# HIGH-SPEED 3D ELECTROMAGNETIC SIMULATION FOR MIC/MMIC CAD USING THE SPECTRAL OPERATOR EXPANSION (SOE) TECHNIQUE

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## ABSTRACT

A layout-oriented 3D electromagnetic simulation tool for the CAD of MICs/MMICs with several new features is described. It exhibits higher speed in multi-frequency analyses than the known standard algorithms by using spectral operator expansion (SOE) with non-regular expansion functions. Its use in the context of CAD is outlined by examples.

## OVERVIEW

The use of 3D electromagnetic simulators in the CAD of hybrid and monolithic MICs has become quite popular in the last few years, in particular, because of urgent needs for more accurate and cost effective MMIC design. With a single MMIC design pass costing abou+t 50.000,-- US$ and three to six months of time, it has become very important to eliminate prediction uncertainties associated with analytical models. For examples junctions and discontinuities are predicted more reliably by using rigorous electromagnetic simulation directly based on the hybrid-mode full wave field equations. Even more important, such first principle simulation takes into account coupling effects in closely spaced discontinuities and between the structures of high packing density circuits, which is beyond the capability of circuit theory-based CAD software. Some of the techniques used in electromagnetic CAD tools available today are, for example, a modified, hybrid moment method using pulse functions and a quasi-static nodal scheme /1/, the method of moments using rooftop functions /2/, the eigenvalue type /3/ and the source type spectral domain approaches /4/, /5/ and the 3D finite element technique /6/. While the approaches /1/.../5/ are more or less specialized to MIC/MMIC structures, the mentioned finite element tool /6/ is capable of treating arbitrary 3D geometries, however, with much less computational efficiency for MICs and MMICs. In addition to the mainly circuit-oriented work referenced /1/.../5/, similar open space solutions have been generated by antenna-oriented groups /7/-/9/. Finally, very recent work concentrated on MIC/MMIC structures of high geometrical complexity /10/, /11/ and the most complex analysis example presented included about 50000 expansion functions.

Despite the unquestioned usefulness of electromagnetic CAD software, from a practical MIC/MMIC design point of view, computational efficiency is still a very critical issue.Comparatively simple circuit structures like a shorted stub matching network including an MIM capacitor and a via hole still require overnight CPU times for a broadband analysis /12/ compared to minutes using a conventional circuit theory-based simulation.

For this reason, the efficiency problem has been addressed in ref. /10/ already. It was found there that for geometrical complexities involving up to about only 1000 expansion functions (unknowns), direct inversion of the resulting equations is preferable. For larger problems, iterative analysis is the more efficient choice due to much slower increase of CPU time with the number of unknowns. Examples given in reference /10/, /11/ show that computation times have been brought down to about 10 min. per frequency of analysis of typical single or coupled MIC/MMIC junction problems (600-800 unknowns) and to about 100 min. per frequency for multiport geometries with about 10000 expansion functions (MicroVAXII CPU times). Note, however, that even 50000 unknowns do not necessarily constitute a circuit structure that would be considered as very complex from a MIC/MMIC designers practical point of view. This depends much on details like the spatial resolution required and, indeed, the complex example addressed in ref. /11/ is just a closely packed MMIC interdigital filter structure analyzed as one electromagnetic entity. Note, in addition, that the number of unknowns,



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when using methods not specialized to MICs/MMICs, like the 3D finite element technique /6/, is again increased by about a factor of 20 to account for discretization in the vertical direction.

The paper presented here describes further improvements in electromagnetic simulation for the CAD of MICs/MMICs. These are mainly due to the use of the spectral operator expansion (SOE) technique. This technique is a generalization of the enhanced spectral domain technique (ESDT) first published in 1985 /13/ and then generalized to its SOE form in 1987 /14/ for the efficient simulation of MIC/MMIC multiconductor structures (a 2D problem). The 3D implementation reported here has been used since 1989 in one of the various field-theory based portions of a commercial CAD package /15/, but this application of the SOE to 3D electromagnetic field problems has not been published in more detail to date. In the SOE technique, the matrix operators representing the conductor current-to-electric field relation for the considered circuit medium are factorized into a few frequency-independent constituents multiplied with simple, analytically derived frequency-dependent cofactors. The SOE technique is generally applicable under conditions to be outlined. Its application is associated with a drastic speed-up in multifrequency analysis, the standard simulation mode in CAD, since the time consuming frequency-independent operator portions have to be computed only once in the first frequency step.

In combination with the SOE technique used, a simple but very efficient scheme of generating non-regular expansion functions has been developed along with the rules for choosing the discretization of conductor geometries in an optimum way. These rules are discussed in detail and throw some interesting light on the physical phenomena associated with electromagnetic simulation in the CAD of MICs and MMICs as used today. As a result of the new features of the electromagnetic tool described here in conjunction with the rules derived, the state of the art is improved considerably. Benchmark tests have shown speedup factors for broadband analyses in the order of magnitude of 10 as compared to standard moment method and spectral domain implementations. Combined with recent progress in computer workstation technology, this brings down analysis times for low-end complexity MIC/MMIC problems close to interactive speed. For example, typical CPU times for single or coupled junctions and discontinuities have been brought down to about 15-30 seconds per frequency on a VaxStation 3100 or SparcStation1.

SOE THEORY

Spectral operator expansion is an extremely general concept in electromagnetic field theory. This becomes obvious, if we consider the fact that setting up any solution of the Helmholtz equation in a piecewise homogeneous medium and using a separable coordinate system for this implies the separation condition for the chosen coordinates. In a carthesian system, this condition reads:

$$k_z^2 = k_z^2(i,m,n) = k_o^2 \varepsilon_{ri}\mu_{ri} - k_{xm}^2 - k_{yn}^2 \quad (1)$$

Here, $k_o$ is the free space wavenumber (frequency parameter), $\varepsilon_{ri}$ and $\mu_{ri}$ are material parameters in the subregion (medium) denoted i and $k_{xm}$ and $k_{yn}$ are separation constants (spectral parameters), i.e. wavenumbers of the elementary x- and y-related functions which are used to set up a solution by superposition. The wavenumber $k_z$ relates to the remaining coordinate and, for MIC/MMIC problems, this is best chosen as vertical to the substrate layer(s) of a configuration, see ref. /4/ for more details. Independent of the specific problem considered and of the coordinate system chosen, wavenumbers like $k_{xm}$ and $k_{yn}$ in eq. (1) each form an infinite set of discrete values increasing with m and n, typically. The discrete values may be related to boundaries or subsectional expansions or to discretization of integration parameters in open problems. For larger values of m and n, eq. (1) can be written in short form as

$$k_z^2 = -k_{\rho mn}^2 (1 - k_o^2 \varepsilon_{ri}\mu_{ri}/k_{\rho mn}^2),$$
$$\text{i.e. } k_z^2 \cong -k_{\rho mn}^2 \text{ with } k_{\rho mn}^2 = k_{xm}^2 + k_{yn}^2. \quad (2)$$

This makes clear that the higher order contributions (high spatial resolution terms) of any solution to the Helmholtz equation for a given frequency ($k_o^2$) have a quasi-static behaviour, i.e. for these terms the Helmholtz operator degenerates to the Laplace operator. Equivalently, in many electrodynamic problems the full-wave operator can be expanded efficiently and accurately into a small, leading contribution plus a few frequency-independent partial operators with or without simple frequency-dependent co-factors. As has been shown for the 2D eigenvalue problem in ref. /14/, the spectral domain operators applying to MIC/MMIC configurations are particularly well suited for such an operator expansion due to their special form in terms of algebraic LSM and LSE contributions.

For the 3D electromagnetic simulation of MICs/MMICs described here, a source-type current density formulation as outlined in ref. /4/ is used, namely

$$\underline{E}_t = \underline{\underline{L}}_I(f) \cdot (\underline{J}_{tex} + \underline{J}_{tim}) = \underline{0} \quad \text{with}$$
$$\underline{E}_{t\nu} = \underline{\underline{Z}}_\nu(f)\, \underline{J}_{t\nu} \quad \text{for} \quad \nu = (m,n). \tag{3}$$

With the same notation applied as in ref. /4/, $\underline{\underline{Z}}_\nu(f)$ is the spectral representation of the operator $\underline{\underline{L}}_\nu(f)$ that involves summation over the double-infinite set $\nu = (m,n)$ of spectral contributions to the problem. As explicitely shown, the operator depends on f, the analysis frequency. The electric Field $\underline{E}$ related to eq. (3) is defined in 3D space while the current density $\underline{J}_t$ is considered as piecewise two-dimensional on or between substrate layers, with $\underline{J}_{tex}$ denoting the excited unknown distribution while $\underline{J}_{tim}$ is the impressed (source) distribution used. Structures with vertical current are treated by a hybrid approach when using the outlined 3D em tool in the frame of the CAD package /15/. The spectral impedances which have been formulated for a general 6-layer substrate configuration can be brought into the form

$$\underline{\underline{Z}}_\nu(f) = \begin{bmatrix} k_{xm}^2 & k_{xm}k_{yn} \\ k_{xm}k_{yn} & k_{yn}^2 \end{bmatrix} \cdot Z_{e\nu}(k_z^2) + \tag{4}$$
$$+k_o^2 \begin{bmatrix} k_{yn}^2 & -k_{xm}k_{yn} \\ -k_{xm}k_{yn} & k_{xm}^2 \end{bmatrix} \cdot Z_{h\nu}(k_z^2).$$

Note, that $Z_{e\nu}$ and $Z_{h\nu}$ are scalar functions which depend on frequency only via the parameter $k_z$. This is independent of the layer configuration prevailing in a specific configuration. Therefore, for values of $\nu$ larger than an easily definable, relatively low threshold $\nu_o$ the functions $Z_{e\nu}$ and $Z_{h\nu}$ can be accurately expanded into a Taylor series about $f_o$, the center frequency of a broadband frequency interval. The formalism used is in complete analogy to equations (4)...(6) in ref. /14/. Practical CAD work using the described em tool has shown that a 3-term Taylor series expansion of the operator portion beyond the threshold $\nu_o$ is sufficient to obtain accurate results over multioctave frequency bands. If necessary, the low default value of $\nu_o$ can be reset for a simulation.

The advantage obtained with the SOE technique has been discussed in ref. /14/ for 2D problems, but is even more drastic for the repeated 3D em analysis of MIC/MMIC geometries as a function of frequency. For example, to obtain a 2 µm spatial resolution over a $1mm^2$ chip area, wavenumbers up to m=500, n=500 have to be taken into account in the em analysis, i.e. values of $\nu$ up to $\nu = 250000$. For finite element or related methods as in ref. /6/, a correspondingly high number of discretization points has to be used on the substrate surface to obtain the same resolution, but even multiplied by a factor of about 20 for the vertical direction. With the SOE technique, $\nu_o = 100$ applies typically for the mentioned case over a 5-100 GHz frequency range. The summation up to $\nu = 250000$ is required only once in an initialization step where the partial , frequency independent operators are set up by presummation. Therefore, SOE analysis over a set of 100 frequencies requires typically only a few times the CPU consumption for a single frequency simulation. For the other methods referenced here /1/-/12/, CPU time increases directly proportional to the number of frequencies.

NONREGULAR EXPANSION

In combination with the SOE technique used nonregular rooftop expansion function are used as is indicated in Fig. 1. The rooftop elements for x- and y-directed current density are intertwined as shown in ref. /10/. A given MIC/MMIC geometry is broken up into rectangular subelements each of which may have a differrent grid. This can be seen in the representative example of Fig. 1. The simulation tool generates the necessary nonregular overlap functions required for interconnection of subelements automatically. A few rules have been developed since the 3D simulator was implemented into the CAD package /15/ which allow accurate simulation with a minimum number of expansion functions.

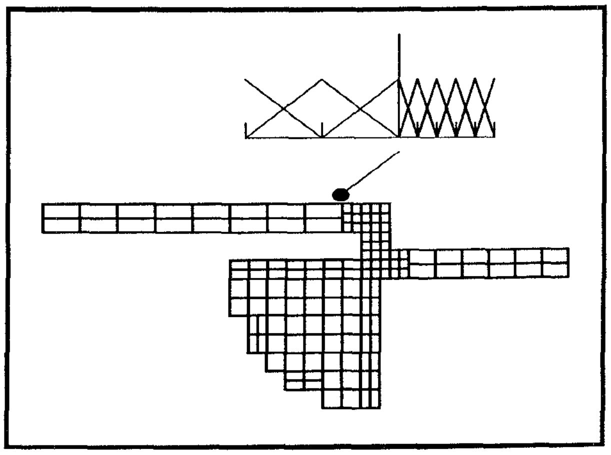

Fig. 1 Radial stub reference structure showing use of nonreg. rooftops

## ANALYSIS ACCURACY

As an example of the accuracy of the high-speed em simulation tool developed, Fig. 2 shows a comparison to computed and measured data taken from ref. /10/. The 2-port structure analyzed in Fig. 2 is a radial stub in a double bended microstrip line with one side of the radial stub parallel coupled to the through line. The SparcStation1 CPU-time for this analysis is less than 1 hour for 100 frequency points, demonstrating clearly the progress achieved for the practical application of 3D em simulation in the CAD of MICs/MMICs. Further details and examples will be given in the presentation.

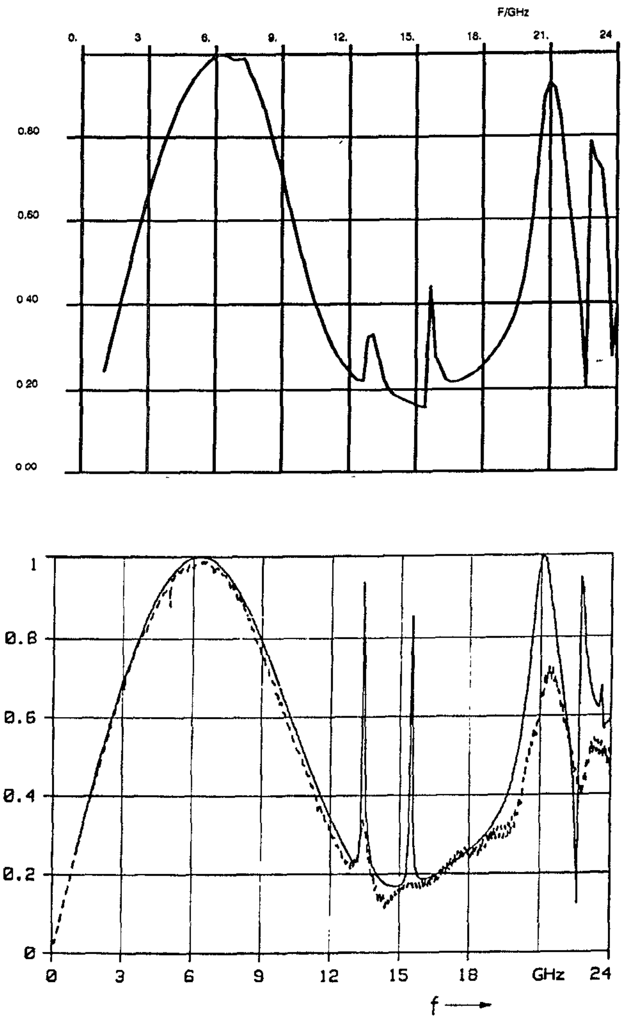


Fig. 2 Reflexion magnitude for the radial stub of Fig. 1, see ref. /10/ also
Top: Computation, this paper
Bottom: Computation, ref. /10/ and measurement, open fixture
Data: $\varepsilon_r$=9.77,h=0.635mm,w=610μm

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