OSA's Empipe DRIVES SONNET's *em* CAPTURING AND OPTIMIZING ARBITRARY STRUCTURES

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INTRODUCTION

Electromagnetic (EM) simulators will not realize their full potential in circuit design unless they are embedded into circuit- and system-level simulation environments and driven by automated optimization algorithms [1]. Without such an integration, EM simulators can only be used to validate designs obtained from optimizing equivalent or empirical circuit models, or to generate look-up tables outside the optimization loop. If the optimized equivalent or empirical circuit model is invalidated, the designer may have to resort to manual adjustments involving repeated EM simulations in a tedious process.

OSA's pioneering work in interfacing EM simulators with circuit optimizers has captivated the attention of leading researchers and designers. Empipe [2], an intelligent interface to Sonnet's *em* [3] has been very successful in the design of microwave and millimeter-wave circuits such as high-temperature superconducting microwave filters [4] and millimeter-wave filters [5]. OSA's interpolation techniques and integrated database system facilitate accurate and fast EM optimization. OSA's novel Space Mapping optimization can significantly speed up EM-based design by bridging EM simulations with faster empirical/analytical models [4,6,7]. A comprehensive library of predefined elementary structures is ready for EM optimization.

Here, we introduce a revolutionary concept of direct EM optimization of arbitrary structures. It is implemented in Empipe which integrates Sonnet's *em* simulations into the powerful optimizers of OSA90 [8]. The exciting feature of optimizing arbitrary structures is based on OSA's technical breakthrough: Geometry Capture [2,9]. User-defined parameters are captured graphically from the layout and the layout is directly optimized without the need of any schematic translation.

Furthermore, such parameters are not limited to geometrical dimensions, but can also include substrate and metallization parameters.

The efficient gradient-based optimizers including ℓ_1, ℓ_2 (the least squares), minimax and Huber accompanied by the sophisticated interpolation technique and database system make EM-based design effortless. First-pass design can be achieved in an optimization loop, which can significantly reduce the time and cost of circuit design cycle. Furthermore, the statistical analysis and design features of this integrated system provide engineers with the capability of performing EM-based tolerance analysis, yield optimization and cost-driven design.

GEOMETRY CAPTURE

One of the most attractive advantages of EM simulators is the ability to analyze structures of arbitrary geometries. The ultimate goal, however, is to adjust such structures in order to meet design goals. Naturally, EM simulator users wish to be able to designate the parameters of interest, and to do it, preferably, directly within the graphical layout representation. To achieve this, the geometrical coordinates of the layout must reflect the numerical values of such parameters. The process of establishing the corresponding relationship is referred to as parameterization of the structure and has to be carried out for each structure of interest.

An Empipe element library [2] was created in our earlier work. The library contains some predefined and already parameterized geometrical primitives (lines, bends, junctions, gaps, stubs, etc.) from which a complete structure is built. This approach gained immediate acceptance by CAD users by virtue of its familiarity and ease of use. However, this approach inherently restricts its applications: it does not accommodate structures which cannot be decomposed into the library primitives. Moreover, even if a structure can be decomposed into those predefined primitives the proximity couplings are inherently omitted since these library elements, simulated individually by ***em***, are then connected in a circuit theoretic fashion.

To provide a tool for parameterizing arbitrary structures a user-friendly "Geometry Capture" technique has been invented and implemented in Empipe Version 2.0, which was released in 1994. Geometry Capture facilitates automatic translation of the values of user-defined parameters to the layout description in terms of absolute coordinates (the latter is the required input to Sonnet's ***em***). During optimization, this translation is automatically performed for each new set of parameter values before ***em*** is invoked.

Using the graphical layout editor ***xgeom*** from Sonnet Software [3], the user generates a set of geometries marking the evolution of the structure under consideration as the parameters of interest change. The change is then processed by Empipe to establish the mapping between those parameter values and the geometrical coordinates.

A. Geometrical Parameters

Without loss of generality consider parameterization of a simple rectangle structure. Two parameters, the length L and width W, are selected to be designable. The complete process of Geometry Capture and EM optimization is shown in Fig. 1. Using a cell size of 2 mil × 1 mil, we first draw the nominal structure as shown in Fig. 2a and save the drawing in the "rect_0.geo" file. The nominal values are L = 8 mil and W = 12 mil. For each of the designable parameters, we create a ".geo" file representing the structure after making an incremental change in that parameter while keeping all the other parameters unchanged (at their nominal values). Figs. 2b and 2c show the structure of Fig. 2a after incremental changes in the parameters W (the increment is 4 times the cell size along the y direction resulting in the value of 16 mil) and L (the increment is twice the cell size along the x direction resulting in the value of 12 mil), respectively. These two drawings are saved in the files "rect_1.geo" and "rect_2.geo", respectively. Figs. 3a-3c show the corresponding screens of ***xgeom***.

We enter all the corresponding data into the Geometry Capture form editor of Empipe which is shown in Fig. 4. The first entry "rect_0.geo" is the name of the file describing the nominal structure. The entry "rect.an" is a user-defined name of the file containing the control parameters for ***em*** simulation. The "DC S-par File" is an optional entry. If the structure is involved in DC or harmonic balance (HB) simulation, then the DC data for the structure is needed (***em*** will produce S parameters for AC only). The last entry in the first group specifies the run-time options for invoking ***em***. The second group of the form editor entries describe individual parameters. These entries and their correspondence to Figs. 2 and 3 are self explanatory. Empipe's Geometry Capture processes the information provided in the form editor, captures the parameters of the structure and stores the results for future use of the structure. In this way a parameterized custom library element is created.

Examining Fig. 4, it should be noticed that although the incremental change made to the parameter W is 4 times the cell size, the "# of Grids" is defined as 2. To preserve the symmetry of the structure along the y direction, the discretized value of W must be changed by an integer multiple of twice the y-cell size. In comparison, the incremental change made to the parameter L is twice the cell size and the "# of Grids" is also defined as 2, which means that the discretized value of L can be changed by an integer multiple of one x-cell size.

B. Dielectric Layers

The information on the dielectric layers of the structure is supplied in the ".geo" file, including the thickness of the layer, the relative dielectric constant, the relative permeability, the dielectric loss tangent and the magnetic loss tangent. Any of these can be designated as a variable, which makes it possible to assign tolerances to the dielectric parameters for statistical analysis, to compare choices of material by simulation, or even to optimize the dielectric parameters directly.

For each of the dielectric parameters of interest, we need to generate a ".geo" file in which the parameter value is different from that of the nominal ".geo" file. For example, suppose that we wish to include the substrate relative dielectric constant as a parameter of the rectangle structure in addition to the parameters W and L. Suppose that we choose to name this parameter as *EPSR*, and its value in the nominal ".geo" file is 9.8. We need to create another ".geo" file ("rect_3.geo", for instance) which contains a different value for the substrate relative dielectric constant, e.g., 9.9. Then, the completed form for Geometry Capture will be the one as shown in Fig. 5.

Theoretically, dielectric parameters do not have to be discretized, i.e., ***em*** can analyze structures with arbitrary dielectric parameter values. However, to invoke ***em*** for every different set of dielectric parameter values, no matter how small is the difference, can be very expensive computationally, especially for statistical analysis and optimization. For this reason, we discretize dielectric parameters and allow the size of the grid (in the example, the grid size for *EPSR* is 0.1) to be specified. ***em*** is invoked only when a dielectric parameter has changed to a new value which is outside the current grid. Small variations in a dielectric parameter value within a grid are accommodated by interpolation, hence excessive ***em*** simulations are avoided.

C. Metallization Loss Parameters

The information of metallization loss, if specified, can be saved in the ".geo" file, which includes the resistivity at DC, the skin effect coefficient and the surface reactance. Any of these parameters can be considered as a variable. Similarly, for each parameter of interest, we need to generate a ".geo" file in which the parameter value is different from that of the nominal ".geo" file.

For example, we wish to include the resistivity as an additional parameter for the rectangle structure. Assume that we choose to name the parameter as *RS*, and its value in the nominal ".geo" file is 0.0002. We need to create another ".geo" file ("rect_4.geo", for instance) which contains a different value for the resistivity, e.g., 0.0003. Then, the completed form for Geometry Capture will be the one shown in Fig. 6.

For the same reason as in the case of dielectric parameters, we allow the metallization loss parameters to be discretized in order to save the computation time of simulation and optimization.

OPTIMIZATION AND INTERPOLATION

Once the structure is defined by one of the library element or snatched by Geometry Capture it is ready for optimization. When one of the available optimizers is invoked the designable parameters will be optimized within the boundaries, if specified, w.r.t. the specifications designated by the user.

During optimization the parameters are automatically discretized and interpolated whenever it is necessary. When the parameter values do not coincide with the discrete grid values required by ***em***, i.e. are off the grid, Empipe will organize ***em*** analyses at an appropriate set of adjacent on-grid points. From this data, interpolation will be performed to obtain the desired result at the off-grid point.

Empipe is equipped with two interpolation algorithms: linear and quadratic. Linear interpolation is adequate when a fine grid is used. Because the cell size is small, it is reasonable to expect accurate results from linearizing the response functions within each cell. Quadratic interpolation generally provides more accurate results than linear interpolation, at the expense of increased computational effort. To evaluate a point with n off-grid parameters, linear interpolation requires *em* simulations at $n + 1$ grid points while the quadratic interpolation algorithm requires $2 \times n + 1$ grid points.

A database is automatically created in the first call to *em* and subsequently updated whenever a new *em* simulation is performed. The efficient database management minimizes the number of calls to *em* and speeds up the optimization process.

EM OPTIMIZATION OF A 10-dB DISTRIBUTED ATTENUATOR

Consider the distributed attenuator depicted in Fig. 7 [10]. The 15 mil substrate has a relative dielectric constant of 9.8. Two types of metallization are defined: the shaded area in Fig. 7 has a high resistivity of 50 Ohms/sq and the feed lines and the grounding pad are assumed to be lossless.

We treat the attenuator as one piece and define 8 geometrical parameters for Geometry Capture, namely P_1, P_2, ..., P_8. P_1, P_2, P_3 and P_4 are assumed to be designable parameters.

The design specifications are given as

$$9.5 \text{ dB} \leq \text{insertion loss} \leq 10.5 \text{ dB from 2 GHz to 18 GHz}$$

$$\text{return loss} \geq 10 \text{ dB from 2 GHz to 18 GHz}$$

The error functions are calculated at three frequencies: 2, 10 and 18 GHz.

First, we perform nominal design using minimax optimization. All the specifications are satisfied after optimization. The responses of the attenuator are shown in Fig. 8. The whole process requires 30 *em* analyses and took about 168 minutes on a network of Sun SPARCstations 1+ with parallel computation.

Starting at the minimax nominal solution we further perform yield optimization by assuming normal distributions with a standard deviation of 0.25 mil for all 8 geometrical parameters.

Estimated from 250 Monte Carlo outcomes, the yield is 82% at the minimax nominal solution. The yield is increased to 97% after optimization. The statistical simulation and optimization called for 113 additional ***em*** analyses. Fig. 9 shows the Monte Carlo sweep of the attenuator responses. The parameter values are listed in Table I.

CONCLUSIONS

We have presented a new EM optimization driver. Our Geometry Capture technique has removed barriers which previously confined EM optimization to a limited number of predefined elements. This has broadened the horizon of exciting applications for microwave engineers to accurately design circuits consisting of complicated structures and investigate new microstrip components. For the first time, EM optimization has been made so simple, straightforward and easy to perform. The capability of making all the geometrical parameters and material-related parameters fully optimizable elevates the design dimensions available to engineers.

ACKNOWLEDGEMENT

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TABLE I
MINIMAX AND YIELD OPTIMIZATION OF
A 10 dB DISTRIBUTED ATTENUATOR

Parameter	Starting point (mil)	Minimax solution (mil)	Centered solution (mil)
P_1	22.0	15.00	15.70
P_2	11.0	14.16	14.06
P_3	7.0	6.06	6.22
P_4	10.0	12.53	11.97
P_5	15.0	15.0	15.0
P_6	15.0	15.0	15.0
P_7	24.0	24.0	24.0
P_8	24.0	24.0	24.0
Yield		82%	97%

P_1, P_2, P_3 and P_4 are designable statistical parameters. P_5, P_6, P_7 and P_8 are fixed statistical parameters. A normal distribution with standard deviation of 0.25 mil is assumed for all parameters.

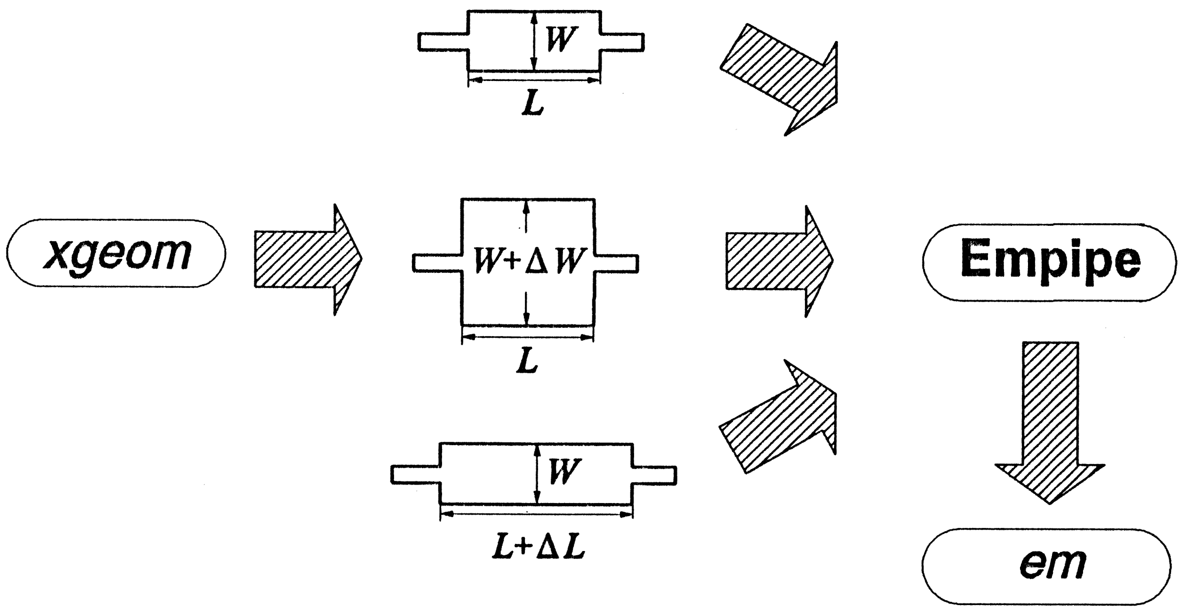
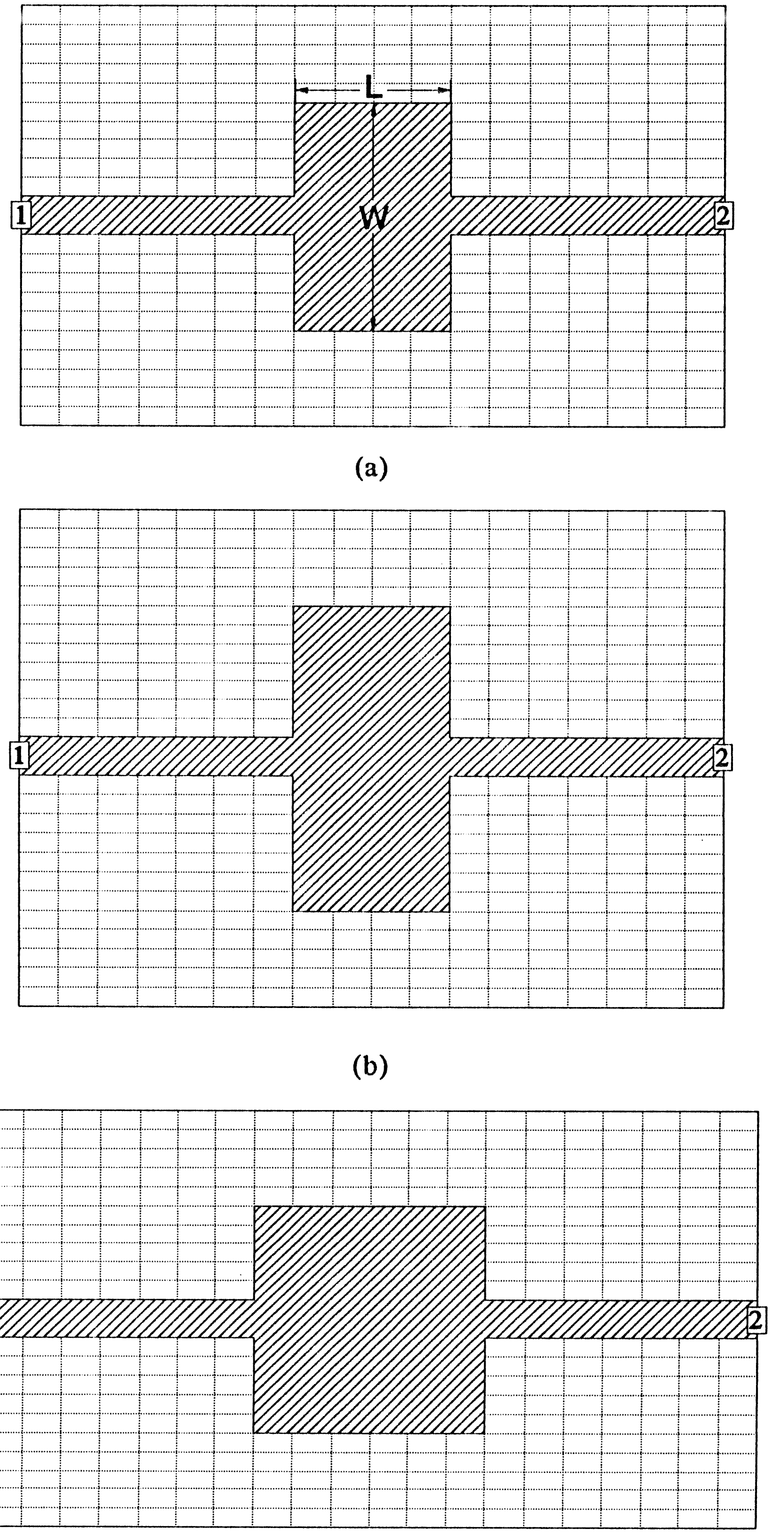
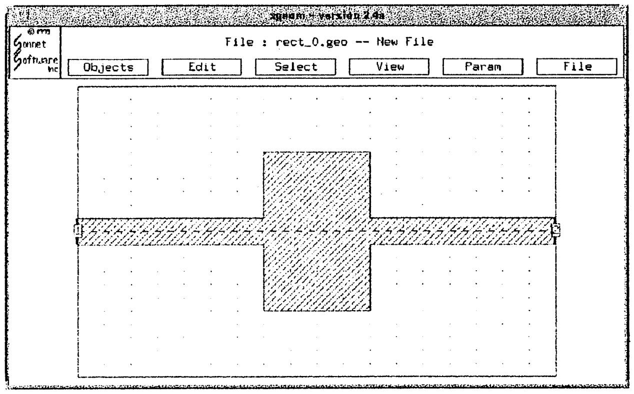


Fig. 1 Illustration of Geometry Capture for parameterizing the rectangle structure w.r.t. *L* and *W*.

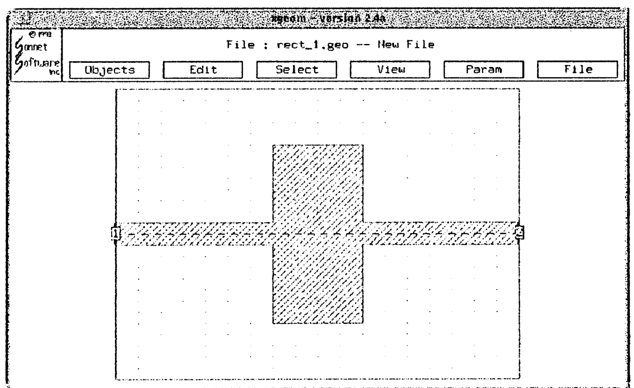


(c)

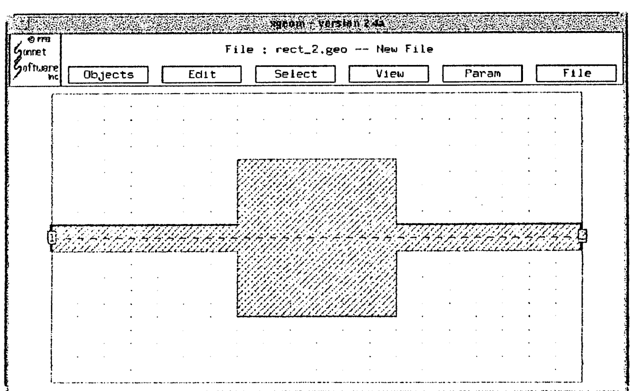
Fig. 2 Layout of the rectangle structure, (a) nominal (rect_0.geo), (b) incremental change in *W* (rect_1.geo) and (c) incremental change in *L* (rect_2.geo).



(a)



(b)



(c)

Fig. 3 The corresponding ***xgeom*** screens of the rectangle structure, (a) nominal (rect_0.geo), (b) incremental change in *W* (rect_1.geo) and (c) incremental change in *L* (rect_2.geo).

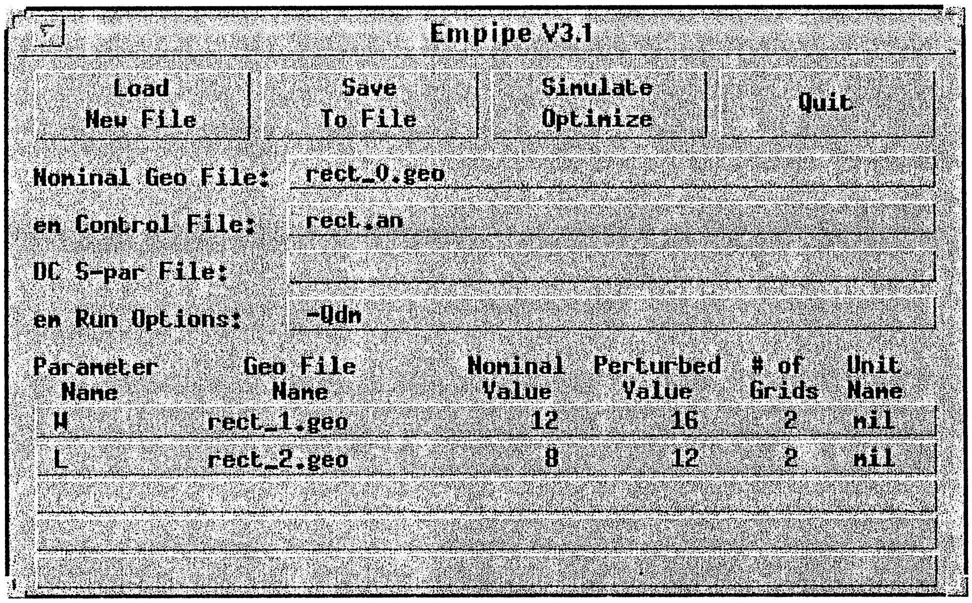


Fig. 4 Geometry Capture form editor for parameterizing the rectangle structure.

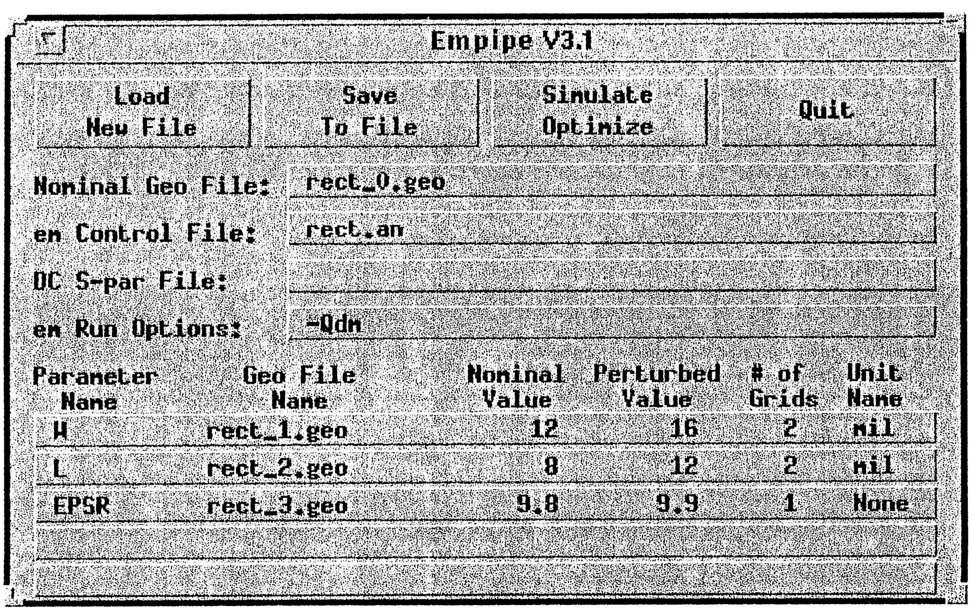


Fig. 5 Geometry Capture form editor of Fig. 4 for parameterizing the rectangle structure, augmented by the dielectric constant.

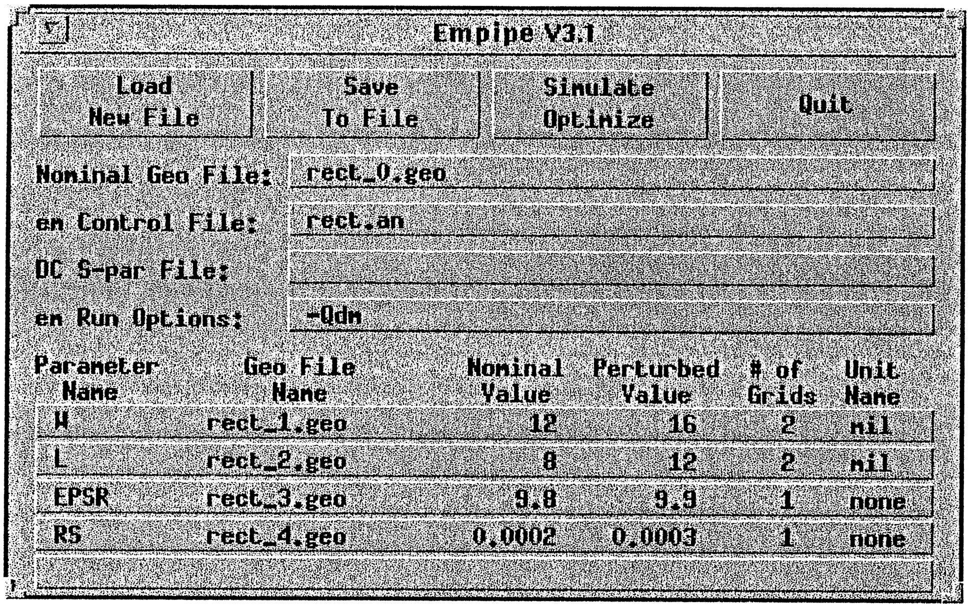
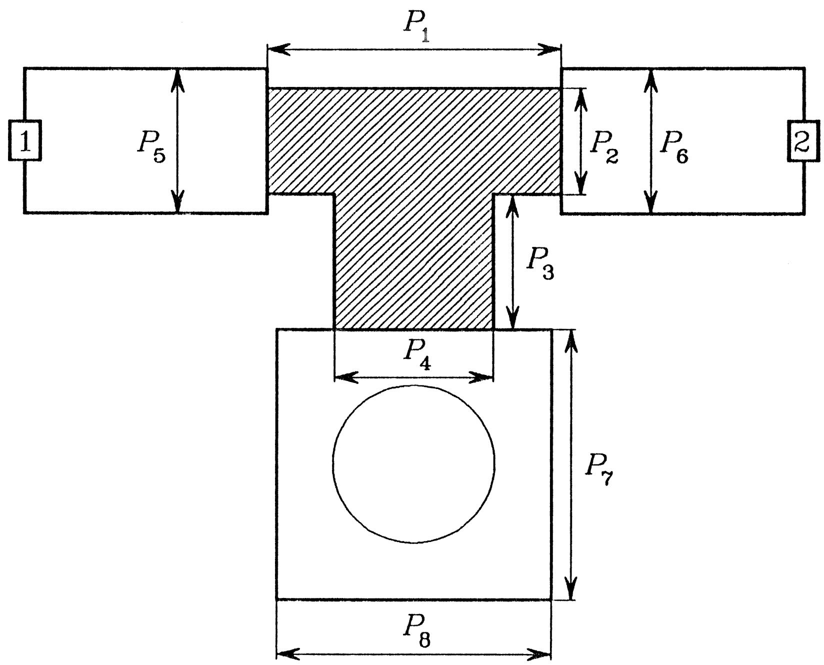
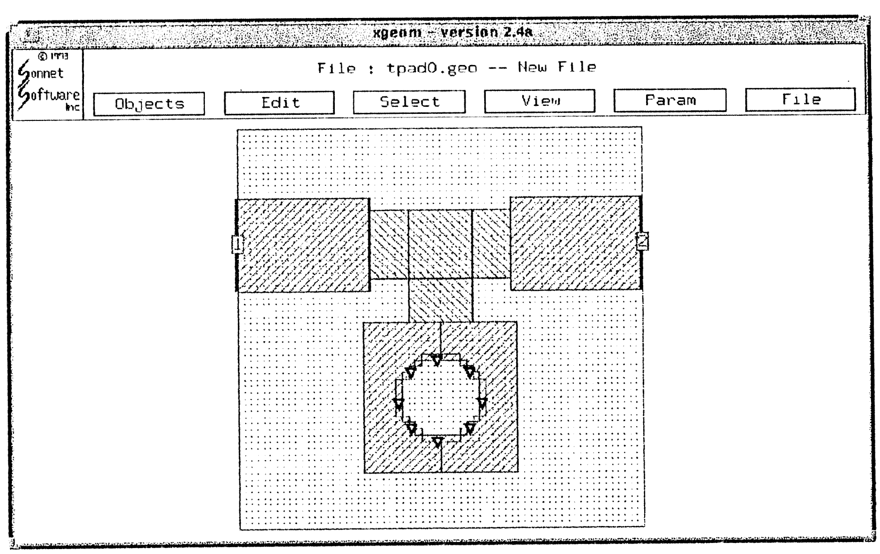


Fig. 6 Geometry Capture form editor of Fig. 5 for parameterizing the rectangle structure, augmented by the resistivity of the metallization layer.

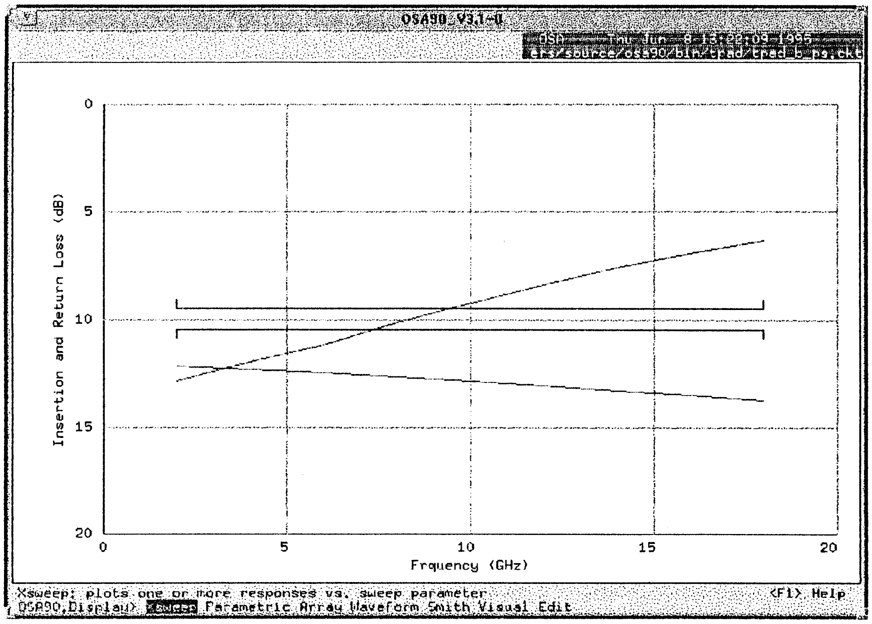


(a)

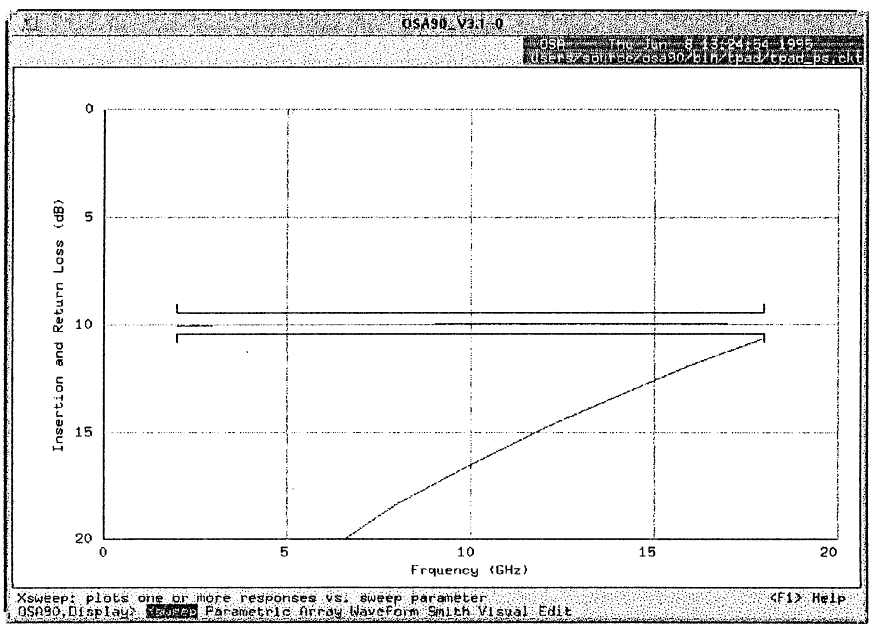


(b)

Fig. 7 The 10-dB distributed attenuator, (a) the geometry structure and (b) the corresponding ***xgeom*** screen.



(a)



(b)

Fig. 8 Insertion loss and return loss of the attenuator (a) before and (b) after minimax optimization. The window specification on the insertion loss is also shown.

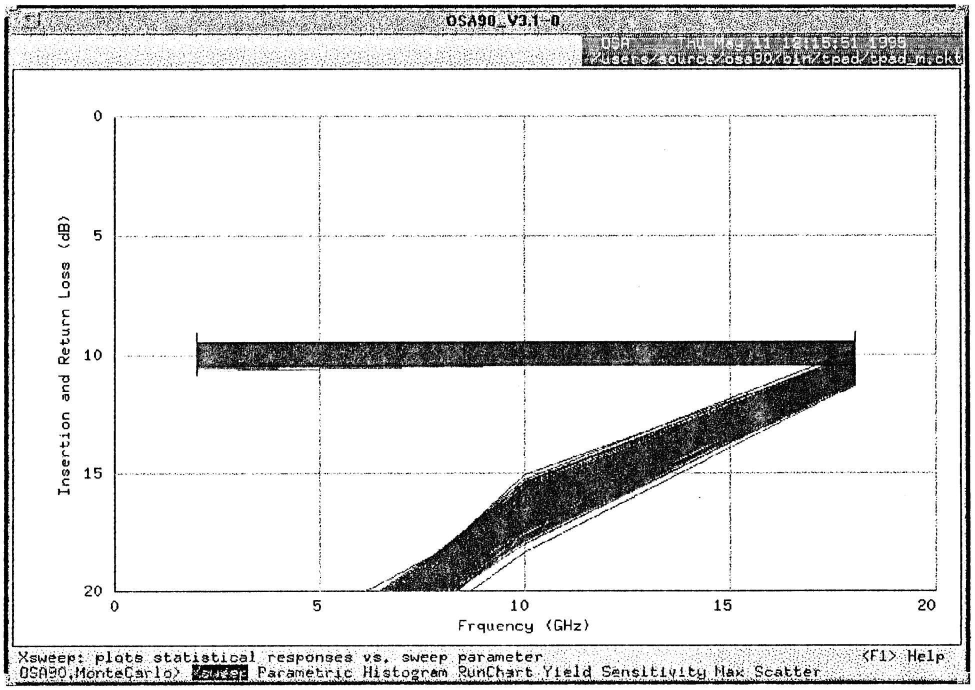


Fig. 9 Monte Carlo sweeps of the attenuator insertion loss and return loss after yield optimization.