system they can be covered more thoroughly.

Much of my RF design knowledge comes from interactions with colleagues. Helen Kim, Ting-Ping Liu, and Dan Avidor of Bell Laboratories, and David Su and Andrew Gzegorek of Hewlett-Packard Laboratories have contributed to the material in this book in many ways. The text was also reviewed by a number of experts: Stefan Heinen (Siemens), Bart Jansen (Hewlett-Packard), Ting-Ping Liu (Bell Labs), John Long (University of Toronto), Tadao Nakagawa (NTT), Gitty Nasserbakht (Texas Instruments), Ted Rappaport (Virginia Tech), Tirdad Sowlati (Gennum), Trudy Stetzler (Bell Labs), David Su (Hewlett-Packard), and Rick Wesel (UCLA). In addition, a number of UCLA students, including Farbod Behbahani, Hooman Darabi, John Leete, and Jacob Rael, "test drove" various chapters and provided useful feedback. I am indebted to all of the above for their kind assistance.

I would also like to thank the staff at Prentice Hall, particularly Russ Hall, Maureen Diana, and Kerry Riordan for their support.

— Behzad Razavi
July 1997

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I have been fortunate to benefit from the support of numerous people during the writing, review, and production phases of this book. I would like to express my thanks here.

Even after several rounds of self-editing, it is possible that typos or subtle mistakes have eluded the author. Sometimes, an explanation that is clear to the author may not be so to the reader. And, occasionally, the author may have missed a point or a recent development. A detailed review of the book by others thus becomes necessary. The following individuals meticulously reviewed various chapters, discovered my mistakes, and made valuable suggestions:

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The book's production was proficiently managed by the staff at Prentice Hall, including Bernard Goodwin and Julie Nahil. I would like to thank both.

As with my other books, my wife, Angelina, typed the entire second edition in Latex and selflessly helped me in this three-and-a-half-year endeavor. I am grateful to her.

— *Behzad Razavi*

ABOUT THE AUTHOR

Behzad Razavi received the BSEE degree from Sharif University of Technology in 1985 and MSEE and PhDEE degrees from Stanford University in 1988 and 1992, respectively. He was with AT&T Bell Laboratories and Hewlett-Packard Laboratories until 1996. Since 1996, he has been associate professor and, subsequently, professor of electrical engineering at University of California, Los Angeles. His current research includes wireless transceivers, frequency synthesizers, phase-locking and clock recovery for high-speed data communications, and data converters.

Professor Razavi was an adjunct professor at Princeton University from 1992 to 1994, and at Stanford University in 1995. He served on the Technical Program Committees of the International Solid-State Circuits Conference (ISSCC) from 1993 to 2002 and VLSI Circuits Symposium from 1998 to 2002. He has also served as guest editor and associate editor of the IEEE Journal of Solid-State Circuits, IEEE Transactions on Circuits and Systems, and International Journal of High Speed Electronics.

Professor Razavi received the Beatrice Winner Award for Editorial Excellence at the 1994 ISSCC; the best paper award at the 1994 European Solid-State Circuits Conference; the best panel award at the 1995 and 1997 ISSCC; the TRW Innovative Teaching Award in 1997; the best paper award at the IEEE Custom Integrated Circuits Conference (CICC) in 1998; and McGraw-Hill First Edition of the Year Award in 2001. He was the co-recipient of both the Jack Kilby Outstanding Student Paper Award and the Beatrice Winner Award for Editorial Excellence at the 2001 ISSCC. He received the Lockheed Martin Excellence in Teaching Award in 2006; the UCLA Faculty Senate Teaching Award in 2007; and the CICC Best Invited Paper Award in 2009. He was also recognized as one of the top ten authors in the fifty-year history of ISSCC. He received the IEEE Donald Pederson Award in Solid-State Circuits in 2012.

Professor Razavi is an IEEE Distinguished Lecturer, a Fellow of IEEE, and the author of Principles of Data Conversion System Design, RF Microelectronics, First Edition (translated to Chinese, Japanese, and Korean), Design of Analog CMOS Integrated Circuits (translated to Chinese, Japanese, and Korean), Design of Integrated Circuits for Optical Communications, and Fundamentals of Microelectronics (translated to Korean and Portuguese), and the editor of Monolithic Phase-Locked Loops and Clock Recovery Circuits and Phase-Locking in High-Performance Systems.

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