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Artificial Transmission Lines for RF *and* Microwave Applications

Ferran Martín

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PREFACE

Transmission lines and waveguides are essential components in radiofrequency (RF) and microwave engineering for the guided transmission of electromagnetic (EM) energy (power and information signals) between two points. Moreover, transmission lines and waveguides are key building blocks for the implementation of passive and active RF/microwave devices of interest in wireless communications (filters, diplexers, splitters, couplers, amplifiers, oscillators, mixers, etc.). In planar technology, low-cost devices can be fabricated by etching patterns (a set of transmission lines and stubs providing certain functionality) in a printed circuit board (PCB), avoiding the use of lumped components, such as capacitors, inductors, or resonators. Transmission line-based circuits are usually designated as distributed circuits, since transmission lines can be described by a network of distributed parameters. In certain designs (e.g., amplifiers and mixers), it is necessary to combine distributed and lumped active elements, such as diodes or transistors. Nevertheless, the main relevant aspect of distributed components is their capability to mimic lumped-reactive elements or a combination of them (e.g., resonators or even more complex reactive circuits). It is thus possible to design fully planar functional devices on the basis of the distributed approach, or to minimize the number of lumped elements (unavoidable in certain components, e.g., active circuits) in the designs.

Distributed circuits have two main drawbacks: (1) their dimensions scale with frequency, and (2) transmission lines exhibit very limited design flexibility. Typically, the required transmission lines in the designs have a length of the order of the wavelength, which means that dimensions may be too extreme if the operating frequencies are moderate or low. Concerning the second aspect, distributed circuits are designed by means of transmission lines with certain phase (at the operating frequency) and characteristic impedance. The phase varies linearly with the length of the line and frequency (to a first-order approximation transmission lines are dispersionless). Therefore, the functionality of distributed circuits is limited to a certain band; namely, the required nominal phase is lost if frequency deviates from the operating value, which means that distributed circuits are bandwidth limited by nature.

The limitations of ordinary transmission lines as building blocks for device design are in part originated from the fact that these lines exhibit a limited number of free parameters for design purposes (by excluding losses, ordinary lines are described by a distributed network with two reactive elements in the unit cell). However, by truncating the uniformity (in the longitudinal direction), by etching patterns in the ground plane, by loading the line with reactive elements, or by using a combination of these (or other) strategies to increase the degrees of freedom of the lines, many possibilities to reduce device size, to improve performance, or to achieve novel functionalities, are open. This book has been mainly conceived to introduce and study alternatives to ordinary lines for the design and implementation of RF/microwave components with superior characteristics in the above cited aspects. We refer to these lines as artificial transmission lines, and the term is as wide as the number of strategies that one can envision to improve the size, performance, or functionality of ordinary lines. The book is devoted to the analysis, study, and applications of artificial lines mostly implemented by means of a planar transmission line (host line) conveniently modified (e.g., with modulation of transverse dimensions, with etched patterns in the metallic layers, and with reactive loading), in order to achieve certain functionality, superior performance, or reduced size. Nevertheless, it will be shown that in certain artificial waveguiding structures, such as electroinductive and magnetoinductive delay lines, the host line is not present. Waveguide-based components are not included in this book, entirely focused on artificial transmission lines in planar technology. Obviously, it is not possible to cover all the material available in the literature, related to the topic of artificial transmission lines, in a single book. Necessarily, the contents of this book are influenced by the personal experience and background of the author. However, many RF/microwave devices and applications of artificial transmission lines reported by other researchers are included in this book, or properly referenced.

The book is devoted to readers that are already familiar with RF/microwave engineering. The aim of writing this book has been to provide an up-to-date state of the art in artificial transmission lines, and an in-depth analysis and study of those aspects, structures, devices, and circuits that are more relevant (according to the criterion of the author) for RF/microwave engineering, including design guidelines that can be useful to researchers, engineers, or students involved in the topics covered by this book. Nevertheless, Chapter 1 is dedicated to the fundamentals of planar transmission lines for coherence and completeness, since most of the concepts of this chapter are used in the subsequent chapters, and are fundamental to understand the principles and ideas behind the design and applications of artificial transmission lines.

Chapter 2 is focused on artificial transmission lines based on periodic structures, where periodicity plays a fundamental role and is responsible for the presence of band gaps in the transmission spectrum of these lines. The Floquet analysis (leading to the concept of space harmonics), complemented by the coupled mode theory (from which useful expressions for the design of periodic artificial lines are derived), and the transfer matrix method (useful to obtain the dispersion relation of the fundamental space harmonic), are included in the chapter. The last part is devoted to the applications, which have been divided into those of periodic nonuniform transmission lines (e.g., harmonic and spurious suppression), and those of reactively loaded lines, where not only the reflection properties of periodic structures but also the inherent slow-wave effect associated to reactive loading, are exploited.

Chapters 3 and 4 are dedicated to artificial transmission lines inspired by metamaterials, or based on metamaterial concepts. The importance of these artificial lines in this book has forced the author to separate the fundamentals/theory and applications into different chapters in order to avoid an excessive chapter length. Thus, Chapter 3 is focused on the theory, circuit models, and main implementations of metamaterial transmission lines, whereas Chapter 4 deals with the applications. Many applications of metamaterial transmission lines are based on the superior controllability of the characteristic impedance and dispersion of these lines, as compared to ordinary lines, related to the presence of reactive elements loading the line. Indeed, metamaterial transmission lines have opened a new way of "thinking" in the design of microwave components, where tailoring the dispersion diagram, and not only the characteristic impedance, is the key aspect (we may accept that metamaterial transmission lines have given rise to microwave circuit design on the basis of impedance and dispersion engineering). The further controllability of the relevant line parameters (phase constant and characteristic impedance) in metamaterial transmission lines, as compared to ordinary lines, has a clear parallelism with the further controllability of the constitutive parameters (permittivity and permeability) in effective media metamaterials (periodic artificial structures exhibiting controllable EM properties, different from those of the materials which they are made). Indeed, we can define an effective permittivity and permeability in metamaterial transmission lines despite that these lines are one-dimensional structures, and we can design the lines in order to support backward (or left-handed) wave propagation (as occurs in metamaterials with simultaneous negative effective permittivity and permeability). However, whereas in effective media metamaterials periodicity and homogeneity (satisfied if the period is much smaller than the wavelength) are necessary conditions to properly define an effective permeability and permittivity, periodicity, and homogeneity are not requirements for impedance and dispersion engineering with metamaterial transmission lines.

The former metamaterial transmission lines were implemented by loading a host line with series capacitors and shunt inductors (CL-loaded approach), or by loading the host lines with electrically small resonators, formerly used for the implementation of bulk effective media metamaterials (metamaterial resonators). This latter approach has been called resonant-type approach. Both approaches are included in this book (and many other latter developments), but special emphasis is put on the resonant-type approach. Moreover, in Chapter 4 there are several applications where, rather than the controllability of the impedance and dispersion of the artificial lines, the working principle is the resonance of a transmission line (host line) loaded with metamaterial resonators (these lines are designated as transmission lines with metamaterial loading in Chapter 4). Since metamaterial transmission lines are inspired by metamaterials, an introduction to these artificial media and the former implementation are included in Chapter 3. Chapter 3 includes also a section devoted to study the main electrically small resonators useful for the synthesis of metamaterials and microwave circuits based on them (resonant-type approach). In Chapter 4, the applications include enhanced bandwidth components, multiband components, filters and diplexers, active devices with novel functionalities (e.g., distributed amplifiers), novel antennas (e.g., leaky wave antennas and antennas for RFID tags), microwave sensors, and so on.

In Chapter 5, the focus is on reconfigurable components based on tunable artificial lines and nonlinear transmission lines. Several materials, components, and technologies (including varactors, RF-MEMS, ferroelectrics, and liquid crystals) for the implementation of tunable components are introduced. Then the chapter focuses on the design of tunable artificial transmission lines and their applications, mostly, although not exclusively, devoted to filters. The last part of the chapter deals with the topic on nonlinear transmission lines, structures that support the propagation of solitons and are of interest for harmonic multiplication.

Finally, other advanced transmission lines or, more generally, waveguiding structures are presented and studied in Chapter 6, including applications. The covered topics are electroinductive and magnetoinductive wave delay lines, common-mode suppressed differential lines, lattice network-based transmission lines, transmission lines loaded with non-Foster components, and metamaterial-based substrate-integrated waveguides. Grouping these topics in a single chapter does not obey to a thematic reason, but to the fact that most of them have been recently proposed and/or are still under development, or even to the fact that they are very specific to be included in the previous chapters (e.g., the electroinductive and magnetoinductive wave delay lines and the substrate-integrated waveguides).

It is the author's hope that the present manuscript constitutes a reference book in the topic on artificial transmission lines and their RF and microwave applications, and that the book can be of practical use to researchers, students and engineers involved in RF and microwave engineering, especially to those active in planar circuit and antenna design.

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CONTENTS

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FUNDAMENTALS OF PLANAR TRANSMISSION LINES

1.1 PLANAR TRANSMISSION LINES, DISTRIBUTED CIRCUITS, AND ARTIFICIAL TRANSMISSION LINES

In radiofrequency (RF) and microwave engineering, transmission lines are two-port networks used to transmit signals, or power, between two distant points (the source and the load) in a guided (in contrast to radiated) way. There are many types of transmission lines. Probably, the most well-known transmission line (at least for nonspecialists in RF and microwave engineering) is the coaxial line (Fig. 1.1), which consists of a pair of concentric conductors separated by a dielectric, and is typically used to feed RF/microwave components and to connect them to characterization and test equipment. Other planar transmission lines are depicted in Figure 1.2. There are many textbooks partially or entirely focused on transmission lines and their RF and microwave applications [1–8]. The author recommends these books to those readers interested in the topic of the present book (artificial transmission lines), which are not familiar with conventional (or ordinary) transmission lines. Nevertheless, the fundamentals of planar transmission lines are considered in this chapter for completeness and for better comprehension of the following chapters. As long as waveguides (and even optical fibers) do also carry electromagnetic (EM) waves and EM energy between two points, they can also be considered transmission lines. However, this book is entirely devoted to planar structures; and for this reason, waveguides are out of the scope of this chapter.

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