CHAPTER 1

Introduction

Preface

This chapter starts with a small introduction on numerical techniques and presents a survey of the literature dealing with the analysis of waveguide discontinuities using several numerical techniques and application of higher-order methods to scattering and antenna problems. It also presents the objectives of the thesis and concludes with the organization of the thesis.

1.1 Introduction

Waveguides and waveguide based components and circuits are still widely used because of their ability to handle high power and mechanical toughness. Designing waveguide circuits calls for an accurate and efficient analysis technique. There are a number of techniques used for the waveguide circuits and components analysis e.g. variational technique, method of moments (MoM), mode matching, finite element method (FEM) and finite difference time domain (FDTD). Out of these, the MoM has been one of the most popular techniques and has spawned a number of quite successful commercial softwares. It solves the integral equation formulation of a problem by expressing the unknown function, often the current densities, as linear combination of known functions called bases or basis functions. These bases exist either over a part of the domain e.g. pulse, triangular functions or span over the entire domain e.g. sinusoidal functions, polynomials of higher order. The basis functions are very often orthogonal. The MoM technique using subdomain functions is easier to implement but require large matrices to be inverted. The main attraction of the entire domain bases is high accuracy with small-sized matrices but at the cost of involved implementation. Though proposed long back, the MoM using polynomial basis functions has become common only in the last two decades. Legendre polynomials are one out of a large number of polynomials that can be used to solve frequency domain integral formulation of waveguide problems using the MoM.

1.2 Literature Survey

Waveguide based components have been one of the most studied circuits and literature on this are abound. Marcuvitz [1], Harrington [2] and Lewin [3] have given ample amount of material on the waveguides. A number of other researchers have also studied waveguide discontinuities and circuits using various techniques. The material is so large as to prohibit an extensive survey.

Windows and irises are perhaps the most important circuits that are used in the design of a vast number of waveguide based components. Design of high performance waveguide filter requires an accurate equivalent network presentation of thick inductive windows, especially those windows that involve higher order mode interaction. Collins [4] has studied a single window using the variational technique. Employing an 'obstacle' formulation, Palais [5] has studied the interaction between two infinitely thin inductive windows. The trial field has been represented using Schwinger function in [6]. Using these functions, the solution of the infinitely thin windows can be used directly with the equivalent network representation of the thick windows. The variational technique has also been used by Rozzi to analyze the thick windows [7]. Both the eigen mode and Schwinger expansion were involved for the aperture.

Microwave filters are one of the most commonly used passive subcomponents in microwave circuits. The available literature on microwave filter is so tremendous that the complete survey will not be presented here. Levy and Cohn [8] have given a good overview of the of the research work on microwave filters with a historical perspective. Exhaustive study of the various types of filter design employing waveguide circuit elements has been compiled by Matthaei *et al.* [9]. It was suggested that the waveguide based filters can be designed by using a number of irises and posts in periodic fashion. Liang, Chang and Zaki [10] carried out the design and tolerance analysis of thick iris based waveguide bandpass filter. A new technique known as Coupled Integral Equations Technique (CIET) to study the resonant iris based waveguide filters was proposed by Amari *et al.* [11]. This new technique was at its heart the mode matching technique, which, however was reformulated in terms of the unknown fields at the discontinuities with the help of suitable basis functions in an integral form. Riemann-Hilbert problem (RHP) of systems of singular integral equations is obtained for this new formulation. FDTD Diakoptics based design and analysis of waveguide band pass filter was presented by Su *et al.* Any complicated structure was presented as set of smaller subsections. Mode-type discrete time-domain Green's function was then used to analyze the characteristics of the subsection in time domain. The various subsections were finally interconnected using a multimode parallel algorithm. A number of examples for the filter design and analysis were demonstrated. Neuronal architecture was suggested by Mediavilla *et al.* [12] for the optimization of waveguide Bandpass filters based on inductive irises.

Another very old problem is waveguide T-junctions. Sharp developed an exact method for the evaluation of the electrical performance of T-junctions realized using rectangular waveguide [13]. The equivalent circuit of a rectangular waveguide based T-junction was derived using this method even for general case where the cross-sectional dimensions of the through waveguide were different from the cross sectional dimensions of the side waveguide. In this method the electrical performance was analyzed by using the equivalent circuit concepts applied to waveguide modes to calculate an admittance matrix relating the propagating and cutoff waveguide modes to each other. Then the cutoff modes were terminated to their characteristic impedance, and an equivalent admittance matrix of the junction was found relating only the propagating modes in each waveguide to each other. The analysis is valid for any number of modes, propagating in the waveguides forming the junction. Though inversion of an infinite matrix is required, any desired accuracy can be obtained by considering a matrix of finite but sufficient size or equivalently considering sufficient number of cutoff modes. Obata and Chiba [14] examined Lewin's theory, which describes an E-pane symmetrical tee junction by an equivalent circuit with only three parameters. It was shown although Lewin's theory is formally correct, its circuit parameters depends on the amplitude of the reflected wave. They also proposed an improved theory to correct this fault. A rigorous technique to model the rectangular waveguide T-junction was suggested by Liang *et al.* [15]. This technique was called Three Plane Mode Matching Technique (TPMMT) because it characterized the waveguide discontinuity three times when the side arm of the T-junction was terminated in short circuit with three different lengths. Lampariello and Oliner [16] gave closed form and simple expressions for the element of equivalent networks for open and slit coupled E-plane tee junctions. To show how suitable changes in the geometry can be taken into account, physically based "stored power" considerations were also developed. Yao *et al.* [17] by using an extension of TPMMT obtained the Scattering parameters of waveguide and ridge waveguide stepped tee junctions. The T-junctions and step dimensions that yield low reflection coefficient in one of the T-junction arm over a wide frequency band were estimated using an optimization process. Using the single port mode matching method, slit coupled ridge waveguide tee- junctions were introduced and modeled by Abdelmonen and Zaki [18]. Nine reflection coefficient computations from the perpendicular arm were used to calculated the three port scattering matrix of the tee junction. Ridge waveguide was studies as a very special case of a slit coupled ridge waveguide tee junction. The S-parameters' dependence on the slit thickness and width was also studied. A rigorous technique for full wave modeling of a generalized double ridge waveguide T-junction was developed by Wang and Zaki [19]. The generalized admittance matrices and scattering matrices of all the three ports of the T-junction are obtained by combining the cascading procedure and computation of magnetic fields of each mode at the shorted ports. A very general and efficient technique, it is based on eigen mode expansion method. For good matching and equal power diversion characteristics, the E-plane stepped waveguide tee junction was modified by Lee *et al.* [20]. They solved it using three plane mode matching technique. The design method of the E-plane stepped waveguide tee junction at interested frequency band was also suggested by them. Cho [21] studied theoretically the reflection and transmission behaviors of an E-plane T-junction in a parallel plate waveguide. The iterative equations for Hz field modal coefficients were obtained by him using the Green's function and iterative procedure. Shulga and Bagatskaya [22] presented a rigorous method for solving 2D scattering by a PEC obstacle of arbitrary cross section shape within an interaction region of waveguide tee junction. This technique was an extension of the conventional Green's theorem approach by using the weight functions, which satisfy not only the wave equation but also the boundary conditions on the scatterer's boundary. Cho [23] by using the overlapping T-block method symmetrically analyzed the scattering matrix of E-plane waveguide tee junction with a quarter-wave transformer. Two overlapping T-blocks were used to model the structure of an E-plane waveguide tee junction with a quarter wave transformer. A binary genetic algorithm was used to optimize the geometry of a quarter wave transformer. To illustrate the rate of convergence and accuracy of a series solution, numerical computations were carried out.

The method of field expansion into eigen modes was used by Patzelt and Arndt to analyze double plane steps into rectangular waveguides [24]. The effect of the evanescent modes fields and power transmission due to higher modes were fully taken into account by this technique. The problem of scattering from a rectangular-to-rectangular waveguide junction was solved with convergent numerical results by Naini and Macphie [25],[26]. This technique was based on the principle of conservation of complex power and the expansion of the waveguide fields into normal modes. Data for multi-section double plane step transformers between X, Ku, K and Ka band waveguides were presented by Arndt, Tucholke and Wriedt [27]. They expanded the waveguide fields into orthogonal modes for the purpose of analysis by taking into the influence of higher order modes.

Chen, Choi and Hahn [28] analyzed an H-plane waveguide component with arbitrary shape using Finite Element Technique (FEM) in conjunction with boundary element method (BEM). A ray representation of the waveguide Green's function was used for the application of BEM in waveguide structure. Generalized network formulation was used by Mongiardo *et al.* [29] for tackling the problem of waveguide step discontinuity. By considering the conservation of the complex power and self reaction across the discontinuities, Eleftheriades, Omar and Katehi [30] derived some important properties of the generalized scattering matrix of waveguide step discontinuities, in the context of mode matching technique. Using a unified mode matching technique, Lin *et al.* [31] suggested a technique for the calculation of modal scattering matrix of a concentric waveguide junction. To enable the effective estimation of the coupling coefficient, the TE and TM modal fields in both waveguides, which are connected to form the junction, are expressed in the Cartesian coordinate system. All the works surveyed here solved some of the important wavguide problems using all most all techniques available. Some of the problems were solved using MoM also. None however have used MoM with higher-order Legendre polynomials as basis and testing functions. We, in this thesis, revisit some of those problems and analyze using MoM with higher-order bases and weights.

One of the earliest works on the application of higher-order polynomial basis functions in the MoM technique appeared in the famous book written by Harrington [33] in 1960's. But it took a few decades more before the computational electromagnetic community working in the MoM started applying higher-order basis functions [34], [35] followed by their application in the FEM. These earlier uses of the higher-order bases succeeded in achieving accurate result with fewer unknowns. The technique still had a few problems associated with it e.g. with the increase in the order of the basis function, the condition number of the MoM matrix also increased. This required the application of the direct matrix inversion technique, which is very slow, robbing-off the gain in terms of the smaller matrix size. Jørgensen *et al.* addressed these issues by modifying the higher-order bases [36], [37].

All these works, however, have quite successfully applied the higher-order technique to the scattering and antenna problems, which when attacked using low-order bases lead to enormously large matrices. According to the author's knowledge, the applications of higher order basis functions in the MoM solution of the MFIE formulation of rectangular waveguide discontinuity analysis are still lacking. This thesis presents the MoM analysis of waveguide discontinuities using higher-order hierarchical Legendre polynomials as bases with Galerkin's specialization.

1.3 Objectives

Objectives of this thesis are to carry out the higher-order MoM analysis for some of the commonly encountered waveguide discontinuities. The problems are analyzed using the MFIE formulation. The problems considered are:

1. Diaphragm with a rectangular window
    (a) Complex permittivity estimation
    (b) Bandpass filter analysis
    (c) Transition window
2. Broadwall transverse slot on a shorted/matched guide
3. Broadwall longitudinal slot on a shorted/matched guide
4. Narrow wall longitudinal slot on a shorted/matched guide
5. Broadwall longitudinal slot doublet on a shorted/matched guide

1.4 Thesis Organization

Chapter 1 presents introduction, an extensive survey of literature and objectives of the work presented in the thesis. Chapter 2 gives the derivation of potential dyadic Green's functions of a rectangular cavity, of a semi-infinite waveguide and that of an infinite waveguide. A thick diaphragm with a rectangular window is analyzed in Chapter 3 and the analysis is applied to estimate the complex permittivity of a low loss solid and, also, to analyze a Ku-band waveguide bandpass filter. Chapter 4 details the analysis of a transverse broad wall slot on a shorted/matched waveguide radiating into another guide. The problem of a longitudinal broad wall slot on a shorted/matched waveguide radiating into another waveguide is analyzed in Chapter 5. A narrow wall longitudinal slot a shorted/matched waveguide radiating into another waveguide is presented in Chapter 6. Chapter 7 considers the broadwall longitudinal slot doublet on shorted/matched guide. The thesis ends with Chapter 8, which talks about the conclusion and future work scope. Chapter 3 to 7 constitute the main body of dissertation work.