University of Missouri-Rolla
Electromagnetic Compatibility Laboratory

Title: Preliminary Experimental Results for NCMS Embedded Capacitance Project

Report Number: TR99-8-029

Author: Juan Chen

Date: September, 1999

Experimental Results for NCMS Embedded Capacitance Project

Prepared for: Electromagnetic Compatibility Laboratory

Prepared by: Juan Chen
Electromagnetic Compatibility Laboratory
University of Missouri-Rolla

September, 1999

ABSTRACT

“Experimental Results for NCMS Embedded Capacitance Project”

by Juan Chen

This report presents experimental setups and measurement results of NCMS embedded capacitance project. This project is still ongoing and the results presented here are for the boards supplied so far -- unpopulated FR-4 boards, Emcap boards, and C-ply boards. Board capacitance and input impedance measurements were made. The results show that boards with embedded capacitance can provide a larger board capacitance and a lower and smoother input impedance.

Keywords: inter-plane capacitance (board capacitance), input impedance, FR-4, Emcap, C-ply, 3M, Merix, Litton

TABLE OF CONTENTS

Page

SECTIONS

APPENDICES

LIST OF ILLUSTRATIONS

LIST OF TABLES

Table Page

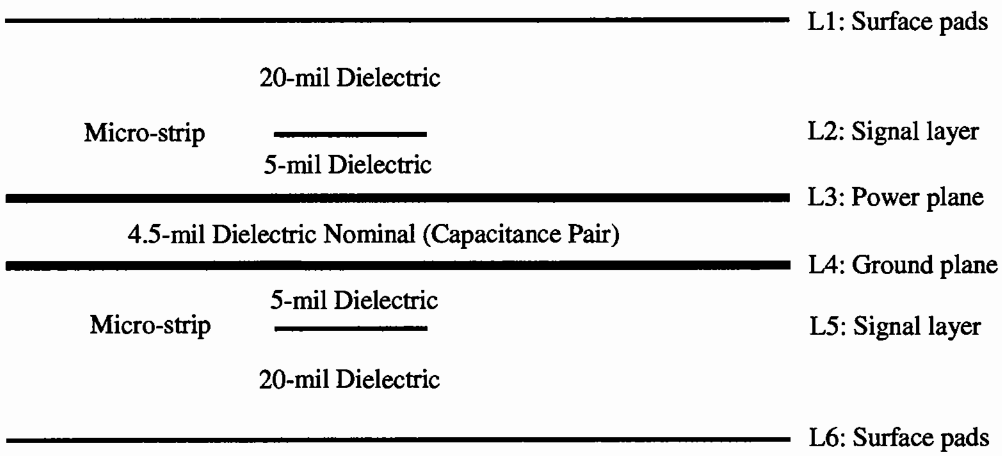
1. Test Boards

Test boards were label as follows,

$TV1-X-Y$

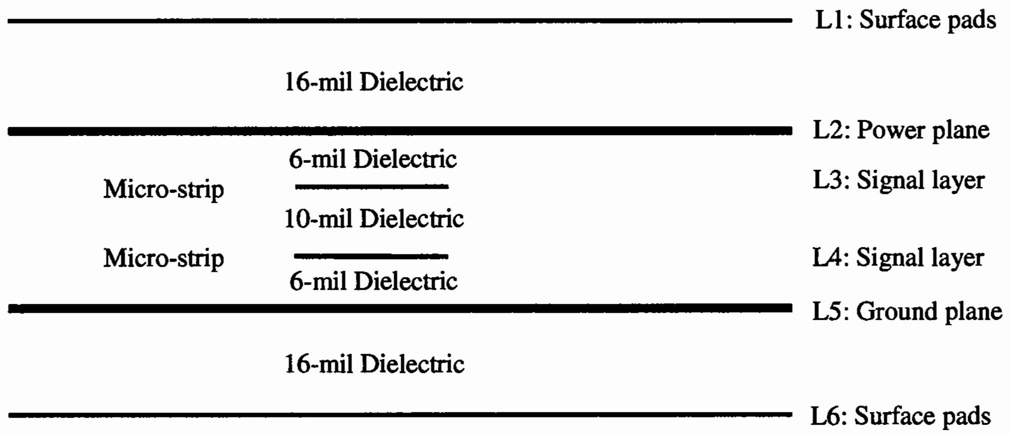
where TV1 means version 1 boards, X indicates the board stack-up, Y indicates the board layout.

Three nominal stack-ups were used as illustrated in Figures 2.1, 2.2, and 2.3. TV1-1-Y boards had six layers with power and ground planes on Layers 3 and 4, respectively. The nominal spacing between these two planes was 4.5 mils. TV1-2-Y boards also had six layers, but the power and ground planes were on Layers 2 and 5, respectively. The nominal spacing between power and ground planes was 22 mils. TV1-3-Y boards consisted of seven layers with a power plane on Layer 2 and two ground planes on Layers 3 and 6. TV1-2-Y boards were made with FR-4 material. TV1-3-Y boards employed embedded capacitance. TV1-1-Y boards were made with both FR-4 and embedded capacitance. The actual stack-up of boards from various fabricators may be different from the nominal stack-up.



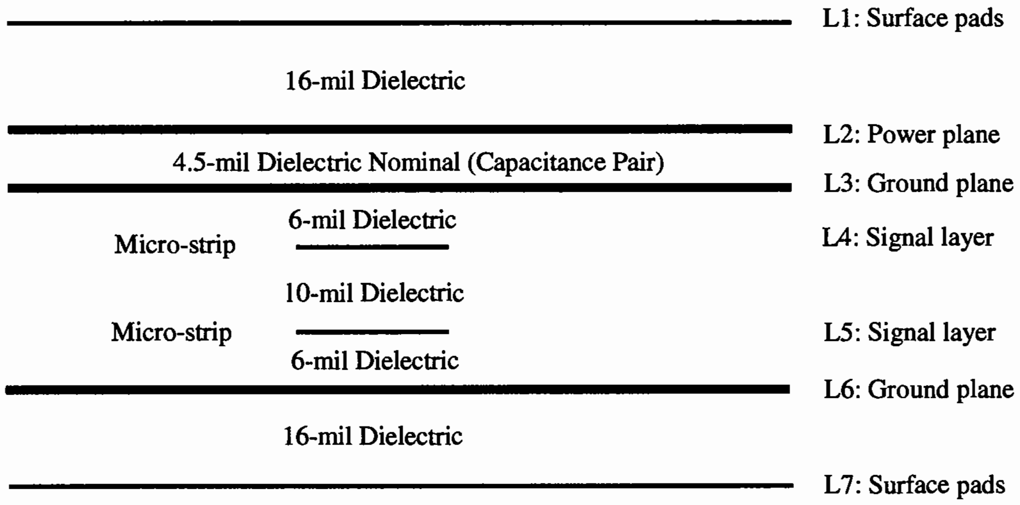
Six-layer board with power and ground planes on Layers 3 and 4.
Thicker line indicates heavier copper.

Figure 1.1. TV1-1-Y Board Stack-Up



Six-layer board with power and ground planes on Layers 2 and 5.
Thicker line indicates heavier copper.

Figure 1.2. TV1-2-Y Board Stack-Up



Six-layer board with power and ground planes on Layers 2, 3, and 6.
Thicker line indicates heavier copper.

Figure 1.3. TV1-3-Y Board Stack-Up

For each stack-up, three board sizes were used, corresponding to three board layouts. The TV1-X-1 board (1-up board) consisted of 8 clock drivers, an oscillator and many resistors and capacitors laid out on a 3-inch by 2-inch board. The TV1-X-4 board (4-up board) contained four copies of the 1-up board on a 6.1-inch by 4.1-inch board. The TV1-X-12 board (12-up board) consisted of 12 copies of the 1-up board on a 9.3-inch by 8.6-inch board. The size of a 12-up board was approximately equal to the size of a personal computer motherboard. The placement of the primary components for each layout is shown in Figures 1.4, 1.5, and 1.6.

To make input impedance measurements, five-pin SMA jacks were soldered on the component side of the board connecting power and ground planes. As will be shown in Section 4.2, the interconnection inductance will be smaller if the connector is mounted on the component side. For TV1-X-1 and TV1-X-4 boards, one jack was attached to each board at location J1 as shown in Figure 1.4 and Figure 1.5. For TV1-X-12 boards, four jacks were mounted to each board at locations J1, J2, J3, and J4 as shown in Figure 1.6.

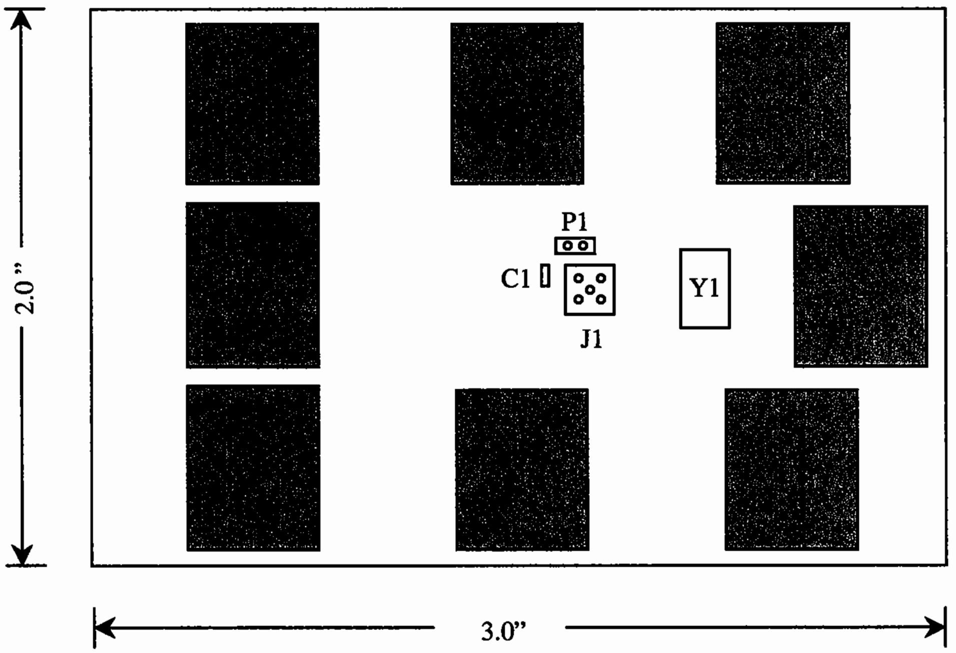


Figure 1.4. TV1-X-1 Board Layout

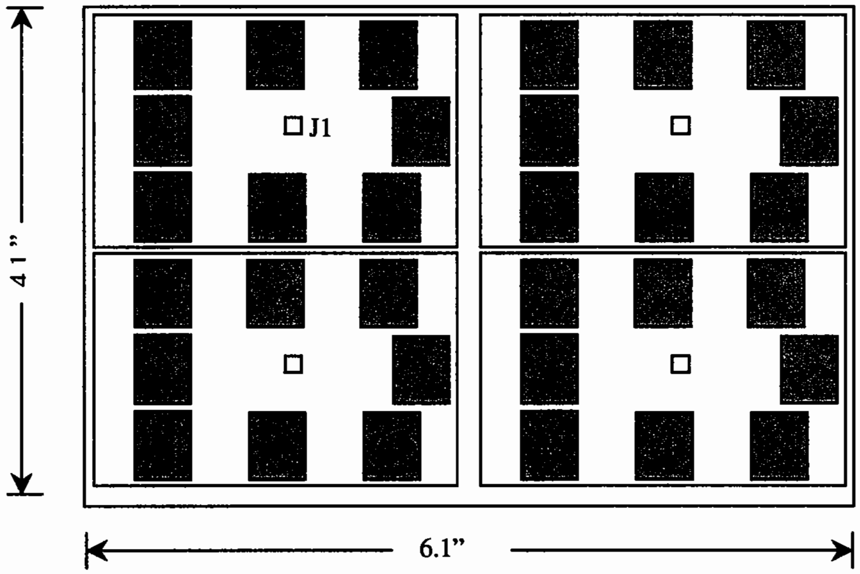


Figure 1.5. TV1-X-4 Board Layout

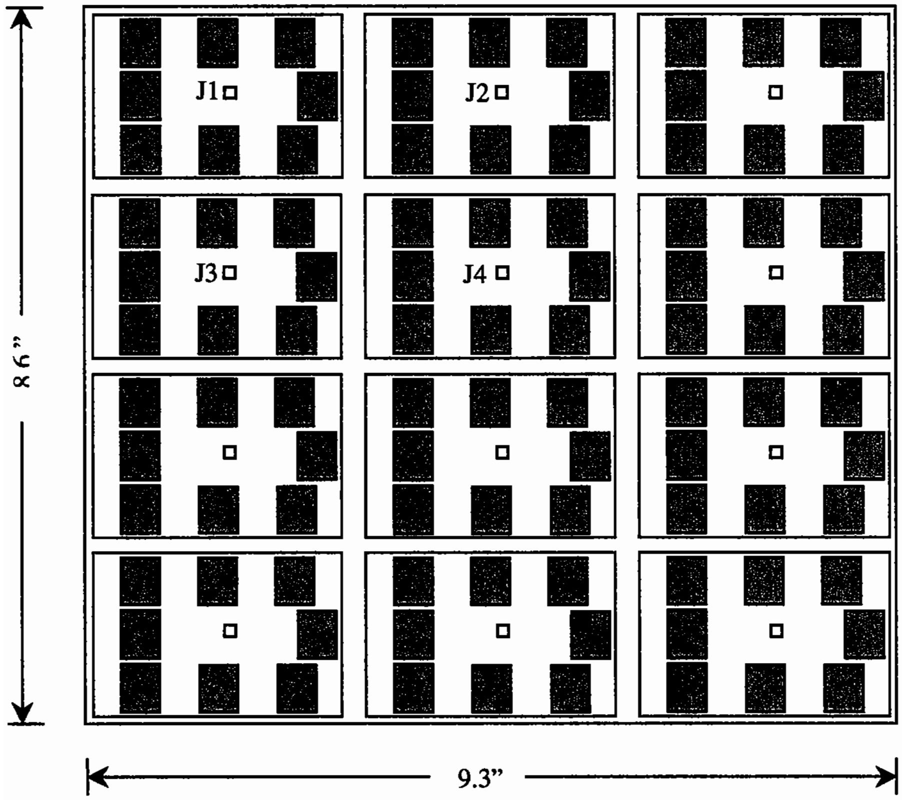


Figure 1.6. TV1-X-12 Board Layout

2. Experimental Setup

The inter-plane capacitance and input impedance of the power bus structure are measured to evaluate the performance of boards with FR-4 or embedded capacitance.

An HP4263B LCR meter with HP16089B Kelvin clip leads was employed to measure the inter-plane capacitance of the test boards. The two clip leads were connected to the two bonding pads of a decoupling capacitor at location C1. Calibration was performed using a model with open and short corrections. Inter-plane capacitance was measured at 1.0 KHz using the parallel capacitance measurement model. Appendix A describes the measurement procedure in detail. Figure 2.1 shows an inter-plane capacitance measurement being made using the LCR meter.

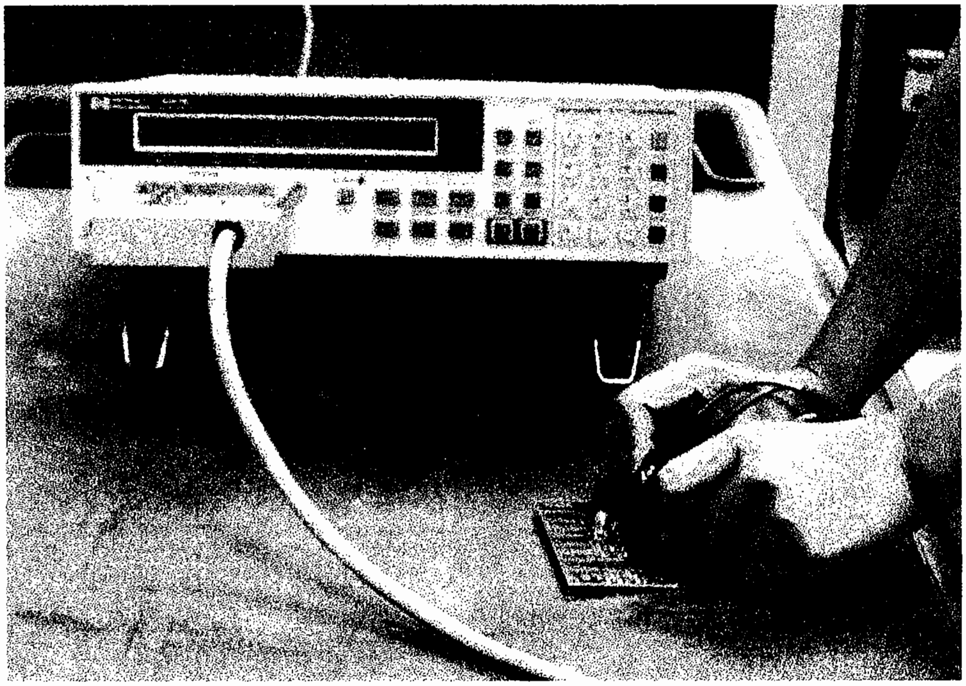


Figure 2.1. Measuring Inter-Plane Capacitance Using HP4263B LCR Meter

An HP8753D network analyzer was used to measure the input impedance of the power bus. The network analyzer was connected to the test boards through a low-loss precision cable and a SMA jack. A S11 one-port error correction model using open, short and matched loads was used to calibrate the network analyzer. Port extension was performed to move the measurement plane to the coax feed terminals. $|S_{11}|$, the ratio of reflected signal to the incident signal at Port 1, was measured and converted to the input impedance data using a built-in function in the network analyzer. The measured frequency range was 30 KHz – 5.0 GHz for TV1-X-1 boards and 30 KHz – 3.0 GHz for TV1-X-4 and TV1-X-12 boards. Appendix B describes the measurement procedure in detail. Figure 2.2 shows an input impedance measurement being made using the network analyzer.

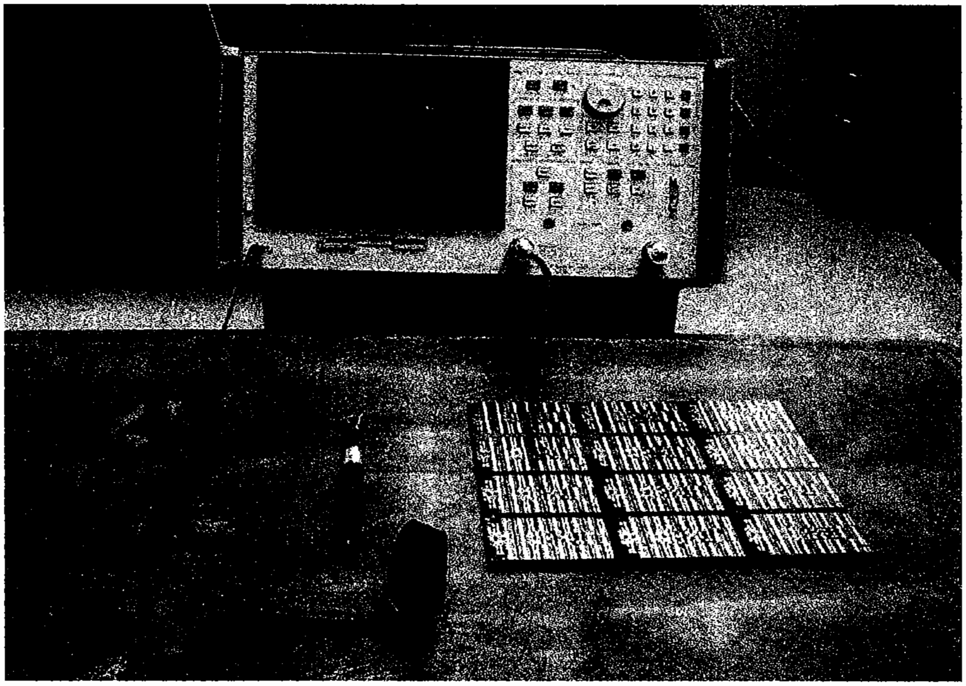


Figure 2.2. Measuring Input Impedance Using HP8753D Network Analyzer

A shorted connector as shown in Figure 2.3 was built especially for the port extension. To make this connector, the four outside conductors were removed. Then the center conductor and the shield of the connector were connected by a patch of copper tape and soldered together.

Figure 2.3. Close-up of the Shorted Connector Used in Port Extension

3. Measurements of 3M Boards

3.1. FR-4 Boards

The FR-4 boards were measured and used as a reference for comparison with the embedded capacitance boards. Two 3M FR-4 boards were provided so far as shown in Table 3.1. They were identical.

Table 3.1. 3M FR-4 Boards ($\varepsilon_r^{(1)}$=4.7, $d^{(2)}$=22mils)

Board #	Stack-up	Series #	$C_{B\ meas}^{(3)}$ (nF)	$C_{B\ cal}^{(4)}$ (nF)
1	TV1-2-1	3M-1	0.32	0.288
2	TV1-2-1	3M-2	0.32	0.288

(1) relative permittivity
(2) spacing between power and return plane
(3) measured board capacitance
(4) calculated board capacitance

The measured input impedance of Board 1 is shown in Figure 3.1. The resonant frequencies are labeled in the figure. In Figure 3.2, the input impedance of the same board is plotted as resistance versus reactance. The peak frequencies in Figure 3.1 and Figure 3.2 are slightly different.

Figure 3.3 plots the input impedance of Board 2.

To evaluate the manufacturing quality and consistency of the test boards, input impedance of Boards 1 and 2 are compared as in Figure 3.4.

To investigate the effect of discrete decoupling capacitors on FR-4 boards, 100-nF, 1-nF, and 22-pF capacitors were added alternately at location C1 on Board 1 and the input impedance was measured. The results are shown in Figure 3.5.

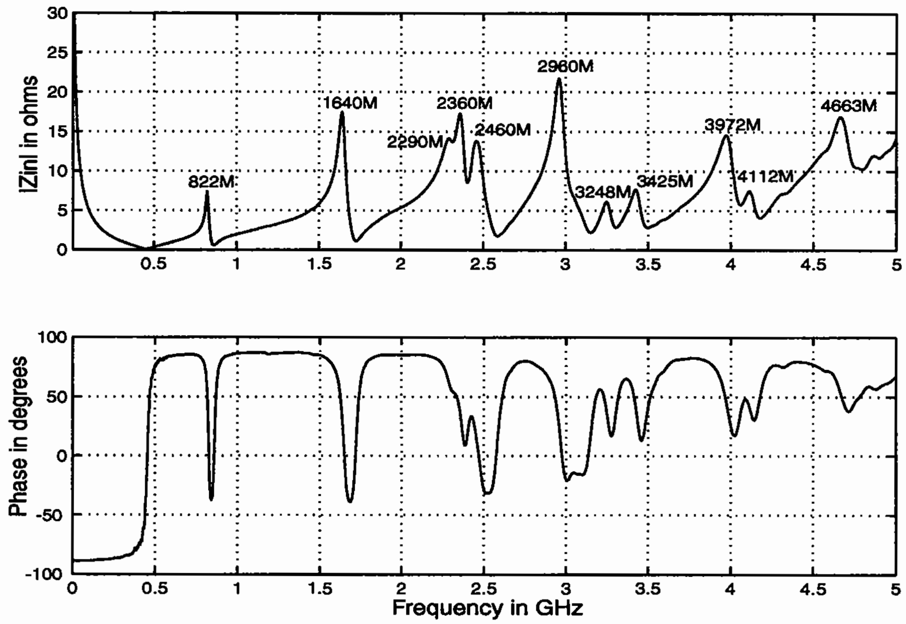


Figure 3.1. Input Impedance of Board 1

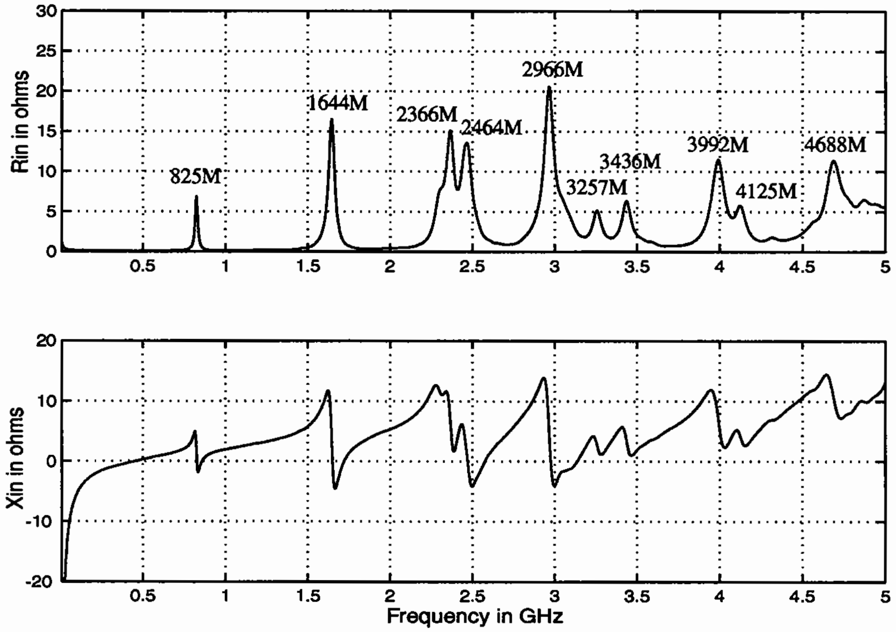


Figure 3.2. Input Impedance of Board 1 Plotted as Resistance and Reactance

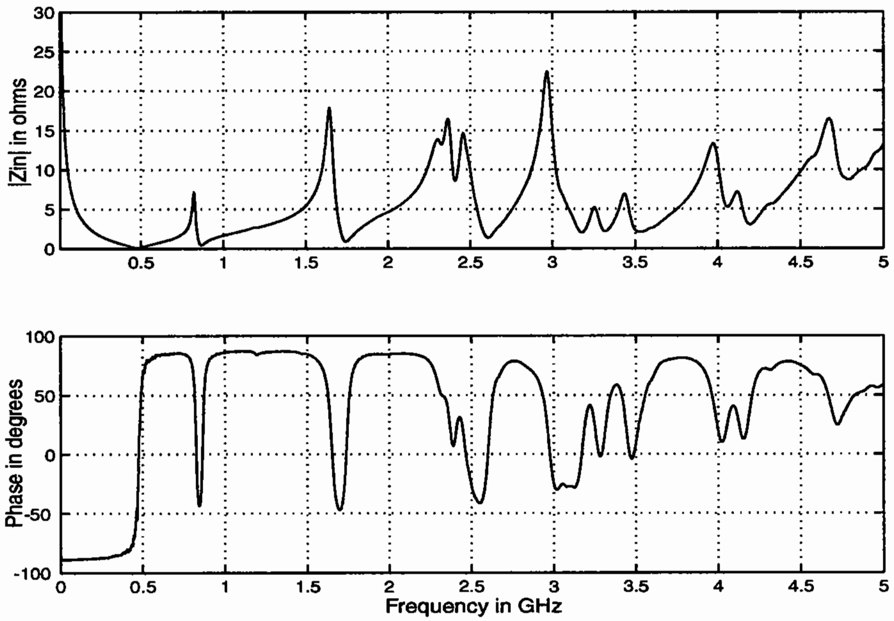


Figure 3.3. Input Impedance of Board 2

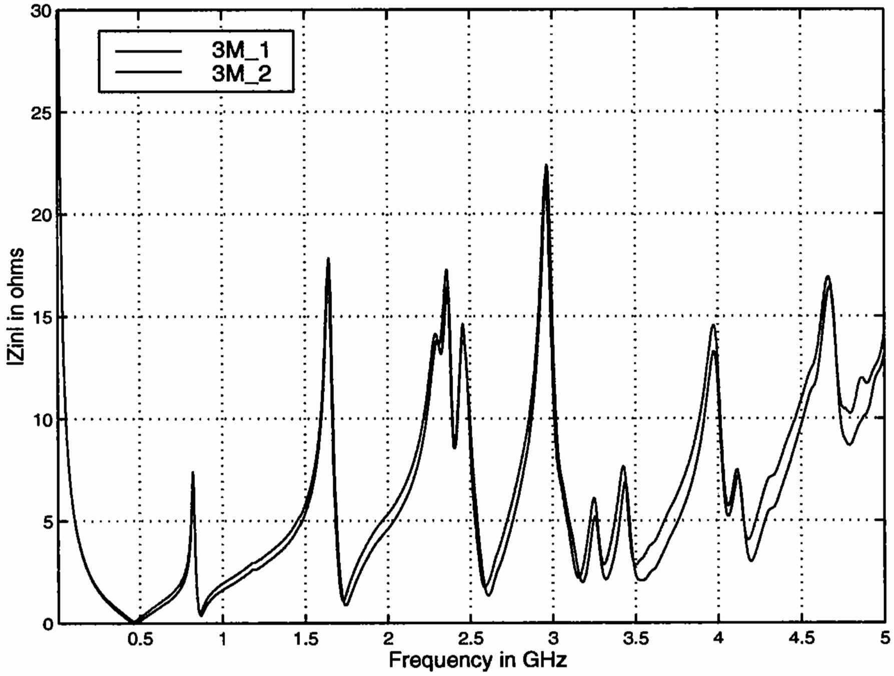


Figure 3.4. Impedance Comparison of Boards 1 and 2

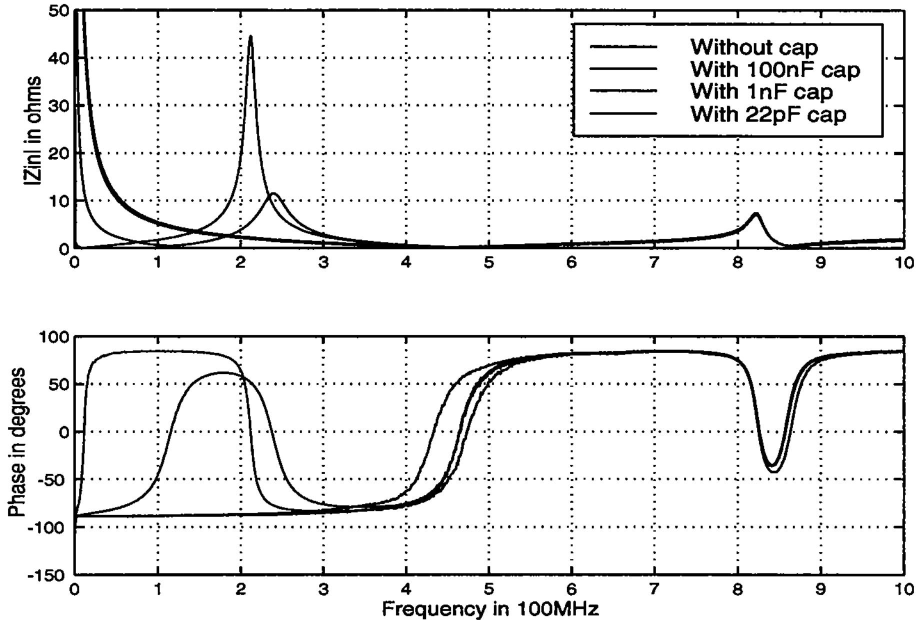


Figure 3.5. Input Impedance of Board 1 With or Without Capacitor

3.2. Boards With C-Ply Material

C-ply material has a relative permittivity of about 300. Two boards using C-ply material have been provided so far as shown in Table 3.2. Board 3 was a 6-layer board and Board 4 was a 7-layer board.

Figure 3.6 compares the input impedance of Boards 3 and 4.

Table 3.2. 3M C-ply Boards (ε_r = ?, d <= 0.5mil)

Board #	Stack-up	Series #	$C_{B\,meas}$ (nF)	$C_{B\,cal}$ (nF)
3	TV1-1-1	3M-1-1	107	--
4	TV1-3-1	3M-5	111	--

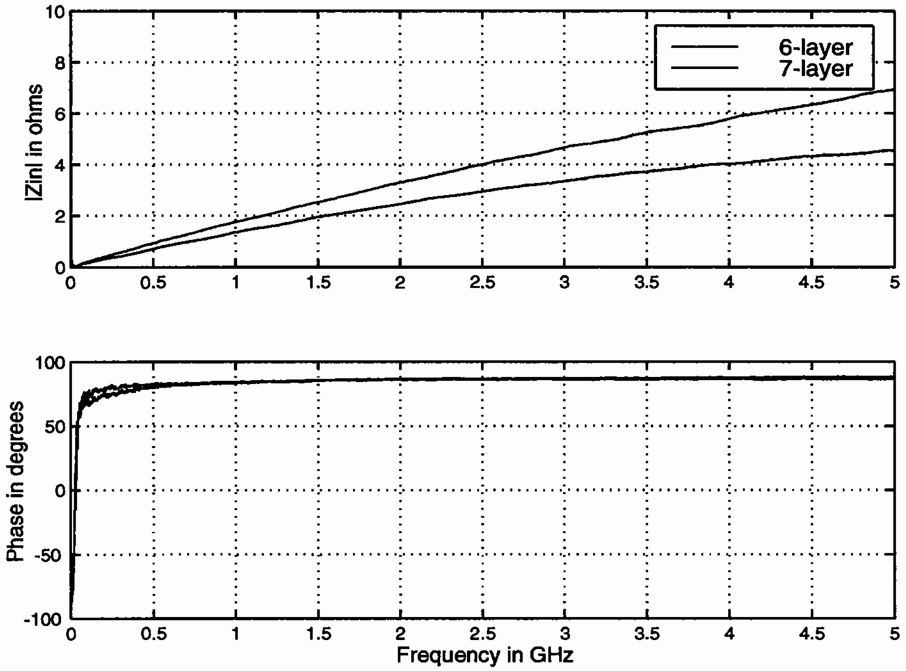


Figure 3.6. Input Impedance of Boards 3 and 4 With C-Ply Material

The network analyzer was used to measure input impedance instead of impedance analyzer because its frequency range is large (up to 6.0 GHz). An experiment was made using the HP 4291A RF impedance/material analyzer as shown in Figure 3.7. The upper frequency limit for the impedance analyzer is only 1.8 GHz. Compared with Figure 3.6, the impedance responses are in good agreement. Appendix C describes the test procedure of measuring input impedance using impedance analyzer in detail.

Figure 3.8 shows the impedance below the first series resonance. It can be used to evaluate the board capacitance at low frequency range.

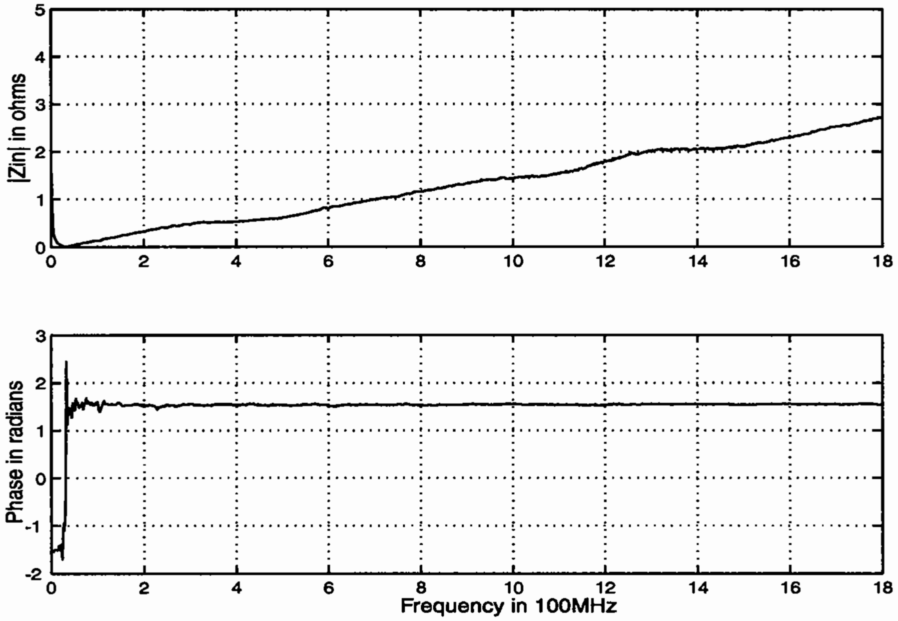


Figure 3.7. Input Impedance of Board 3 Using HP4291A Impedance Analyzer

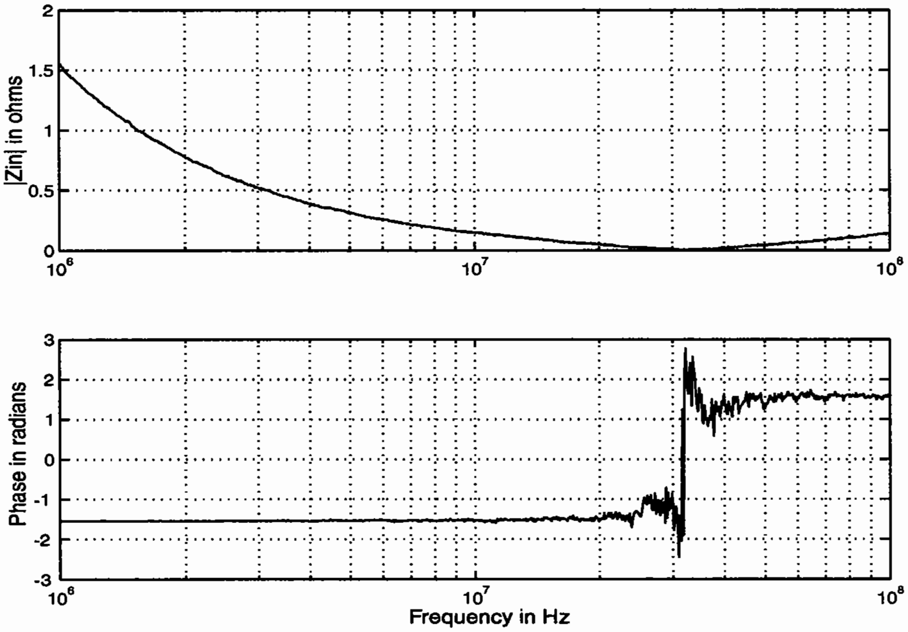


Figure 3.8. Input Impedance of Board 3 Before the Series Resonance

4. Measurements of Merix Boards

4.1. FR-4 Boards

Two FR-4 boards were provided as shown in Table 4.1. They are identical.

The measured input impedance of Board 1 is shown in Figure 4.1. The resonant frequencies are labeled in the figure. The impedance of Board 2 is shown in Figure 4.2. The impedance of Boards 1 and 2 are compared in Figure 4.3.

Table 4.1. Merix FR-4 Boards ($\varepsilon_r = 4.6$, d = 20.5 mils)

Board #	Stack-up	Series #	$C_{B\,meas}$ (nF)	$C_{B\,cal}$ (nF)
1	TV1-2-1	Merix/FR406	0.40	0.30
2	TV1-2-1	Merix/406	0.40	0.30

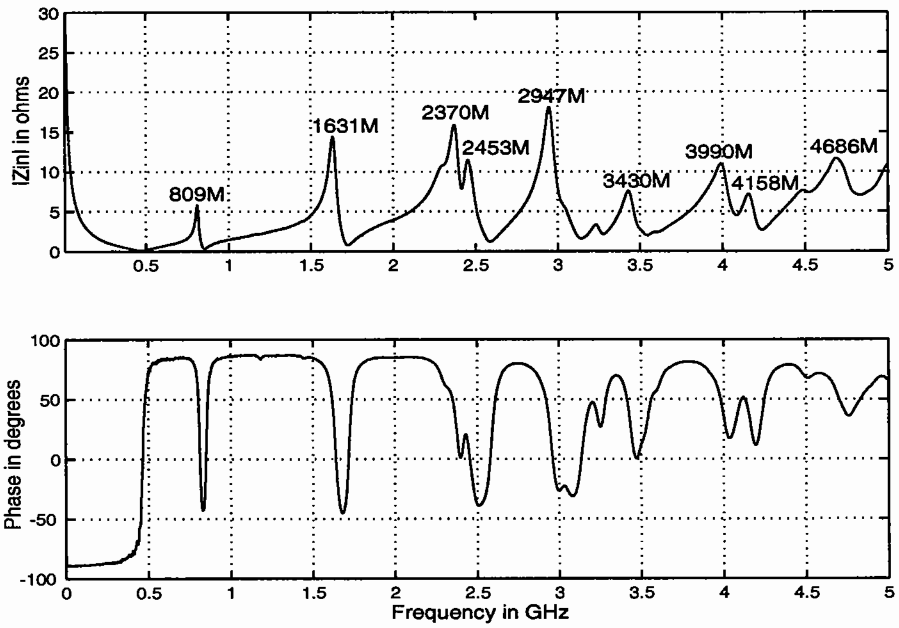


Figure 4.1. Input Impedance of Board 1

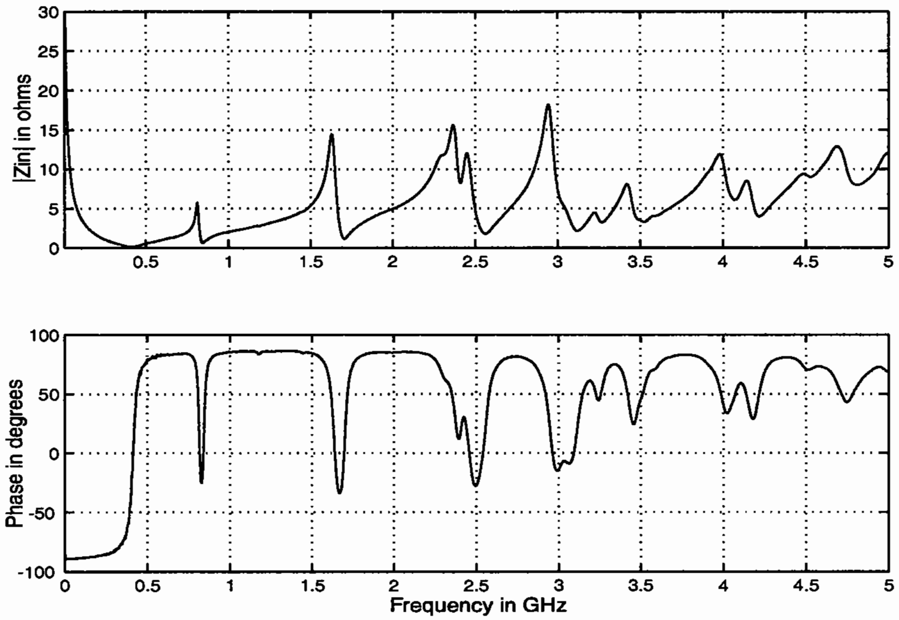


Figure 4.2. Input Impedance of Board 2

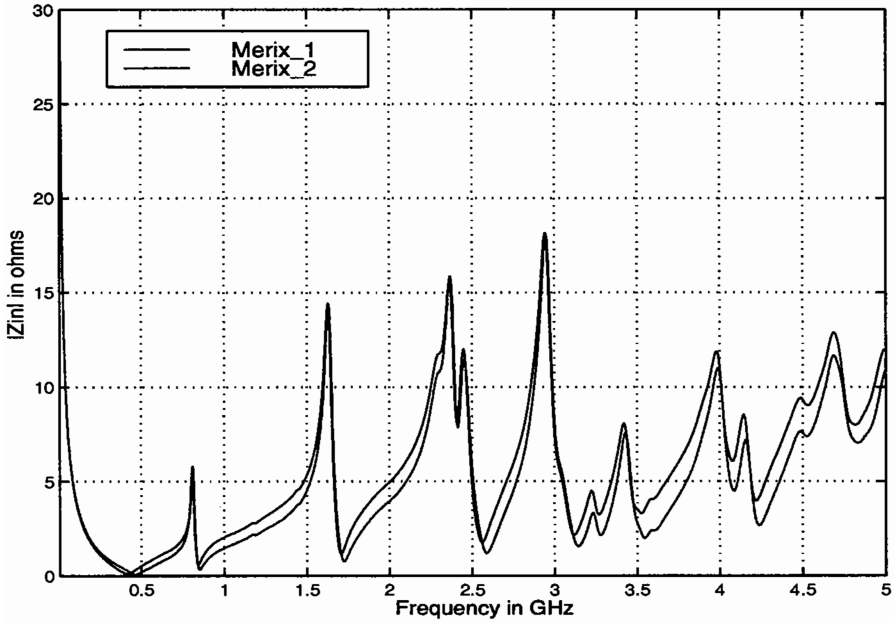


Figure 4.3. Impedance Comparison of Boards 1 and 2

In addition, Board 1 from 3M and Board 1 from Merix are compared in Figure 4.4. From the figure, boards made by different fabricators have a bigger difference than boards made by the same fabricator.

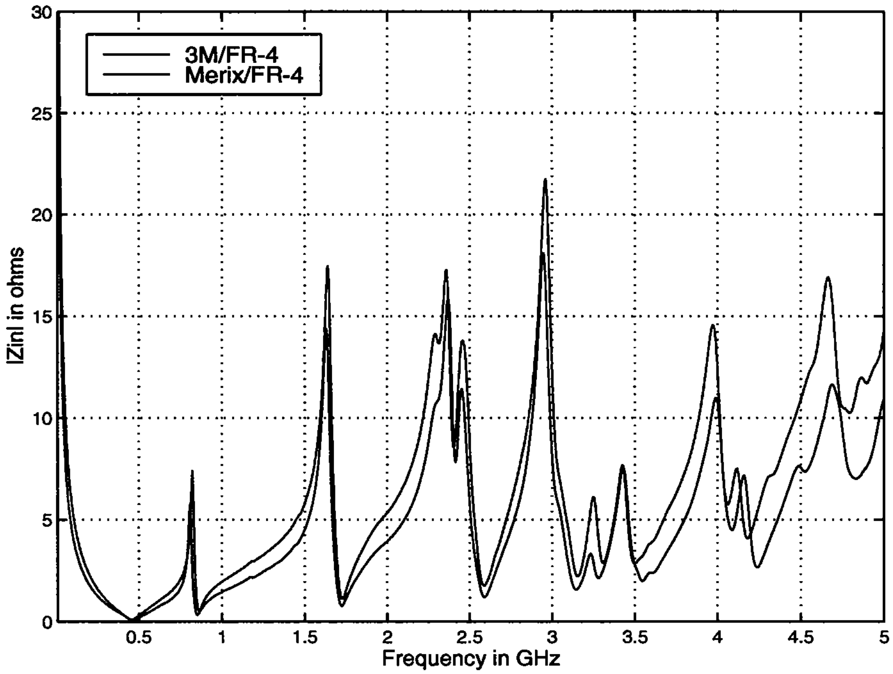


Figure 4.4. Comparison of 3M and Merix TV1-2-1 FR-4 Boards

4.2. Boards With Emcap Material

Fourteen Emcap boards were provided by Merix as shown in Table 4.2. Among these boards, Boards 3, 4, 5, and 6 were identical; Boards 7 and 8 were identical; Boards 9 and 10 were identical; Boards 11 and 12 were identical; Boards 13 and 14 were identical; Board 15 and 16 were identical.

Table 4.2. Merix Emcap Boards ($\varepsilon_r = 28$, d = 3.9 mils)

Board #	Stack-up	Series #	$C_{B\,meas}$ (nF)	$C_{B\,cal}$ (nF)
3	TV1-1-1	3	11.2	9.7
4	TV1-1-1	3	--	9.7
5	TV1-1-1	4	11.6	9.7
6	TV1-1-1	4	--	9.7
7	TV1-1-4	1	48.8	40.4
8	TV1-1-4	4	--	40.4
9	TV1-1-12	3	150.8	129.1
10	TV1-1-12	4	--	129.1
11	TV1-3-1	9916A (1)	11.0	9.7
12	TV1-3-1	9916A (3)	--	9.7
13	TV1-3-4	9916A (1)	48.1	40.4
14	TV1-3-4	9916A (3)	--	40.4
15	TV1-3-12	9916A (1)	149.4	129.1
16	TV1-3-12	9916A (3)	--	129.1

Figure 4.5 compares the input impedance of Boards 1 (FR-4 board) and 3 (Emcap board). From the figure, the Emcap board exhibits a big improvement in the input impedance response. Figure 4.6 shows a log plot of the impedance curve of Board 3.

Figure 4.7 shows the impedance of Board 5, which was identical to Board 3.

The impedance amplitudes of Boards 3 and 5 are compared in Figure 4.8. The two curves are very close to each other.

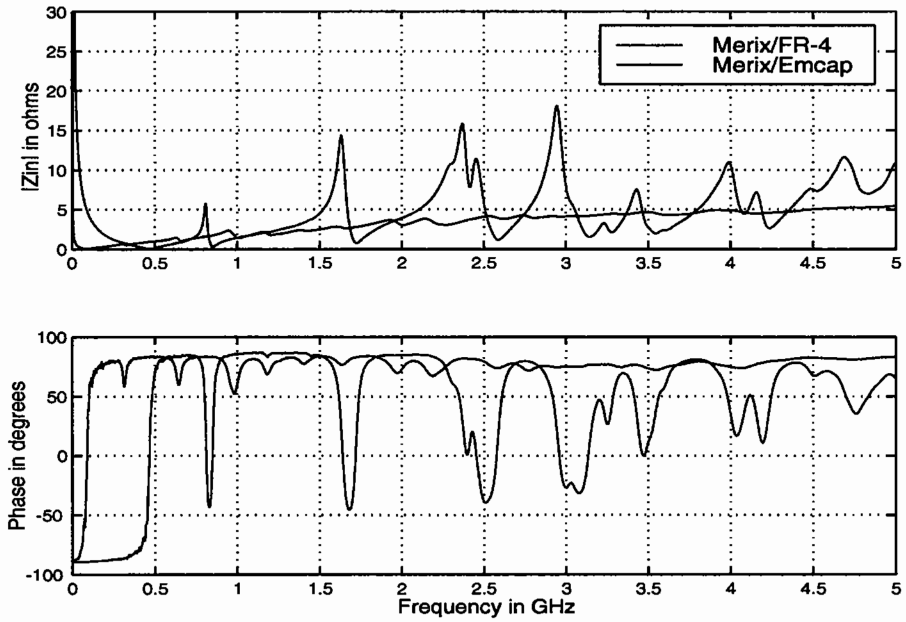


Figure 4.5. Input Impedance of Board 1 and 3

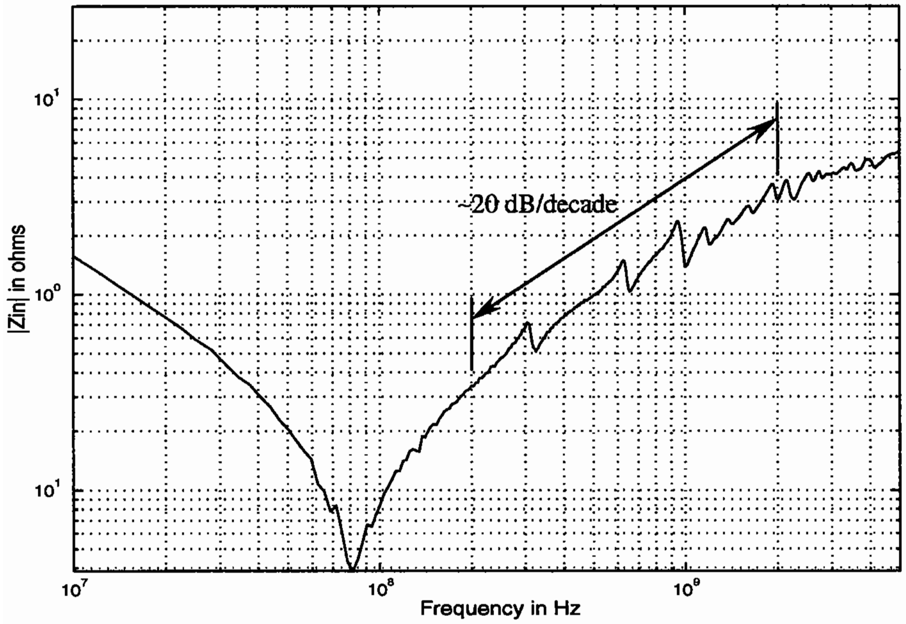


Figure 4.6. A Log Impedance Plot of Board 3

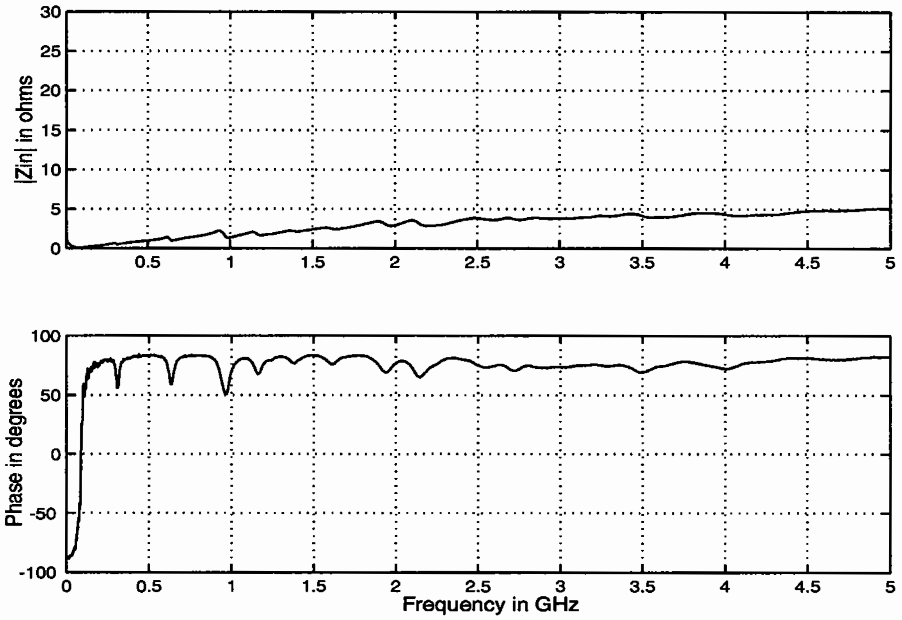


Figure 4.7. Input Impedance of Board 5

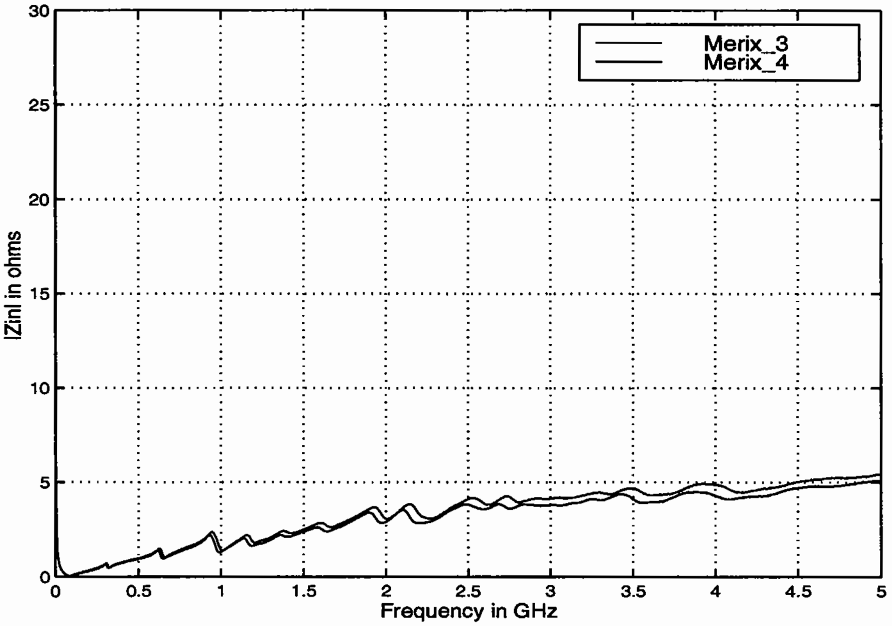


Figure 4.8. Input Impedance of Boards 3 and 5

Figure 4.9 compares the impedance responses of Boards 3 (a 6-layer TV1-1-1 board) and 11 (a 7-layer TV1-3-1 board). Similarly, Boards 7 and 13 are compared in Figure 4.10.

In 12-up boards, four SMA jacks were attached to each board at locations J1, J2, J3, and J4, which have different distances from the edge of the board.

Figure 4.11 compares the impedance responses at these four locations on Board 9. Figure 4.12 shows similar results on Board 15.

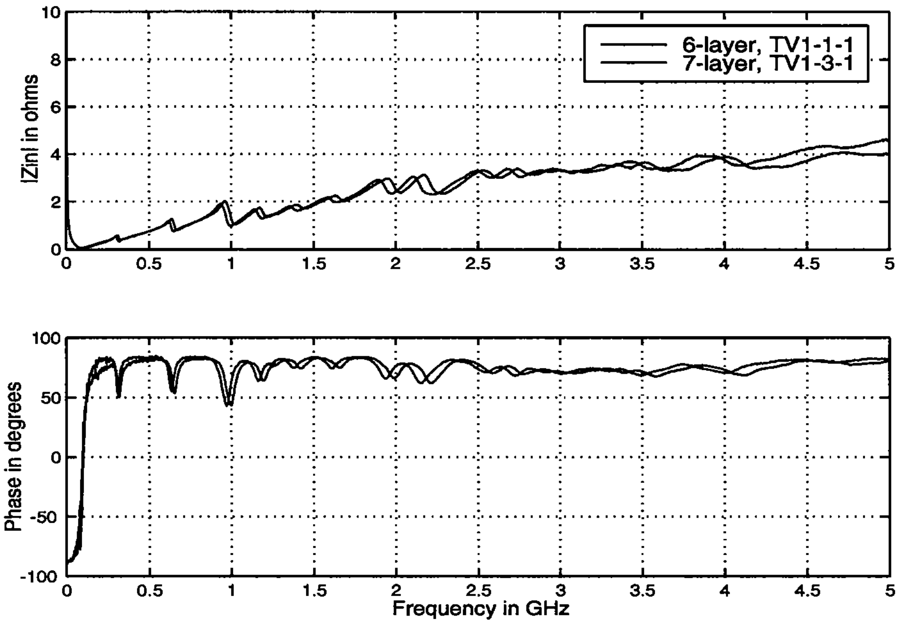


Figure 4.9. Input Impedance Comparison of Boards 3 and 11

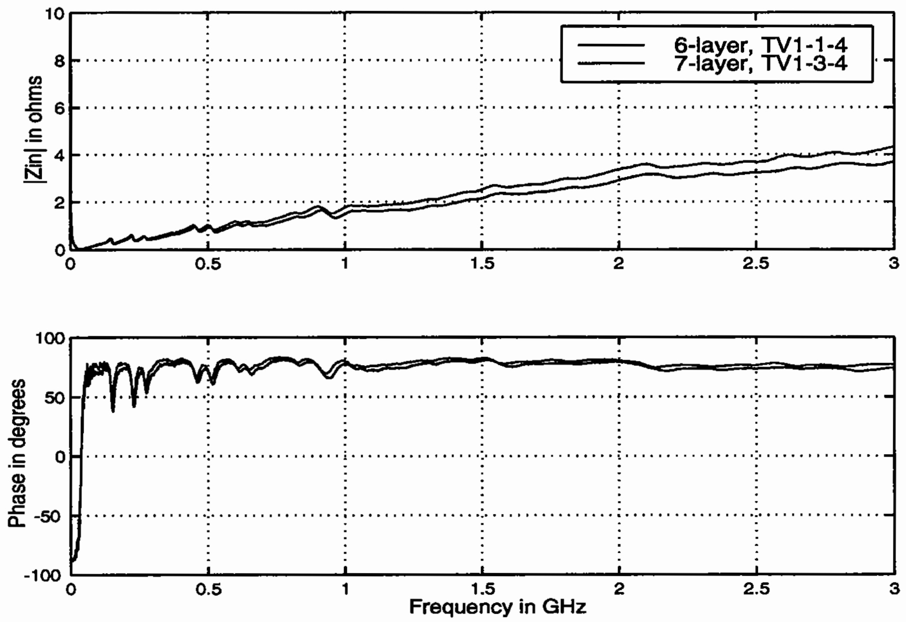


Figure 4.10. Input Impedance Comparison of Boards 7 and 13

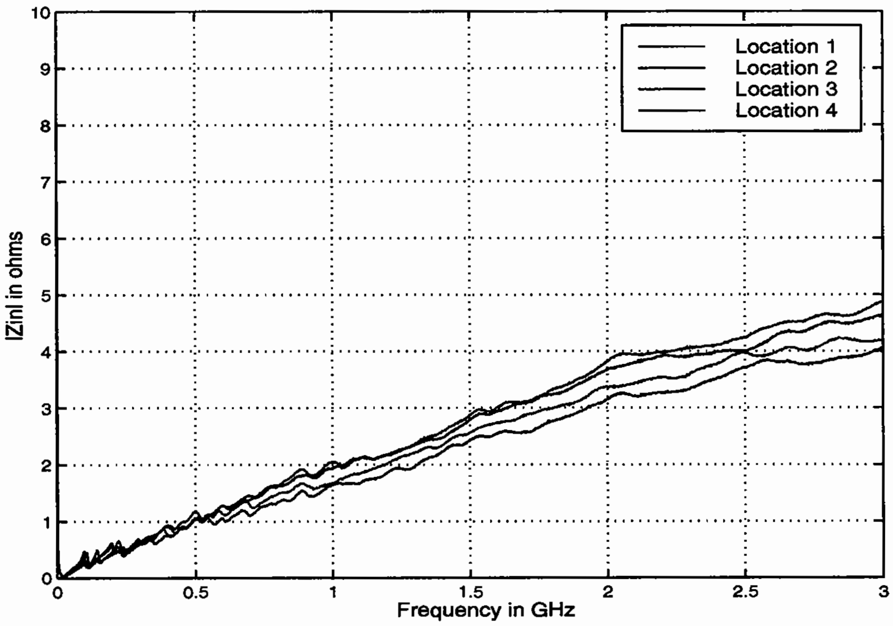


Figure 4.11. Input Impedance of Board 9 at Locations J1, J2, J3, and J4

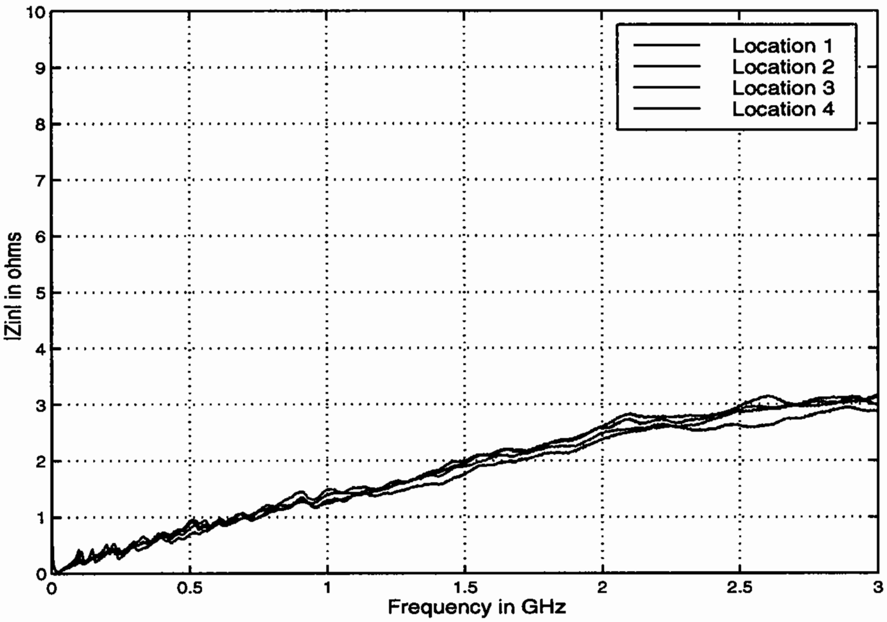


Figure 4.12. Input Impedance of Board 15 at Locations J1, J2, J3, and J4

With a larger inter-plane capacitance, discrete decoupling capacitors are less effective because a larger C_{board} value will move the resonant peak to a lower frequency. To evaluate the effect of discrete capacitors, a 100-nF and a 10-nF capacitor was added alternately at location C1 on Board 3 and the input impedance of the power bus was measured as shown in Figure 4.13.

Figure 4.14 compares the input impedance of Merix Board 3 with Emcap and 3M Board 3 with C-ply materials. The impedance curve of C-ply board, the red curve, is smoother but has a slightly deeper slope than the blue curve.

For each version of the test board, at least two identical boards were provided. The plots in Figure 4.15 compare the input impedance of 6 pairs of identical boards.

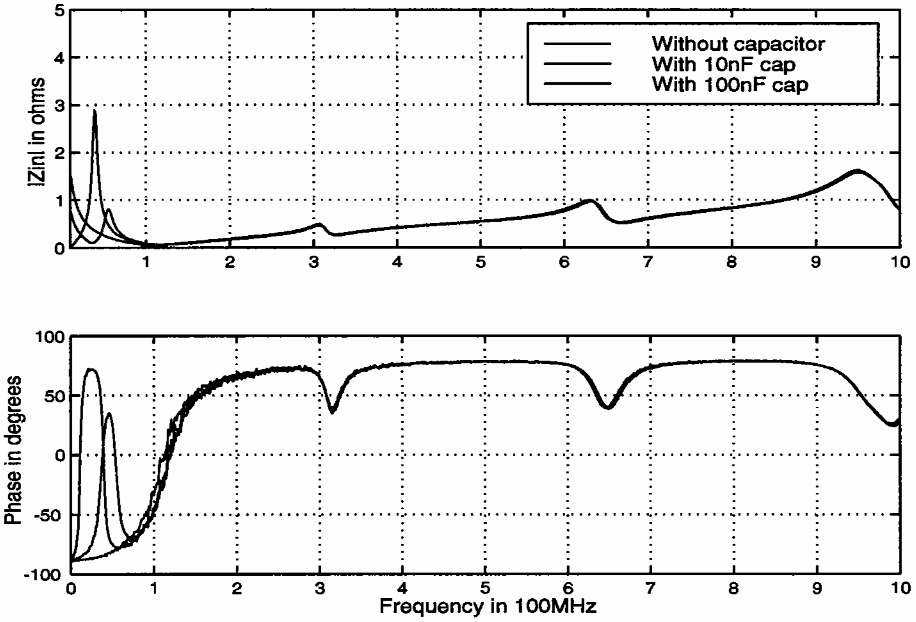


Figure 4.13. Input Impedance of Board 3 With or Without Capacitor

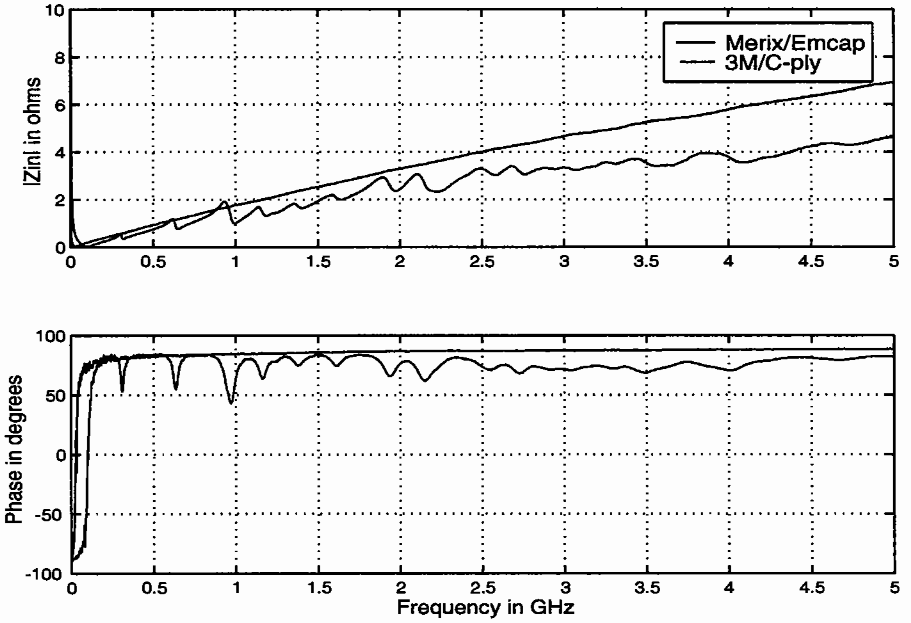
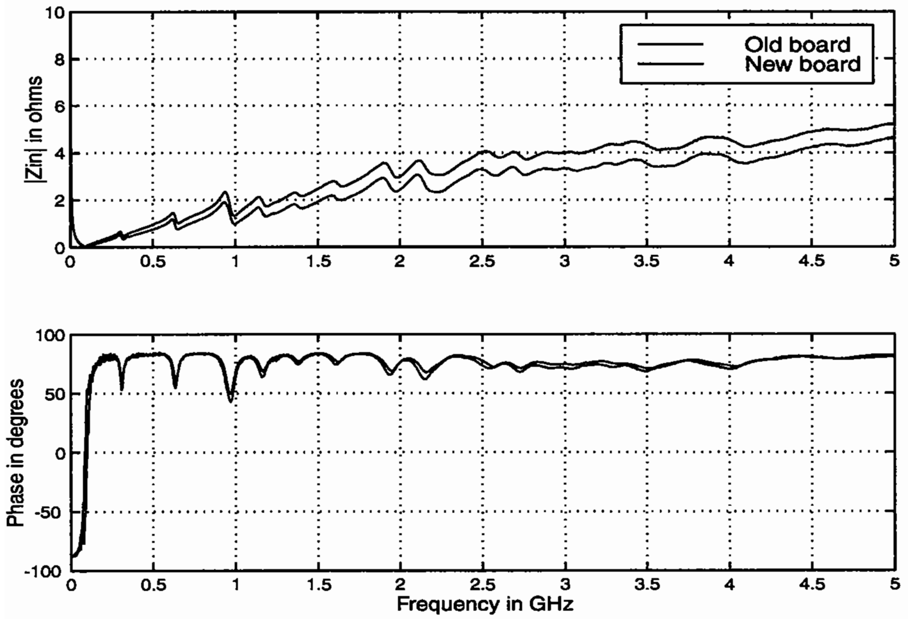
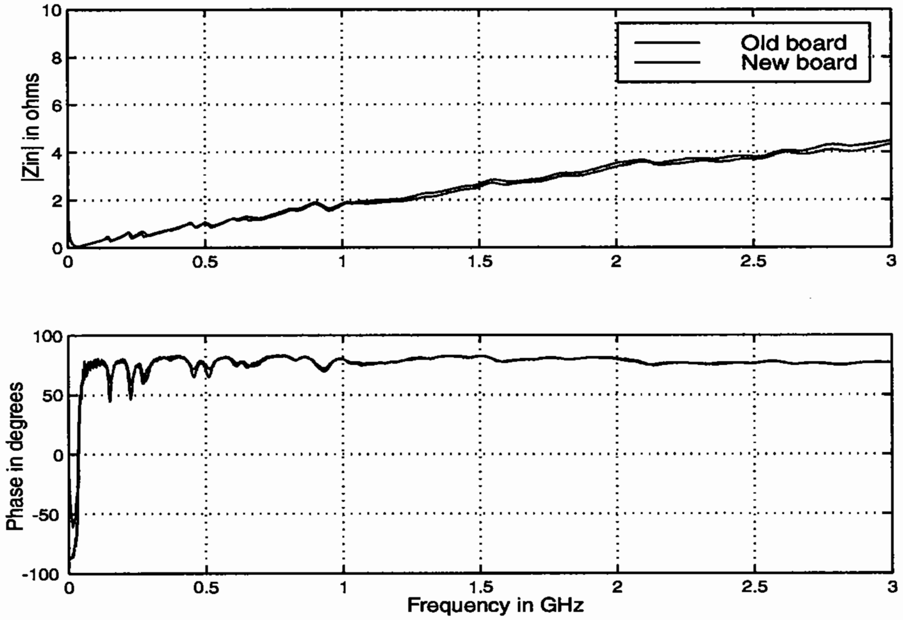


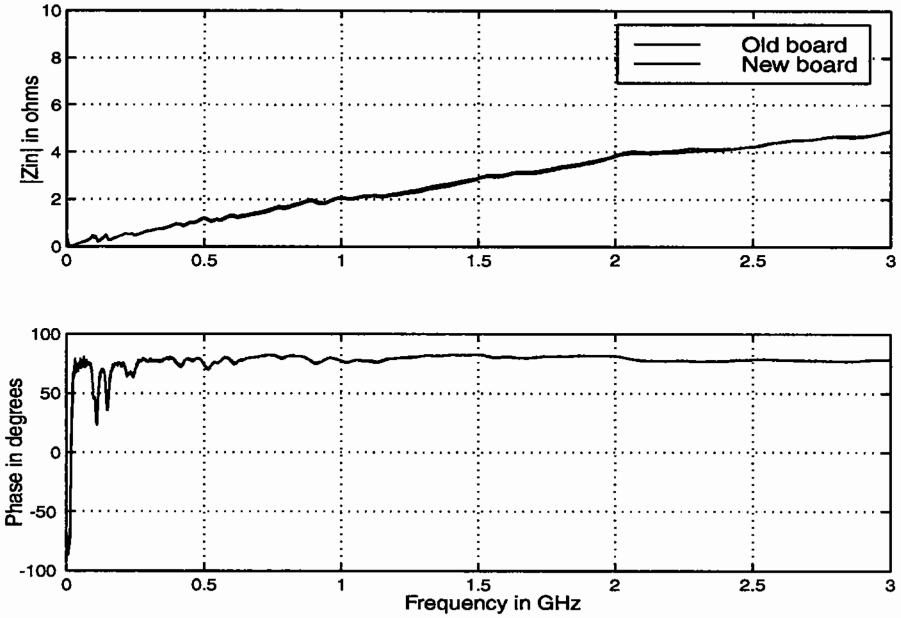
Figure 4.14. Input Impedance of TV1-1-1 Emcap and C-Ply Boards



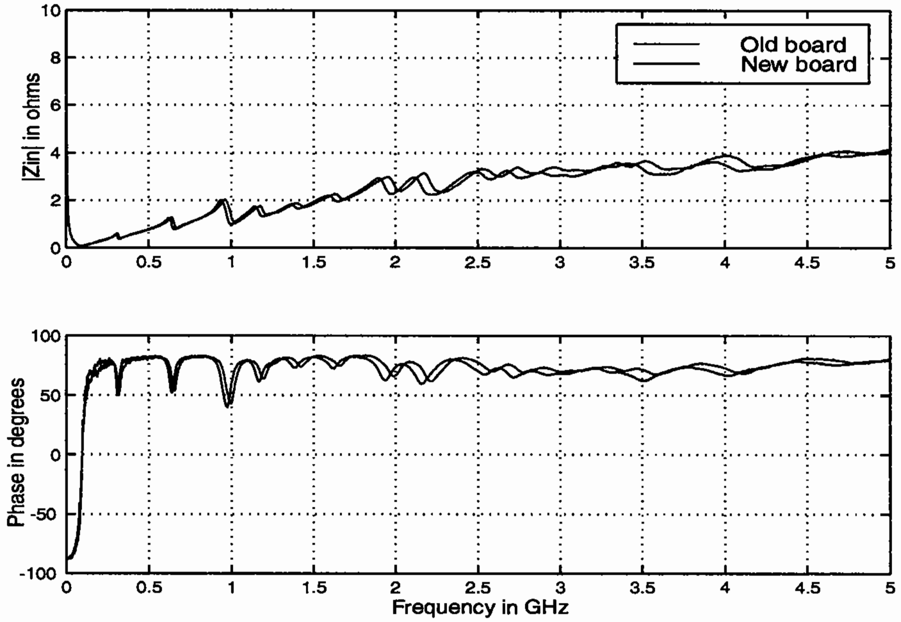
Comparison of Boards 3 and 5



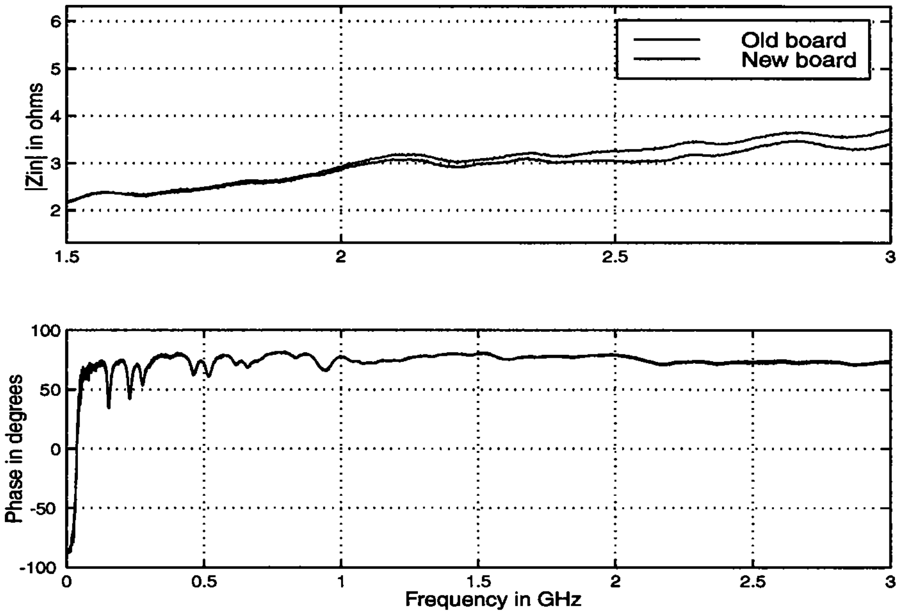
Comparison of Boards 7 and 8



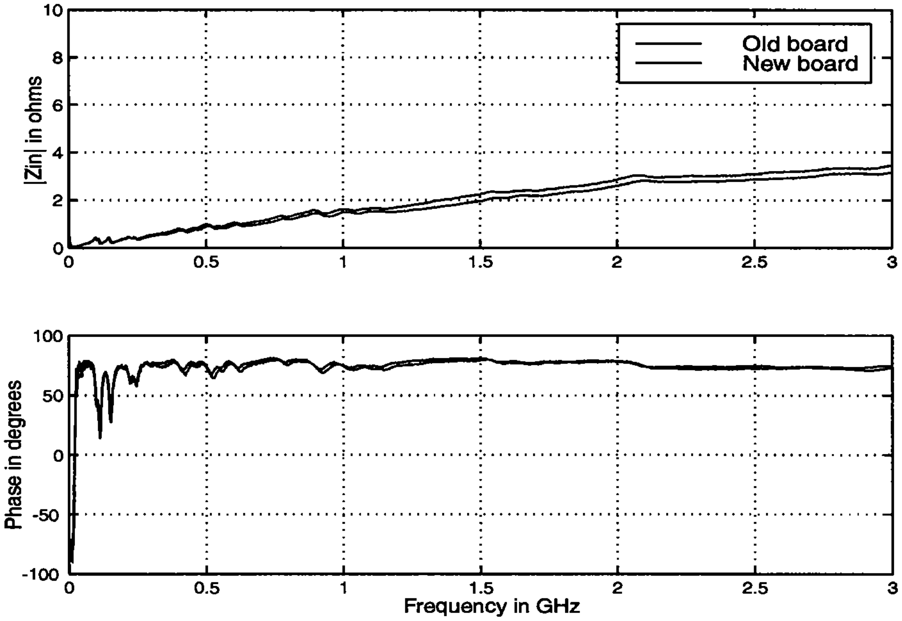
Comparison of Boards 9 and 10



Comparison of Boards 11 and 12



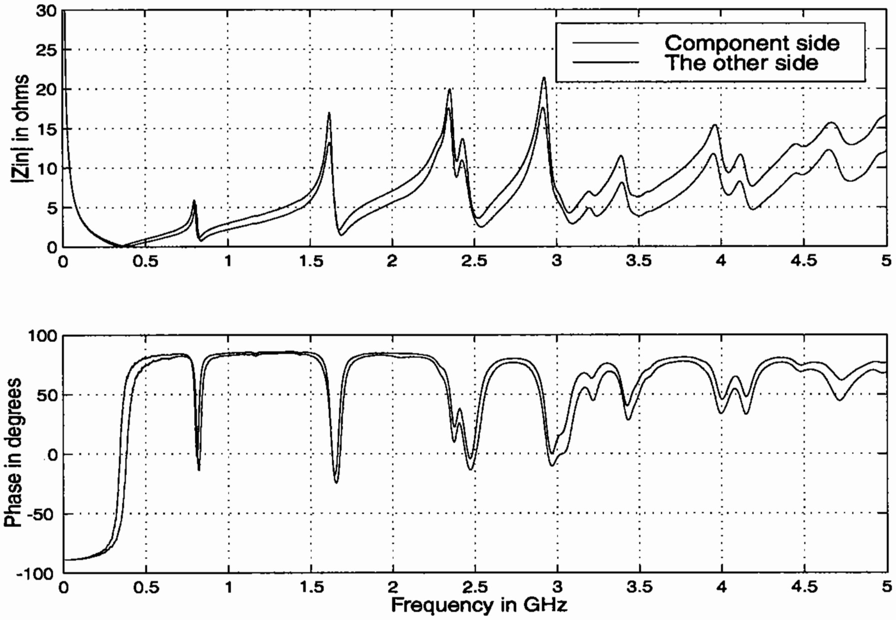
Comparison of Boards 13 and 14



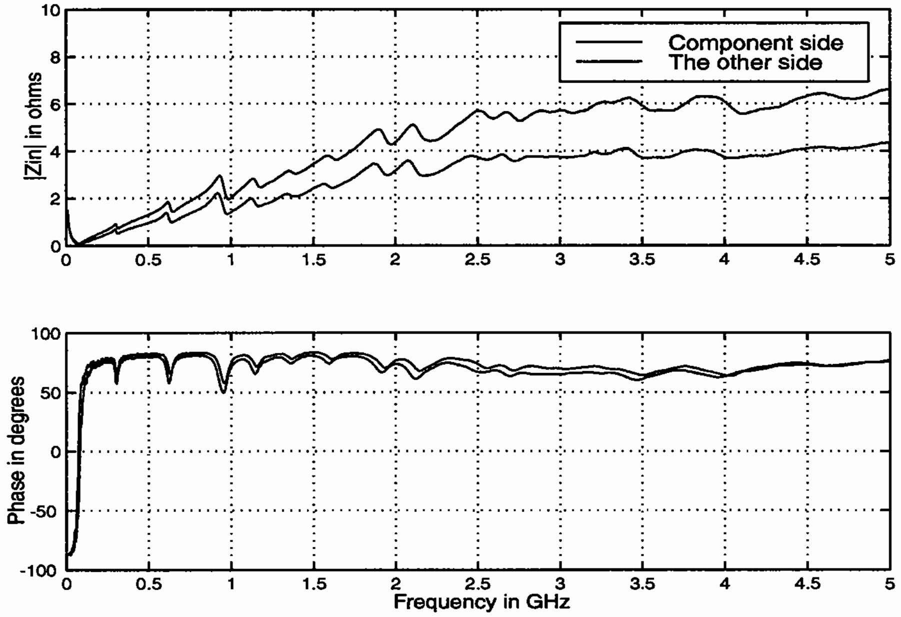
Comparison of Boards 15 and 16

Figure 4.15. Comparison of Boards of the Same Version

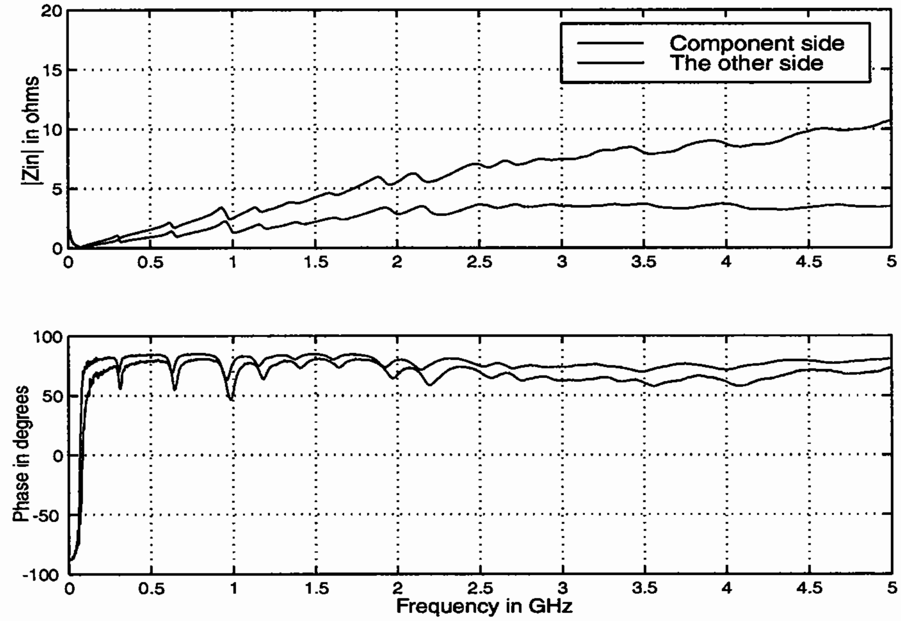
On the test boards, the SMA connector can be mounted on the component side (Layer 1) or the other side (Layer 6 or 7). The configuration should be chosen to have minimum interconnection inductance and minimum input impedance. In this experiment, the connector was mounted on the component side of one test board and the other side on an identical test board to evaluate the impedance response and the interconnection inductance of the measurement loop. The results are shown in Figure 4.16. From the figure, for all stack-ups, the first configuration presents a lower impedance response and a smaller interconnection inductance of the measurement loop. Therefore, the SMA connector should be mounted on the component side.



Impedance Comparison of TV1-2-1 Boards 1 (connector on the component side) and 2 (connector on the other side)



Impedance Comparison of TV1-1-1 Boards 3 (connector on the component side) and 5 (connector on the other side)



Impedance Comparison of TV1-3-1 Boards 11 (connector on the component side) and 12 (connector on the other side)

Figure 4.16. Comparison of the Test Configurations of Mounting the Connector on the Component Side or the Other Side

5. Measurements of Litton Boards

5.1. FR-4 Boards

Two FR-4 boards were provided so far from Litton as shown in Table 5.1. Board 1 was a 4-up board and Board 2 was a 12-up board.

Table 5.1. Litton FR-4 Boards ($\varepsilon_r = 4.0$, d = 7.4 mils)

Board #	Stack-up	Series #	$C_{B\,meas}$ (nF)	$C_{B\,cal}$ (nF)
1	TV1-1-4	00299	3.6	3.1
2	TV1-1-12	00298	12.5	9.8

Figure 5.1 shows the measured input impedance of Board 1. Figure 5.2 shows the measured input impedance of Board 2. Although the resonant peaks are significant compared to the base, the highest peak values are only 6.5 ohms in Figure 5.1 and 5 ohms in Figure 5.2.

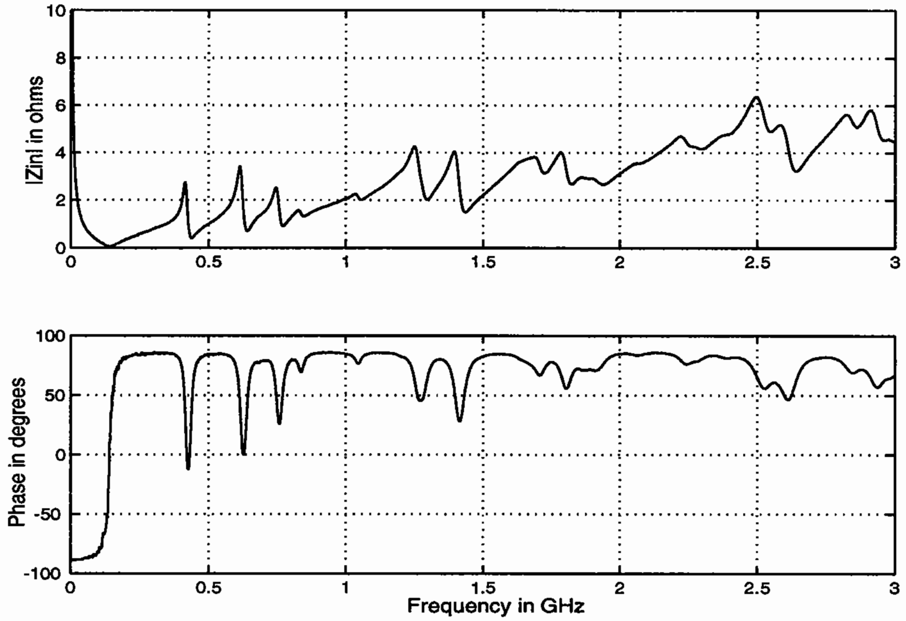


Figure 5.1. Input Impedance of Board 1

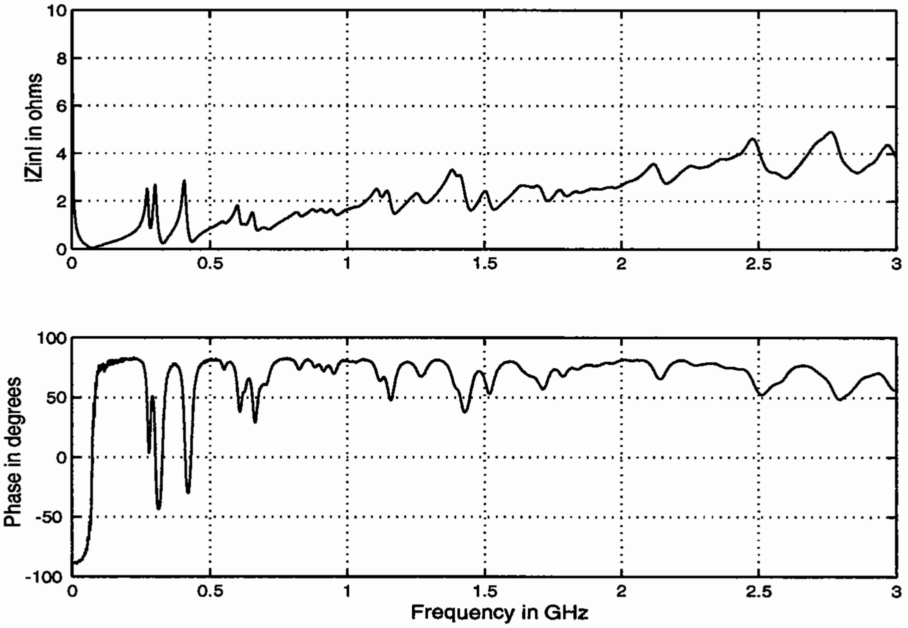


Figure 5.2. Input Impedance of Board 2

APPENDIX A

Test Procedure for Measuring Inter-Plane Capacitance Using HP4263B LCR Meter

The test procedure for measuring the inter-plane capacitance of the power bus structures is described as below. The words in **bold** face indicate a button on the front panel. The words in *italics* indicate a submenu on the display screen. The "^" symbol stands for the blue button on the front panel and indicates the alternate function of a button. For example, "**^ + • (Reset)**" means the Reset function selected by pressing the blue button first and then the • button.

1. Turn on the LCR meter.

2. Reset the system: Press **^ + • (Reset)** to reset the system to factory configuration, use the right-up arrow button on the front panel to select *yes* in the submenu, then press **Enter**.

3. Set the cable length to 1 meter: Press **^ + 3 (Cable)**, use the right-up button to select *1m*, then press **Enter**.

4. Select the measurement parameter: Press **Meas Prmtr**, choose *Cp* in the submenu, then select *D* in the next submenu, press **Enter**.

5. Set the test signal frequency: Press **Freq**, use the left-down or right-up buttons to decrease or increase the frequency to the desired value. The frequency of *1kHz* was used in the experiment. After selecting the frequency, press **Enter**.

6. Perform open and short corrections: Press **^ + 4 (Open)**, the *OpenMeas* in the submenu blinks, press **Enter**, wait until the screen prompts *Open Correction Complete.* Next, connect the two clips to each other to make a short connection, press **^ + 5 (short)**, then press **Enter**, wait until the screen prompts *Short Correction Complete.*

7. Make measurement: Let one clip lead touch the power pad of location C1 and the other clip lead touch the ground pad, record the Cp reading in the screen.

For more information on how to use the HP4263B LCR meter, refer to the user's guide [1].

APPENDIX B

Test Procedure for Measuring Input Impedance Using HP8753D Network Analyzer

The test procedure for measuring the input impedance of the power bus structures is described below. The words in **bold** face indicate a button on the front panel, the words in *italics* indicate a submenu on the display screen.

1. Turn on the network analyzer, warm up 45 minutes.

2. Connect a precision cable to Port 1. Port 2 is unused.

3. Set up measurements: (This step must be done before calibration, since
the settings cannot be changed after calibration.)

a). Set frequency range: Press **START**, then press **1+M/u** to set the start frequency to 1 MHz. Press **STOP** and **5+G/n** to set the stop frequency to 5 GHz.

b). Set the number of sampling points: Press **MENU**, select *NUMBER OF POINTS* in the submenu, then use the up arrow button below the knob to increase this number to 1601 points.

c). Reduce the IF bandwidth to get a stable curve: Press **AVG**, select *IF BW* in the submenu, then use the down arrow button below the knob to decrease the bandwidth to 1000 Hz.

4. Calibration:

a). Change the model of calibration kit: Press **CAL**, then press *CAL KIT[7mm]* in the submenu, select *3.5mmD* as the model of the calibration kit. ("7mm" is the default model.) Press *RETURN.*

b). Set calibration type: Press *CALIBRATE MENU*, then select *S11 1-PORT* submenu, since only port 1 is used.

c). Calibrate: Connect the open termination and press *OPEN* in screen menu. Do the same with the short and matched load terminations. After calibration, press *DONE 1-PORT CAL.* A "Cor" sign will appear at the left side of the screen.

d). Save the calibration: Press **SAVE/RECALL**, choose the first submenu *SAVE STATE* to save the settings and calibrations to the internal memory of the network analyzer.

5. Port extension:

a). Change the display format: Press **MEAS**, select *Refl: FWD S11 (A/R).* Press **FORMAT**, then select *SMITH CHART.*

b). Extend the port: Connect the shorted 5-pin connector to the cable, press **CAL**, select *MORE* in the submenu, then select *PORT EXTENSIONS.* Next, press *EXTENSIONS* submenu on the top to turn the extension on, then press *EXTENSION PORT 1.* Use the knob to increase the delay until the line in the Smith chart turn into a dot in the short position. Press *RETURN*, a "Del" sign will appear in the left side of the screen.

6. Display the results:

a). Remove the connector from the cable, connect the test board.

b). Change the display format: Press **FORMAT**, select *LIN MAG.*

c). Display impedance magnitude: Press **MEASURE**, select *Refl: FWD S11 (A/R)*, then select *CONVERSION.* In the submenu, choose *Z:Refl*, then press *RETURN.*

d). Display impedance phase: Press **DISPLAY**, then press *DUAL CHAN* to turn it on. The screen is split into two parts. Press **CHAN 2** in the panel to activate Channel 2. Press **MEAS**, select *Refl: FWD S11 (A/R)*, then select *CONVERSION*, choose *Z:Refl* submenu, press *RETURN.* Press **FORMAT**, select *PHASE.*

Now the title for Channel 1 is "CH1 Z:R lin mag", for Channel 2 is "CH2 Z:R phase".

e). Press **SCALE REF** then *AUTO SCALE* to get a good display.

For more information on how to use the HP8753D network analyzer, refer to the user's guide [2].

APPENDIX C

Test Procedure for Measuring Input Impedance Using HP4291A HF Impedance/Material Analyzer

The test procedure for measuring input impedance of the power bus structures is described below. The words in **bold** face indicate a hard key on the front panel. The words in *italics* indicate a submenu in the display screen.

1.Turn on the analyzer, warm up 30 minutes.

2. Calibration:

a). Settings: Press **Format**, select *SMITH CHART.* Press **Meas**, select *REFL.COEF(Γ).* Press **Sweep**, then *NUMBER of POINTS*, use ↑ and ↓ to set it to 1601 points.

Press **Cal**, then *CALIBRATE MENU.*

b). Turn the connector on the high impedance test head until the connector sleeve is fully extended. Connect the open termination by fixing the center conductor and turning only the shield. Press *OPEN*, wait until hearing the beep. Do the same with the short, 50 Ω, and low-loss capacitor terminations. After calibration, press *DONE: CAL.* A "CO+" notation will appear in the left side of the display.

3. Port Extension:

a). Attach a 7mm to 3.5mm-f precision adapter to the test head, then connect a precision microwave cable to the adapter. Next, connect an open or short probe same as the one used on the test board.

b). Press *PORT EXTENSION* in the **Cal** menu, press *EXTENSION* to toggle it on. Then press *EXTENSION VALUE.* Use the knob or enter propagation delay (several ns) to adjust the extension length until the line in the Smith chart turns into a dot in open or short positions. Press *RETURN.* A "Del" notation will appear in the left side of the display.

4. Fixture compensation:

With the open probe attached to the end of the cable, press *FIXTURE COMPEN*, then *COMPEN MENU*, press *OPEN*. Do the same to the short probe. Press *DONE:COMPEN*. A "CMP" notation will appear in the left side of the display.

5. Set up the analyzer:

a). Connect the test board.

b). Set up the analyzer:

Press **Start + 1 M/μ** to set the start frequency to 1 MHz.

Press **Stop + 1 G/n** to set the stop frequency to 1 GHz.

Press **Meas + Ch1**, select *IMPEDANCE: MAG(*$|Z|$*)*.

Press **Meas + Ch2**, select *PHASE(*θ_Z*)*.

Press **Format + Ch1**, select *LIN Y-AXIS*.

Press **Format + Ch2**, select *LIN Y-AXIS*.

Press **Display**, select *DUAL CHAN ON* and *SPLIT DISP ON*.

The display will split into two plots, corresponding to impedance magnitude and impedance phase.

6. Measure the board:

a). Press **Scale/Ref** then *AUTO SCALE* for both channels to get a good display.

Press **Marker** for a marker, use the knob to move the marker.

b). Obtain an equivalent circuit: Press **Display**, then *EQUIV CKT MENU*, then *SELECT EQU CKT*, select an appropriate model then press *CALCULATE EQU PARAMS*, the parameter values will appear on the display.

c). Record the data using LabVIEW.

For more information on how to use HP4291A HF Impedance/Material Analyzer, refer to the user's guide [3].

REFERENCES

[1] *HP 4263B LCR Meter User's Guide, 1st edition*, Hewlett Packard, HP Part No. 04263-90011, February, 1996.

[2] *HP 8753D Network Analyzer User's Guide*, Hewlett Packard, HP Part No. 08753-90257, September, 1995.

[3] *HP 4291A RF Impedance/Material Analyzer User's Guide*, HP part No. 04291-90011, March, 1994.