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

Prof. T.S. Horng (? ? ?)

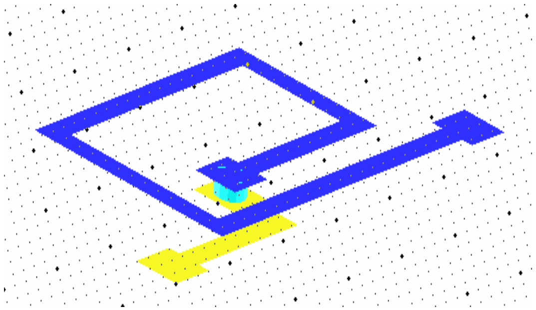
E.E. Dept., National Sun Yat-Sen Univ.

Email: jason@ee.nsysu.edu.tw

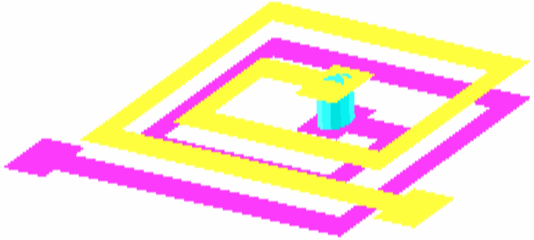
Outline

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

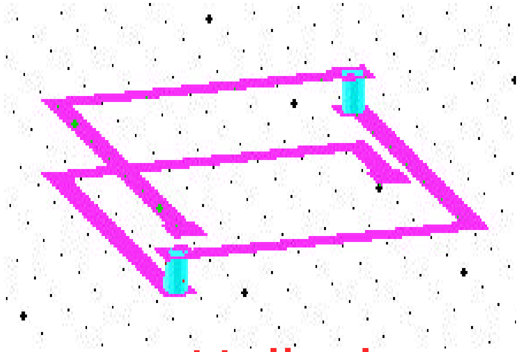
Design Trend



Planar Spiral



Stacked Spiral



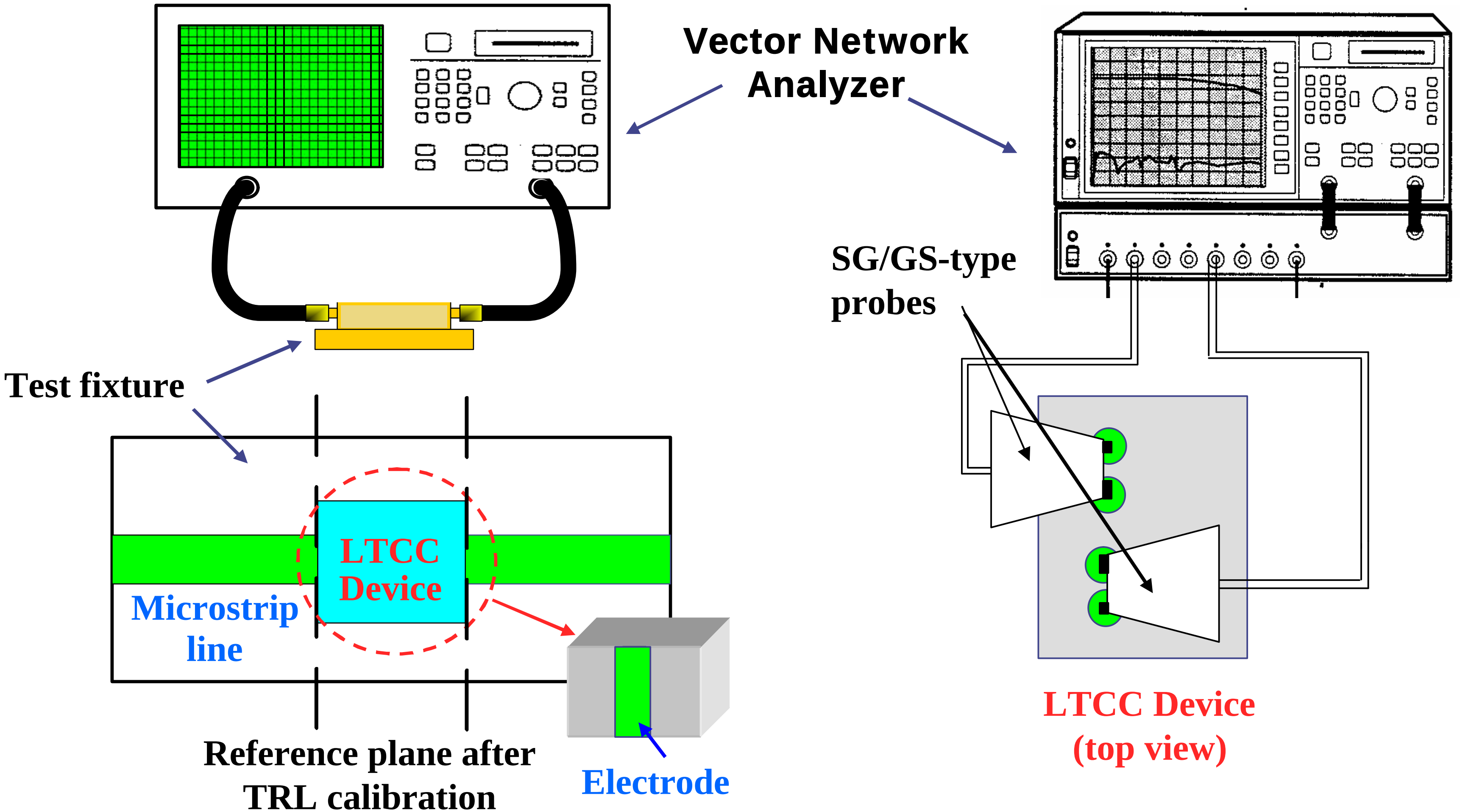
Helical

LTCC Inductor	Planar Spiral	Stacked Spiral	Helical
Area (under the same L_{eff})	Large	Smaller	Smallest
SRF (under the same L_{eff})	Low	Higher	Highest
Q (under the same L_{eff})	Low	Higher	Highest
No. of Layers	2	2	≥ 2

Measurement Techniques

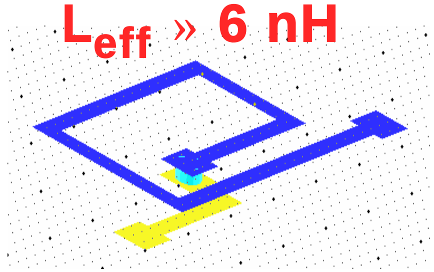
Test Fixture

Microwave Probes

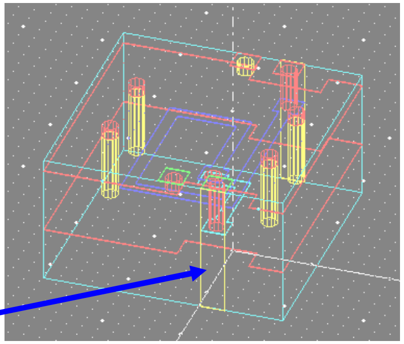


Test-Fixture Measurement vs. HFSS Simulation

Spiral inductor

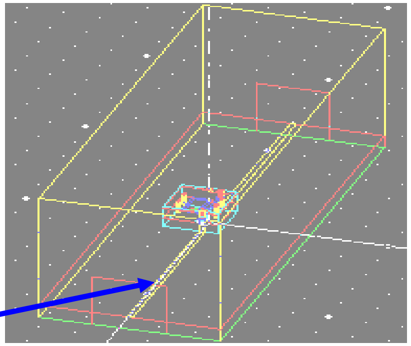


The whole LTCC device

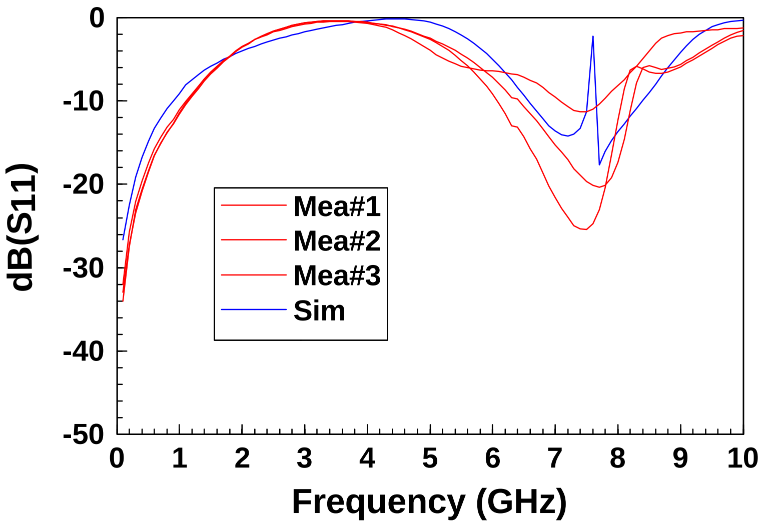


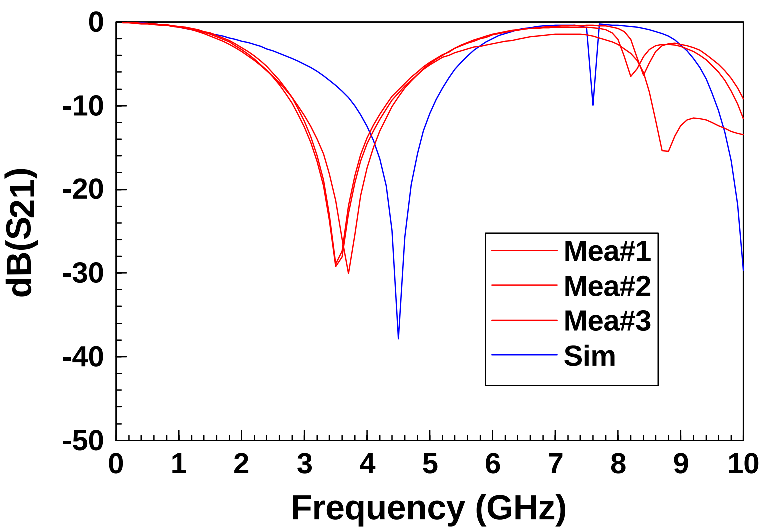
Electrode

LTCC device on test fixture

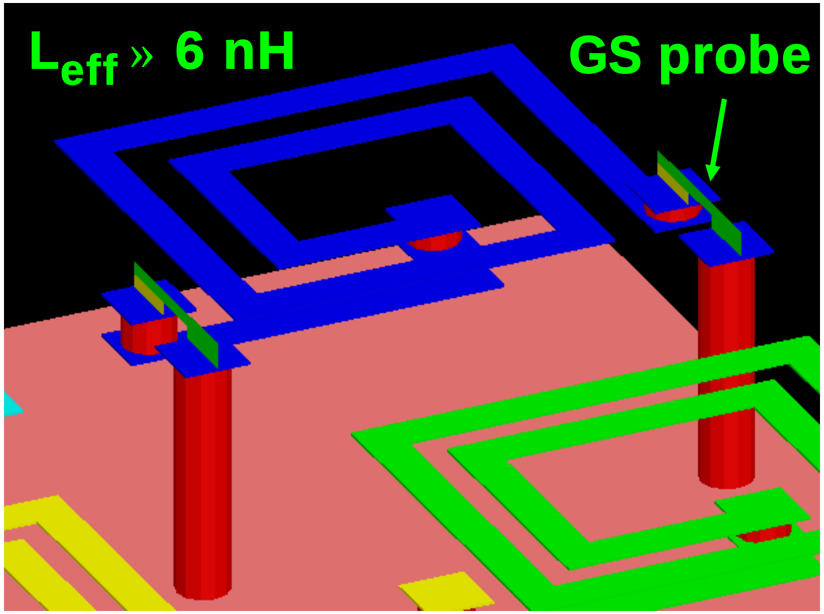


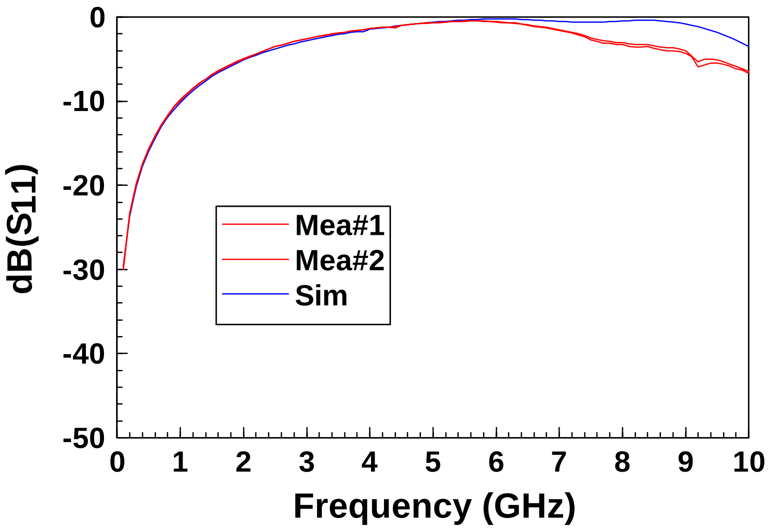
Microstrip line

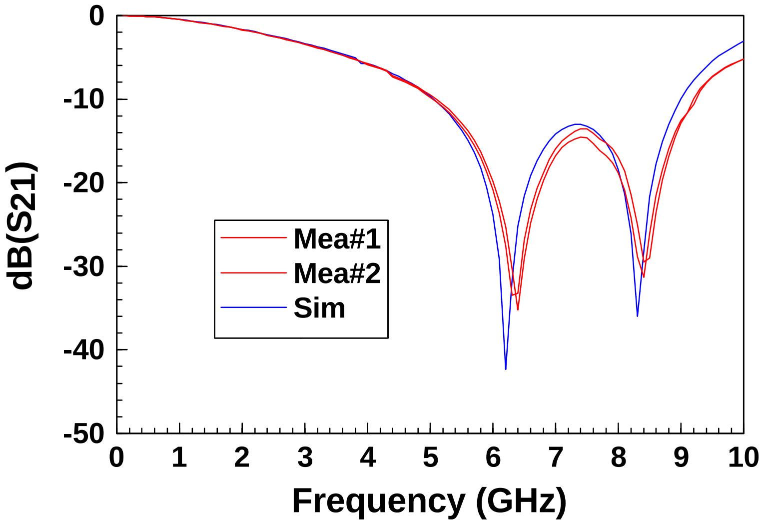




Microwave-Probe Measurement vs. HFSS Simulation







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

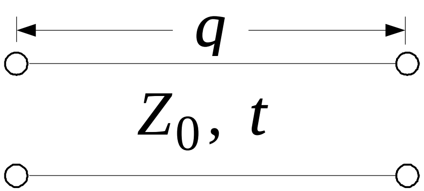
A New Modified-T Model for Lossless Transmission Line

Lossless transmission line

Z_0: Characteristic impedance

τ: Propagation delay

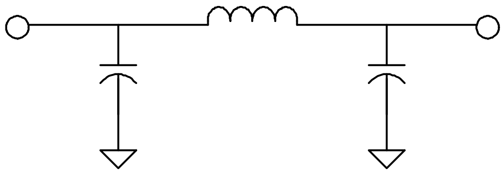
θ: Electrical length



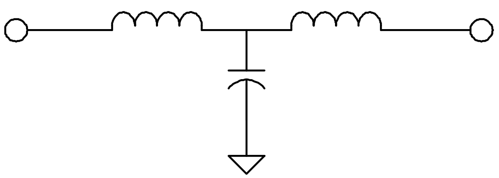
? $\approx$

$$\theta = 0 \rightarrow \pi \Leftrightarrow \omega = 0 \rightarrow \omega_{\theta}$$

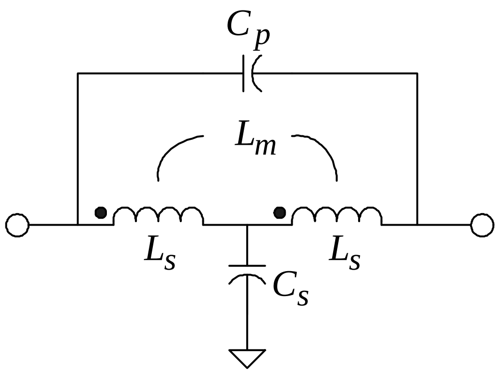
Equivalent π model



Equivalent T model



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 π ?

Derivation of Element Values of Equivalent Modified-T Model

$$
\begin{bmatrix} \dfrac{-j\cot q}{Z_0} & \dfrac{j\csc q}{Z_0} \\ \dfrac{j\csc q}{Z_0} & \dfrac{-j\cot q}{Z_0} \end{bmatrix} \approx
$$

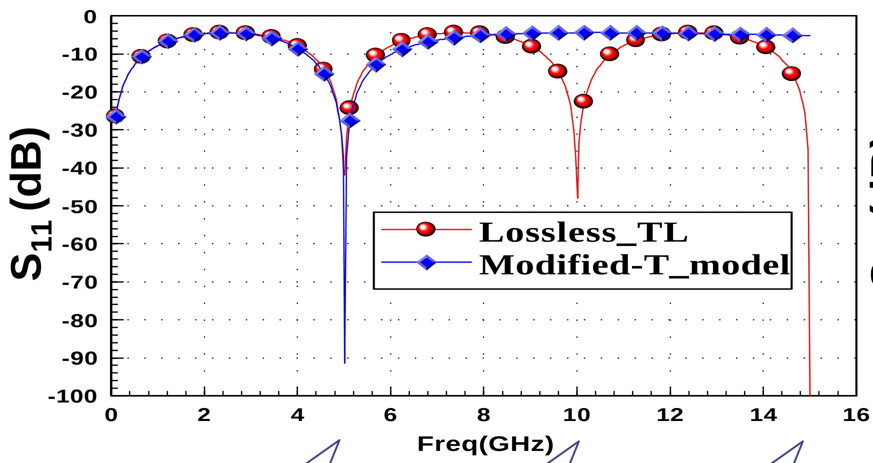
$$
\begin{bmatrix}
\dfrac{jw L_s + \dfrac{1}{jw C_s}}{jw(L_s+L_m)\left[jw(L_s-L_m)+\dfrac{2}{jw C_s}\right]} + jw C_p & \dfrac{jw L_m - \dfrac{1}{jw C_s}}{jw(L_s+L_m)\left[jw(L_s-L_m)+\dfrac{2}{jw C_s}\right]} - jw C_p \\
\dfrac{jw L_m - \dfrac{1}{jw C_s}}{jw(L_s+L_m)\left[jw(L_s-L_m)+\dfrac{2}{jw C_s}\right]} - jw C_p & \dfrac{jw L_s + \dfrac{1}{jw C_s}}{jw(L_s+L_m)\left[jw(L_s-L_m)+\dfrac{2}{jw C_s}\right]} + jw C_p
\end{bmatrix}
$$

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

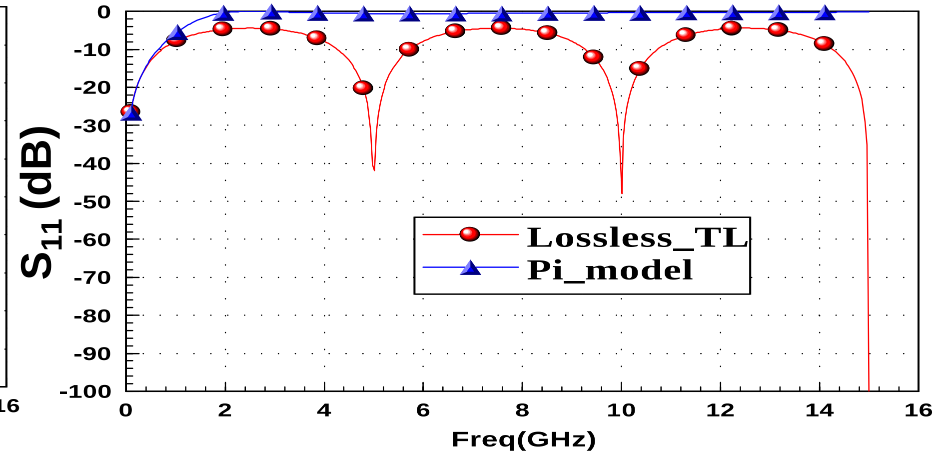
$$
C_s \approx \frac{t}{Z_0}\ \text{(F)},\quad C_p \approx \frac{t}{Z_0 p^2}\ \text{(F)}
$$

Comparison of Bandwidth among Equivalent Models

Modified-T model



π model

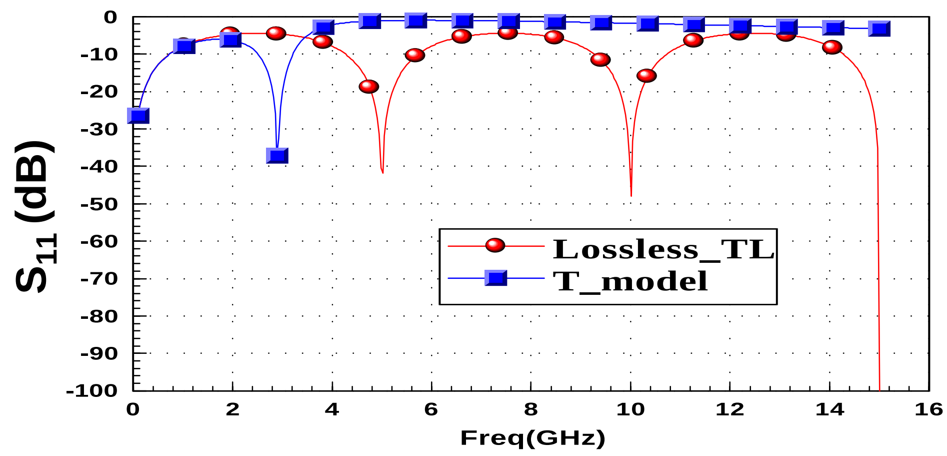


q = p

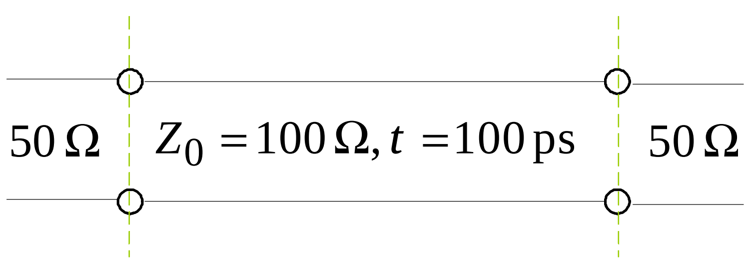
q = 2p

q = 3p

T model

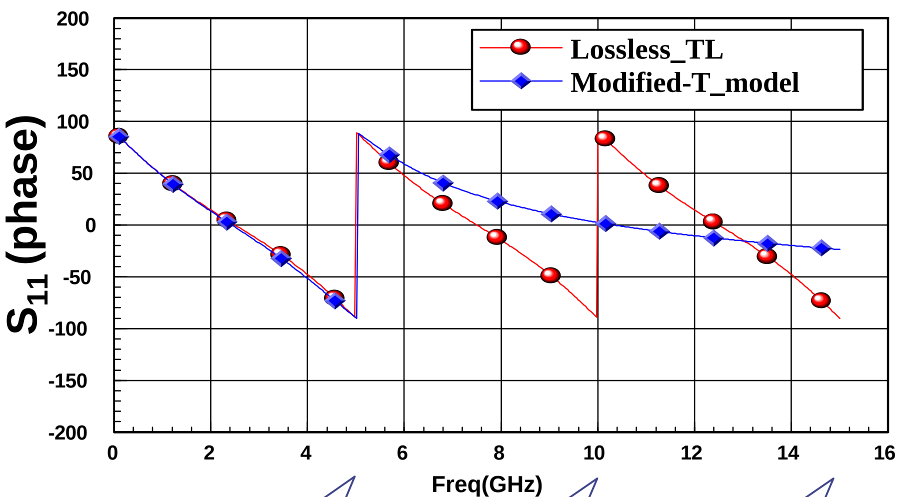


Transmission-line circuit



Comparison of Bandwidth among Equivalent Models

Modified-T model

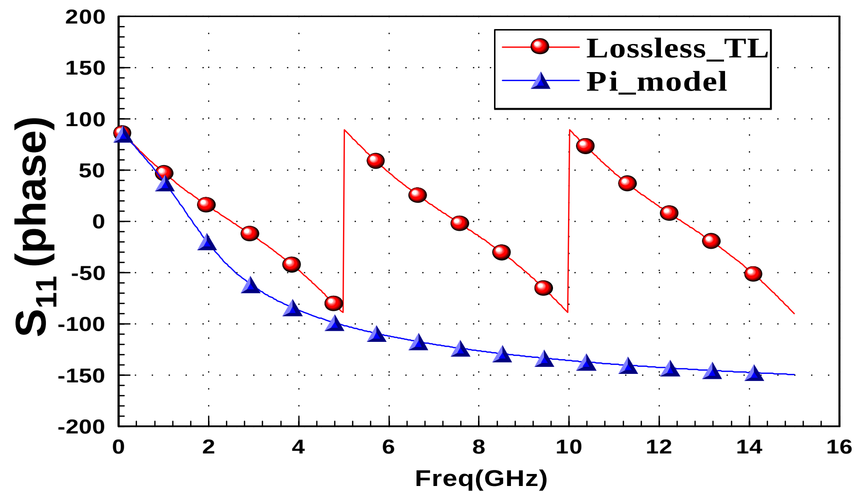


q = p

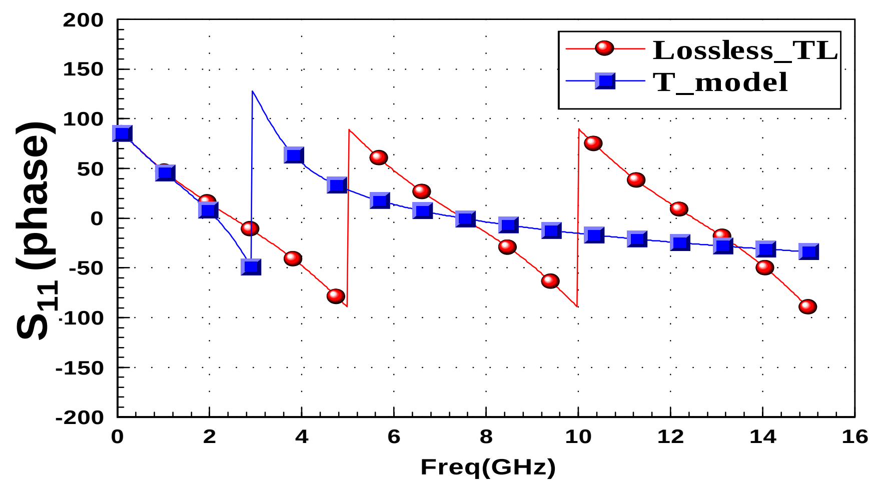
q = 2p

q = 3p

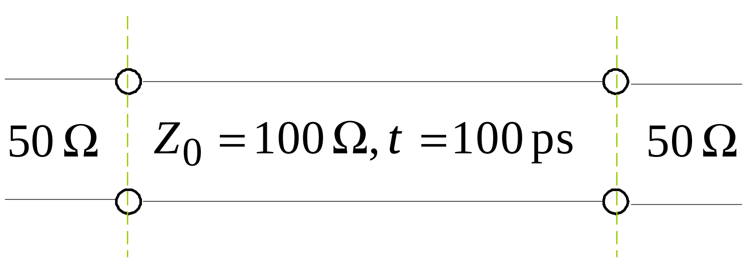
π model



T model

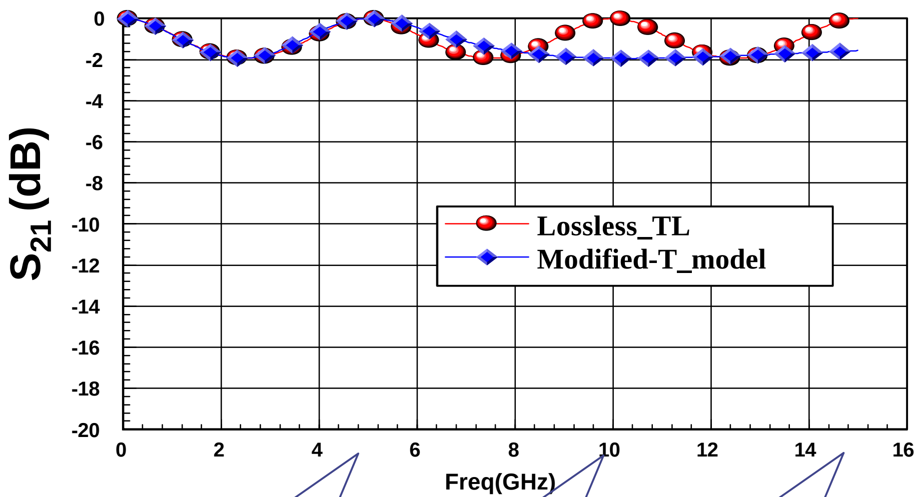


Transmission-line circuit



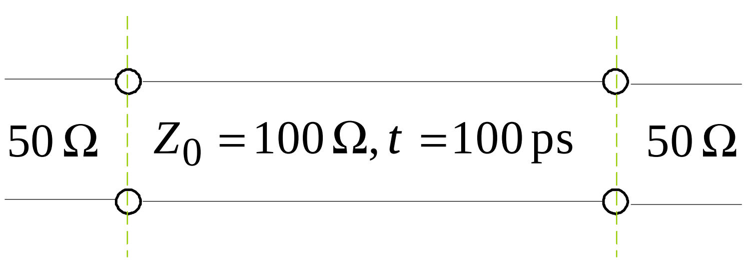
Comparison of Bandwidth among Equivalent Models

Modified-T model

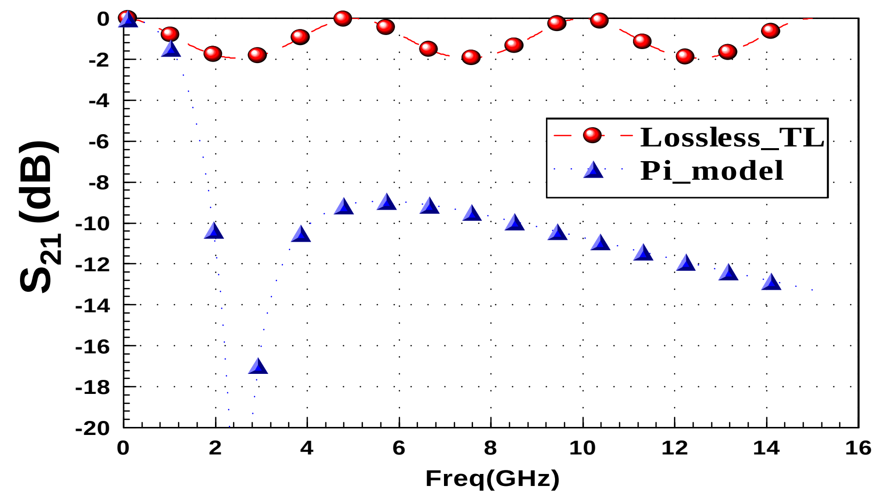


$q = p$ $q = 2p$ $q = 3p$

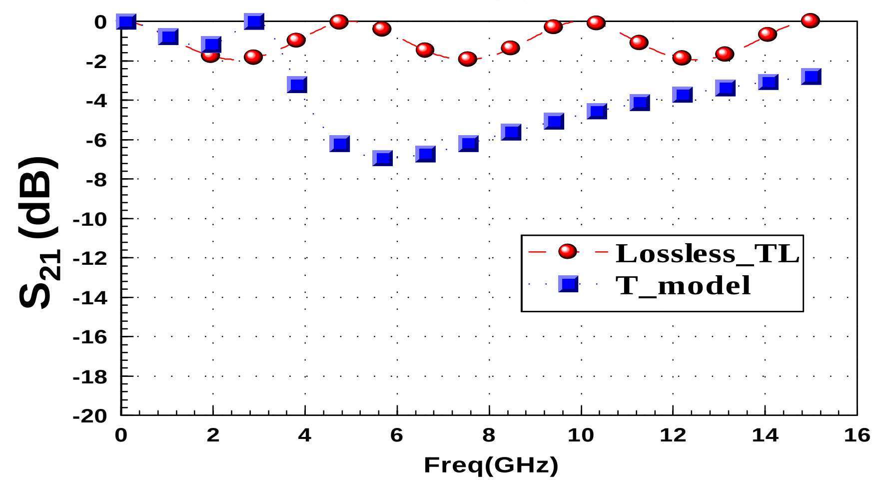
Transmission-line circuit



π model

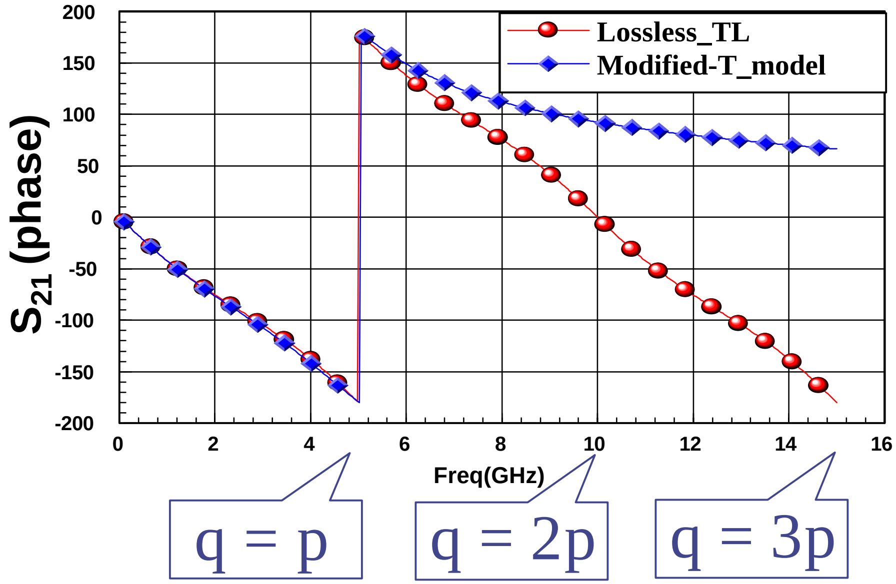


T model

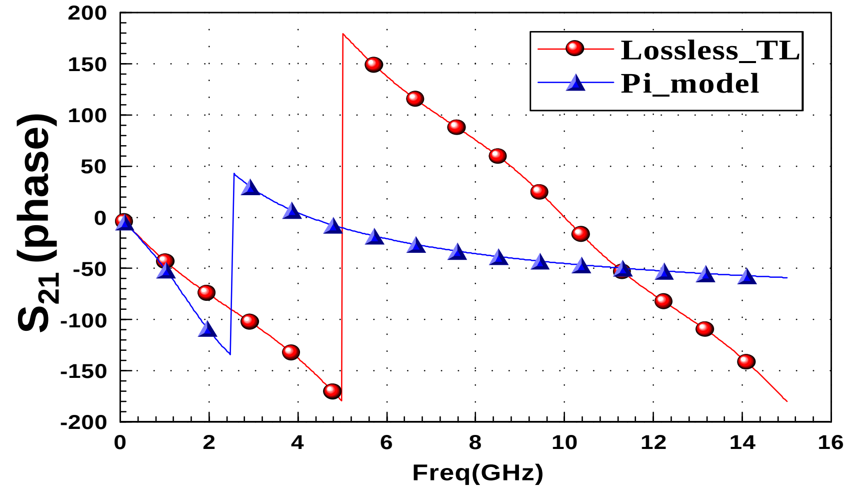


Comparison of Bandwidth among Equivalent Models

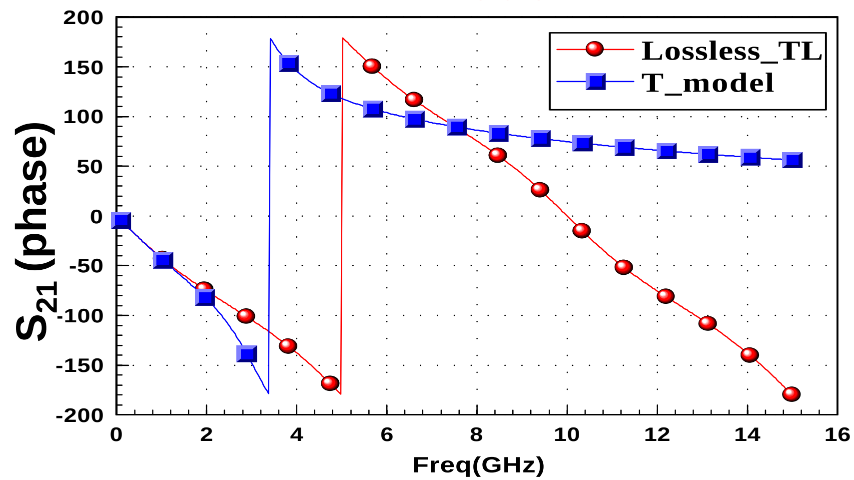
Modified-T model



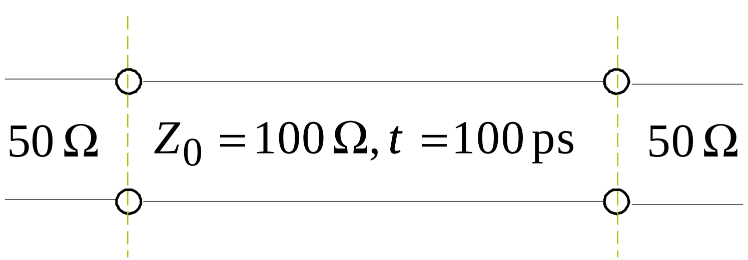
π model



T model



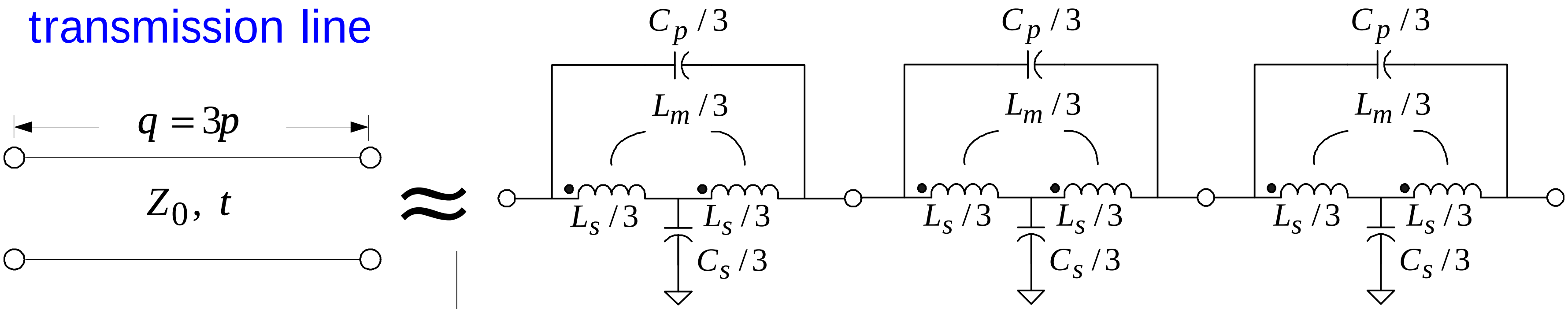
Transmission-line circuit

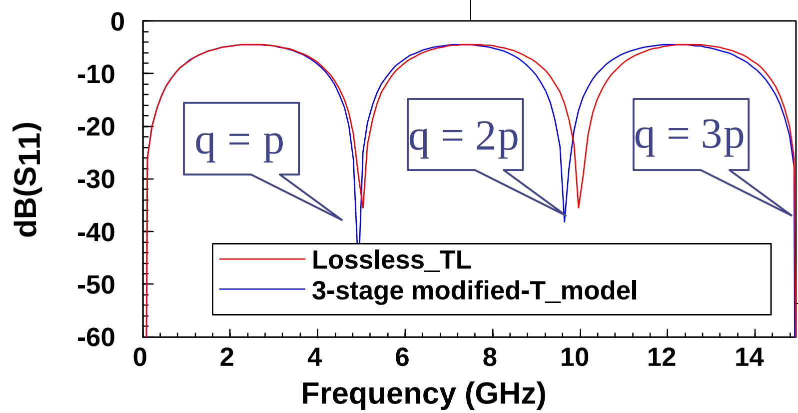


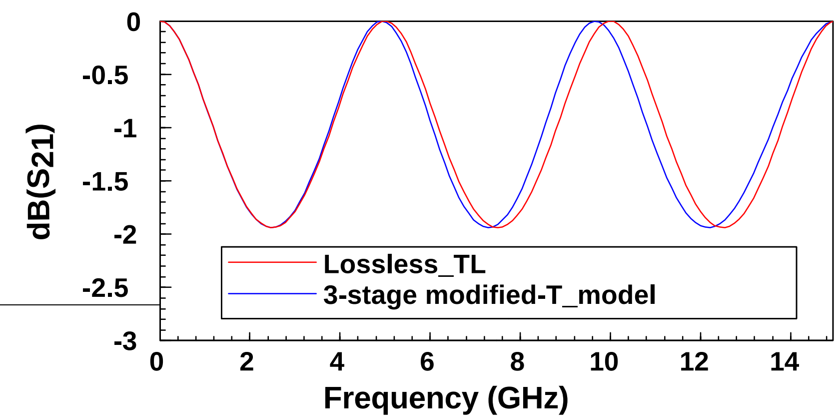
Distributed Modified-T Model

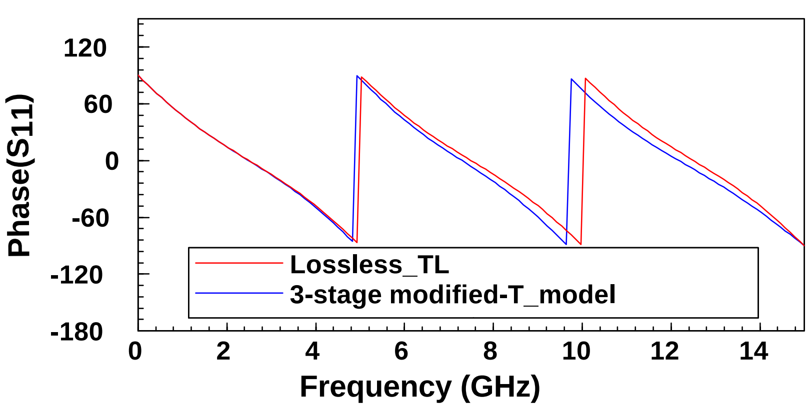
3π-long transmission line

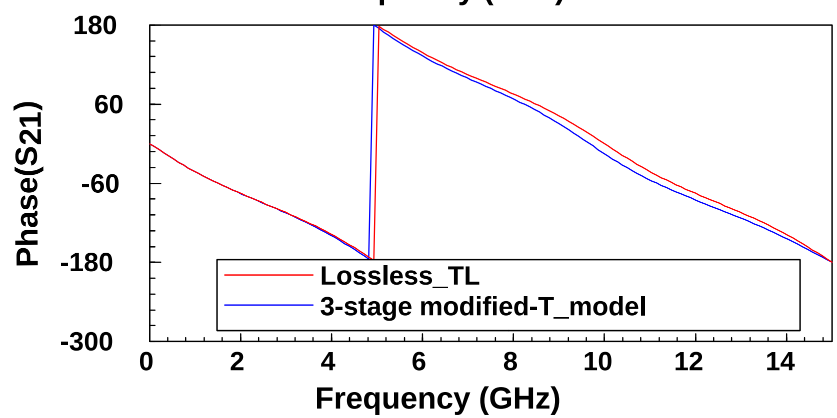
3-stage modified-T model





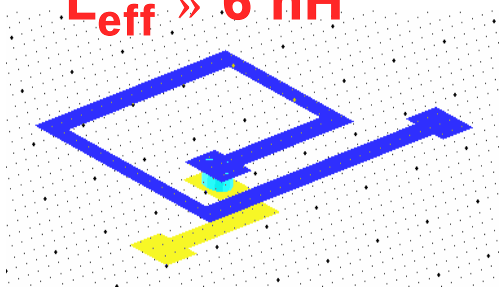




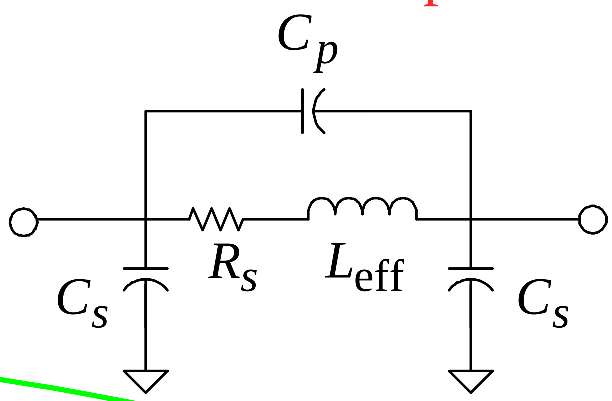


Modified-T Models for Spiral Inductors

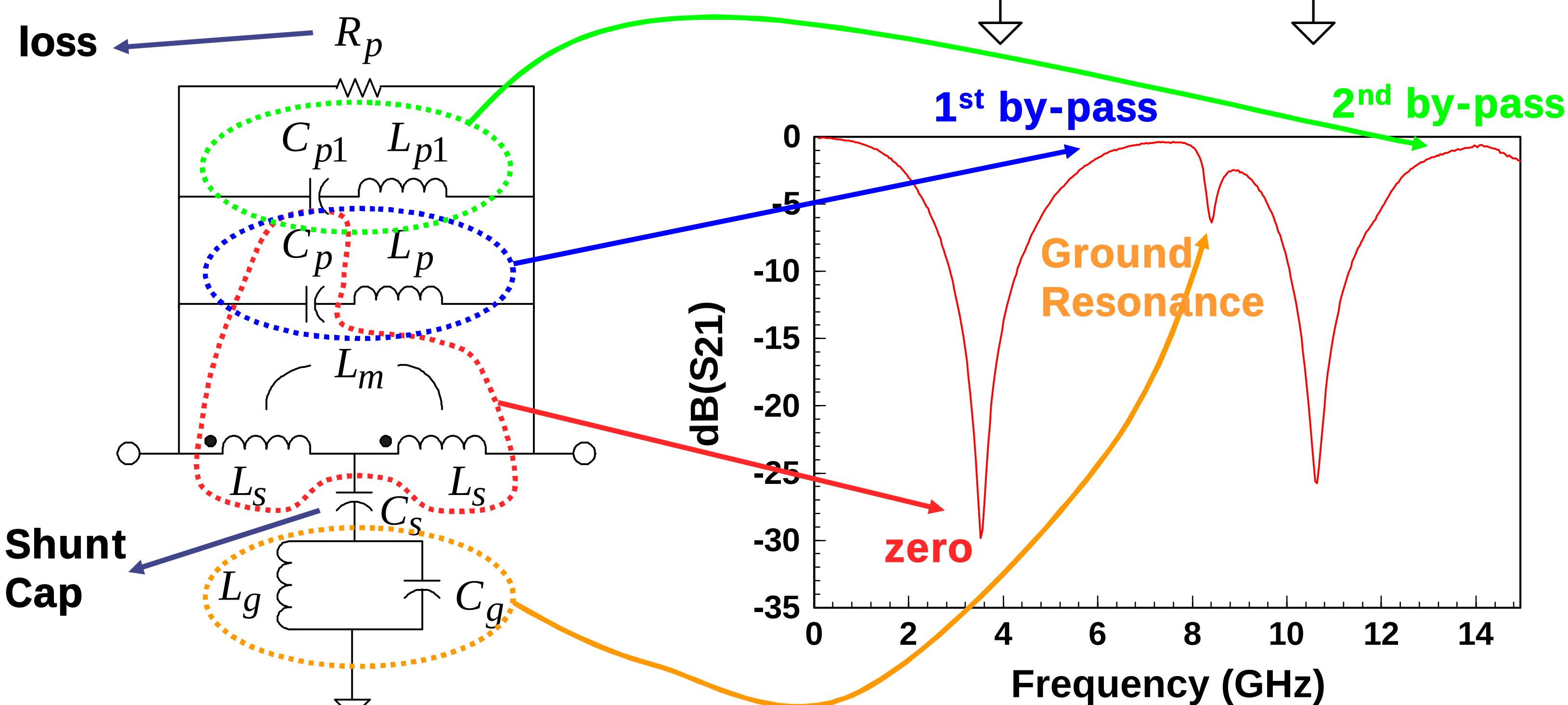
L_{eff} » 6 nH



Conventional p model

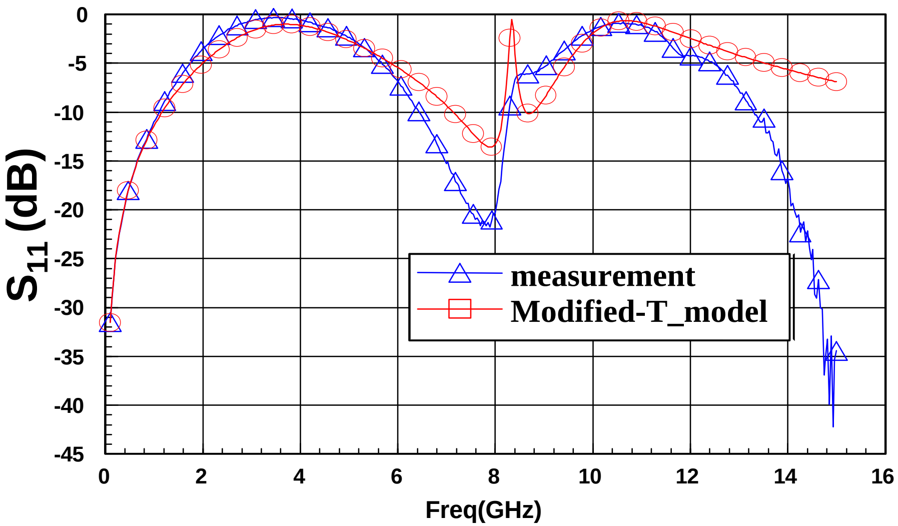


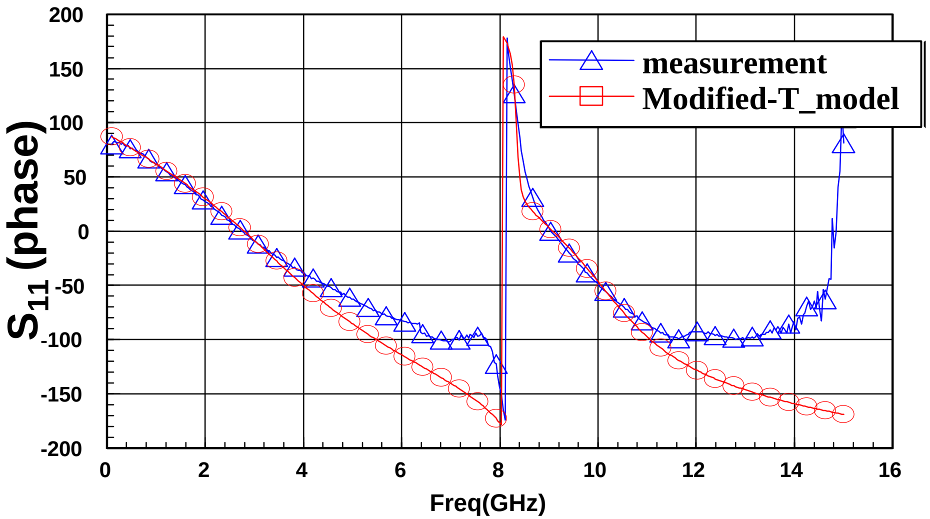
Modified-T model



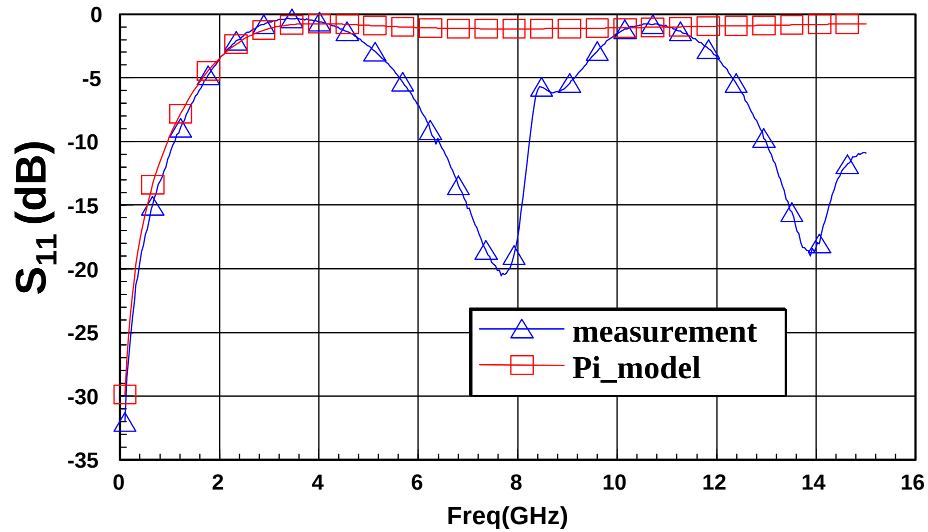
Comparison of Bandwidth between Two Inductor Models

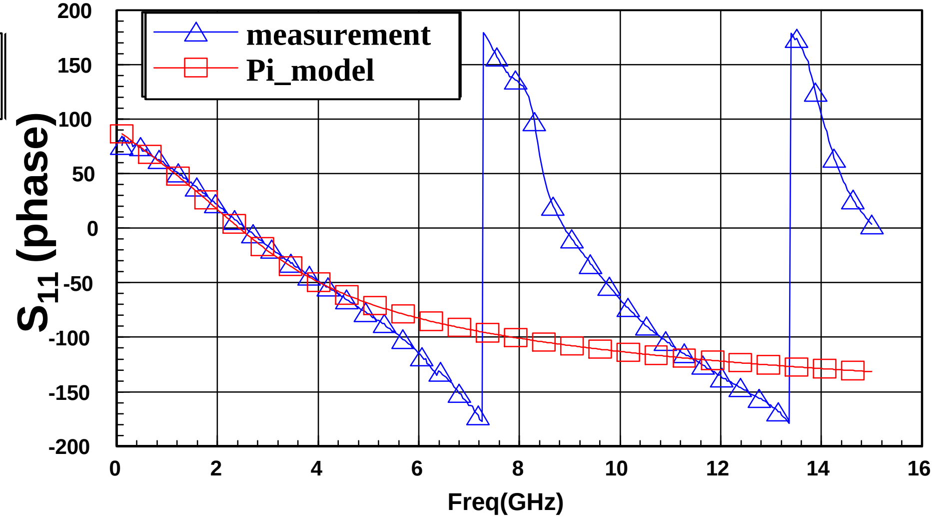
Modified-T model





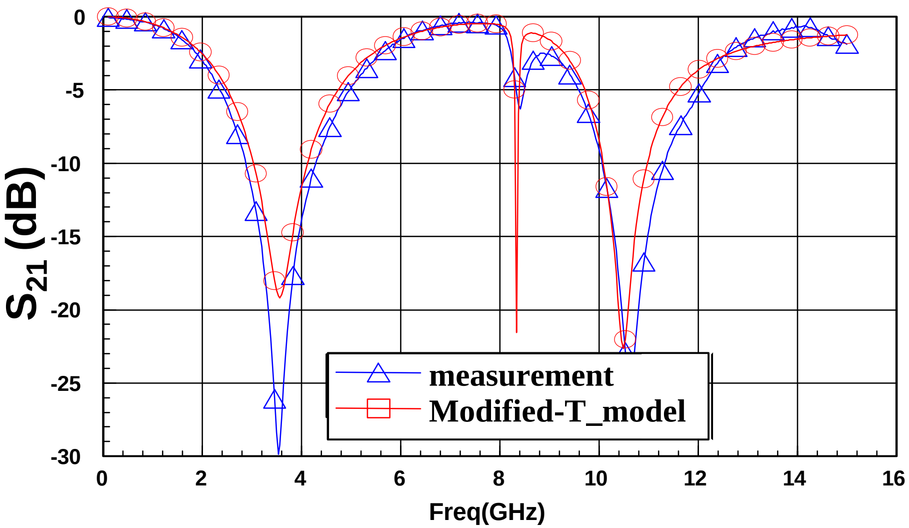
Conventional π model

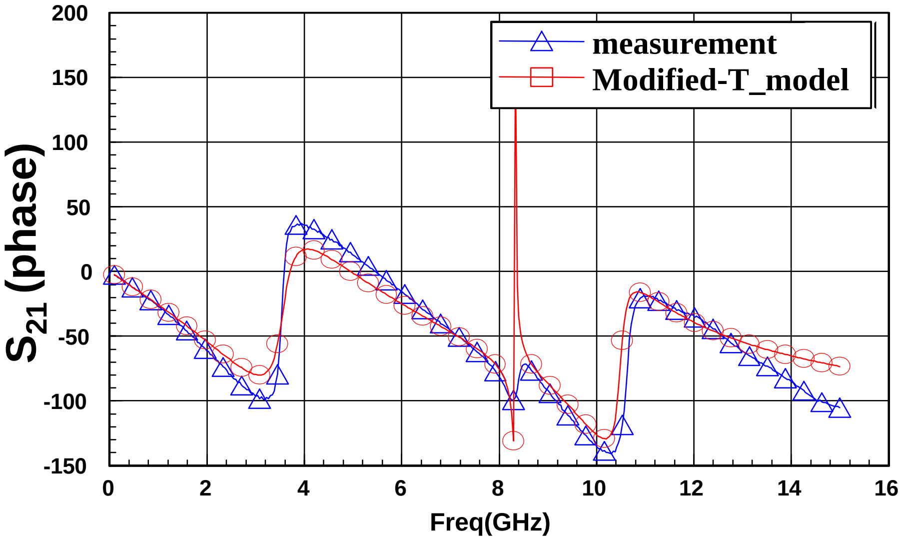




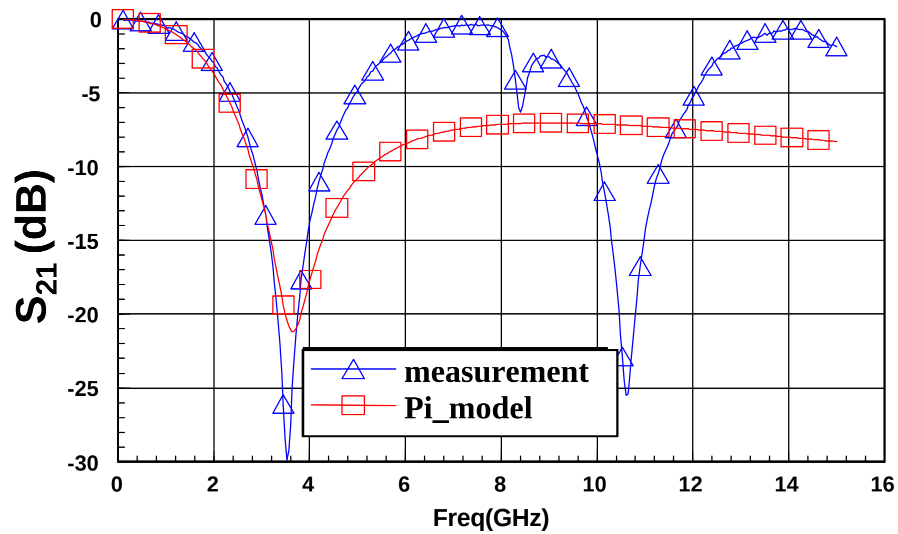
Comparison of Bandwidth between Two Inductor Models

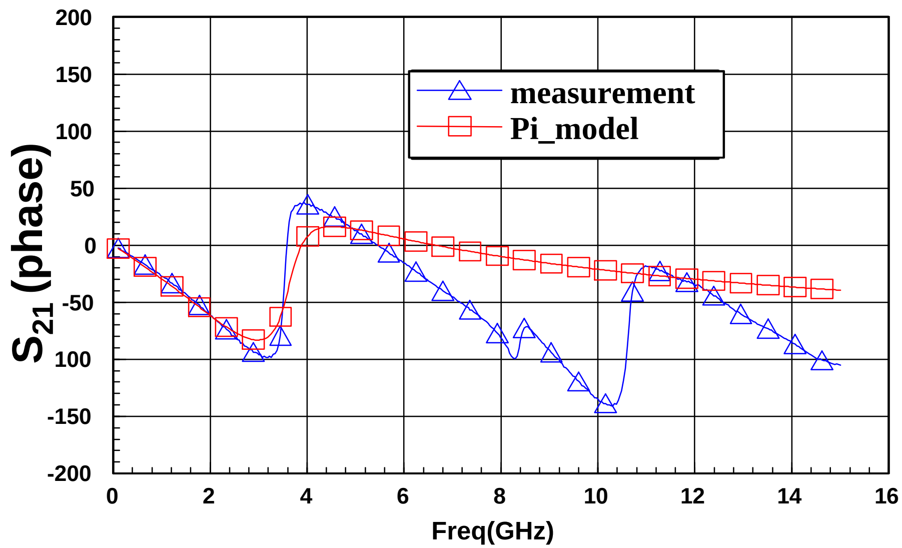
Modified-T model





Conventional π model





Outline

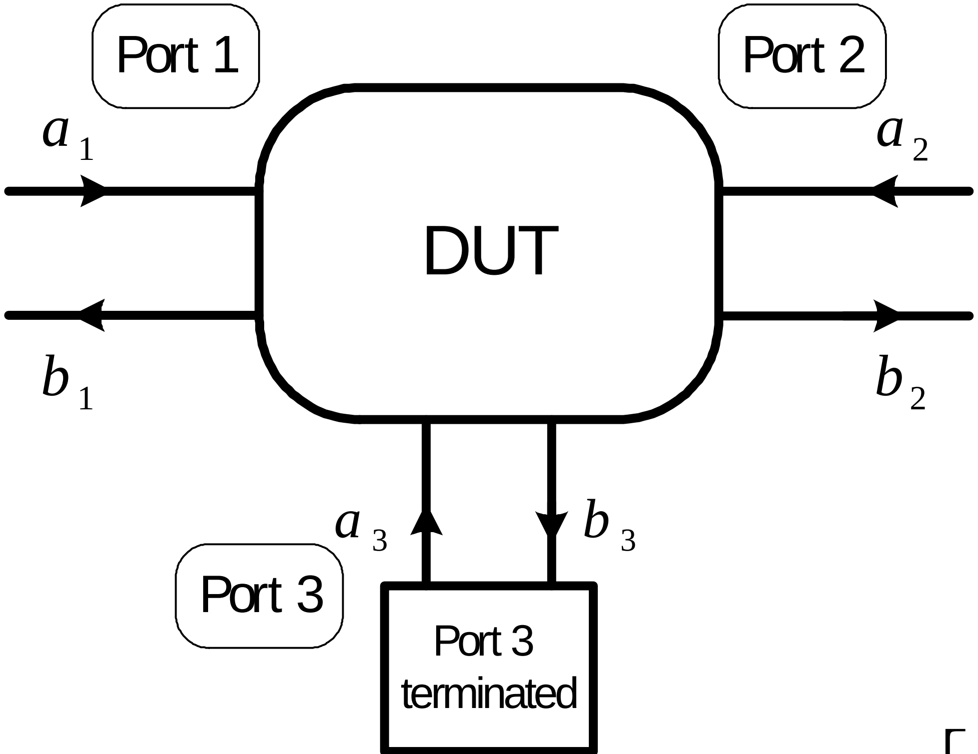
- LTCC Embedded Inductors
- **PCB Balanced Devices**
- Conclusions

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



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

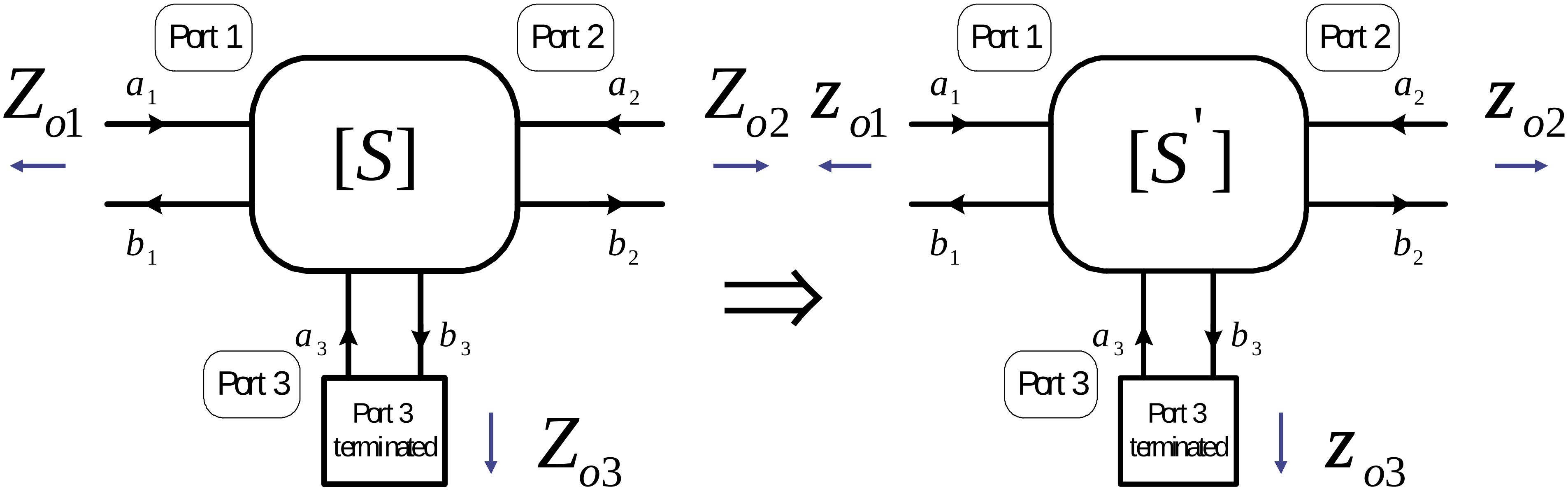
$$[S^{p3t}] = \begin{bmatrix} S_{11}^{p3t} & S_{12}^{p3t} \\ S_{21}^{p3t} & S_{22}^{p3t} \end{bmatrix}$$

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

Reflection due to port termination

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

Partial Renormalization



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

$$\text{where } \; G_k = \frac{z_{0k} - Z_{0k}}{z_{0k} + Z_{0k}}, \quad \text{for } k = 1,2$$

Renormalization Transforms

- Three partial 2-port S-parameter measurements

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

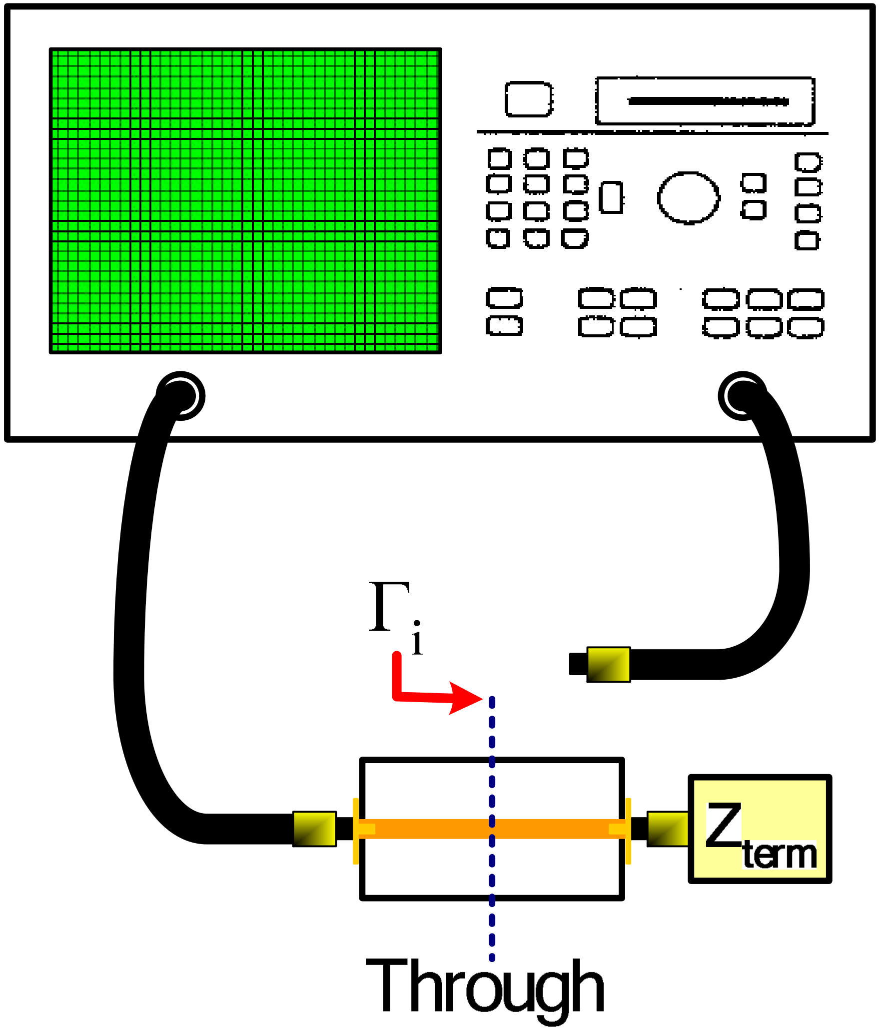
- After partial renormalizations

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

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

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

Determination of $[\zeta_0]$



- Use TRL Calibration
- $z_{0i} = Z_0 \frac{1+\Gamma_i}{1-\Gamma_i}$

DC-Block Branch-Line Coupler

Design guide

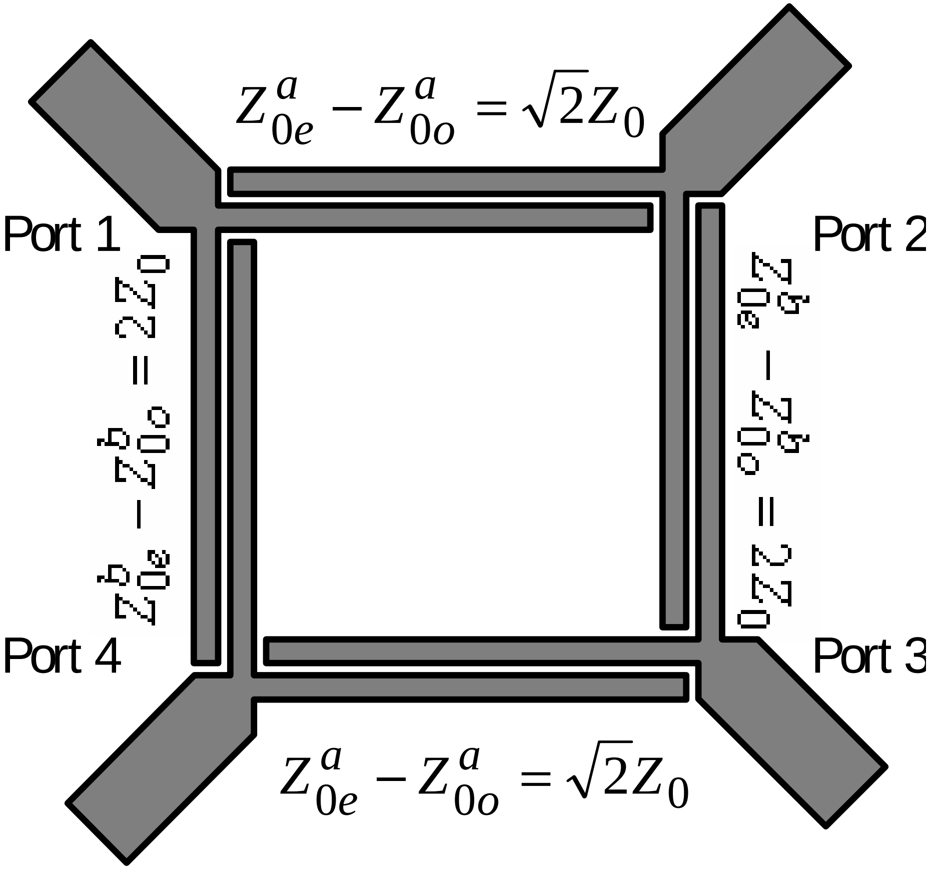
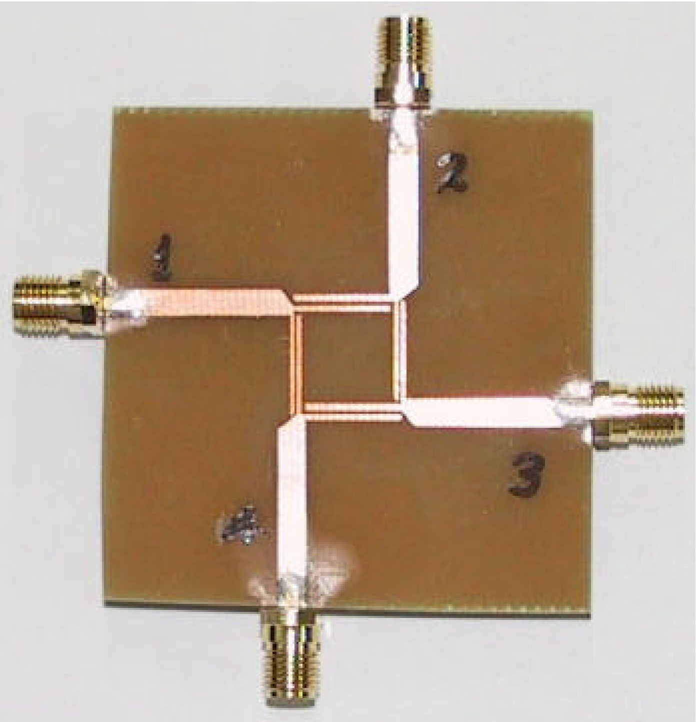
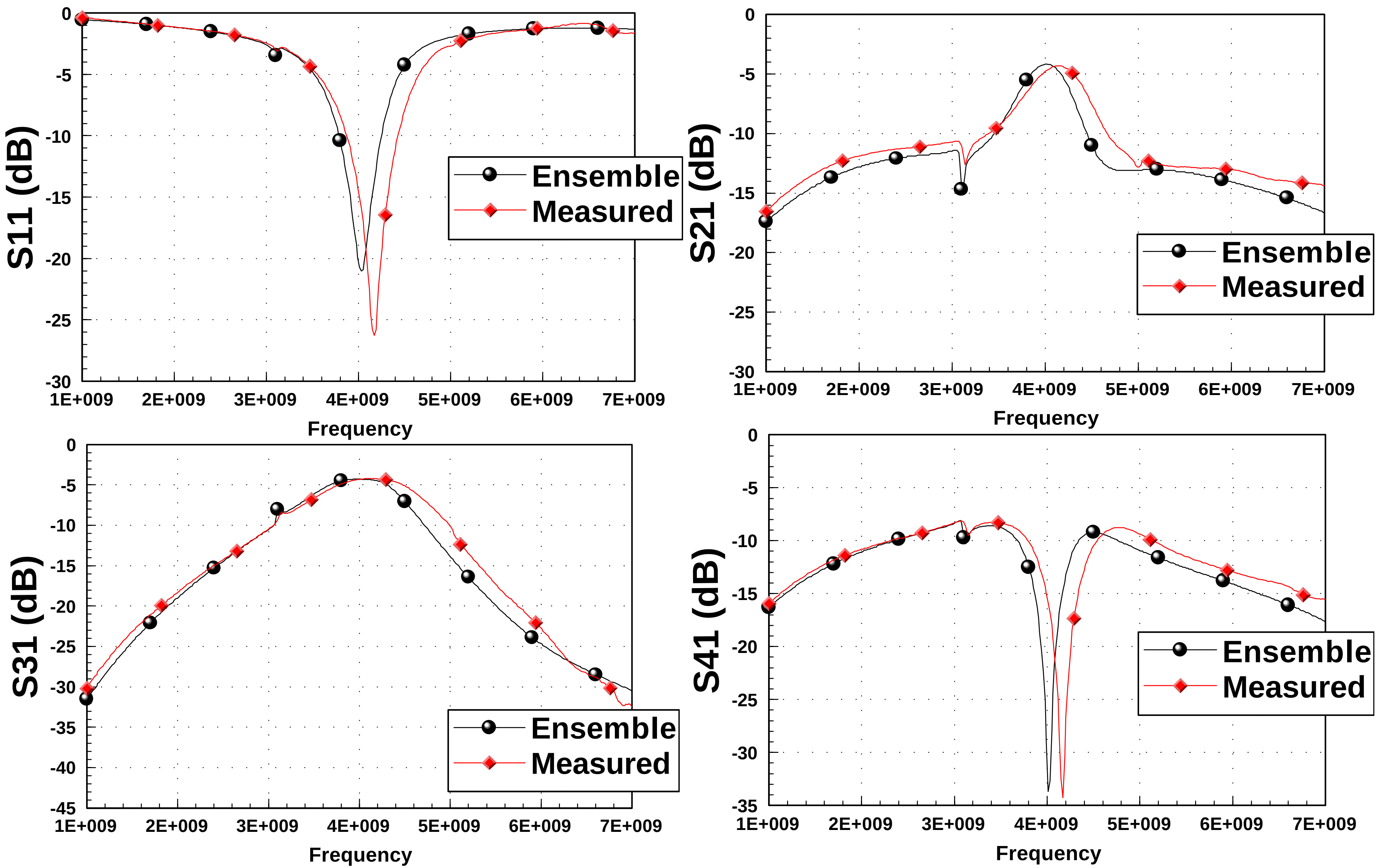


Photo of component



Comparison between Ensemble Simulation and Measurement



Impedance Transform
Branch-Line Coupler

Design guide

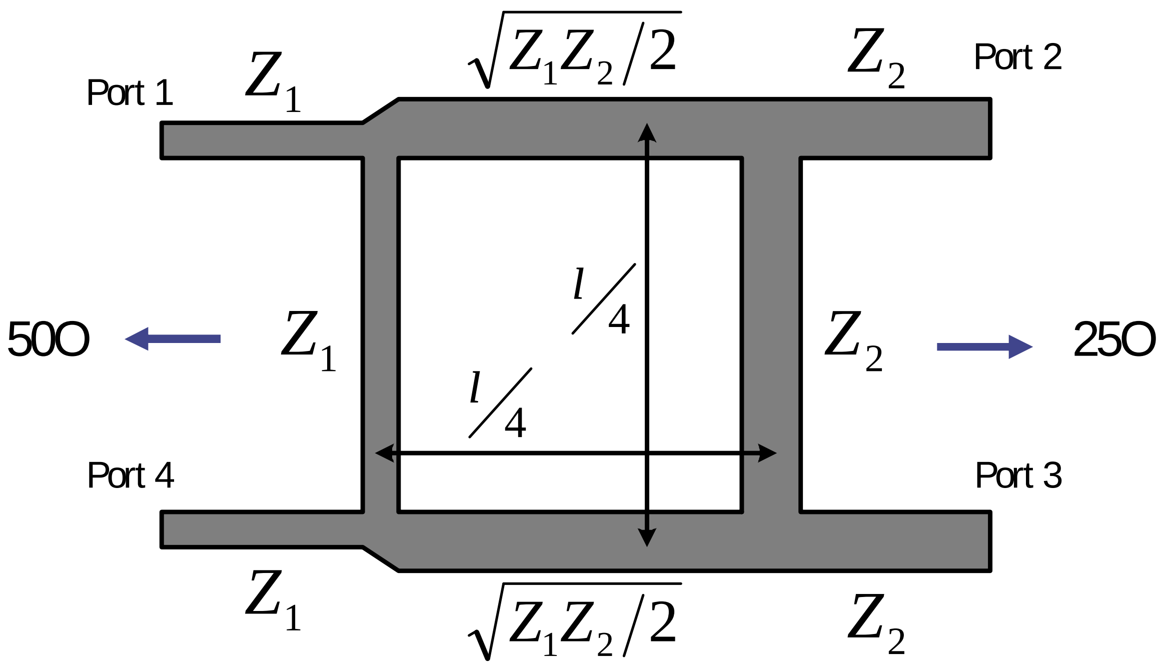
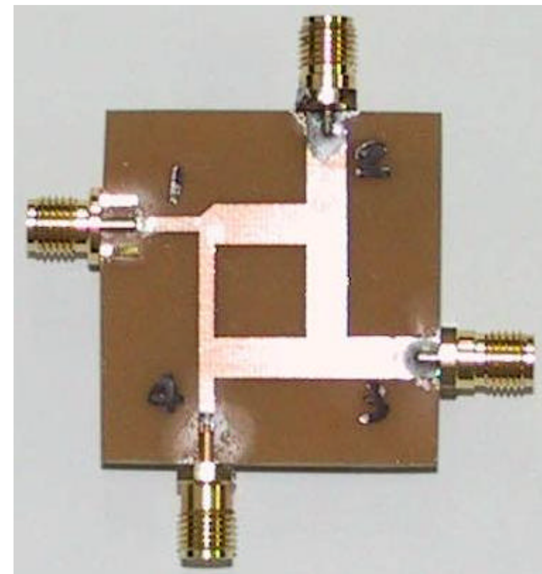


Photo of component

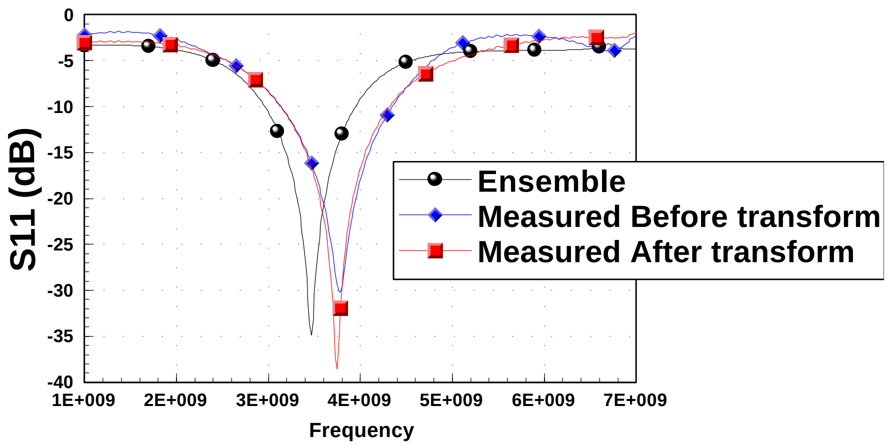


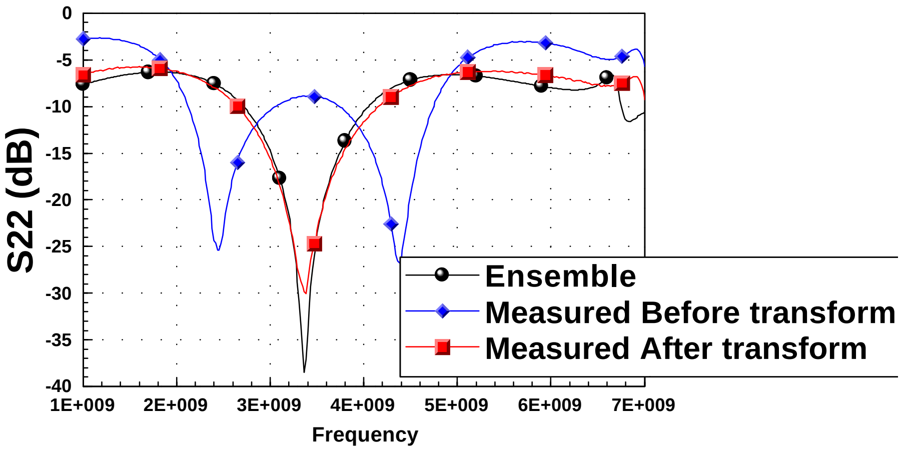
Generalized S-parameter Transform

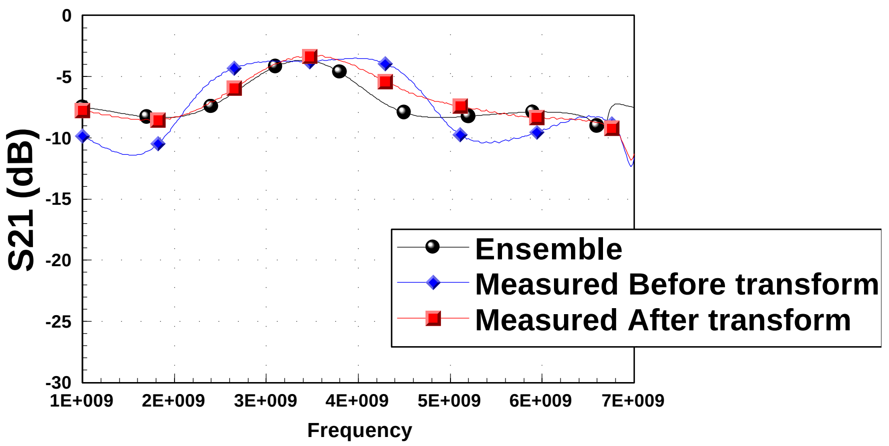
$$[S] \Rightarrow [Z]: \quad [Z] = \sqrt{[Z_0]}\,([U]-[S])^{-1}([U]+[S])\sqrt{[Z_0]}^{-1}$$

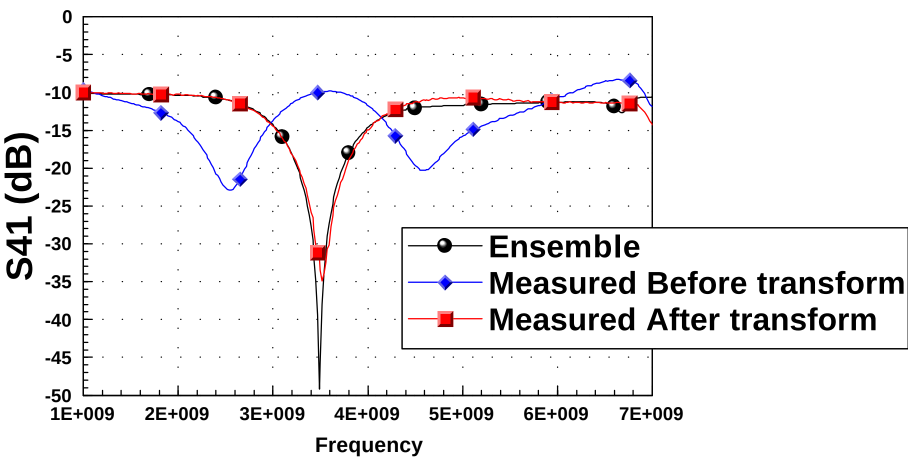
$$[Z] \Rightarrow [S']: \quad [S'] = \sqrt{[x_0]}^{-1}([Z]-[x_0])([Z]+[x_0])^{-1}\sqrt{[x_0]}$$

Comparison between Ensemble Simulation and Measurement



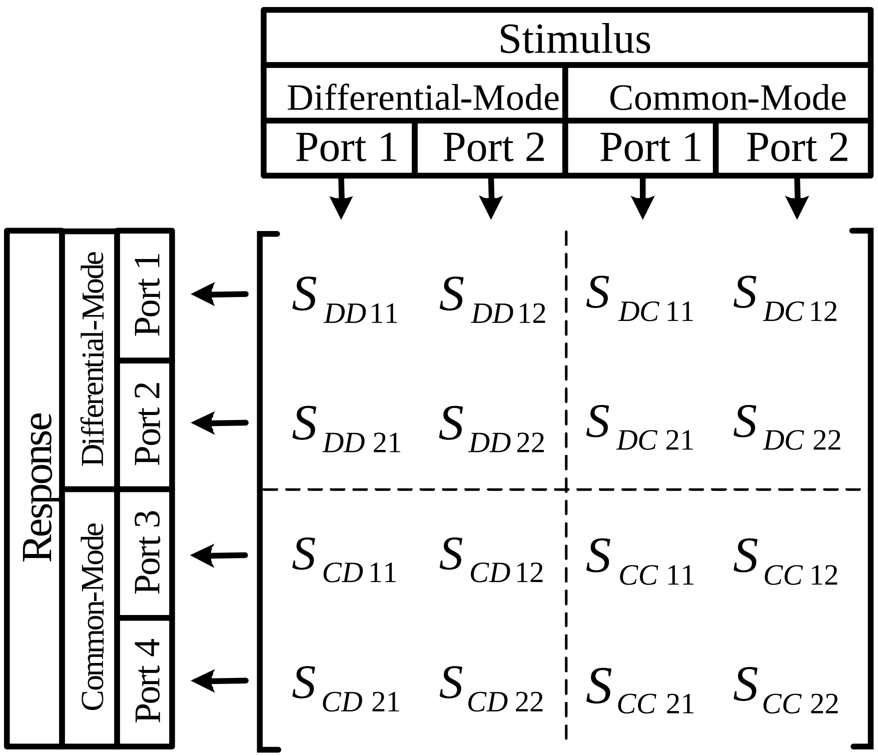






Mixed-Mode S parameters

Mixed-Mode S Matrix



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

Common-Mode Rejection Ratio

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

Mixed-Mode Transform

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

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

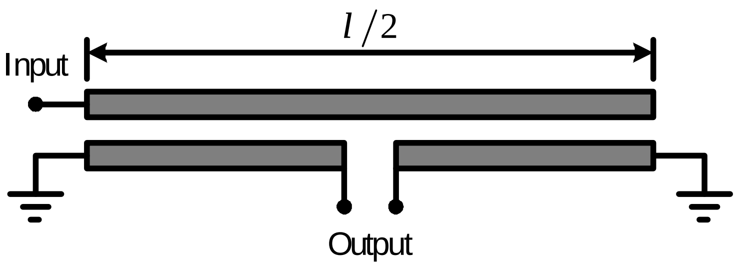
$$[S^{mm}] = [M][S^{se}][M]^{-1}$$

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

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

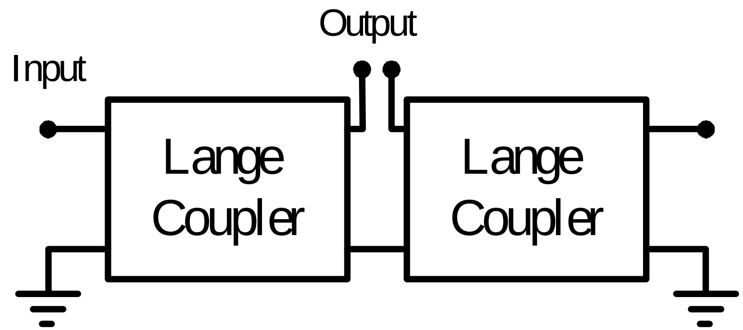
Lange-Type Marchand Balun

Design guide



Planar type

⇒



Lange type

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

Mixed-mode [S]

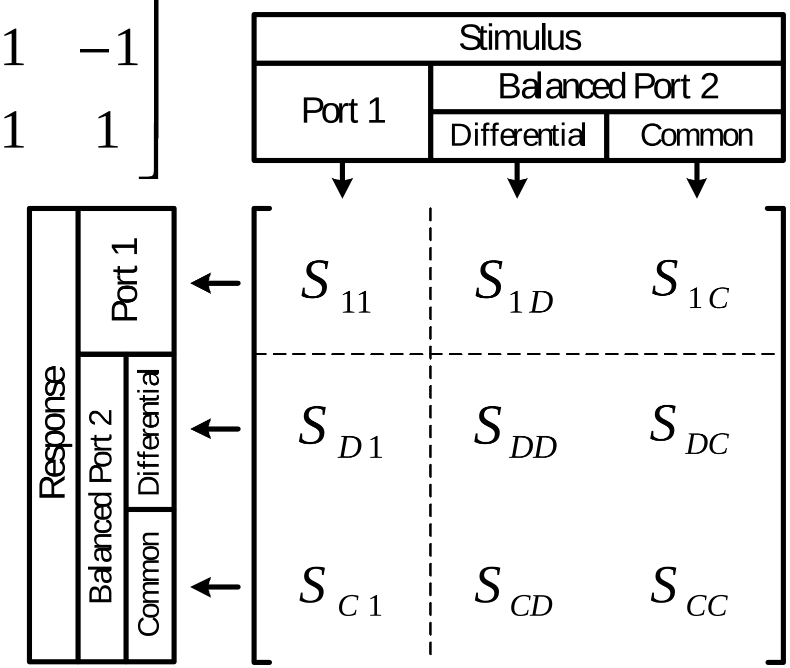
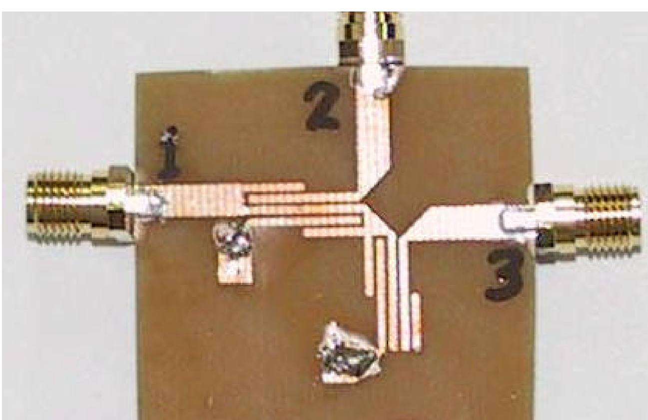
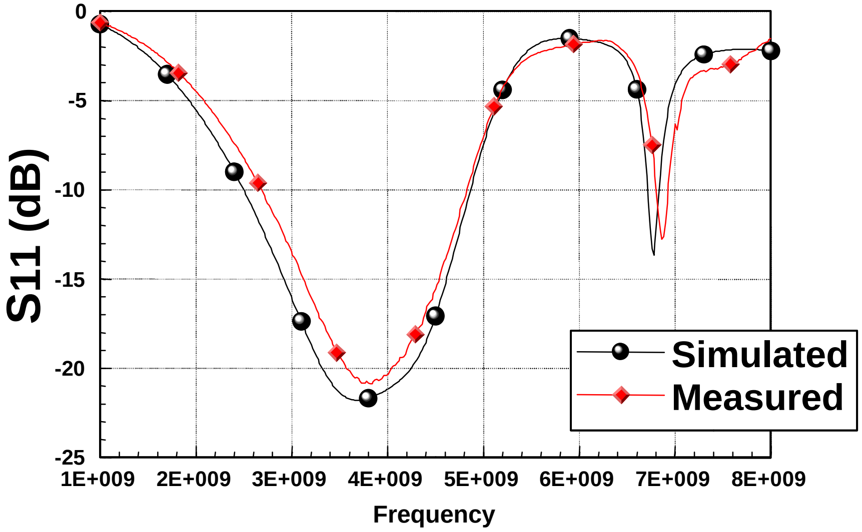
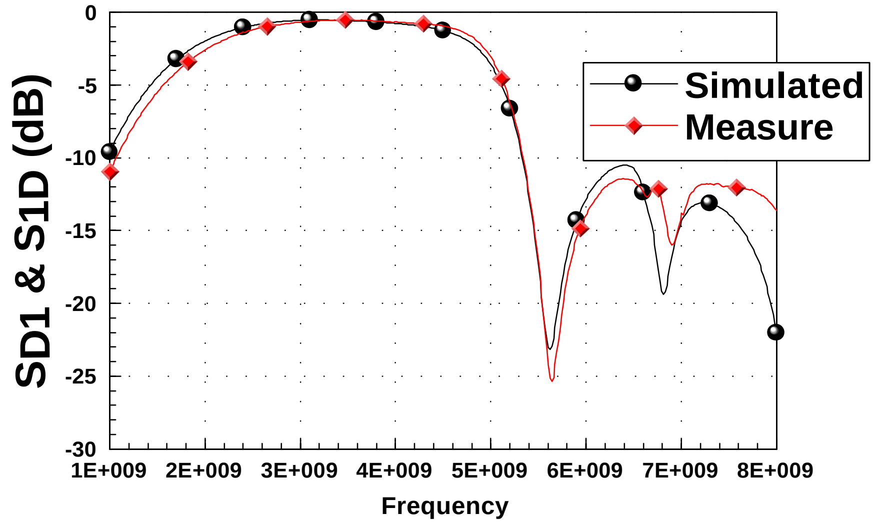


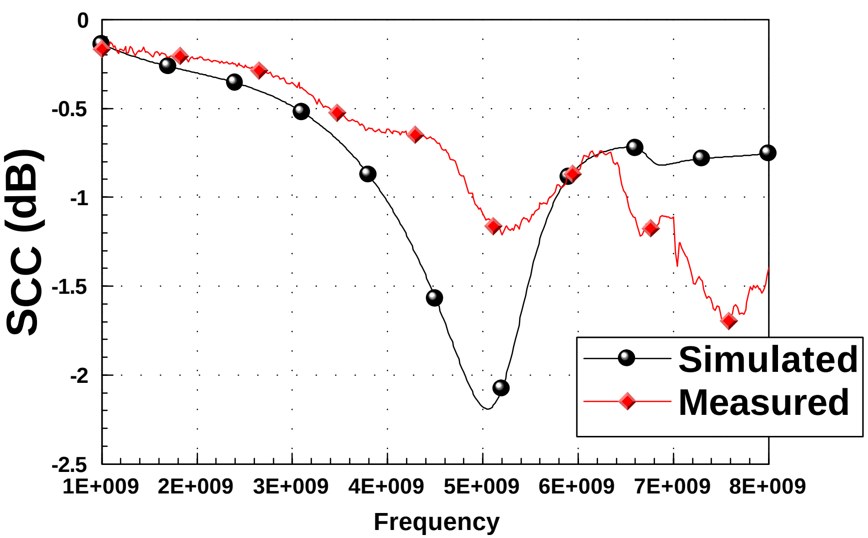
Photo of component

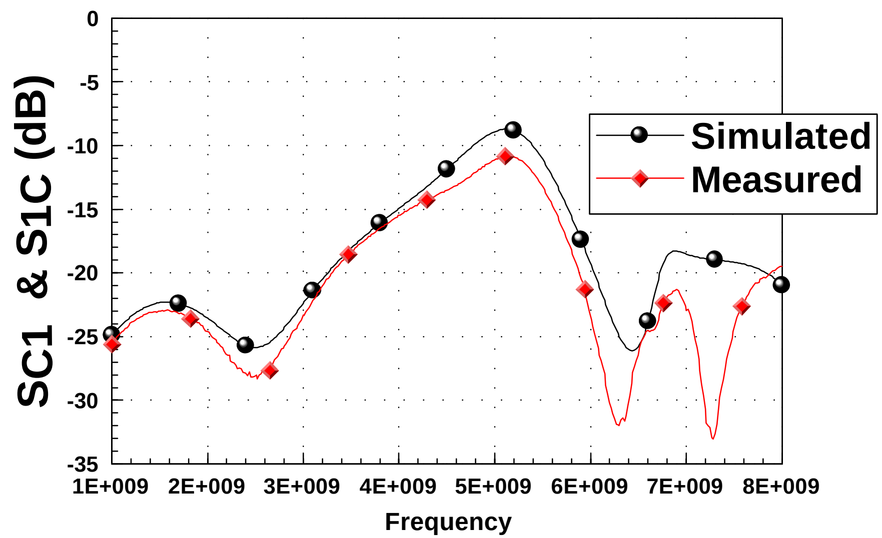


Comparison between HFSS Simulation and Measurement

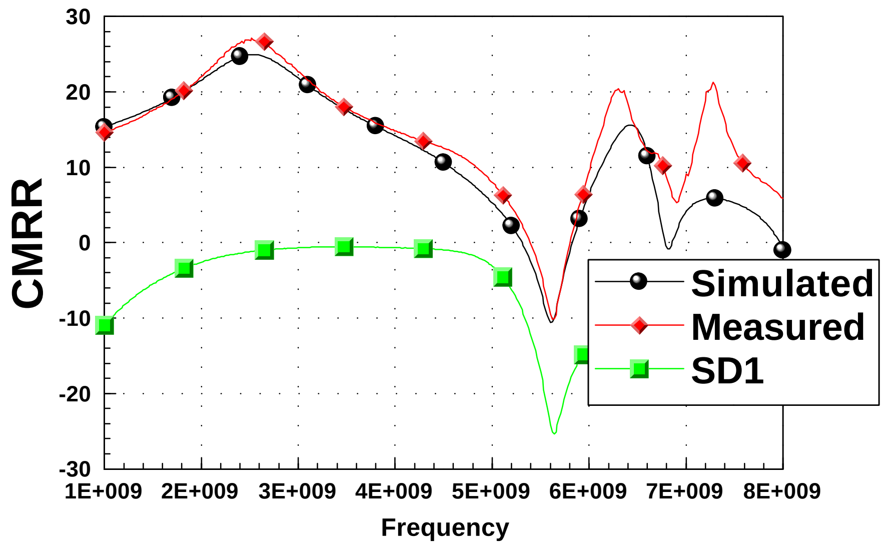


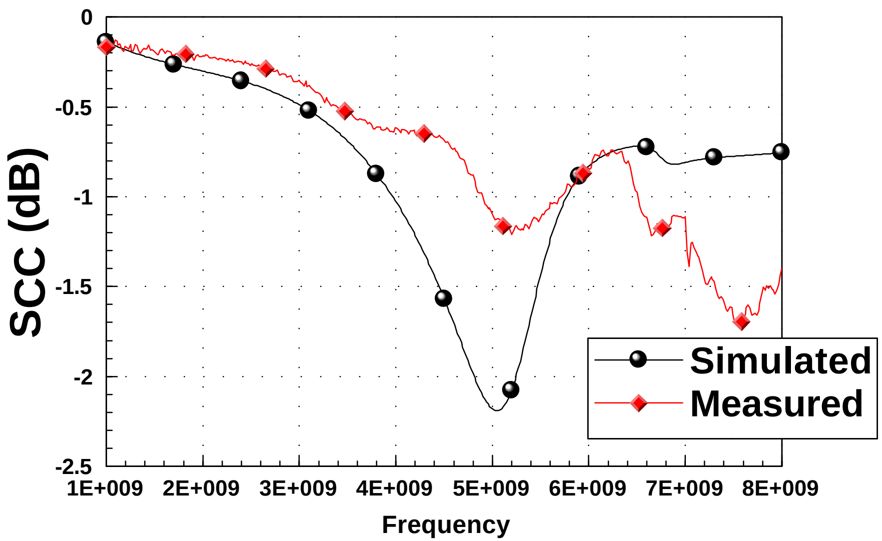


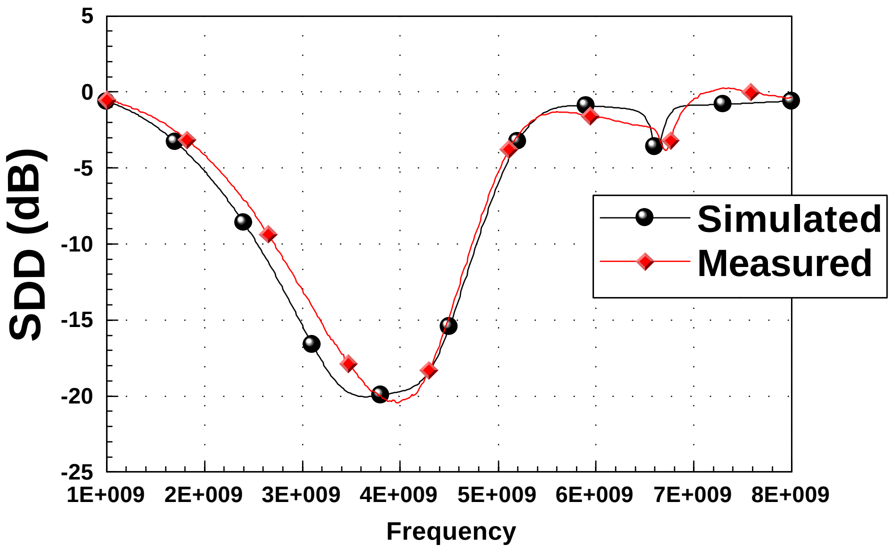


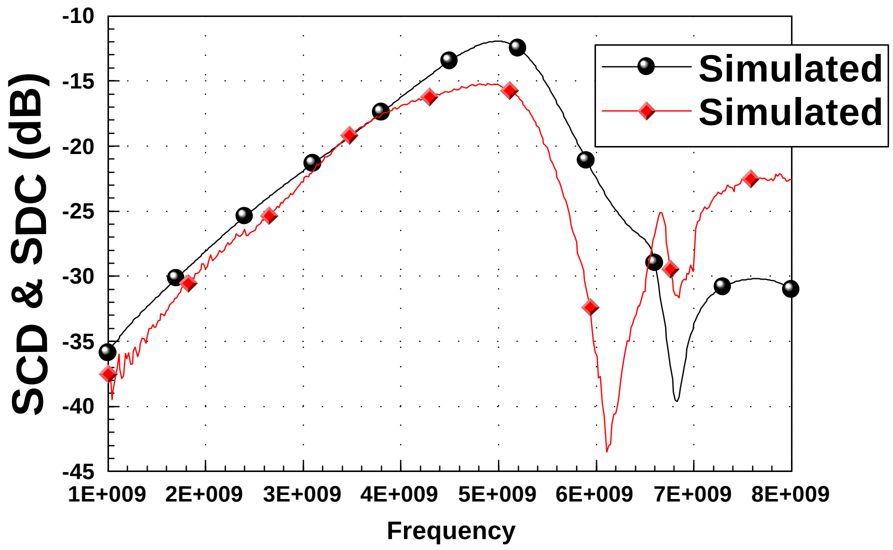


Comparison between HFSS Simulation and Measurement



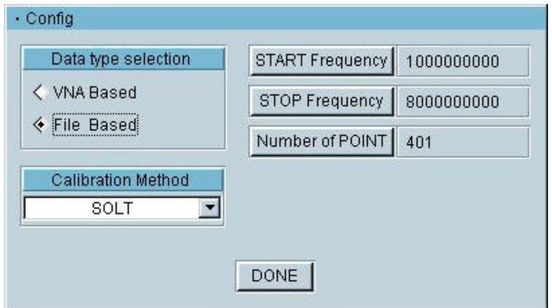






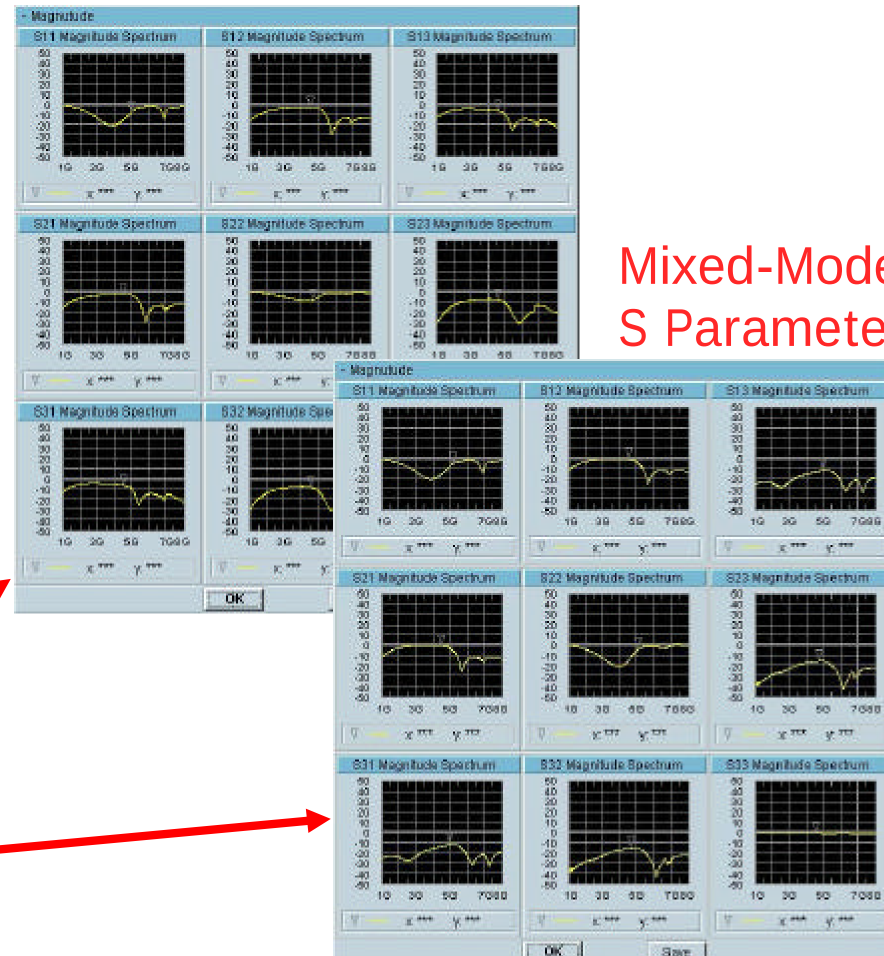
Semi-Automatic Measurement System

VNA setup via Vee

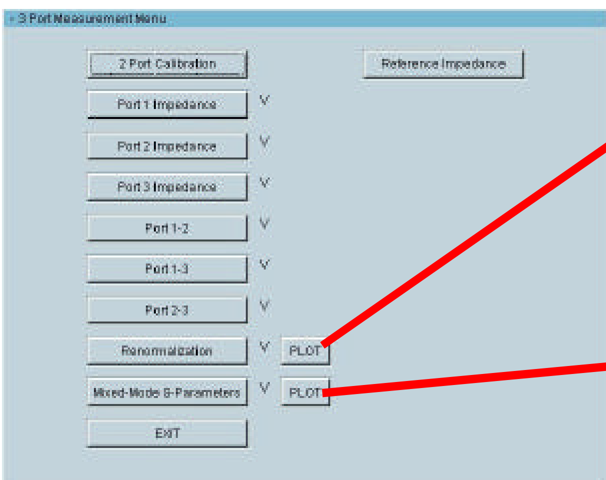


Single-ended S parameters

Mixed-Mode S Parameters

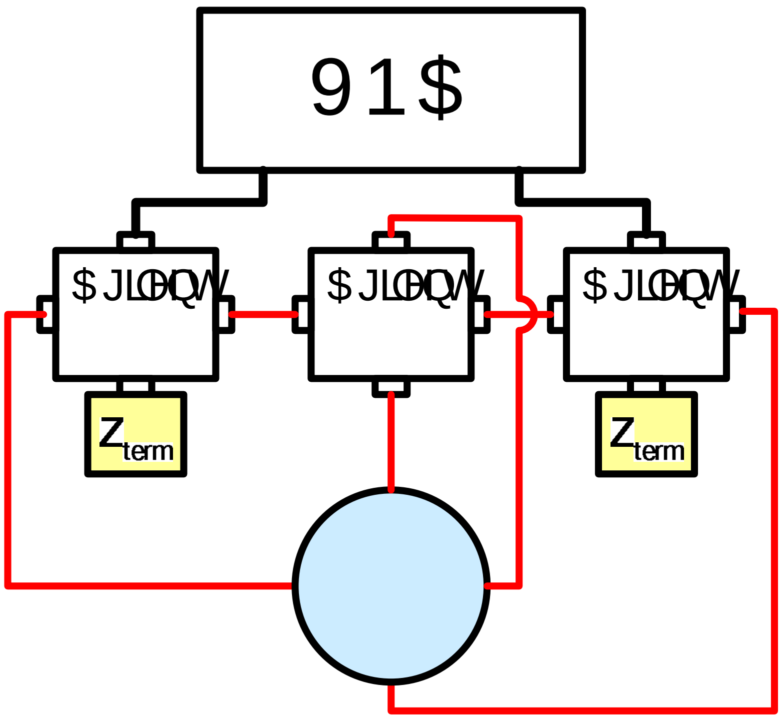


Measure, renormalize and Transform

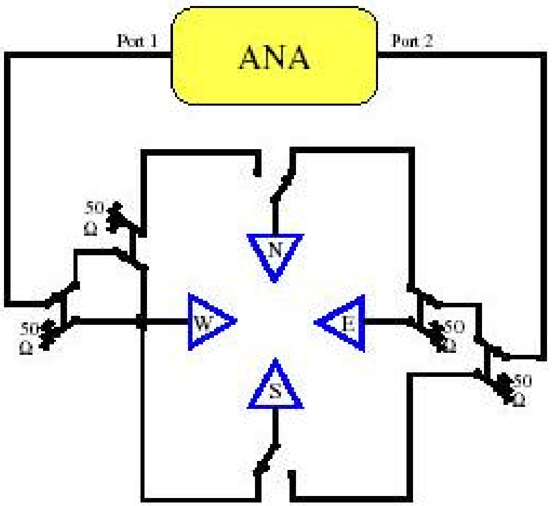


Application to On-Wafer Measurement

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

1. K. Lim, et. al., “RF-system-on-package (SOP) for wireless communications,” IEEE Microwave Magazine, pp. 88-99, March 2002.
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.