Coplanar Waveguide Circuits, Components, and Systems

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Preface

This book is intended to provide a comprehensive coverage of the analysis and applications of coplanar waveguides to microwave circuits and antennas for graduate students in electrical engineering and for practicing engineers.

Coplanar waveguides are a type of planar transmission line used in microwave integrated circuits (MICs) as well as in monolithic microwave integrated circuits (MMICs). The unique feature of this transmission line is that it is uniplanar in construction, which implies that all of the conductors are on the same side of the substrate. This attribute simplifies manufacturing and allows fast and inexpensive characterization using on-wafer techniques.

The first few chapters of the book are devoted to the determination of the propagation parameters of conventional coplanar waveguides and their variants. The remaining chapters are devoted to discontinuities and circuit elements, transitions to other transmission media, directional couplers, hybrids and magic-T, microelectromechanical systems (MEMS) based switches and phase shifters, high-$T_c$ superconducting circuits, tunable devices using ferroelectric materials, photonic bandgap structures, and printed circuit antennas. The author includes several valuable details such as the derivation of the fundamental equations, physical explanations, and numerical examples.

The book is an outgrowth of 15 years of research conducted by the author as a member of the Communications Technology Division (CTD) at the National Aeronautics and Space Administration (NASA), Glenn Research Center (GRC) in Cleveland, Ohio. Over the past few years, interest among engineers in coplanar waveguides has increased tremendously, with some of the concepts being extensively pursued by NASA for future space programs and missions. Numerous articles exist, but there is no collective publication. Thus the decision to publish a book on coplanar waveguides appears to be appropriate.

In the course of writing this book, several persons have assisted the author and offered support. The author first expresses his appreciation to the management of CTD at GRC for providing the environment in which he worked on
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CHAPTER 1

Introduction

A coplanar waveguide (CPW) fabricated on a dielectric substrate was first demonstrated by C. P. Wen [1] in 1969. Since that time, tremendous progress has been made in CPW based microwave integrated circuits (MICs) as well as monolithic microwave integrated circuits (MMICs) [2] to [5].

1.1 ADVANTAGES OF COPLANAR WAVEGUIDE CIRCUITS

1.1.1 Design

A conventional CPW on a dielectric substrate consists of a center strip conductor with semi-infinite ground planes on either side as shown in Figure 1.1. This structure supports a quasi-TEM mode of propagation. The CPW offers several advantages over conventional microstrip line: First, it simplifies fabrication; second, it facilitates easy shunt as well as series surface mounting of active and passive devices [6] to [10]; third, it eliminates the need for wraparound and via holes [6] and [11], and fourth, it reduces radiation loss [6]. Furthermore the characteristic impedance is determined by the ratio of $a/b$, so size reduction is possible without limit, the only penalty being higher losses [12]. In addition a ground plane exists between any two adjacent lines, hence cross talk effects between adjacent lines are very week [6]. As a result, CPW circuits can be made denser than conventional microstrip circuits. These, as well as several other advantages, make CPW ideally suited for MIC as well as MMIC applications.

1.1.2 Manufacturing

Major advantages gained in manufacturing are, first, CPW lends itself to the use of automatic pick-and-place and bond assembly equipments for surface-mount component placement and interconnection of components, respectively
Second, CPW allows the use of computer controlled on-wafer measurement techniques for device and circuit characterization up to several tens of GHz [13], [14]. These advantages make CPW based MICs and MMICs cost effective in large volume.

1.1.3 Performance

The quasi-TEM mode of propagation on a CPW has low dispersion and hence offers the potential to construct wide band circuits and components. In CPW amplifier circuits, by eliminating via holes and its associated parasitic source inductance, the gain can be enhanced [15].

1.2 TYPES OF COPLANAR WAVEGUIDES

Coplanar waveguides can be broadly classified as follows:

- Conventional CPW
- Conductor backed CPW
- Micromachined CPW

In a conventional CPW, the ground planes are of semi-infinite extent on either side. However, in a practical circuit the ground planes are made of finite extent. The conductor-backed CPW has an additional ground plane at the bottom surface of the substrate. This lower ground plane not only provides mechanical support to the substrate but also acts as a heat sink for circuits with active devices. A conductor backed CPW is shown in Figure 1.2. The micromachined CPWs are of two types, namely, the microshield line [16] and the CPW suspended by a silicon dioxide membrane above a micromachined groove [17].
These lines are illustrated in Figures 1.3 and 1.4, respectively. The advantages of the microshield line are its extremely wide bandwidth, minimal dispersion and zero dielectric loss. The advantage of the later CPW is that it is compatible with commercial CMOS foundry process and hence, is capable of monolithically integrating CMOS devices and circuits.

1.3 SOFTWARE TOOLS FOR COPLANAR WAVEGUIDE CIRCUIT SIMULATION

Recently accurate models for CPW discontinuities, such as open circuits and short circuits, lumped elements, such as inductors and capacitors, and three- and four-port junctions, such as, tee- and crossjunctions, have become com-

![Figure 1.2](image1.png)

**FIGURE 1.2** Schematic of a conductor-backed coplanar waveguide (CBCPW).

![Figure 1.3](image2.png)

**FIGURE 1.3** Cross section of a microshield line. (From Reference [16], © IEEE 1995.)
FIGURE 1.4 Cross section of a coplanar waveguide suspended by a silicon dioxide membrane over a micromachined substrate. (From Reference [17], © IEEE 1997.)

mercially available [5], [18] to [21]. In addition electromagnetic simulation software for 2-D and 3-D structures have also become commercially available [21] to [25].

1.4 TYPICAL APPLICATIONS OF COPLANAR WAVEGUIDES

1.4.1 Amplifiers, Active Combiners, Frequency Doublers, Mixers, and Switches

The CPW amplifier circuits include millimeter-wave amplifiers [26], [27], distributed amplifiers [28], [29], cryogenically cooled amplifiers [30], cascode amplifiers [31], transimpedance amplifiers [32], dual gate HEMT amplifiers [33], and low-noise amplifiers [34]. The CPW active combiners and frequency doublers are described in [35] and [36], respectively. The CPW mixer circuits include ultra-small drop in mixers [37], beam lead diode double-balanced mixers [38], harmonic mixers [39], MMIC double-balanced mixers [40], [41] and double-balanced image rejection, MESFET mixers [42]. The CPW PIN diode SPDT switches are described in [43] and [44].

1.4.2 Microelectromechanical Systems (MEMS) Metal Membrane Capacitive Switches

The rapid progress made in the area of semiconductor wafer processing has led to the successful development of MEMS based microwave circuits. In a CPW
the conductors are located on the top surface of a substrate which makes it ideally suited for fabricating metal membrane, capacitive, shunt-type switches [45]. CPW MEMS shunt switches with good insertion loss characteristics, reasonable switching voltages, fast switching speed, and excellent linearity have recently been demonstrated [45]. These switches offer the potential to built new generation of low-loss high-linearity microwave circuits for phased array antennas and communication systems.

1.4.3 Thin Film High-Temperature Superconducting /Ferroelectric Tunable Circuits and Components

Recent advances made in the area of thin film deposition techniques, such as sputtering, laser ablation and chemical vapor deposition, and etching technologies, have resulted in the application of high temperature superconducting (HTS) materials to microwave circuits [46]. The HTS circuits have low microwave surface resistance over a wide range of frequencies. As a result signal propagation takes place along these transmission lines with negligible amount of attenuation. Furthermore the advantage of using CPW is that only one surface of the substrate needs to be coated with HTS material before patterning. Recently HTS low-pass and band-stop CPW filters have been demonstrated in [47] and [48], respectively.

In addition by incorporating ferroelectric materials such as, SrTiO$_3$ with HTS materials such as, YBa$_2$Cu$_3$O$_{7-x}$, low-loss, voltage-tunable MMICs with reduced length scales can be constructed [49] and [50]. These MMICs have potential applications in phased array antenna systems and frequency agile communications systems. Recently voltage tunable CPW YBa$_2$Cu$_3$O$_{7-x}$/SrTiO$_3$ phasewhitters, mixers and filters have been demonstrated [50].

1.4.4 Photonic Bandgap Structures

When an electromagnetic wave propagates along a conductor backed CPW considerable amount of energy leakage takes place. The energy that leaks, propagates along the transverse directions away from the line, and excites a parallel plate mode between the CPW top and bottom ground planes. The parasitic parallel plate mode is the leading cause for crosstalk between adjacent circuits. The cross talk can be suppressed by constructing a photonic bandgap lattice on the CPW top ground planes as demonstrated in [51].

1.4.5 Printed Antennas

A radiating element is constructed from a conventional CPW by widening the center strip conductor to form a rectangular or square patch [52]. This patch produces a single-lobe, linearly polarized pattern directed normal to the plane of the conductors. The advantage gained over conventional microstrip patch antenna is lower crosspolarized radiation from the feed [52]. In [53] a
conductor backed CPW with a series gap in the center strip conductor is used to couple power to a patch through an aperture in the common ground plane. This design offers the flexibility of inserting semiconductor devices in the series gap of the feed for controlling the coupling.

1.5 ORGANIZATION OF THIS BOOK

This book is organized to serve as a text for a graduate course in MICs and MMICs, as well as a reference volume for scientists and engineers in industry. Chapter 1 gives an overview of the advantages, types, and typical applications of CPW.

Chapters 2 through 5 are devoted to the basic structures such as conventional CPW, conductor backed CPW, CPW with finite-width ground planes, elevated CPW, and CPW suspended inside a conducting enclosure. Analytical expressions to compute, the effective dielectric constant and characteristic impedance of the lines are provided.

Chapter 6 discusses coplanar stripline (CPS) and its variants. Analytical expressions to compute, the effective dielectric constant and the characteristic impedance are provided.

Coupled CPWs have several applications in the design of microwave components such as, directional couplers and filters. In Chapter 7 the even-mode and odd-mode characteristics of both edge coupled as well as broadside coupled CPWs are presented.

When an electromagnetic wave propagates along a CPW it suffers attenuation due to conductor and dielectric losses. In Chapter 8 the attenuation characteristics of conventional, micromachined, and superconducting CPWs are discussed.

Discontinuities such as, open circuits and circuit elements, such as air-bridges, are an integral part of practical CPW circuits. A good understanding of their characteristics is essential for design success. Hence Chapter 9 is devoted to CPW discontinuities.

Transitions between CPW and other transmission media are essential for integrating various components and subsystems into a complete system. Chapter 10 presents transitions between CPW and the following transmission lines: microstrip, slotline, coplanar stripline, balanced stripline, and rectangular waveguide.

Coupling of power from one line to another takes place when the lines are placed in close proximity to each other. In Chapter 11 the design and construction of directional couplers are presented. These couplers can be realized using either edge coupled CPW or broadside coupled CPW. In addition the construction and design of hybrid couplers and magic-Ts are also discussed.

Finally, Chapter 12 presents several emerging applications of CPW. These applications include microelectromechanical systems (MEMS) based switches.
and phase shifters, high-temperature superconducting circuits, tunable components based on ferroelectric materials, photonic bandgap structures and printed circuit antennas.

REFERENCES


