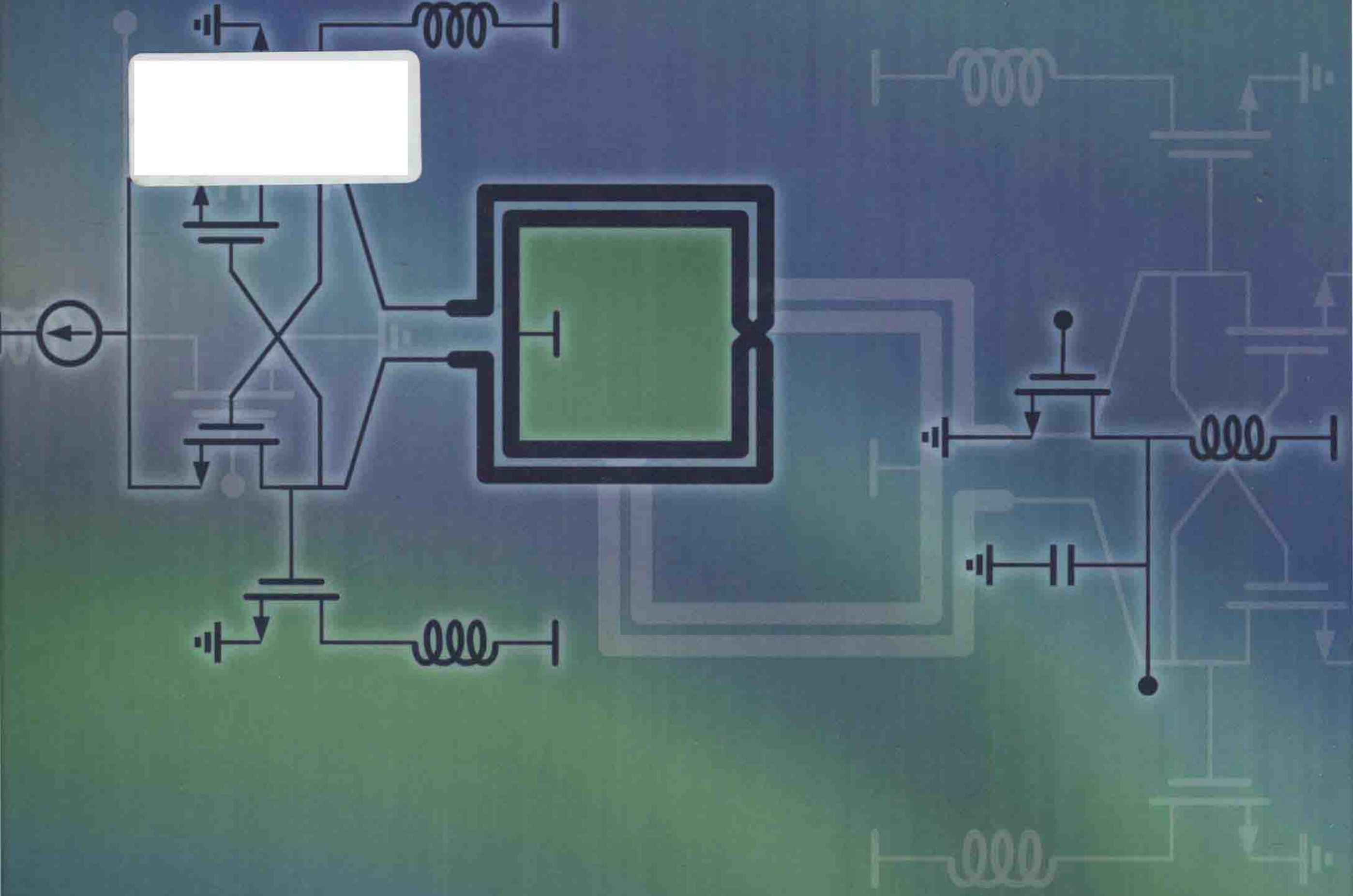

RADIO FREQUENCY INTEGRATED CIRCUITS AND SYSTEMS

Hooman Darabi

Radio Frequency Integrated Circuits and Systems

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Radio Frequency Integrated Circuits and Systems

Focusing on the core topics of RF IC and system design, this textbook provides the in-depth coverage and detailed mathematical analyses needed to gain a thorough understanding of the subject. Throughout, theory is linked to practice with real-world application examples; practical design guidance is also offered, covering the pros and cons of various topologies, and preparing students for future work in industry. Written for graduate courses on RFICs, this uniquely intuitive and practical book will also be of value to practicing RF IC and system designers.

Key topics covered include:

- RF components, signals and systems
- Two-ports
- Noise
- Distortion
- Low-noise amplifiers
- Mixers
- Oscillators
- Power amplifiers
- Transceiver architectures

Lecture slides and a solutions manual for instructors are provided online to complete the course package.

Hooman Darabi is a Senior Technical Director and Fellow of Broadcom Corporation, California, and an Adjunct Professor at the University of California, Los Angeles. He is an IEEE Solid State Circuits Society distinguished lecturer, and an IEEE Fellow. His research interests include analog and RF IC design for wireless communications.

"Excellent textbook for students keenly interested to learn how to design IC transceivers. Lots of focused and relevant fundamental background from the viewpoint of the well-known industrial researcher. The book is also good as a convenient refresher for seasoned IC designers."

Bogdan Staszewski, *Delft University of Technology*

"Although this is not the first book on RF circuits, it is the most up-to-date one that I know. For instance, it includes recent circuit insights to make CMOS radio receivers more interference robust. I especially like the intuition that Hooman Darabi develops and the depth of coverage without becoming overly mathematical."

Eric Klumperink, *University of Twente*

To my family

PREFACE

In the past twenty years, radio frequency (RF) integrated circuits in CMOS have evolved dramatically, and matured. Started as a pure research topic in mid-1990 at several universities, they have made their way into complex systems-on-a-chip (SoCs) for wireless connectivity and mobile applications. The reason for this dramatic evolution comes primarily from two main factors: the rapid improvement of CMOS technology, and innovative circuits and architectures. In contrary to the common belief that RF and analog circuits do not improve much with technology, a faster CMOS process has enabled a number of topologies that have led to substantially lower cost and power consumption. In fact, many of the recent inventions may not have been possible if it were not for a better and faster technology. This rapid change has caused the modern RF design to be somewhat industry-based and, consequently, it is timely, and perhaps necessary, to provide an industry perspective. To that extent, the main goal of this book has been to cover possibly fewer topics, but in a much deeper fashion. Even for RF engineers working on routine products in industry, a deep understanding of fundamental concepts of RF IC design is very critical, and it is the intention of this work to break this gap. During the course of writing the book, I have tried to address the topics that I would have wanted as a *wish list* for my fellow future colleagues. Our main focus then has been to elaborate the basic definitions and fundamental concepts, while an interested designer with strong background can explore other variations on his or her own.

The contents of this book stem largely from the RF courses taught at the University of California Los Angeles and Irvine, as well as many years of product experience at Broadcom. Accordingly, the book is intended to be useful both as a text for students and as a reference book for practicing RF circuit and system engineers. Each chapter includes several worked examples that illustrate the practical applications of the material discussed, with examples of real life products, and a problem set at the end (with solutions manual) to complement that.

RF circuit design is a *multi-disciplinary* field where a deep knowledge of analog integrated circuits, as well as communication theory, signal processing, electromagnetics, and microwave engineering is crucial. Consequently, the first three chapters as well as parts of Chapter 4 cover selected topics from the aforementioned fields, but customized and shaped properly to fit the principles of RF design. It is, however, necessary for the interested students or RF engineers to have already taken appropriate senior level undergraduate courses.

An outline of each chapter is given below along with suggestions for the material to be covered if the book is to be used for a 20-lecture quarter based course. Furthermore, at the beginning of each chapter a list of specific items to be covered, as well as more detailed suggestion of which sections to include for the class use, are outlined. For beginner and intermediate practicing engineers we recommend following the selected topics suggested for class use, while more advanced readers may focus on the other topics assigned for reading.

Chapter 1 contains a review of basic electromagnetic concepts and particularly inductors and capacitors. Among many students and RF engineers, often the basic definition of capacitors and inductors is neglected, despite using them very regularly. A short reminder is deemed necessary. Furthermore, some basic understanding of Maxwell's equations is needed to understand transmission lines, electromagnetic waves, the antenna concept, and scattering parameters. These are discussed in Chapter 3. The chapter also gives an overview of integrated inductors and capacitors in modern CMOS. A total of two lectures is expected to be needed to cover the key ideas.

Chapter 2 deals with basic communication and signal processing concepts, which are a crucial part of RF design. The majority of the material is gathered to provide a reminder, and may be left to be studied outside the class, depending on the students' background. However, we cannot emphasize enough the importance of them. Spending a total of two or three lectures on the stochastic processes, modulation section, as well as a brief general reminder of passive filters and the Hilbert transform may be helpful.

Chapter 3 is concerned with several key concepts in RF design such as available power, matching topologies, transmission lines, as well as scattering parameters, and complements Chapter 1. Two lectures may be dedicated to cover the first three sections, while the more advanced material on transmission lines, the Smith chart, and scattering parameters may be very briefly touched, or omitted altogether depending on the students' background.

In Chapter 4 we discuss noise, noise figure, sensitivity, and an introduction to phase noise. The introductory part on types of noise may be assigned as reading, but the noise figure definition, minimum noise figure, and sensitivity sections must be covered in full. A total of two to three lectures suffices.

Chapter 5 covers distortion and blockers. A large portion of this chapter (as well as Chapter 10) may be left for a more advanced course, and one lecture should suffice to cover only the basic concepts. However, the material may be very appealing to RF circuit and system engineers who work in industry. A thorough knowledge of this chapter is crucial to understand Chapter 10.

Chapters 6 to 9 deal with RF circuit design. Chapter 6 is mostly built upon the concepts covered in Chapters 3 and 4, and deals with low-noise amplifiers. Three lectures may be dedicated to cover most of the topics presented in this chapter.

Chapter 7 provides a detailed discussion on receiver and transmitter mixers. Roughly two lectures may be dedicated to this chapter to cover basic active and passive topologies with some limited discussion on noise. The majority of the material on M-phase and upconversion mixers may be assigned as reading.

Chapter 8 discusses oscillators, including LC, ring, and crystal oscillators, and an introduction to phase-locked loops. The chapter is long, and the latter three topics may be assigned as reading, while two lectures could be dedicated to LC oscillators, and a brief introduction to phase noise. A detailed discussion of phase noise is very math intensive, and may be beyond the scope of an introductory RF course. Thus, it may be sufficient to focus mostly on the premises of an abstract linear oscillator, and summarize Bank's general results to provide a more practical perspective.

Power amplifiers are discussed in Chapter 9. Basic PA classes are presented in the first few sections, followed by efficiency improvement and linearization techniques. Most of the material on the latter subject may be skipped, and one or two lectures may be assigned to cover a few examples of classes (perhaps only classes A, B, and F), as well as the introductory material on general concerns and tradeoffs.

Finally, in Chapter 10 transceiver architectures are presented. This is one of the longest chapters of the book, and much of the material can be assigned as reading. The last section covers some practical aspects of the design, such as packaging and production issues. It presents a few case studies as well. The topics may be appealing for practicing RF engineers, but the entire section may be skipped for class use. A maximum of two lectures is sufficient to cover selected key transceiver architectures.

I have been very fortunate to have been working with many talented RF designers and instructors throughout my career at UCLA, and subsequently at Broadcom. They have had an impact on this book in one way or another. However, I wish to acknowledge the following individuals who have directly contributed to the book: Dr. David Murphy from Broadcom who co-wrote most of Chapter 8, and provided very helpful insight on Chapter 6, particularly the LNA topologies; Dr. Ahmad Mirzaei from Broadcom as well, who helped on the writing of some sections of Chapters 9 and 10, and proofread the entire book painstakingly. They both have been major contributors to this book beyond the chapters mentioned. I am very grateful to my advisor Prof. Asad Abidi from UCLA who has been a great inspiration on writing this book in general, and particularly for his insights and unique analysis which has been used in sections 1.7, 1.9.3, and 4.2/4.4 (FET equivalent noise and NF). I would also like to thank Dr. Hwan Yoon from Broadcom with whom I had numerous helpful discussions on the Chapter 1 material, and particularly the integrated inductors. My sincere thanks go to Professor Eric Klumperink of University of Twente, who proofread most of the book diligently, and provided valuable insight on various topics. I would also like to acknowledge my sister Hannah, who helped in the design of the book cover. Lastly, I wish to thank my wife, Shahrzad Tadjpour, who not only provided technical feedback on the book, but for her general support throughout all these years.

CONTENTS

1 RF components

In this chapter basic components used in RF design are discussed. A detailed modeling and analysis of MOS transistors at high frequency may be found in [1], [2]. Although mainly developed for analog and high-speed circuits, the model is good enough for most RF applications operating at several GHz, especially for the nanometer CMOS processes used today. Thus, we will offer a more detailed study of inductors, capacitors, and LC resonators instead in this chapter. We will also present a brief discussion on the fundamental operation of distributed circuits and transmission lines, and follow up on that in Chapter 3. In Chapters 4 and 6, we will discuss some of the RF related aspects of transistors, such as more detailed noise analysis as well as substrate and gate resistance impact.

LC circuits are widely used in RF design, with applications ranging from tuned amplifiers, matching circuits, and LC oscillators. Inspired by superior noise and linearity compared to transistors, historically, radios have relied heavily on inductors and capacitors, with large portions of the RF blocks occupied by them. Although this dependence has been reduced in modern radios, mostly for cost concerns, still RF designers deal with integrated inductors and capacitors quite often.

We start the chapter with a brief introduction to electromagnetic fields, and take a closer look at capacitors and inductors from the electromagnetic field perspective. We will then discuss capacitors, inductors, and LC resonators from a circuit point of view. We conclude the chapter by presenting the principles and design tradeoffs of integrated inductors and capacitors.

The specific topics covered in this chapter are:

- capacitance and inductance electromagnetic and circuit definitions;
- Maxwell's equations;
- distributed elements and introduction to transmission lines;
- energy, power, and quality factor;
- lossless and low-loss resonance circuits;
- integrated capacitors and inductors.

For class teaching, we recommend focusing on Sections 1.7, 1.8, and 1.9, while Sections 1.1–1.6 may be assigned as reading, or only a brief summary presented if deemed necessary.

1.1 ELECTRIC FIELDS AND CAPACITANCE

Let us start with a brief overview of electric fields and electric potential. We shall define the concept of capacitance accordingly.

Published first in 1875 by Charles Coulomb, the French army officer, Coulomb's law states that the force between two point charges, separated in vacuum or free space by a distance, is proportional to each charge, and inversely proportional to the square of the distance between them (Figure 1.1). It bears a great similarity to Newton's gravitational law, discovered about a hundred years earlier. Writing the force ($\boldsymbol{F}_t$) as a force per unit charge gives the electric field intensity, $\boldsymbol{E}$ measured in V/m (or volt per meter) as follows:

$$\boldsymbol{E} = \frac{\boldsymbol{F}_t}{Q_t} = \frac{Q}{4\pi\epsilon_0 r^2}\boldsymbol{a}_r,$$

where the ***bold*** notation indicates a vector in 3D space, $\epsilon_0 = \frac{1}{36\pi} \times 10^{-9}$ F/m (or farads per meter) is the permittivity in free space, and Q is the charge in C (or coulomb).[1] $\boldsymbol{a}_r$ is the unit vector pointing in the direction of the field, which is in the same direction as the vector $\boldsymbol{r}$ connecting the charge Q to the point of interest P in space (see Figure 1.1). Q_t is a test charge to which the force (or field) created by Q is applied.

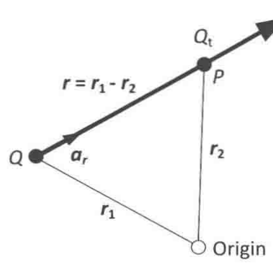

Figure 1.1 Coulomb's law

In many cases the electric field can be calculated more easily by applying Gauss's law instead. It states that the electric flux density,[2] $\boldsymbol{D} = \epsilon_0\boldsymbol{E}$ (measured in C/m^2) passing through any closed surface is equal to the total charge enclosed by that surface,[3] and mathematically expressed as:

$$\oint_S \boldsymbol{D} \cdot \mathrm{d}\boldsymbol{S} = Q,$$

where $\oint_S \boldsymbol{D} \cdot \mathrm{d}\boldsymbol{S}$ indicates the integral over a closed surface. The *dot* product ($\cdot$) indicates the product of the magnitude and the cosine of the smaller angle. The charge Q could be the sum of several charge points, that is: $Q = \sum Q_i$, a volume charge distribution: $Q = \int_V \rho_V \mathrm{d}V$, or a surface distribution, ... The nature of the surface integral implies that only the normal component of $\boldsymbol{D}$ at the surface contributes to the charge, whereas the tangential component leads to $\boldsymbol{D} \cdot \mathrm{d}\boldsymbol{S}$ equal to zero.

[1] Not to be confused with Q used as quality factor later in this chapter. [2] Only in free space.
[3] The expression itself is a result of Michael Faraday's experiment. Gauss's contribution was providing the mathematical tools to formulate it.