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

CMOS射频集成电路设计

The Design of CMOS Radio-Frequency Integrated Circuits

英文原版

[美] Thomas H. Lee 著

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内容简介

本书详细讲述了CMOS技术在吉赫兹射频电路中的应用。本书首先从电子学基本理论和IC技术的发展史入手，简要描述了无源RLC网络、无源IC器件和晶体管模型，然后重点讲述了特高频电路和宽带放大器的设计方法，如一些重要的近似方法和某些器件的模拟结果等。在射频电路的设计中，主要讲述了低噪声放大器、混频器、功率放大器、高频振荡器以及频率同步器的设计原理和方法。作者在书中列举了350多个电路实例，并附有大量习题。

本书可作为高等院校电子和通信等专业高年级本科生或研究生的教材，也可供有关工程技术人员作为工程设计的参考用书。

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前　言

20世纪末，以计算机和通信技术为代表的信息科学和技术，对世界的经济、军事、科技、教育、文化、卫生等方面的发展产生了深刻的影响，由此而兴起的信息产业已经成为世界经济发展的支柱。进入21世纪，各国为了加快本国的信息产业，加大了资金投入和政策扶持。

为了加快我国信息产业的进程，在我国《国民经济和社会发展第十个五年计划纲要》中，明确提出“以信息化带动工业化，发挥后发优势，实现社会生产力的跨越式发展。”信息产业的国际竞争将日趋激烈。在我国加入WTO后，我国信息产业将面临国外竞争对手的严峻挑战。竞争成败最终将取决于信息科学和技术人才的多少与优劣。

在20世纪末，我国信息产业虽然得到迅猛发展，但与国际先进国家相比，差距还很大。为了赶上并超过国际先进水平，我国必须加快信息技术人才的培养，特别要培养一大批具有国际竞争能力的高水平的信息技术人才，促进我国信息产业和国家信息化水平的全面提高。为此，教育部高等教育司根据教育部吕福源副部长的意见，在长期重视推动高等学校信息科学和技术的教学的基础上，将实施超前发展战略，采取一些重要举措，加快推动高等学校的信息科学和技术等相关专业的教学工作。在大力宣传、推荐我国专家编著的面向21世纪和“九五”重点的信息科学和技术课程教材的基础上，在有条件的高等学校的某些信息科学和技术课程中推动使用国外优秀教材的影印版进行英语或双语教学，以缩短我国在计算机教学上与国际先进水平的差距，同时也有助于强化我国大学生的英语水平。

为了达到上述目的，在分析一些出版社已影印相关教材，一些学校已试用影印教材进行教学的基础上，教育部高等教育司组织并委托高等教育出版社开展国外优秀信息科学和技术优秀教材及其教学辅助材料的引进研究与影印出版的试点工作。为推动用影印版教材进行教学创造条件。

本次引进的系列教材的影印出版工作，是在对我国高校的信息科学和技术专业的课程与美国高校的进行对比分析基础上展开的；所影印出版的教材均由我国主要高校的信息科学和技术专家组成的专家组，从国外近两年出版的大量最新教材中精心筛选评审通过的内容新、有影响的优秀教材；影印教材的定价原则上应与我国大学教材价格相当。

教育部高等教育司将此影印系列教材推荐给高等学校，希望有关教师选用，使用后有什么意见和建议请及时反馈。也希望有条件的出版社，根据影印教材的要求，积极参加此项工作，以便引进更多、更新、更好的外国教材和教学辅助材料。

同时，感谢国外有关出版公司对此项引进工作的配合，欢迎更多的国外公司关心并参与此项工作。

教育部高等教育司

二〇〇一年四月

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

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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、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

The field of radio frequency (RF) circuit design is currently enjoying a renaissance,driven in particular by the recent, and largely unanticipated, explosive growth in wireless telecommunications. Because this resurgence of interest in RF caught industry and academia by surprise, there has been a mad scramble to educate a new generation of RF engineers. However, in trying to synthesize the two traditions of " conventional" RF and lower-frequency IC design, one encounters a problem: " Traditional" RF engineers and analog IC designers often find communication with each other difficult because of their diverse backgrounds and the differences in the media in which they realize their circuits. Radio-frequency IC design, particularly in CMOS, is a different activity altogether from discrete RF design. This book is intended as both a link to the past and a pointer to the future.

The contents of this book derive from a set of notes used to teach a one-term advanced graduate course on RF IC design at Stanford University. The course was a follow-up to a low-frequency analog IC design class, and this book therefore assumes that the reader is intimately familiar with that subject, described in standard texts such as *Analysis and Design of Analog Integrated Circuits* by P. R. Gray and R. G. Meyer (Wiley, 1993). Some review material is provided, so that the practicing engineer with a few neurons surviving from undergraduate education will be able to dive in without too much disorientation.

The amount of material here is significantly beyond what students can comfortably assimilate in one quarter or semester, and instructors are invited to pick and choose topics to suit their tastes, the length of the academic term, and the background level of the students. In the chapter descriptions that follow are included some hints about what chapters may be comfortably omitted or deferred.

Chapter 1 presents an erratic history of radio. This material is presented largely for cultural reasons. The author recognizes that not everyone finds history interesting, so the impatient reader is invited to skip ahead to the more technical chapters.

Chapter 2 surveys the passive components normally available in standard CMOS processes. There is a focus on inductors because of their prominent role in RF circuits, and also because material on this subject is scattered in the current literature(although, happily, this situation is rapidly changing).

Chapter 3 provides a quick review of MOS device physics and modeling. Since deep submicron technology is now commonplace, there is a focus on approximate analytical models that account for short-channel effects. This chapter is necessarily brief, and is intended only as a supplement to more detailed treatments available elsewhere.

Chapter 4 examines the properties of lumped, passive *RLC* networks. For advanced students, this chapter may be a review and may be skipped if desired. In the author's experience, most undergraduate curricula essentially abandoned the teaching of inductors long ago, so this chapter spends a fair amount of time examining the issues of resonance, Q, and impedance matching.

Chapter 5 extends into the distributed realm many of the concepts introduced in the context of lumped

networks. Transmission lines are introduced in a somewhat unusual way, with the treatment avoiding altogether the derivation of the telegrapher's equation with its attendant wave solutions. The characteristic impedance and propagation constant of a uniform line are derived entirely from simple extensions of lumped ideas. Although distributed networks play but a minor role in the current generation of silicon IC technology, that state of affairs will be temporary, given that device speeds are doubling about every three years.

Chapter 6 provides an important bridge between the traditional " microwave plumber's" mind-set and the IC designer's world view by presenting a simple derivation of the Smith chart, explaining what S-parameters are and why they are useful. Even though the typical IC engineer will almost certainly not design circuits using these tools, much instrumentation presents data in Smith-chart and S-parameter form, so modern engineers still need to be conversant with them.

Chapter 7 presents numerous simple methods for estimating the bandwidth of high-order systems from a series of first-order calculations or from simple measurements. The former set of techniques, called the method of open-circuit (or zero-value) time constants, allows one to identify bandwidth-limiting parts of a circuit while providing a typically conservative bandwidth estimate. Relationships among bandwidth, delay, and risetime allow us to identify important degrees of freedom in trading off various parameters. In particular, gain and bandwidth are shown not to trade off with one another in any fundamental way, contrary to the beliefs of many (if not most) engineers. Rather, gain and *delay* are shown to be more tightly coupled, opening significant loopholes that point the way to amplifier architectures which effect that tradeoff and leave bandwidth largely untouched.

Chapter 8 takes a detailed look at the problem of designing extremely high-frequency amplifiers, both broad- and narrowband, with many " tricks" evolving from a purposeful violation of the assumptions underlying the method of open-circuit time constants.

Chapter 9 surveys a number of biasing methods. Although intended mainly as a review, the problems of implementing good references in standard CMOS are large enough to risk some repetition. In particular, the design of CMOS-compatible bandgap voltage references and constant-transconductance bias circuits are emphasized here, perhaps a little more so than in most standard analog texts.

Chapter 10 studies the all-important issue of noise. Simply obtaining sufficient gain over some acceptable bandwidth is frequently insufficient. In many wireless applications, the received signal amplitude is in the microvolt range. The need to amplify such minute signals as noiselessly as possible is self-evident, and this chapter provides the necessary foundation for identifying conditions for achieving the best possible noise performance from a given technology.

Chapter 11 follows up on the previous two or three chapters to identify low-noise amplifier (LNA) architectures and the specific conditions that lead to the best possible noise performance, given an explicit constraint on power consumption. This power-constrained approach differs considerably from standard discrete-oriented methods, and exploits the freedom enjoyed by IC designers to tailor device sizes to achieve a particular optimum. The important issue of dynamic range is also examined, and a simple analytical method for estimating a large-signal linearity limit is presented.

Chapter 12 introduces the first intentionally nonlinear element, and the heart of all modern transceivers: the mixer. After identifying key mixer performance parameters, numerous mixer topologies are examined. As with the LNA, the issue of dynamic range is kept in focus the entire time.

Chapter 13 presents numerous topologies for building RF power amplifiers. The serious and often unsatisfactory tradeoffs among gain, efficiency, linearity, and output power lead to a family of topologies, each with its particular domain of application. The chapter closes with an examination of load-pull experimental characterizations of real power amplifiers.

Chapter 14 provides a review of classical feedback concepts, mainly in preparation for the following chapter on phase-locked loops. Readers with a solid background in feedback may wish to skim it, or even skip it entirely.

Chapter 15 surveys a number of phase-locked loop circuits after presenting basic operating theory of both first- and second-order loops. Loop stability is examined in detail, and a simple criterion for assessing a PLL's sensitivity to power supply and substrate noise is offered.

Chapter 16 examines in detail the issue of oscillators and frequency synthesizers. Both relaxation and tuned oscillators are considered, with the latter category further subdivided into LC and crystal-controlled oscillators. Both fixed and controllable oscillators are presented. Prediction of oscillation amplitude, criteria for start-up, and device sizing are all studied.

Chapter 17 extends to oscillators the earlier work on noise. After elucidating some general criteria for optimizing the noise performance of oscillators, a powerful theory of phase noise based on a linear, time-varying model is presented. The model makes some surprisingly optimistic (and experimentally verified) predictions about what one may do to reduce the phase noise of oscillators built with such infamously noisy devices as MOSFETs.

Chapter 18 ties all the previous chapters together and surveys architectures of receivers and transmitters. Rules are derived for computing the intercept and noise figure of a cascade of subsystems. Traditional superheterodyne architectures are examined, along with low-IF image-reject and direct-conversion receivers. The relative merits and disadvantages of each of these is studied in detail.

Finally, Chapter 19 closes the book the way it began: with some history. A nonuniform sampling of classical (and distinctly non-CMOS) RF circuits takes a look at Armstrong's earliest inventions, the "All-American Five" vacuum tube table radio, the first transistor radio, and the first toy walkie-talkie. As with the first chapter, this one is presented purely for enjoyment, so those who do not find history lessons enjoyable or worthwhile are invited to close the book and revel in having made it through the whole thing.

A book of this length could not have been completed in the given time were it not for the generous and competent help of colleagues and students. My wonderful administrative assistant, Ann Guerra, magically created time by handling everything with her remarkable good cheer and efficiency. Also, the following Ph.D. students went far beyond the call of duty in proofreading the manuscript and suggesting or generating examples and many of the problem-set questions: Tamara Ahrens, Rafael Betancourt-Zamora, David Colleran, Ramin Farjad-Rad, Mar Hershenson, Joe Ingino, Adrian Ong, Hamid Rategh, Hirad Samavati, Brian Setterberg, Arvin Shahani, and Kevin Yu. Ali Hajimiri, Sunderarajan S. Mohan, and Derek Shaeffer merit special mention for their conspicuous contributions. Without their help, given in the eleventh hour, this book would still be awaiting completion.

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Despite the delight taken by students in finding mistakes in the professor's notes, some errors have managed to slip through the sieve, even after three years of filtering. Sadly, this suggests that more await discovery by you. I suppose that is what second editions are for.

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