CHAPTER ONE

Introduction

1.1 PROLOGUE

The rapid development of computer techniques and information technologies in recent decades has fueled the need for efficient tools for electromagnetic modeling of microwave and millimeter-wave integrated circuits, high-speed and high-density very large scale integration (VLSI) circuits including computer chips, and wireless communication applications. A number of computational techniques are currently used for electromagnetic modeling by practicing microwave and antenna engineers, including the method of moments (MoM), the finite difference time domain (FDTD) method, and the finite element method (FEM). Among these, the FDTD, introduced by K. S. Yee in 1966 [1], appears to be one of the most widely used methods for many engineering applications [1–8].

The FDTD method can be implemented in a relatively straightforward manner. It can easily deal with complex geometrical features as well as different material properties; in addition, it can efficiently handle communication waveforms with wide bandwidths. Various modifications and extensions of the original FDTD algorithm have been implemented to enhance its performance, including hybrid methods [9, 10], higher-order FDTD schemes [11, 12], and Berenger's perfectly matched layer (PML) [13]. The latter enables us to truncate the FDTD mesh with boundaries that are very close to the structures being modeled.

Although the FDTD technique is simple and versatile, it places a heavy burden on computer resources when it involves modeling a complex problem that occupies a large computational volume. This is because it uses a fine spatial resolution in the frequency band of interest, usually 20 cells or more per wavelength, in order to achieve a reasonable degree of accuracy. Although progress in computer technology has made it possible to use the conventional FDTD technique to

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solve relatively large problems, it is important to enhance its capabilities further in order to tackle even larger problems.

The multiresolution time domain (MRTD) scheme, recently introduced by Krumpholz and Katehi [14, 15], shows excellent potential for achieving this goal by reducing the grid density to a level close to the Nyquist sampling rate. The use of scaling and wavelet functions and the application of the multiresolution analysis—in conjunction with the MoM-based discretization of Maxwell equations—form the cornerstones of the MRTD scheme. In this scheme, the electromagnetic fields are represented in terms of expansions of scaling and wavelet functions for spatial variation, and rectangular pulse functions for time variation.

The technique has a number of advantages, including a unified and higher-order field expansion structure for both the FDTD and MoM techniques. To put it slightly differently, the FDTD method is the simplest version of the MRTD scheme. We will show how the users of the MRTD scheme, described herein, can significantly reduce the requirements of computation time and memory for a class of electromagnetic simulation problems. We will also present numerous examples to demonstrate that the MRTD scheme is developing rapidly and that it has been applied successfully to the analysis of a broad variety of microwave and antenna structures [14–26].

1.2 OBJECTIVES

Our objectives here are: (1) to detail the essential characteristics and applications of the MRTD scheme, which are based mainly on the field expansions of scaling and high-level wavelet functions of the cubic spline Battle–Lemarié, Haar, Daubechies, and biorthogonal Cohen–Daubechies–Feauveau (CDF) as well as the biorthogonal interpolating wavelet families; (2) to develop a unified theoretical framework suitable for the electromagnetic modeling of guided-wave structures, millimeter-wave integrated circuits (MMICs), radar target scattering and antennas, and wireless communication applications; and (3) to demonstrate the advantages of the MRTD scheme over the conventional FDTD method for certain types of applications.

In order to fulfill the above objectives, the MRTD scheme is applied in conjunction with an adjustable multiple image technique (MIT) or an automatic image generator (AIG) to truncate the boundaries of the computational domain characterized by a perfect electric conductor (PEC) or a perfect magnetic conductor (PMC). An anisotropic perfectly matched layer (APML) is used to truncate open boundaries. Also, two-dimensional (2D) and three-dimensional (3D) versions of the MRTD plane-wave incidence and the near-to-far-zone field transforms are developed for scattering and radiation applications.

Before closing this section it may be useful to point out that the MRTD formulations presented herein still retain the concept of the leapfrog algorithm employed in the conventional FDTD method and inherit most of its advantages.

1.3 OVERVIEW

This monograph is designed to cover both the theoretical and practical aspects of the MRTD scheme and comprises twelve chapters and four appendixes, each of which focuses on a topic pertaining to the systematic development of the MRTD scheme and its applications. It covers the entire range of state-of-the-art topics that are pertinent to the current development of the MRTD, including the construction of the MRTD framework, choice of basis functions for field representations in the context of the MRTD, and applications to practical electromagnetic wave propagation problems.

Chapter 1 serves as an introduction, in which the background, objective, motivation, and an overview of the MRTD scheme are presented. In Chapter 2 the mathematical basis of the multiresolution analysis (MRA) is discussed, including the concepts of signal space and scaling and wavelet functions. This chapter also addresses the topic of generalized field expansions in terms of scaling and wavelet functions, which serves as the foundation of the MRTD development.

Chapter 3 mainly focuses on the following types of wavelet bases that are commonly used in the MRTD analysis: cubic spline Battle–Lemarié, Daubechies, biorthogonal Cohen–Daubechies–Feauveau (CDF), and biorthogonal interpolating wavelet bases. The construction—as well as the properties—of the scaling and wavelet functions is discussed and the three-dimensional multiresolution time domain update algorithms are developed in a homogeneous uniform space for all the basis function families.

Next, in Chapter 4, we introduce the fundamentals of the MRTD algorithm. This chapter provides a simple explanation of the MRTD kernel and develops a coherent relationship among the FDTD, MoM, and MRTD in a discrete computational space. In addition, the generalized MRTD update equations for dealing with a hybrid computational space that involves both conductors and dielectric materials are presented. The stability of the MRTD scheme and the orthogonal and integral relations in the implementation of the scheme are summarized as well.

In Chapter 5, we examine the issue of mesh truncations for a structure enclosed with either PEC or PMC walls. Also, we introduce the concept of the MIT—which is a flexible tool for determining the number of images on each side of a PEC-shielded structure, such as a shielded cavity, in the computational domain. In addition, we introduce the principle of the AIG, a software package that can easily generate images for a (fully or partially) shielded microwave structure. The MRTD-MIT method is then validated by analyzing a number of representative structures shielded by a PEC, including an empty rectangular cavity and a partially filled resonant cavity. The MRTD results are compared with those derived from the FDTD scheme as well as from analytical solutions. We show that even though the MRTD scheme requires only a small fraction of the computer memory and CPU time in comparison to those required by the conventional FDTD methods, its results compare very favorably with the latter in terms of accuracy.

Chapter 6 focuses on the applications of the unsplit APML s for mesh truncation of open boundaries in the context of the MRTD scheme. After introducing the APML medium, the governing equations inside the APML regions are developed. Following this, we discuss various aspects of implementing the APMLs, including the treatment of different types of APML regions, for example, APML faces, edges, and corners, choice of APML parameters, and the derivation of APML update equations.

Next, in Chapter 7, we describe the application of a one-dimensional (1D) MRTD scheme for electromagnetic wave propagation in a multilayer dielectric system, using scaling and high-level multiresolution wavelet functions to illustrate the structure and construction of the MRTD scheme in a systematic manner. We also examine the computational resources required by the MRTD scheme and compare the MRTD results with those derived from the FDTD. Additionally, we validate the results by comparing them against analytical solutions.

In Chapter 8, we go on to develop a two-dimensional (2D) MRTD model in conjunction with the unsplit APML for truncation of open regions in guided-wave structures. This chapter consists of two parts. The first presents a 2D-MRTD scheme for the analysis of printed millimeter-wave transmission lines by utilizing the transverse resonance property of guided-wave structures, while the second deals with the problem of TE_z and TM_z wave propagation in a parallel-plate transmission line. We also demonstrate that the MRTD scheme generates results that are in excellent agreement with those obtained by using the FDTD approach, the MoM, and analytical methods.

Chapter 9 discusses the development of a three-dimensional (3D) MRTD scheme, which is applied in conjunction with the APML, MIT, or AIG for the mesh truncation of open regions as well as PEC-shielded boundaries. Applications of the MRTD-APML, MRTD-MIT, and MRTD-AIG schemes are illustrated by analyzing a number of representative microwave structures. In particular, by utilizing only the field quantities defined in the original structure, a systematic algorithm for dealing with inhomogeneous media inside a microwave structure is developed in order to construct the constitutive relations and update equations in the MRTD transform domain. The characteristics of microstrip lines and inhomogeneously filled dielectric cavities are investigated and the MRTD results are validated once again.

In Chapter 10, the MRTD scheme is applied to the problem of monolithic millimeter-wave integrated circuit (MMIC) structures, including microstrip lines, microstrip patch antennas, and microstrip low-pass and band-pass filters. It is shown that good agreement between the MoM, FDTD, and MRTD techniques is achieved, despite the fact that the MRTD technique requires only around 15% of computational space and about 25% or less of the computational CPU time, as compared to the FDTD method.

In Chapters 11 and 12, we concentrate on scattering problems involving both two- and three-dimensional structures by utilizing the "scattered field" formulation. We also develop the 2D and 3D versions of the plane-wave incidence and the near-to-far-zone field transformation in the context of the MRTD to calculate either the scattering width (SW) or the radar cross section (RCS). We then employ these schemes to analyze a variety of PEC and dielectric targets, and we validate the MRTD results by comparing them with those derived from the FDTD as well as the MoM.

In addition to the twelve chapters, we also include four appendixes, which provide supplementary materials that help clarify the theoretical developments and show the derivation of various mathematical relations and update equations. In Appendix A, we introduce the concept of the generalized differential matrix operators (GDMOs), for formulation of engineering electromagnetic problems, and discuss the applications of the GDMOs in the formulation of practical electromagnetic problems. In Appendix B, we summarize most of orthogonal and integral relations that are frequently employed in the cubic spline Battle–Lemarié scaling and wavelet based MRTD scheme. Appendix C focuses on the development of the MRTD-APML algorithm for all APML faces, edges, and corners and presents a two-step approach for deriving the APML update equations. Finally, in Appendix D, we summarize the properties of the scaling and wavelet functions for the convenience of readers. In particular, this appendix provides various expressions of the cubic-spline Battle–Lemarie scaling and wavelet functions, as well as their mother functions, and also presents some of their important properties that are not commonly found in the literature.

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