Design-oriented Electromagnetic Modeling for MMICs

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ABSTRACT

Following a broader overview of the status of microwave CAD during EuMC '95, this paper now focusses on the progress and trends of full-wave electromagnetic (EM) simulation software as it is widely used today in the industry for MMIC design. The addition of new features, performance enhancements and improved functionality having emerged over the last 3 - 4 years is outlined. Also, still existing shortcomings, trade-offs and sources of numerical error are addressed. The use of such design-oriented EM software and associated linking methodologies in the context of microwave and mm-wave CAD is discussed.

INTRODUCTION

Full-wave EM simulation techniques for microwave integrated circuit (MIC) structures are now around for about 20 years and have matured into a wide range of commercial tools [1], [2]. Recent overviews are available to describe their role and importance in the context of microwave and mm-wave CAD, e.g. [3], [4]. While in the 1980s the major importance of EM tools was in the domain of discontinuity and junction modeling [5] - [7], they are now on the way of gradually bridging the gap between network (NW) theory-based and electromagnetic (EM) field theory-based simulation of hybrid and monolithic MICs (MMICs), see [8] - [10] and associated references. This implies that today passive MIC configurations up to the level of complexity of an entire filter or matching network can be EM simulated or even optimized [11], [12] and the feasibility of handling active MMIC function blocks has been demonstrated [8], [9].

Voltage V, Current I Lumped Components TEM Transm. Lines (TL) No Radiation Equiphase Fields (quasi-static) NW Theory, TL Theory Y,Z - Parameters	Wave Amplitudes A Distrib. Components Modal Waves (hybrid) Dispersion, Surface Waves, Radiation (often quasi-TEM) EM Theory, GW Theory S-Parameters	EM Waves and Quasi-Optics
EM Techniques for MIC / MMIC Compaction, Parasitic Coupling and Distrib. Component Modeling		Scattering, Antennas

Fig. 1 Graph and table illustrating the application and methodology of simulation tools depending on the electrical size of structures and circuits, respectively (TL: Cross-section << λ)

The main area of application of EM tools for MMIC design, as it stands now, is distributed and geometrically complex component modeling, the consideration of parasitic coupling due to circuit compaction and the full-wave analysis of circuit blocks for verification of mainly NW-based design, particularly for frequencies into the mm-wave region. Such verification allows to check a MMIC for unwanted performance reductions caused by electrodynamic effects before submitting the generated layout for processing. Of course, the transition between the quasi-static domain and the full-wave region (mostly using quasi-TEM waveguiding structures like microstrip and CPW) is continuous and not sharp as schematicized in Fig. 1. The above graph mainly illustrates the traditional (NW theory, TL theory) versus emerging EM and generalized guided wave (GW) theory-based CAD methodology, see also [2], [13]. Further, except for start-up electronic design considerations, the standard approach to MMIC design is the use of discontinuity, junction and component models (analytical, empirical e.g. Foundry type or EM theory-based) together with NW theory for interconnecting those to a full circuit, thus hybridizing the above two methodologies. This is justified by the quasi-TEM character of MMIC transmission line structures and components, also allowing approximate definition, calculation and exchange of electrical parameters (V, I . . . S) between the two domains of Fig. 1. Finally, a well-compacted MMIC today, for yield and other reasons, is typically below the size of one wavelength λ, again justifying the outlined CAD approaches.

The key trade-off between NW theory-based CAD and full-wave EM simulation of MMICs is between achievable design speed and circuit complexity on the one hand and prediction accuracy for tightly compacted circuits on the other hand. A typical linear single-function MMIC simulation based on NW techniques does not take more than a few CPU seconds for a broadband sweep on modern desktop computers, while the same task using first principle full-wave EM analysis for the passive subcircuits needs 2 - 3 orders of magnitude longer depending on the geometrical resolution required (e.g. often hours of CPU time). This comparison is already assuming the use of MIC / MMIC specific tools, namely of the so-called 2.5D („mostly planar“ or „3D planar“) EM simulators specialized for single- and multilayer thin conductor metallizations plus vias to ground and intermetal vias, reflecting closely the planar, photolithographic MIC process technologies, see refs. [1] - [4] and [14], [15]. These tools have become the industrial workhorses for full-wave EM CAD in MMIC design because of the outlined reasons, because of the underlying mature and robust integral equation (IE) formulations and due to the associated, long-proven, efficient method of moments (MoM) solution techniques. For the same reason, they are in the focus of this paper. Vector finite element techniques (VFEM) are also highly mature, but not adapted well to MMIC design, coming along with higher memory and CPU time requirements. Finite difference time domain (FDTD) and frequency domain (FDFD) techniques have made enormous advances too recently (also the related TLM method) and have been turned into mature, powerful tools, but are again limited in usefulness for MIC / MMIC design. Conductor edge treatment, non-regular gridding and surface conformal techniques are still immature and their true potential is more for real 3D structures like packages and waveguide components. The generation of fast broadband responses using FDTD is an advantage, but similar speed-up is gained by the fast sweep techniques of 2.5D EM tools discussed further below. The method of lines (MOL, see e.g. [16]) is the only numerical technique similarly adapted to MMIC geometries, but has not been matured and commercialized so far as a serious competitor to the MoM-IE approaches. Note, that these remarks are given just for readability and convenience. A detailed comparison of the pros and cons of the outlined techniques can be traced through the technical literature referenced in [1] - [16] and is beyond the scope of this paper.

STATUS OF 2.5D EM TOOLS

As outlined obove, 2.5D (or „3D planar“) full-wave EM simulators have become the MMIC industry's workhorses for the final design stages of layout-compaction and verification. Their success is not only due to MMIC-specific efficiency, but also to well-developed embedding into and adaptation for the broader context of microwave CAD software and layout processing. All of the underlying numerical techniques are very similar, using elementary harmonic wave function expansions for the EM field and sheet current density to represent conductor surfaces. Because of this, analytical preprocessing of the respective algorithms can be partially or even dominantly done in the Fourier Domain or so-called Spectral Domain (SD), leading to the often-used terminology Spectral Domain Approach (SDA). On the other hand, „MoM tools“ is also a common term, since solution of the resulting electric field integral equation (EFIE) or mixed-potential integral equation (MPIE) is generally achieved by the method of moments (MoM), using rooftop (rectangular support) or mixed rectangular-triangular conductor current density expansions. Selected references outlining the key mathematical procedures as they emerged over the years and became fairly standard, are for example [6], [17], [[18]. The use of vias (vertical current contributions) is today a natural feature of commercial 2.5D EM simulators like [19] - [23], too.

Differences between such simulators exist, for example, in the use of a boxed (shielded) versus an open field volume, implying adaptation more to MMICs or to planar antennas. However, some of the tools are also boxed versions but with an absorbing cover plane, thus approximating radiation into free space for widely opened lateral shielding walls. Another important difference is the use of a regularly gridded groundplane of the field volume (2^M x 2^N terms harmonic wave expansion) in contrast to an arbitrary, user-defined continuous spatial field resolution. Regular gridding allows the application of FFT for fast matrix filling along with regular simple or bundled rooftop current density (electric or magnetic) contributions, also comes along with good, transparent convergence properties. On the other hand, continuous spatial field resolution provides geometric flexibility in combination with non-regular mixed rectangular-triangular meshing of the planar conductors and does not force structures implicitly into a given regular grid. Further EM simulator aspects that differ from tool to tool are direct versus block-wise and / or iterative equation solvers, a variety of source formulation and S-parameter extraction techniques etc. The commercialization and intense industrial use of 2.5D EM tools particularly during the last 5 years has produced a multitude of features, only some of which can be outlined here and in the presentation.

Advances introduced recently for the majority of commercially available 2.5D full-wave EM simulators are obvious from the referenced product information [19] - [23] or have even been described in more detail in various publications. These are briefly summarized in the following:

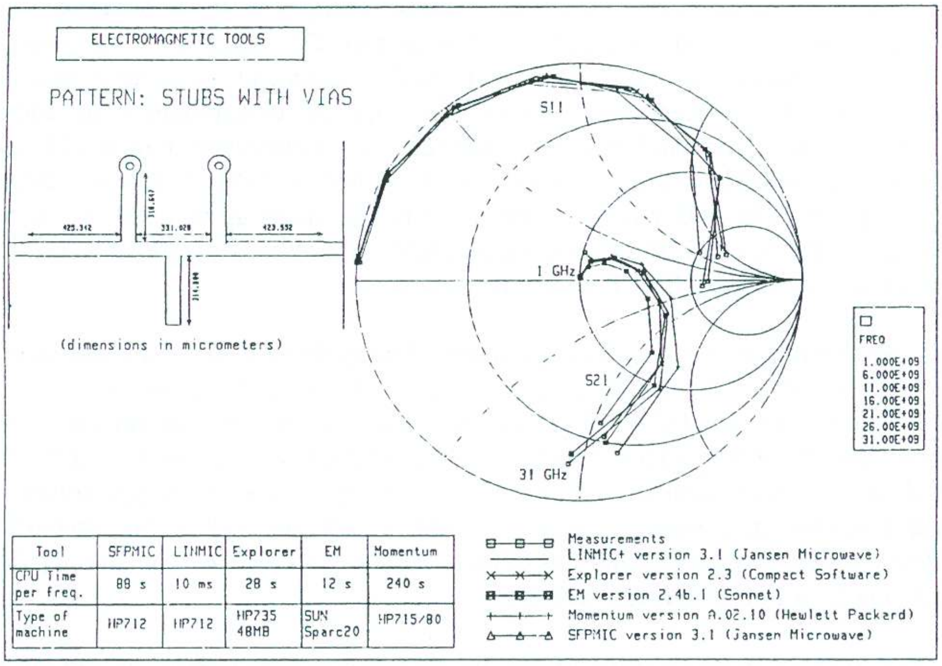
- Acceleration techniques to speed up simulation over a broad frequency range. Here, the most fundamental is the so-called Spectral Operator Expansion (SOE) technique published already 1991 [24], with a 2D version of this even dating back to 1987. It exploits the fact that the kernel of the relevant integral equation can be split into a very small portion with strong frequency dependence leaving a considerably larger portion with weak frequency dependence for automated series expansion. Essentially, this allows to reduce the matrix filling time for a broadband sweep to a numerical expense otherwise needed for just 2 - 3 frequencies [22]. Alternative speed-up techniques introduced are the Adaptive Lanczos Padé Sweep (ALPS) technique, exploiting rational function approximation of the EM-simulated structure with a finite number of dominant poles and zeros [20]. Very similar to this is the Adaptive Frequency Sampling (AFS) technique used in [21] and also the Intelligent Frequency Selection (IFS) technique implemented in [19]. For more details see for example [13], [25], [26]. The SOE has the potential for further speed up by combination with one of the latter techniques. The rational fitting used for acceleration is also a suitable vehicle for automated equivalent circuit and subsequent SPICE netlist generation.

- Better representation of conductor edge current density distribution and associated simulation accuracy has been introduced by several groups to replace dense, uniform meshes, see for example [25]. All of the tools listed in [19] - [23] allow for some kind of non-uniform mesh and thus for increased current density at strip edges. Automated edge meshing looks promising at the first glance, but does not always enhance accuracy. Particularly, for tightly coupled strip type filters, interdigital structures and couplers, piecewise full-wave 2D EM simulation with entire domain expansion functions reflecting the true edge singularities often turn out to be superior in accuracy [12], [22] with a computation time 2 - 3 orders of magnitude lower.

- The door to much more complex MMIC geometries has been opened by the introduction of EM diakoptic techniques and this is seen as a major promising direction [8], [9], [27]. The Diakoptic Approach (DA) should not be mistaken or misunderstood as the very common hybrid approach, mixing network theory for interconnection with field theory for circuit blocks. Diakoptic computation is rigorous and remains entirely in the field theory domain, starting with the computation of layout blocks uncoupled in a first solution step than progressively taking into account parasitic coupling between structures in one, two or three further iterations. The advantage is that only the individual block matrixes have to be inverted, but never the matrix representing the full circuit. Also the DA is well suited to allow importation of external S-parameter blocks subject to clearly defined and well-chosen reference planes on strips within a circuit. An approximate Cell Coupling (CC) technique has been introduced by Sonnet [19] recently, in which the coupling between large subsections is estimated from the coupling of two single rooftop cells.

- There are a range of further improvements, that can be concluded from the product sheets and the open literature like the introduction of dielectric substrate bricks [19], a range of techniques for speeding up the computation of matrix elements or the derivation of closed-form Green's functions [28]. Finally, 2.5D EM simulation has been demonstrated including voltage-controlled current sheets for MESFET and HEMT analysis. The direct use of EM simulators in optimization is also a topic of ongoing interest [11], [12], [29].

The wide variety of implementations outlined, associated with a range of different algorithmic details, naturally has the consequence of some spread produced in the numerical results obtained from the discussed 2.5D full-wave EM simulators. This is well reflected in Fig. 2, where computations for a fairly simple MMIC structure (one out of 8 structures in ref. [30]) are compared for the frequency range of 1 - 31 GHz with RFOW measured data. The spread visible above is still surprisingly high for EM tools all based on first principle, full-wave theory. Note, that in comparison LINMIC+ vrs. 3.1 is a hybrid EM simulator using NW theory for the interconnection of mostly EM-based models from a layout-oriented library [22], with the advantage of 3 orders of magnitude CPU time reduction. The disparity of computed S-parameters is probably quite typical for state-of-the-art MMIC design work and calls for further maturing and even standardization of certain EM tool features, definitions and parameter settings. It is not just a matter of convergence issues [31], but starts already with box size setting, implicit formulation of EM sources, feed line lengths in N-port computation, method of electrical parameter extraction etc.



Tool	SFPMIC	LINMIC	Explorer	EM	Momentum
CPU Time per freq.	88 s	10 ms	28 s	12 s	240 s
Type of machine	HP712	HP712	HP735 48MB	SUN Sparc20	HP715/80

Fig. 2 Example taken from a Benchmark Comparison conducted 1995 under the European Gallium Arsenide Infrastructure Program (EGIP), see ref. [30]

The generation of EM simulator input data, either directly from a graphical user interface (GUI) or by translation from GDS II or from other representations produced by CAD systems, is an important non-algorithmic aspect to be discussed. The same applies to output visualization and further utilities supporting MMIC design work. Finally, as indicated in Fig. 3, methodologies of linking EM tools, other simulators and libraries as they have emerged under the recent European EDGE Project (ESPRIT 21.404, Enhanced Design for GaAs/Si ICs in Europe) will be outlined and can be considered as a first step towards forming an intra-team CAD open architecture.

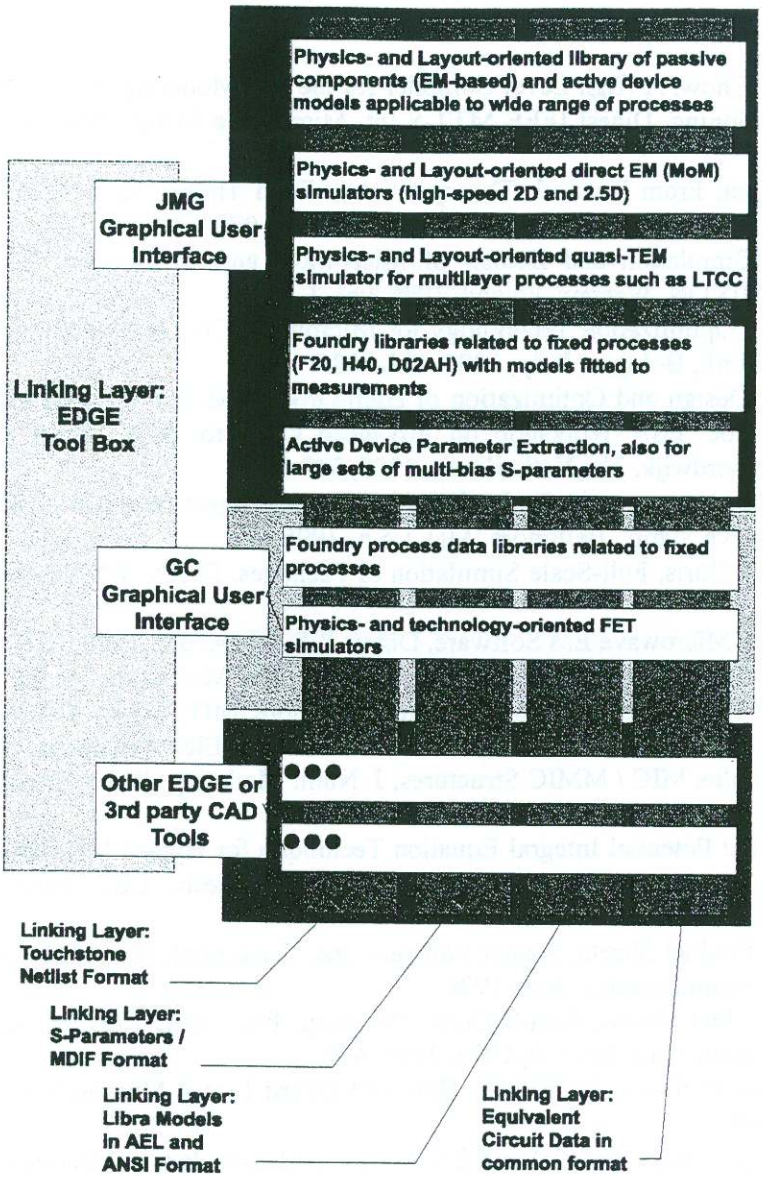


Fig. 3 Visualization of linking methodology [32] used for the embedding of EM simulators and interconnection of CAD tools

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