A Comprehensive CAD Approach to the Design of MMIC's up to MM-Wave Frequencies

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(Invited Paper)

Abstract —**This paper is an extended and updated contribution based on an unpublished presentation given at the 1986 MTT-S Microwave Symposium, Workshop on Trends in Microwave CAD. The paper discusses the main requirements for the computer-aided design of MMIC's, emphasizing in detail the various physical effects, which are important in the development of monolithic circuit designs. Based on these considerations, a comprehensive CAD approach has been developed, which forms the core of a layout-orientated, process-independent simulator for an MMIC design engineering workstation (EWS). The CAD solutions developed and in progress for this EWS are described. The solutions include a new field-theory-based, high-resolution generator which produces the modal characteristics of complex MMIC microstrip structures. Another portion used as a support tool is a three-dimensional, hybrid-mode-based analysis package for discontinuities, nonelementary rectangular conductor patterns, and the analysis of coupling problems. Thus, the layout-oriented analysis and optimization scheme developed can handle interdigitated and spiral components as well as complex coupling situations. The sophistication and simulation accuracy of the approach described are illustrated by a variety of component examples and a four-stage monolithic traveling wave amplifier.**

I. Introduction

The COMPUTER-AIDED DESIGN (CAD) of microwave analog circuits is now commonplace, with several commercial CAD packages being available to the circuit designer. However, good as these packages are, they were originally developed for the analysis of linear electronic circuits with some hybrid microwave integrated circuits capabilities, and the models used are therefore limited in their applicability to the latest GaAs MMIC technology. There is consequently a growing demand for the improvement of the CAD tools available to the MMIC designer [1], [2] and it is the purpose of this paper to describe some of the latest developments in this field.

The monolithic microwave integrated circuit is now a mature technology, with more than 100 companies worldwide claiming an MMIC capability. Given such a stable technology base with many GaAs foundries available, the commercial edge for any company is fast becoming its ability to design IC's accurately and achieve a first-time design success. MMIC's are not readily tunable after manufacture, and the time scales and costs involved in a design iteration are high. Current MIC CAD programs have been adapted to fulfill to some degree MMIC designers aims; however, the small component sizes and close intercomponent separations inherent in the GaAs IC are beyond the accuracy of many of the MIC-based component models used. Clearly, therefore, there is an urgent need for the development of CAD tools tailored specifically to the special demands of MMIC technology [1],[2].

The ability to fabricate monolithic MIC's places very stringent demands on the circuit design tools. The aim of creating complete circuit functions on a chip area of typically 1 sq mm automatically results in individual components being within, say, 100 μm of each other for a 200-μm chip thickness. This close spacing means that intercomponent electromagnetic coupling becomes an important part of the circuit operation. Equally, at the IC layout stage, component placement, aspect ratio, and orientation are often altered to optimize GaAs area utilization. Here changes in strip widths, the addition of bends, and other discontinuities can cause significant performance changes. Apart from the layout problems, today's MMIC technology involves the fabrication of multilevel structures with nonnegligible metal thicknesses. The use of passivation layers and intermetal dielectric layers means that component analyses have to account for multidielectric media. All of the above requirements show the need for a microwave circuit simulator which can analyze a circuit in terms of the component layout and optimize the circuit in terms of component geometry.

II. MMIC Process Design Consequences

The MMIC design approach has to deal with GaAs process technologies more complex than those that can be dealt with using current commercial CAD simulators. Such technologies are based on multilayer dielectrics or air bridges on a GaAs substrate. An example of a multilayer dielectric medium is shown in Fig. 1, which is the Plessey GaAs IC Foundry process specifically developed as a high-yield, reproducible, reliable, and fully passivated scheme for the production of microwave IC's.

In the process of Fig. 1, the active devices (FET's) are realized using an etched channel technology on ion-implanted material, this material also being used for the IC

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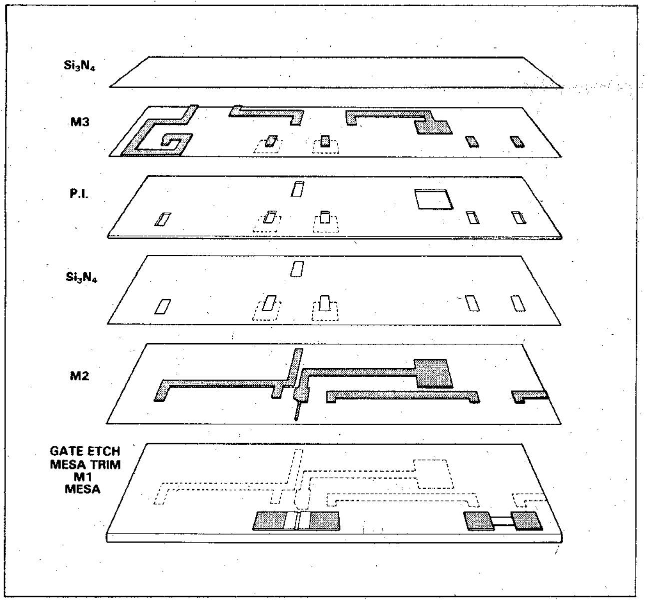

Fig. 1. Schematic of current GaAs IC standard production and foundry process.

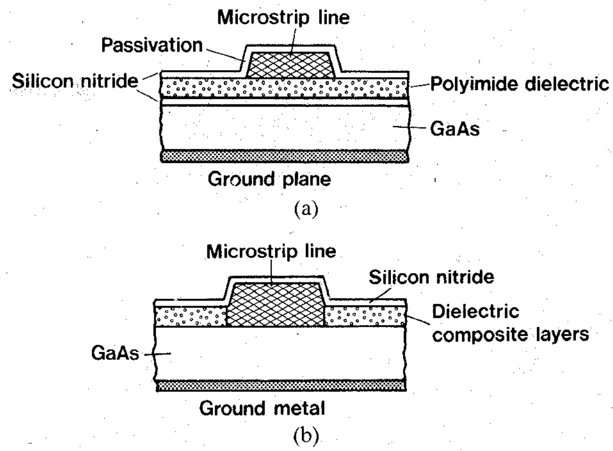

Fig. 2. Cross-sectional view of (a) multidielectric and (b) single-dielectric microstrip used in the standard MMIC production process.

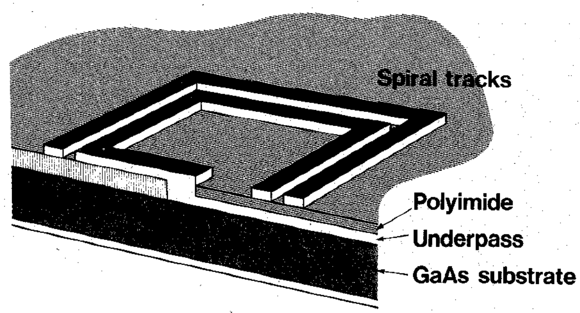

Fig. 3. Typical coupling situation between conductors on two different metallization layers as shown for a spiral inductor underpass.

resistors. The other passive elements and interconnects are produced by a two-level metallization scheme which allows for complex low-loss circuit topologies. These metal layers are separated by a composite silicon nitride dielectric layer used for passivation of the active devices and a polyimide dielectric layer. The dielectric separation enables two types of MIM capacitors to be fabricated. Finally, a thin layer of silicon nitride is introduced on top of the MMIC for passivation. Unlike many GaAs processes, this production process does not use air bridges, since their excessive use is viewed as a yield hazard. Instead, the multilevel dielectric and metal sequence allows underpassing, thus giving the circuit designer the possibility to use small-area, three-dimensional structures.

One of the aspects that has to be addressed is the use of multidielectric media, such as thin layers of silicon nitride, silicon dioxide, polyimide, or air (due to bridging), on top of a GaAs substrate. Despite the thinness of these layers, their electrical effects on component behavior are strong, especially for microstrip widths as used in MMIC's. For the structures shown in Fig. 2, the change in the transmission line characteristics compared with conventional single layer microstrip is far from negligible. On a 200-μm GaAs substrate, a 3-μm polyimide layer below the strip conductor reduces the effective dielectric constant of a 20-μm-wide microstrip by about 17 percent. At the same time, the characteristic impedance increases by 10 percent. For coupled lines and interdigitated structures, the effects are even more dramatic. They are due to the disparity of the dielectric constants of the thin layers and the GaAs substrate and as such they affect the propagation constants of the modes characterizing component behavior. In particular, this applies to interdigitated and spiral-type components built up from a network of multistrip sections [3]–[5].

The addition of thin dielectric films in a GaAs process not only allows the manufacture of metal–insulator–metal capacitors; it also provides the isolation for microstrip tracks on different metallization levels. At their coincidence there exists a relatively strong and mainly capacitive coupling between the conductors. These situations occur at microstrip crossings, air bridges, and underpasses, the latter two structures being used in defining spiral inductors, as shown in cross section in Fig. 3.

Such a construction causes considerable feedback in a planar inductor element, thus producing a noticeable influence on its first parasitic resonance frequency [5]. For this reason, a reliable and generally applicable analysis of these underpass configurations with multiple microstrip structures is required [7].

III. MMIC Coupling Mechanisms

Incorporation of coupling effects in MMIC simulation is one of the most important requirements for efficient design, especially with the commercial pressure to increase on-chip component density. At present, CAD solutions do exist for coupled and multiple coupled transmission lines [3], [6]. With coupling distances of the order of a substrate thickness or less, the effective dielectric constants of the strip structure modes can deviate 5 percent or more from that of the single strip. Thus, it is obvious that even though isolated component models can be very accurate, they will soon become useless if they are laid down in a situation where coupling phenomena are dominant. Capacitive and inductive coupling descriptions for component proximity

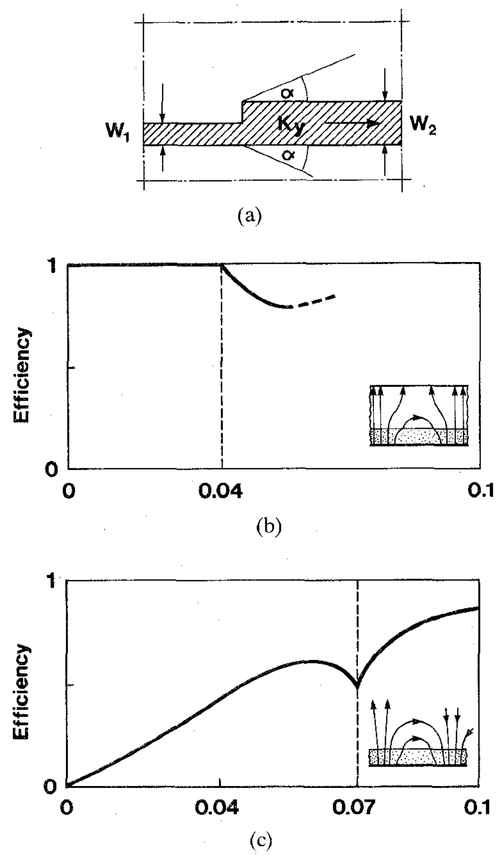

Fig. 4. (a) Visualization of spurious wave excitation in a MIC at a strip discontinuity, (b) excitation efficiency for the lowest order parasitic mode in covered circuit media, and (c) open antenna media as a function of normalized frequency.

effects in MMIC's apply only in situations in which the chip dimensions are small compared to the operational wavelength. This, for many practical circuits, occurs up to X-band frequencies but even today a systematic layout-orientated CAD approach is not available.

In MMIC media used into the mm-wave range, dynamic coupling mechanisms, which include the phenomena of radiation and the excitation of parasitic waves (surface waves, package modes), represent the most complex form of interaction between components. Up to the present, these mechanisms have received attention mainly in the field of microstrip antenna research [8], and it is only recently that the methods have been applied to describe circuit structures [9], [10]. However, in considering coupling mechanisms in MIC's and MMIC's, it has to be pointed out that they differ in principle from those in open media, due to the presence of a metallic cover as part of the circuit package [11]–[13]. This difference is illustrated in Fig. 4, where Fig. 4(a) shows in schematic form how a leaky, higher order mode is excited at an asymmetric step discontinuity. In such a case, electromagnetic energy leaks from the wider microstrip at an angle α determined by the propagation constants $K\rho\ sw$ and Ky of the dominant surface wave in the substrate medium and the excited first higher strip mode [14], [15]. For covered media, as used for MMIC's, the angle α is in the plane of the substrate, whereas in open media energy is radiated through a leaky microstrip mode into free space [16].

These different mechanisms are shown quantitatively in Fig. 4(b) and (c) for a microstrip open end. The excitation efficiency e_{sw} in Fig. 4(b) describing that proportion of the total leakage energy that converts to the lowest order parasitic LSM_0 wave is found to be unity up to the onset of the second surface wave mode due to the presence of a cover. In Fig. 4(c), that is, the open medium [9], e_{sw} is at first nearly zero, because most of the leakage energy is radiated into free space at low frequencies. The surface wave excitation efficiency then increases linearly to about $e_{sw} = 0.5$, which occurs at a frequency of 60 GHz for a 200-μm GaAs substrate. As a result any full-wave approach to the simulation of coupled structures in MMIC's will have to take the circuit cover into account.

IV. Metal Thickness Effects

Another area for improved analysis in MMIC's is the effect of metal thickness, which becomes noticeable in certain cases. This aspect ratio in hybrid circuits is typically in the range 0.002–0.100, whereas in MMIC's it is 0.02–0.30. For a single microstrip, the effect of finite metal thickness on the main strip characteristics is usually negligible. Kowalski and Pregla [17], for example, report a 1 percent change in the effective dielectric constant for a microstrip on alumina with an aspect ratio of 0.10 and a width to substrate thickness of 0.10. The situation is different for tightly coupled MMIC structures where thickness to gap values of 0.1–0.3 are not unusual. Kitazawa *et al.* [18], analyzing coplanar guide ($\epsilon_r = 20$), found that in the extreme ($t/w = 0.1$, $t/s = 0.1$) the decrease of effective dielectric constant compared to that for zero metal thickness is found to be 10 percent. For GaAs MMIC's ($\epsilon_r = 12.85$) whose substrate has a metal ground plane, the effect is certainly smaller for comparable geometries and can be estimated to be around 5 percent. Nevertheless, this means that the effect of finite metal thickness on tightly coupled structures with different potentials is noticeable.

The analysis of losses is not possible without considering finite metal thickness in MMIC design. For field-theoretical computations based on the assumption of zero strip thickness, the use of a perturbation approach to determine the loss is not directly possible without certain modifications being introduced [18], [19]. Furthermore, the classic perturbation approach is only valid for metal thicknesses large compared with skin depth. It does not result automatically in the inverse metal thickness law for conductor loss at low frequencies or thin metallizations. Only when a modification is made in which the magnetic field $H(t = 0)$ is applied as a boundary condition to the finite thickness case, is the correct approximate behavior obtained over both low and high frequencies [21], [22].

V. MMIC Simulation Requirements

In order to analyze MMIC's up to the mm-wave region, a simulator has to have certain attributes. These are that the simulator should be able to analyze a circuit design in terms of its topological and physical parameters including frequency dependence, and that the simulator should not be tied to a given MMIC GaAs process, thus allowing for process updating and new technologies. The need to analyze a broad class of components purely in terms of their physical structure means that an underlying electromagnetic field-theoretical description has to be considered. Although powerful field theory techniques are available, the speed in computing component behavior is currently too slow for interactive design. A method of attaining adequate simulation times is to adopt a data base solution, in which the data are generated off-line by a set of field-theory-based CAD tools [4].

The accurate description of lumped elements for use in a MMIC simulator is a problem by itself. Their high geometric and structural complexity has to be complemented by highly complex model descriptions in CAD analysis. Typical examples are spiral inductors, spiral transformers, and interdigital capacitors. Analytical models can be used but are only adequate at very low frequencies, within which parasitic effects can be neglected. Full-wave 3-D solutions are not feasible, because the associated boundary value problems are much too complicated. Therefore, the accurate characterization of spiral and interdigitated components at high frequencies requires new sophisticated modeling methods and CAD strategies. Although a large data base can be built up for MMIC design from systematic measurements of components, direct simulation from structural and geometric data is a much better solution. Successful modeling of this type has been reported for multiturn square spirals and even spiral transformers [23].

VI. EWS Simulator

Taking into consideration these system requirements, an MMIC simulator is being developed for an engineering workstation which will be able to interact with a circuit layout editor (Fig. 5). The requirement for having both a simulator and a layout system in the same EWS exists since there is a considerable correlation between the circuit layout topology and circuit electrical performance in high-component-density MMIC's. In addition to the two named subsystems, additional modeling and analysis CAD tools are required for generating electrical and topological data bases.

The core for the simulator to the EWS approach is a MIC/MMIC software package described recently [24], together with an efficient passive component analysis extension [25] and microwave transistor modeling routines [24], [26]. In addition, the simulator contains a microstrip structure analysis and electrical characteristic lookup table generator [4] and is supplemented by a field-theoretical 3-D analysis program [27]. Recently, the software has been integrated into a fully interacting simulator, its element library increased to include additional MMIC component modules, and an advanced lookup table generator added [22]. The simulator was based on a layout-orientated software for MIC's developed in 1978/79 [28], [29].

The simulator contains the stated requirements for a fully integrated, layout-orientated, and process-independent MMIC design EWS. Electrical descriptions of the components are generated from their metal layout structure. The MMIC process is introduced by generating trans-

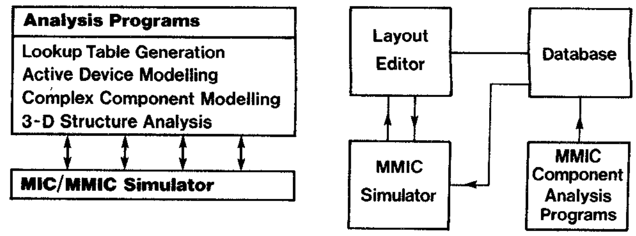

Fig. 5. Schematic of the subsystems for a new engineering workstation for MMIC design.

mission-line characteristics in lookup table form from the components' cross-sectional geometry and the physical data on the multilayer dielectric media. The component library covers a wide range of layout structures from complex components such as spiral inductors to strip discontinuities such as steps in strip widths, 90° bends, and two metallization layer crossovers. Circuit optimization is performed in terms of varying component geometry to a design specification. The interactive circuit simulation requires computation times of minutes using modern workstation computers.

In view of future MMIC complexity, the simulator can treat an array of up to 40 unconnected ports either fully connected into a single circuit or separated into isolated subnetworks, e.g., user-defined amplifier stage subnetworks which are finally interconnected to form a multifunction chip. Such a formalism has the advantage that both the important function performances and the complete circuit performance are accessible at the same time. Further, the simulator allows the storage of components and subnetwork computations for repeated introduction into the full circuit simulation.

The network algorithm employed internal to the simulator is a modification of the well-known subnetwork growth approach [30], [31]. In the simulator, it records the generated subnetwork configuration in terms of multiport admittance and control parameters. The advantage of the growth approach is that all interconnection operations need to be made only on the minimum network matrix required at a particular point during the network simulation. This matrix size minimization allows for high numerical stability and accuracy, further enhanced by accurate admittance matrix manipulation operations.

VII. Microstrip Electrical Characteristics Generation

One of the key features of the MMIC design approach is the automated generation of hybrid-mode transmission-line electrical characteristics by a field-theory-based lookup table generator for single-strip and multistrip configurations in a general multidielectric medium. This lookup table concept represents a fundamental, very efficient, and general alternative to the development of analytical models, which are hardly feasible for media more complex than conventional microstrip [24], [26], [4], [22].

These generators are based on full-wave numerical analysis of MMIC structures [32]–[34]. For the discussed application, the respective programs have to operate with a high

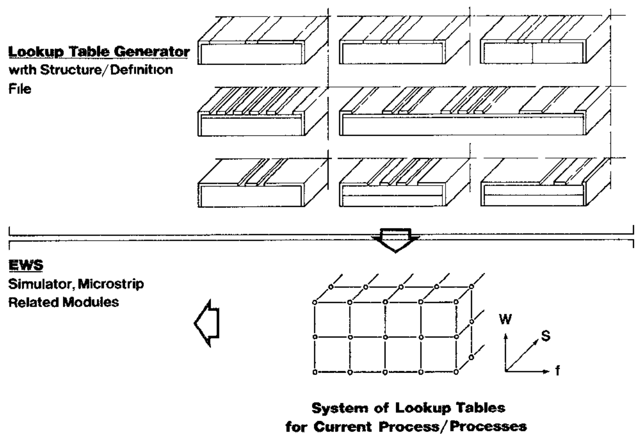

Fig. 6. Representation of the second-generation lookup table generator showing its range of applications and interaction with the layout-oriented simulator.

level of confidence for an extremely wide range of applications. Numerical stability and automatic control are required. The generator has to find all the relevant modal solutions for any structure of technical interest in MMIC design from those that are narrow or wide, from tightly coupled to those that are loosely coupled (resulting in near mode degeneracy). The capability of analyzing very fine, narrow structures is particularly important since they occur commonly in the design and analysis of complex MMIC components.

The first lookup table generator applied was based on an enhanced spectral-domain technique [4], a technique well suited for high-speed computation of strip characteristics. It was capable of handling a variety of substrate media and able to handle up to ten coupled strips symmetrically arrayed and of equal width [24]. Its accuracy has been demonstrated by comparing its MMIC microstrip analysis with measurements made up to 24 GHz [21].

The need, however, to further generalize and improve the modeling of passive components requires a more general lookup table generator. As a result, a new generator which can be applied to the structure range shown in Fig. 6 has been developed. This generator has several improvements in that it is based on a new spectral operator expansion technique [22], abbreviated SOET herein, which is a generalization of the enhanced spectral-domain method [4]. The SOET makes it possible to represent analytically to a large extent the functional dependency of the hybrid-mode operators that occur in 2-D and 3-D full-wave MMIC problems. It decouples the frequency and modal propagation constant parameters from the space-dependent functions of such operators.

As a consequence, numerical solutions with high spatial resolution can be achieved in reasonable CPU times even for complex geometries, i.e., about 100X faster than the conventional spectral-domain method. Another advantage is its particularly high numerical stability. The cross-sectional geometries to which the new table generator can be applied may have up to three dielectric layers above and three below the strip plane. A wide range of strip configurations can be analyzed involving cases of complete asymmetry in both strip width and position for up to ten strips. Grounded strips/fins can be included at the left and the right boundary or in the middle of the microstrip structure. With the SOET, insight can also be obtained for higher order modes excited in a package [22]. For both fundamental and higher order modes, MMICTL can display strip current densities, and transverse electric field can be displayed in the form of optional graphics. Strip configurations with strip width ratios up to 400:1 have been analyzed without problems.

The lookup tables from these generators are written as functions of strip width, gap width, and frequency. The information in the lookup table is used by the simulator during circuit analysis by interpolation between the geometric and frequency function table sets. Using this method the application of the tables is considerably faster than the use of good analytical models. Further the generation of such tables opens up the possibility of generalized and more accurate MMIC component simulation.

An example of the electromagnetic characteristics produced by the lookup table generator is presented in Fig. 7. These plots provide an insight into the characteristics of the modes associated with MMIC multistrip configurations. Fig. 7(a) and (b) presents the surface current densities and transverse electric fields for the pi-mode and c-mode propagating on a pair of nonsymmetric coupled strips ($W1 = 10$ μm, $S = 10$ μm, $W2 = 40$ μm). The substrate configuration is a 200-μm-thick GaAs/polyimide sandwich, and the operating frequency is 60 GHz. The total chip width considered for the field region is 2 mm, the plots of Fig. 7 covering the range $x = 1.0$ to 1.1 mm. The associated design quantities have an accuracy of better than 1 percent in all but the conductor loss, which is directly affected by the current distribution. Particularly high accuracy is obtained numerically [22] when the edge condition [35] is explicitly described in the expansion functions for each strip.

VIII. Improvements to MMIC Component Modeling

The availability of multidielectric-layer-based lookup tables means that complex MMIC passive components can be described [25]. With the described simulator, four- and six-strip coupled, folded and unfolded Lange couplers, interdigital capacitors, and multiturn rectangular spiral inductors and transformers can be analyzed [3], [4], [10], [2].

Another application opened by the use of more general lookup tables is the geometry-related modeling of FET's for the mm-wave range, utilizing the high-resolution numerical analysis with the latest table generator [42]. The basic idea behind such modeling is that the FET associated parasitics are mainly determined by the metallization pattern, while the active functions (controlled current source) become effective only in the short-channel portions of a device, as shown in Fig. 8. By combining the elementary passive and active constituents in a segmentation approach, good distributed component models are expected,

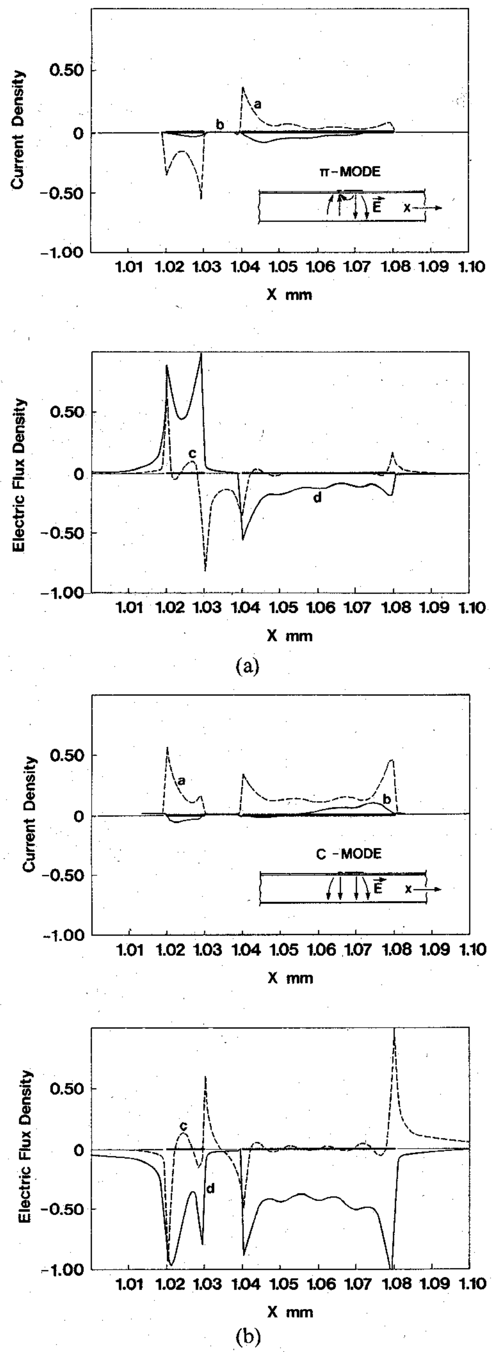

Fig. 7. Field and current density computed by the table generator for a nonsymmetric strip configuration on a 200-μm GaAs substrate at 60 GHz. (a) π-mode. (b) c-mode.

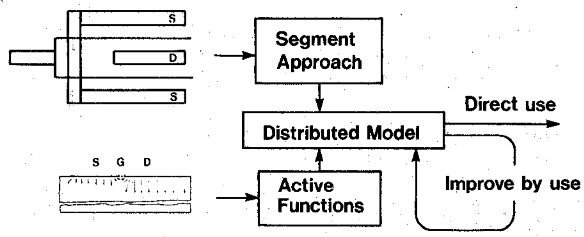

Fig. 8. Schematic of a geometry-related FET modeling approach using the new generator for a transmission-line analysis of the FET metallization pattern.

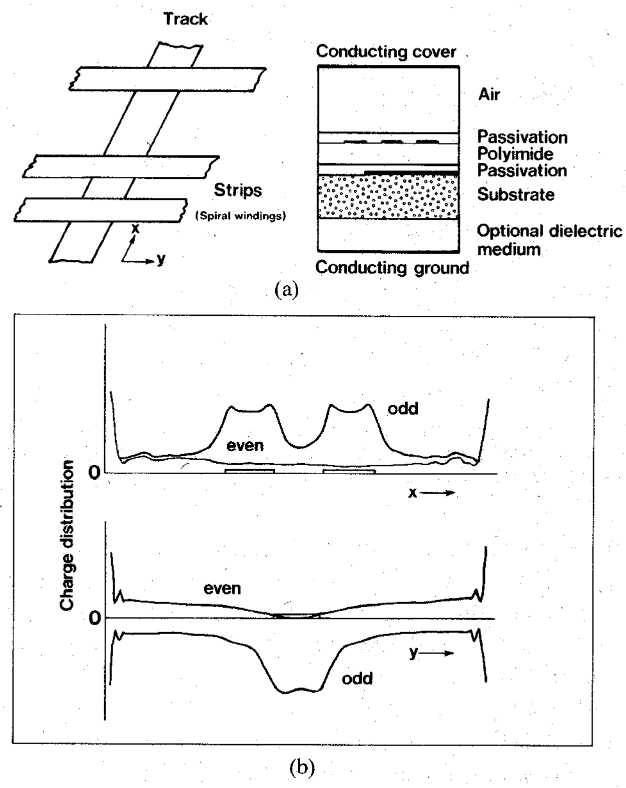

Fig. 9. (a) Crossing of strips on different metallization levels in a multidielectric circuit medium. (b) Associated computed charge distribution for even and odd excitation.

as indicated by the behavior of the passive and active components in equivalent circuit models when fitted to the measurement data of FET's with a wide range of geometries [36].

As far as 3-D field-theoretical CAD analysis is concerned, two software routines have been written as support tools to the simulator. The first one, a static spectral-domain solution for single-strip and multistrip crossings in MMIC media [7], is used in the simulation of complex spiral and interdigitated components to determine the excess capacitances associated with underpasses, dielectric, and air bridges. The geometries and substrate configurations assumed in such an analysis are shown in Fig. 9(a). Fig. 9(b) gives an example of the computed longitudinal charge distributions on a conductor track passing under two coupled strips for excitation with equal (e) and oppositely equal (o) potentials. A similar static analysis is available in the evaluation of correction capacitances for coupled corner structures in square spirals, the simulation method's details and accuracy being verified by measured spiral component data [10].

With regard to a first approximation of coupling in high-density connection track areas, the simulator contains two component modules which can analyze single and coupled meandered lines [37]. The geometry of the basic coupled meander structure, shown in Fig. 10(a), is defined by the structural parameters, strip width, fold dimensions, meander direction, chamfered or unchamfered bends, and number of folds. In simulating these structures, an automatic segmentation approach is used which considers coupling between adjacent folds within the meander, including

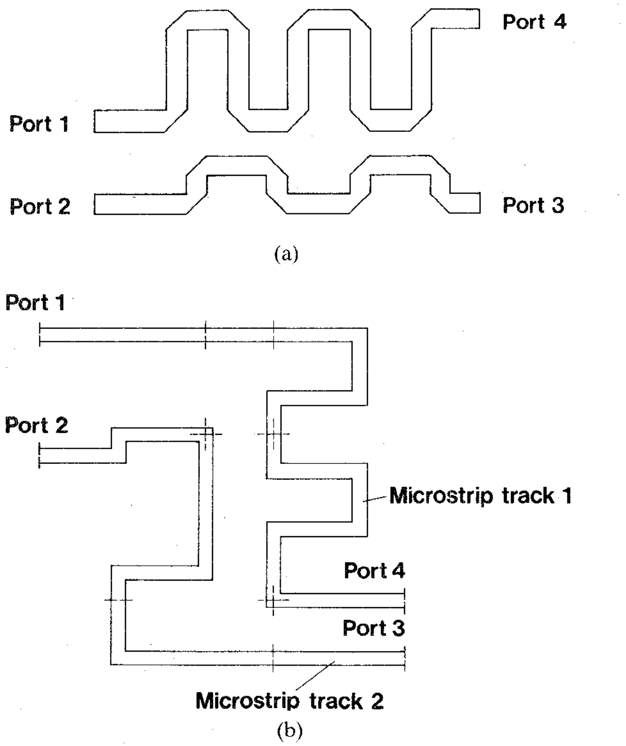

Fig. 10. (a) Coupled meander lines for a generally defined module configuration and (b) its application to a nonconventional transmission line structure in MMIC's.

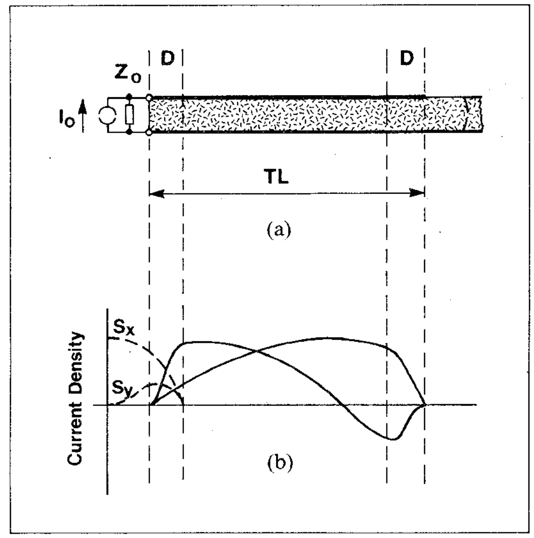

Fig. 11. (a) Idealized schematic of an MIC discontinuity problem and (b) its expansion function description scheme.

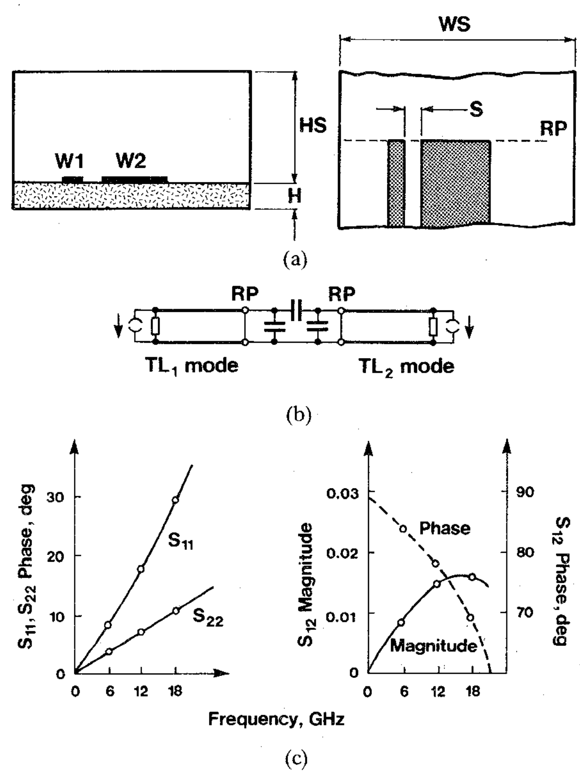

Fig. 12. Dynamic coupling problem for two nonsymmetric coupled microstrip lines. (a) Physical structure of the configuration. (b) Equivalent circuit representation. (c) Computed scattering parameters.

the parallel portions in the coupled case. The approximation made is that the approach is a piecewise 2-D analysis in comparison to a 3-D analysis. By using these modules quite general configurations can be treated, as shown in Fig. 10(b).

Presently, the only 3-D full-wave analysis tool employed is a stand-alone support package whose 3-D eigenvalue approach has already been verified [38]. This tool performs a 3-D hybrid mode analysis for a variety of discontinuities and composite MMIC structures up to the geometric complexity of simple filter configurations [27]. It is based on a source formulation procedure for hybrid and monolithic MIC's with a spectral-domain field description [13]. A modular version [27] allows the simulation of a wide range of rectangular strip conductor patterns by means of a layout-oriented input file. For gap and open end discontinuities in open media, similar approaches have been published recently [9], [10]. However, as has been pointed out, the leakage and coupling mechanisms in that work do not represent the situation of covered MMIC's. To illustrate the solution procedure followed in the 3-D analysis tool used here, Fig. 11 shows a schematic representation of a one-port discontinuity problem with the current source I_0 and the discontinuity region D, where (S) is the source region from which precomputed vector sources excite the guided modes of interest (N sources for an N-port, Sy for the longitudinal direction, Sx for the transverse direction). TL is the transmission line region where precomputed modal current densities (wave functions) are sufficient to satisfy the boundary conditions with good accuracy; and D represents the regions in the vicinity of discontinuities and sources where additional expansion functions have to be used.

One of the advantages of this approach is that it yields the scattering matrix of a strip N-port configuration in a single step, without repeated generation of the respective system of equations as in previous related eigenvalue methods [33], [39].

As a basic example, Fig. 12 describes the mode conversion at the open ends of coupled microstrip lines of different widths. The structure in Fig. 12(a) is situated on a standard 25-mil alumina substrate. The first-order equivalent circuit of Fig. 12(b) illustrates how the two fundamental modes on the asymmetric coupled strips interact at the open end (the capacitive π-circuit), the structural separation of the modes as in the equivalent circuit actually not being given in the physical configuration. As the numerical results of Fig. 12(c) show, there is weak coupling in the asymmetric case, confirming the equivalent circuit of Fig. 12(b). The reflection coefficients of the open-end two-port exhibit linear phase angles with increase in frequency describable by equivalent open end length, so at present the 3-D full-wave program is still far too time consuming for direct integration into the simulator and for interactive use. It is mainly used for fundamental modeling purposes, design checks, and verification of the analytical discontinuity models.

IX. MMIC Component Simulation

The accuracy of the EWS simulator's component library has been verified by comparing the predicted component performances against the measured MMIC component performances. In all cases tested, very close agreement has been demonstrated with the measured results. To illustrate the quality of the analysis verification examples are described below.

Consider first of all the folded 3-dB Lange coupler shown in Fig. 13(a) and realized on the described foundry IC process. Test examples of this circuit element were fabricated with strip widths ranging from 8 to 16 μm and gap widths from 4 to 8 μm.

The measured and simulated two-port embedded performance of the coupler is shown in Fig. 13(b) and (c). One reason for the good simulation accuracy is the consideration of all four field modes in the analysis, which contribute to the coupler's action in the interdigitated four-strip section.

As well as achieving good modeling accuracy, the topology-based simulation has allowed the critical examination of the operational features of such MMIC components. For instance, the transmission loss in excess of 3 dB was shown by the simulator to be mainly caused by the polyimide intermetallic spacer layer used. In addition, the polyimide layer has increased the phase difference between the 1-E mode and the 2O-mode [3]. It is the interaction of these modes which dominates the coupler function, and consequently the coupler exhibits relatively poor isolation losses.

The seven-turn spiral inductor of Fig. 14 is a standard MMIC component. It has track and gap dimensions of 12 μm and the inner turn is on a 100×100 μm grid. Again comparing the simulation results against the de-embedded measurements made on an HP8510 network analyser system, it can be seen in Fig. 14(a)–(d) that the simulation results closely follow the measured reflection and transmission losses over the full 1–18 GHz frequency range. In particular the simulator has predicted well the parasitic resonance at 8 GHz as well as the dip at 11 GHz in the reflection parameters. The simulator has even modeled the differences in $S11$ and $S22$ caused by the unsymmetrical positioning of the inductor's underpass.

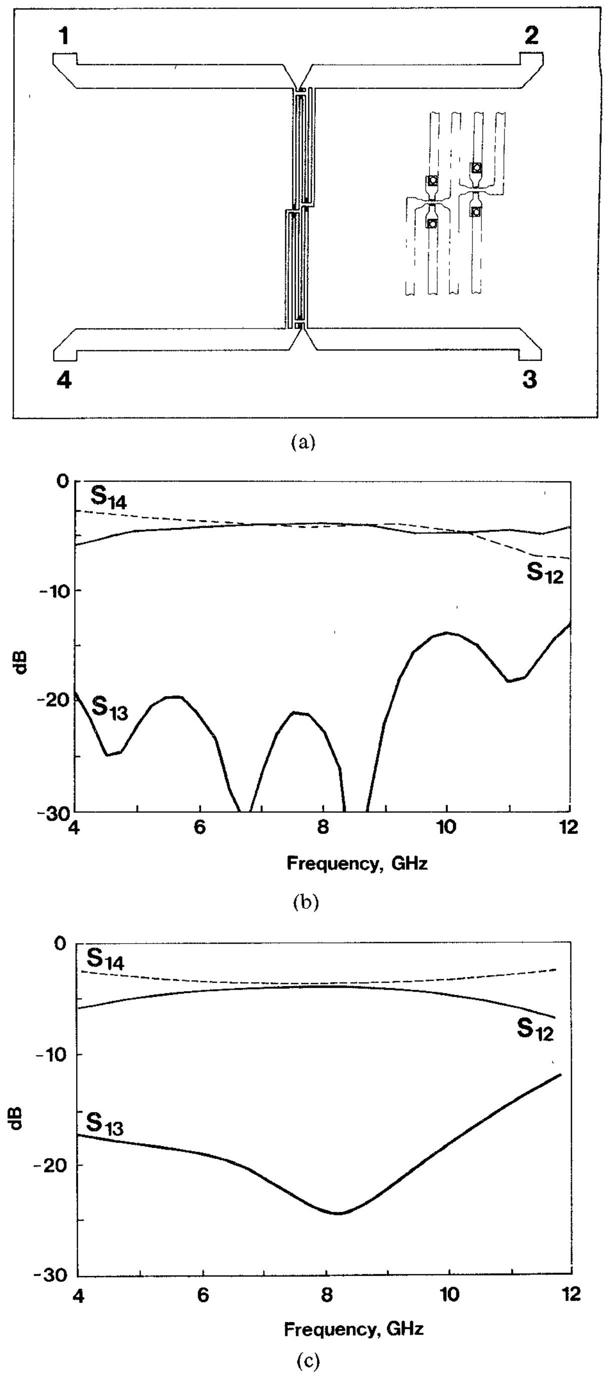

Fig. 13. Lange coupler realisation with (a) details of cross-over construction, and (b) measured performance in comparison to (c) simulated performance.

Direct component simulation has the benefit of high accuracy and flexibility; for computational speed, equivalent circuit models have the advantage. However, the generation of equivalent circuit models capable of fitting the values over very wide frequency ranges is a difficult task. To illustrate this, Fig. 14(a) and (b) also shows the response predicted by a conventional equivalent circuit model. This model fits the inductor measured results (Fig. 14(c) and (d)) only for frequencies up to the 8-GHz first parasitic resonance point. Above 8 GHz, the model cannot

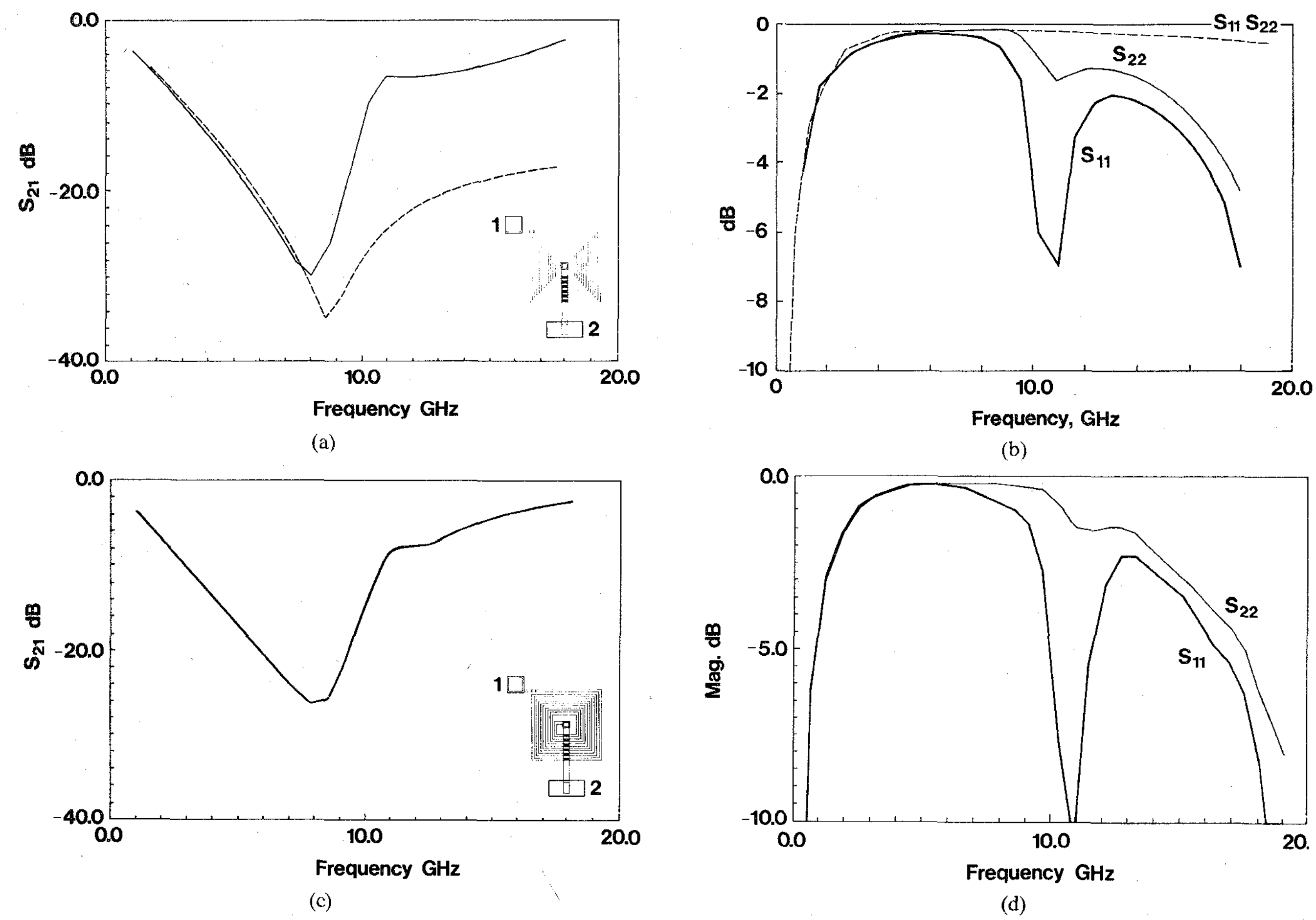

Fig. 14. Spiral inductor: (a), (b), simulated (full line) and simple circuit model (broken line) and (c), (d) measured transmission and reflection losses.

adequately describe the inductor's behavior. This shortcoming has recently been overcome by the development of an improved description based on a transmission line model [25]. Such improved models are generated in the EWS based on the direct simulations and can be stored in a library for future use by the inductor module incorporated in the simulator.

The applicability of the simulator has also been demonstrated on more complex GaAs IC circuit elements such as the planar spiral transformer [23], [24]. The advantage of using these components in circuit design in order to reduce GaAs area has been demonstrated by Podell *et al.* [41] on commercially supplied MMIC's. The transformer can perform several circuit functions simultaneously, for example, dc blocking, RF choking, and impedance matching, as shown in the balanced amplifier of Fig. 9 [3], [23]. Again, excellent agreement between the simulator predictions and the measured performances was seen [23].

X. Circuit Simulation

Having demonstrated the simulation accuracy for MMIC elements, attention was turned to analyzing a complete MMIC with the simulator. Fig. 15 shows the Calma plot of a four-stage traveling wave amplifier circuit in development which was used as an example of the simulator's use on a full chip design. Although this circuit looks at first glance to be fairly simple, it does provide a complex microwave design problem. The circuit contains a high number of discontinuities (in particular, the 90° bends), there are a number of areas where mutual coupling effects are probable, the common nonideal grounding strip has to be checked for floating potentials, and, finally, a nonstandard spiral inductor is used on the drain of the third FET device. Other features in the circuit include mesa resistors for the drain and gate line load terminations, isolated mesa resistor test structures, and silicon nitride dc decoupling capacitors.

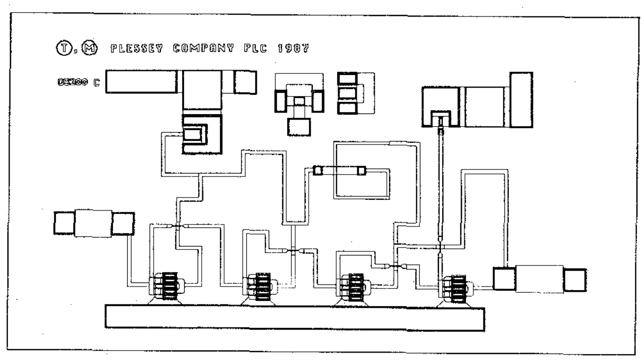

Fig. 15. Layout of a MMIC four-stage traveling wave amplifier.

The above circuit was initially designed using a commercially available PC-based CAD package which predicted a

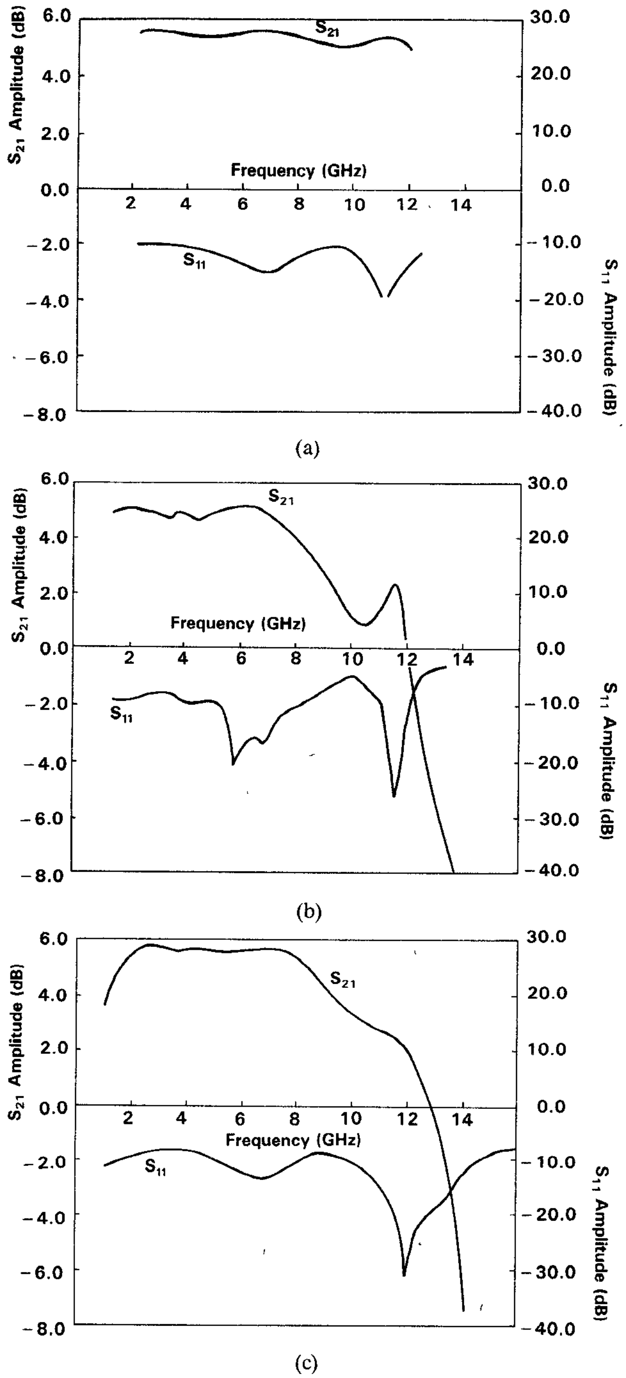

Fig. 16. Four-stage amplifier. (a) Commercial PC CAD simulation. (b) Measured performance. (c) EWS simulator analysis.

5.5-dB gain to 12 GHz as shown in Fig. 16(a). The measured performance illustrated in Fig. 16(b) reveals a very different performance, with a drop in gain apparent above 7 GHz. In view of this large discrepancy, the layout-oriented simulator was used to investigate the original circuit design. The resultant simulation shown in Fig. 16(c) takes account of discontinuities, mutual coupling, and nonideal grounding effects. The simulator identified the causes for the gain roll-off as follows. First, it was found that the high number of 90° bends in the MMIC layout had modified the overall performance considerably. Second, the effects of mutual coupling between apparently unconnected circuit nodes started to become significant at the higher frequency end. Finally, the simulation identified some circuit sensitivity to the bond wire grounding. The only minor discrepancies between the simulated and the measured performances were a 0.5-dB difference in overall gain level and a local dip in the measured gain at 10 GHz. The 0.5-dB gain level discrepancy is within the expected tolerance of the process used, but as yet the dip at 10 GHz cannot be explained. Nevertheless, these results prove the superior simulation quality of the layout-dependent EWS tools.

XI. Future Trends and Conclusions

In the next few years further improvements will undoubtedly be made in the field of CAD for MMIC's. It is expected that the complexity of the CAD tools will be increased and that field-theory-based component descriptions will become more commonplace. In linear (small-signal) circuit design, more complex MMIC structure analysis software and more accurate models for discontinuities and junctions will become available. As well as the above improvements to passive component modeling, there will still be an incentive to develop better descriptions of active MMIC components. The particular demands of MMIC design will undoubtedly inspire more layout-oriented simulators to be developed such as the one described in this paper.

One of the intentions of this paper was to describe a comprehensive approach to MMIC CAD which includes a variety of layout-oriented and field-theory-based features. Although there are few fundamental physical differences between hybrid and monolithic MIC's, some physical effects and design constraints are more pronounced in MMIC's. Consequently, commercially available CAD packages can only be considered to offer zero-order design solutions to the MMIC designer. More sophisticated models and design philosophies are therefore necessary to match the technological and physical complexity of the MMIC and thereby provide first- and second-order modeling accuracies. This article has attempted to describe some of the progress made toward realizing a sophisticated MMIC CAD simulator for a dedicated engineering workstation.

The treatment of nonlinear problems in conjunction with the simulator is seen to be very important but it is beyond the scope of this article.

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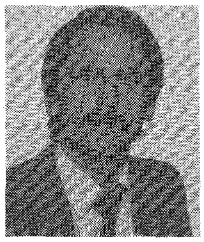

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Dr. Eddison has published over 20 papers and has been issued several U.K. patents. In 1986 he was appointed Manager of Plessey's GaAs IC technology R&D department, where he is currently responsible for the GaA IC process R&D line.