Emerging Trends in Millimeter-Wave CAD

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***Abstract*— This paper discusses three emerging trends in the area of millimeter-wave (mm-wave) electromagnetic (EM) simulation and computer-aided design (CAD). Diakoptics techniques for frequency- and time-domain EM-simulation methods are needed for mm-wave circuit design. Development of artificial neural network (ANN) models is likely to result in an efficient use of EM simulators. Possible applications of knowledge-based tools are suggested for initial stages of the design process.**

***Index Terms*— ANN modeling, diakoptics, EM simulation, knowledge-based design, mm-wave CAD.**

I. Introduction

ELECTROMAGNETIC (EM) simulation techniques for high-frequency structures developed over the last decade have helped to bring microwave circuits and monolithic microwave integrated circuit (MMIC) computer-aided design (CAD) software to a level of maturity. The key contribution of EM-simulation techniques to microwave CAD has been in the domain of accurate models for microwave components [1]. As a result, the microstripline-based microwave-circuit design has been brought to almost a first-pass success level. Modeling still remains a major bottleneck for CAD of certain classes of microwave circuits (such as coplanar waveguide (CPW) circuits, multiple layered circuits, and integrated circuit-antenna modules) and for most of the millimeter-wave (mm-wave) (above about 40 GHz) circuits. The efficient use of EM-simulation techniques in the development of accurate mm-wave CAD tools is still a topic of research. The use of EM simulators for accurate and practical design of mm-wave circuits can be made possible by innovative developments in diakoptics methods for frequency- and time-domain analyses. The diakoptics (or decomposition or segmentation) approach consists of partitioning the circuits into smaller parts, carrying out the characterization of each of the smaller parts, and combining these characterizations (by network theory-based methods) to yield the response of the overall circuit. Since the EM analysis is carried out only for a smaller portion at any time, the computational requirement can become manageable and practical for design purposes.

Another recent development that may lead to an efficient usage of EM simulation for mm-wave CAD is the use of artificial neural network (ANN) models trained by full-wave EM simulators [2]–[4]. In this methodology, EM simulation is used to obtain S-parameters for all the components to be modeled over the ranges of designable parameters for which these models are expected to be used. An ANN model for each one of the components is developed by training an ANN configuration using the data obtained from EM simulations. A simultaneous training-*cum*-testing approach developed at the University of Colorado [5] is well-suited for this purpose. Such ANN models have been shown to retain the accuracy obtainable from EM simulators and at the same time exhibit the efficiency (in terms of computer time required) that is obtained from lumped network models normally implemented in commercially available microwave network simulators (like the HP MDS). Similar ANN models need to be developed for commonly used components, sub-circuits, and prototype circuits at mm-wave frequencies. ANN's are also well suited for modeling of active devices (including thermal effects) and for circuit optimization.

Another aspect of mm-wave design that should receive attention in the near future is the possibility of employing knowledge-based tools for "initial design." The design process consists of several steps starting from: 1) problem identification and moving through; 2) specifications generation; 3) concept generation; 4) analysis; 5) evaluation; 6) initial design; and 7) detailed design. Currently available microwave CAD tools address only the last step, i.e., transformation from an initial design to an optimized detailed design. It has been pointed out [6] that knowledge-based tools are needed for earlier stages of the design process.

Following brief reviews of mm-wave CAD and simulation, this paper discusses the concept of diakoptics in EM simulation, and the roles of ANN modeling and knowledge-based tools for mm-wave CAD.

II. MM-Wave CAD

MM-wave circuit design differs from the lower frequency microwave-circuit design in several aspects. The key factors contributing to these differences are discussed in this section.

A. Enhanced Parasitic Couplings

Parasitic EM coupling among various parts of a circuits can substantially modify the performance of mm-wave circuits. These effects have also been observed at microwave frequencies [7], [8]. An example in [7] demonstrates that spurious coupling resulting from a folded shorted-stub matching network in the vicinity ($\sim$800 μm away) of a microstrip line in a GaAs MMIC can cause S_{21} to decrease by $\sim$3.67 dB at 10 GHz. However, the network approach used for design of microwave (and lower frequency circuits) is not able to account for this external EM coupling unless network models

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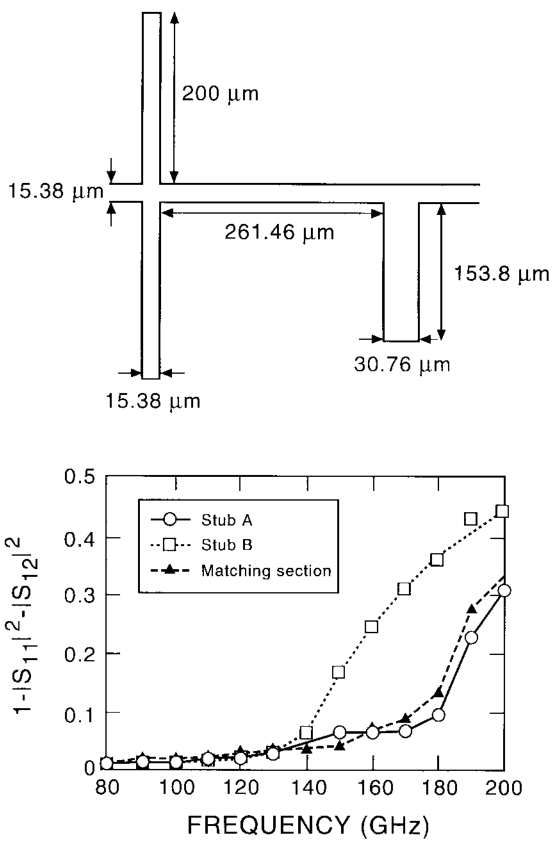

Fig. 1. Dramatic increase in radiation loss in a microstrip matching network ($\varepsilon_r = 12.8$, $h = 100$ μm, $W = 15.38$ μm) observed at frequencies above 140 GHz (from [8]).

could be derived for these spurious coupling effects. For this reason, these external EM coupling effects are not yet incorporated in the design of even microwave circuits when currently available CAD software are used for design. At mm-wave frequencies, these parasitic EM coupling effects can become too significant to be ignored, and the design methodology needs to be modified accordingly.

B. Lack of Accurate Component Models

Ten years ago, the critical bottleneck in accurate microwave design was the availability of accurate models for several components in monolithic microwave circuits, and a similar situation exits today for monolithic and hybrid mm-wave circuits. This modeling problem becomes more acute at mm-wave frequencies because of the wider variety of transmission structures and devices used at these frequencies. Also, because the dimensions become electrically bigger at mm-wave frequencies, components cannot be accurately represented by lumped network models. The ANN modeling approach, described in Section V, can contribute to an appropriate solution.

C. More Dispersive Transmission Structures

As the frequencies of operation move from the microwave to mm-wave range, the need for maintaining the mechanical integrity of the substrates demands that the thicknesses of the dielectric or semiconductor substrates not be reduced proportionately. Consequently, the substrates used for the design of mm-wave circuits are electrically thicker than those used at microwave frequencies. For planar transmission lines, like microstrips, slot lines, CPW's, etc., this increase in electrical thickness makes their characteristics more dispersive. Formulas (mostly based on quasi-static approximations) for design of these structures are no longer accurate and need to be modified. Also, the effect of conductor thickness, which is often negligible at lower frequencies, needs to be taken into account at mm-wave frequencies. Two-dimensional EM field solvers are needed for characterization of these transmission structures at mm-wave frequencies. Also, while designing mm-wave transmission structures, care need to be taken to avoid higher order propagating modes.

D. Enhanced Transmission Losses

Conductor losses in transmission structures increase as the square root of frequency and dielectric losses are directly proportional to frequency. Additional losses due to surface roughness could also be considerably higher. Also, the radiation losses at discontinuities and open-ends get substantially enhanced at mm-wave frequencies [8]. Fig. 1 [8] shows the dramatic increase in the radiation losses that can take place from a microstrip impedance-matching circuit ($\varepsilon_r = 12.8$, $h = 100$ μm, $W = 15.38$ μm) in the millimeter-wave frequency range. An accurate characterization of various losses is a prerequisite for mm-wave design.

III. EM Simulation

A. EM-Simulation Methods

The term EM simulation implies numerical solution of Maxwell's equations for EM fields for a given structure for a specified environment (boundary conditions). These field computations may be carried out either in frequency domain (when the solution is obtained for sinusoidal excitation in a specified range of frequencies) or in time domain (when the response is obtained as a function of time). The most commonly used techniques for frequency-domain simulation are: 1) the solution of integral equation by methods of moments [9]–[11] as commonly used for planar microwave and mm-wave structures and 2) finite-element method (FEM) [9], [10] used for general three-dimensional structures. These two techniques are used in the most popular EM simulators for microwave and millimeter frequency ranges. Among the time-domain solution techniques, the most commonly used approach is the finite-difference time-domain (FDTD) method [9], [10], [12]. The transmission-line matrix (TLM) method [9], [10], [13, pt. 3] is another time-domain technique used for EM simulation. Time-domain responses may be used to find frequency-domain results by applying fast Fourier transformation. Time-domain analysis is required when nonlinear active devices (for which only time-domain models are available) are included in mm-wave circuits. Harmonic-balance methods [14], used for response of nonlinear circuit to a single-frequency excitation, make use of the time-domain analysis for the nonlinear active part of the circuits and frequency-domain analysis for the linear passive part of the circuits. The two solutions are balanced at the interface between linear and nonlinear parts at various harmonics of the excitation frequency.

B. Limitations of EM Simulation at mm Waves

Difficulties in applications of EM simulators to mm-wave (and microwave) design arise because of the intensive computer central processing unit (CPU) time and memory requirements. Three-dimensional simulators (FEM, FDTD method, TLM method, etc.) require gridding of the space where fields are present in the circuit. For planar circuits, simulators using the method of moments (MOM) require a two-dimensional surface gridding. Values for various components of electrical and magnetic fields are then computed at each of the discretized points on the grid. This is a time-consuming operation made practical only by recent advances in computer technology. Circuit parameters of interest like S-parameters or other representations of input–output relationships are derived from the field values by appropriate post-processing of simulation results. Compared to conventional network-analysis-based circuit-design tools used at lower frequencies, any design based on EM simulation needs approximately two orders of magnitude longer CPU time and RAM allocation.

Although, in principle, EM-field simulation based on Maxwell's equations is rigorous, any practical implementation of EM-simulation methods does require some approximations either in description of the structure (and surrounding environment) to be analyzed, or in terms of boundary conditions, or in terms of the computational implementation of the method itself. Integral-equation-based MOM simulators assume infinite lateral extent of the substrate and ground planes (or a rectangular boundary with electric and/or magnetic walls). Thickness of the conductors and their resistivity are accounted for only in approximate manners (the latter by an equivalent surface impedance). Quite often, approximations are used in computations of the Green's functions involved. Some of these are based on the assumption of an electrically thin substrate layer. The precise effects of these approximations are not generally known to users of these simulators, and there is a definite need for validation of the results obtained for mm-wave circuits. Also, absorbing boundary conditions (ABC's) need to be implemented when the structure is open and the fields extend outside. In spite of all the recent developments in ABC's [15], this item does become a definite factor limiting the accuracy of results obtained from these methods.

Extraction of the circuit parameters of interest from the field values obtained from EM simulation is not a trivial step, and can constitute a source of error for circuit designers.

The effects of all these factors on the accuracy of mm-wave design have not been evaluated and documented so far. An investigation of this kind is definitely needed for development of accurate mm-wave CAD tools.

C. EM Simulation for MM-Wave CAD

Applications of EM simulation to microwave design have recently been discussed [16]. For mm-wave design, EM simulators can be used for three functions. These are: 1) modeling of circuit elements like transmission structures, discontinuities and components derived from sections of transmission structures; 2) optimization of circuit elements, like optimum chamfering of 90° CPW bends [17] as reported recently; and 3) building a library of circuit elements to be used for design and optimization of mm-wave circuits. The latter application has been recently illustrated [18] where various CPW components (CPW line, bend, open-circuit, short-circuit, step-junction, and T-junction) were modeled using an EM simulator and then used in a network simulator for design and optimization of CPW circuits like a CPW folded double-stub filter and a 50-Ω 3-dB power-divider circuit. The EM-ANN modeling approach [2] has been used successfully in these applications [17], [18].

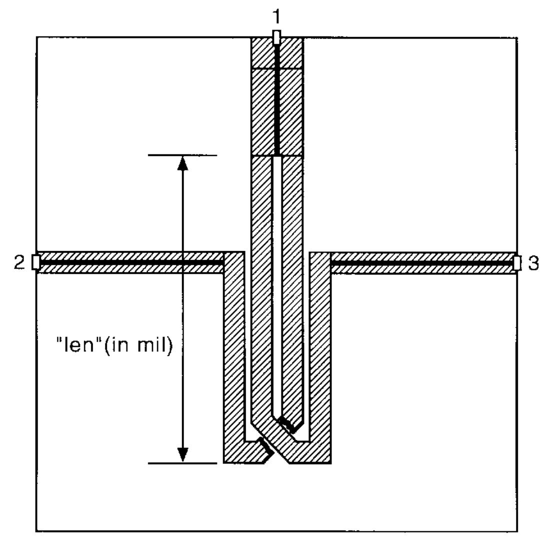

Fig. 2. The "tapped" inductor structure characterized by EM simulation (from [16]).

Another important role of EM simulators in mm-wave CAD is to incorporate into the design procedure the effect of external mutual coupling among various parts of the circuit layout. At lower frequencies, the network-analysis-based approach is used for circuit design and constitutes the basic infrastructure for all commercially available microwave-circuit simulators. In this network-based approach, interactions among the various circuit components are limited to interconnections among a set of well defined components' ports. However, this network approach is not valid when the fields produced by individual components in the neighboring space start interacting and cause what is known as parasitic EM coupling among the components. When an EM simulation of the total mm-wave circuit is carried out, all these EM coupling effects are accounted for. However, computational requirements associated with EM simulation make direct simulation of a complete mm-wave circuit almost impractical. For example, EM analysis of a single inductor element [16] (shown in Fig. 2) with 1110 subsections in moment-method-based planar analysis required 11 MB of RAM and took 37 min of CPU time per frequency point on an HP735 workstation.

We need an approach that makes use of EM simulation in a more efficient manner so as to make EM analysis-based mm-wave circuit design more practical. Two approaches could be suggested for this purpose.

In one of the possible approaches, external EM interactions among elements are emulated by introducing circuit components to form extra signal paths [19]. For the example illustrated in this reference, a two-port network is used to model the EM coupling among two nonadjacent elements in a three-pole Chebyshev filter using cascaded high-temperature superconductor (HTS) resonators. Individual sections are modeled by EM simulation and cascaded using network approach. The difference between the response of this cascade and EM-simulation response of the complete filter is used to model this two-port network characterizing the EM coupling between, say, the first and third resonators. Once this network model for external coupling is derived, a network-analysis-based simulator can be used for filter design. This approach is similar to network modeling of mutual coupling among elements of an antenna array [20], as used in multiport network modeling and CAD of arrays of printed microstrip patches.

IV. Diakoptics for MM-Wave Design

An emerging approach for efficient use of EM simulators for mm-wave design is based on the concepts of diakoptics [21], [22] or segmentation or decomposition [23]–[26]. These techniques have been proposed for: 1) quasi-static analysis [23], [24]; 2) frequency-domain analysis [25], [28]–[30]; and 3) time-domain simulation methods [27], [31].

A. Diakoptic Methods for Static/Quasi-Static Analysis

A diakoptics method (called domain-decomposition method) has been reported [23] for extraction of capacitance matrices of multilayered three-dimensional interconnects in VLSI circuits. This approach uses magnetic walls to cut the complex interconnect net into many cells. Each cell is decomposed into subregions and partial differential equation (PDE) in each subregion is solved separately. Thus, one can use the most efficient method in each region independently. Subregions with homogeneous dielectric layers may be analyzed analytically. Adjacent regions are selected to be overlapping and an iteration algorithm based on the Schwarz Alternating Method is used for solution. Computing time and memory used are reduced to less than one-tenth of the general FEM solution without diakoptics.

Another example of diakoptics in quasi-static field analysis is the development of segmented boundary-element method (SBEM) [24] for characterization of multilayered multiconductor transmission structures used in the design of multilayered microwave circuits. In this method, the cross section of the transmission structure is first separated into several homogeneous regions that are analyzed separately by the BEM. An example, shown in Fig. 3, illustrates the procedure. The results are then combined to yield the overall characterization by using network interconnection approach. This strategy makes it possible to take into account any local modification by redoing the analysis for only those regions that are affected by any specific modification. A three-dimensional full-wave version

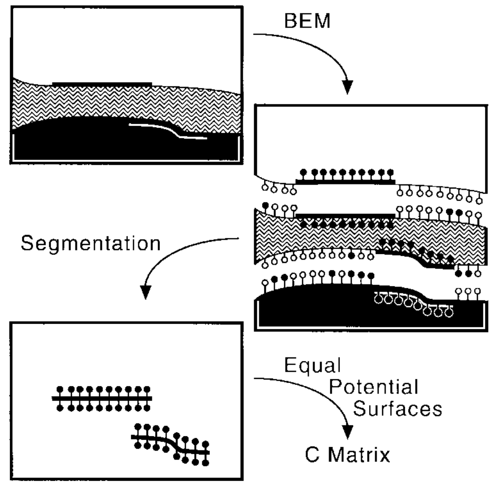

Fig. 3. Analysis of a multilayered transmission structure by segmentation and SBEM (reprinted with permission from K. C. Gupta *et al.*, *Microstrip Lines and Slotlines,* 2nd ed., p. 20 [Norwood, MA: Artech House, 1996]).

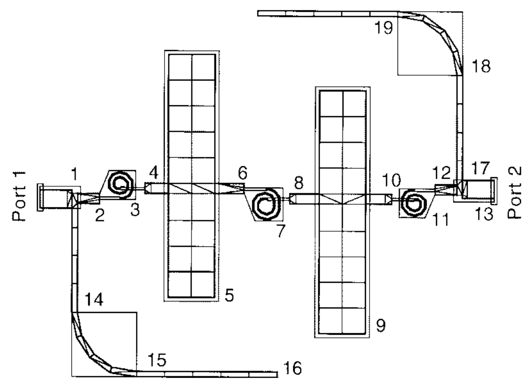

Fig. 4. The configuration of a low-pass filter used to illustrate the multilevel MOM (from [21]).

of this approach could become an efficient tool for mm-wave design.

B. Diakoptics Methods for Frequency-Domain Dynamic Analysis

For integral-equation-based method-of-moments EM simulators, multilevel moments method [21], [28], [29] can be used to reduce the computational complexity of the EM simulation. In this approach, the circuit is divided into several subcircuits by inserting artificial ports. Each subcircuit is then simulated separately and current density profiles obtained. By demanding current continuity at the artificial ports introduced, the current distributions are combined to form a set of basis functions for upper level MOM. Amplitudes of these basis functions are found with the upper level MOM. During the implementation of lower level MOM, the presence of metallization other than the subcircuit considered is ignored. Errors introduced by this are reduced by an iterative procedure with refines the upper level basis functions. In a numerical example [21] of a low-pass filter, shown in Fig. 4, it has been demonstrated that even for a small number of unknowns ($n = 825$), this technique

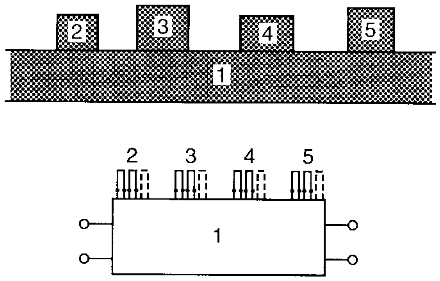

Fig. 5. Segmentation method applied to analysis of a waveguide filter circuit (based on [29]).

reduces the solution time by a factor of 4 for an accuracy of −80 dB in S-parameters values. In this case, the circuit was partitioned into 19 subcircuits, which were analyzed separately at lower level MOM and then combined for the upper level MOM analysis.

Another demonstration of the use of diakoptics ideas in frequency-domain microwave analysis is the segmentation approach [26] applied with the mode-matching method [30]. In this approach, the waveguide circuit is divided into a number of rectangular shaped cells, each modeled as a subcircuits with multiport interconnections to the neighboring cells. Fig. 5 illustrates the implementation of this method for a simple example from [30]. This is a fixed-value waveguide phase-shifter circuit with four shorted stubs. The configuration is divided into five cells, each characterized as a multiport component. The number of ports in cells numbered 2–5 is equal to the number of modes considered necessary for representation of fields in these cells. Admittance matrix representations for the multiport network representation of the cells are obtained from the ratio of the tangential electric field to the tangential magnetic field values at the cell boundaries, as evaluated from the Green's functions for the cell fields. Thus, the overall analysis approach combines the EM-field analyses within the cells with the network analysis for interconnecting the cells to yield the circuit response. Following a somewhat similar approach, Arndt *et al.* [25] have described hybrid mode-matching/contour-integral and mode-matching/finite-element waveguide building blocks for CAD and optimization of waveguide components.

Another approach for full-wave segmentation analysis of arbitrarily shaped planar circuits is based on obtaining generalized scattering-matrix (GSM) descriptions of all the subcircuit segments [32]. Fig. 6 illustrates the basic idea. The planar circuit is divided into several smaller segments with corresponding multiport network parameters that are obtained by full-wave space-domain integral-equation technique. This method differs from the standard network-analysis-based simulators in that the interconnections among the components are not limited to a single mode of wave propagation on the interconnecting lines. In GSM characterizations, higher order modes (evanescent as well as propagating) are accounted for. This multimodal characterization is expressed in terms of multiport interconnections in a manner similar to that described in connection with the two-dimensional planar analysis reported earlier [33]. A limitation of this approach is that spurious external EM couplings that are not expressed in terms of higher order modes do not get included in the analysis.

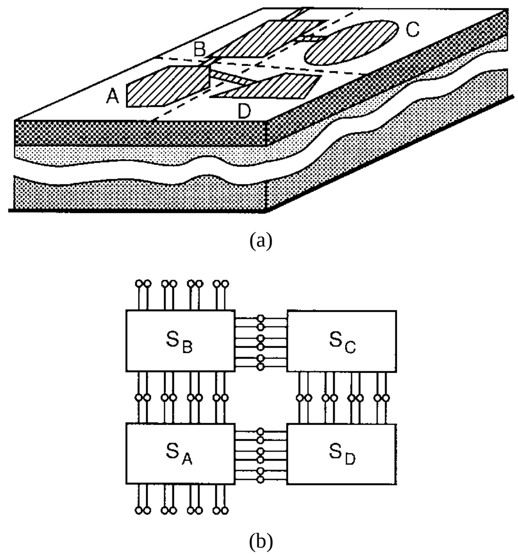

Fig. 6. Application of the GSM approach to full-wave analysis of planar circuits (from [32]).

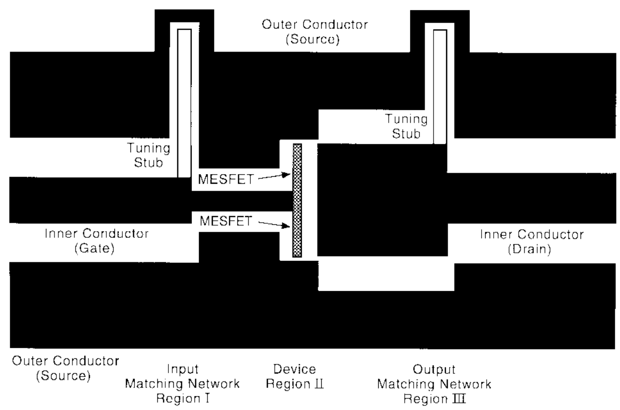

Fig. 7. A mm-wave amplifier circuit analyzed by time-domain diakoptics by separating the layout in three regions (from [27]).

C. Diakoptic Methods for Time-Domain Analysis

Application of diakoptics in the time-domain approach has been demonstrated recently [27] where an entire mm-wave amplifier, including EM fields inside the transistor, is simulated with an FDTD algorithm. The circuit, shown in Fig. 7, is divided into three regions. The simulation of each region is performed separately and coupled to the next region properly along with all the required information from the preceding region. This technique allows one to use large time steps in the passive matching-network regions, while much smaller time steps are used in the active transistor region. This drastically reduces the computation time, and the memory requirement is lowered by approximately 66%.

Another example of time-domain diakoptics [31] involves analysis of waveguide discontinuities by the TLM method by partitioning the circuit into subdomains that can be analyzed independently and then connected together. The procedure is illustrated by an example of a 45° inclined iris shown

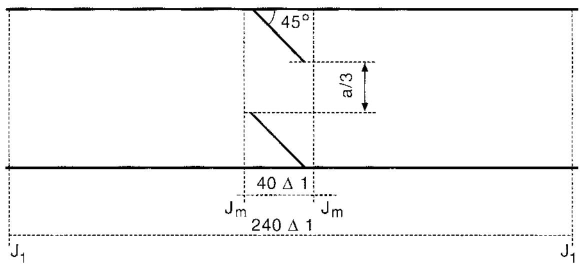

Fig. 8. Example of an inclined iris in a waveguide used for illustrating the TLM diakoptics procedure (from [31]).

in Fig. 8. In the conventional TLM procedure, computation boundaries need to be located at J_1 where only one waveguide mode is required for finding the ABC. In the TLM diakoptics approach, regions on either side of the discontinuity are replaced by appropriate boundary conditions accomplished by presimulating a semi-infinite waveguide and using the time-domain response of such a structure to terminate the computation domain around the discontinuity structure at J_m. When the ABC is obtained by considering five modes in the semi-infinite waveguide, computation boundaries can be placed just a few cells away from the discontinuity. For the same mesh size (62×30), this approach reduced the computer CPU time from about 1 h to 30 s.

Further developments in both time- and frequency-domain diakoptics or decomposition techniques are needed to make use of these concepts for practical mm-wave design. It may be pointed out that diakoptic solutions of EM problems are very suitable for concurrent computing [34]. Parallelism in diakoptic methods comes from the property that the solution of one subnetwork does not depend on the solution of any other subnetwork. Subnetworks (smaller components of the mm-wave circuit) can, therefore, be analyzed concurrently. This feature will improve the computation efficiency of the diakoptic methods further.

V. ANN Modeling

The use of an ANN is a very promising tool for mm-wave design. Potential applications include: 1) component modeling; 2) circuit design using ANN models; and 3) optimization using ANN models of mm-wave circuits.

A few applications of ANN computing to microwave design have been recently reported [2]–[6], [17], [18], [35]. The key feature of these applications is the training of ANN's to carry out the EM analysis of various passive components and detailed analysis of active devices. This allows the replacement of time-consuming EM-simulation software with dramatically more efficient ANN computing modules. We can look forward to the use of ANN tools in the following areas related to mm-wave design.

A. Modeling of Nonlinear Devices

Efficient and accurate models for nonlinear behavior of active mm-wave devices like heterojunction bipolar transistors (HBT's), MESFET's, and high electron-mobility transistors (HEMT's) including thermal effects could be developed using the ANN modeling approach. This could be achieved by starting with the existing models and modifying these models by developing an ANN configuration to model the differences among the available approximate models and the results based on experimental characterization (or an accurate analysis). This approach (called the hybrid DeltaS model in [2]) has been used successfully earlier in development of EM-ANN models for microstrip vias and vertical interconnects [2] and also for chamfered 90° bends in CPW's [17].

B. Modeling of CPW Components and Discontinuities

CAD tools for CPW circuits have not yet been adequately developed because of the lack of accurate and efficient models for CPW components. Compared to microstrip-circuit modeling, we have at least one additional parameter (gap width) that makes the conventional model fitting techniques more difficult. Also, the need to locate air-bridges near discontinuities calls for the effects of air-bridges to be accounted for in the model development process. The EM–ANN modeling approach appears to be well suited for this purpose [17], [18]. An example in [18], describing the design of a CPW folded double-stub filter, shown in Fig. 9, points out that the circuit optimization (requiring seven circuit analyses) time using EM-ANN models was only 3 min. This should be compared to the 14 h needed for one circuit analysis (for results at 17 frequency points) when a direct EM simulation is carried out on the same HP 700 workstation.

C. Modeling of Multilayered Circuits

The design of multilayered mm-wave circuits requires two new classes of components to be characterized and modeled: multilayered multiconductor transmission-line components and inter-layer interconnects using either vertical vias or EM coupling through apertures in the inter-layer ground planes. Lack of CAD models for these components is the current bottleneck in the design of multilayer mm-wave circuits. Again, the EM–ANN modeling approach will help in providing a design solution.

D. Design of Integrated Circuit–Antenna Modules

Design of integrated circuit–antenna modules (or active antennas [36], as they are more popularly known) is another emerging area that could benefit by the ANN modeling approach. Appropriate ANN models for microstrip patches and other printed radiating elements could be linked to currently available powerful circuit simulators, thus allowing designers to handle active antenna design in a convenient manner.

E. Circuit Optimization

Apart from modeling, ANN computing could play a key role in circuit (and component) optimization. In this case, the repeated analysis, performed by linear/ nonlinear/EM simulator(s), can be replaced by an ANN module yielding the circuit performance as a function of various designable parameters (whose optimum values we are trying to choose). Efficiency

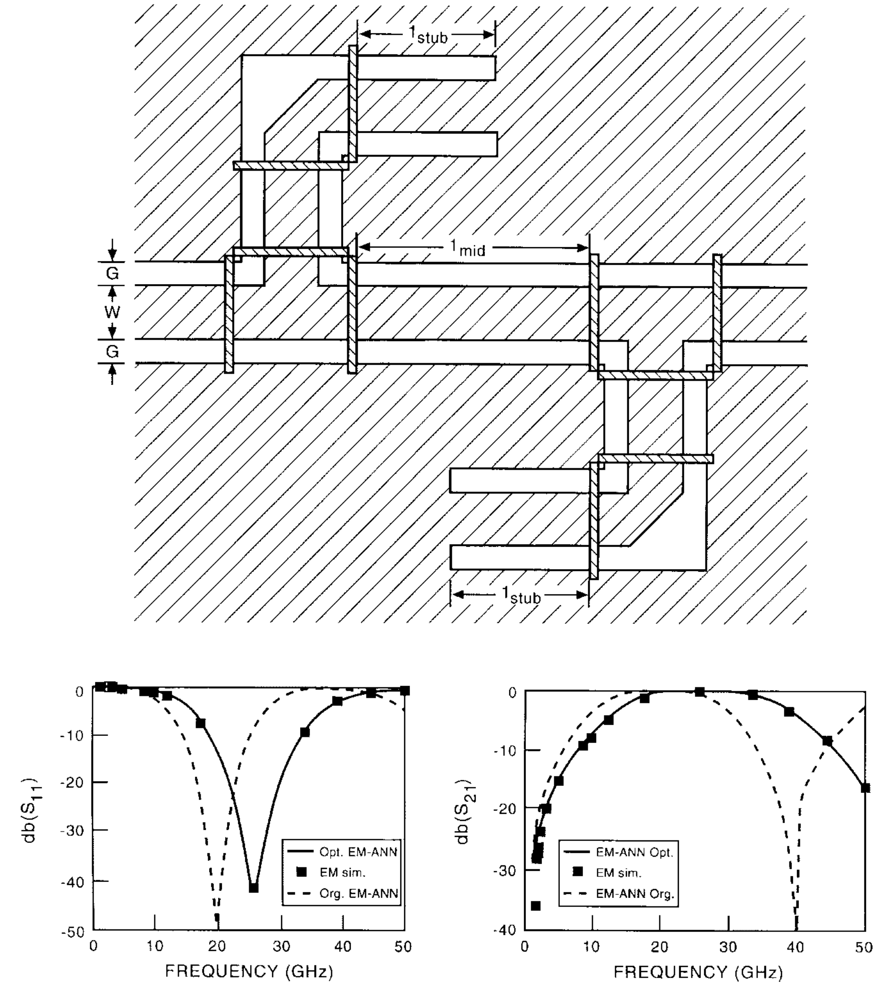

Fig. 9. Layout and performance of a CPW folded double-stub filter, which was optimized by using the EM-ANN modeling approach. Results for S_{11} and S_{21} show performance of initial nonoptimized circuit (dotted curves), performance of optimized circuit (continuous curves), and verification by full-wave analysis (solid square points) (from [18]).

resulting from such an optimization process needs to be investigated for different classes of mm-wave circuits.

VI. Knowledge-Based Design

In addition to CAD methodology, which is used currently for microwave and several other design domains, a methodology knows as knowledge-aided design (KAD) has been proposed [37]. KAD may be defined as a system that enhances design by having computers make knowledge available to the designers. In order to appreciate the role of KAD in design, we need to discuss in detail the various steps involved in the design process.

A. Anatomy of the Design Process

The sequence of various steps in a typical design process [38] is shown in Fig. 10. One starts with problem identification. This phase is concerned with determining the need for a product. A product is identified, resources allocated, and end-users are targeted. The next step is drawing up the product design specification (PDS), which describes the requirements and performance specifications of the product. This is followed by a "Concept Generation" stage where preliminary design decisions are made. Several alternatives will normally be considered. Decisions taken at this stage determine the general configuration of the product and, thus, have enormous implications for the remainder of the design process. At each of these design stages, there is usually a need for feedback to earlier stages and reworking of the previous steps. The analysis and evaluation of the conceptual design lead to concept refinement, for example, by placing values on numerical attributes. The performance of the conceptual design is tested for its response to external inputs and its consistency with the design specifications. These steps lead to an "initial" design.

The step from initial design to the final detailed design involves modeling, computer-aided analysis, and optimization. CAD tools currently available to us for high-frequency design primarily address this step only.

B. Role of Knowledge Aids

The design process outlined above can be considered to consist of two segments. Initial steps starting from the product identification to the initial design may be termed as "design-in-the-large" [39]. The second segment that leads from an

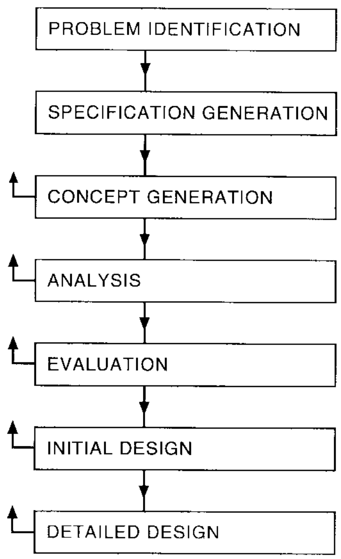

Fig. 10. Sequence of steps in a typical design process.

initial design to the detailed design has been called "design-in-the-small." It is for this second segment that most of the microwave CAD tools have been developed.

It is in the "design-in-the-large" segment that important and expensive design decisions are made. Here, a "knowledge-based system" is the most likely candidate technology that could help designers. Understanding this part of the design process is a prerequisite for developing knowledge aids for mm-wave design. An extensive discussion on these and related topics is available in a three-volume treatise on artificial intelligence in engineering design [40].

C. Knowledge Aids for Design

Development of knowledge aids may be based on developing a task structure [41] for the design process. A generic task oriented-methodology involves: 1) a description of the tasks; 2) proposed methods for it; 3) decomposition of the task into subtasks; 4) methods available for various subtasks; 5) knowledge required for implementing various methods; and 6) any control strategies for these methods.

A method for accomplishing a generic design task is known as the propose–critique–modify (PCM) [42] approach, shown in Fig. 11. This approach consists of the following:

1) proposal of partial or complete design solutions;
2) verification of proposed solutions;
3) critiquing the proposal by identifying causes of failure, if any;
4) modification of proposals to satisfy design goals.

D. Applications to MM-Wave Design

Use of knowledge-based approaches to the initial stages of mm-wave design is an area that needs to be explored. We currently heavily depend upon the accumulated experience of senior designers for executing these design steps. Recognizing the significant contribution of these steps to the final design, efforts in developing technology aids for this purpose would be worthwhile.

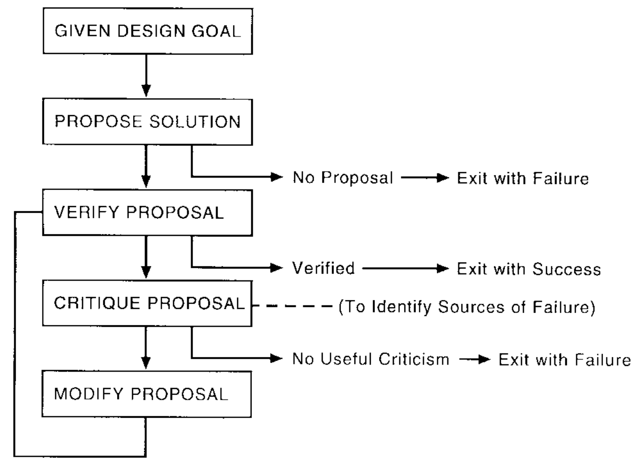

Fig. 11. PCM approach for arriving at an initial design.

Knowledge-based systems developed for initial design of mm-wave circuits would also be very helpful for instruction or training of design engineers. For example, a system that can present all the relevant options for, say, designs of digital phase shifters at mm-wave frequencies, could educate the designer about the relative merits of various phase-shifter configurations as well as lead to a design for meeting a particular set of specifications.

VII. Concluding Remarks

There is a definite need to develop design tools to bring the mm-wave CAD to the level of maturity that is available for microwave CAD today. Research and development efforts are required in techniques leading to more efficient use of full-wave analysis methods. These include diakoptics methods for frequency- and time-domain EM simulations, use of the ANN modeling approach, and application of knowledge-based techniques.

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