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978-0-521-83526-8 - Planar Microwave Engineering: A Practical Guide to Theory, Measurement, and Circuits

Thomas H. Lee

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PLANAR MICROWAVE ENGINEERING

Modern wireless communications hardware is underpinned by RF and microwave design techniques. This insightful book contains a wealth of circuit layouts, design tips, and measurement techniques for building and testing practical gigahertz systems. The book covers everything you need to know to design, build, and test a high-frequency circuit. Microstrip components are discussed, including tricks for extracting good performance from cheap materials. Connectors and cables are also described, as are discrete passive components, antennas, low-noise amplifiers, oscillators, and frequency synthesizers. Practical measurement techniques are presented in detail, including the use of network analyzers, sampling oscilloscopes, spectrum analyzers, and noise figure meters. Throughout the focus is practical, and many worked examples and design projects are included. A CD-ROM included with the book contains a variety of design and analysis programs. The book is packed with indispensable information for students taking courses on RF or microwave circuits and 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 has written more than a hundred technical papers and authored the acclaimed text *The Design of CMOS Radio-Frequency Integrated Circuits*, now in its second edition. He holds thirty-five U.S. patents and has co-founded several companies, including Matrix Semiconductor.

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A Practical Guide to Theory,
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THOMAS H. LEE
Stanford University



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CONTENTS

<i>Preface</i>	<i>page</i> xiii
1 A MICROHISTORY OF MICROWAVE TECHNOLOGY	1
1. Introduction	1
2. Birth of the Vacuum Tube	11
3. Armstrong and the Regenerative Amplifier/Detector/Oscillator	14
4. The Wizard War	18
5. Some Closing Comments	27
6. Appendix A: Characteristics of Other Wireless Systems	27
7. Appendix B: Who Really Invented Radio?	29
2 INTRODUCTION TO RF AND MICROWAVE CIRCUITS	37
1. Definitions	37
2. Conventional Frequency Bands	38
3. Lumped versus Distributed Circuits	41
4. Link between Lumped and Distributed Regimes	44
5. Driving-Point Impedance of Iterated Structures	44
6. Transmission Lines in More Detail	46
7. Behavior of Finite-Length Transmission Lines	51
8. Summary of Transmission Line Equations	53
9. Artificial Lines	54
10. Summary	58
3 THE SMITH CHART AND S-PARAMETERS	60
1. Introduction	60
2. The Smith Chart	60
3. S-Parameters	66
4. Appendix A: A Short Note on Units	69
5. Appendix B: Why 50 (or 75) Ω ?	71

4	IMPEDANCE MATCHING	74
1.	Introduction	74
2.	The Maximum Power Transfer Theorem	75
3.	Matching Methods	77
5	CONNECTORS, CABLES, AND WAVEGUIDES	108
1.	Introduction	108
2.	Connectors	108
3.	Coaxial Cables	115
4.	Waveguides	118
5.	Summary	120
6.	Appendix: Properties of Coaxial Cable	121
6	PASSIVE COMPONENTS	123
1.	Introduction	123
2.	Interconnect at Radio Frequencies: Skin Effect	123
3.	Resistors	129
4.	Capacitors	133
5.	Inductors	138
6.	Magnetically Coupled Conductors	147
7.	Summary	157
7	MICROSTRIP, STRIPLINE, AND PLANAR PASSIVE ELEMENTS	158
1.	Introduction	158
2.	General Characteristics of PC Boards	158
3.	Transmission Lines on PC Board	162
4.	Passives Made from Transmission Line Segments	178
5.	Resonators	181
6.	Combiners, Splitters, and Couplers	183
7.	Summary	230
8.	Appendix A: Random Useful Inductance Formulas	230
9.	Appendix B: Derivation of Fringing Correction	233
10.	Appendix C: Dielectric Constants of Other Materials	237
8	IMPEDANCE MEASUREMENT	238
1.	Introduction	238
2.	The Time-Domain Reflectometer	238
3.	The Slotted Line	246
4.	The Vector Network Analyzer	254
5.	Summary of Calibration Methods	264
6.	Other VNA Measurement Capabilities	265
7.	References	265
8.	Appendix A: Other Impedance Measurement Devices	265
9.	Appendix B: Projects	268

9 MICROWAVE DIODES	275
1. Introduction	275
2. Junction Diodes	276
3. Schottky Diodes	279
4. Varactors	281
5. Tunnel Diodes	284
6. PIN Diodes	287
7. Noise Diodes	289
8. Snap Diodes	290
9. Gunn Diodes	293
10. MIM Diodes	295
11. IMPATT Diodes	295
12. Summary	297
13. Appendix: Homegrown “Penny” Diodes and Crystal Radios	297
10 MIXERS	305
1. Introduction	305
2. Mixer Fundamentals	306
3. Nonlinearity, Time Variation, and Mixing	312
4. Multiplier-Based Mixers	317
11 TRANSISTORS	341
1. History and Overview	341
2. Modeling	351
3. Small-Signal Models for Bipolar Transistors	352
4. FET Models	361
5. Summary	368
12 AMPLIFIERS	369
1. Introduction	369
2. Microwave Biasing 101	370
3. Bandwidth Extension Techniques	381
4. The Shunt-Series Amplifier	395
5. Tuned Amplifiers	413
6. Neutralization and Unilateralization	417
7. Strange Impedance Behaviors and Stability	420
8. Appendix: Derivation of Bridged T-Coil Transfer Function	427
13 LNA DESIGN	440
1. Introduction	440
2. Classical Two-Port Noise Theory	440
3. Derivation of a Bipolar Noise Model	445
4. The Narrowband LNA	451
5. A Few Practical Details	455

6. Linearity and Large-Signal Performance	457
7. Spurious-Free Dynamic Range	462
8. Cascaded Systems	464
9. Summary	467
10. Appendix A: Bipolar Noise Figure Equations	468
11. Appendix B: FET Noise Parameters	468
14 NOISE FIGURE MEASUREMENT	472
1. Introduction	472
2. Basic Definitions and Noise Measurement Theory	472
3. Noise Temperature	477
4. Friis's Formula for the Noise Figure of Cascaded Systems	479
5. Noise Measure	480
6. Typical Noise Figure Instrumentation	481
7. Error Sources	487
8. Special Considerations for Mixers	491
9. References	492
10. Appendix: Two Cheesy Eyeball Methods	492
15 OSCILLATORS	494
1. Introduction	494
2. The Problem with Purely Linear Oscillators	494
3. Describing Functions	495
4. Resonators	515
5. A Catalog of Tuned Oscillators	519
6. Negative Resistance Oscillators	524
7. Summary	528
16 SYNTHESIZERS	529
1. Introduction	529
2. A Short History of PLLs	529
3. Linearized PLL Model	532
4. PLL Rejection of Noise on Input	536
5. Phase Detectors	537
6. Sequential Phase Detectors	542
7. Loop Filters and Charge Pumps	544
8. Frequency Synthesis	551
9. A Design Example	561
10. Summary	564
11. Appendix: Inexpensive PLL Design Lab Tutorial	565
17 OSCILLATOR PHASE NOISE	574
1. Introduction	574
2. General Considerations	576

CONTENTS		xi
	3. Detailed Considerations: Phase Noise	579
	4. The Roles of Linearity and Time Variation in Phase Noise	582
	5. Circuit Examples – <i>LC</i> Oscillators	592
	6. Amplitude Response	597
	7. Summary	599
	8. Appendix: Notes on Simulation	600
18	MEASUREMENT OF PHASE NOISE	601
	1. Introduction	601
	2. Definitions and Basic Measurement Methods	601
	3. Measurement Techniques	604
	4. Error Sources	611
	5. References	612
19	SAMPLING OSCILLOSCOPES, SPECTRUM ANALYZERS, AND PROBES	613
	1. Introduction	613
	2. Oscilloscopes	614
	3. Spectrum Analyzers	625
	4. References	629
20	RF POWER AMPLIFIERS	630
	1. Introduction	630
	2. Classical Power Amplifier Topologies	631
	3. Modulation of Power Amplifiers	650
	4. Additional Design Considerations	679
	5. Summary	687
21	ANTENNAS	688
	1. Introduction	688
	2. Poynting’s Theorem, Energy, and Wires	690
	3. The Nature of Radiation	691
	4. Antenna Characteristics	695
	5. The Dipole Antenna	697
	6. The Microstrip Patch Antenna	707
	7. Miscellaneous Planar Antennas	720
	8. Summary	721
22	LUMPED FILTERS	723
	1. Introduction	723
	2. Background – A Quick History	723
	3. Filters from Transmission Lines	726
	4. Filter Classifications and Specifications	738
	5. Common Filter Approximations	740

xii	CONTENTS
6. Appendix A: Network Synthesis	766
7. Appendix B: Elliptic Integrals, Functions, and Filters	774
8. Appendix C: Design Tables for Common Low-pass Filters	781
23 MICROSTRIP FILTERS	784
1. Background	784
2. Distributed Filters from Lumped Prototypes	784
3. Coupled Resonator Bandpass Filters	803
4. Practical Considerations	841
5. Summary	843
6. Appendix: Lumped Equivalents of Distributed Resonators	844
<i>Index</i>	847

PREFACE

First, it was called *wireless*, then *radio*. After decades in eclipse *wireless* has become fashionable once again. Whatever one chooses to call it, the field of RF design is changing so rapidly that textbook authors, let alone engineers, are hard pressed to keep up. A significant challenge for newcomers in particular is to absorb an exponentially growing amount of new information while also acquiring a mastery of those foundational aspects of the art that have not changed for generations. Compounding the challenge is that many books on microwave engineering focus heavily on electromagnetic field theory and never discuss actual physical examples, while others are of a cookbook nature with almost no theory at all. Worse still, much of the lore on this topic is just that: an oral tradition (not always correct), passed down through the generations. The rest is scattered throughout numerous applications notes, product catalogs, hobbyist magazines, and instruction manuals – many of which are hard to find, and not all of which agree with each other. Hobbyists are almost always unhappy with the theoretical bent of academic textbooks (“too many equations, and in the end, they still don’t tell you how to *make* anything”), while students and practicing engineers are often unhappy with the recipe-based approaches of hobby magazines (“they don’t give you the theory to show how to *change* the design into what I actually need”). This book is a response to the students, hobbyists, and practicing engineers who have complained about the lack of a modern reference that balances theory and practice.

This book is a much-expanded version of notes used in the teaching of EE414, a one-term advanced graduate laboratory course on gigahertz transceiver design at Stanford University. Even so, it is intended to satisfy a much broader audience than simply those seeking a Ph.D. In EE414, students spend approximately nine weeks designing, building, and testing every building block of a 1-GHz transceiver using microstrip construction techniques. These building blocks include various antennas and microstrip filters as well as a low-noise amplifier, mixer, PLL-based frequency synthesizer and FM modulator/demodulator, and power amplifier. The “final exam” is a successful demonstration of two-way communications with these FM transceivers. I am deeply grateful to the students of the first class in particular, who graciously and

enthusiastically served as guinea pigs as the course material and notes were being developed in real time (at best). The present form of the text owes a great deal to their suggestions.

It is true that you will find here a certain number of theoretical discussions of measurement techniques and microwave design, replete with complex transfer functions and transforms galore. That’s necessary because an important function of a Ph.D. program is the mental torment of graduate students. But hobbyists who just want to “get to the good stuff” right away are free to ignore all of the equations and to focus instead on the many practical rules of thumb or on the numerous ways to build and characterize microwave circuits with inexpensive components and equipment. Every effort is made to provide verbal and physical explanations of what the equations *mean*. The weekend experimenter may enjoy in particular the projects included in many of the chapters, ranging from homemade diodes to a sub-\$10 microwave impedance measurement system. The practicing engineer will find much useful information about how to extract the most reliable data from leading-edge instrumentation, with a special focus on understanding calibration methods (and their limitations) in order to avoid making subtle, but surprisingly common, errors. Younger engineers may also enjoy finding answers to many of their questions about everyday RF items (Does *BNC* really stand for “baby N connector”?¹ Why is everything 50 Ω ? Who was Smith, and why did he invent a chart?). Readers are invited to pick and choose topics to suit their tastes; this book is a smorgasbord, as is clear from the following brief descriptions of the chapters.

Chapter 1 provides a short history of RF and microwave circuits. It is impossible to provide anything remotely approaching a comprehensive overview of this vast topic in one chapter, and we don’t even try. Our hope is that it provides some entertainment while establishing a context for the rest of the book.

Chapter 2 introduces some definitions and basic concepts. We try to devise a less arbitrary definition of *microwave* than the simple frequency-based one offered in many other places. We also try very hard to avoid actually solving Maxwell’s equations anywhere, preferring instead to appeal to physical intuition. Again, this book is about design and testing, not pure analysis, so any analysis we perform is dedicated to those aims.

The Smith chart and S-parameters are staples of classical microwave design, so Chapter 3 provides a brief introduction to them. The complex appearance of the chart is off-putting to many who would otherwise be interested in RF and microwave design. We therefore offer a brief history of the Smith chart to explain why it’s useful, even today. In the process, we hope to make the Smith chart a little less intimidating.

At high frequencies, power gain is hard to come by, so impedance matching is a standard task of every microwave engineer. Chapter 4 presents a number of impedance matching methods, along with a brief explanation of the Bode–Fano limit, which helps let us know when we should quit trying (or when we shouldn’t even try).

¹ No.

After having witnessed eager students inadvertently destroy expensive fixturing, it became clear that a chapter on the care and feeding of connectors was necessary. Chapter 5 surveys a number of popular connectors, their historical origins, their domain of application, and the proper ways to care for them. Cables and their characteristics are discussed as well.

Chapter 6 examines the characteristics of lumped passive elements at microwave frequencies. Simple circuit models (appropriate for design, but not necessarily accurate enough for analysis) are presented to alert the student to issues that may prevent circuits from functioning as desired. To no small degree, an important lesson in RF and microwave design is that there are always irreducible parasitics. Rather than conceding defeat, one must exploit them as circuit elements. Retaining simple mental models of parasitics allows you to devise clever ways of accomplishing this goal.

In Chapter 7 we introduce the most common way of building microwave circuits (either in discrete or integrated form): microstrip. Although the chapter focuses on this one particular method of implementing planar circuits, we also spend a little time discussing coplanar waveguide and coplanar strips, as well as stripline. After introducing basic concepts and some simple (but reasonably accurate) design equations, we examine a large number of passive components that may be realized in microstrip form.

Once you've designed and built some circuits, you'll need to characterize them. One of the most basic measurements you will make is that of impedance. Chapter 8 presents several methods for making impedance measurements, ranging from time-domain reflectometry to vector network analysis. We spend considerable time describing various calibration techniques, for maladroitness here often causes engineers to obtain \$1 answers from a \$100,000 instrument. For those who don't want to choose between buying a home and buying a network analyzer, we present a simple "slotted line" measurement device that can be fashioned for about \$10 yet functions up to at least several gigahertz. The 40-dB cost reduction is not accompanied by a 40-dB utility reduction, fortunately. For example, once calibrated, the device can even be used to determine frequency within 1–2%.

Chapter 9 is devoted to microwave diodes. Engineers accustomed to lower-frequency design are often surprised at the wide variety of functions that diodes can perform. Especially surprising to many newcomers is that some diodes are capable of amplification and even of oscillation.

Chapter 10 builds on that foundation to describe numerous mixers, heart of the modern superheterodyne transceiver. Lumped and distributed implementations are presented, as are active and passive circuits. Depending on the available technology and the design constraints, any of these may be appropriate in a given situation.

Active circuits are more interesting, of course (at least to the author), and so Chapter 11 presents a survey of transistors. The device physicists have been working overtime for decades to give us JFETs, MOSFETs, MESFETs, HEMTs, VMOS, U MOS, LDMOS, HBTs, . . . , and the list just keeps growing. We attempt to provide a somewhat unified treatment of these transistors, and focus on just two types (MOSFETs and bipolars) as representative of a much wider class.

Chapter 12 considers how to squeeze the most out of whatever transistor technology you are given. We spend a few pages describing how to bias transistors because, at microwave frequencies, many of the lower-frequency techniques have serious implementation consequences (parasitics, again). We then describe methods for extending bandwidth by factors of 2–3 with modest increases in circuit complexity. And for the first time anywhere (to the author’s knowledge), we present a detailed derivation of the transfer function and optimum conditions for the bridged T-coil bandwidth boost network.

In Chapter 13, we shift our goals from “give me all the bandwidth you can” to “give me the lowest-noise amplification possible.” We discuss noise models and then present the theory of noise matching. We discover that the conditions that maximize power transfer almost never coincide with those that minimize noise factor, and so a compromise strategy is necessary. Again, although we focus the discussion on just one or two types of transistors, the general concepts presented apply to all amplifiers.

Once you’ve built what you believe is a low-noise amplifier, you have to prove it. Chapter 14 describes the principles underlying noise figure measurement, along with descriptions of how to get the wrong answer (it’s very easy). Depending on your objectives (making your LNA look good, or your competitor’s look bad), you can either commit or avoid those errors.

Chapter 15 describes how to produce controlled instability to build oscillators. The old joke among frustrated microwave engineers is that “amplifiers oscillate, and oscillators amplify.” We hope that the simplified presentation here allows you to design oscillators that really do oscillate, and even on frequency.

Virtually every modern transceiver has a frequency synthesizer somewhere. Chapter 16 describes phase-locked loop synthesizers, along with an extended discussion of spur-producing design defects (and their mitigation). Although the theoretical discussion can get very complex, the design examples should help the impatient hobbyist put together a working design without having to understand every equation.

Chapter 17 analyzes the important subject of phase noise. It’s not sufficient for an oscillator to oscillate. The putative scarcity of spectrum obligates all transmitters to follow a “good neighbor” policy and not transmit much energy outside of its assigned band. All oscillators are imperfect in this regard, so Chapter 17 identifies where phase noise comes from and how you can reduce it.

Chapter 18 describes phase noise measurement methods. As with noise figure, there are many subtle (and not so subtle) ways to bungle a phase noise measurement, and we try to steer you clear of those.

Chapter 19 describes spectrum analyzers, oscilloscopes, and probes. Too often, engineers place all of their faith in the instrument, forgetting that connecting their circuit to these devices is up to them. And if done with insufficient care, the quality of the measurement can degrade rapidly. This chapter highlights the more common of these errors – and ways to avoid them. Also, since high-frequency probes are so expensive, we offer a way to build one for a few dollars. To supplement the probe, we also offer a couple of fast pulse-generator circuits with which you may test probe and oscilloscope combinations.

Chapter 20 presents numerous ways to implement power amplifiers at RF and microwave frequencies. At one time, it was sufficient to design for a particular gain and output power. Unfortunately, demands have increased steadily as the telecommunications revolution has unfolded, and now one must achieve high efficiency, low cost, high robustness to varying load conditions, and high linearity. We attempt to survey numerous methods for achieving all of these goals.

The aim of Chapter 21 is showing how to get power into and out of the air. Antennas are mysterious, and we hope to take at least some of the mystery out of antenna design with the material in this chapter. We focus on microstrip patch antennas, but we precede that discussion with an examination of classic nonplanar antennas (e.g., the dipole) to identify important concepts.

Finally, Chapters 22 and 23 focus on the design of passive filters. The presentation is divided roughly into lumped design in Chapter 22 and microstrip distributed filters in Chapter 23. Throughout, we make a concerted effort to focus on practical details, such as the effect of component tolerance, or finite Q . We hope that the numerous design examples and simulation results will illuminate the design procedures and allow you to converge rapidly on an acceptable, repeatable design.

Again, these chapters are ordered in a quasirandom way. You are in no way obligated to read them linearly in the sequence presented. Skip around as you like. It's *your* book.

This text has been informed by the many wonderful mentors, colleagues, and students who have generously shared their knowledge and viewpoints over the years. Stanford Professor Malcolm McWhorter (now Emeritus) oversaw the development of a delightfully unorthodox BNC microstrip mounting arrangement for EE414's prerequisite, an introductory microwave laboratory course called EE344. As discussed later in this book, this mounting method is ideal for students and hobbyists because it allows for the rapid and inexpensive prototyping of circuits in the low-gigahertz frequency range. Howard Swain and Dieter Scherer, both formerly of Hewlett-Packard and both virtuoso designers of widely used microwave instruments, helped to create EE344 and have continued to help teach it. The present mentor of the course, Professor Donald Cox, has graciously communicated lessons learned from teaching EE344 over the years, and the contents of this book have been adjusted as a direct result. I am also greatly indebted to Professor David Rutledge of Caltech, not only for generously allowing the inclusion of *Puff* in the CD-ROM collection of software accompanying this text but also for the great wealth of knowledge he has imparted to me, both in person and from his many publications. I've also benefitted enormously from the fact that simple proximity to David Leeson automatically increases your knowledge of microwave systems by several dB. Having so knowledgeable a faculty colleague has been a godsend.

I have also been the beneficiary of the hard work of several dedicated graduate students who built and tested most of the projects described in this book. Stanford Ph.D. candidates Sergei Krupenin, Arjang Hassibi, Talal Al-Attar, Moon-Jung Kim, and Michael Mulligan merit special mention in particular for their efforts. Rob Chavez of Agilent, while nominally a student in EE414, worked long hours to help other

students and the teaching assistant. Future EE414 students, as well as readers of this book, owe him thanks for the insights and suggestions that have shaped this material.

Funding is the fuel that keeps the academic engine purring, and here I have been most fortunate. Generous equipment grants from Hewlett-Packard and Agilent Technologies have given generations of students the privilege of hands-on work with leading-edge gear that not many schools can afford. Support from the William G. Hoover Faculty Scholar Chair and The David and Lucile Packard Foundation has given me tremendous freedom, making it possible to develop new courses, pursue some crazy research ideas, and write textbooks.

Finally, I am most deeply grateful to my loving wife, Angelina, for her patient support during the writing of this book, and for otherwise living up to her name in every way. Without her forbearance, it would have been impossible to complete two book manuscripts in one long year.