国外大学优秀教材——微电子类系列（影印版）

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# RF MICROELECTRONICS

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# 出版前言

微电子技术是信息科学技术的核心技术之一，微电子产业是当代高新技术产业群的核心和维护国家主权、保障国家安全的战略性产业。我国在《信息产业“十五”计划纲要》中明确提出：坚持自主发展，增强创新能力和核心竞争力，掌握以集成电路和软件技术为重点的信息产业的核心技术，提高具有自主知识产权产品的比重。发展集成电路技术的关键之一是培养具有国际竞争力的专业人才。

微电子技术发展迅速，内容更新快，而我国微电子专业图书数量少，且内容和体系不能反映科技发展的水平，不能满足培养人才的需求，为此，我们系统挑选了一批国外经典教材和前沿著作，组织分批出版。图书选择的几个基本原则是：在本领域内广泛采用，有很大影响力；内容反映科技的最新发展，所述内容是本领域的研究热点；编写和体系与国内现有图书差别较大，能对我国微电子教育改革有所启示。本套丛书还侧重于微电子技术的实用性，选取了一批集成电路设计方面的工程技术用书，使读者能方便地应用于实践。本套丛书不仅能作为相关课程的教科书和教学参考书，也可作为工程技术人员的自学读物。

我们真诚地希望，这套丛书能给国内高校师生、工程技术人员以及科研人员的学习和工作有所帮助，对推动我国集成电路的发展有所促进。也衷心期望着广大读者对我们一如既往的关怀和支持，鼓励我们出版更多、更好的图书。

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# RF Microelectronics

## 影 印 版 序

近年来，由于无线通信的广泛需求和迅速发展，射频集成电路已成为 IC 集成电路设计中被普遍关注和大量研究的课题。尤其是因为硅 CMOS 工艺的长足进步，器件的截止频率已能满足多数现代无线通信应用要求。在实现诸如无线局域网（WLAN）射频前端收发器的设计中，其噪声性能也能符合要求；因此了解和掌握射频集成电路的工作原理与分析方法，对正确有效地设计射频、数字模拟混合信号集成电路是至关重要的。

Behzad Razavi 所著的 RF Microelectronics 一书就是针对上述需要的。它既可供高年级大学生或研究生作教科书用，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。相对其他 RF CMOS 电路的书籍而言，本书的特点是系统级的介绍较为详细，即它将无线通信电路系统的描述、器件特性及单元电路分析融合在一起，使读者有一个完整的概念。

本书第 1 和第 2 章首先介绍了在射频电子学经常遇到的概念和术语，并给出了评价射频电路性能的主要指标，如表征非线性度的 1-dB 增益压缩点和三阶交调点、灵敏度和动态范围等。其中对随机信号和噪声的描述很有特色，例如定义随机过程为一组时间的函数或多次测量的集合，这对理解随机信号的本质很有帮助。

在通信系统中，模拟和数字信号的调制、解调是必须的过程。本书第 3 章先用简洁的数学公式定义和描述了模拟信号的调幅、调相和调频调制方法，然后自然地扩展到数字信号调制的幅移、相移和频移键控调制。本书数字信号调制机理的讨论十分明了，是一个对数字信号系统不甚熟悉的读者很好的入门介绍。另外，在书中还对各种调制方法的功率效率进行了讨论。

本书第 4 章专门介绍 3 种在无线通信系统中通用的多路存取技术：FDMA，TDMA 和 CDMA，及几种常用的无线通信标准，如 GSM 和 Qualcomm 公司的 CDMA，这些对了解系统的工作方式很有帮助。

第 5 章是本书的重点，讨论了无线前端收发器的结构和集成电路的实现。它在介绍单元电路之前，先比较了各种接收器和发送器的结构，包括外差和零差式；然后给出了几种常见的无线收发器的设计实例。这些设计都已在产品中实现并被用于无线系统中，其中有 GSM 和 DECT 收发器的电路框图。这些高层次的讨论对理解后续的构成收发器的单元电路设计和工作原理打下了基础。

本书的第 6 章至第 9 章详细讨论了低噪声放大器和混频器、振荡器、频率综合器和功放器电路原理及分析方法。电路的实现以 MOS 器件为主，但也有用双极型晶体管作实例的。电路的工作原理讨论较为简要，但对各个电路单元要达到的技术指标和评价标准给出了不少

实际应用系统的具体数据，这对于读者建立相关电路设计的定量概念颇有益处。

本书的作者是美国 UCLA（加州大学洛杉矶分校）的教授，他曾在 HP 实验室工作过，有丰富的模拟电路设计经验。近年来更在射频 CMOS 的电路理论和设计研究方面大有建树，并成功地创办了用硅 CMOS 工艺实现的 WLAN 芯片设计公司。他写的另一本有关 CMOS 模拟集成电路的书 Design of Analog CMOS Integrated Circuits，作为电路教学的教科书，为美国多所大学采用。

如上所述，本书在讨论 RF CMOS 电路的工作原理和分析上略为简明。读者如果想了解更多的电路分析知识和方法，来作为学习 RF 系统级设计、分析的补充，则可参考 Thomas H. Lee 的 The Design of CMOS Radio-Frequency Integrated Circuits。

余志平于清华大学

2003 年 10 月

# Preface

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 Reardon for their support.

Behzad Razavi
July 1997

# Contents

# 1

# INTRODUCTION TO RF AND WIRELESS TECHNOLOGY

"This phone uses GFSK modulation in DECT-TDMA/TDD with zero-IF I/Q detection," said the engineer. "How can we modify it to work with DCS1800 as well?" asked the manager. "We would need to add a duplexer, at least one more LO with SSB mixing, and probably two SAW filters," replied the engineer . . .

Telephones have gotten much more complicated than they used to be. So have RF circuits. The nonspecialist who uses a cellular phone (cellphone) to call home probably does not know that hundreds of scientists and engineers have worked for almost a century to make wireless technology affordable. Nor does he know that there is more computing power in the phone than in some of the early personal computers.

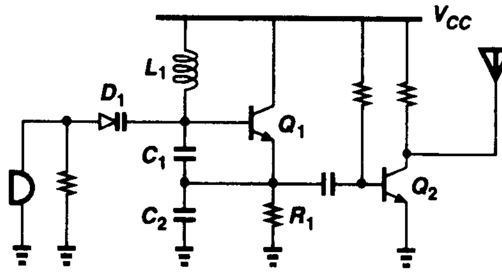
Wireless technology came to existence when, in 1901, Guglielmo Marconi successfully transmitted radio signals across the Atlantic Ocean. The consequences and prospects of this demonstration were simply overwhelming; the possibility of replacing telegraph and telephone communications with wave transmission through the "ether" portrayed an exciting future. However, while two-way wireless communication did materialize in military applications, wireless transmission in daily life remained limited to one-way radio and television broadcasting by large, expensive stations. Ordinary two-way phone conversations would still go over wires for many decades.

The invention of the transistor, the development of Shannon's information theory, and the conception of the cellular system—all at Bell Laboratories—paved the way for affordable mobile communications, as originally implemented in car phones and eventually realized in portable cellular phones.

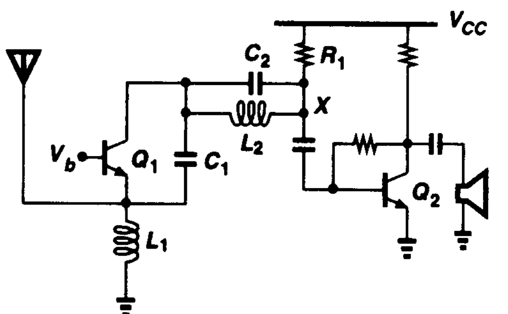
But why the sudden surge in wireless electronics? Market surveys show that in the United States more than 28,000 people join the cellular phone system *every day*, motivating competitive manufacturers to provide phone sets with increasingly higher performance and lower cost. In fact, the present goal is to reduce both the power consumption and price of cellphones by 30% every year—although it is not clear for how long this rate can be sustained. A more glorious prospect, however, lies in the power of two-way wireless communication when it is introduced in other facets of our lives: home phones, computers, facsimile, and television. While an immediate objective of the wireless industry is to combine cordless and cellular phones so as to allow seamless communications virtually everywhere, the long-term plan is to produce an "omnipotent" wireless terminal that can handle voice, data, and video as well as provide computing power. Other luxury items such as the global positioning system (GPS) are also likely to become available through this terminal sometime in the future. Personal communication services (PCS) are almost here.

## 1.1 COMPLEXITY COMPARISON

To gain an early perspective on modern RF design, first consider the system depicted in Fig. 1.1, a simple frequency modulation (FM) transceiver. In Fig. 1.1(a), $Q_1$ operates as both an oscillator and a frequency modulator; that




(a)




(b)

**Figure 1.1** (a) FM transmitter, (b) FM receiver.

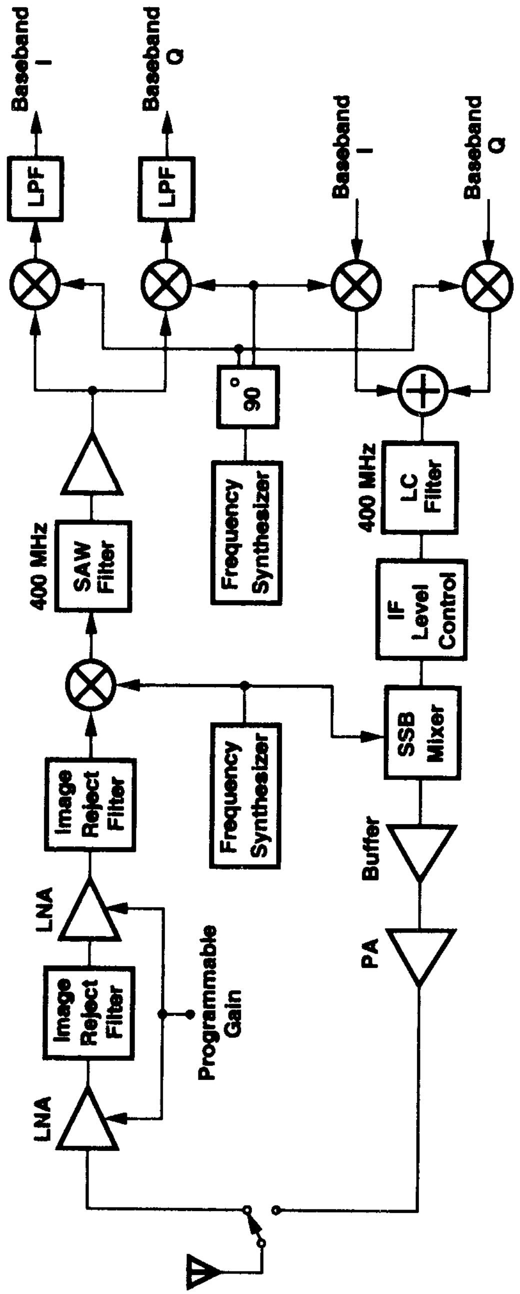



**Figure 1.2** RF section of a cellphone [1]

is, the audio signal produced by the microphone varies the bias voltage across the varactor diode $D_1$, thereby modulating the frequency of oscillation. In the receive path, $Q_1$ serves as both an oscillator and a demodulator, generating the audio signal at node $X$. The result is then amplified and applied to the speaker.

Now consider the circuit of Fig. 1.2, the RF section of a cellphone [1]. This circuit is orders of magnitude more complex than the FM circuits of Fig. 1.1, and we will postpone its analysis until Chapter 5. Why have RF designers gone from the circuit of Fig. 1.1 to that of Fig. 1.2? What is the thought process behind this evolution? Is all of this complexity really necessary? These questions will be answered in Chapters 2 through 5 as we develop our understanding of RF communication systems and architecture and circuit design issues.

## 1.2 DESIGN BOTTLENECK

Today's pocket phones contain more than one million transistors, with only a small fraction operating in the RF range and the rest performing low-frequency "baseband" analog and digital signal processing (Fig. 1.3). In other words, the baseband section is, in terms of the number of devices, yet several orders of magnitude more complex than the circuit of Fig. 1.2. The definition of RF and baseband will become clear later, but here we note that the RF section is still the design bottleneck of the entire system. This is so for three reasons.

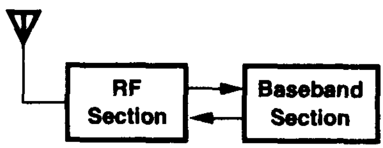



**Figure 1.3** RF and baseband processing in a transceiver.

**Multidisciplinary Field** In contrast to other types of analog and mixed-signal circuits, RF systems demand a good understanding of many areas that are not directly related to integrated circuits (ICs). Shown in Fig. 1.4, most of these areas have been studied extensively for more than half a century, making it difficult for an IC designer to acquire the necessary knowledge in a reasonable amount of time. Even at present, the literature pertaining to RF design appears in more than 30 journals and conferences.

Owing to this issue, traditional wireless system design has been carried out at somewhat disjointed levels of abstraction: communication theorists create the modulation scheme and baseband signal processing; RF system experts plan the transceiver architecture; IC designers develop each of the building blocks; and manufacturers "glue" the ICs and other external components together. In fact, architectures are often planned according to the available off-the-shelf components, and ICs are designed to serve as many architectures as possible, leading to a great deal of redundancy at both system and circuit levels.