MICROSTRIP CIRCUIT SIMULATION AND OPTIMIZATION USING ELECTROMAGNETIC FIELD SIMULATOR

J.W. Bandler, S. Ye, R.M. Biernacki and S.H. Chen

SOS-92-7-R

November 1992

MICROSTRIP CIRCUIT SIMULATION
AND OPTIMIZATION
USING ELECTROMAGNETIC FIELD SIMULATOR

J.W. Bandler, S. Ye, R.M. Biernacki and S.H. Chen

I. INTRODUCTION

Accurate planar microstrip structure models are fundamental to today's microwave integrated circuit designs. Commercially available CAD software packages provide microstrip library components that can be used for simulation and optimization purposes. Most of these component libraries are based on analytic formulas developed by creating a formula to fit numerical simulation results. LINMIC+/N from Jansen Microwave, however, offers a direct or lookup table approach to model multiconductor strip line structures. Accurate 2D spectrum domain simulation is applied separately to establish the lookup table which can be used for simulation and optimization. Microstrip discontinuities are also modeled by utilizing the information contained in the lookup table.

In this paper, we present for the first time an integration of a general purpose CAD software package *OSA90/hope* from Optimization Systems Associates inc. with a full-wave 3D EM simulator *Em* from Sonnet Software Inc. The special *Datapipe* feature of *OSA90/hope* establishes a channel for high speed data communication between the two programs, such that *OSA90/hope* directly drives *Em* as an on-line component simulator for circuit simulation and optimization. We overcome the special difficulty caused by finite grid size present in the numerical analysis techniques by an interpolation scheme. Arbitrary microstrip components can be optimized, exploiting their full potential for microwave and millimeter-wave applications.

Section II illustrates the communication mechanisms between *OSA90/hope* and *Em*. Different interfacing prototypes are discussed in Sections III and IV, and intepolation is oulined in Section V. Section VI presents application examples which include a design optimization of a 26-40 GHz interdigital capacitor filter with 13 optimization variables, demonstrating significant application potentials of such an integration for microwave and millimeter-wave circuit designs.

II. INTERFACING *Em* TO *OSA90/hope* THROUGH *Datapipe*

The EM simulator *Em* [1] performs the electromagnetic analysis of planar microstrip circuits by solving for the current distribution in the microstrip metallization using the Method of Moments [2]. The analysis takes into account effects such as coupling, dispersion, discontinuities, metallization, radiation losses and de-embedding etc.

The general purpose microwave CAD program *OSA90/hope* [3] has a unique *Datapipe* feature which utilizes the UNIX inter-program communication mechanism for fast data transfer between *OSA90/hope* and certain external programs. A special *Datapipe* called *Empipe* was developed for the communication between *OSA90/hope* and *Em*. Using *Empipe*, *OSA90/hope* can perform complete circuit simulation using *Em* for passive planar structure analyses.

The general structure of the interconnection is shown in Fig. 1. *OSA90/hope* is the parent program, the *Empipe* interface is a child program and *Em* is a grandchild of *OSA90/hope*. When *OSA90/hope* requires *Em* to simulate a structure it invokes *Empipe*. *Empipe* in turn prepares necessary input data files for *Em*, invokes *Em* and sends back simulation result from *Em* output data files to *OSA90/hope*.

Empipe consists of a set of programs which form a two-stage connection to interface *Em* with *OSA90/hope*, as shown in Figs. 2 and 3.

Stage 1: An *Empipe* program is invoked by *OSA90/hope* to create appropriate *.geo file(s) for *Em*, where the *.geo file is the data file required by the *Em* simulator [1]. This may involve a child program as shown in Fig. 2(a), if the name or content of the *.geo file is known (e.g., generated by *Xgeom* graphical editor [1]) and is not subject to change. Alternatively, a "translator" type child program can be used. It translates the dimensions and substrate information of the structure to *.geo file format and generate the *.geo file for *Em*, as shown in Fig. 2(b). Such a translator allows the user to manipulate the structure dimensions without using *Xgeom*.

Stage 2: This *Empipe* program is invoked by *OSA90/hope* after *Stage 1* has been invoked. It executes *Em* to simulate the created *.geo data file if necessary, as shown in Fig. 3. As the input to this *Empipe* program, *OSA90/hope* passes the *.geo file identifier, frequency point and frequency range. The frequency point is the frequency specified for the current simulation. The frequency range may correspond to the frequency range specified in the sweep block of the *OSA90/hope* input file. A simulation control file is first created in this stage describing the frequency unit and the actual frequency or frequencies where simulation is desired. *Em* simulation is invoked if the data file is new or if the frequency point (or range) was not covered in previous runs with the same data file. A working copy of the *S* parameters is created from the response file(s) generated by *Em*. If *Em* simulation is not required, the working *S* parameter file is used. In either case the *S* parameters at the specified frequency is retrieved from the *S* parameter file and send back to *OSA90/hope*.

With *Empipe*, a microstrip structure can be simulated accurately by the EM simulator and treated as a normal netlist component in circuit input file for circuit simulation and optimization.

III. CIRCUIT SIMULATION AND OPTIMIZATION WITH FIXED STRUCTURES

For a fixed microstrip structure, a *.geo file can be created by using *Xgeom* [1]. Through *Empipe* the *.geo file is referred to as a normal circuit component. The user has a full control of the *.geo file, i.e., the microstrip structure including substrate, size, grid, geometry, accuracy, etc., via *Xgeom*. A circuit can be described both by *.geo data file(s) and *OSA90/hope* built-in library components. However, since the contents of the *.geo data file is not modifiable within the *OSA90/hope* input file in an automated fashion, a change of a specific microstrip dimension can not be achieved without manually changing the *.geo data file. This connection between *OSA90/hope* and *Em* allows the user to optimize non *Em* built-in components while keeping the microstrip structure(s) described by *.geo data file(s) fixed.

IV. CIRCUIT SIMULATION AND OPTIMIZATION WITH PRE-PROGRAMMED STRUCTURES

In general if a microstrip structure can be described by its geometrical parameters, an *Empipe* program can be created to translate the geometrical dimensions into coordinates and generates a *.geo data file for *Em* to use, as shown in Fig. 2(b). Such pre-programmed structures can be used not only for circuit simulation but also for optimization, since the structures are defined by its geometrical parameters not directly by coordinates.

It should be realized the important implication of this simulation and optimization capabilities from the integration of a general CAD tool with an accurate and efficient EM simulator. We can achieve very accurate simulation results for normal microstrip components, including discontinuities, virtually without frequency and parameter limitations. Furthermore, we have given microwave design engineers powers to optimize special and novel structures for their design objectives which would otherwise be tedious, if not impossible, to achieve manually or by using the conventional "cut and assemble" approach.

The *Empipe* pre-programmed component library contains both common and special microstrip components. These components are actually child programs linking *Em* with *OSA90/hope* as illustrated in Fig. 2(b) and Fig. 3. The common microstrip components include microstrip line, step, tee, cross, etc. Very accurate results can be achieved due to the accuracy of *Em* simulation, especially for microstrip discontinuities. Special components such as double-folded stub, interdigital capacitor, spiral inductor, etc., can not only be simulated but optimized as a conventional circuit component.

V. INTERPOLATION FOR OUT-OF-GRID DIMENSIONS

Numerical techniques need to discretize a continuous problem in order to simulate. If a microstrip structure has two or more geometrical parameters in one direction, for example, W_1 and W_2 of a step discontinuity component, it is likely that the structural coordinate parameters may not coincide with the equal-spaced grid points. The discontinuity originated by finite grid size may cause the optimization process difficult to converge. In order to overcome this discontinuity problem, we have employed linear interpolation to smooth the responses.

Let Δx_i be the ith grid size and $x_i = n_i \Delta x_i + \theta_i \Delta x_i$, where n_i is an integer and $0 < \theta < 1$, for $i = 1, \ldots, m$. Denote $x_{i0} = n_i \Delta x_i$, then

$$\begin{aligned} f(x_1, \ldots, x_m) & \approx f(x_{10}, \ldots, x_{m0}) \\ & \quad + \Sigma \{[f(x_{10}, \ldots, x_i, \ldots, x_{m0}) - f(x_{10}, \ldots, x_{i0}, \ldots, x_{m0})]/\Delta x_i\} \theta_i \Delta x_i \\ & = (1 - \Sigma \theta_i)\, f(x_{10}, \ldots, x_{m0}) + \Sigma\, f(x_{10}, \ldots, x_i, \ldots, x_{m0})\, \theta_i \end{aligned}$$

where $f(x_1, \ldots, x_m)$ represents the response function.

This interpolation scheme has been implemented for the pre-programmed components. The *Stage 2* of *Empipe* shown in Fig. 3 has been designed to perform the corresponding computations. It is obvious that with the interpolation scheme the CPU time for simulation may substantially increase. However the interpolation assists the optimization process since no extra perturbation for gradient computation would be necessary.

VI. APPLICATIONS

Microstrip Rectangular Structure

We choose a microstrip rectangular structure simulation to illustrate *Empipe* connection between *OSA90/hope* and *Em* for fixed microstrip structures. The fixed structure from D'inzeo, *et al.* [4] is shown in Fig. 4. We first used *Xgeom* to create a *.geo data file for the structure. The data file was then included in an *OSA90/hope* input file where the structure is treated as a circuit component. The simulation was from 2 GHz to 18 GHz with 0.1 GHz step. A Sun SPARCstation 1 was used. The CPU time used by running *OSA90/hope* with the *Empipe* connection to *Em* was approximately the same as the time used by running stand-alone *Em*. Fig. 5 illustrates $|S_{21}|$ in dB which is very close to the measurements published in [4]. Such an agreement can not be achieved by using current microstrip models based on equivalent circuits.

Double Folded Stub Filter

The structure considered here is a double folded stub [5] for band-stop filter applications, as shown in Fig. 6. Compared with the conventional double stub structure show in Fig. 7, this structure may substantially reduce the physical space while achieving the same purpose. The symmetrical double folded stub can be described by 4 parameters, W, S, L_1 and L_2.

We fix W and optimize L_1, L_2 and S to move the center frequency of the stop band from 15 GHz to 13 GHz. We assume the specifications for the filter as

$|S_{21}| > -3$ dB for f < 9.5 GHz and f > 16.5 GHz

$|S_{21}| < -30$ dB for 12 GHz < f < 14 GHz

The substrate thickness and the dielectric constant are 5 mils and 9.9, respectively, and $W = 4.8$ mils.

The optimization was done in two steps. First, we used 2.4 mil grid size in both X and Y directions for *Em* simulation. Then we reduced the grid size to 1.6 mils for fine resolution. The values of the variables $\{L_1, L_2, S\}$ before and after optimization are {74, 62, 13} mils and {91.82, 84.71, 4.80} mils, respectively. Fig. 8(a) and (b) show the $|S_{21}|$ in dB before and after optimization. This example demonstrates the power and flexibility of using *Empipe*. Special microstrip structures can be simulated by *Em* and further optimized by *OSA90/hope*.

26-40 GHz Interdigital Capacitor Filter Design Optimization

The 26-40 GHz millimeter-wave bandpass filter [6] is built on 10 mil thick substrate with dielectric constant 2.25. The filter utilizes thin microstrip line to realize inductance and interdigital capacitor to π capacitor 2-port. The design specifications are

$|S_{11}| < -20$ dB and $|S_{21}| > -0.5$ dB for 26 GHz < f < 40 GHz

The original design was carried out to match the inductance and capacitance from the structures to a lumped circuit prototype at the center frequency. However, the frequency-dependent behaviour of the actual structures simulated from *Em* made the design very difficult to achieve by manually tuning the structures. We created symmetrical interdigital capacitor and other related *Empipe* components and optimized the filter design. There were 13 optimization variables including the finger length and patch widths of the interdigital filter, as shown in Fig. 9. Equal ripple response of the filter was achieved after minimax optimization. Fig. 10 shows the filter response after rounding the variables to 0.1 mil resolution.

VII. CONCLUSIONS

We have demonstrated a novel interconnection of a general CAD program *OSA90/hope* with an accurate EM solver *Em* through *Empipe*. By such an interconnection we take the advantages of both systems and provide microwave design engineers with a CAD system which has the versatility of a general CAD program with very accurate planar structure simulation capabilities. Conventional and special microstrip structures can be simulated and optimized virtually without frequency and parameter limitations. It is especially valuable for millimeter-wave integrated circuit design.

A double folded stub structure is optimized for band stop filter application which may not even be properly modeled by standard equivalent circuit microstrip components. A 26-40 GHz bandpass filter design was optimized, demonstrating the power and flexibility of the *Empipe* connection.

REFERENCES

[1] *Em User's Manual* and *Xgeom User's Manual*, Sonnet Software, Inc., 135 Old Cove Road, Suite 203, Liverpool, NY 13090-3774, May. 1992.

[2] J.C. Rautio and R.F. Harrington, "An electromagnetic time-harmonic analysis of arbitrary microstrip circuits," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-35, 1987, pp. 726-730.

[3] *OSA90/hope User's Manual*, Optimization Systems Associates Inc., P.O.Box 8083, Dundas, Ontario, Canada L9H 5E7, 1992.

[4] G. D'inzeo, F. Giannini, C.M. Sodi and R. Sorrentino, "Method of analysis and filtering properties of microwave planar networks," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, 1978, pp. 462-471.

[5] J. Rautio, Sonnet Software, Inc., 135 Old Cove Road, Suite 203, Liverpool, NY 13090-3774. Private communication, 1992.

[6] D. Swanson, Watkins-Johnson Company, 3333 Hillview Avenue., Stanford Research Park, Palo Alto, CA 94304-1204. Private communication, 1992.

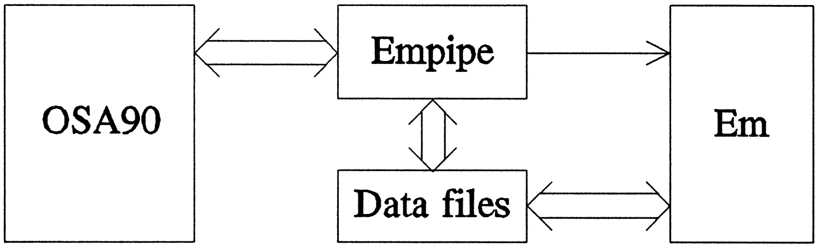


Fig. 1. General structure of the connection between *OSA90/hope* and *Em*.

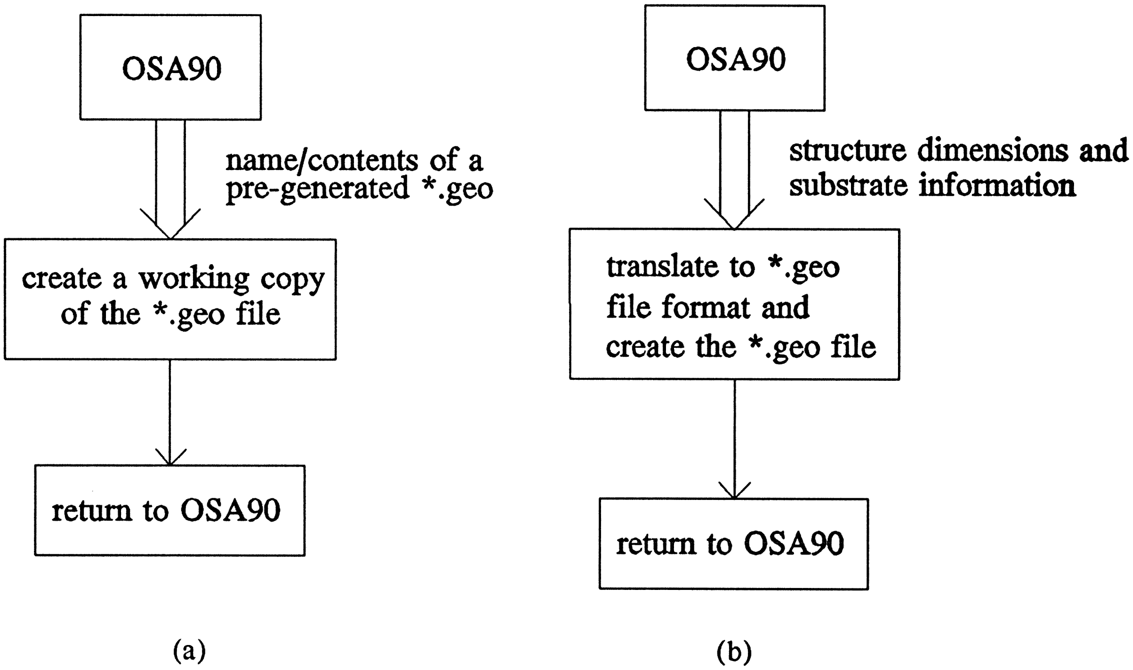


Fig. 2. Flow diagram illustrating Stage 1 of *Empipe* for interfacing *Em* simulator with *OSA90/hope*: (a) create a working copy of a pre-generated *.geo file and (b) create *.geo file(s) from a geometrical dimension "translator".

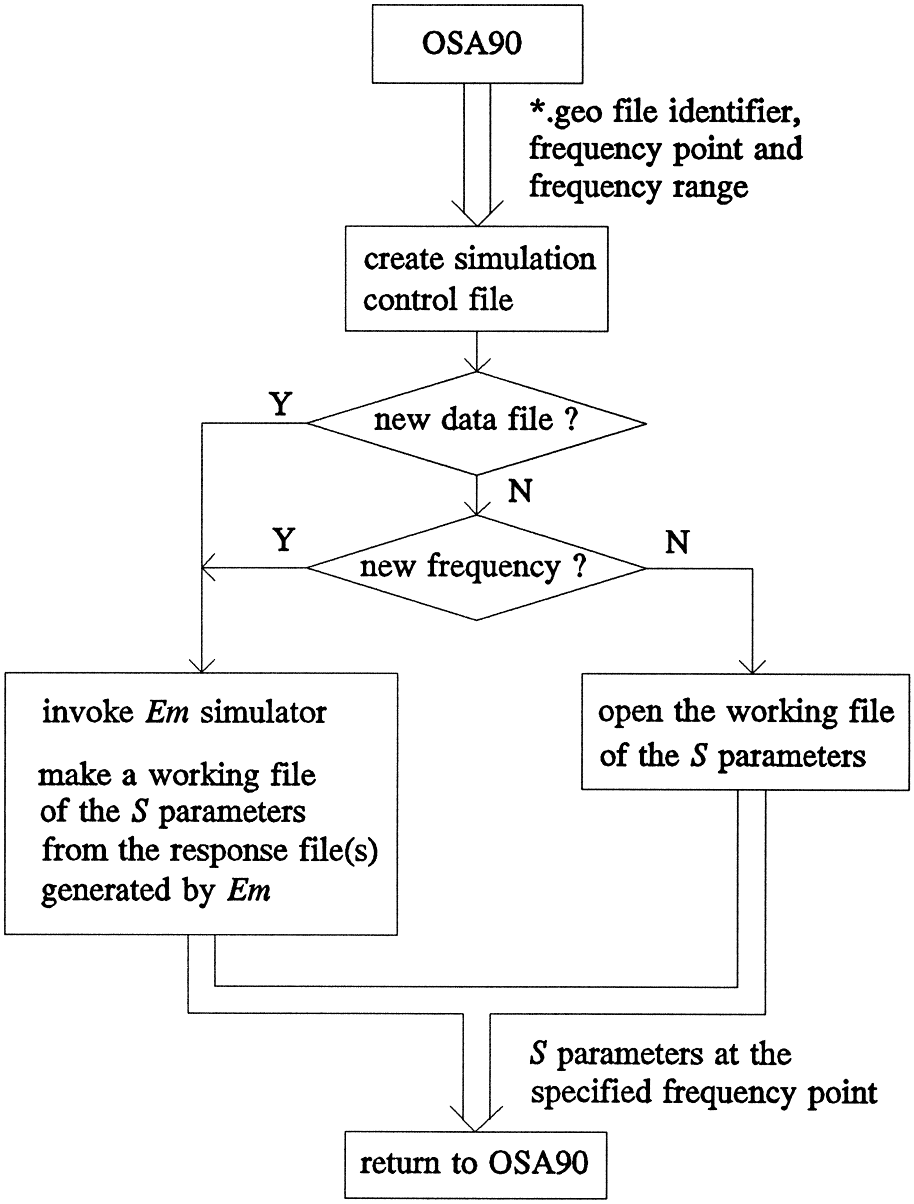


Fig. 3. Flow diagram illustrating Stage 2 of *Empipe* for interfacing the *Em* simulator with *OSA90/hope*: *S* parameters are computed by *Em* and transferred to *OSA90/hope*.

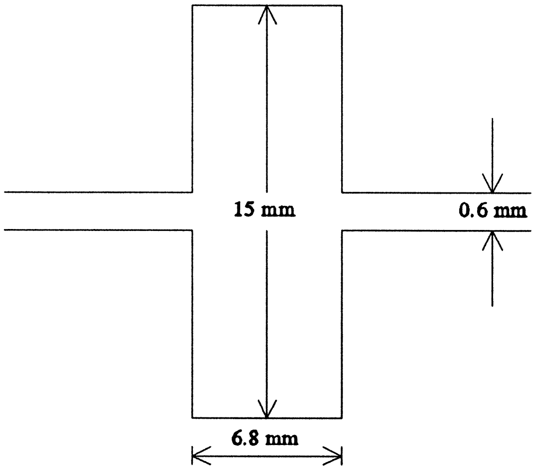


Fig. 4. A microstrip rectangular structure where the thickness and dielectric constant of the substrate are 0.635 mm and 10.0, respectively.

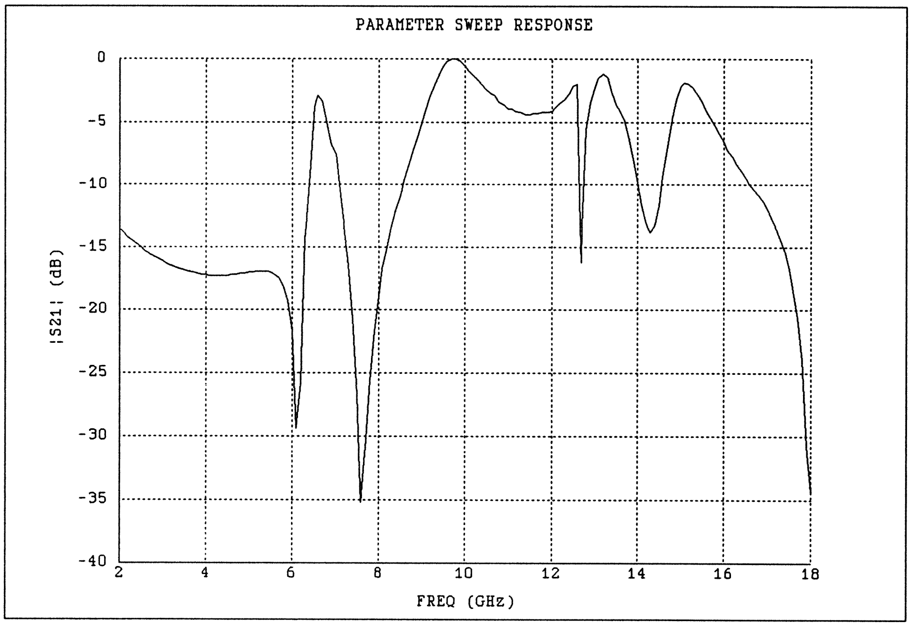


Fig. 5. $|S_{21}|$ in dB vs. frequency for the rectangular structure.

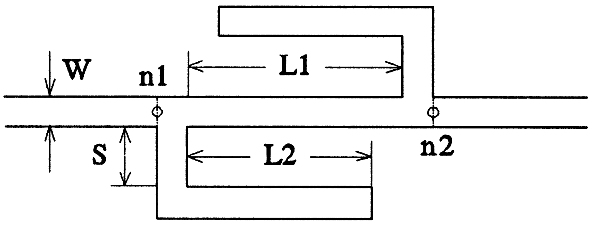


Fig. 6. Double folded stub microstrip structure for band-stop filter applications.

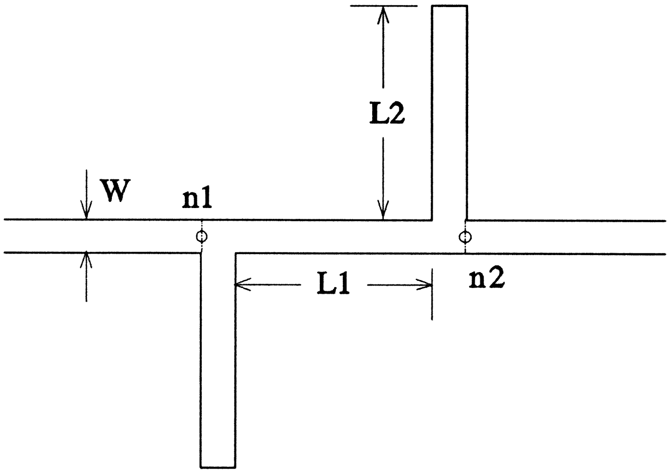
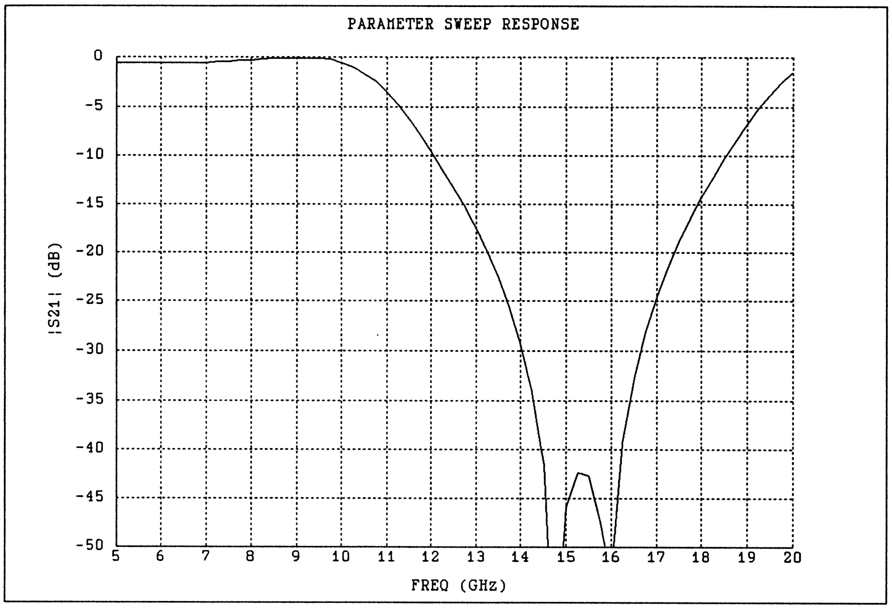
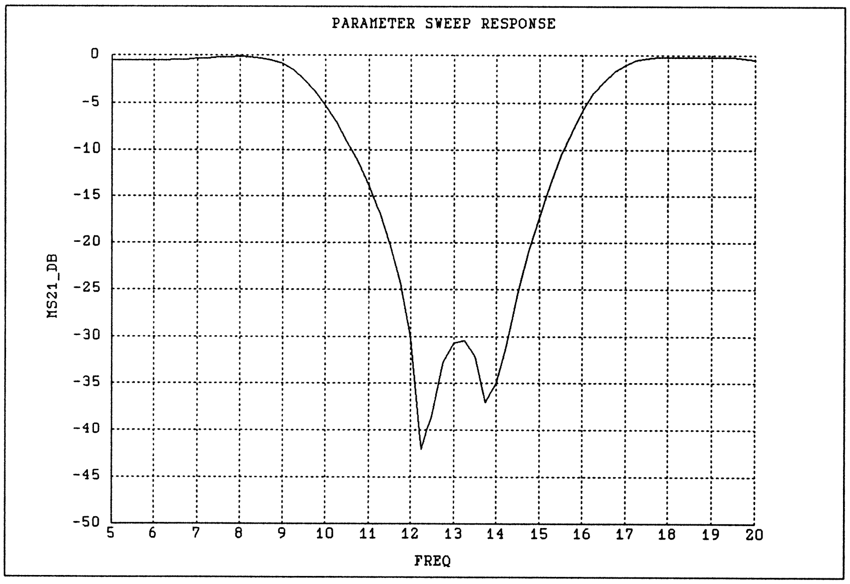


Fig. 7. Double stub microstrip structure.



(a)



(b)

Fig. 8. Double folded stub band-stop filter structure simulation. (a) before optimization, and (b) after optimization.

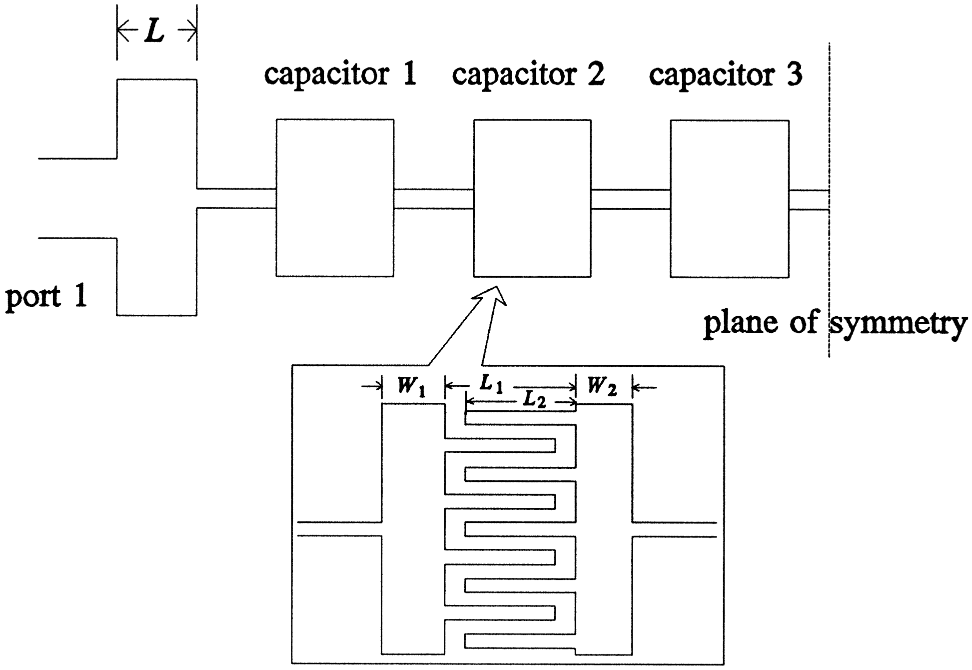


Fig. 9. 26-40 GHz interdigital capacitor filter. Substrate thickness, dielectric constant and shielding height are 10 mils, 2.25 and 120 mils, respectively. The optimization variables include L, L_1, L_2, W_1 and W_2, totalling 13.

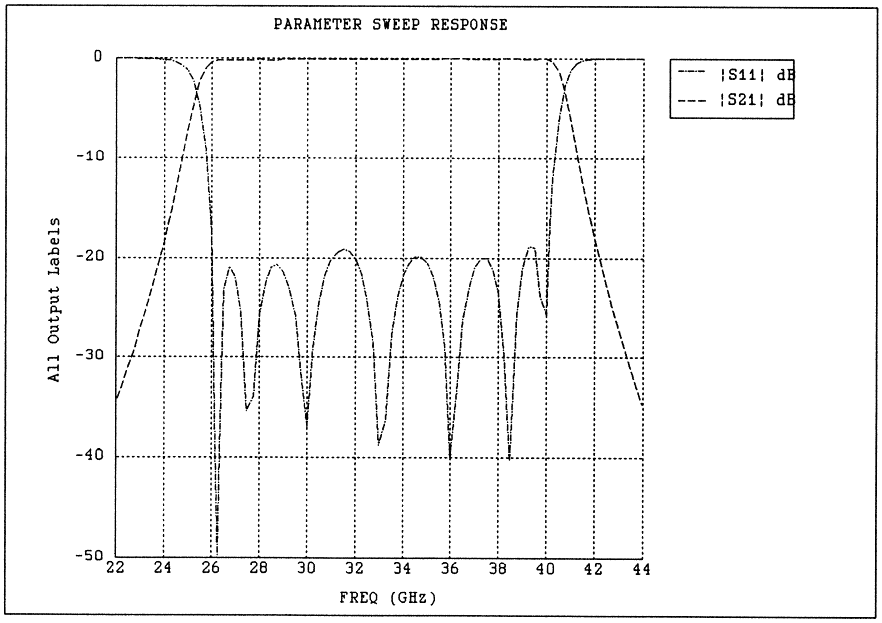


Fig.10. 26-40 GHz interdigital capacitor filter simulation after optimization. All the optimization variables have been rounded to 0.1 mil resolution.