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MODELING OF MICROWAVE AND MILLIMETER WAVE PASSIVE COMPONENTS IN EUROPE

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ABSTRACT

This paper reviews some of the most significant contributions of European research groups to the modeling of passive microwave and millimeter wave components. Rather than to the components themselves, the attention is focused on the methodologies for modeling the various types of components, including hybrid and monolithic integrated circuits as well as conventional structures.

1. INTRODUCTION

The design of microwave components is increasingly relying on computer techniques. The advances in microwave technology and the use of millimeter wave frequencies lead to circuit structures for which computer-aided design (CAD) techniques are indispensable. Extremely accurate design techniques are required not only, as is known, in the area of (M)MIC's, but also in many applications of conventional microwave technology, like, for instance, in space system applications, where tuning elements can degrade the circuit performances.

Component modeling is the first step in the computer aided design of microwave circuits [1]. It consists of developing models of the various components suitable for their numerical characterization. Circuit analysis and optimization are the subsequent steps of CAD procedures.

Accurate and, at the same time, efficient modeling is therefore a key problem in the CAD of microwave structures. Modeling involves an appropriate balance of analytical and numerical effort. One has to select among different approaches, depending on the problem at hand and on the available computing resources. Criteria for choosing one method or another depend on various aspects, such as versatility, computing time, memory storage, efficiency [2]. As a general rule, the more analytical effort is required, the more efficient but less versatile is the numerical method. Very general numerical methods have very broad applicability, but have generally a much lower computational efficiency.

Aim of this paper is to give a general description of the research activities in the area of the modeling of passive components in Europe. The attention is mainly focused on the methodologies for modeling the components rather than to the components themselves. Since it would be impossible to mention all significant contributions in such a vast area, only a few selected topics are briefly mentioned. They are selected among those that, in author's view, have received particular attention or have been significantly developed by European or Europe-related research groups. This review reflects the personal biased experience of the author and is certainly far from being exhaustive. The author is conscious of many important omissions and apologizes for them.

The modeling of passive microwave components involves problems with different degrees of complexity depending on the relevant field equations and the number of space dimensions. Quasi-static modeling of transmission lines, based on the solution of Laplace's equation in two dimensions, is considered in the next section. Two-dimensional models for planar circuits are discussed in section 3, while the modeling of three-dimensional structures is considered in the subsequent sections 4a. (numerical approaches) and 4b. (semi-analytical approaches). Although the models of 3-D components and multiaxial discontinuities are far more complicated than those of transmission lines, they are both considered in these sections. Specific mention to the problems associated with monolithic circuits is made in section 5.

2. QUASI-STATIC MODELS OF PRINTED CIRUCIT TRANSMISSION LINES

For applications at relatively low frequencies, quasi-static models can be adopted to characterize microwave integrated circuit components. Actually, the design of microstrip circuits is still based on such models. The advantage is due to the possibility of obtaining closed-form expressions for the line characteristics. Compared to microstrip, coplanar lines are a less known transmission medium, for which work is still to be done. Fouad Hanna has developed conformal mappings for asymmetric CPW with infinite or finite dielectric thickness by [3]. Based on exact or approximate conformal mappings closed-form expressions accounting for a large class of coplanar structures have been proposed by Ghione and Naldi [4]. Their static formulas account for upper shielding, conductor backing, finite-extent ground planes and line-to-line coupling.

Quasi-TEM models for the analysis of multistrip multilayer transmission lines on anisotropic substrates have been developed by Horno and co-workers [5-6]. The approach adopted is based on a variational technique applied in the spectral domain.

3. TWO-DIMENSIONAL MODELS FOR PLANAR CIRCUITS

An important area of investigation in connection with the modeling of microwave integrated circuits (MIC's) (but also other configurations) is that of two-dimensional circuits. The theory of two-dimensional or planar circuits started in Europe and Japan almost at the same time. In Italy, Ridella and his collaborators developed planar circuit models in terms of the impedance or admittance matrix formulation [7-10]. The term *planar circuit*, however, was introduced by Okoshi and Miyoshi [11] to designate an electric circuit with one dimension much smaller than the wavelength, so that a two-dimensional model could be applied. This expression has been widely adopted, though it is somewhat misleading (see for instance [12]).

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The interest in the planar circuit approach resides mainly on the possibility of analyzing stripline and microstrip structures with a higher degree of accuracy than with conventional one-dimensional models. In addition, wider degree of freedom is achieved in the design of microstrip components. The applicability of two-dimensional models to microstrip structures, however, is limited mainly by the effects of fringing field at the strip edges. This difficulty has been partly overcome by the eigenfunction (resonant mode) expansion technique, which allows a different effective model to be used for each resonant mode of the planar structure [13], [14]. Reasonably good agreement with the experiments can obtained, including also radiation loss [15]. (This approach is actually known among antenna people under the name of *cavity model* of patch antennas). The resonant mode expansion technique can also be used to develop wide band lumped equivalent circuits of planar structures [16]. One example of application to the CAD of radial line stubs is given in [17]

Irregularly shaped planar circuits can be analyzed by subdividing the structure into elements of simple shape. Both the segmentation method introduced in Japan by Okoshi and the planar waveguide model developed in Germany by the group led by Wolff [18], [19] can be used to this purpose. With the planar waveguide model the microstrip line is replaced by a magnetic wall waveguide of suitable effective width filled with a dielectric of effective permittivity. In this manner, by using mode matching techniques, a variety of discontinuity problems, such as steps, T- and Y-junctions, crossings, bends etc., have been analyzed [20], [21]. A new algorithm of more general applicability has recently been proposed for the wide band simulation of arbitrarily shaped two-dimensional circuits in frequency domain [22]. A modified eigenfunction expansion method of very fast convergence behavior is used. Excellent agreement with experimental waveguide circuits has been demonstrated.

In recent years time-domain numerical methods have been attracting increasing attention from researchers. This is not only due to the possibility of analyzing transients, but also because it is possible to perform wide band analyses with a single computational process. A two-dimensional formulation of the finite-difference method in time domain (FD-TD) has been developed by Gwarek [23], [24] This method appears to compete with the contour-integral (CI) method (or boundary element method) proposed in [25] for arbitrarily shaped planar circuits. Computer time using FD-TD is lower than with CI when more than five or six frequency computations are made. A significant advantage of FD-TD is the possibility of treating inhomogeneuos structures. By inhomogeneously filling the two-dimensional circuit it is possible to effectively simulate the dispersive behavior of microstrip circuits [26].

4a. THREE-DIMENSIONAL MODELING : NUMERICAL APPROACH

Approaches to three-dimensional modeling belong roughly to two categories: one is that of strictly numerical methods, the other is represented by semi-analytical methods. Strictly numerical methods consist of the direct discretization of the field equations with minimum analytical effort. A certain amount of analytical processing, on the contrary, is required by the methods of the second category. No sharp distinction between the two categories exists, however, the classification being somewhat arbitrary.

The transmission-line matrix (TLM) method simulates the wave propagation in time domain by discretizing the space into a three-dimensional transmission-line matrix. This method has been invented in England by P.B. Johns and originally applied to two-dimensional problems [27]. After extension to three-dimensional structures [28], [29] a number of improvements of the method have been developed by European researchers particularly in France and England [30-32]. An extensive account on TLM method has recently been given by Hoefer [33].

An effective approach to the modeling of three dimensional microwave structures of complicated geometries is the finite element method (FEM). For space limitation this method is not discussed here. An account on FEM applications on three-dimensional electromagnetic structures has been given by Ferrari [34].

Another important numerical approach to the modeling of planar structures is the Method of Lines introduced into the microwave community by Schultz and Pregla [35] and then mostly developed at FermUniversitaet, Hagen [36-38]. This is a three-dimensional method where a discretization procedure is applied in the plane of the substrate, while an analytical formulation is retained in the normal direction. The structure is then modeled as a number of *lines* orthogonal to the substrate. This method has several interesting features. It can be applied to arbitrarily shaped planar structures [36] including anisotropic substrates [37] and finite metallization thickness. A comprehensive treatment of this method is given in [38].

4b. THREE-DIMENSIONAL MODELING: SEMI-ANALYTCAL APPROACH

Analytical procedures, when applicable, can reduce the computational effort involved by the modeling of three-dimensional microwave structures.

A classic approach to the numerical modeling of discontinuities is the mode-matching technique (or modal analysis). This method has been developed for the analysis of waveguide discontinuities by Clarricoats and co-workers since 1967 [39], [40]. By associating a transmission-line to a waveguide mode, the modeling of discontinuities is obtained in terms of generalized N-port networks. Different matrix formulations (S-matrix, transmission matrix [41], Y-matrix [42] etc.) can then be used to analyze cascaded discontinuities, leading to different numerical algorithms.

Similar to mode-matching, the field-matching technique can be used to determine the modes of waveguides with complicated cross sections [43], [44].

It is impossible to mention here even a small fraction of the work which has been developed in Europe using mode-matching technique or its modifications. In a very quick survey one should mention the work done at the University of Bremen on the characterization of a large number of components in various technologies (waveguides, finline, microstrip) and transitions (see, for instance, [45-48]).

The mode-matching technique requires the knowledge of the modal spectrum of the waveguides or transmission lines at both sides of the discontinuity. For microwave and millimeter wave IC's this is often a non trivial problem, also because of the possible existence of complex modes, as pointed out by Omar and Schuenemann [49], [50]. A very efficient and well known method for the analysis of planar transmission lines is the spectral domain technique (SDT). The SDT is too popular and too well known to be discussed here. A survey of this method, furnished with a vast reference list, has been given by Jansen [51].

As discussed by Citerne [52] in a recent review on numerical approaches to the modeling of millimeter wave passive components, the spectral domain technique can be used to compute the modal spectra of the transmission lines. It can then be combined with mode-matching [53] or finite element method [54] to evaluate the scattering matrix of the discontinuity.

Variational techniques for the characterization of the spectrum of various integrated transmission lines have been developed by Rozzi and co-workers [55-58]. By a proper use of the edge condition very efficient computations of the modal spectra including complex modes are obtained. The orthonormalized discrete and the continuum spectrum of the inset dielectric guide (IDG) has been derived by Rozzi and Ma [58] using a generalized concept of transverse equivalent circuit (transverse resonance diffraction).

Open guided structures such as microstrips are subject to radiate at discontinuities in the form of either space or surface waves. Specific models are needed to account for such phenomena. Integral equation techniques in connection with patch antennas have been developed at the Ecole Polytechnique Fédérale at Lausanne. A mixed potential integral equation is formulated, where Green's function is given by Sommerfeld integrals. The method of moments on a subsectional basis is applied to analyze printed circuits of arbitrary shape [59-60]. This technique has recently been applied and experimentally verified also in France by Citerne's group, to investigate microcrostrip gap discontinuities [61].

5. MODELING OF HIGH DENSITY IC's

Even with modern computing capabilities, the analysis of complicated configurations can easily be too time consuming. Equivalent models and look up tables based on suitable full wave generators become necessary.

The characterization of integrated circuits on semiconductor substrates, using either rigorous techniques or equivalent transmission-line models, has been the subject of research activities by more than one group in Europe. An account has recently been given in [62]

One of the key problems in the design monolithic microwave and millimeter wave integrated circuits however is the modeling of the effects due to the close proximity of the components as well as the interaction with the package. Multifunction chips have the potential of drastically reduce the costs associated with assembling and testing, but require circuit elements to be laid with high packing densities. In addition, multilevel interconnects (air bridges, underpasses, multiple crossings, etc), as well as three-dimensional lumped elements consisting of multilevel metallizations with complex geometries are realized in the last generation of MMIC's [62]. Models to account for coupling phenomena and complex geometries have been developed by Jansen and co-workers to construct look-up table generators for CAD. [63, 64] This area is certainly one of the main issues in future research work in the modeling of electromagnetic structures all over the world.

6. CONCLUSIONS

An attempt has been made to review some of the main contributions of European research groups to the modeling of passive microwave and millimeter wave components, including hybrid and monolithic IC's, as well as components realized in conventional technology. The author wish to thank the many colleagues who have provided substantial information for this work. He apologizes for the many unavoidable omissions. An overview on the modeling techniques being developed in Europe can also be found in the recent *Focus on Computer Oriented Design Techniques for Microwave Circuits* published by Alta Frequenza [66].

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