国外电子与通信教材系列

英文版

PEARSON

射频电路设计

——理论与应用

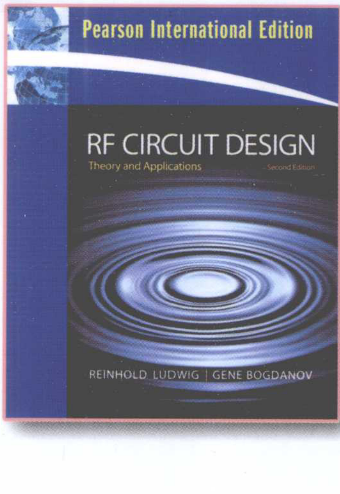
（第二版）

RF Circuit Design

Theory and Applications

Second Edition

[美] Reinhold Ludwig
Gene Bogdanov 著



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内容简介

本书从低频电路理论到射频、微波电路理论的演化过程出发，讨论以低频电路理论为基础并结合高频电压、电流的波动特征来分析和设计射频、微波系统的方法——微波等效电路法，使不具备电磁场理论和微波技术背景的读者也能了解和掌握射频、微波电路的基本设计原则和方法。全书共10章，涵盖传输线、匹配器、滤波器、混频器、放大器和振荡器等主要射频微波系统单元的理论分析和设计问题及电路分析工具（圆图、网络参量和信号流图）。书中例题非常有实用价值。全书大多数电路都经过ADS仿真，并提供标准MATLAB计算程序。

本书适合作为通信、电子类学科学生的双语课程教材，也适合工程技术人员参考。

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序

2001年7月间，电子工业出版社的领导同志邀请各高校十几位通信领域方面的老师，商量引进国外教材问题。与会同志对出版社提出的计划十分赞同，大家认为，这对我国通信事业、特别是对高等院校通信学科的教学工作会很有好处。

教材建设是高校教学建设的主要内容之一。编写、出版一本好的教材，意味着开设了一门好的课程，甚至可能预示着一个崭新学科的诞生。20世纪40年代MIT林肯实验室出版的一套28本雷达丛书，对近代电子学科、特别是对雷达技术的推动作用，就是一个很好的例子。

我国领导部门对教材建设一直非常重视。20世纪80年代，在原教委教材编审委员会的领导下，汇集了高等院校几百位富有教学经验的专家，编写、出版了一大批教材；很多院校还根据学校的特点和需要，陆续编写了大量的讲义和参考书。这些教材对高校的教学工作发挥了极好的作用。近年来，随着教学改革不断深入和科学技术的飞速进步，有的教材内容已比较陈旧、落后，难以适应教学的要求，特别是在电子学和通信技术发展神速、可以讲是日新月异的今天，如何适应这种情况，更是一个必须认真考虑的问题。解决这个问题，除了依靠高校的老师和专家撰写新的符合要求的教科书外，引进和出版一些国外优秀电子与通信教材，尤其是有选择地引进一批英文原版教材，是会有好处的。

一年多来，电子工业出版社为此做了很多工作。他们成立了一个“国外电子与通信教材系列”项目组，选派了富有经验的业务骨干负责有关工作，收集了230余种通信教材和参考书的详细资料，调来了100余种原版教材样书，依靠由20余位专家组成的出版委员会，从中精选了40多种，内容丰富，覆盖了电路理论与应用、信号与系统、数字信号处理、微电子、通信系统、电磁场与微波等方面，既可作为通信专业本科生和研究生的教学用书，也可作为有关专业人员的参考材料。此外，这批教材，有的翻译为中文，还有部分教材直接影印出版，以供教师用英语直接授课。希望这些教材的引进和出版对高校通信教学和教材改革能起一定作用。

在这里，我还要感谢参加工作的各位教授、专家、老师与参加翻译、编辑和出版的同志们。各位专家认真负责、严谨细致、不辞辛劳、不怕琐碎和精益求精的态度，充分体现了中国教育工作者和出版工作者的良好美德。

随着我国经济建设的发展和科学技术的不断进步，对高校教学工作会不断提出新的要求和希望。我想，无论如何，要做好引进国外教材的工作，一定要联系我国的实际。教材和学术专著不同，既要注意科学性、学术性，也要重视可读性，要深入浅出，便于读者自学；引进的教材要适应高校教学改革的需要，针对目前一些教材内容较为陈旧的问题，有目的地引进一些先进的和正在发展中的交叉学科的参考书；要与国内出版的教材相配套，安排好出版英文原版教材和翻译教材的比例。我们努力使这套教材能尽量满足上述要求，希望它们能放在学生们的课桌上，发挥一定的作用。

最后，预祝“国外电子与通信教材系列”项目取得成功，为我国电子与通信教学和通信产业的发展培土施肥。也恳切希望读者能对这些书籍的不足之处、特别是翻译中存在的问题，提出意见和建议，以便再版时更正。

吴佑寿

中国工程院院士、清华大学教授

“国外电子与通信教材系列”出版委员会主任

出 版 说 明

进入21世纪以来，我国信息产业在生产和科研方面都大大加快了发展速度，并已成为国民经济发展的支柱产业之一。但是，与世界上其他信息产业发达的国家相比，我国在技术开发、教育培训等方面都还存在着较大的差距。特别是在加入WTO后的今天，我国信息产业面临着国外竞争对手的严峻挑战。

作为我国信息产业的专业科技出版社，我们始终关注着全球电子信息技术的发展方向，始终把引进国外优秀电子与通信信息技术教材和专业书籍放在我们工作的重要位置上。在2000年至2001年间，我社先后从世界著名出版公司引进出版了40余种教材，形成了一套“国外计算机科学教材系列”，在全国高校以及科研部门中受到了欢迎和好评，得到了计算机领域的广大教师与科研工作者的充分肯定。

引进和出版一些国外优秀电子与通信教材，尤其是有选择地引进一批英文原版教材，将有助于我国信息产业培养具有国际竞争能力的技术人才，也将有助于我国国内在电子与通信教学工作中掌握和跟踪国际发展水平。根据国内信息产业的现状、教育部《关于“十五”期间普通高等教育教材建设与改革的意见》的指示精神以及高等院校老师们反映的各种意见，我们决定引进“国外电子与通信教材系列”，并随后开展了大量准备工作。此次引进的国外电子与通信教材均来自国际著名出版商，其中影印教材约占一半。教材内容涉及的学科方向包括电路理论与应用、信号与系统、数字信号处理、微电子、通信系统、电磁场与微波等，其中既有本科专业课程教材，也有研究生课程教材，以适应不同院系、不同专业、不同层次的师生对教材的需求，广大师生可自由选择和自由组合使用。我们还将与国外出版商一起，陆续推出一些教材的教学支持资料，为授课教师提供帮助。

此外，“国外电子与通信教材系列”的引进和出版工作得到了教育部高等教育司的大力支持和帮助，其中的部分引进教材已通过“教育部高等学校电子信息科学与工程类专业教学指导委员会”的审核，并得到教育部高等教育司的批准，纳入了“教育部高等教育司推荐——国外优秀信息科学与技术系列教学用书”。

为做好该系列教材的翻译工作，我们聘请了清华大学、北京大学、北京邮电大学、南京邮电大学、东南大学、西安交通大学、天津大学、西安电子科技大学、电子科技大学、中山大学、哈尔滨工业大学、西南交通大学等著名高校的教授和骨干教师参与教材的翻译和审校工作。许多教授在国内电子与通信专业领域享有较高的声望，具有丰富的教学经验，他们的渊博学识从根本上保证了教材的翻译质量和专业学术方面的严格与准确。我们在此对他们的辛勤工作与贡献表示衷心的感谢。此外，对于编辑的选择，我们达到了专业对口；对于从英文原书中发现的错误，我们通过与作者联络、从网上下载勘误表等方式，逐一进行了修订；同时，我们对审校、排版、印制质量进行了严格把关。

今后，我们将进一步加强同各高校教师的密切关系，努力引进更多的国外优秀教材和教学参考书，为我国电子与通信教材达到世界先进水平而努力。由于我们对国内外电子与通信教育的发展仍存在一些认识上的不足，在选题、翻译、出版等方面的工作中还有许多需要改进的地方，恳请广大师生和读者提出批评及建议。

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Preface

High-frequency circuit design continues to enjoy significant industrial attention, triggered by a host of radio-frequency (RF) and microwave (MW) products. Improved semiconductor devices, new board materials, and advanced fabrication technologies have made possible a proliferation of high-speed digital and analog systems that profoundly influence wireless communication, global positioning, radar, remote sensing, and related electrical and computer engineering disciplines. As a consequence, this interest has translated into market demands for trained engineers and professionals with knowledge of high-frequency circuit design principles. Since the publication of the first edition of this textbook in January, 2000, the need for well-educated RF professionals has surged, making a text that teaches the fundamentals of high-frequency circuits even timelier.

The objective of this second edition remains the same: to present the fundamental RF design aspects and the underlying distributed circuit theory with minimal emphasis on electromagnetics. We have written this book in a manner that requires no EM background beyond a first year undergraduate physics course in fields and waves. Students and practicing engineers equipped with rudimentary exposure to circuit theory and/or microelectronics can read this book and grasp the entire spectrum of high-frequency circuit principles involving passive and active discrete devices, transmission lines, filters, amplifiers, mixers, oscillators and their design procedures. Lengthy mathematical derivations are either relegated to the appendices or placed in examples, thereby separating dry theoretical details from the main text. Although de-emphasizing theory creates a certain loss in precision, it promotes readability and focus on the underlying circuit concepts.

What has changed from the first edition? Besides our obvious attempt to eliminate typos and inconsistencies, the second edition was improved in several important ways. First, we have added *Practically Speaking* sections at the end of each chapter. In these sections, key design concepts and measurement procedures are discussed in detail. Topics such as the construction of an attenuator, a microstrip filter, or the simulation of a low noise RF amplifier with bias and matching networks, are presented similarly to a lab component that accompanies the lectures. Equipped with the right instrumentation and software simulator, the reader can easily replicate the circuits. Second, topics of interest, helpful definitions, and noteworthy observations are placed on the *margins* and offset from the main text. In addition to highlighting their importance, this approach allows us to emphasize and better explain items that do not directly fit into the flow of the main text. For example, the coverage of a Phase Lock Loop (PLL) system would exceed the scope of this book. However, a brief explanation of a PLL provides context and extra motivation for the underlying high-frequency circuits. It furthermore inspires the readers to explore these topics on their own. Third, more emphasis is placed on nonlinear design principles, specifically in regard to oscillators and their associated resonator circuits.

Accepting the challenge to deliver a high degree of linear and nonlinear design experience, we have included a number of examples that analyze in considerable depth, often extending over several pages, the philosophy and the intricacies of various modeling approaches. While linear scattering parameter simulations are adequate under certain conditions, nonlinear simulations, for instance the harmonic balance analysis, are required for more sophisticated designs. Oscillator and mixer, as well as amplifier designs can greatly benefit from a nonlinear circuit simulation. Naturally, the use of appropriate simulation tools creates problems in terms of their capabilities, accuracies, speeds, and not least costs. The availability of circuit simulators and RF software tools has steadily increased over the years. Indeed, the authors are routinely contacted about simulators that offer "exceptional" performances under particular constraints. It is not our goal to render an assessment or endorsement of a specific simulator (the authors have no commercial, nor professional ties with any vendor). In general, professional high-frequency simulators are expensive and require familiarity to use them effectively. Several years ago, the ECE department at WPI decided after an extensive review to adopt Advanced Design Systems (ADS) of Agilent Technologies as the default high-frequency circuit simulator for its undergraduate and graduate electrical and computer engineering students. For this reason, and because of its wide-spread industrial use, we rely on ADS simulations for most of our circuits. However, for readers without access to commercial simulators, we created a number of standard MATLAB M-files that can be downloaded from our website listed in Appendix G. Because MATLAB is a popular and relatively inexpensive mathematical tool, many examples discussed in this book can be executed and the results graphically displayed in a matter of seconds. Specifically, the various Smith Chart computations of impedance transformations should appeal to the reader.

Since our goal focuses on circuits, the textbook purposely omitted high-speed digital circuits as well as coding and modulation aspects. Although important, these topics would require too many additional pages and would move the book too far away from its original intent of providing a fundamental, one- or two-semester introduction to RF circuit design. In the ECE department at WPI, this does not constitute a disadvantage, as most of these topics are taught in specialized communication systems engineering courses.

The organization of this text is as follows: **Chapter 1** presents a general explanation of why basic circuit theory needs to be modified as the operating frequency is increased to a level where the wavelength becomes comparable with circuit dimensions. **Chapter 2** then develops the fundamental concepts of distributed circuit theory. **Chapter 3** introduces the Smith Chart as a generic tool for dealing with the periodic impedance behavior on the basis of the reflection coefficient. **Chapter 4** presents networks and flow-graph representations, and how the terminal conditions can be described with so-called scattering parameters. The network models and their scattering parameter descriptions are utilized in **Chapter 5** to develop passive RF filter configurations. To address active devices, **Chapter 6** provides a review of key semiconductor fundamentals, followed by their circuit models representation in **Chapter 7**. The impedance matching and biasing of bipolar and field effect transistors is taken up in **Chapter 8**. **Chapter 9** focuses on a number of key high-frequency amplifier configurations and their design intricacies, ranging from low noise to high power applications. Finally, **Chapter 10** introduces the reader to nonlinear systems and their design, covering oscillator and mixer circuits.

This book is used in the ECE department at WPI as a required text for its standard 7-week (5 lecture hours per week) course in RF circuit design (ECE 3113, *Introduction to RF Circuit Design*). The course has primarily attracted an audience of 3rd and 4th year undergraduate students with a background in microelectronics. The course does not include a separate laboratory, although a total of six practical circuits (all part of the Practically Speaking sections) are presented to the students who are then instructed to conduct their own measurements with a network analyzer. In addition, ADS simulations are incorporated as part of the regular lectures. Each chapter is self-contained, with the goal of providing wide flexibility in organizing the course material. At WPI, the content of approximately one three semester hour course is compressed into a 7-week period (consisting of a total of 28-29 lectures). The topics covered in ECE 3113 are shown in the table below.

EE 3113, Introduction to RF Circuit Design

Chapter 1, Introduction	Sections 1.1-1.6
Chapter 2, Transmission Line Analysis	Sections 2.1-2.12
Chapter 3, Smith Chart	Sections 3.1-3.5
Chapter 4, Single- and Multi-Port Networks	Sections 4.1-4.5
Chapter 7, Active RF Component Modeling	Sections 7.1-7.2
Chapter 8, Matching and Biasing Networks	Sections 8.1-8.4
Chapter 9, RF Transistor Amplifier Designs	Sections 9.1-9.4

The remaining material is targeted for a second (7-week) term covering more advanced topics such as microwave filters, equivalent circuit models, oscillators and mixers. An organizational plan is provided below.

Advanced Principles of RF Circuit Design

Chapter 5, A Brief Overview of RF Filter Design	Sections 5.1-5.5
Chapter 6, Active RF Components	Sections 6.1-6.6
Chapter 7, Active RF Component Modeling	Sections 7.3-7.5
Chapter 9, RF Transistor Amplifier Designs	Sections 9.5-9.8
Chapter 10, Oscillators and Mixers	Sections 10.1-10.4

Obviously, the entire course organization remains subject to change depending on total classroom time, student background, and interface requirements with related courses. At the writing of this 2nd edition, a new graduate course is being designed that combines the advanced RF circuit topics of Chapters 5-10 with a classical graduate-level electromagnetics text.

Pearson offers many different products around the world to facilitate learning. In countries outside the United States, some products and services related to this textbook may not be available due to copyright and/or permissions restrictions. If you have questions, you can contact your local office by visiting www.pearsonhighered.com/international or you can contact your local Pearson representative.

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The staff of Prentice Hall, specifically Alice Dworkin, Rose Kernan, and G. Muthukumar, Senior Project Manager, Laserwords Private Limited, Chennai, India, are thanked for their support in making this book project a reality.

Contents

1

Introduction

For the past several years, analog and digital design engineers have continually been developing and refining circuits for increasingly higher operating frequencies. Analog circuits for wireless communication in the low to high gigahertz (GHz) range and concomitantly the rapid improvement of clock speeds of microprocessors, memory chips, and peripheral units in high-performance mainframes, workstations, and personal computers exemplify this trend. Global positioning systems require carrier frequencies in the range of 1227.60 and 1575.42 MHz, wireless local area networks and HiperLAN operate at 2.4 GHz, and optical communication channels can transport data of up to 40 gigabits per second (Gbps). The low-noise amplifier in a personal communication system (PCS) may operate at 1.9 GHz and fit on a circuit board smaller in size than a dime. Satellite broadcasting in the C-band involves 4 GHz uplink and 6 GHz downlink systems. In general, due to the rapid expansion of wireless communication, more compact amplifier, filter, oscillator, and mixer circuits are being designed and placed in service at frequencies generally above 1 GHz. There is little doubt that this trend will continue unabated, resulting not only in engineering systems with unique capabilities, but also special design challenges not encountered in conventional low-frequency systems.

This chapter reviews the implications as one migrates from low- to high-frequency circuit operation. It motivates and provides the physical rationales that have resulted in the need for new engineering approaches to design and optimize these circuits. The example of a mobile phone circuit, components of which will be analyzed in more detail in later chapters, serves as a vehicle to outline the goals and objectives of this textbook, and its organization.

The chapter begins with a brief historical discussion explaining the transition from direct current (DC) to high-frequency modes of operation. As the frequency increases and the associated wavelengths of the electromagnetic waves becomes comparable to the dimensions of the discrete circuit components such as resistors, capacitors, and inductors, these components start to deviate in their electric responses from the ideal frequency behavior. It is the purpose of this chapter to provide the reader with an appreciation and understanding of high-frequency passive component characteristics. In particular, due to the availability of sophisticated measurement equipment, the design engineer must know exactly why and how the high-frequency behavior of his or her circuit differs from the low-frequency realization. Without this knowledge, it will be impossible to develop and understand the special requirements of high-performance systems.

LUMPED THEORY
Circuit elements are assumed to have zero spatial extent (point form).

DISTRIBUTED THEORY
Circuit elements are modeled as having finite size relative to the wavelength.