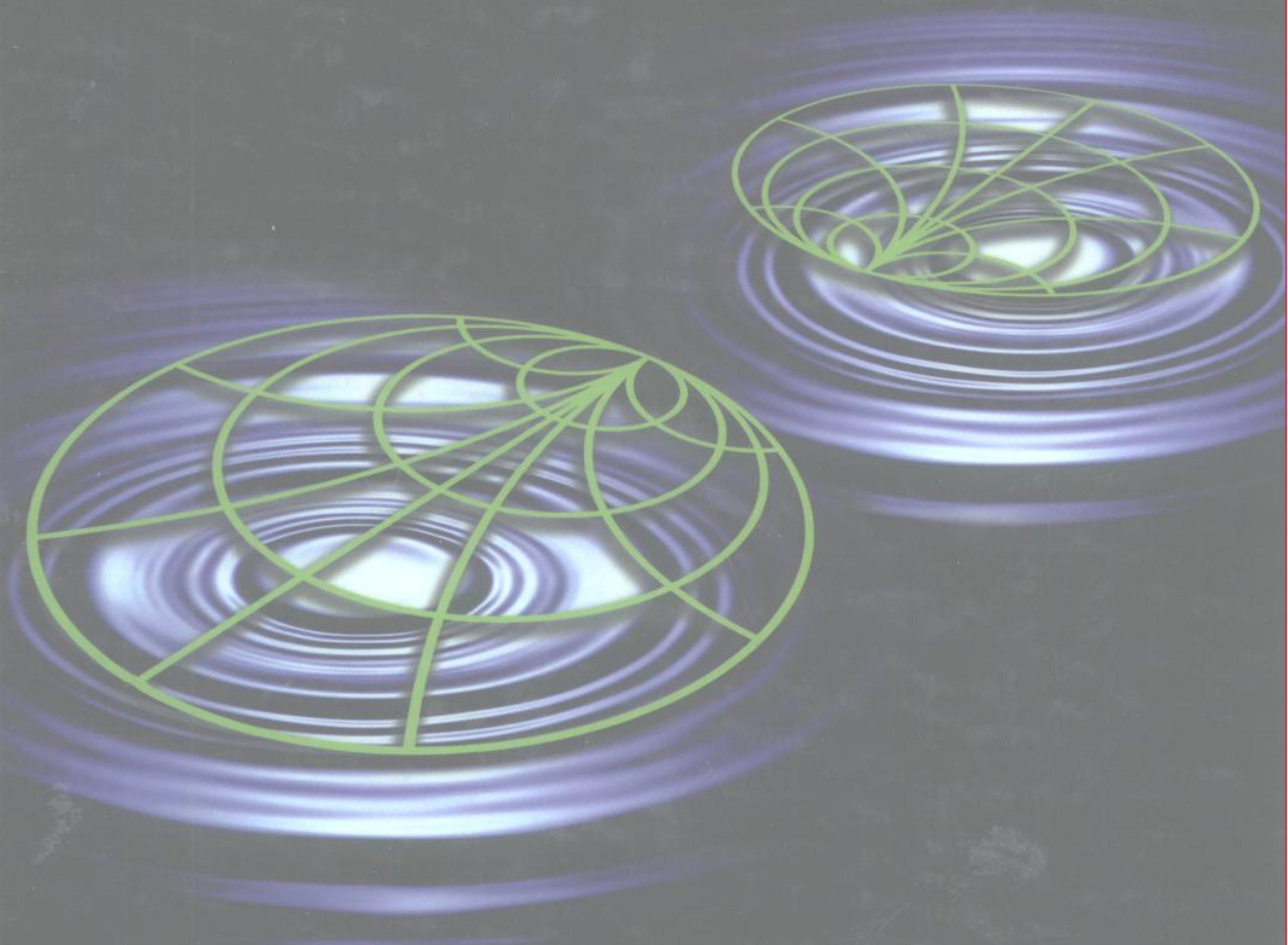
RF Circuit Design

Theory and Applications



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DEDICATION

To our families and the memory of my father F. Ludwig

Preface

The field of high-frequency circuit design is receiving significant industrial attention due to a host of radio-frequency (RF) and microwave (MW) applications. Improved semiconductor devices have made possible a proliferation of high-speed digital and analog systems as observed in wireless communication, global positioning, RADAR, and related electrical and computer engineering disciplines. This interest has translated into a strong demand for engineers with comprehensive knowledge of high-frequency circuit design principles.

For the student, the professional engineer, and even the faculty member teaching this material there is, however, a general problem. The majority of existing textbooks appear to target two separate audiences: A) the advanced graduate-level population with a broad theoretical background, and B) the technologists with little interest in mathematical and physical rigor. As a result, RF circuit design has been presented in two very different formats. For the advanced students the entry into this field is often pursued through an electromagnetic field approach, while for the technologists the basic circuit aspect embedded in Kirchhoff's laws is the preferred treatment. Both approaches make it difficult to adequately address the theoretical and practical issues surrounding high-frequency design principles. The basic circuit approach lacks, or only superficially covers, the wave nature of currents and voltages whose reflection and transmission properties constitute indispensable ingredients of the RF circuit behavior. The electromagnetic field approach certainly covers the wave guide and transmission line aspect, but falls far short of reaching the important aspects of designing high-frequency amplifier, oscillator, and mixer circuits.

The objective of this textbook is to develop the RF circuit design aspects in such a way that the need for transmission line principles is made clear without adopting an electromagnetic field approach. Therefore, no EM background is necessary beyond a first year undergraduate physics course in fields and waves as provided by most colleges and universities. Students equipped with the knowledge of basic circuit theory and/or an exposure to microelectronics can use this book and cover the entire spectrum from the basic principles of transmission and microstrip lines to the various high-frequency circuit design procedures. Lengthy mathematical derivations are either relegated to the appendices or placed in examples, separated from the main text. This allows the omission of some of the dry theoretical details and thus focuses on the main concepts.

Accepting the challenge of providing a high degree of design experience, we have included many examples that discuss in considerable detail, in many cases extending over several pages, the philosophy and the intricacies of the various design approaches.

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This has caused some problems as well, specifically with respect to the circuit simulations. Obviously, we cannot expect the reader to have ready access to modern computer simulation tools such as MMICAD or ADS to name but two of the popular choices. Professional high-frequency simulation packages are generally expensive and require familiarity to use them effectively. For this reason we have created a considerable number of MATLAB M-files that the interested student can download from our website listed in Appendix G. Since MATLAB is a widely used 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 the impedance transformations should appeal to the reader. Nonetheless, all design examples, specifically the ones presented in Chapters 8 to 10, have been independently simulated and verified in MMICAD for the linear circuit models, and ADS for the nonlinear oscillator and mixer models.

In terms of material coverage, this textbook purposely omitted the high-speed digital circuits as well as coding and modulation aspects. Although important, these topics would simply have required too many additional pages and would have moved the book too far away from its original intent of providing a fundamental, one- or two-semester, introduction to RF circuit design. At WPI this does not turn out to be a disadvantage, since most of the material can readily be acquired in available communication systems engineering courses.

The organization of this text is as follows: **Chapter 1** presents a general explanation of why basic circuit theory breaks down as the operating frequency is increased to a level where the wavelength becomes comparable with the discrete circuit components. In **Chapter 2** the transmission line theory is developed as a way to replace the low-frequency circuit models. Because of the voltage and current wave nature, **Chapter 3** introduces the Smith Chart as a generic tool to deal with the impedance behavior on the basis of the reflection coefficient. **Chapter 4** discusses two-port networks with their flow-chart representations and how they can be described on the basis of the so-called scattering parameters. These network models and their scattering parameter descriptions are utilized in **Chapter 5** to develop passive RF filter configurations. Before covering active devices, **Chapter 6** provides a review of some of the 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** in an effort to eliminate potentially dangerous reflections and to provide optimal power flow. **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 designs in oscillator and mixer circuits.

This book is used in the Electrical and Computer Engineering Department at WPI as required text for the standard 7-week (5 lecture hours per week) course in RF circuit design (EE 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 laboratory, although six videotapes of practical circuit performances conducted at *Philips Semiconductors* and in-class RF circuit measurements with a network analyzer are included. In addition, MMICAD and ADS simulations are incorporated as part of the regular lectures. Each chapter is fairly 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 25–28 lectures). The topics covered 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

However, the entire course organization will always remain subject to change depending on total classroom time, student background, and interface requirements with related courses.

Please refer to the companion website at http://www.prenhall.com/ludwig for more material including all of the art files in this text in pdf format.

ACKNOWLEDGEMENTS

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Donation of the MIMICAD RF simulation design package by Optotek and a university license of ADS provided by Hewlett-Packard Corporation are gratefully acknowledged.

Contents

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CHAPTER 1

Introduction

It is common knowledge that both analog and digital design engineers are continually developing and refining circuits for increasingly higher operational frequencies. Analog circuits for wireless communication in the gigahertz (GHz) range and the ever-increasing clock speeds of computer circuits in high-performance mainframes, workstations, and, of course, personal computers exemplify this trend. Global positioning systems require carrier frequencies in the range of 1227.60 and 1575.42 MHz. The low-noise amplifier in a personal communication system 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 evolution from low- to high-frequency circuit operations. It motivates and provides the physical rationales that have prompted the need for new engineering approaches to design and optimize these circuits. The example of a cellular 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.

1.1 Importance of Radiofrequency Design

The beginning of electrical circuit design is most likely traced back to the late eighteenth and early nineteenth centuries when the first reliable batteries became available. Named after their inventor A. Volta (1745–1827), the Voltaic cells permitted the supply of reliable DC energy to power the first crude circuits. However, it soon became apparent that low-frequency alternating current (AC) power sources can transport electricity more efficiently and with less electric losses when transmitted over some distance and that rerouting the electric energy could be facilitated through transformers that operate in accordance with Faraday's induction law. Due to pioneering work by such eminent engineers as Charles Steinmetz, Thomas Edison, Werner Siemens, and Nikolas Tesla, the power generation and distribution industry quickly gained entry into our everyday life. It was James Maxwell (1831–1879) who, in a paper first read in 1864 to the Royal Society in London, postulated the coupling of the electric and magnetic fields whose linkage through space gives rise to wave propagation. In 1887 Heinrich Hertz experimentally proved the radiation and reception of electromagnetic energy through air. This discovery heralded the rapidly expanding field of wireless communication, from radio and TV transmissions in the 1920s and 1930s to cellular phones and Global Positioning Systems (GPS) in the 1980s and 1990s. Unfortunately, the design and development of suitable high-frequency circuits for today's wireless communication applications is not so straightforward. As will be discussed in detail, conventional Kirchhoff-type voltage and current law analysis tools, as presented to first- and second-year undergraduate electrical engineering students, apply strictly only to DC and low-frequency lumped parameter systems consisting of networks of resistors, capacitors, and inductors. They fail when applied to circuits governed by electromagnetic wave propagation.

The main purpose of this textbook is to provide the reader with theoretical and practical aspects of analog circuit design when the frequency of operation extends into the **radio frequency** (RF) and **microwave** (MW) domains. Here conventional circuit analysis principles fail. The following questions arise:

- At what upper frequency does conventional circuit analysis become inappropriate?

- What characteristics make the high-frequency behavior of electric components so different from their low-frequency behavior?
- What "new" circuit theory has to be employed?
- How is this theory applied to the practical design of high-frequency analog circuits?

This book intends to provide comprehensive answers to these questions by developing not only the theoretical framework but also delivering the practical applications through a host of examples and design projects.

To identify more clearly the issues that we will address, let us examine the generic RF system shown in Figure 1-1.

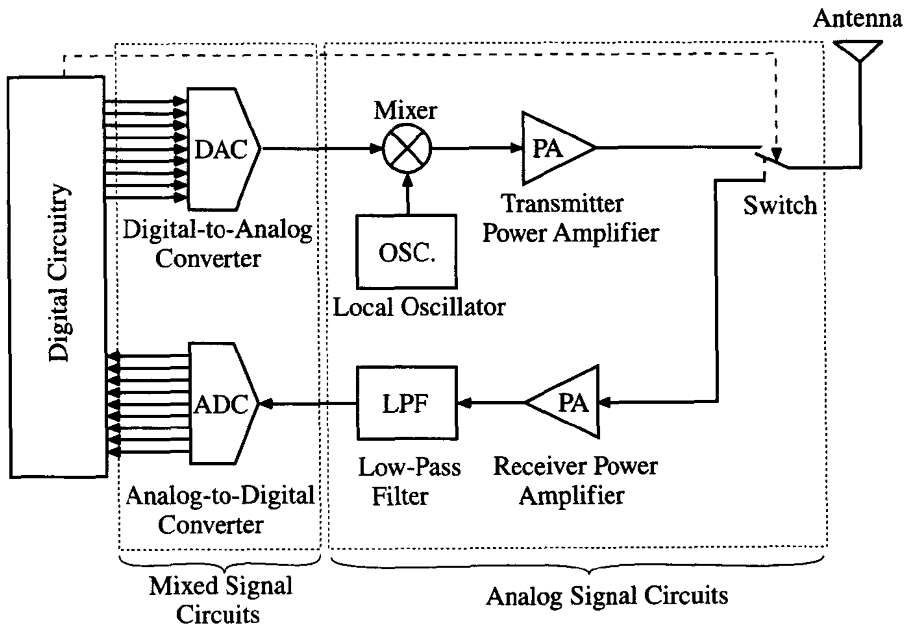

Figure 1-1 Block diagram of a generic RF system.

Typical applications of this configuration are **cellular phones** and **wireless local area networks** (WLANs). The entire block diagram in Figure 1-1 can be called a **transceiver,** since it incorporates both transmitter and receiver circuits and uses a single antenna for communication. In this configuration the input signal (either a voice or a digital signal from a computer) is first digitally processed. If the input signal is a voice signal, as is the case in cellular phones, it is first converted into digital form; then compressed to reduce the time of transmission; and finally appropriately coded to suppress noise and communication errors.

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