Iterative, monotonically convergent hybrid-mode simulation of complex, multiply-branched (M)MIC conductor geometries

Werner Wertgen* and Rolf H. Jansen**

* University of Duisburg, Dept. of El. Eng., West Germany
** Industrial Microwave and RF Tech. Inc., Ratingen, West Germany

Abstract

The unconditionally and monotonically convergent iterative full-wave simulation of multiply-branched (M)MIC shielded conductor geometries is described. The approach developed avoids segmentation and has been verified on problems with up to 50000 patch expansion functions, for example, on a bandpass filter containing 5 closely packed multi-finger interdigital capacitors.

Introduction

The full-wave analysis of planar microstrip components has become quite important as a complement and for the enhancement of conventional (M)MIC CAD /1/,/2/. Discontinuity coupling, radiation-like effects, interaction with the package, and package resonances are not taken care of in purely topological simulation using microwave circuit theory and segmentation into substructures. Therefore, electrodynamic simulation tools are required in addition to standard CAD, particularly for the design of MMICs with high packing density.

For the S-parameter computation of irregular planar (M)MIC shapes some approaches using standard Galerkin techniques with uniform rectangular discretization grid and rooftop functions have been published recently /3-5/. A particularly efficient member in this group of direct solvers is the database technique with accelerated system generation /5/. However, these direct techniques loose their efficiency for problems with more than 1000-2000 unknowns. Iterative solvers suited to overcome such complexity limitations as excessive CPU-time consumption and memory requirements for geometrically complex microstrip structures have not been established in the em design of (M)MICs up to now.

In /6/ we have presented recently full-wave analyses of irregular shielded (M)MIC structures using iterative approaches based on Spectral Iterative Techniques (SIT) and on standard conjugate gradient methods. Due to the special properties of the associated operator, these methods do not yet exhibit convergence behaviour satisfactory for practical design work. The paper presented here concentrates on one of two new iterative, reliably and monotonically converging simulation approaches to shielded (M)MIC configurations /7/ which is capable of treating problems with as much as about 100000 unknowns on modern minicomputers. It is based on the conjugate residual method (CR algorithm /8/) into which the necessary modifications have been introduced. This iterative approach is outlined in detail here and demonstrated for a geometrically complex MMIC simulation problem with about 50000 unknowns. To our knowledge, this is by far the highest number of unknowns treated sucessfully to date in MIC or MMIC em simulation.

Basic Equation and Discretization

For convenience of the reader, the mathematical formulation of the (M)MIC simulation problem is briefly summarized here.

A shielded microstrip medium with lossless dielectric layers and ideal conductors is assumed. The analysis starts from a scattering type source formulation as in /2,5-7/ with the analytically derived dyadic electric field integral operator $\overleftrightarrow{\mathcal{L}}$ in space domain and the corresponding well known spectral impedance matrix $\tilde{Z}$. Using normalized field quantities, $\overleftrightarrow{\mathcal{L}}$ is a real integral operator with the mathematical property of selfadjointness, but it is indefinite.

The basic source type equation written in terms of the operator is

$$\overleftrightarrow{\Theta}\, \overleftrightarrow{\mathcal{L}}\, \overleftrightarrow{\Theta}\, \vec{J}_s = \overleftrightarrow{\Theta}\, \vec{E}_{s,inc} \qquad (1)$$

$$\text{with } \vec{E}_{s,inc} = -\overleftrightarrow{\mathcal{L}}\, \overleftrightarrow{Q}\, \vec{J}_{s,imp} \qquad (2)$$

$\vec{E}_{s,inc}$ is the incident electric field generated by a suitable impressed source current distribution $\vec{J}_{s,imp}$ and $\vec{J}_s$ is the unknown conductor surface current density. $\overleftrightarrow{\Theta}$, $\overleftrightarrow{Q}$ represent window operators associated with the conductor shape and the source region, respectively. To compute a numerical solution to (1) for the purpose of S-parameter generation, a discretization with a standard grid and rooftop functions is adequate for irregular and also for curved (M)MIC geometries /7/. To perform this, the considered circuit region enclosed between shielding walls is divided into $N_x x N_y$ rectangular cells. In order to illustrate the subdivision of a complex geometry, a recently treated MMIC interdigital capacitor example /7/ is shown in Fig. 1 with a grid of $N_x=128$, $N_y=256$. With a finger spacing of $g=5\mu m$ and a finger width of $W_F=20\mu m$, this example demonstrates at the same time that an accurate representation of the current distribution in MMIC configurations may require to handle quite a high number of unknowns. The rooftop elements for both current components J_{sx}, J_{sy} are assembled by a scanning process and in the case of Fig. 1 this results in an expansion of the unknown quantity $\vec{J}_s$ in terms of $M_u=9861$ elements.

The rooftop functions used for expansion are also used as test functions from which a Galerkin system of equations $\mathbf{Ax}=\mathbf{b}$ results, with $\mathbf{A}$ being a real, symmetric and indefinite coefficient matrix. The complexitxy of the problems considered here, with $M_u=2000...100000$ unknowns typically, makes direct solutions inefficient.

CH2848-0/90/0000-0559$01.00 © 1990 IEEE

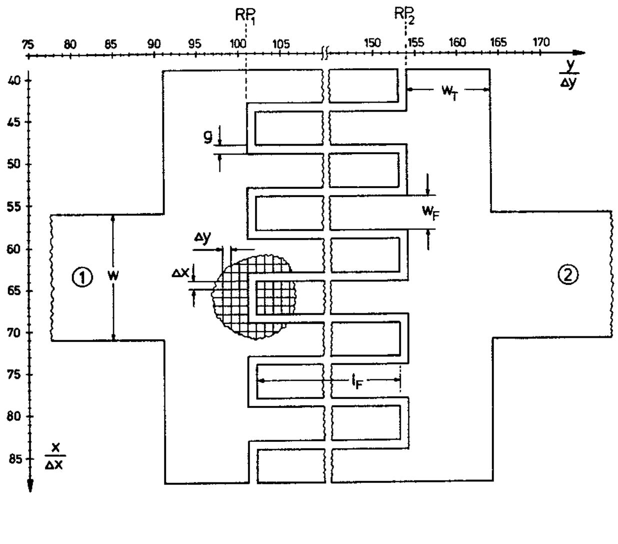

Fig. 1 Discretization of 10-finger MMIC interdigital capacitor on h=100μm GaAs using M_u=9861 rooftop exapnsion functions
(w=75μm, w_F=20μm, l_F=255μm, $g=\Delta x=\Delta y$=5μm)

Numerical Solution using a Specific Implementation of the CR-Algorithm

The key points of arriving at stable iterative solutions for numerically large problems are in the representation of the approximate operator using suitable mapping techniques and in the specific form of the conjugate gradient (cg) algorithm used for the solution. The mapping process $\vec{\Theta}\,\vec{\mathfrak{L}}\,\vec{\Theta}\,\vec{\mathfrak{P}}_k$ on any variational function $\vec{\mathfrak{P}}_k$ in iteration step k is performed approximately by expansion of $\vec{\mathfrak{P}}_k$ in the rooftop space. A brief schematic of this mapping is given in equations (3), (4).

$$\begin{bmatrix} \tilde{E}_{xk} \\ \tilde{E}_{yk} \end{bmatrix} = \begin{bmatrix} \tilde{Z}_{xx} & \tilde{Z}_{xy} \\ \tilde{Z}_{xy} & \tilde{Z}_{yy} \end{bmatrix} \cdot \begin{bmatrix} \mathcal{F}_{cs}\{\Theta_x P_{xk}\} \\ \mathcal{F}_{sc}\{\Theta_y P_{yk}\} \end{bmatrix} \tag{3}$$

First the component functions P_{xk},P_{yk} are transformed into the spectral domain with problem-specific cosine-sine (F_{cs}) and sine-cosine (F_{sc}) Fourier transforms. Then the spectral operator $\tilde{Z}$ is applied resulting in the electric field associated with the variational function in the iteration step k.

$$\mathbf{A}\mathbf{p}_k = \begin{bmatrix} \Theta_x \mathcal{F}_{cs}^{-1} \tilde{F}_{tx} & 0 \\ 0 & \Theta_x \mathcal{F}_{cs}^{-1} \tilde{F}_{tx} \end{bmatrix} \cdot \begin{bmatrix} \tilde{E}_{xk} \\ \tilde{E}_{yk} \end{bmatrix} \tag{4}$$

A discrete representation $\vec{\Theta}\,\vec{\mathfrak{L}}\,\vec{\Theta}\,\vec{\mathfrak{P}}_k$ is obtained with equation (4) performing the characteristic matrix-vector multiplication $\mathbf{A}\mathbf{p}_k$ as required in cg-type algorithms. Here $\mathbf{p}_k$ is an Euclidian vector containing the expansion coefficients of $\vec{\mathfrak{P}}_k$. The test spectra $\tilde{F}_{tx}$, $\tilde{F}_{ty}$ are again related to rooftop functions. With this, the implicit iteration matrix **A** is mathematically equivalent to the Galerkin matrix mentioned before. However, the moment equations are solved in the following by an iterative algorithm without generating the large moment matrix. All transformations between spatial and spectral domain in (3), (4) are carried out with suitably adapted FFT procedures. These procedures are very fast and the spectral resolution can be increased in steps of the characteristic FFT-length.

The mathematical features of the implicit iteration matrix determines the type of cg-algorithm used. For the here given symmetric but indefinite system the standard cg-algorithm, the biconjugate gradient algorithm included, suffers from instabilities and the cg-method related to the normal equation is limited by its poor convergence properties, because the condition number appears squared /7/.

High speed and unconditionally and monotonically convergence properties are obtained here with a specific implementation of the conjugate residual algorithm (5). From a strictly mathematical point of view the symmetric but indefinite iteration matrices **A** prevailing here require precautions like a Lanczos type generation of the vector $\mathbf{p}_k$ /7/,/8/. The investigations made by the authors for (M)MIC configurations, however, have shown that stagnation of the residual error may still occur in iterations with a CR-algorithm using such a precaution. The reason for this is that much of the advantage of such a modification is lost due to round-off errors, particularly in the class of complex problems considered here. On the other hand, the implementation (5) of the CR-algorithm used here applies a direct, recursive generation of the vector $\mathbf{p}_k$. This does not have the mathematically ensured properties of the Lanczos step in a strict sense, but could theoretically lead to convergence problems. However, for the specific integral equation and class of problems considered here it is found that the direct generation of p_k works well even in cases where the Lanczos type generation leads to stagnation. Obviously, the round-off errors always present to a noticeable degree in large problems have the beneficial effect here to avoid theoretically possible complications by producing a slight perturbation.

CR-algorithm

(5a)

Choose $\mathbf{x}_0$ and set $\mathbf{r}_0 = \mathbf{p}_0 = \mathbf{b} - \mathbf{A}\,\mathbf{x}_0$, $\mathbf{p}_{-1} = 0$;

compute for k = 0, 1, 2, 3, . . .

if $err_k = \|\mathbf{r}_k\| / \|\mathbf{b}\| < \delta_{err}$, stop else compute

$$d_k = \langle \mathbf{A}\mathbf{p}_k, \mathbf{A}\,\mathbf{p}_k \rangle,$$

$$\alpha_k = \frac{\langle \mathbf{r}_k, \mathbf{A}\,\mathbf{p}_k \rangle}{d_k},$$

$$\mathbf{x}_{k+1} = \mathbf{x}_k + \alpha_k \mathbf{p}_k,$$

$$\mathbf{r}_{k+1} = \mathbf{r}_k - \alpha_k \mathbf{A}\mathbf{p}_k,$$

(5b)

direct type, recursive **generation of** $\mathbf{p}_k$

$$\beta_k = - \frac{\langle \mathbf{A}\mathbf{p}_k , \mathbf{A}\mathbf{r}_{k+1} \rangle}{d_k},$$

$$\mathbf{p}_{k+1} = \mathbf{r}_{k+1} + \beta_k \mathbf{p}_k ,$$

$$\mathbf{A}\mathbf{p}_{k+1} = \mathbf{A}\mathbf{r}_{k+1} + \beta_k \mathbf{A}\mathbf{p}_k .$$

Equations (3)-(5) represent the new iterative technique on which we concentrate here. For other strategies see /7/. The main computing time consumption is needed for steps (3) and (4). Note, that the CR-algorithm in the form (5) needs only one operator evaluation per iteration step.

The algorithm presented here has been found to have excellent numerical stability and along with this provides the capability of treating geometrically complex layouts with up to 10^5 unknown surface current density expansion coefficients on powerful minicomputers. For practical requirements the iterations are stopped if the relative residual error

$err_k = \| \mathbf{A}\mathbf{x} - \mathbf{b} \| / \| \mathbf{b} \|$ is lower than $\delta_{err} = 10^{-3}...10^{-4}$.

Once a numerical solution is obtained, S-parameters are evaluated by a projection method. The computed longitudinal current distribution on the feed strip of a configuration is projected into standing wave terms with precomputed propagation constants /5,7/

Geometrically Complex Application Examples

With M_u=9861 unknowns, the 10-finger MMIC interdigital capacitor shown in Fig. 1 was the largest problem treated in a recent contribution by the authors. To obtain S.parameters for an N-port configuration, iterative solutions for N linearly independent excitation states are required per frequency point. For two-ports like the one in Fig. 1 a symmetrical and a anti-symmetrical excitation state are used for S-parameter generation. For design purposes, the MMIC capacitor structure is sufficiently well characterized with only 50 iteration steps ($err_k \approx 10^{-3}$) for each frequency point and excitation case. A single iteration scheme with multiple excitation states seems feasible but has not yet been investigated. Computation time for the structure in Fig. 1 was 2.3 sec per iteration step on a CONVEX C220 computer. The results obtained agreed well with the measured S-parameters of a very similar MMIC capacitor (g = 4.8µm) treated by Esfandiari /9/,/7/.

As a considerable more complex application example, Fig. 2 shows the layout geometry of a bandpass filter containing five interdigital capacitors closely packed on a 200µm GaAs substrate. This is another example taken from Esfandiari's paper /9/. The structure is described as one entire electrodynamic domain with high resolution applying M_u=48918 expansion coefficients. The S-parameter magnitude $|S_{12}|$ obtained with the presented iterative simulation approach is shown in Fig. 3 with the dashed line representing the measured transmission as given in /9/. The latter agrees well with the computed result and thus confirms the numerical analysis. Fig. 4 represents the computed phase information of the MMIC-filter for which measurements are not available.

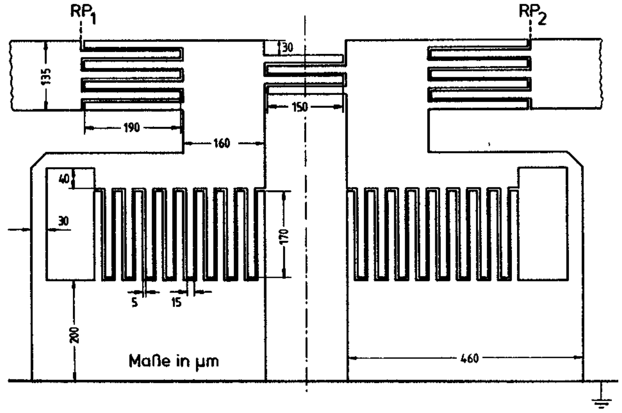

Fig. 2 Layout of a closely packed MMIC filter structure on 200µm GaAs (geometrical data are in um, RP_1, RP_2: reference planes)

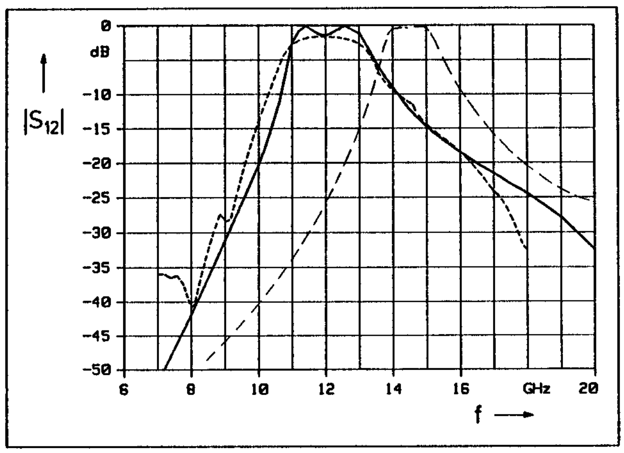

Fig. 3 Iterative analysis of the structure of Fig. 2 in comparison to measured data /9/
——— this paper (lossless), - - - - - measured (lossy),
- · - · - CAD simulation using segmentation into individual interdigital capacitors

For comparison to a conventional CAD simulation using segmentation of the MMIC bandpass filter of Fig. 2 into individual capacitors, Fig. 3 contains a third curve. This latter curve has been generated by using accurate full-wave capacitor models of the LINMIC+ CAD package /2/ and interconnecting these as network elements. Despite of the accuracy of the capacitor models proven in a variety of verification examples, the CAD simulation based on segmentation results in a considerable misprediction of the bandpass center frequency and band width. As found in many other cases, this is primarily due to neglection of the coupling between the elements of the closely packed configuration. This interpretation given here is further confirmed by the results obtained by Chow et al. on the same bandpass filter using a hybrid (mixed lumped-distributed) electromagnetic approach /10/.

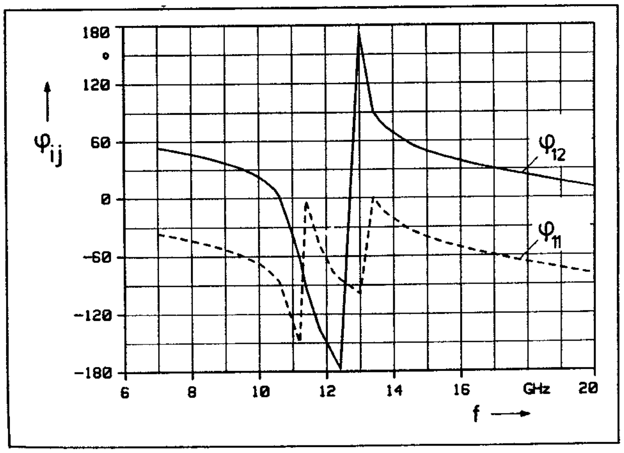

Fig. 4 Computed phase information for the MMIC-filter of Fig.2, measurements not available

In ref. /10/, Chow et al. precompute the capacitances by analytical expressions and insert these into a system of numerical electromagnetic equations to take into account coupling effects. Their results show only a relatively small misprediction of center frequency and bandwidth. It should be noted, however, that such a hybrid approach becomes increasingly inaccurate at higher frequencies or for electrically larger structures.

As a final detail of the bandpass filter example considered, the convergence properties related to the iterative analysis are illustrated in Fig. 5. Because of the resonant behaviour of the structure analyzed the eigenvalue spectrum of the discretized operator is such that a stop criterion of $err_k = 10^{-4}$ is required if one wants to have accurate results through the full frequency range up to 20 GHz. For most frequencies and excitation states in the performed iterative simulation, the relative residual error err_k falls down to 10^{-4} in less than 1000 iteration steps. Time consumption is about 8 sec per iteration step on a CONVEX C220 computer.

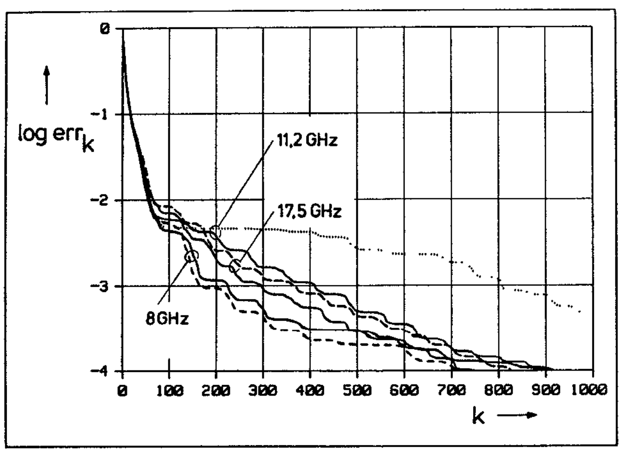

Fig. 5 Convergence behavior associated with the iterative analysis of the filter of Fig. 2 using M_u=48918 unknowns

CONCLUSION

With the iterative approach presented here, the electromagnetic hybrid-mode characterization of shielded (M)MIC configurations of very high geometrical complexity has become feasible in an efficient, stable and monotonically convergent manner up to high mm-wave frequencies. For the unsegmented configurations considered in such analyses frequency dependent S-parameter datafiles are generated for direct use in layout-oriented microwave CAD. The remark may be made that it is possible to set-up parallel computers with relative simple architecture consisting mainly of an FFT signal processor array to achieve dramatic computing time reduction for such iterative solutions.

ACKNOWLEDGEMENTS

This work was supported by Stiftung Volkswagenwerk, West Germany, and Industr. Microwave and RF-Tech., Inc., Ratingen, West Germany

REFERENCES

/1/ R.H. Jansen, Proc. Int. Workshop on mm-Waves, Perugia, Italy April 1989, and Alta Frequenza, Vol. LVIII-No. 5-6, 1989, 551-558

/2/ R.H. Jansen et al., LINMIC+ 2.1, Datasheet May 1989, incl. 3D em simulator portion

/3/ J.C. Rautio, R.F. Harrington, IEEE Trans. MTT-35, 1987, 726-730

/4/ R.W. Jackson, IEEE Trans. MTT-37, 1989, 81-89

/5/ W. Wertgen, R.H. Jansen, Europ. Microw. Conf. Proc., London, 1989, 199-204

/6/ W. Wertgen, R.H. Jansen, IEEE MTT-S Digest, 1988, 709-712

/7/ W. Wertgen, R.H. Jansen, Intern. Journal of Num. Modelling, Vol.2, 1990, to be published

/8/ R. Fletcher, in G.A. Watson, Proc. Dundee Conf. on Num. Analysis, 1975, 73-89

/9/ R. Esfandiari, D.W. Maki, M. Siracusa, IEEE Trans. MTT-31, 1983, 57-64

/10/ Y.L. Chow et al., 16th Europ. Microw. Conf. Proc., Dublin, Ireland, 1986, 625-630