Benchmark for the Verification of Microwave CAD Software[1]

Robert Furlow and Raynor Y. Shimoda
Boeing Defense and Space Group
High Technology Center
P.O. Box 3999, MS 7J-65
Seattle WA 98124-2499

Dylan F. Williams and Roger B. Marks
National Institute of Standards and Technology
Mail Code 813.01, 325 Broadway
Boulder, CO 80303

K. C. Gupta
MIMICAD Center, University of Colorado
Campus Box 425
Boulder, CO 80309-0425

Abstract

A set of microstrip structures which constitute a comprehensive benchmark for the verification of microwave Computer Aided Design (CAD) software has been developed in a collaborative effort. The benchmark is designed to exhibit a wide range of physical mechanisms which may or may not be incorporated into commercial microwave CAD software. The structures are characterized experimentally with respect to a well understood calibration in which the reference impedance is set real.

Introduction

A set of microstrip test structures constituting a comprehensive benchmark for the verification of microwave Computer Aided Design (CAD) software was developed under a collaborative effort with Boeing High Technology Center, the National Institute of Standards and Technology (NIST), and the MIMICAD Center at the University of Colorado. The benchmark differs from previous efforts in a number of ways.

The test structures selected for inclusion in the benchmark were gathered from a number of companies participating in the MIMICAD Center. A central criterion for inclusion of any structure in the benchmark is disagreement of simulations of at least one commercial simulator with either previously measured results or results of another commercial simulator. This was done to insure that the experiments would be sensitive enough to distinguish between correct and incorrect simulations. The structures were limited to a single layer of metal with a maximum of two ports and a single dielectric layer substrate. No air-bridges or active layers were permitted.

The benchmark is designed to exhibit effects of all of the physical phenomena typically present in MMICs. Only a few of the physical phenomena present in MMICs are emphasized in

---

each structure, however, to simplify the identification of deficiencies in CAD software. The number of test structures was limited in order to allow duplicate structures on the wafer and to permit sufficient spacing between structures to avoid possible coupling to adjacent structures.

Many of the physical phenomena which are typically present in MMICs are dependent on physical parameters which are difficult to scale with frequency. Examples are metal conductivity, surface roughness, metal thickness, and GaAs material parameters. In a departure from some previous verification experiments, the structures were not scaled with frequency, but were fabricated with a MMIC process on a 5.08 cm diameter, 100 μm thick gallium arsenide wafer so as to emphasize the actual phenomena present in MMICs. The conductors were formed of evaporated gold, 0.8 μm thick, using a lift-off process. Vias were fabricated by RIE with a backside conductor of 5 μm plated gold. The structures were laid out on a 0.5 μm grid with a 2.0 μm minimum feature size.

Experimental Description

The mask layout is shown in Figure 1. Two multi-line microstrip calibration sets were placed at the center of the wafer and four duplicates of each of the fifteen test structures selected for the project were distributed around the wafer. A summary of the test structures and the test criteria present in each of them is given in Table 1 and the physical parameters of the wafer are summarized in Table 2.

TABLE 1. Effects tested by structure

(•) - marginal effect

Structure	Metal thickness	Tight Coupling	Loose Coupling	Fringing Fields	2D Currents	Conductor Loss	Non Cartesian	3D Current
Spiral Inductor	•					•		(•)
Interdigitated Cap	•	•						
10 GHz Radial Stub 120°					•		•	
35 GHz Radial Stub 120°					•		•	
35 GHz Radial Stub 60°				•			•	
Dual Radial Stubs 70°			•	•			•	
Dual Radial Stubs 120°			•		•		•	
35 GHz DC Block	•	•				(•)		
35 GHz Band Pass Filter	•	•				(•)		
Mitered Meander Line			•	(•)				
Curved Meander Line			•	(•)			•	
Dual Shunt Stubs			(•)	•	•			
Series Steps				•	•			
Resonator without Via						•		
Resonator with Via						•		•

Table 1 shows that the structures were designed to test for the failure of simulations which neglect or do not properly account for finite metal thickness, loose (parasitic) and tight coupling of circuit elements, fringing fields, two and three dimensional current distributions, conductor loss, and non-rectangular geometries.

TABLE 2. Physical Measurements of Wafer Parameters

Parameter	Measured Value	Variation
Width of 50 Ω Microstrip Lines	73.09 μm	.081 μm 1σ
Substrate Thickness	101 μm	±3 μm
Relative Dielectric Constant	12.9	---
Evaporated Gold Thickness	0.7486 μm	---
Adhesion Metal Thickness	0.0250 μm Ti, 0.0350 μm Pt	---
Total Conductor Thickness	0.8086 μm	0.026 μm 1σ
Sheet Resistance	0.0346 Ω/sq	1.73x10–4 Ω/sq 1σ

TABLE 3. Calculated and Measured Capacitances per Unit Length

Method	Includes Metal Thickness	C (pF/cm)
Linecalc [5]	Yes	1.918
R.H. Jansen's MMictl [6,7]	Yes	1.923
Spectral Domain	No	1.906
Measured	Yes	1.967

Scattering Parameter Calibration

The scattering parameter (S-parameter) calibration was performed using the rigorous and broadband multi-line thru-reflect-line (TRL) calibration technique of Marks [1]. The calibration set consisted of a thru line of length 950 um, five lines of additional length 0.5 mm, 1.96 mm, 2.94 mm, 6.035 mm, and 18.01 mm, and a symmetric reflect consisting of identical opens offset 325 um from the end of the line. The reference plane was located at the center of the thru. The two sets of measurements were performed, the first from 50 MHz to 50 GHz and the second at NIST from 50 MHz to 40 GHz. In order to examine any higher order effects, in some cases the measurement frequency range exceeds that over which the structure would normally be used.

The capacitance of the microstrip lines was determined from the resistance per unit length of the lines using the technique of Williams and Marks [2]. A comparison of the calculated values and the measured values is shown in Table 3. The measured S-parameters were transformed to a 50 Ω real reference impedance using the procedure of Marks and Williams [3,4] and the measured capacitance.

The two sets of measurements were carefully checked for consistency. No serious discrepancies were noted over the range for which measurements were available from each institution except for the 0.5 mm line structure, which showed a 2.0 dB discrepancy in reflection coefficient. This line was used only in the measurements for frequency coverage in the 40 to 50 GHz range. It was determined that the coplanar probes, when contacting the 0.5 mm thru, coupled strongly to the adjacent short structure at its resonant frequency of 46 GHz, degrading the 50 GHz calibration between 45 and 47 GHz. The lateral separation of these structures was 500 μm.

Additional measurements are being performed in a round robin exercise among the MIM-ICAD Center sponsors in order to provide some additional indication of error bounds in the measurement.

Comparison of Simulated and Measured Results

We have completed preliminary comparison of the measured results with analysis of the structures performed by a commercial circuit simulator[5] and PMESH, a full wave electromagnetic simulator, developed at the University of Colorado[8]. The circuit simulator's discontinuity models are based on closed form expressions derived either from measured data or full wave analysis. This approach allows faster computational speed and the use of optimization but does not account for interactions between the circuit elements. PMESH solves for the S-parameters of a planar conductor in an un-shielded environment. Conductor loss, dielectric loss and radiation are accounted for in the simulation. PMESH allows flexible meshing of the conductor using arbitrary rectangular and triangular elements. The computational time is much longer than the commercial simulator but interactions between circuit elements are taken into account. Some representative results of this comparison are presented here.

The layout of the 35 GHz dc block is shown in Figure 2. As can be seen from Figure 3 analysis of this structure by the earlier version of the circuit simulator exhibited only a single minimum in the magnitude of S11 at 35 GHz. The new version is corrected and the worst case differences in measurement and simulation over the 0.05 to 40 GHz frequency range are $\Delta S21 = 0.015$, $\Delta S11 = 0.045$, and $\angle S21 = 5.7°$. The full wave simulation was performed over a 10 to 40 GHz range using the gridding shown in Figure 8. The worst case differences in measurement and the full wave analysis over the 10 to 40 GHz frequency range are $\Delta S21 = 0.05$, $\Delta S11 = 0.069$, and $\angle S21 = 5.5°$. The mesh was not refined at the open ends of the coupled lines, this possibly accounts for the difference in magnitude of S21 from measured. The large difference in $\angle S11$ between measurement and full wave simulation can be attributed to large uncertainty in vector analyzer angle measurements of S11 when $|S11|$ is less than 0.1.

The layout of the 35 GHz band pass filter is shown in Figure 4. The comparison of measured and modeled results are shown in Figure 5. There is a 1.4% difference in resonant frequency between measurement and simulated. The worst case differences in measurement and the circuit simulator over the 0.05 to 40 GHz frequency range are $\Delta S21 = 0.146$, $\Delta S11 = 0.291$, and $\angle S21 = 17.1°$. The full wave simulation was performed over a 10 to 40 GHz range using the gridding shown in Figure 9. The worst case differences in measurement and the full wave analysis over this range are $\Delta S21 = 0.267$, $\Delta S11 = 0.237$, and $\angle S21 = 46.5°$.

The layout of a dual radial stub with a designed center frequency of 35 GHz is shown in Figure 6. The circuit simulator model originally used was composed of two separate radial stub models (MRSTUB) and not the butterfly stub model (MBSTUB). The worst case differences in measurement and the original model over the 0.05 to 35 GHz frequency range are $\Delta S21 = 0.136$, $\Delta S11 = 0.049$, $\angle S21 = 10.8°$ and $\angle S11 = 22.5°$. As can be seen in Figure 7, above 35 GHz there is a step in $\angle S21$ in the original model. The analysis was redone using the MBSTUB model although the rotation of the stub back toward the left port could not be included. The agreement with measurement is improved, without the step in ∠S21. The worst case differences in measurement and the MBSTUB based model over the 10 to 40 GHz frequency range are ΔS21 = 0.057, ΔS11 = 0.027, ∠S21 = 6.88° and ∠S11 = 7.63°. Full wave analysis over to 10 to 40 GHz frequency range using the gridding shown in Figure 10 gives worst case errors of ΔS21 = 0.018, ΔS11 = 0.036, ∠S21 = 5.69° and ∠S11 = 6.08°.

Conclusions

Given the penalty of computation time, the use of full wave electromagnetic simulators can improve the accuracy of the analysis provided proper grid refinement is used. Some type of autogridding would be desirable to this end. The determination of the resonant frequency of resonant structures is particularly sensitive to refinement of the conductor gridding.

Acknowledgments

The authors thank Bor-Yen Mao of the Boeing HTC Materials and Devices Lab, Janet Anstett of the University of Colorado MIMICAD Center and Kurt Phillips of NIST for their valuable assistance in performing the fabrication, PMESH analysis and measurements of the wafer and test structures.

References

1. R. B. Marks, "A multi-line method of Network Analyzer Calibration," IEEE Trans. Microwave Theory and Tech., vol. 39, pp. 1205-1215, 1991.
2. D. F. Williams and R. B. Marks, "Transmission Line Capacitance Measurement," IEEE Microwave and Guided Wave Letters, vol. 1, No. 9, pp.243-245, September 1991.
3. R. B. Marks and D. F. Williams, "Characteristic Impedance Determination Using Propagation Constant Measurement," IEEE Microwave and Guided Wave Letters, June 1991.
4. D. F. Williams and R. B. Marks, "The Interpretation and Use of S- Parameters in Lossy Lines," 36th Automatic RF Techniques Group Conference Proceeding, Monterey CA, Nov. 1990.
5. Libra Versions 2.1 & 3.0, EEsof Inc., Westlake Village, CA. Such identification does not imply a recommendation or endorsement by NIST nor does it imply that the identified items are necessarily the best available for the purpose.
6. Jansen Microwave, Ratingen, Germany.
7. R. H. Jansen, "Recent Advances in the Full-Wave Analysis of Transmission Lines for Application in MIC and MMIC Design," Int. Microwave Symposium Proceeding, Paper M 111, Brazil, Argentina, 1987.
8. D. I. Wu, D. C. Chang, B. L. Brim, "Accurate Numerical Modeling of Microstrip Junctions and Discontinuities," Int. Journal of Microwave and Millimeter-Wave Computer-Aided Engineering, Vol. 1, pp. 48-58, January 1991.

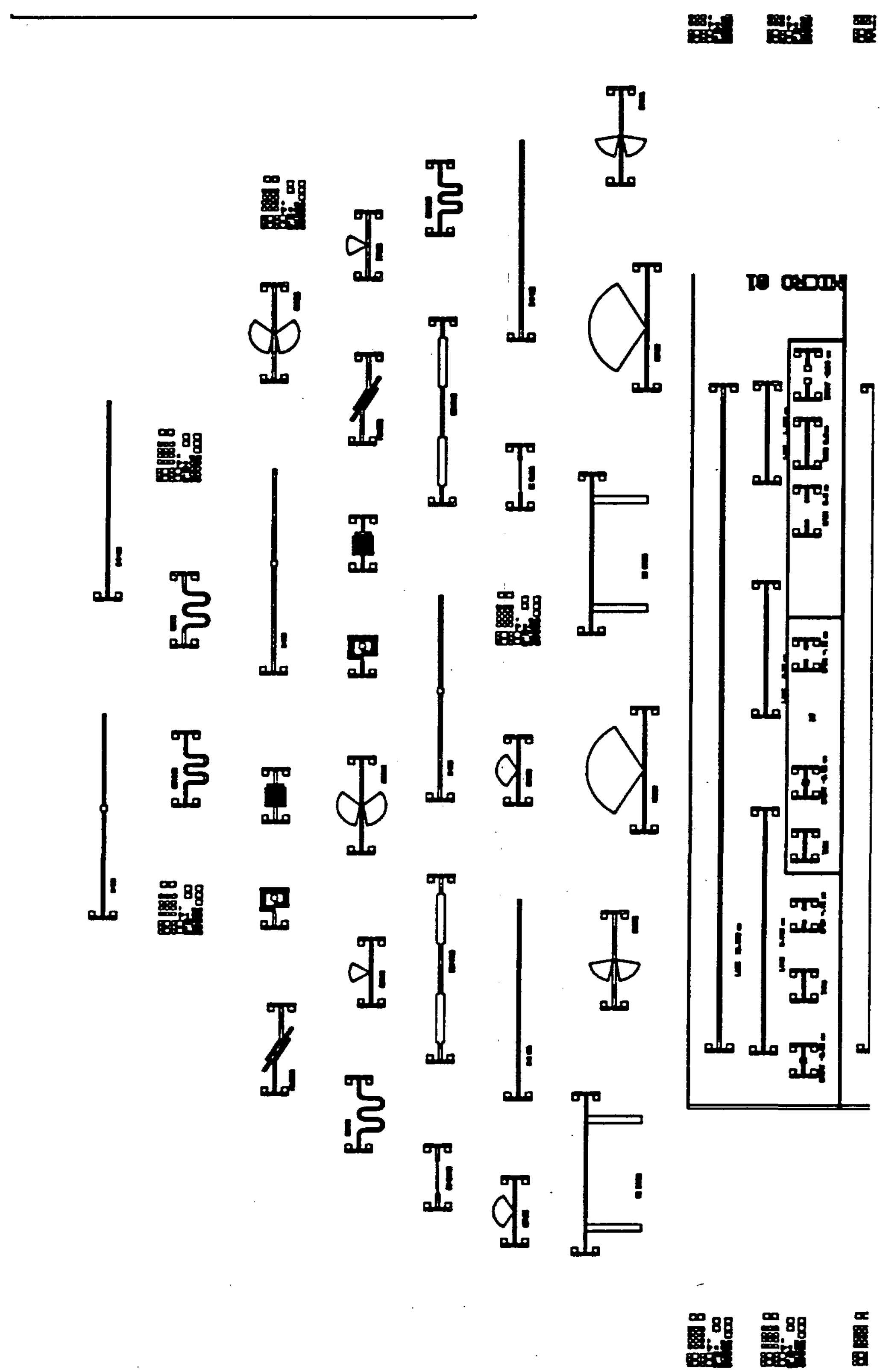

FIGURE 1. Wafer Layout (top half)

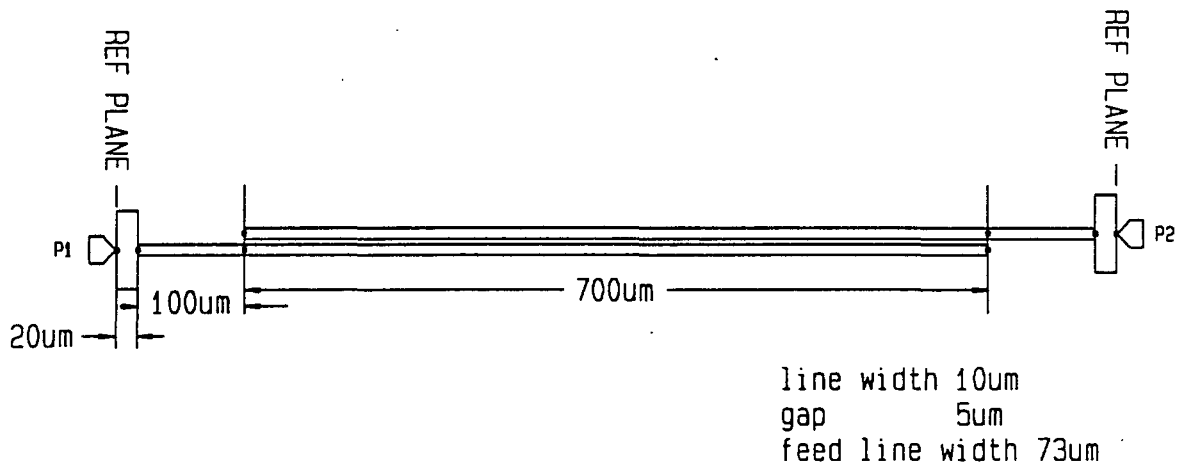

FIGURE 2. Layout of 35 GHz DC Block

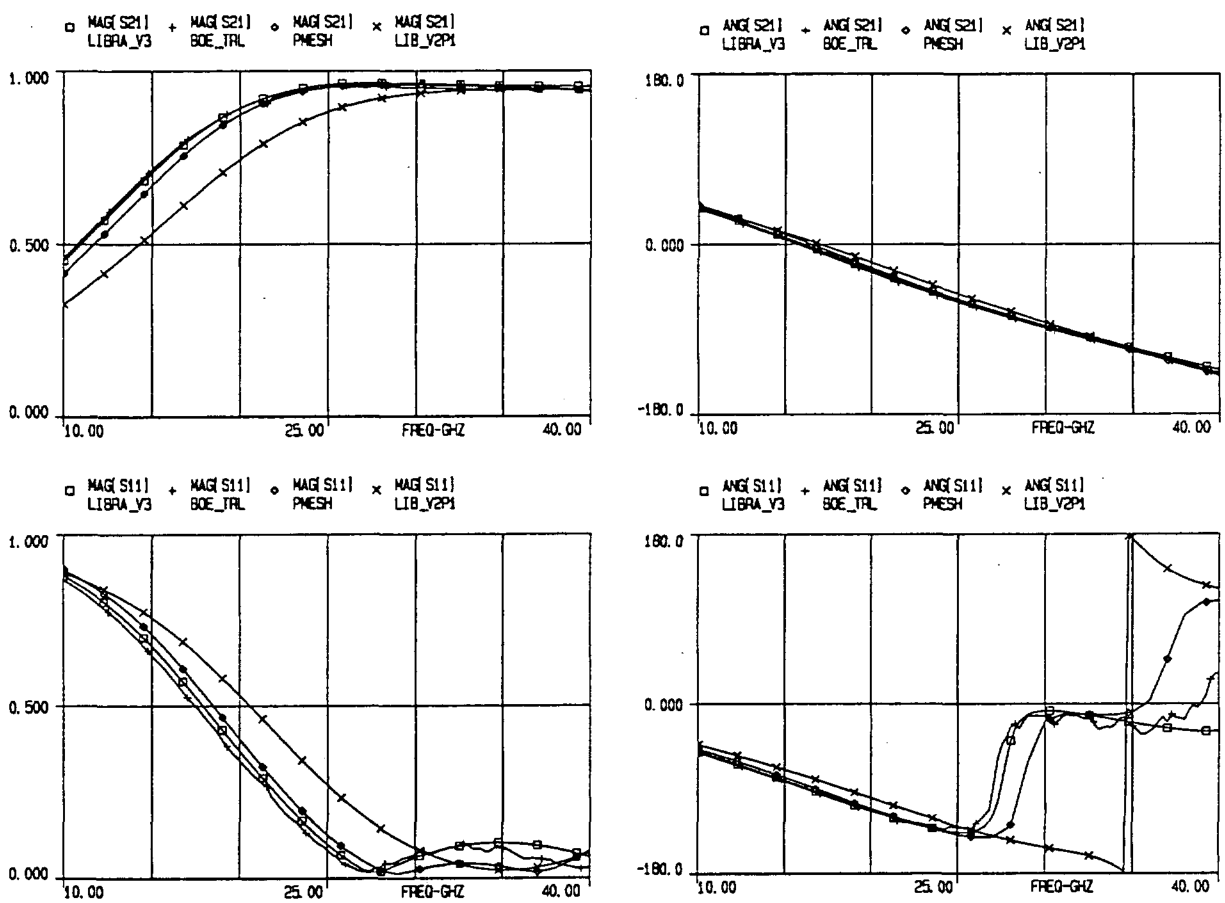

FIGURE 3. Measured and Modeled S Parameters of the 35 GHz DC Block

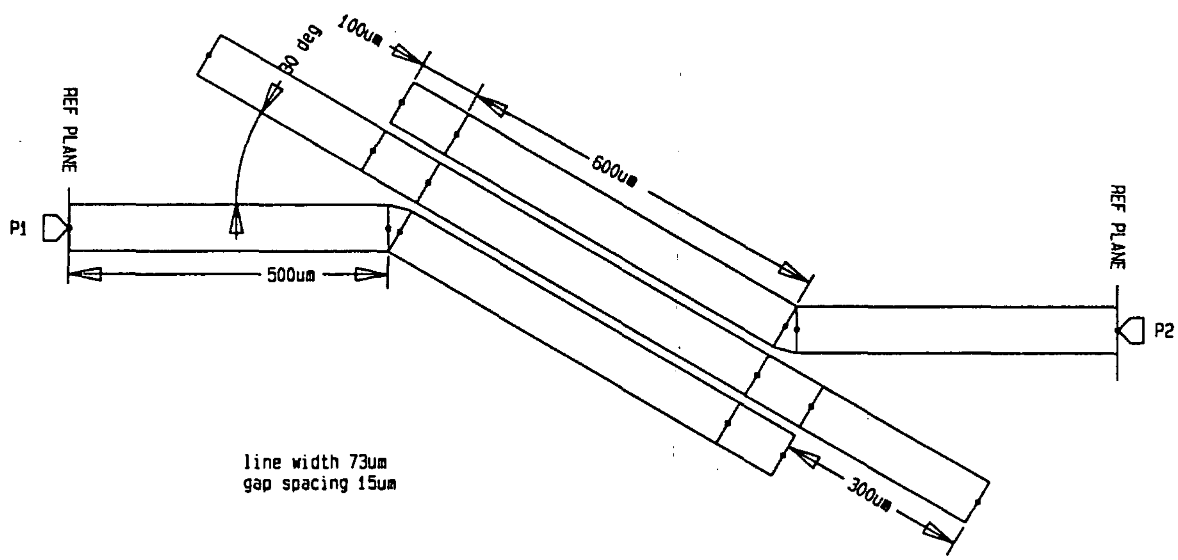

FIGURE 4. Layout of the 35 GHz Band Pass Filter

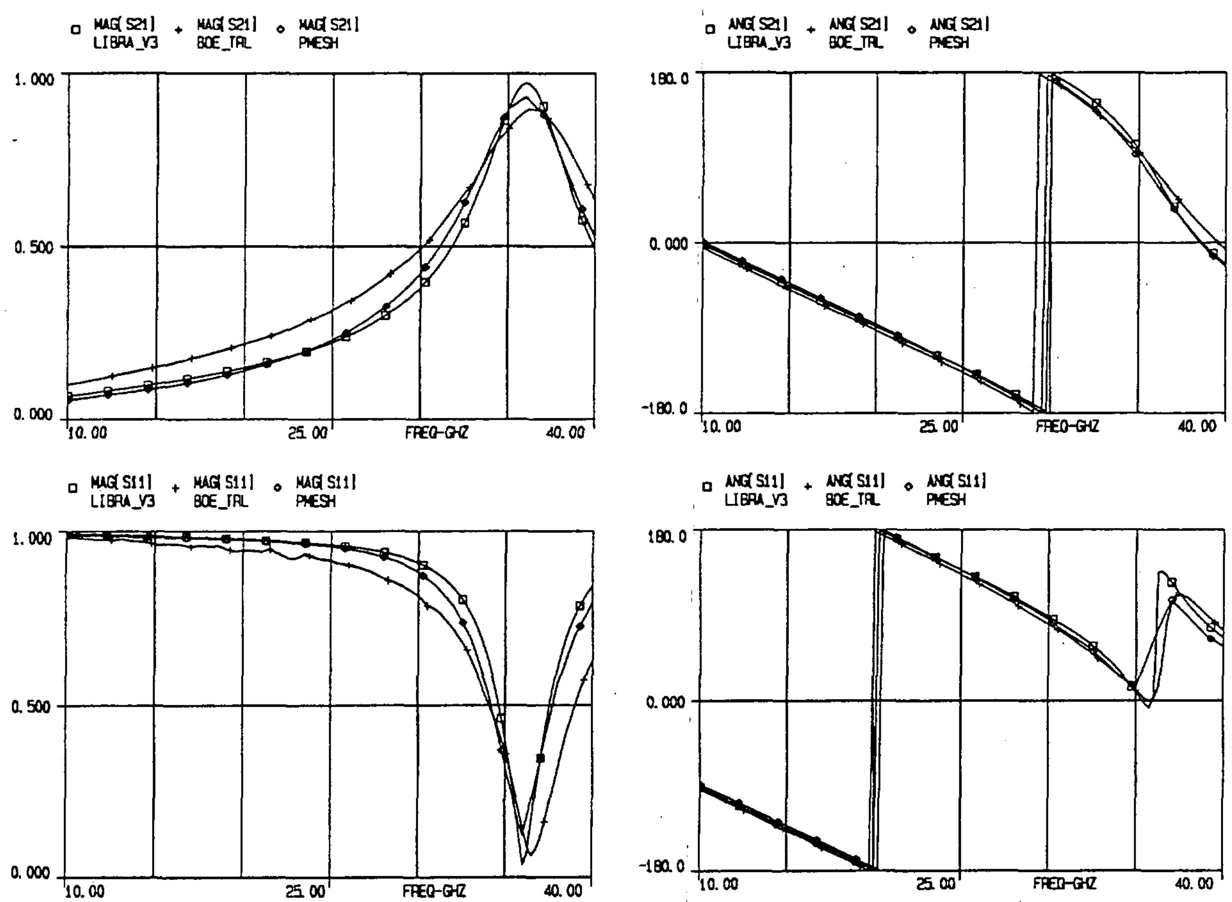

FIGURE 5. Measured and Modeled S-parameters of the 35 GHz Band Pass Filter

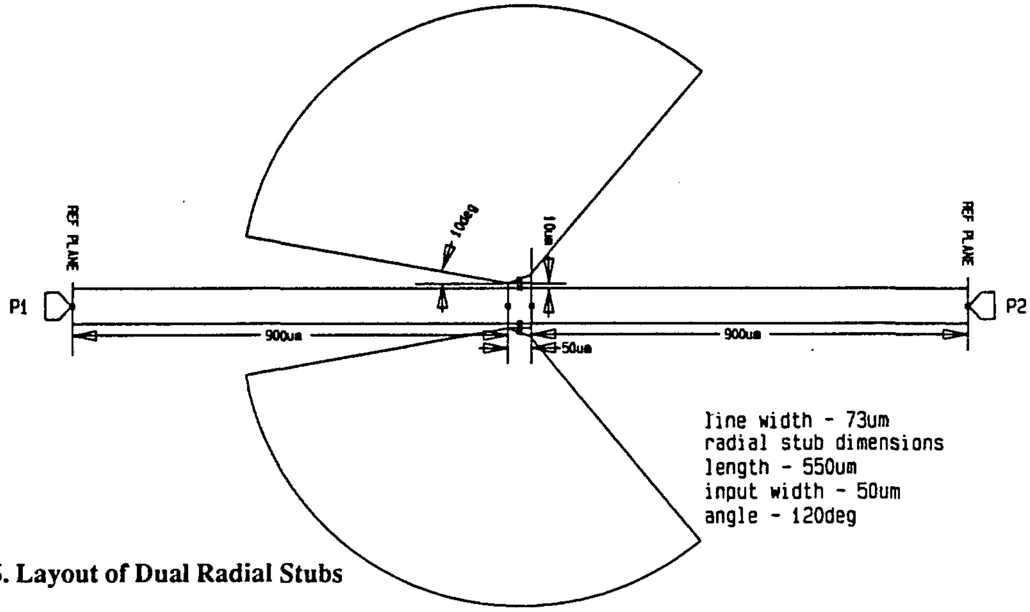

FIGURE 6. Layout of Dual Radial Stubs

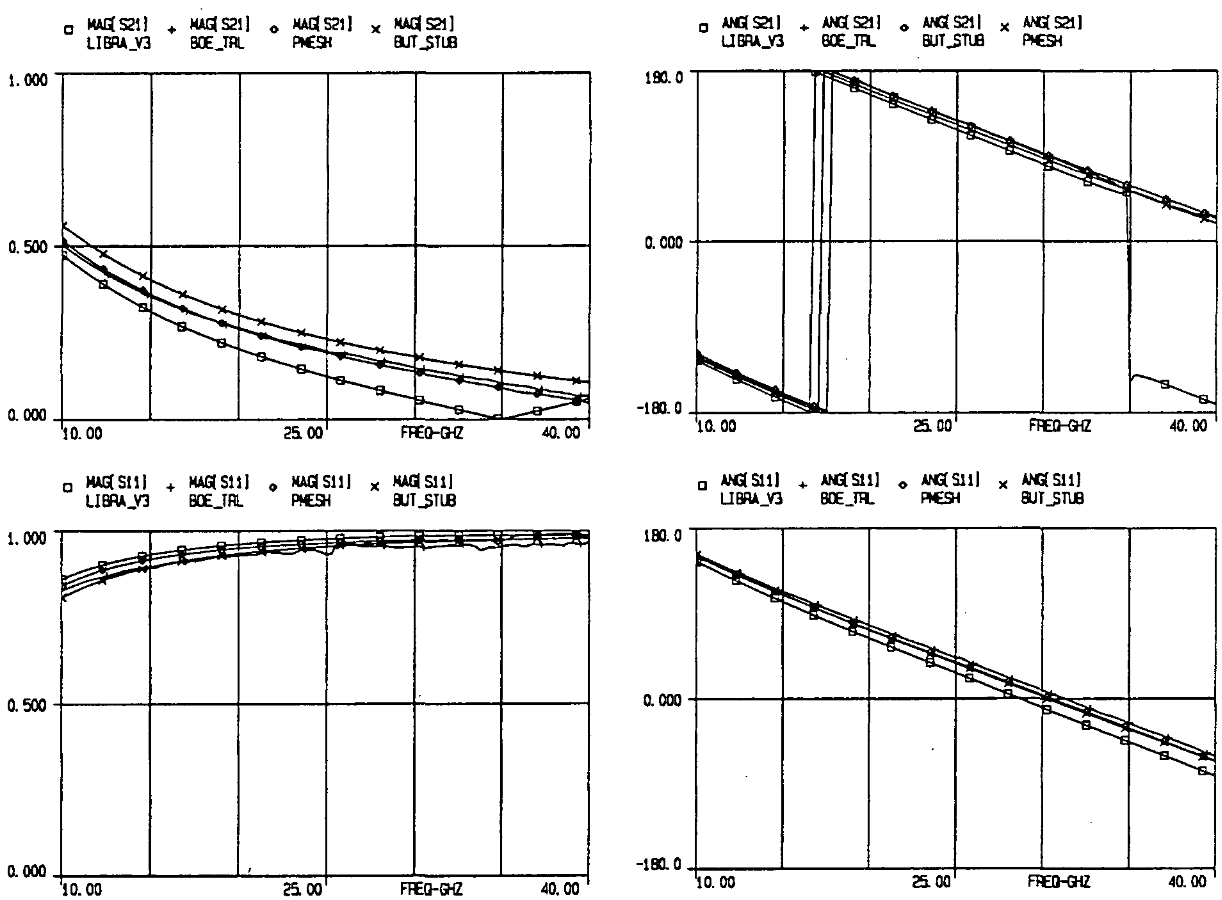

FIGURE 7. Measured and Modeled S Parameters of the Dual Radial Stub

FIGURE 8. PMESH Gridding of the DC Block

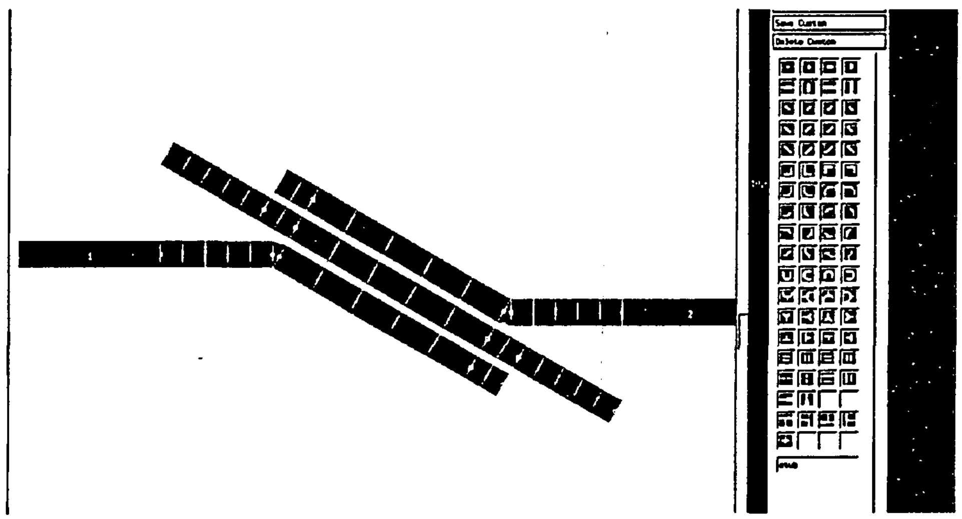

FIGURE 9. PMESH Gridding of the 35 GHz Band Pass Filter

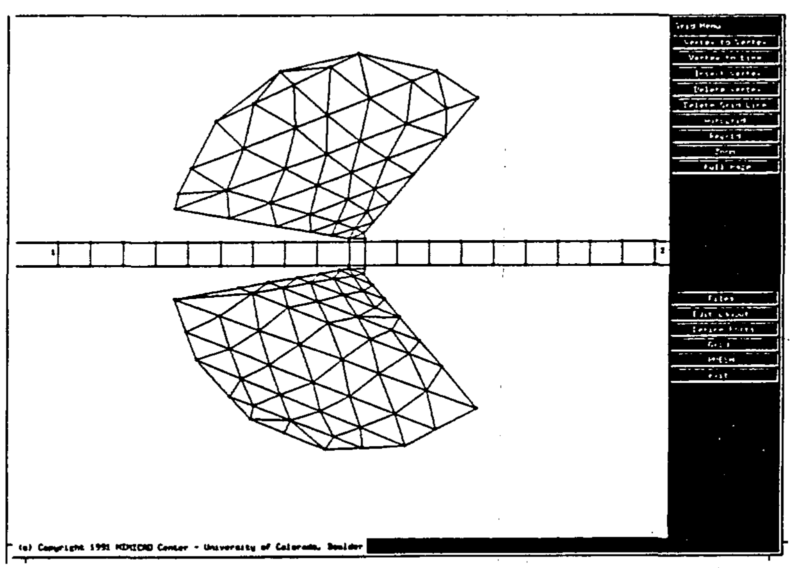

FIGURE 10. PMESH Gridding of the Dual Radial Stub