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THE DESIGN OF CMOS RADIO-FREQUENCY INTEGRATED CIRCUITS

Second Edition

This is an expanded and thoroughly revised edition of Thomas H. Lee's acclaimed guide to the design of gigahertz RF integrated circuits.

In order to provide a bridge between system and circuit issues, there is a completely new chapter on the principles of wireless systems. The chapters on low-noise amplifiers, oscillators, and phase noise have been significantly expanded. The chapter on architectures now contains several examples of complete chip designs, including a GPS receiver and a wireless LAN transceiver, that bring together all the various theoretical and practical elements involved in producing a prototype chip. To complement the new material, every other section of the book has been revised and updated.

The book is packed with physical insights and design tips, and it includes a historical overview that sets the whole field in context. It contains hundreds of circuit diagrams and many homework problems. This is an ideal textbook for students taking courses on RF design and a valuable reference for practicing engineers.

Thomas H. Lee received his Sc.D. from the Massachusetts Institute of Technology and is an Associate Professor of Electrical Engineering at Stanford University. He has been a Distinguished Lecturer of both the IEEE Solid-State Circuits Society and the IEEE Microwave Theory and Techniques Society. He is the winner of four "best paper" awards at international conferences as well as a Packard Foundation Fellowship winner. Professor Lee is the author of more than a hundred technical papers and holds thirty U.S. patents. He has co-founded several companies, including Matrix Semiconductor.

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SECOND EDITION

THOMAS H. LEE
Stanford University

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To my parents, who had no idea what they were starting when they bought me a pair of walkie-talkies for my sixth birthday

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PREFACE TO THE SECOND EDITION

Since publication of the first edition of this book in 1998, RF CMOS has made a rapid transition to commercialization. Back then, the only notable examples of RF CMOS circuits were academic and industrial prototypes. No companies were then shipping RF products using this technology, and conference panel sessions openly questioned the suitability of CMOS for such applications – often concluding in the negative. Few universities offered an RF integrated circuit design class of any kind, and only one taught a course solely dedicated to CMOS RF circuit design. Hampering development was the lack of device models that properly accounted for noise and impedance at gigahertz frequencies. Measurements and models so conflicted with one another that controversies raged about whether deep submicron CMOS suffered from fundamental scaling problems that would forever prevent the attainment of good noise figures.

Today, the situation is quite different, with many companies now manufacturing RF circuits using CMOS technology and with universities around the world teaching at least something about CMOS as an RF technology. Noise figures below 1 dB at gigahertz frequencies have been demonstrated in practical circuits, and excellent RF device models are now available. That pace of growth has created a demand for an updated edition of this textbook.

In response to many suggestions, this second edition now includes a chapter on the fundamentals of wireless systems. After a brief overview of wireless propagation, we introduce a necessarily truncated discussion of Shannon's famous channel capacity theorem in order to establish a context for discussion of modern modulation methods. To avoid getting bogged down in the arcana of information theory, we cover only those concepts essential to understanding why wireless systems appear as they do. A few illustrative systems – such as IEEE 802.11 wireless LANs, second- and third-generation cellular technology, and emerging technologies such as ultra-wideband (UWB) – are briefly examined in this context.

The chapter on passive *RLC* components now directly precedes a much expanded chapter on passive IC components, rather than following it. The chapter on MOS device physics has likewise been updated to reflect recent scaling trends and augmented

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to provide readers with an improved understanding of models that are suitable for hand calculation; it also offers some reasonable speculations on how scaling trends are likely to affect technology in the next several years. The related chapter on LNA design includes a detailed discussion of our much-improved understanding of MOS noise mechanisms at radio frequencies. It is with great pleasure that I acknowledge here the kind and timely assistance of Dr. Andries Scholten and his colleagues at Philips for providing a wealth of data just days before the manuscript submission deadline. The clarity and rigor of their work informs much of the new material presented in both the device physics and LNA chapters.

In another rearrangement, the chapter on feedback now precedes that on power amplifiers in order to establish principles necessary for understanding several linearization methods. Readers familiar with the first edition will also note that the power amplifier chapter has been greatly expanded to include much more on the subject of techniques for linearization and efficiency enhancement.

The chapter on transceiver architectures now includes much more detailed coverage of the direct conversion architecture. Persistent, dedicated work by a host of determined engineers has overcome many of the daunting challenges that underlies the pessimism expressed in the first edition.

That chapter now includes illustrative examples to provide a comprehensive overview of how the knowledge of the preceding chapters may be integrated into a coherent whole. It also is a natural place to discuss briefly several topics that – while essential to the realization of practical transceivers – lie somewhat outside of the scope of a book on RF circuits. Additional commentary on practical details such as simulation, floorplanning, packaging, and the like are to be found here as well.

Significant refinements, clarifications, and corrections have been applied to nearly all of the chapters, thanks to a wealth of ongoing research and also to the valuable suggestions of many dedicated students and engineers who have been kind enough to convey their comments over the past five years. The suggestions and corrections provided by Professor Yannis Tsividis and his students at Columbia University have proven especially valuable.

As mentioned in the preface to the first edition, students often take particular delight in pointing out the professor's errors. The rich list of suggestions compiled by graduate students has stimulated substantial improvements in clarity that future students will appreciate. Thanks to all those who identified mistakes and contributed suggestions, this edition has considerably fewer errors than would otherwise have been the case. Alas, experience shows that perfection is unattainable, and I know that I'll hear from readers about some typo, error, or unclear explanation (but please be gentle). That's what *third* editions are for.

Finally, I am most deeply grateful for the love, encouragement and understanding of my brilliant, beautiful and otherwise amazing wife, Angelina, who no doubt hopes that I'm kidding about a third edition, but is much too sweet to say so.

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PREFACE TO THE FIRST EDITION

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 [Chapter 4 in the second edition – Ed.] surveys the passive components normally available in standard CMOS processes. There is a focus on inductors

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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 [2e Ch. 5] 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 [2e Ch. 3] 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 [2e Ch. 6] 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 [2e Ch. 7] 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 [2e Ch. 8] 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 [2e Ch. 9] 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.

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Chapter 9 [2e Ch. 10] 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 [2e Ch. 11] 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 [2e Ch. 12] 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 [2e Ch. 13] 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 [2e Ch. 15] 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 [2e Ch. 16] 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 [2e Ch. 17] 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 [2e Ch. 18] extends to oscillators the earlier work on noise. After elucidating some general criteria for optimizing the noise performance of oscillators,

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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 [2e Ch. 19] 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 [2e Ch. 20] 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.

The author is also extremely grateful to the text's reviewers, both known and anonymous, who all had excellent, thoughtful suggestions. Of the former group, Mr. Howard Swain (formerly of Hewlett-Packard), Dr. Gitty Nasserbakht of Texas Instruments, and Professors James Roberge of the Massachusetts Institute of Technology and Kartikeya Mayaram of Washington State University deserve special thanks for spotting typographical and graphical errors, and also for their valuable editorial suggestions. Matt and Vickie Darnell of Four-Hand Book Packaging did a fantastic job of copyediting and typesetting. Their valiant efforts to convert my "sow's ear" of a manuscript into the proverbial silk purse were nothing short of superhuman. And Dr. Philip Meyler of Cambridge University Press started this whole thing by urging me to write this book in the first place, so he's the one to blame.

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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