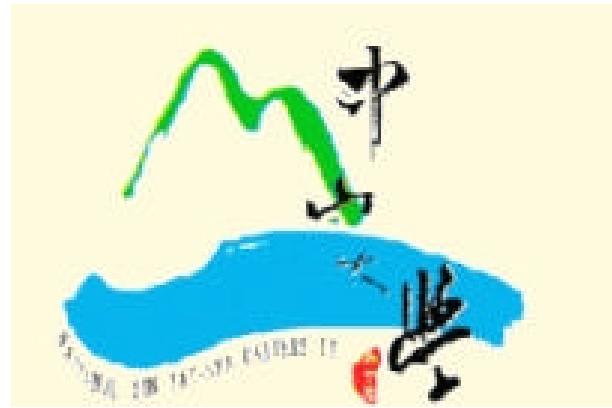


# Design, Measurement and Modeling of LTCC Embedded Inductors and PCB Balanced Devices



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Email: [jason@ee.nsysu.edu.tw](mailto:jason@ee.nsysu.edu.tw)

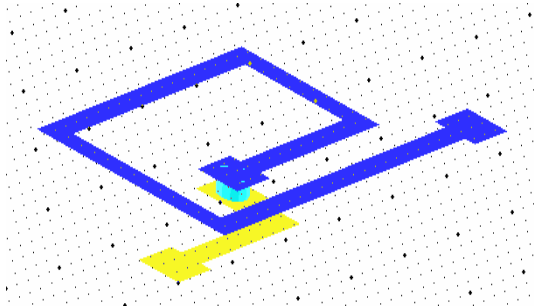
# Outline

◆ **LTCC Embedded Inductors**

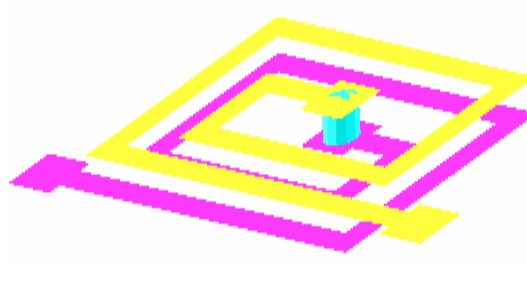
◆ PCB Balanced Devices

◆ Conclusions

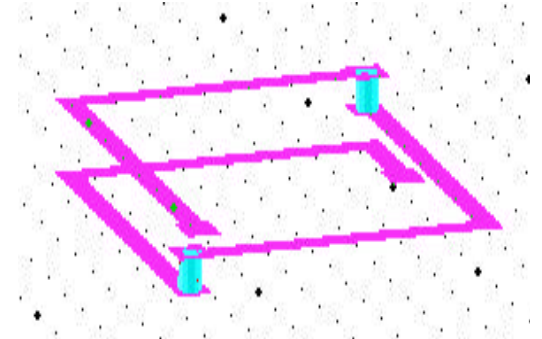
# Design Trend



Planar Spiral



Stacked Spiral



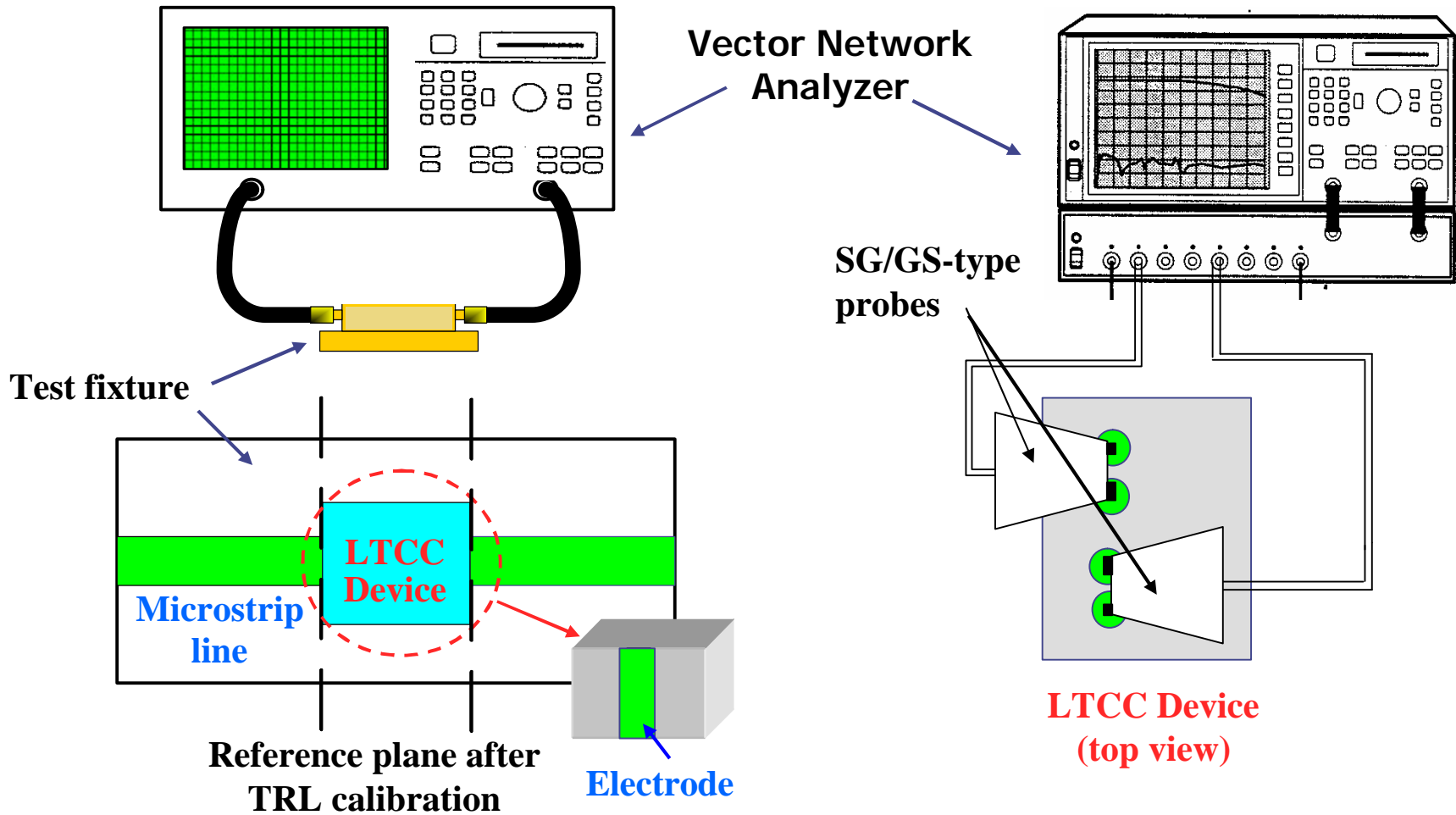
Helical

| LTCC Inductor                       | Planar Spiral | Stacked Spiral | Helical  |
|-------------------------------------|---------------|----------------|----------|
| Area<br>(under the same $L_{eff}$ ) | Large         | Smaller        | Smallest |
| SRF<br>(under the same $L_{eff}$ )  | Low           | Higher         | Highest  |
| $Q$<br>(under the same $L_{eff}$ )  | Low           | Higher         | Highest  |
| No. of Layers                       | 2             | 2              | $\geq 2$ |

# Measurement Techniques

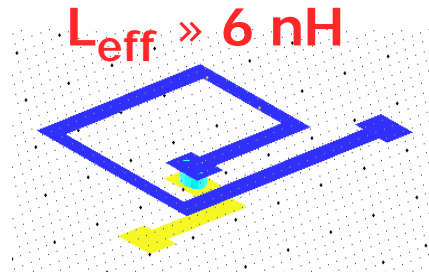
Test Fixture

Microwave Probes

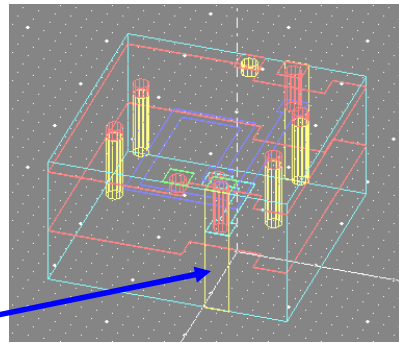


# Test-Fixture Measurement vs. HFSS Simulation

Spiral inductor

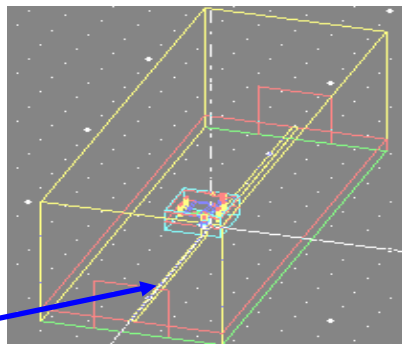


The whole LTCC device

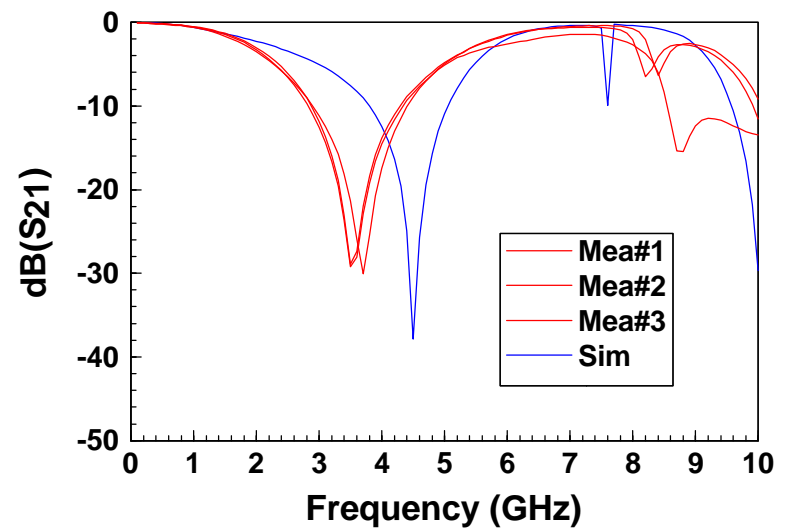
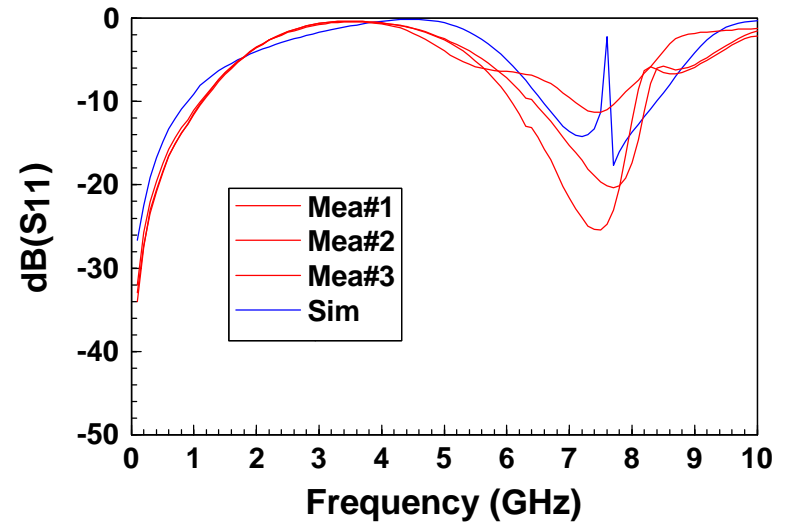


Electrode

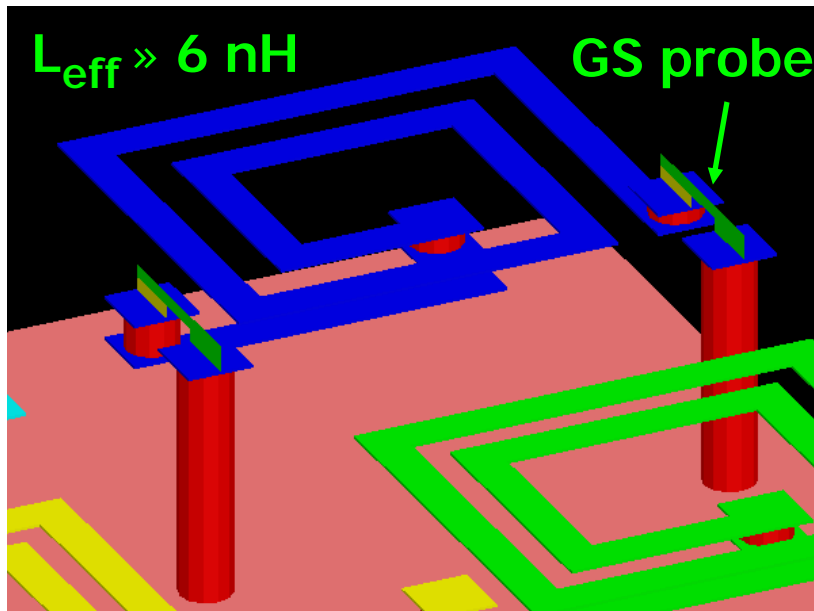
LTCC device on test fixture



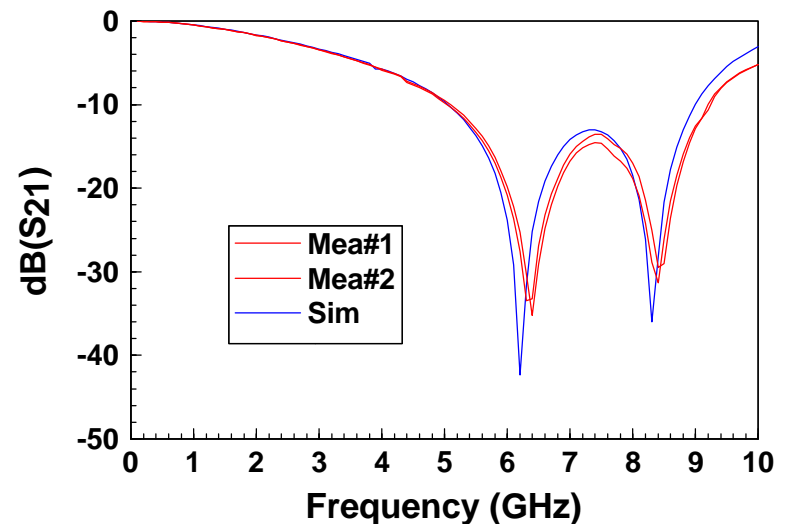
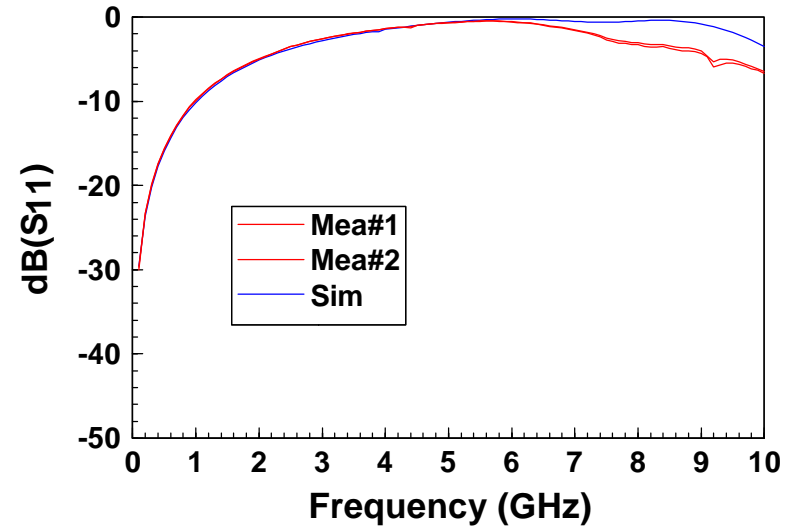
Microstrip line



# Microwave-Probe Measurement vs. HFSS Simulation



- ✓ Smaller area
- ✓ Higher SRF
- ✓ Higher Q factor
- ✓ Better measured data repeatability
- ✓ Better agreement between simulation and measurement



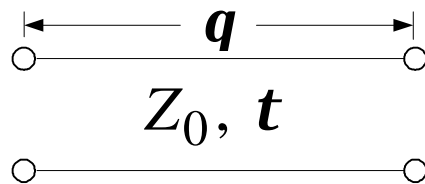
# A New Modified-T Model for Lossless Transmission Line

Lossless transmission line

$Z_0$ : Characteristic impedance

$\tau$ : Propagation delay

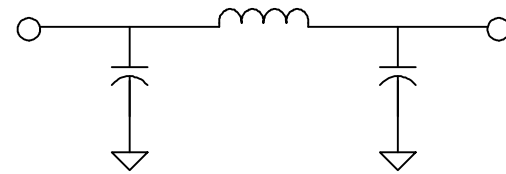
$\theta$ : Electrical length



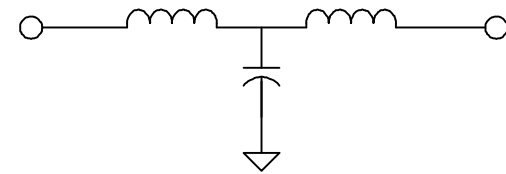
?

$\approx$

Equivalent  $\pi$  model



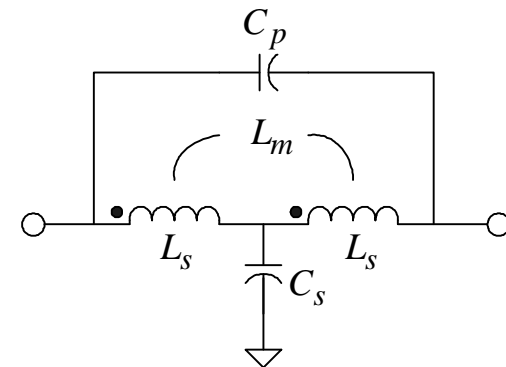
Equivalent T model



$$q = 0 \rightarrow p \Leftrightarrow w = 0 \rightarrow w_q$$

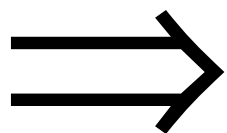
Equivalent modified-T model

➤ Is it possible to create an equivalent single-stage lumped model for a lossless transmission line having electrical length up to  $\pi$  ?



# Derivation of Element Values of Equivalent Modified-T Model

$$\begin{bmatrix} \frac{-j \cot \mathbf{q}}{Z_0} & \frac{j \csc \mathbf{q}}{Z_0} \\ \frac{j \csc \mathbf{q}}{Z_0} & \frac{-j \cot \mathbf{q}}{Z_0} \end{bmatrix} \approx \begin{bmatrix} \frac{j\omega L_s + \frac{1}{j\omega C_s}}{j\omega(L_s + L_m) \left[ j\omega(L_s - L_m) + \frac{2}{j\omega C_s} \right] + j\omega C_p} & \frac{j\omega L_m - \frac{1}{j\omega C_s}}{j\omega(L_s + L_m) \left[ j\omega(L_s - L_m) + \frac{2}{j\omega C_s} \right] - j\omega C_p} \\ \frac{j\omega L_m - \frac{1}{j\omega C_s}}{j\omega(L_s + L_m) \left[ j\omega(L_s - L_m) + \frac{2}{j\omega C_s} \right] - j\omega C_p} & \frac{j\omega L_s + \frac{1}{j\omega C_s}}{j\omega(L_s + L_m) \left[ j\omega(L_s - L_m) + \frac{2}{j\omega C_s} \right] + j\omega C_p} \end{bmatrix}$$

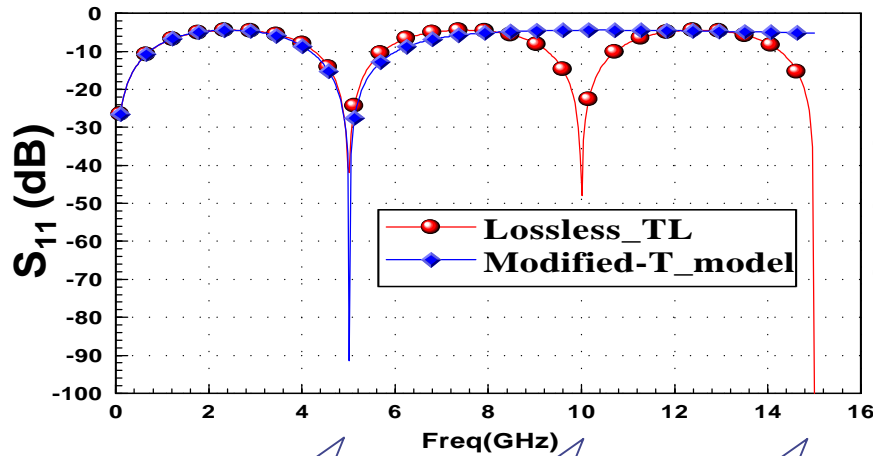


$$L_s \approx Z_0 t \left( \frac{1}{4} + \frac{1}{p^2} \right) \quad (\text{H}), \quad L_m \approx Z_0 t \left( \frac{1}{4} - \frac{1}{p^2} \right) \quad (\text{H})$$

$$C_s \approx \frac{t}{Z_0} \quad (\text{F}), \quad C_p \approx \frac{t}{Z_0 p^2} \quad (\text{F})$$

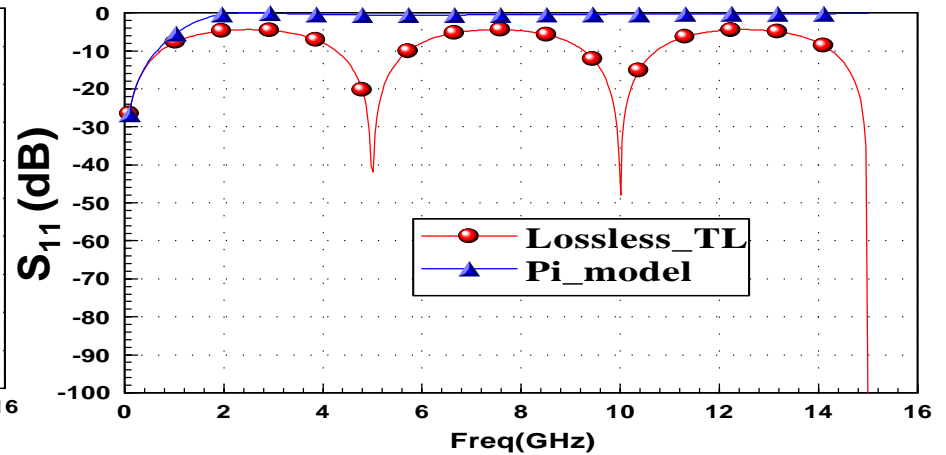
# Comparison of Bandwidth among Equivalent Models

Modified-T model

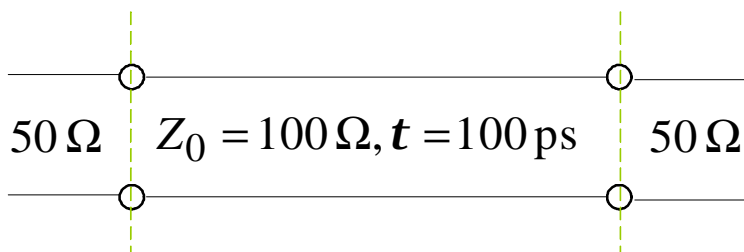


$q = p$        $q = 2p$        $q = 3p$

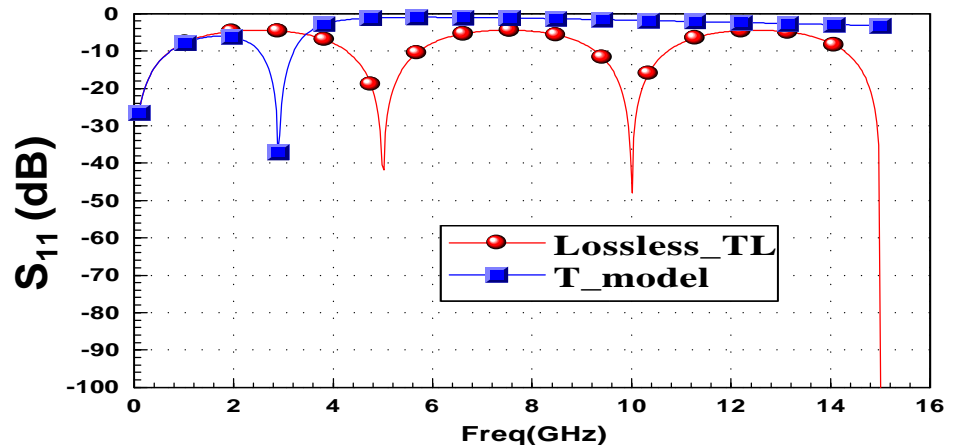
$\pi$  model



Transmission-line circuit

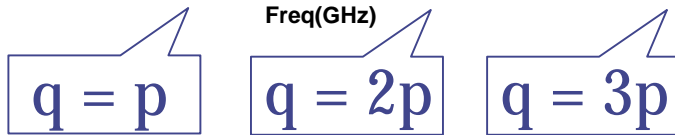
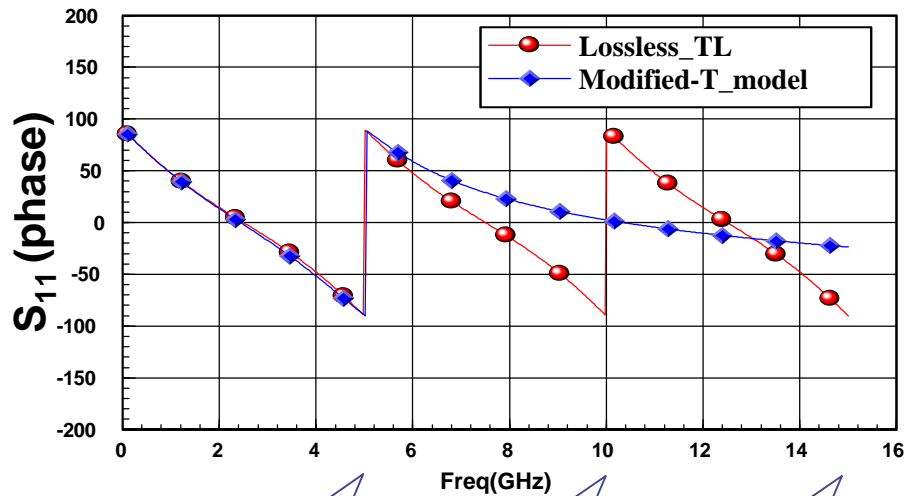


T model

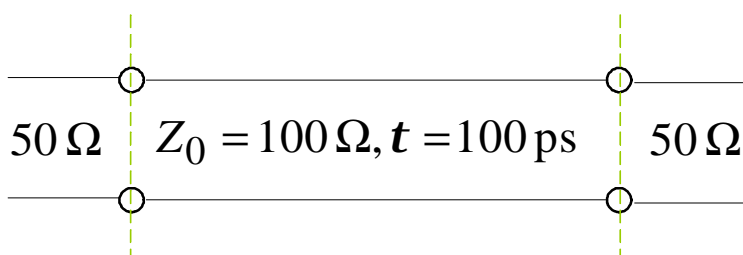


# Comparison of Bandwidth among Equivalent Models

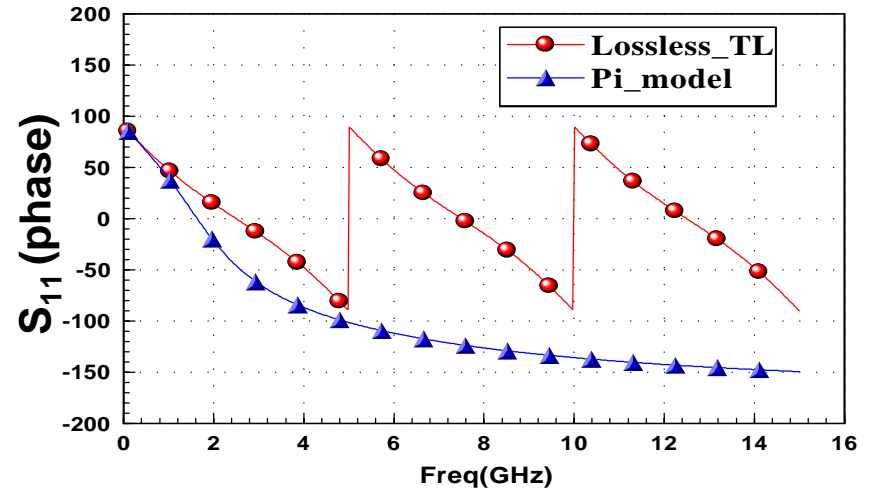
Modified-T model



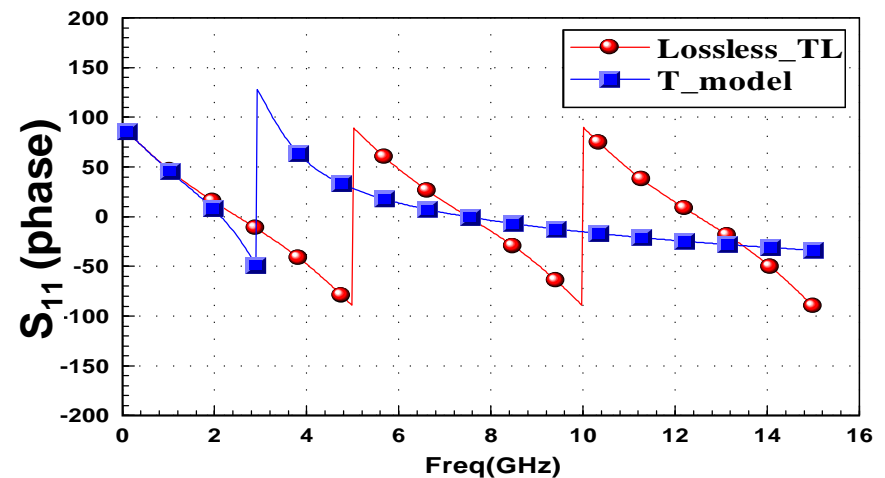
Transmission-line circuit



$\pi$  model

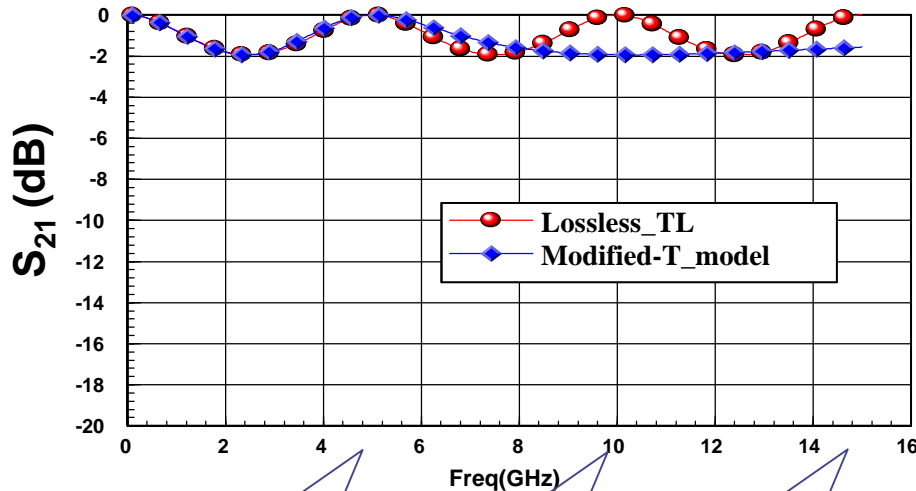


T model



# Comparison of Bandwidth among Equivalent Models

Modified-T model

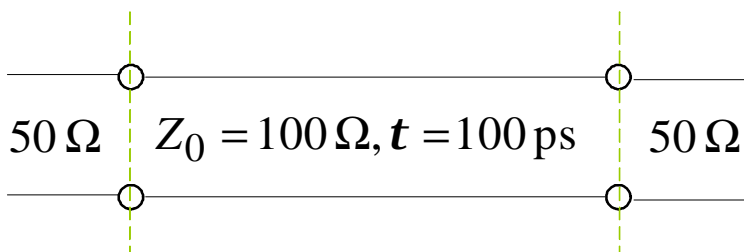


$q = p$

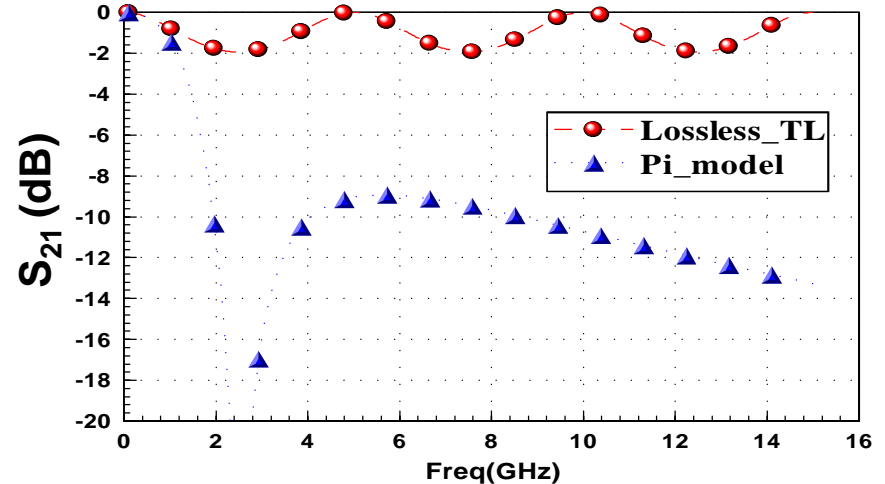
$q = 2p$

$q = 3p$

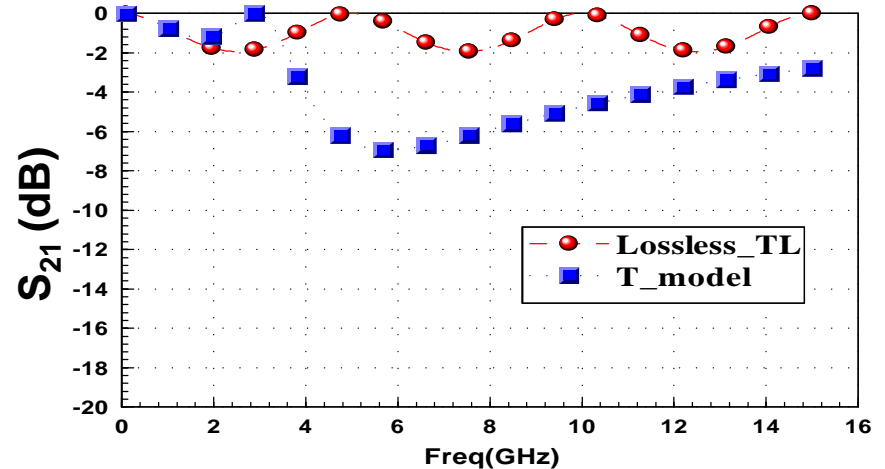
Transmission-line circuit



$\pi$  model

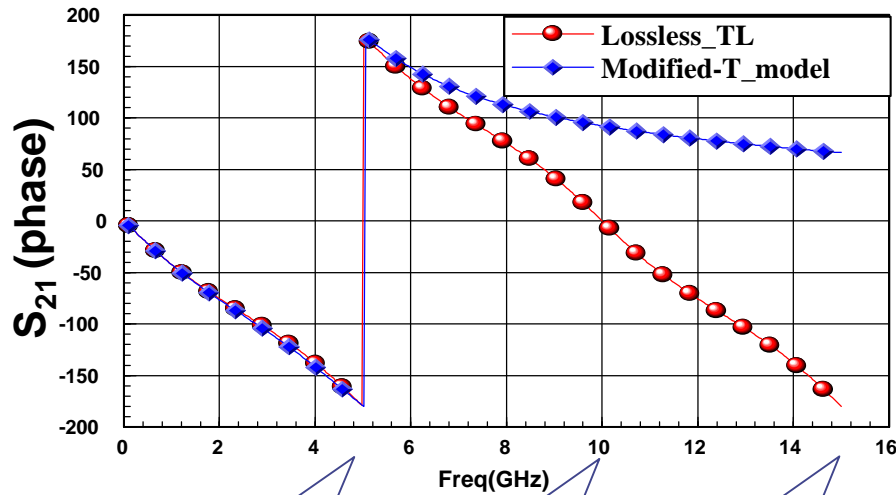


T model



# Comparison of Bandwidth among Equivalent Models

Modified-T model

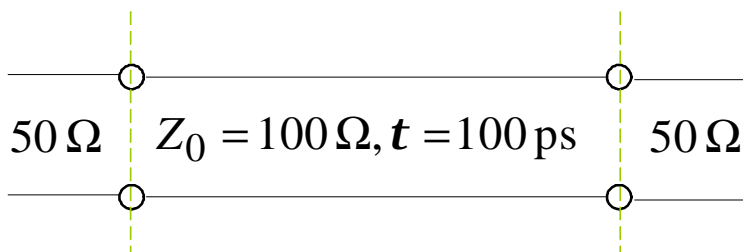


$$q = p$$

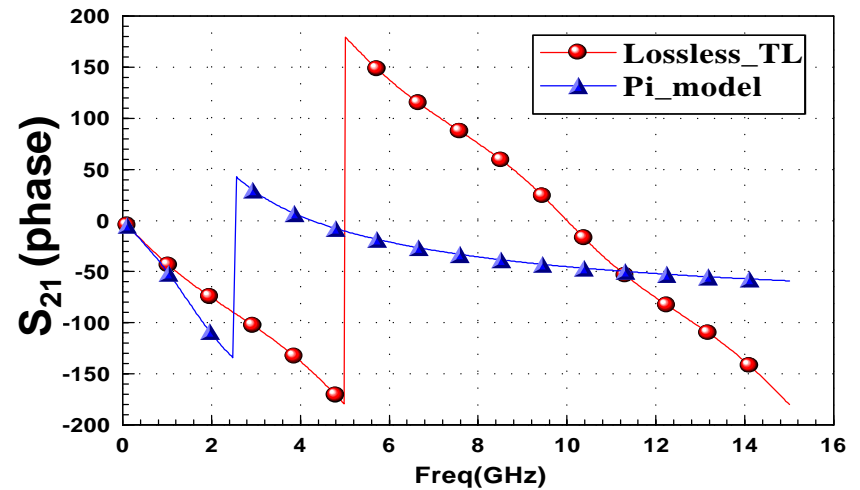
$$q = 2p$$

$$q = 3p$$

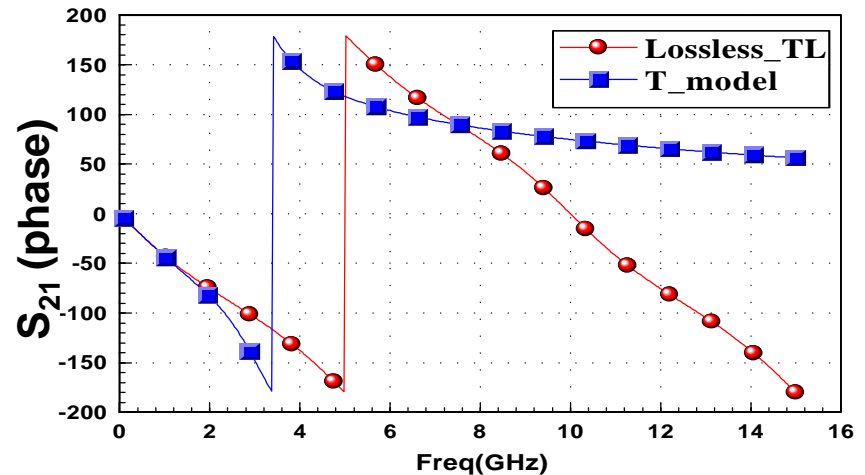
Transmission-line circuit



$\pi$  model

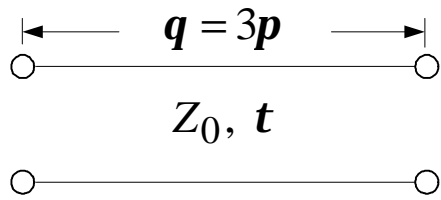


T model

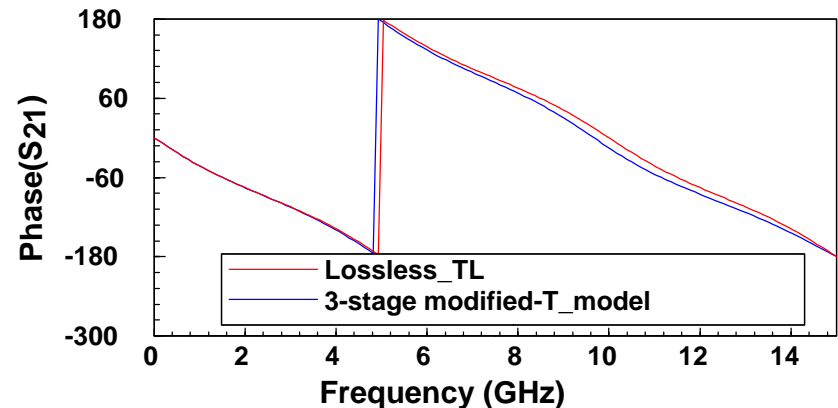
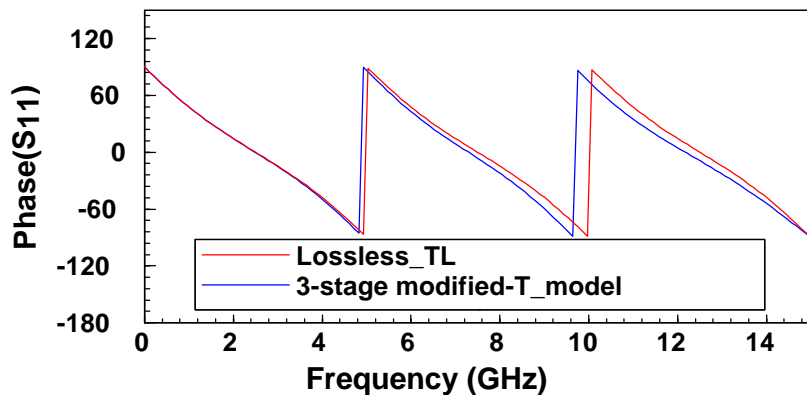
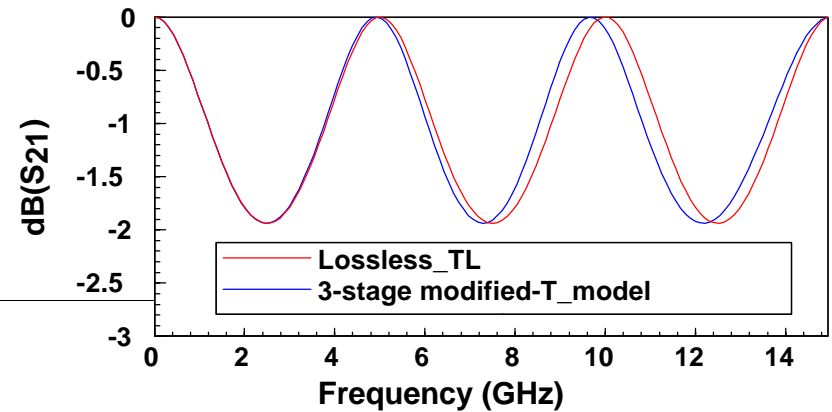
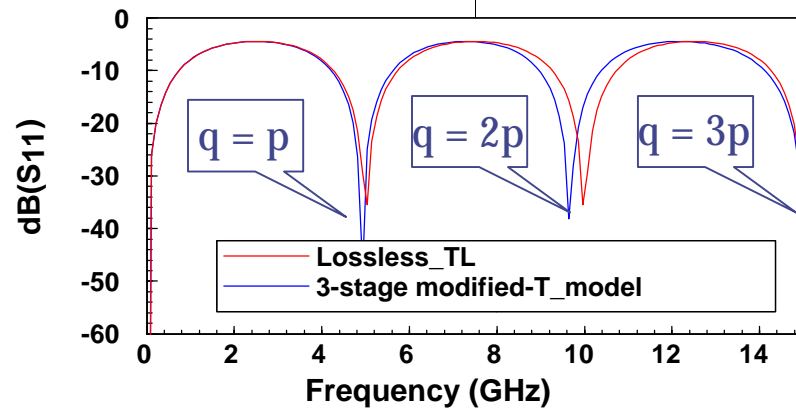
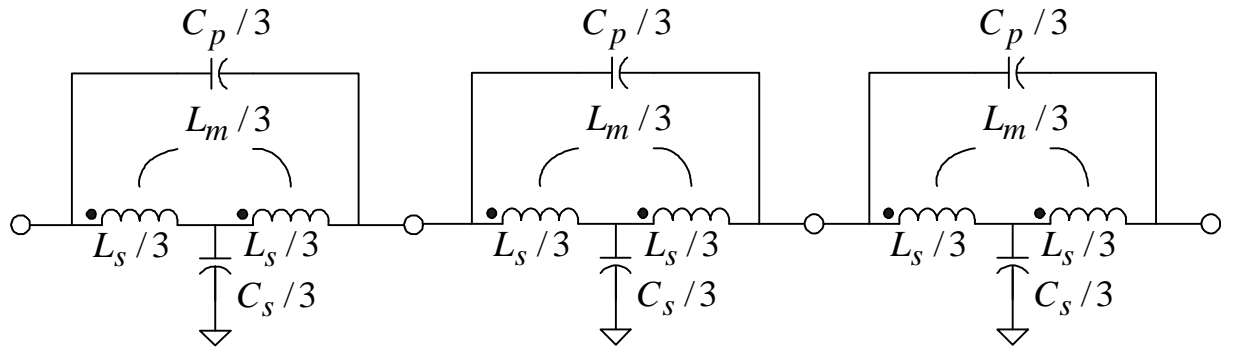


# Distributed Modified-T Model

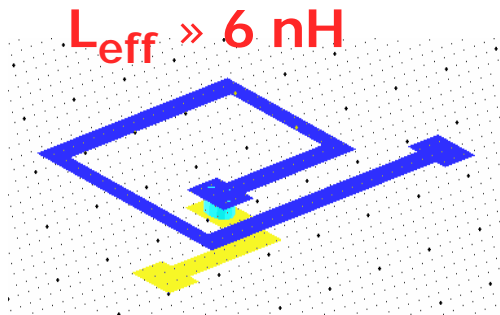
$3\pi$ -long  
transmission line



3-stage modified-T model

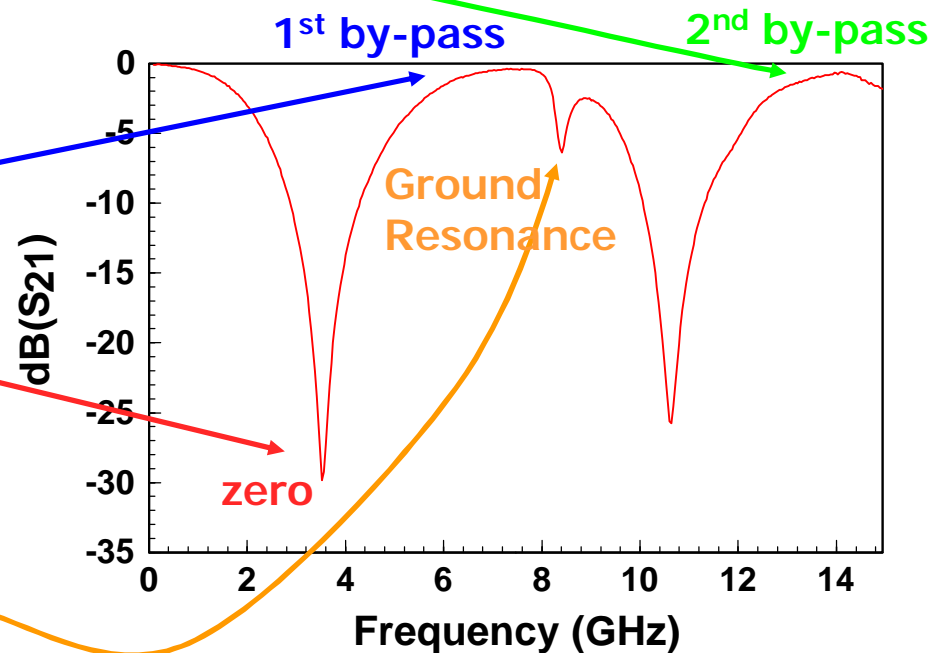
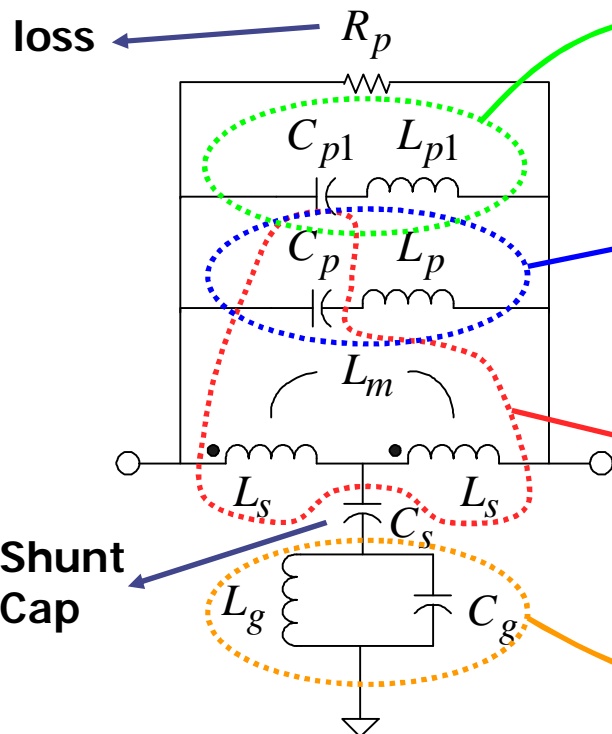
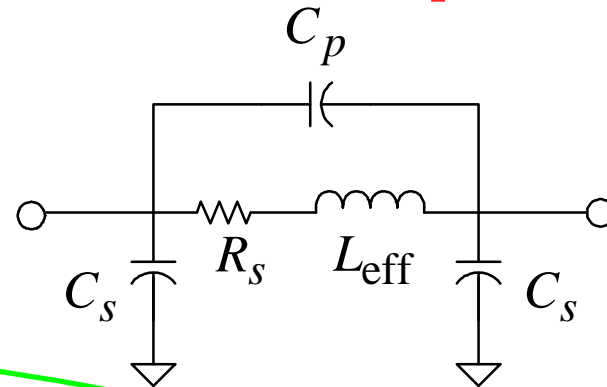


# Modified-T Models for Spiral Inductors



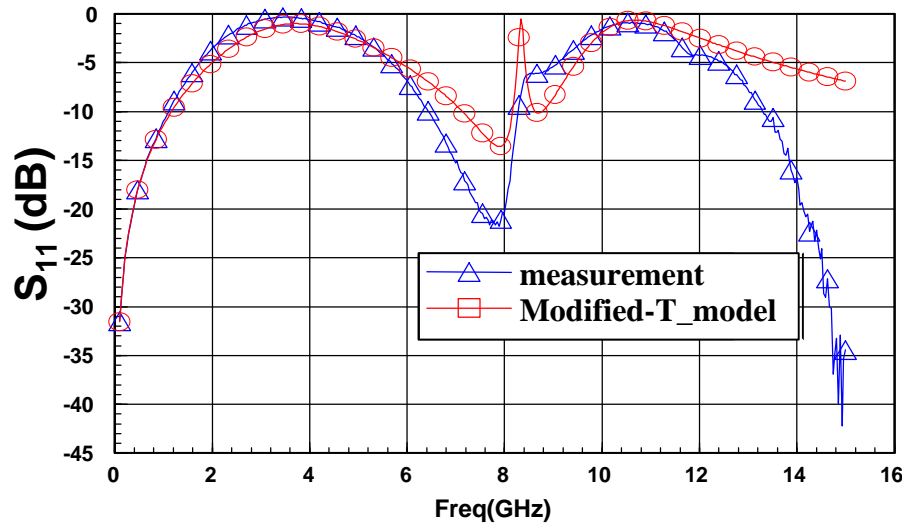
Modified-T model

Conventional p model

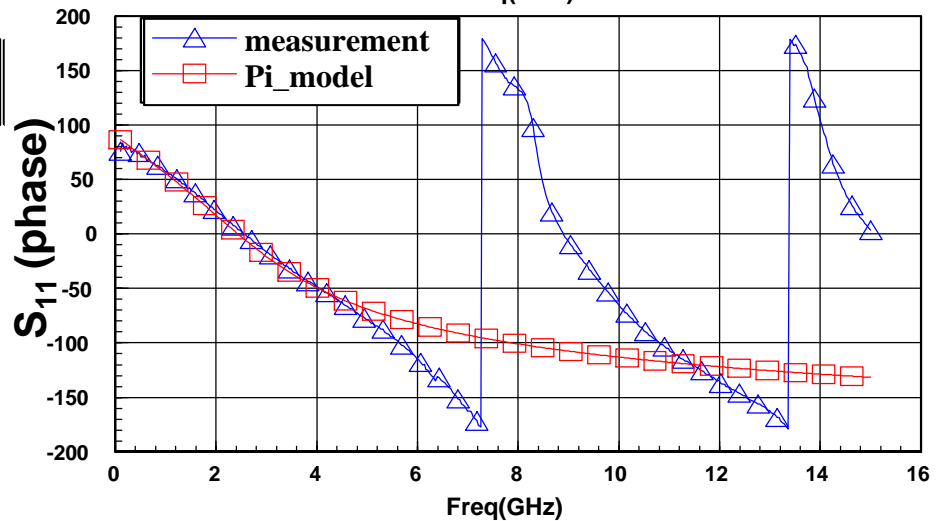
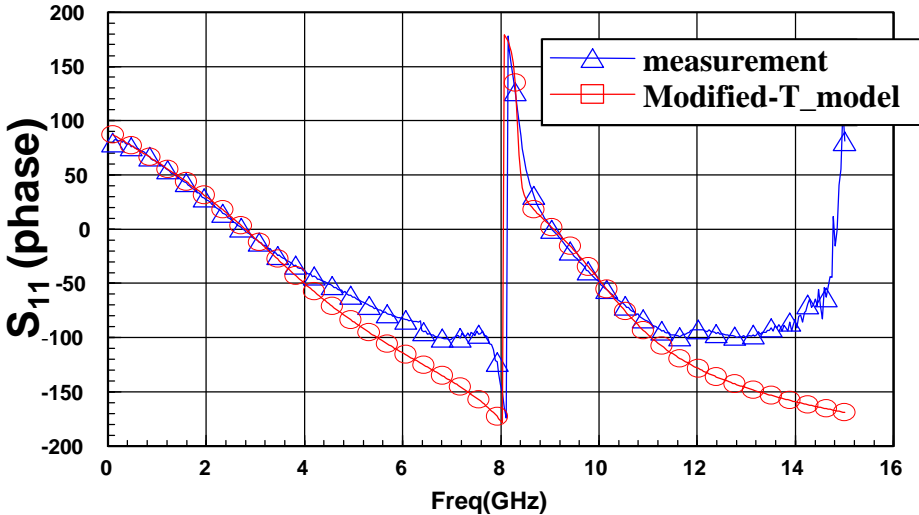
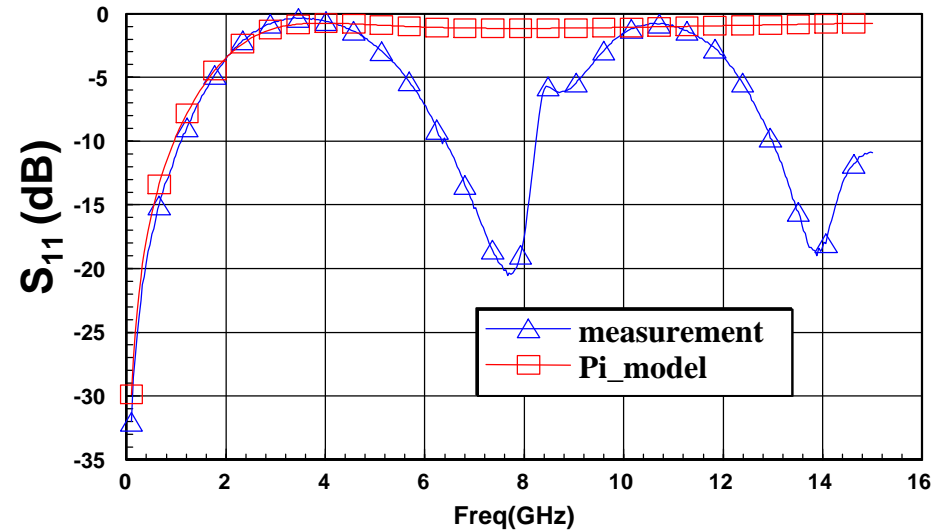


# Comparison of Bandwidth between Two Inductor Models

## Modified-T model

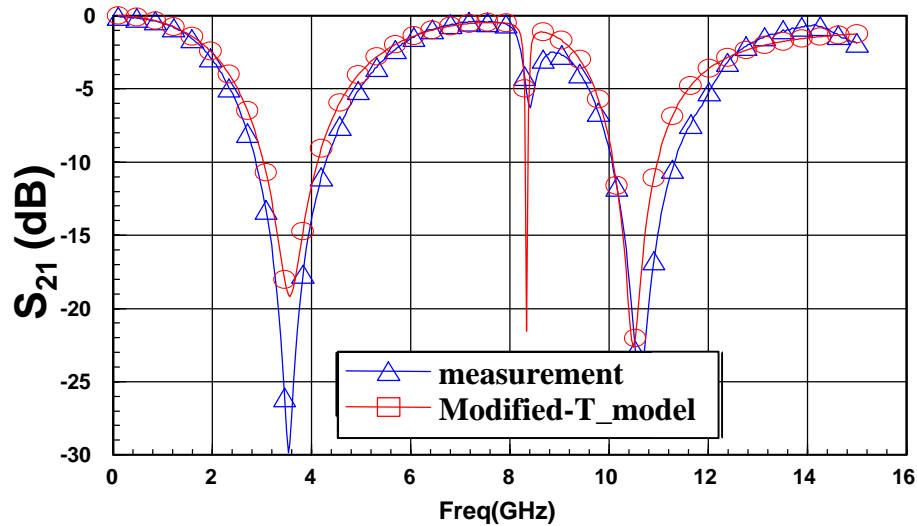


## Conventional $\pi$ model

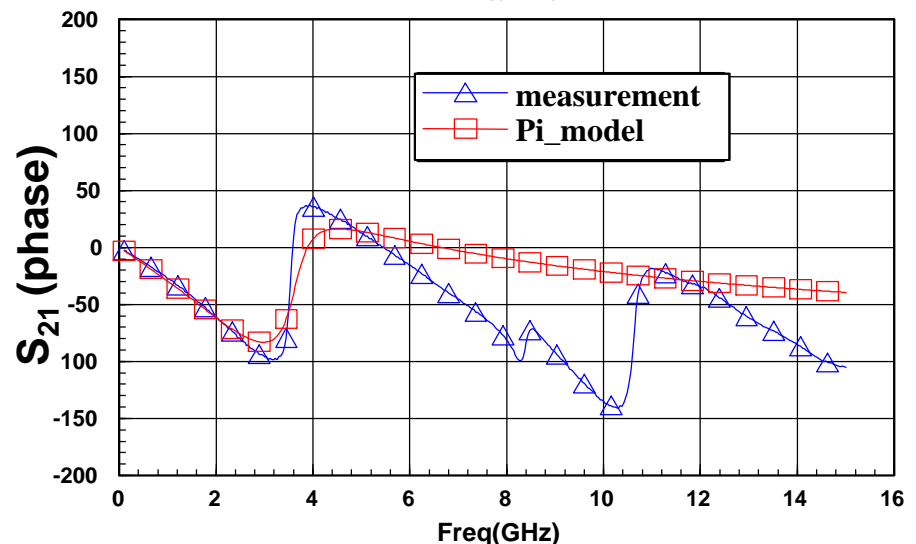
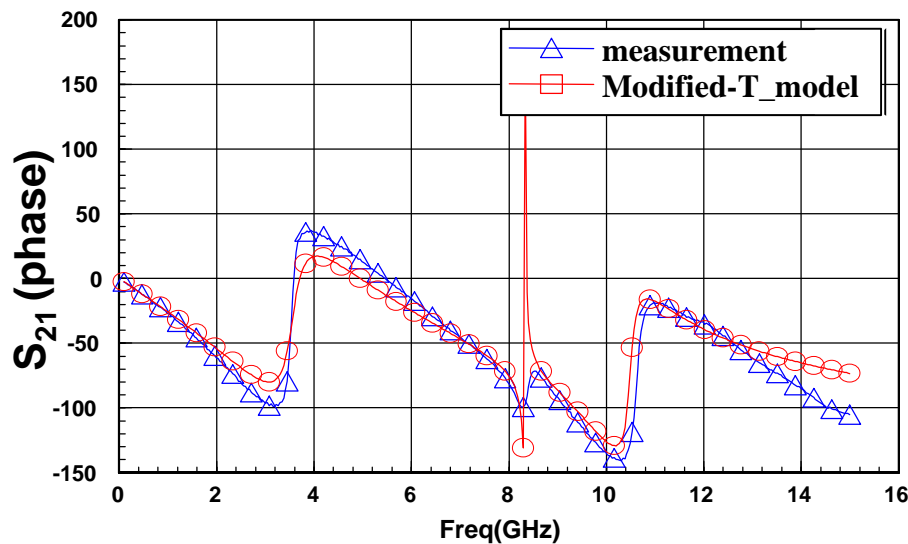
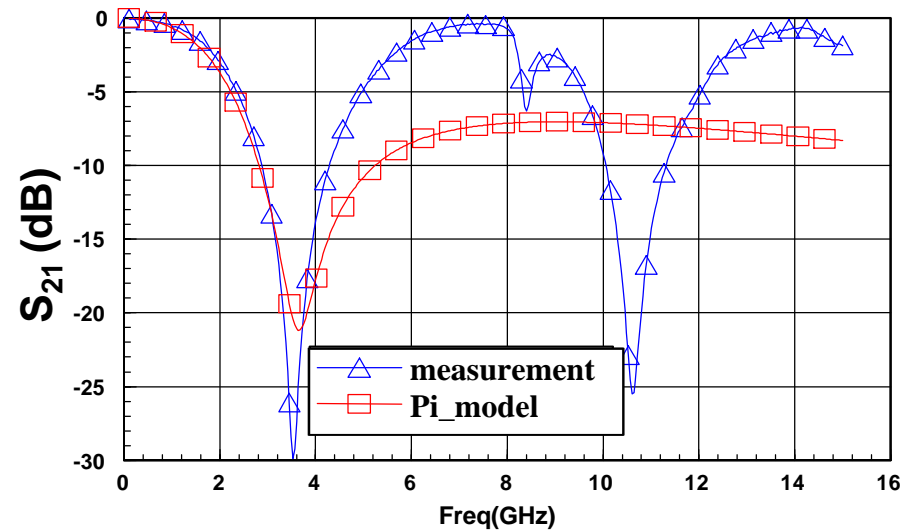


# Comparison of Bandwidth between Two Inductor Models

## Modified-T model



## Conventional $\pi$ model



# Outline

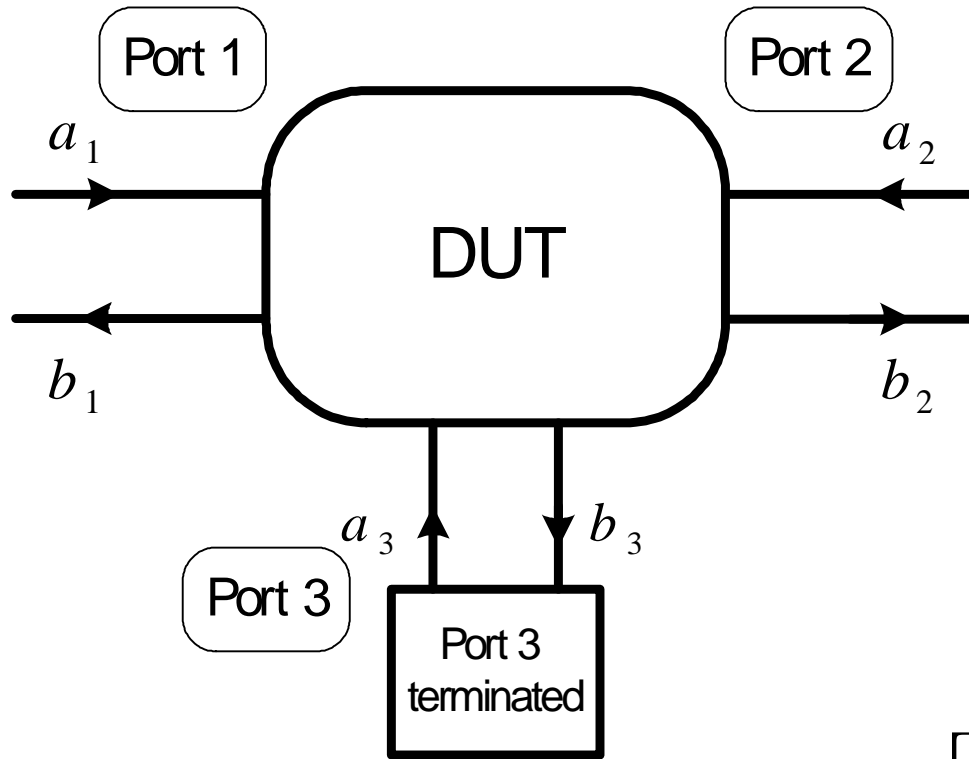
- ◆ LTCC Embedded Inductors
- ◆ **PCB Balanced Devices**
- ◆ Conclusions

# Measurement Systems for Multiport and Mixed-Mode S-Parameters

- Pure Mode Network Analyzer
- Multiport Network Analyzer Using Full-N Port Calibration
- Two-Port Network Analyzer Using Renormalization Techniques

# Port Termination Problem

## Three-port Network



Reflection due to port termination

$$\Gamma_3 = \frac{a_3}{b_3}$$

## Three-port S parameters

$$b_1 = S_{11}a_1 + S_{12}a_2 + S_{13}a_3$$

$$b_2 = S_{21}a_1 + S_{22}a_2 + S_{23}a_3$$

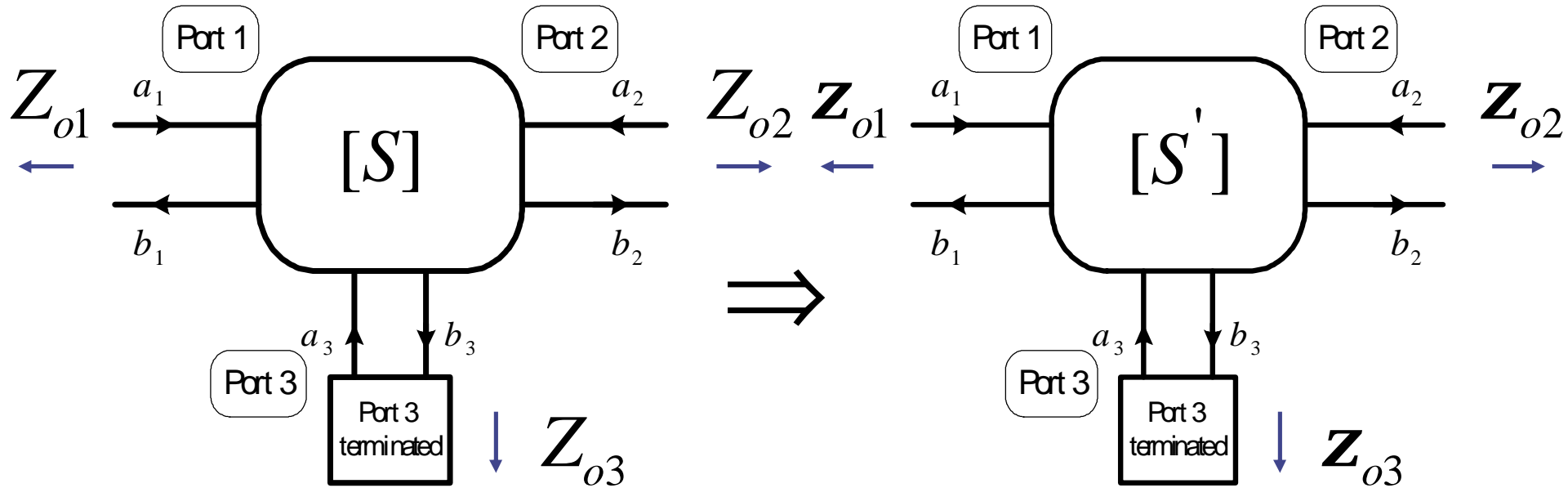
$$b_3 = S_{31}a_1 + S_{32}a_2 + S_{33}a_3$$

Measured two-port S parameters

$$[S^{p3t}] = \begin{bmatrix} S_{11}^{p3t} & S_{12}^{p3t} \\ S_{21}^{p3t} & S_{22}^{p3t} \end{bmatrix}$$

$$= \begin{bmatrix} S_{11} + \frac{S_{13}S_{31}\Gamma_3}{1 - S_{33}\Gamma_3} & S_{12} + \frac{S_{13}S_{32}\Gamma_3}{1 - S_{33}\Gamma_3} \\ S_{21} + \frac{S_{23}S_{31}\Gamma_3}{1 - S_{33}\Gamma_3} & S_{22} + \frac{S_{23}S_{32}\Gamma_3}{1 - S_{33}\Gamma_3} \end{bmatrix}$$

# Partial Renormalization



$$[S'] = ([U] - [S])^{-1} ([S] - [\Gamma]) ([U] - [S][\Gamma])^{-1} ([U] - [S])$$

where  $G_k = \frac{\mathbf{z}_{0k} - Z_{0k}}{\mathbf{z}_{0k} + Z_{0k}}$ , for  $k = 1, 2$

# Renormalization Transforms

- Three partial 2-port S-parameter measurements

$$[S^{p3t}] = \begin{bmatrix} S_{11}^{p3t} & S_{12}^{p3t} \\ S_{21}^{p3t} & S_{22}^{p3t} \end{bmatrix}, [S^{p2t}] = \begin{bmatrix} S_{11}^{p2t} & S_{13}^{p2t} \\ S_{31}^{p2t} & S_{33}^{p2t} \end{bmatrix}, [S^{p1t}] = \begin{bmatrix} S_{22}^{p1t} & S_{23}^{p1t} \\ S_{32}^{p1t} & S_{33}^{p1t} \end{bmatrix}$$

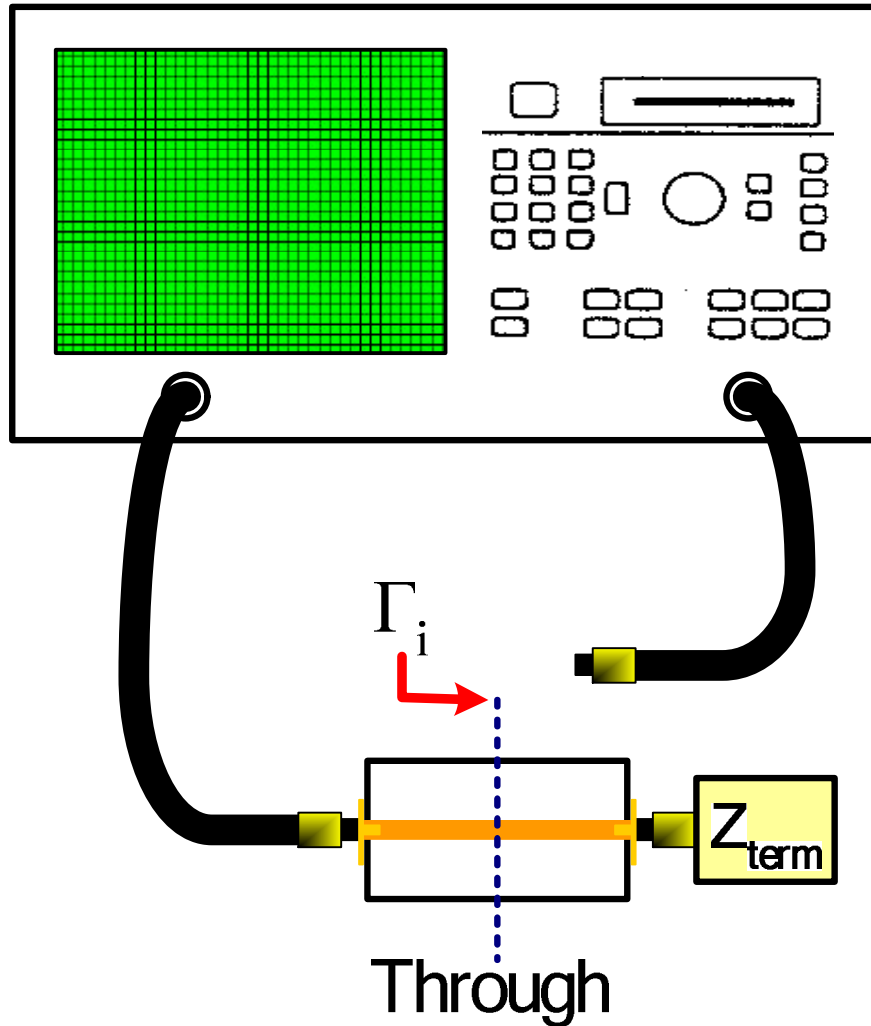
- After partial renormalizations

$$[S^{m1}] = \begin{bmatrix} S_{11}^{m1} & S_{12}^{m1} \\ S_{21}^{m1} & S_{22}^{m1} \end{bmatrix}, [S^{m2}] = \begin{bmatrix} S_{11}^{m2} & S_{13}^{m2} \\ S_{31}^{m2} & S_{33}^{m2} \end{bmatrix}, [S^{m3}] = \begin{bmatrix} S_{22}^{m3} & S_{23}^{m3} \\ S_{32}^{m3} & S_{33}^{m3} \end{bmatrix}$$

- Construct the S matrix of the three-port network normalized to  $[\zeta_0]$  and then transform it back to the S matrix normalized to  $[Z_0]$  :

$$[S'] = \begin{bmatrix} S_{11}^{m1} & S_{12}^{m1} & S_{13}^{m2} \\ S_{21}^{m1} & S_{22}^{m1} & S_{23}^{m3} \\ S_{31}^{m2} & S_{32}^{m3} & S_{33}^{m2} \end{bmatrix} \quad \text{renormalized to} \quad \Rightarrow \quad [S]$$

# Determination of $[\zeta_0]$



➤ Use TRL Calibration

$$\text{➤ } z_{0i} = Z_0 \frac{1 + \Gamma_i}{1 - \Gamma_i}$$

# DC-Block Branch-Line Coupler

Design guide

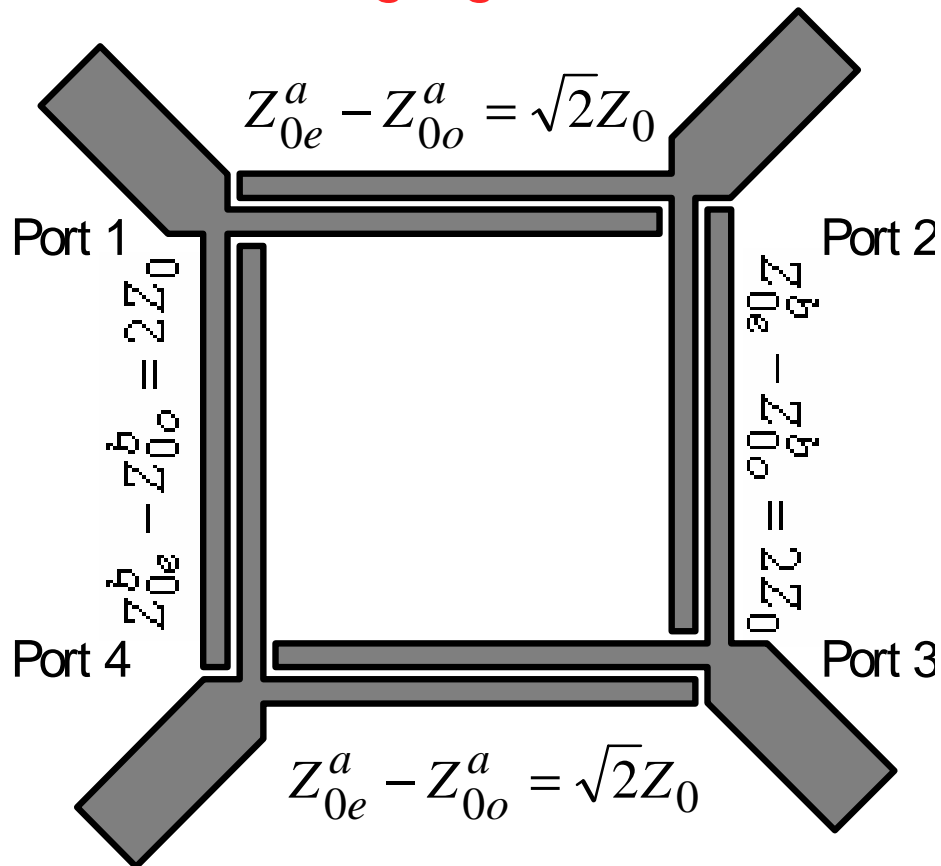
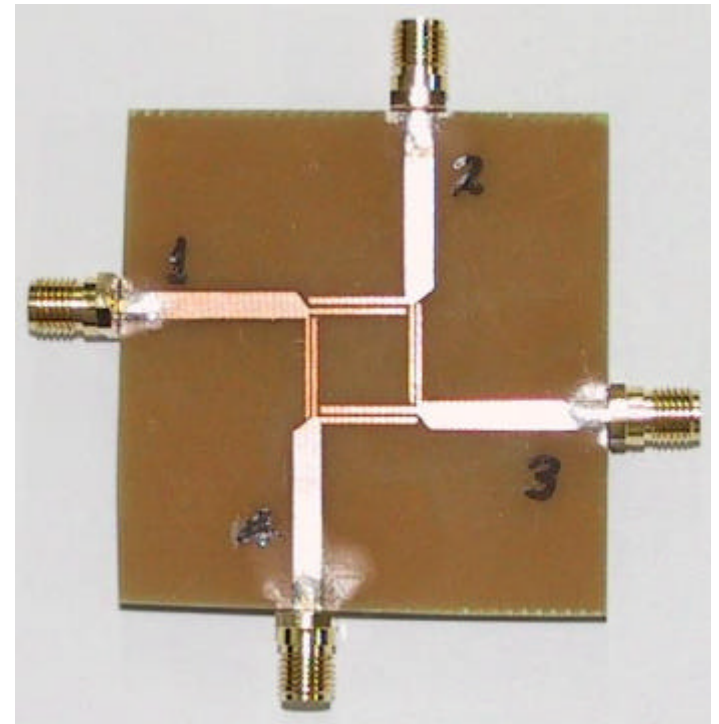
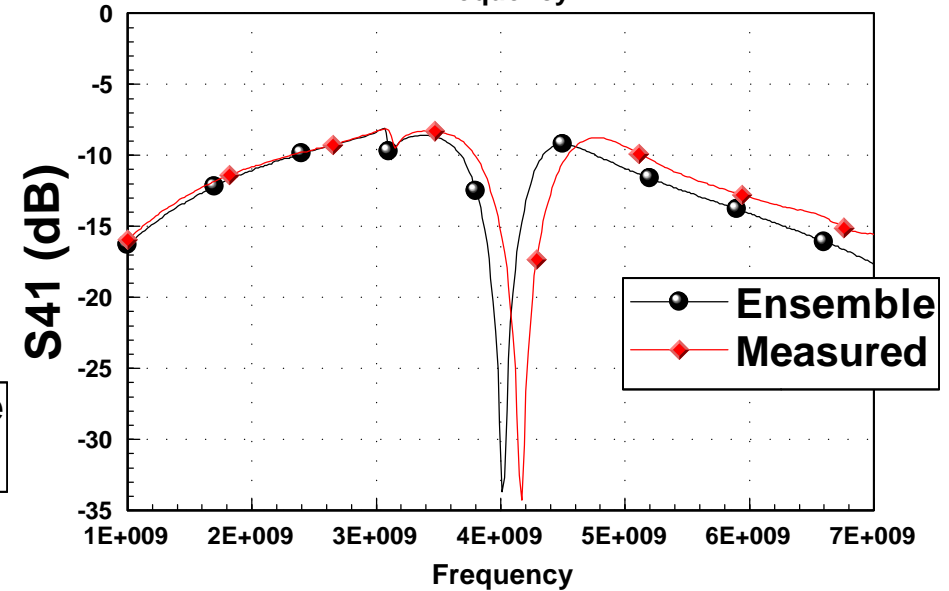
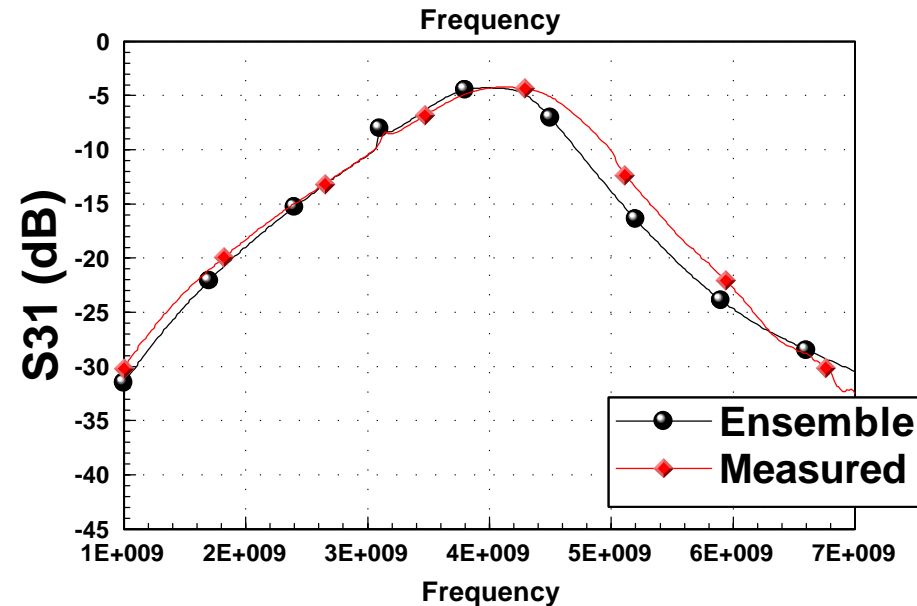
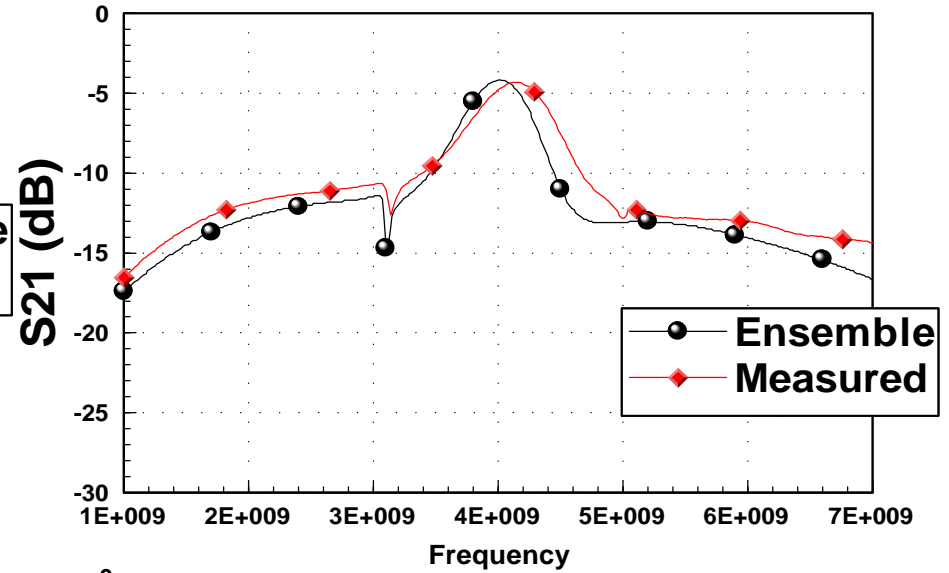
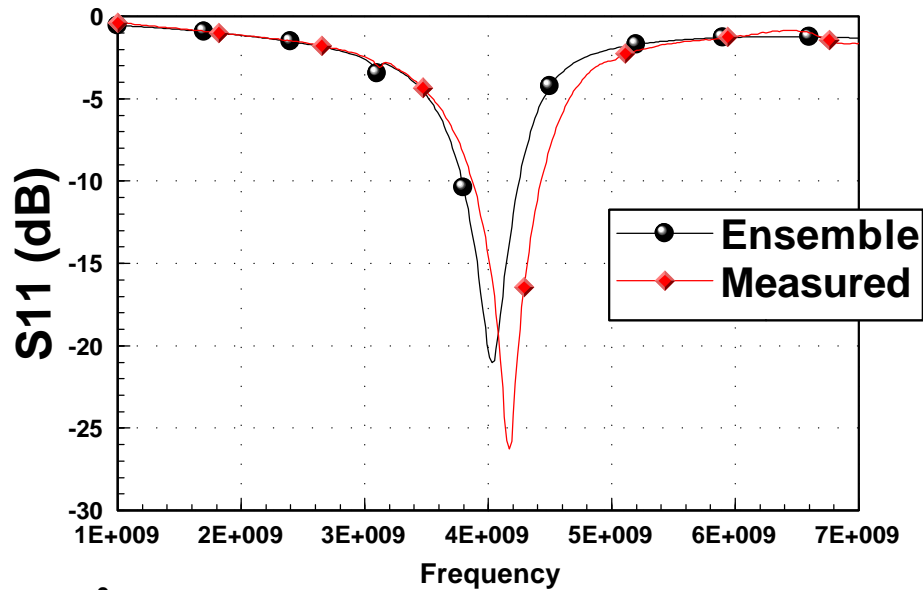


Photo of component



# Comparison between Ensemble Simulation and Measurement



# Impedance Transform Branch-Line Coupler

Design guide

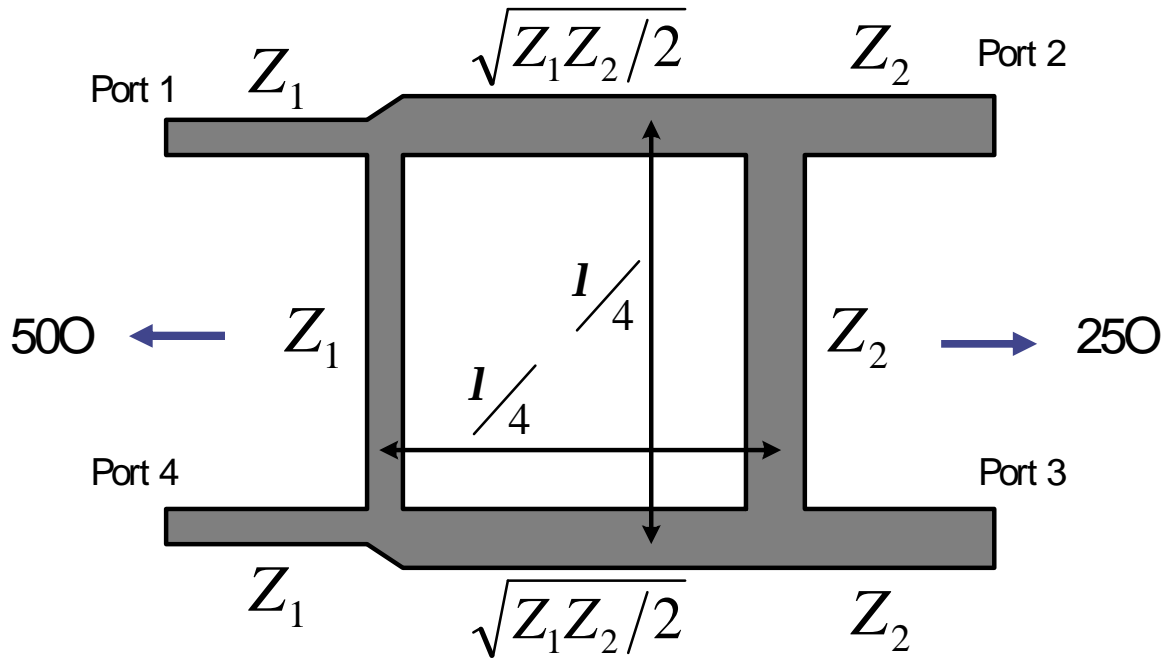
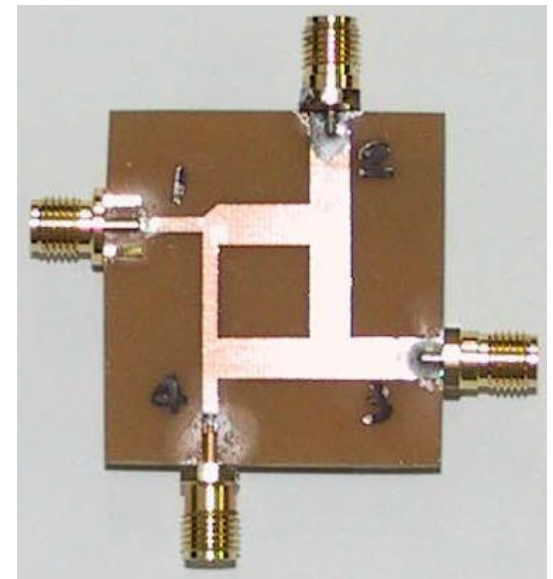


Photo of component

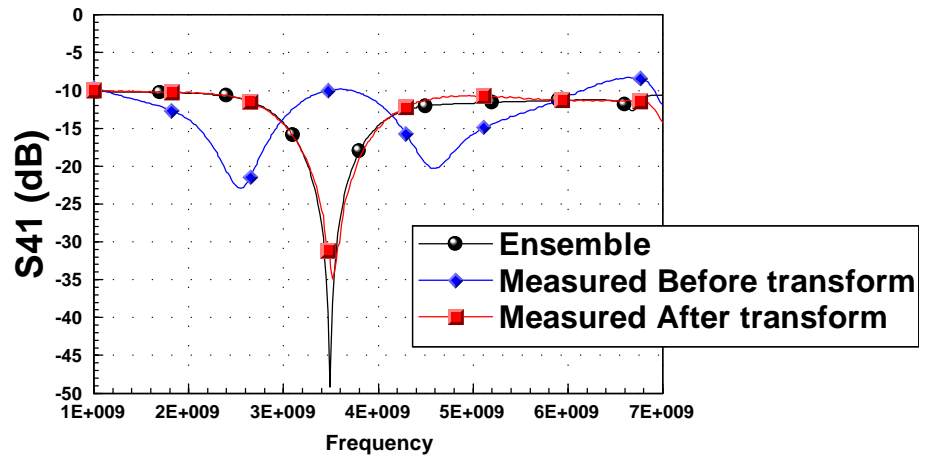
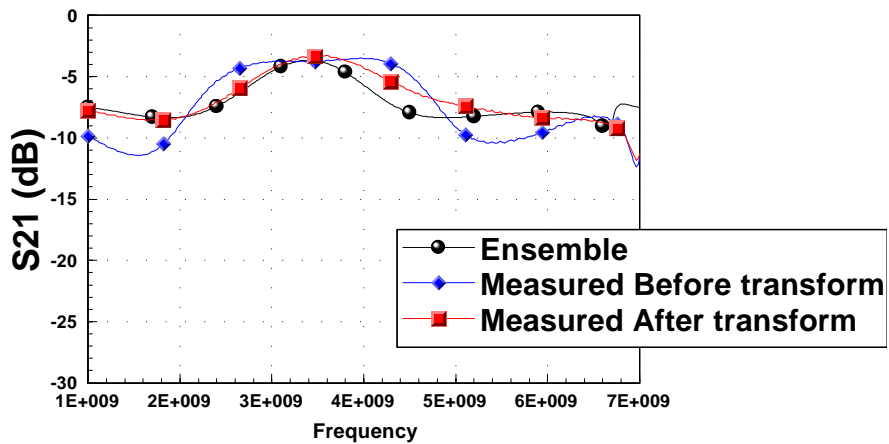
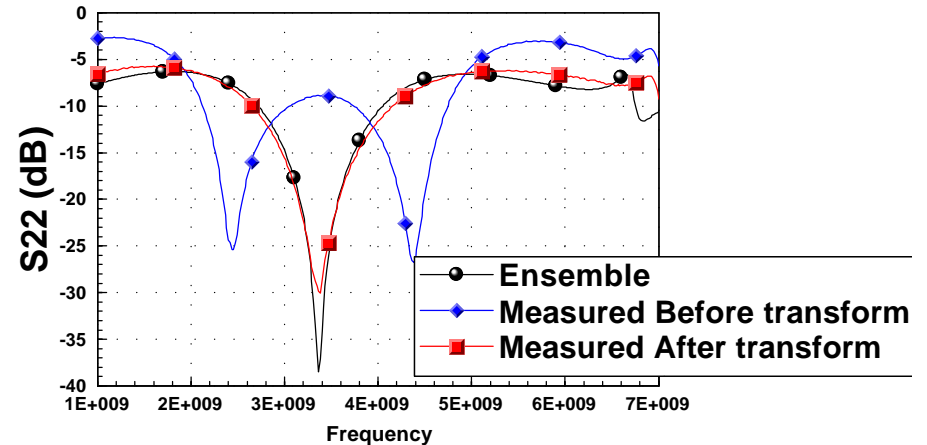
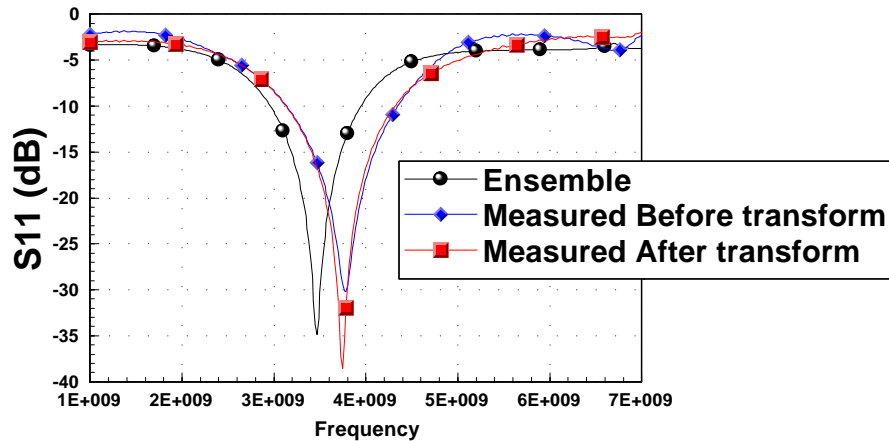


## Generalized S-parameter Transform

$$[S] \Rightarrow [Z]: [Z] = \sqrt{[Z_0]} ([U] - [S])^{-1} ([U] + [S]) \sqrt{[Z_0]}^{-1}$$

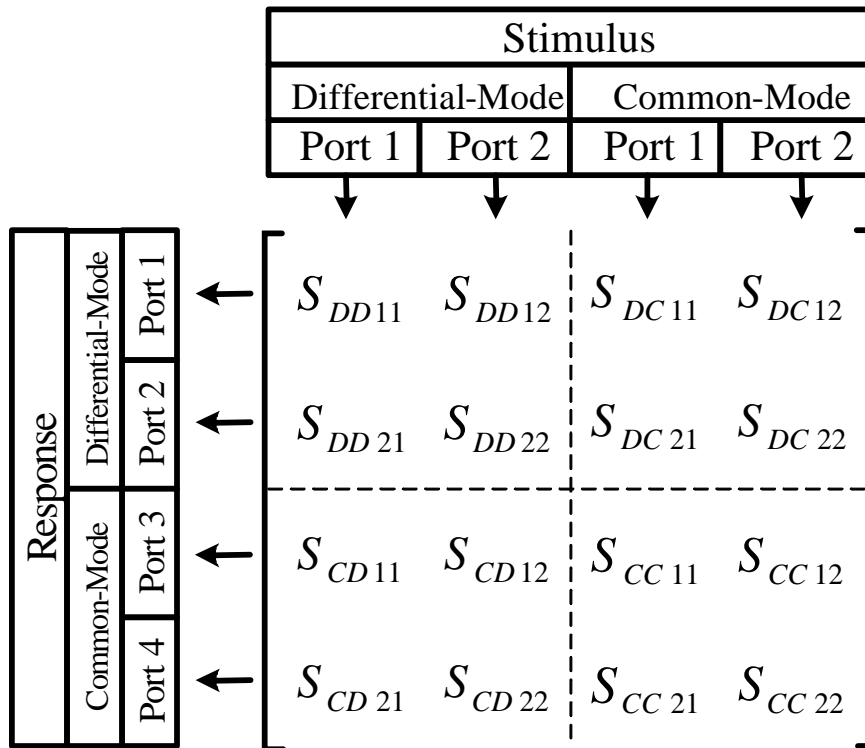
$$[Z] \Rightarrow [S']: [S'] = \sqrt{[x_0]}^{-1} ([Z] - [x_0]) ([Z] + [x_0])^{-1} \sqrt{[x_0]}$$

# Comparison between Ensemble Simulation and Measurement



# Mixed-Mode S parameters

## Mixed-Mode S Matrix



Common-Mode Rejection Ratio

$$\text{CMRR} = \frac{S_{DD21}}{S_{CC21}}$$

$$\begin{bmatrix} [b_D] \\ [b_C] \end{bmatrix} = \begin{bmatrix} [S_{DD}] & [S_{DC}] \\ [S_{CD}] & [S_{CC}] \end{bmatrix} \begin{bmatrix} [a_D] \\ [a_C] \end{bmatrix} = [S^{mm}] \begin{bmatrix} [a_D] \\ [a_C] \end{bmatrix}$$

# Mixed-Mode Transform

$$\begin{bmatrix} a_{D1} \\ a_{D2} \\ a_{C1} \\ a_{C2} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix}$$

$$\Rightarrow [a^{mm}] = [M][a^{se}]$$

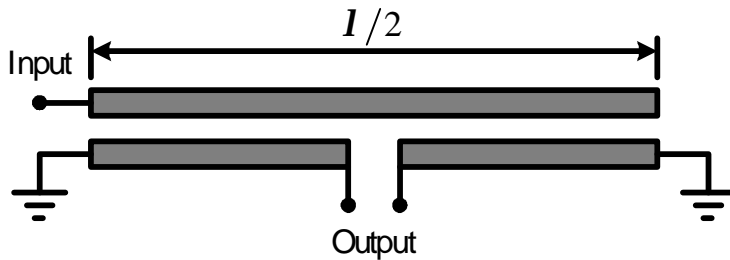
$$[S^{mm}] = [M][S^{se}][M]^{-1}$$

$$\begin{bmatrix} b_{D1} \\ b_{D2} \\ b_{C1} \\ b_{C2} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix}$$

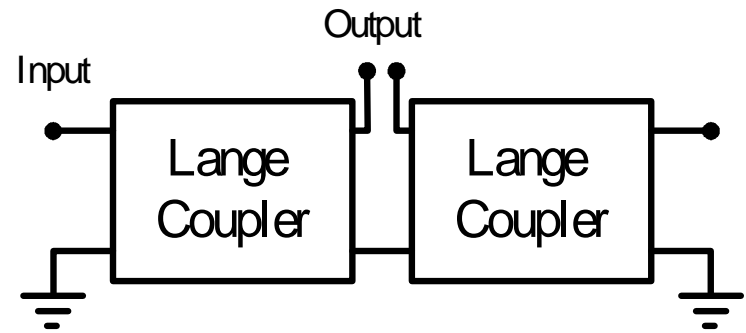
$$\Rightarrow [b^{mm}] = [M][b^{se}]$$

# Lange-Type Marchand Balun

Design guide



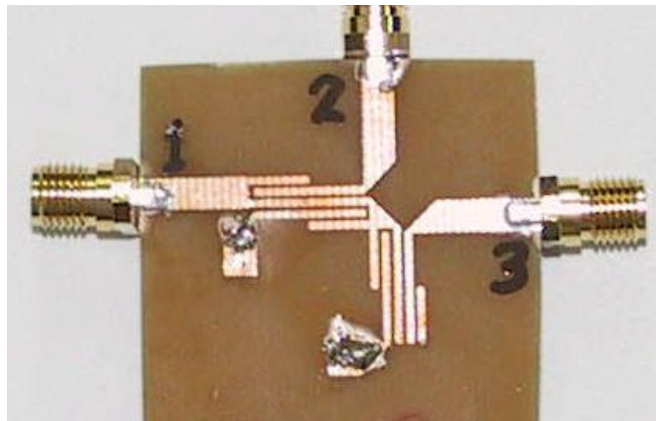
Planar type



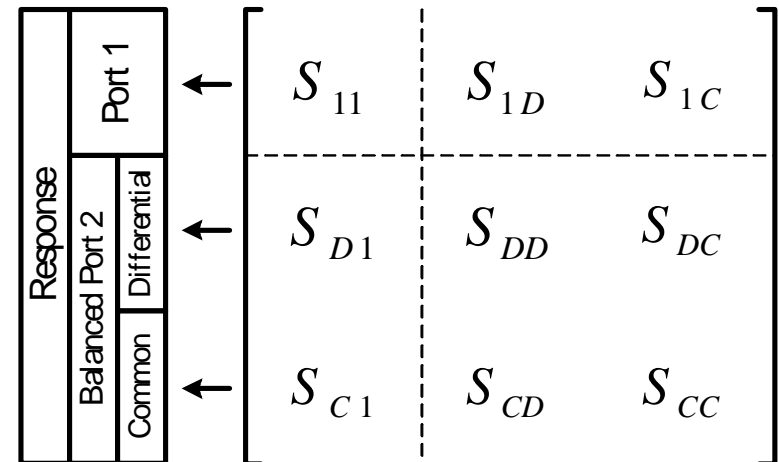
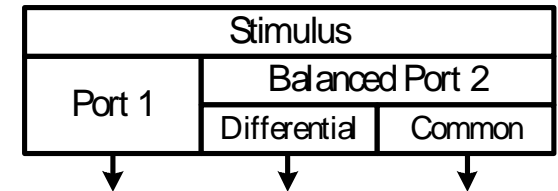
Lange type

$$C = \left( \sqrt{1 + \frac{2Z_0^{\text{out}}}{Z_0^{\text{in}}}} \right)^{-1}, \quad [M] = \frac{1}{\sqrt{2}} \begin{bmatrix} \sqrt{2} & 0 & 0 \\ 0 & 1 & -1 \\ 0 & 1 & 1 \end{bmatrix}$$

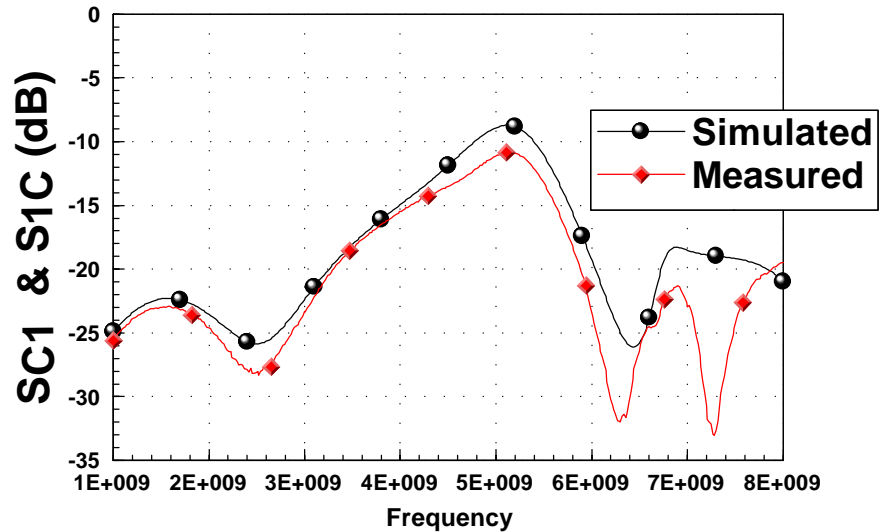
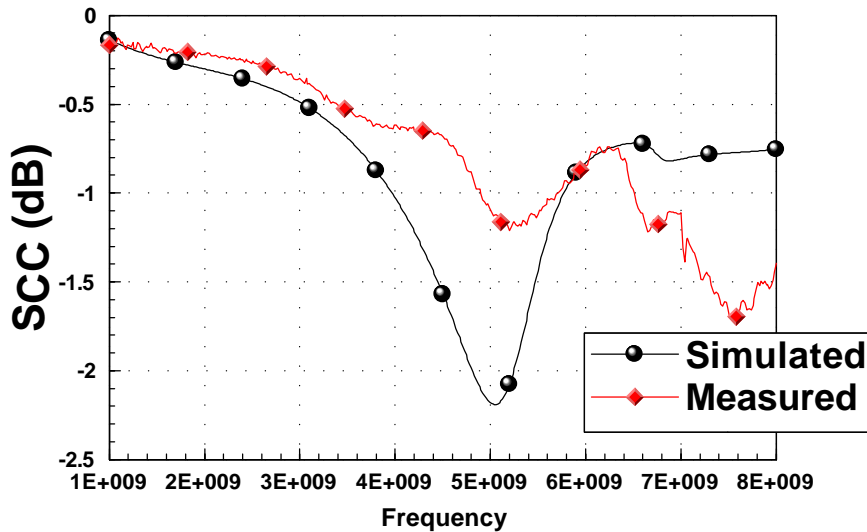
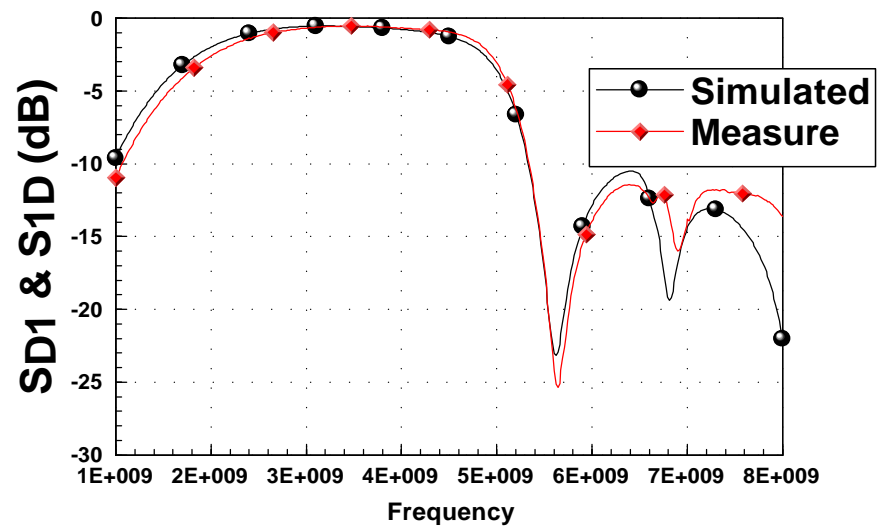
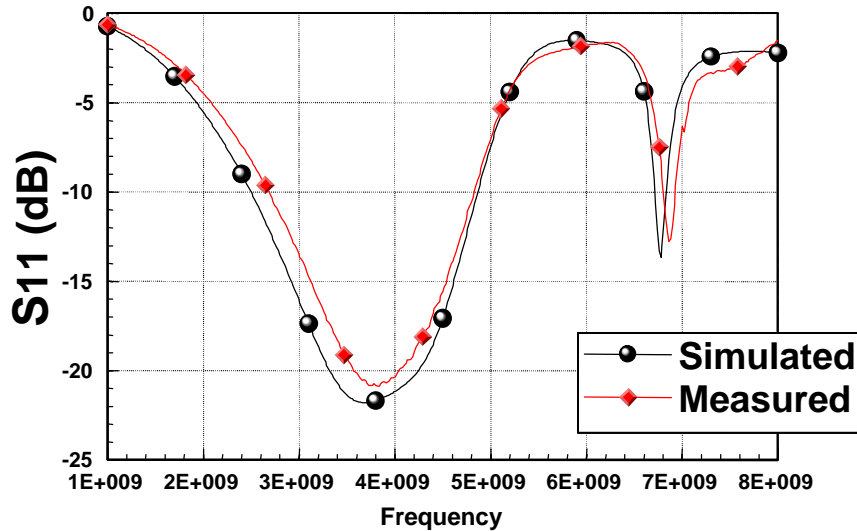
Photo of component



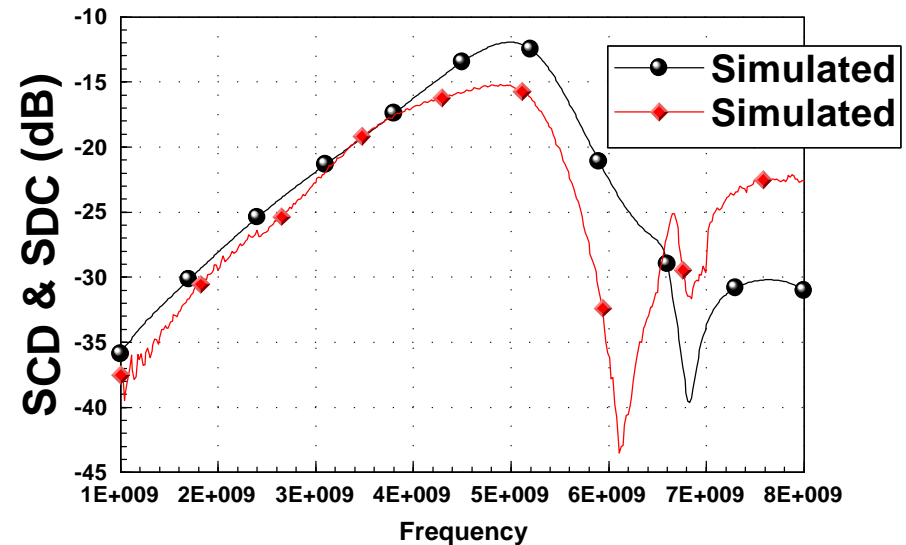
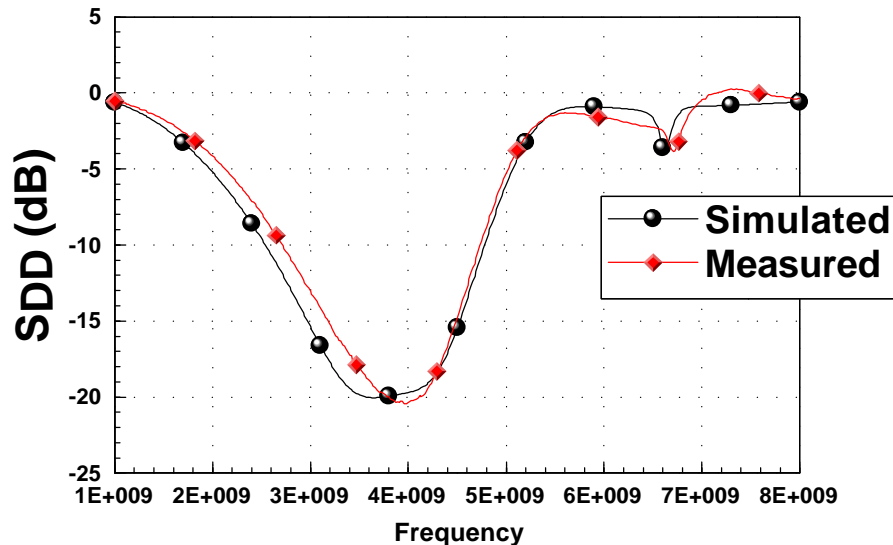
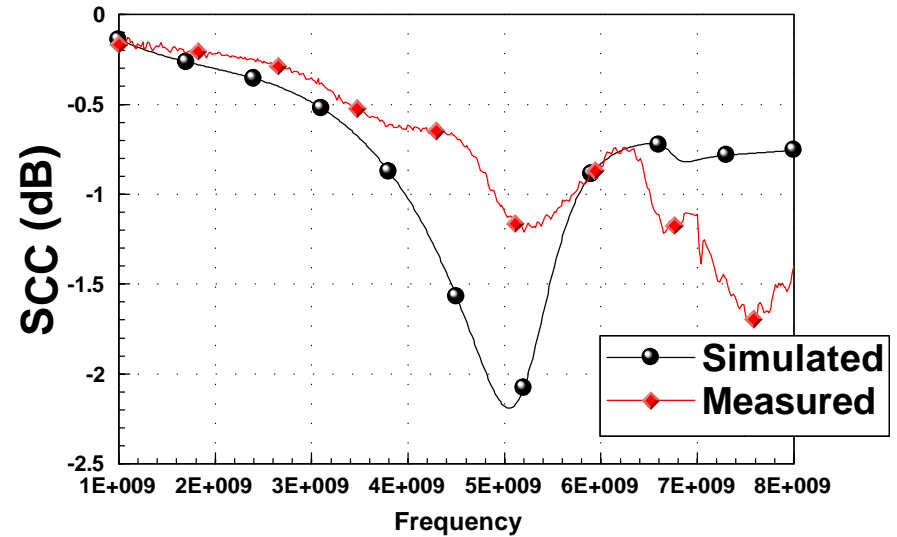
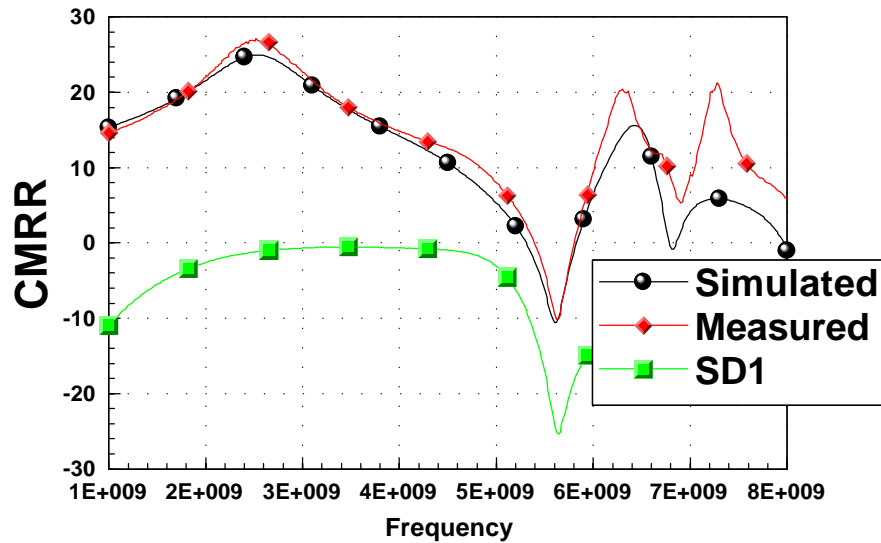
Mixed-mode [S]



# Comparison between HFSS Simulation and Measurement

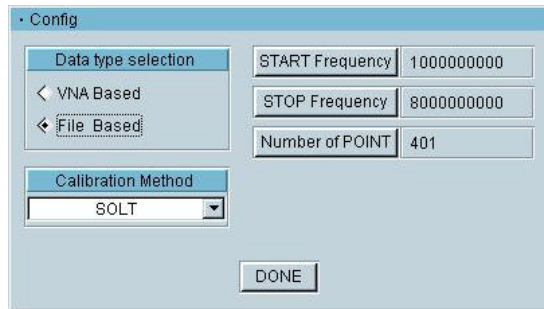


# Comparison between HFSS Simulation and Measurement

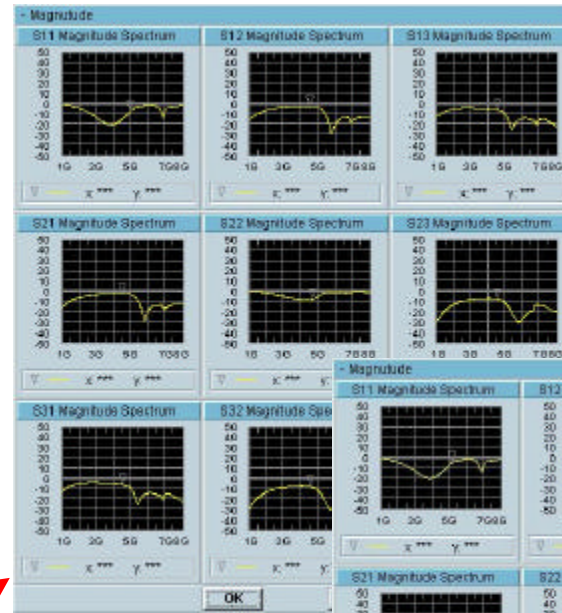


# Semi-Automatic Measurement System

VNA setup via Vee

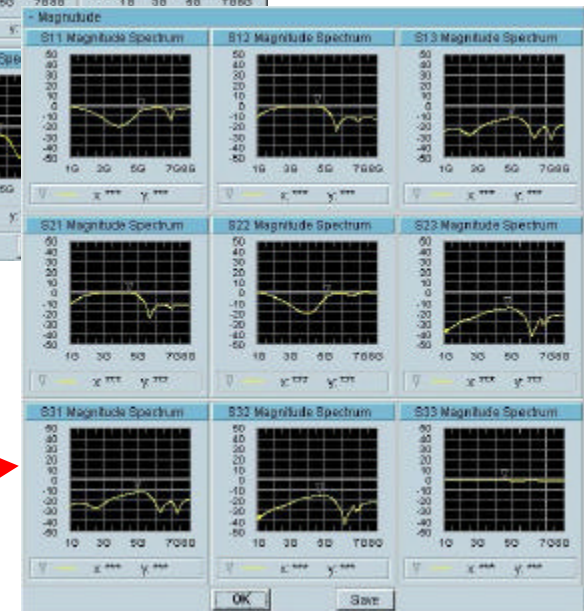
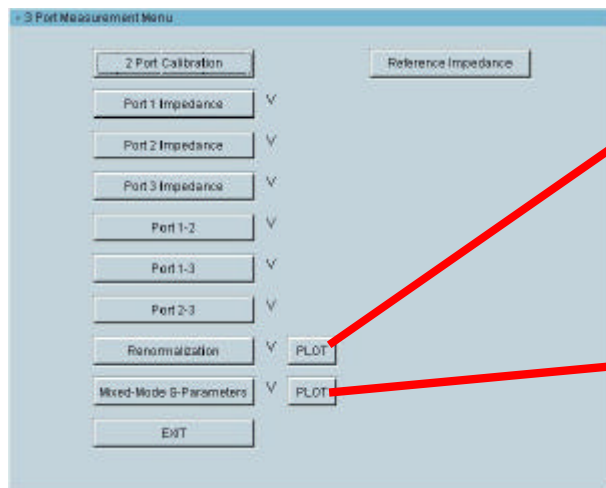


Single-ended S parameters



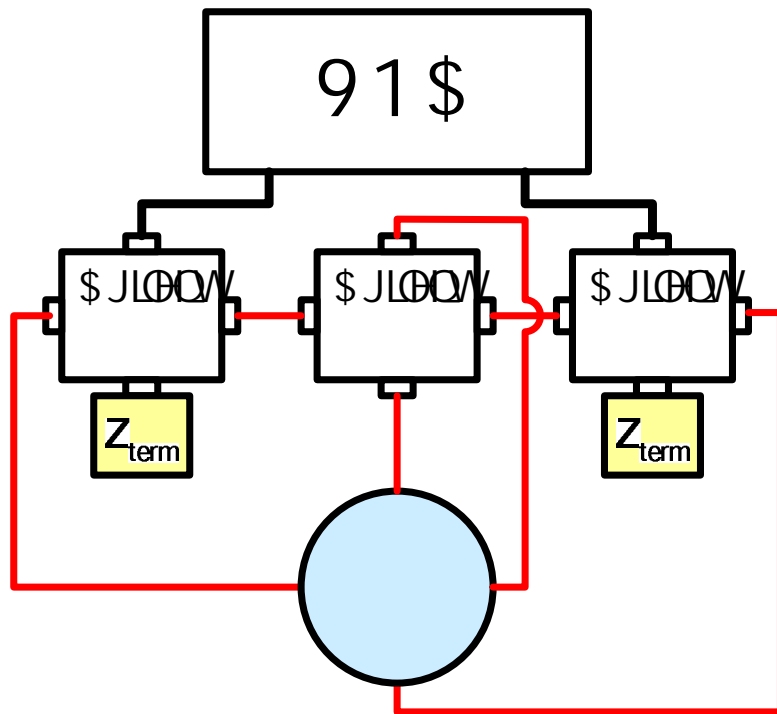
Mixed-Mode S Parameters

Measure, renormalize and Transform

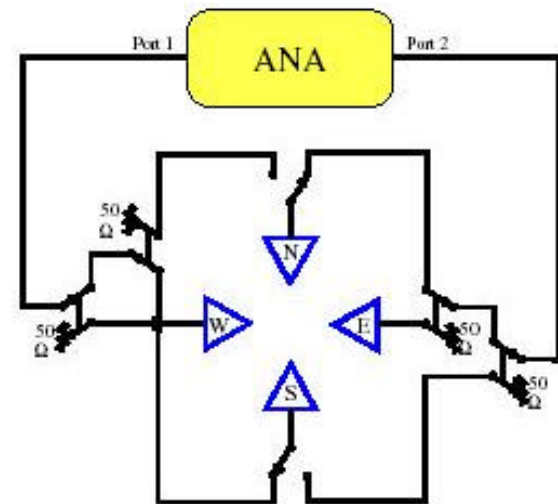


# Application to On-Wafer Measurement

Our proposed System



System made by NIST



# Conclusions

- Various types of LTCC Embedded Inductors have been designed and measured. Simulated results agree with measurements quite well.
- A new modified-T equivalent circuit has been proposed to model LTCC inductors over an extremely large bandwidth successfully.
- Very cost-effective multiport network analyzer system based on renormalization techniques has been developed to measure balanced devices.
- Several examples of multiport and balanced devices on PCB have been designed and measured. Comparison between simulation and measurement shows excellent agreement.

# References

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2. J.C. Tippet and R.A. Speciale, “A rigorous technique for measuring the scattering matrix of a multiport device with a 2-port network analyzer,” IEEE Transactions on Microwave Theory and Techniques, pp. 661-666, May 1982.
3. L.-Q. Yang, Design and modeling of embedded inductors and capacitors in low-temperature cofired ceramic technology, Master’s Thesis, National Sun Yat-Sen University at Kaohsiung Taiwan, 2002.
4. D.-C. Tsai, Measurement of balanced devices using vector network analyzers, Master’s Thesis, National Sun Yat-Sen University at Kaohsiung, Taiwan, 2002.