R. K. Mongia • I. J. Bahl • P. Bhartia • J. Hong

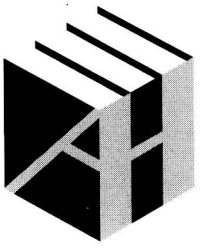
RF AND MICROWAVE COUPLED-LINE CIRCUITS

SECOND EDITION

RF and Microwave Coupled-Line Circuits

Second Edition

R. K. Mongia
I. J. Bahl
P. Bhartia
J. Hong



ARTECH
HOUSE
BOSTON | LONDON
artechhouse.com

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the U.S. Library of Congress.

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library.

ISBN-13: 978-1-59693-156-5

Cover design by Yekaterina Ratner

685 Canton Street
Norwood, MA 02062

10 9 8 7 6 5 4 3 2 1

RF and Microwave Coupled-Line Circuits

Second Edition

For a listing of recent titles in the *Artech House Microwave Library*, turn to the back of this book.

In memory of Dr. K. C. Gupta—a friend, colleague, and mentor

Foreword to the First Edition

It has been a privilege for me to go through the manuscript of the *RF and Microwave Coupled-Line Circuits.*

Sections of coupled transmission structures are critical components in distributed RF and microwave passive circuits. Significance of their role as basic building blocks is second only to the sections of single transmission structures. Their applications in design of directional couplers and filters are well known, but equally important is the role played by coupled-line sections in the design of baluns, capacitors, inductors, transformers and dc blocks. Availability of high dielectric constant materials has extended the usage of coupled-line sections to lower microwave and RF frequencies. Traditionally, coupled sections consisting of two single lines have been used extensively. However, as the circuit designers understand modeling and characterization of multiple coupled lines, we can look forward to significantly larger applications of multiple coupled transmission line structures. Three-line balun structures reported recently are a step in this direction. Also, as the multilayer RF and microwave circuits become more popular, couplings among the transmission lines at different levels of a multilayer structure become a critical design consideration. In some cases this multilayer-multiconductor coupling can be advantageous as a useful circuit component, while in other cases this coupling can become an undesirable effect that should be mitigated. Both of these situations need the modeling and characterization of multiconductor transmission line structures.

Recognizing the role of coupled lines, it is hard to comprehend why a comprehensive book on this topic has not been available so far. But then, someone has to be the leader. Bahl and Bhartia have a history of providing to the microwave design community several well-needed "firsts," and this book is their most recent contribution. Congratulations Rajesh, Inder, and Prakash on a book which I am confident will be very well received in the RF/microwave community.

K. C. Gupta
University of Colorado at Boulder
November 1998

Preface to the Second Edition

The first edition of *RF and Microwave Coupled-Line Circuits* was published in 1999. While the fundamentals of coupled line circuits have not changed in the past 8 years, further innovations in coupled line filters and other applications have occurred with changes in technology and use of new fabrication processes, such as the use of low temperature cofired ceramic (LTCC) substrates. In this case for example, it is common to use multilayer structures, with 10–25 layers being quite common. Thus, multilayer coupling needs to be better understood and explained for realizing an optimum three-dimensional design and structure that LTCC permits.

Over the years the first edition of this book has been well received in the marketplace and has been used extensively in industry by microwave engineers. Practitioners have pointed out some errors that crept into print in the first edition and over the years have suggested topics that should be added for completeness, or deleted in some cases, as they were not very useful in practice. Coupled circuits are fundamental to the realization of a large number of microwave and RF circuits, which, in turn, are essential to the development of electronic warfare, radar, communication, and navigation systems, and hence support the need for comprehensive textbooks in this area.

In the past few years, mainly driven by the desire towards miniaturization, many novel configurations of coupled-line components, such as directional couples, filters, and baluns, have been reported. Most practicing microwave and RF engineers are not fully aware of the advancements in this area.

In view of these concerns, the authors, encouraged by the publishers, felt that a revised version of *RF and Microwave Coupled-Line Circuits* would be useful for the microwave community. To ensure a fresh look, Dr. Jia-Sheng Hong, an eminent specialist in the microwave filters area, was invited to become a coauthor for the second edition. Dr. Hong has made suggestions on modifications to the book and has contributed fully in the preparation of some chapters that are closer to his area of expertise.

With the deletion of some chapters in their entirety and the addition of new chapters and new material in other chapters, overall the book remains the same size as the first edition. The first few chapters reflect only minor changes, as these incorporate the fundamentals of microwave transmission lines, networks, and coupled lines, which have not changed. Some additions and changes have been made to accommodate the multilayer design of coupled lines for the sake of having a self-contained, complete text. Most of the major changes occur in the "Applications" part of the text (i.e., Chapter 8 onward). Thus, Chapter 9, on filters, includes

the design of bandstop filters using coupled lines and a discussion of software packages used for filter design, together with their limitations and strengths.

Chapters 10 and 11 are new, building on the discussion of filters in Chapter 9. These two chapters discuss advanced filter technology, and the design of filters using new materials and technologies. Chapter 10 concentrates on coupled line filters with many specialized characteristics that are often encountered in practice. This includes designs using unevenly coupled stages, nonuniform coupled lines, meandered parallel lines, and defected ground structures. A number of other currently important topics such as filters with source-load coupling and asymmetric port excitation are also covered.

Chapter 11 takes a different direction, tackling filters using advanced materials and technologies. These include superconductor coupled-line filters, micromachined filters, miniature interdigital filters on silicon, LTCC filters which require multilayer coupling, liquid crystal polymer filters, and ultra-wideband filters. These topics encompass the new direction and materials in filter technology that will replace the older thick film and organic substrate technology over the coming decade as demands and pressures for smaller, lighter-weight, lower-cost filters mount.

Chapters 12 and 13 are essentially the former Chapters 10 and 11 with revisions as appropriate and the inclusion of new material to update the chapters and make them current.

Thus, Chapter 12 discusses the design of common microwave components requiring coupled line technology. This includes dc blocks, transformers, interdigital capacitors, and spiral inductors.

Chapter 13 covers baluns. Baluns in different configurations (e.g., microstrip to balanced stripline, planar transmission line, and Marchand type) are discussed in detail. The former Chapters 12 and 13 on high-speed circuit interconnects and multiconductor transmission lines have been deleted in their entirety. The main reason for this deletion is that although the material was relevant and useful, most engineers using the text did not feel that these chapters added much and preferred to see a greater expansion of the coverage on filters, which we have included.

Recognizing the current reality that engineers use software packages for their design and no longer do hand calculations, we have included a short discussion in each chapter where possible about current software packages that allow one to design the circuit discussed in that chapter. As an example, in Chapter 9, Section 9.2.5 covers the current software packages that are available for designing the types of filters discussed, together with their strengths, limitations, and shortcomings. We expect this feature to be of significant interest to the design engineer.

In all, there is about 35–40% new material in this second edition, though we have endeavored to keep the overall length the same as the first edition. In summary, this second edition includes one thoroughly revised and two new chapters by Dr. Hong, two less important chapters have been deleted, less important sections have been replaced by current topics, and the number of figures and their sizes have been reduced.

The authors believe that this edition will be as well accepted by professors, researchers, practicing engineers, and students, as the first edition was. Overall, this edition is more comprehensive in that equations that are not too commonly

used, as well as the lesser-used tables, have been eliminated, and material that renders the text more understandable has been added.

The preparation of any text such as this requires significant cooperation and coordination. The authors express their gratitude to colleagues from several organizations for assisting with this work and for providing permission for use of copyright figures and tables. We would specially like to thank Dr. Protap Pramanick for his suggestions and input. The help provided by Dr. James Rautio and other members of staff at Sonnet Software, Inc., is acknowledged. We appreciate the support of our work organizations and especially our families for their understanding, support, and encouragement and putting up with us during the writing phase. Last but not least, we appreciate the input from the reviewers and the support and cooperation that we received from the Artech House staff, in particular, Mark Walsh, Barbara Lovenvirth, and Rebecca Allendorf.

R. K. Mongia
I. J. Bahl
P. Bhartia
J. Hong
May 2007

Preface to the First Edition

There are a number of textbooks on microwave transmission lines. Recent ones include extensive information on the modern planar lines such as microstrip, slotlines, coplanar waveguides, and the like. At the next level of complexity are the various functional circuits such as couplers, hybrids, filters, and baluns, which use the elemental transmission line in different configurations to achieve the desired functionality and meet system performance requirements. Much of this functionality involves coupling between transmission lines, and extensive research has been conducted in the design and analysis of such structures. Initially, much of the literature was oriented to coaxial lines and waveguides. With the evolution and the popularity of planar transmission lines, however, it was felt desirable to put together all aspects of coupled circuits using these lines under one cover.

Most current texts, we found, contained perhaps a chapter or two on some specific components, especially couplers and filters. This text attempts to treat the topic in its entirety, starting with the fundamental theory of coupled structures and the application of this to the design and analysis of specific components such as couplers, filters, baluns, and so forth. This treatment emphasizes planar transmission lines, the CAD tools available for the design of these structures, use of full-wave analyses and accurate semiempirical equations for component design, novel structures and configurations, and new applications.

This book is primarily intended for design engineers and research and development specialists who are involved in the area of coupled-line circuit design, analysis, development, and fabrication. The layout of the book facilitates its use as a text for a graduate course and for short courses on specific component design.

The book is divided into 13 chapters. The first chapter introduces the reader to the topic and covers the nature of coupled structures, the importance of these structures in microwave circuits, and some applications. A good introduction to the principal components using coupled lines (i.e., directional couplers and filters) is also given.

The second chapter establishes the basic circuit parameters and representation of microwave networks. Fundamental network analysis tools such as impedance and scattering matrix techniques are introduced together with the properties of two-, three-, and four-port networks. Relationships between the commonly used matrix representation forms such as ABCD, scattering, and impedance are established to permit the researcher or designer to work in the system of his or her preference.

The fundamental building blocks for coupled-line circuits (i.e., transmission lines) are covered in Chapter 3. In particular, the characteristics of the commonly

used planar lines, such as microstrip, coplanar, and striplines are covered in detail. In addition, the characteristics of coupled lines in these configurations under different conditions such as broadside coupling, edge coupling, or, in the case of coplanar waveguides, coupling with shields present are discussed. Whereas Chapter 3 concentrates on characteristics of physical transmission lines, Chapter 4 presents the general analysis of uniformly coupled asymmetrical lines, including forward and backward couplers. These fundamentals permit a more in-depth coverage of the coupling of uniform lines, which is covered in the next chapter. Even- and odd-mode analysis is covered together with an analysis of uniformly coupled asymmetrical lines. Forward and backward directional coupler design methods using the aforementioned techniques are also given in the chapter.

The next few chapters are devoted to the design of various types of directional couplers. Many directional couplers by their very nature and design have a narrowband performance. In a number of applications, broadband performance is essential. The design and performance of forward-directional couplers using asymmetrical coupled lines are the subject of Chapter 5. Coupled-mode theory, also discussed in this chapter, is very useful for the analysis of general weakly coupled systems.

Parallel-coupled backward TEM directional couplers using a single section or multisections are discussed in Chapter 6, together with limitations and methods for improving the directivity of such couplers. This permits the reader to have a good understanding of how these circuits work and the methods, including lumped-element compensation and dielectric overlay, that can be used to improve directivity. While we dealt with broadband couplers using multisection couplers in Chapter 6, one can also obtain this type of characteristic of performance using nonuniform lines. Additional flexibilities, and at the same time complexities, are introduced with this line, but in many cases it is essential to resort to this process because of physical or performance constraints imposed by the overall circuit design. In Chapter 7, the design and synthesis procedure for such couplers is outlined, together with some other techniques to obtain broadband performance.

Finally, the last type of coupler that requires special treatment is the tight coupler. Tight couplers, as described in Chapter 8, can be designed and fabricated in a number of configurations. Some of the most prevalent forms are the branch-line coupler, rat-race coupler, and lumped-element coupler. These are fully covered in this chapter, together with a large number of other layouts including the multiconductor couplers and tandem couplers. A number of novel designs are also discussed, including the interdigital Lange couplers and compact couplers for wireless applications. The material provided gives the designer a good grasp of the principles and techniques involved in the design of these coupler types, together with the advantages and disadvantages of the specific couplers. This information and understanding is critical to the designer in assisting him or her to choose the appropriate coupler type to meet not only the electrical performance characteristics but also to meet any form, fit, and function requirements imposed.

Besides the directional couplers covered in the previous chapters, perhaps the most commonly used form of coupled line circuits is the filter. This is covered extensively in Chapter 9, starting with a definition of filter parameters and leading on to filter synthesis, design, and realization. Modern miniature filters are discussed,

as they are critical to the wireless communications area, and an assessment of the capabilities of a number of software packages available for filter design is provided.

The next two chapters delve into a number of other commonly used coupled circuits. Chapter 10 covers the analysis and design of a number of dc blocks, coupled-line transformers, interdigital capacitors, spiral inductors, and transformers, while Chpater 11 treats the design and analysis of baluns. In particular, the Marchand balun is discussed in detail, together with other types of baluns such as the coplanar waveguide balun, triformer balun, and planar transformer balun.

Whereas the preceding chapters have used coupling as a means of achieving a specific function and performance, in many cases coupling is not desirable and can create problems. This is typically the electromagnetic compatability/electromagnetic interference problem that is encountered by any circuit designer. To try to cover the topic of coupled circuits in its entirety, we have included high-speed digital interconnections in Chapter 12 to bring about an awareness of the cross-talk problem and provide ways to mitigate this problem. Finally, many of the passive devices covered could use multiconductor lines for their design. The literature on this topic is very dispersed. In Chapter 13, we have provided the essential information for the designer to permit the use of multiconductor lines as the building block for the type of coupled-line circuit one wished to design.

As with any comprehensive treatment of a topic, one must draw upon the works of a large number of researchers and authors. We have taken special care to reproduce equations and diagrams and believe that this text is a valuable addition to the microwave circuit designer's library.

The preparation of this text has depended on a number of very supportive individuals and organizations. Naturally, the time spent during evenings and weekends comes at the expense of time with our families. For their support and understanding we are eternally grateful. The organizations that we work for have also supported this project in many ways and we wish to express our thanks to them. While always dangerous to mention specific names because some others will feel left out, we have no hesitation in recognizing the contributions and acknowledging with our thanks the assistance of Josie Dunn for typing the manuscript and Bob Gervais of the Defence Research Establishment, Ottawa, who devoted large blocks of time in preparing the illustrations. Part of the manuscript has been handled efficiently by Tanya Morrision of ITT GaAsTEK, Roanoke. The Artech House team did an excellent job on the final book. We would like to thank Mark Walsh, Barbara Lovenvirth, Hilary Sardella, Judi Stone, Steve Cartisano, and Elaine Donnelly for their patience, support, and cooperation. Finally, we want to thank the reviewers for their thoroughness and excellent suggestions for improving the text.

R. K. Mongia
I. J. Bahl
P. Bhartia

Contents