A NOVEL CAD TOOL AND CONCEPT COMPATIBLE WITH THE REQUIREMENTS OF MULTILAYER GAAS MMIC TECHNOLOGY

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Abstract - An efficient field-theoretical tool applicable to a broad class of passive circuit structures has been developed as a CAD kernel component for multilayer GaAs MMIC design. It is based on a new, enhanced spectral domain technique (ESDT) which results in a reduction of CPU-times by one or two orders of magnitude compared to the conventional spectral domain approach. The field-theoretical package can be used, therefore, to generate multidimensional lookup tables in the frame of a general purpose linear CAD program. Together with the associated CAD concept and interpolation technique, the new tool constitutes a shift away from analytical models obtaining improvements with respect to generality, reliability of prediction, accuracy and even efficiency.

Technical Background - Modern GaAs MMIC technology frequently makes use of thin auxiliary dielectric layers in addition to the supporting semi-insulating GaAs substrate (1). These may have the function of passivation layers or may originate from the construction of overlay capacitors and crossings. Also, they may have been deposited as second-level insulators which are partially covered by conductors in a later step of the fabrication process. The thicknesses of such layers are usually in the range of a fraction of a micron to several microns. The materials commonly used are polyimide (organic, ε_r=3.5), silicon nitride (Si_3N_4, ε_r = 5.5...7) and silicondioxide (SiO_2, ε_r = 4...5). These media have dielectric constants ε_r which differ considerably from that of the supporting GaAs material (ε_r = 12.95). Despite of their small thickness, therefore, they have a relatively strong effect on the performance of circuit structures involving electric field components parallel to the substrate surface. The simplest example for this is a narrow single microstrip line which on a single-layer substrate has an effective dielectric constant slightly higher than (ε_r + 1)/2. This numerical value is changed noticeably by the introduction of one or two additional dielectric layers. The effect is particularly pronounced for circuit components involving coupled line structures as the elementary building blocks. This includes various types of couplers, meander lines, coupled lines, coupled line and stub filters, interdigital capacitors and spiral inductors as well as gap coupled resonator structures.

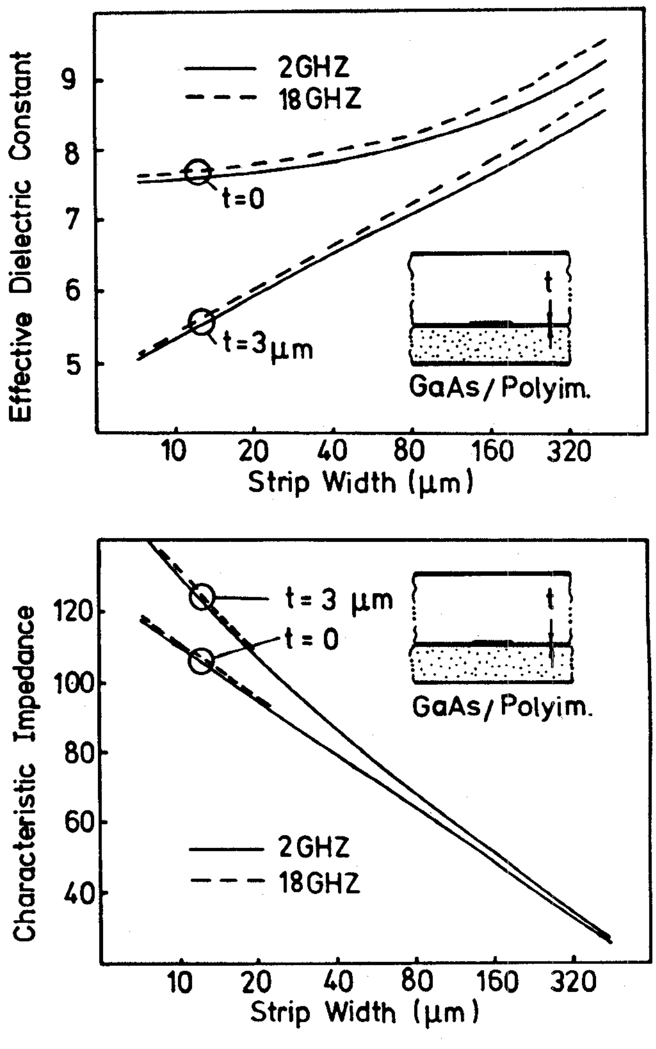

Fig. 1 Effect on single microstrip characteristics produced by a thin layer of polyimide on top of a 200 µm thick GaAs substrate

The order of magnitude of the effects produced by thin auxiliary dielectric layers becomes obvious from Fig. 1 where a comparison is made for single microstrip on a GaAs substrate with and without an

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additional polyimide film. Though the thin layer introduced there has a thickness of only 1.5% relative to the substrate, its effect is a reduction of the effective dielectric constant of about 30% for a strip width of 10 μm. The associated increase in characteristic impedance is 20%. For wide microstrips the decrease of effective dielectric constants can be estimated easily from a parallel plate capacitor approximation which gives about 6% in the prevailing situation. To this a further, smaller decrease caused by the presence of the conducting circuit cover has to be added. In case that narrow, tightly coupled line structures are involved as for example in interdigital capacitors, the changes in electrical behaviour due to thin dielectric layers may be even more drastical than those visible in Fig. 1. In the extreme, performance of such a component is dictated essentially by the interface value (IFV) of dielectric constant $(\varepsilon_r+1)/2$ if strip and gap width are in the order of magnitude of film thickness. It is easy to see, therefore, that even 100% or more is not a fictitiously large figure of change for a respective effective dielectric constant. Also, due to the physical mechanisms acting the sensitivity of electrical parameters with respect to the thicknesses of underlay and overlay dielectric films may be relatively high. Finally, thin dielectric films may considerably change the loss properties of MMIC transmission lines and components.

Accurate computer-aided design of GaAs MMICs is complicated by the multilayer situation. The analytical CAD models available for passive MIC structures are restricted to the conventional microstrip circuit environment. They consider only two dielectric media, the substrate and the air-filled space above (2), (3). On the other hand, numerical CAD tools based on a rigorous frequency-dependent field-theoretical formulation are capable of handling multilayer configurations in principle. However, these tools are much too time consuming for direct use in CAD, even for the elementary transmission line structures (4), (5). The problem is that computer optimization of MICs requires a high number of repeated analyses for circuits of realistic complexity in a quick, interactive mode. At the present time and on average industry computers, only analytical models seem to be fast enough for this.

Nevertheless, it is easy to see that the development of more sophisticated analytical expressions covering the multilayer situation does not show a way out of the dilemma. The derivation of accurate, explicit formulas characterizing passive MIC structures in terms of physical parameters (geometry, dielectric constants, frequency) becomes extremely difficult if more than about 4 parameters are involved. This is particularly true if numerical values varying over a wide range have to be considered. The complexity of equations necessary for a high-quality description of coupled microstrip characteristics on a single-layer substrate may serve as an example for this (6). It can be conjectured that the inclusion of additional dielectric layers and geometry parameters would make the derivation of good wide range analytical models a prohibitively complicated task.

The Field-Theoretical Tool - In view of the described technical background, a different approach to the design of multilayer GaAs MMICs has been persued starting from a previously presented efficient hybrid-mode single-to-multiconductor/multilayer stand-alone package (7), (8). A novel, considerably enhanced field-theoretical tool has been developed with computation times further reduced by a factor of 10 ... 100 depending on the number of conductors considered. The technique by which this has been achieved is new and may be denoted as enhanced spectral domain technique (ESDT). It gives accurate, full-wave frequency-dependent results, however, with most of the time consuming computations performed only once in a preliminary, low-frequency step. The technique is applicable to hybrid-mode printed circuit problems in general and could become a standard procedure for this reason. It has particular advantages for MIC eigenvalue problems (transmission lines and resonators), but is also suited to speed up the solution of excitation problems.

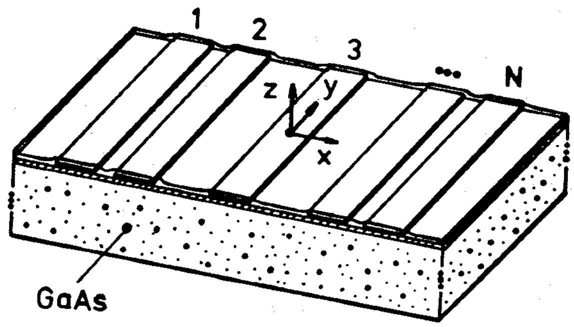


Fig. 2 Representative MMIC strip configuration on a GaAs substrate including a second layer dielectric and a dielectric passivation layer (here N = 1 ... 10)

The type of configuration to which the new field-theoretical package applies is shown in Fig. 2 where the conducting circuit cover has been removed. This includes the single strip, symmetrical coupled strips and regular arrays with N = 3 ... 10 strips involving an additional center gap or not, with or without center strip (7), (8). The dielectric layers may be present or not. The tool provides in a standardized format modal effective dielectric constants, attenuation factors, normalized modal strip currents and voltages as well as strip characteristic impedances based on the transported power per strip/longitudinal strip current definition (9). From this and the associated length of a section of N multiple coupled strips the 2N-port admittance matrix is computed for further processing in the controlling CAD package. Since the field-theoretical analysis uses a hybrid mode formulation it includes dispersion. The package also incorporates a sophisticated treatment of transmission loss equivalent to that of the original stand-alone computer program (7), (8). A description of the enhanced spectral domain technique (ESDT) used in the field-theoretical approach is performed best starting with the formulation of the strip type MIC eigenvalue problem is symbolic form, namely with the equations

$$\underline{E}_t = L_\infty(p_o+\Delta p)\cdot\underline{J}_t = 0 \text{ on the strips,} \qquad \text{Eq. 1}$$
$$\underline{\tilde{E}}_t = \underline{\underline{\tilde{Z}}}\,(p_o+\Delta p)\cdot\underline{\tilde{J}}_t \quad \text{in the SD.}$$

These equations relate the tangential electric field $\underline{E}_t$ and the surface current density $\underline{J}_t$ in the plane of the strip metallization in analytical form. While the relationship in the space domain is described by a linear integral operator $L_\infty(p_o+\Delta p)$ it is an algebraic one in the spectral domain and given there by the spectral impedance matrix $\underline{\underline{\tilde{Z}}}(p_o+\Delta p)$. The quantity $p = p_o+\Delta p$ is the unknown nonstandard eigenvalue (10) which the problem depends on, here the considered modal effective dielectric constant of the multiconductor configuration. This parameter enters into the formulation only as a constituent of the wavenumbers k_{zi} with respect to the vertical coordinate, i.e.

$$k_{zi}^2 = k_o^2(\varepsilon_{ri}-p)-k_x^2 = k_o^2(\varepsilon_{ri}-p_o)-k_x^2-k_o^2\Delta p, \quad \text{Eq. 2}$$

where k_o^2 is the free space wavenumber, ε_{ri} is the dielectric constant of the i th dielectric layer involved and k_x is the x-related wavenumber (the spectral variable). In the enhanced spectral domain technique used here, the parameter p_o is a fixed crude estimate of the unknown eigenvalue p if a sufficiently low frequency is considered. It is a previous modal solution for high operating frequencies. The numerical solution of the field-theoretical problem is achieved applying Galerkin's method in the spectral domain and solving the resulting algebraic homogeneous linear system of equations

$$\sum_k^K \alpha_k(\underline{\tilde{J}}_{tj},\ \underline{\underline{\tilde{Z}}}(p_o+\Delta p)\underline{\tilde{J}}_{tk}) = \sum_k^K \alpha_k A_{jk}(\Delta p) = 0 \quad \text{Eq. 3}$$

in terms of the variable perturbation parameter Δp. The subscripts j = 1 ... K, k = 1 ... K denote test and expansion functions, respectively. The coefficients $A_{jk}(\Delta p)$ of this linear system are scalar products as indicated by the parenthesis notation (,). With the specific splitting of $p = p_o+\Delta p$ introduced here these scalar products can be written as

$$A_{jk}(\Delta p) = \int_{k_{xo}}^{\infty} \underline{\tilde{J}}_{tj}\ \underline{\underline{\tilde{Z}}}(p_o)\underline{\tilde{J}}_{tk}\ dk_x+\Delta A_{jk}(\Delta p), \qquad \text{Eq. 4}$$

with the choice $\quad k_{xo}^2 \gg k_o^2\Delta p.$

The main point about this formulation is that the repeated generation of the system of equations, Eq. 3, which is required to find the unknown modal eigenvalue $p = p_1 \ldots p_N$ (the zeroes of the respective determinant) can be performed in a small fraction of the computation time compared to a formulation in terms of p directly. At low frequencies, i.e. with a sufficiently small value of k_o^2, the inequality presumed in Eq.4 can be satisfied easily for any reasonably chosen lower inegration limit k_{xo} and even a crude start value p_o. The time consuming integral appearing as the first contribution in Eq.4 has to be computed only once in the iterative search for each modal nontrivial solution of Eq.3. The same scheme applies if a low frequency solution $p = p_o+\Delta p$ has been found and an additional solution is required for a higher frequency which means starting with a new value of $p_o = p$ again. The ESDT starts with a low frequency solution or at high frequencies if a good approximation p_o is available, respectively, so that the inequality in Eq.4 can be satisfied with sufficient margin to yield accurate coefficients $A_{jk}(\Delta p)$. An additional important feature of the technique is that the first set of initial modal solutions obtained is then used to generate new, compact optimum sets of modal expansion functions for each of the involved strips in an automatic fashion. If α_{ko} are the elements of the eigenvector associated with an initial solution, the current density representation is rearranged according to

$$\underline{\tilde{J}}_t = \sum_n^N \beta_n\cdot\underline{\tilde{J}}_{tn} \text{ with } \underline{\tilde{J}}_{tn} = \sum_k^{Kn} \alpha_{ko}\cdot\underline{\tilde{J}}_{tk}\ , \qquad \text{Eq. 5}$$

where n is the strip identifier and K_n the respective partial number of initial expansion functions. The symbolic representation of Eq.5 implies, for the multiconductor problem treated here that the longitudiual and transverse strip current distributions obtained as solutions in the start frequency step serve as separate closed-form expansion functions at higher operating frequencies. This is probably the best possible and most compact expansion one can find. Its use reduces computation times drastically if a higher number of strips is involved, without any technically relevant loss in accuracy. For example, the frequency dependent characteristics of a symmetric configuration of 10 coupled strips in a multilayer MMIC environment can be analyzed accurately by the described technique using only 10 expansion functions.

Novel CAD Concept - The field-theoretical package described has been structured to serve as a CAD kernel component in the frame of a hybrid and monolithic MIC design program. It is still far from being fast enough for direct use in interactive circuit optimization. However, it constitutes a drastic increase in efficiency compared to the present state of the art and can be used therefore to generate extended multidimensional lookup tables under the control of the MIC design program. The frequency-dependent design information layed down in these tables is extracted by accurate, parabolic interpolation during the course of circuit analysis and optimization. This process is considerably faster than the computational work required to run through the elaborate analytical expressions necessary to model over a wide range of parameters and frequencies even such simple transmission line structures as single and symmetrical coupled microstrip with good accuracy (6),(11),(12). Beyond that, the field-theoretical tool developed provides loss parameters with a high quality of prediction. Analytical models can hardly achieve this since loss depends directly on the field distribution. So, the CAD tool and associated concept essentially eliminate the need for explicit expressions as far as the characteristics of single and multiconductor configurations in GaAs MMICs, including loss and dispersion, are concerned. This covers the dominant portion of labour to be done by a typical linear computer-aided MIC design program. It applies to the single-layer substrate and the multilayer situation. The lookup tables generated by the field-theoretical tool provide the elementary building blocks to model discontinuities, junctions and more complex circuit elements like couplers, meander lines, filters and printed lumped elements. For example, the analytical modeling of discontinuities and junctions is predominantly performed in terms of the electrical parameters of the involved lines in the majority of state of the art descriptions (2),(3). This principle is extended here to the multilayer MMIC situation with the argument that essentially the same type of field distributions prevail. Accordingly, quantities like effective dielectric constant, effective width and characteristic impedance can be used as long as only single lines are involved in an elementary circuit structure. For coupled line structures, i.e. with N=2...10 strips, the respective 2N-ports are generated and then interconnected in a network approach to describe more complicated components like couplers and lumped elements (8).

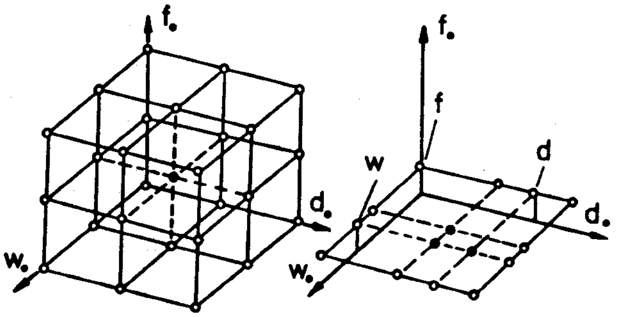
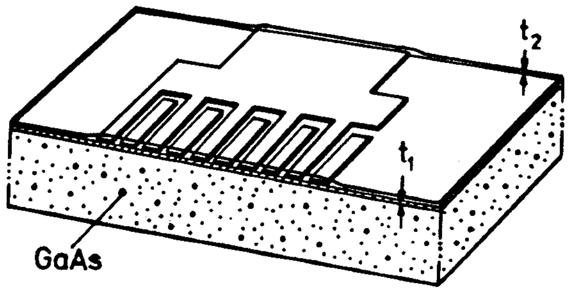


Fig. 3 Multidimensional interpolation by successive ordered, onedimensional parabolic interpolation (f=frequency, w=strip width, d=strip coupling distance)

The principle of the interpolation technique used in the CAD concept is visualized in Fig.3. For a fixed number N=2...10 of strips, each electrical quantity of interest is represented in the respective data file by a threedimensional array of discrete values with the variable parameters f,w and d grouped around user-defined start values. For N=1 the representation is reduced by one dimension. The necessary data cubes are generated by the field-theoretical tool at the begin of a design task under control of the general purpose CAD program. If they exist already at the begin of a CAD session the generation can be inhibited. Interpolation with respect to frequency is made first since all electrical quantities of the general single-to-multiconductor structures vary only weakly with f if they are normalized properly. As Fig.3 shows, 9 onedimensional parabolic interpolation steps are required to reduce the cubic lattice to a plane one which applies to the specific value of f. The next 3 interpolation steps are made with respect to the width w, the final one introduces the specific value of strip distance d. The process yields typical accuracies in the order of magnitude of 0.1%. It is considerably faster than even the analytical models described in refs. (6),(11),(12) for the single-layer case (N=1,2) which have been derived from an earlier field-theoretical approach (9) with accuracies of about 1%. In the final stage of a CAD task, the new concept allows further increased precision by contraction of the data cubes around the accepted, near optimum parameters.



$t_1=0, t_2=0$	$t_1=2\mu m, t_2=0$	$t_1=0, t_2=1\mu m$
C=0.24 pF	C=0.13 pF	C=0.27 pF
L=0.13 nH	L=0.14 nH	L=0.12 nH

Fig. 4 Influence of thin dielectric layers of polyimide on the electrical properties of a 10-strip interdigital capacitor structure (geometry: CAP1 of ref. (13))

The necessity of the approach chosen in order to achieve good design results for multilayer MMIC components is clearly visible in Fig.4. While the thin films have little effect on the parasitic inductance L they have a large influence on the series capacitance. C and L were obtained by computer matching from the simulated Y-parameters of the component, the latter determined as in ref. (8). The advantages of the approach as compared to analytical modeling are fourfold. First, the fast field-theoretical tool comes along with a generality never achievable by analytical expressions. Since it is based on a rigorous, frequency-dependent formulation, secondly, it provides highest possible reliability and accuracy. Finally, it constitutes even an improvement in efficiency.The CPU time required for the lookup tables is gained back by the fast interpolation in a typical design task.

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