Milan, 26 September 2022

Recent developments in millimetre-wave measurement: S-parameters and material properties

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Advances in Leakage Corrections for On-wafer S-parameter Measurements

Dr. Chong Li

Senior Lecturer (Associate Professor)

Microwave and Terahertz Electronics (MaTE) Group,
James Watt School of Engineering,
University of Glasgow, UK

MaTE
Microwave&THz Electronics

University of Glasgow
VIA VERITAS VITA

Overview

- Introduction
- Error terms and error models in leaky on-wafer systems
- Conventional calibration algorithms and procedures
- Latest advances in leakage correction techniques
- Conclusions and future works
- Acknowledgement

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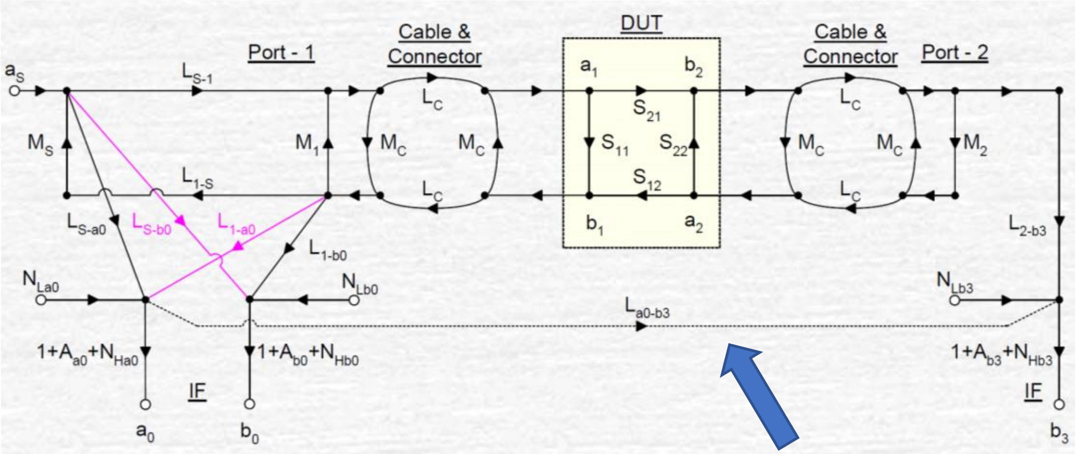
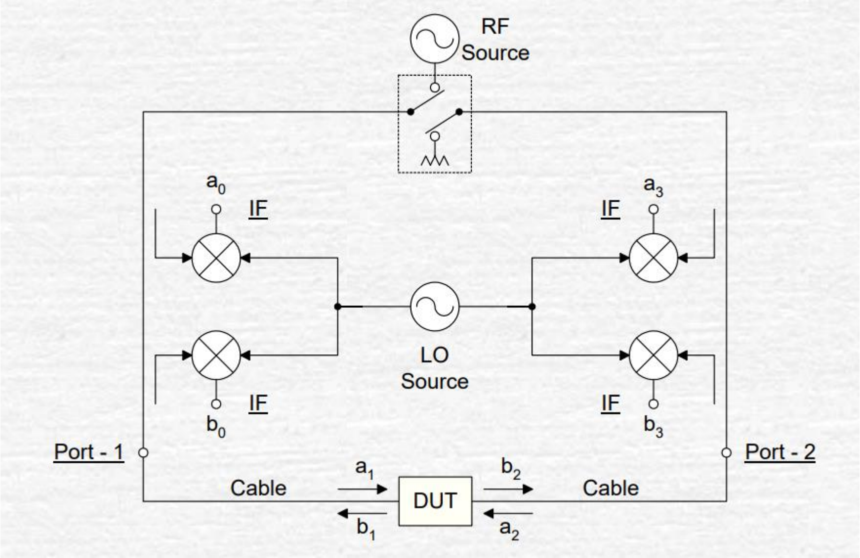
Introduction

Signal leakage in a waveguide based S-parameter test system

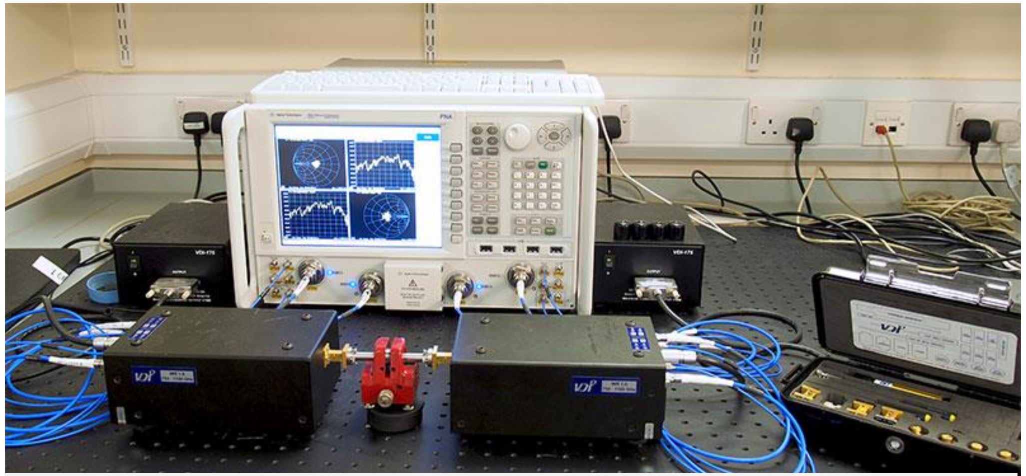
- Primarily inside the VNA
- Also found in the test fixture



Flowgraph showing all the possible signal paths (by D. Rytting)



Simplified block diagram of a VNA system by D. Rytting



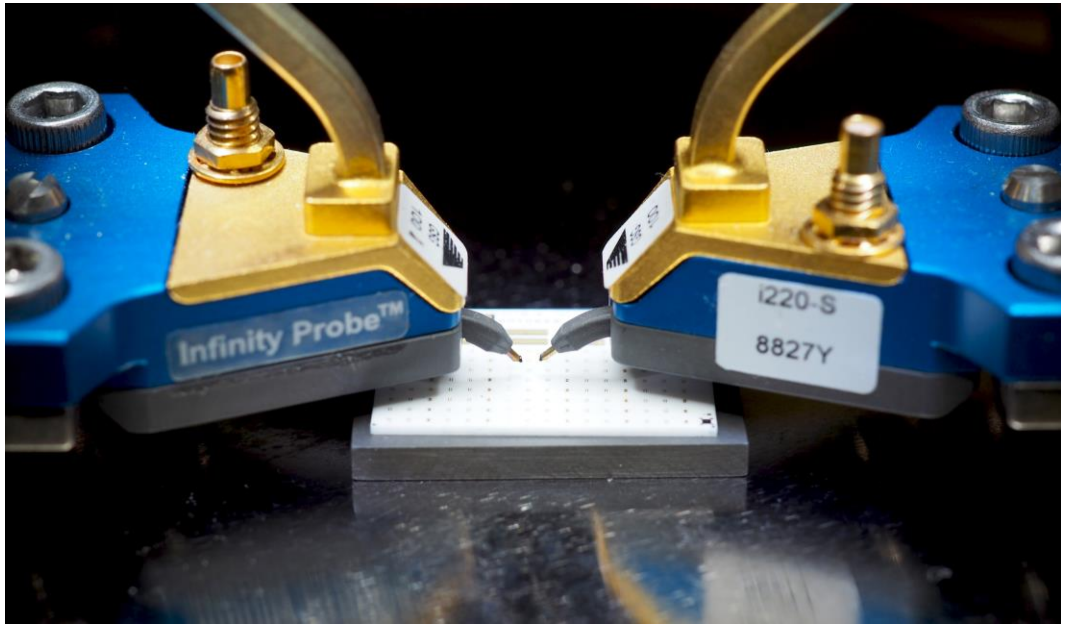
750 GHz-1.1 THz VNA+Swissto12's MCK

Introduction

Signal leakage in an on-wafer S-parameter test system

- Inside the VNA
- Bu primarily between the probes

140 - 220 GHz/220 - 325 GHz On-wafer Systems



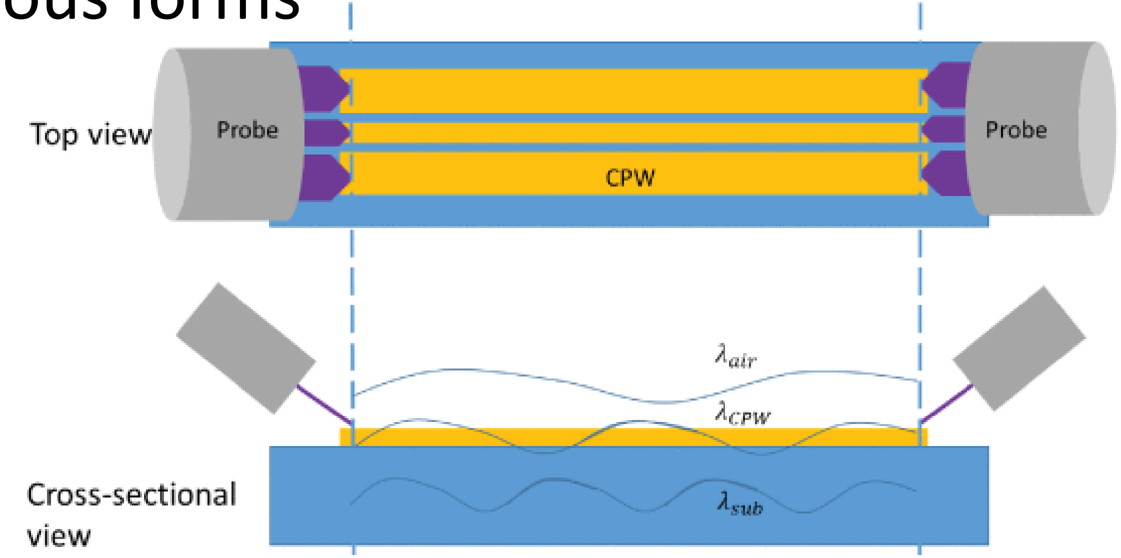
Introduction

Signal leakage exists between probes in various forms

- Radiative over the air
- Transmissive through substrate
- Direct capacitive/inductive coupling

and it is normally

- Frequency dependent
- Subject to test environment
- Affected by nature of devices under tests (DUT) e.g. electrical property and geometry



Liu et al IEEE MTT 2018

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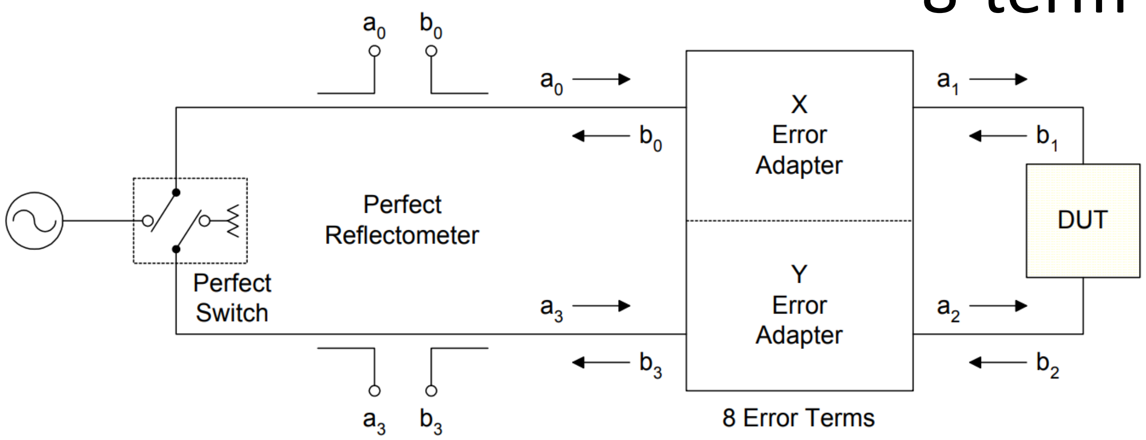
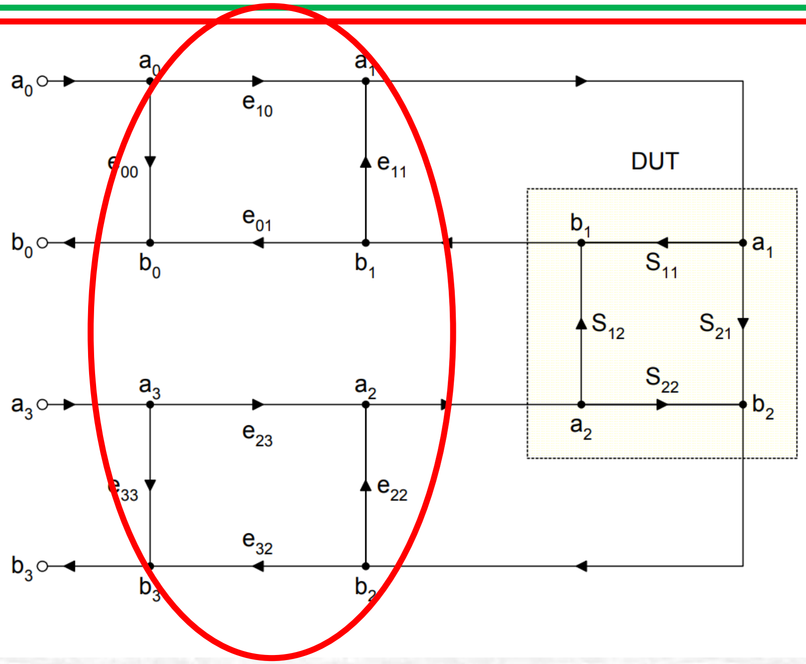
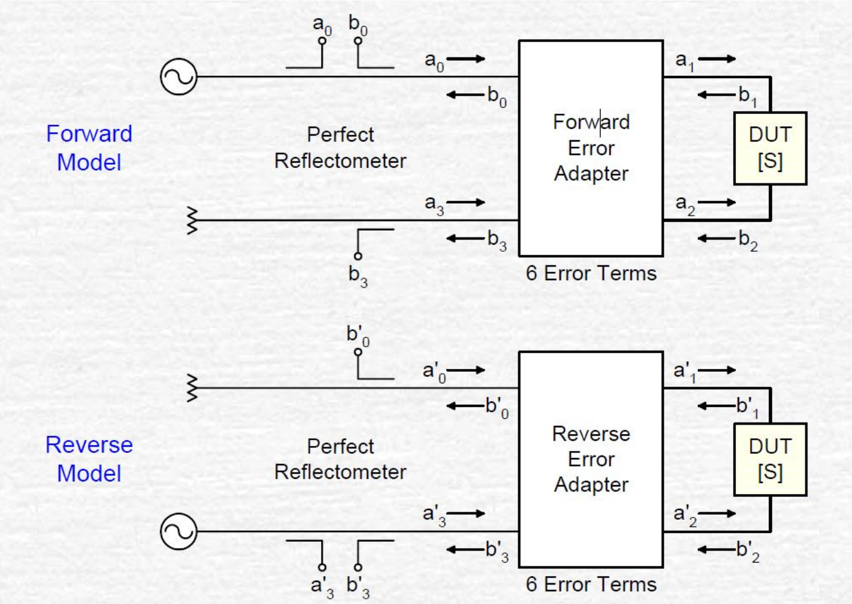
The 8 & 12 error terms and the error models

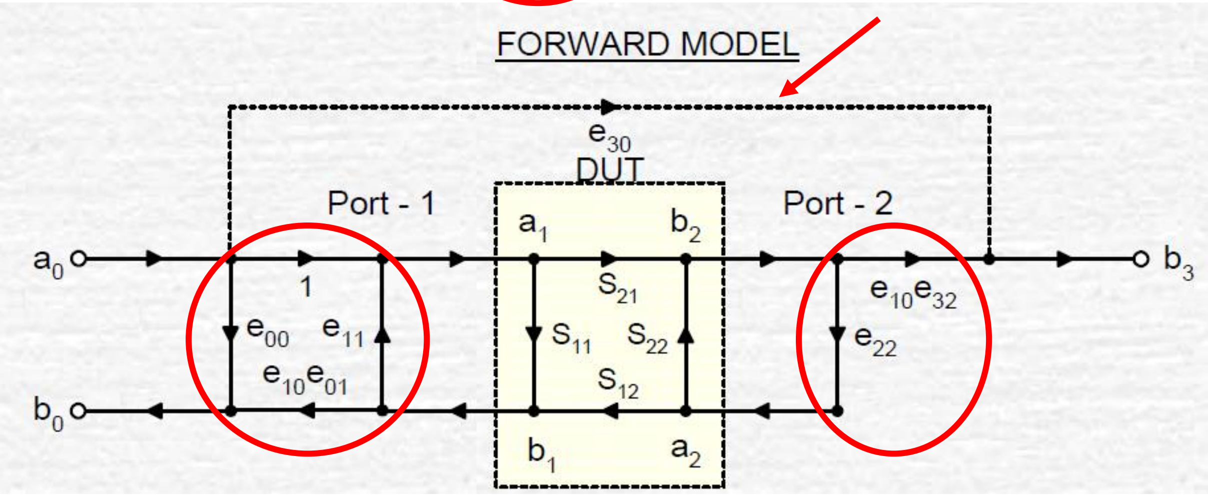
8-term model



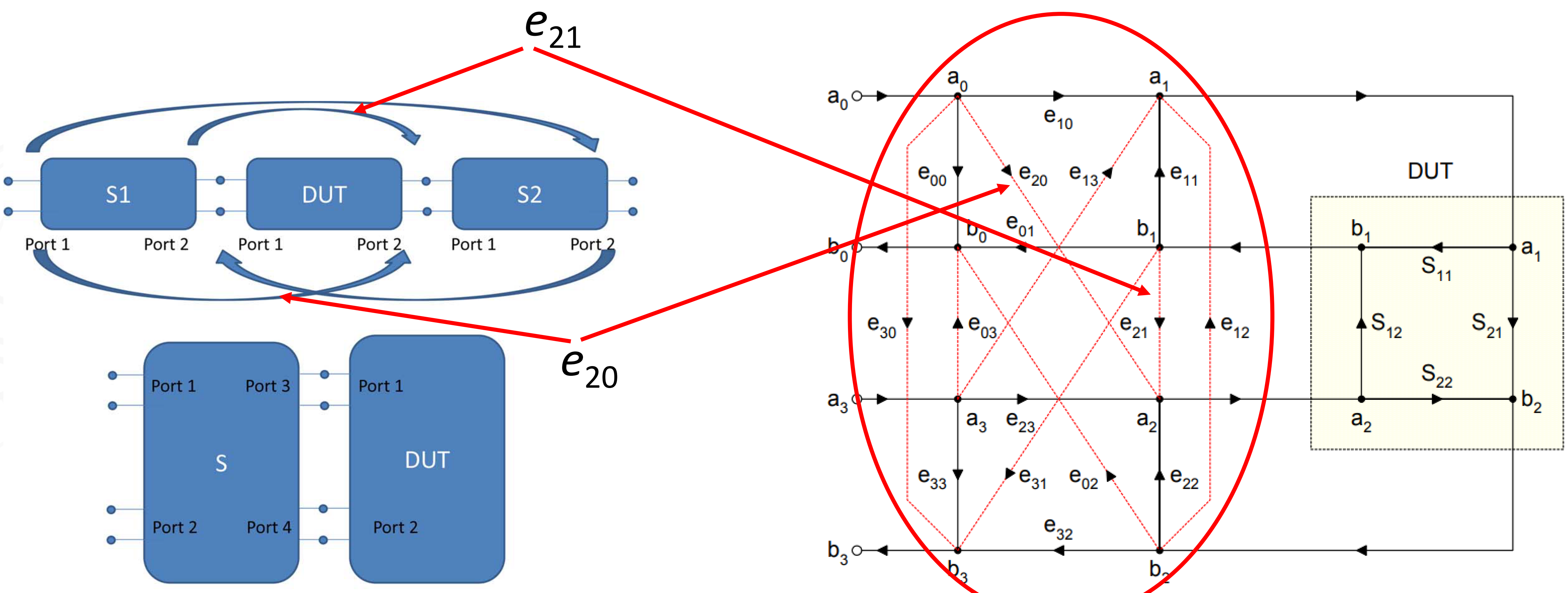


12-term model





The 16 error terms and the model



Williams et al IEEE MTT 2014

Butler et al IEEE MTT 1991

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The error matrix and solving the unknowns

How to obtain the error terms: solve the error matrix

Error Model	$\begin{bmatrix} b_0 \\ b_3 \\ \hline a_0 \\ a_3 \end{bmatrix} = \left[\begin{array}{c\|c} T_1 & T_2 \\ \hline T_3 & T_4 \end{array}\right] \begin{bmatrix} b_1 \\ b_2 \\ \hline a_1 \\ a_2 \end{bmatrix}$
Linear-in-T Form	$T_1 S + T_2 - S_M T_3 S - S_M T_4 = 0$
Measured S-Parameters	$S_M = (T_1 S + T_2)(T_3 S + T_4)^{-1}$
Actual S-Parameters	$S = (T_1 - S_M T_3)^{-1}(S_M T_4 - T_2)$

- 8 term model: all leakage are zeros; at least 3 equations/3 two-port standards required
- 12 term model: VNA internal leakage included; at least 4 equations/3-4 two-port standards required
- 16 term model: all leakage included; at least 4 equations/5 two-port standards required

Error matrix and solving the unknowns

8-Term Calibration Examples

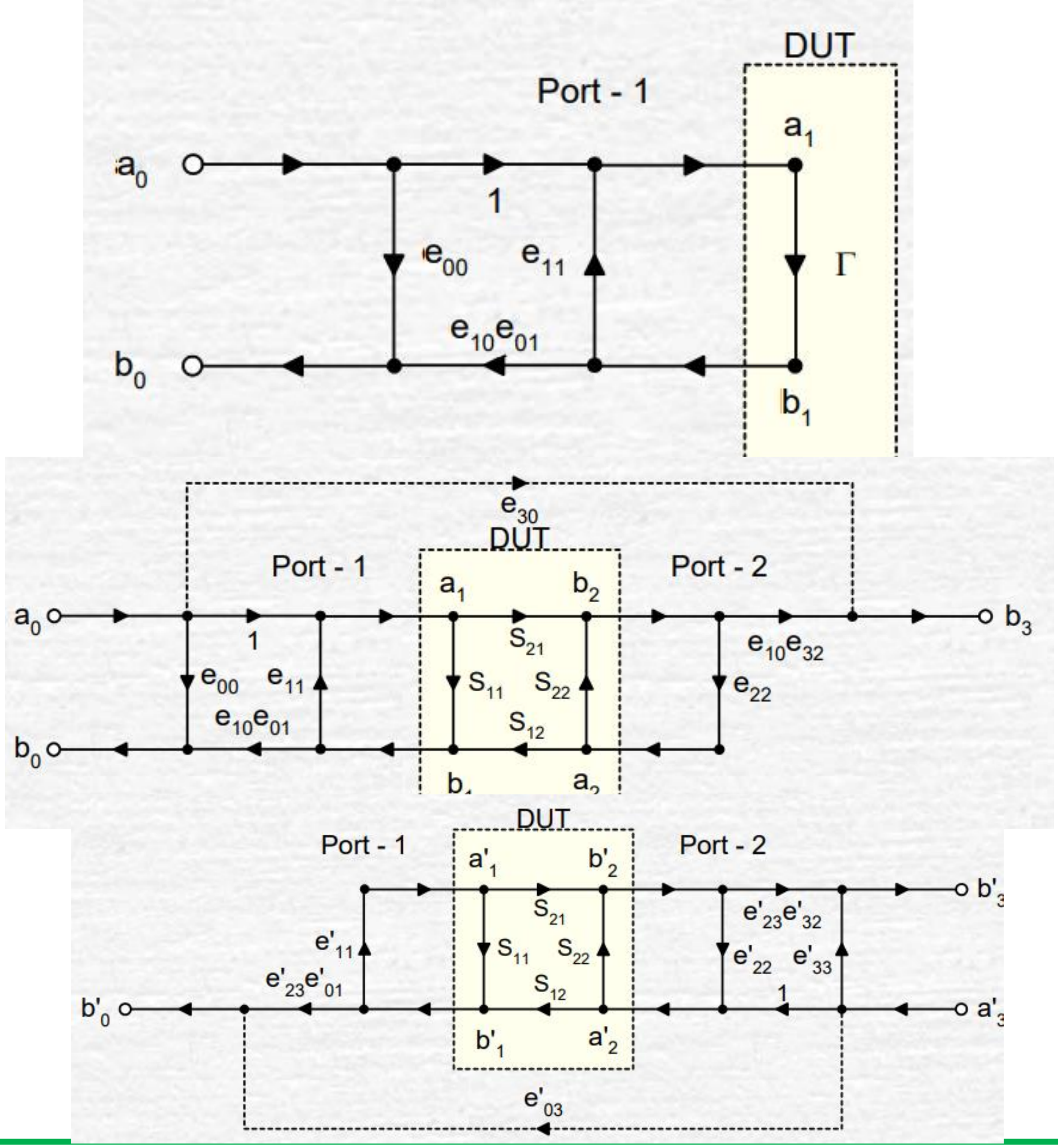
TRL & LRL	Thru (T) or Line (L) with known S-parameters [4 conditions]	Unknown equal Reflect (R) on port-1 and port-2 [1 condition]	Line (L) with known S_{11} and S_{22} [2 conditions]
TRM & LRM	Thru (T) or Line (L) with known S-parameters [4 conditions]	Unknown equal Reflect (R) on port-1 and port-2 [1 condition]	Known Match (M) on port-1 and port-2 [2 conditions]
TXYZ & LXYZ	Thru (T) or Line (L) with known S-parameters [4 conditions]	3 known Reflects (XYZ) on port-1 or port-2 [3 conditions]	
Traditional TOSL (Overdetermined)	Thru (T) with known S-parameters [4 conditions]	3 known Reflects (OSL) on port-1 [3 conditions]	3 known Reflect (OSL) on port-2 [3 condition]
LRRM	Line (L) with known S-parameters [4 conditions]	2 unknown equal Reflects (RR) on port-1 and port-2 [2 conditions]	Known match (M) on port-1 [1 condition]
UXYZ	Unknown Line (U) with $S_{12} = S_{21}$ [1 condition]	3 known Reflects (XYZ) on port-1 [3 conditions]	3 known Reflects (XYZ) on port-2 [3 conditions]

Calibration procedure (12-term)

- STEP 1: Calibrate Port-1 & Port-2 using One-Port procedure

  Open/Short/Load

- STEP 2: Connect Ports 1 & 2 together ,
  - Solve for e11, e00, & (e10e01),
  - Calculate (e10e01) from Δe
  - Measure S21M gives e30 directly S11M - e00 S11Me11 - Δe e22 = e10e32 = (S21M - e30)(1 - e11e22)
  - Reverse



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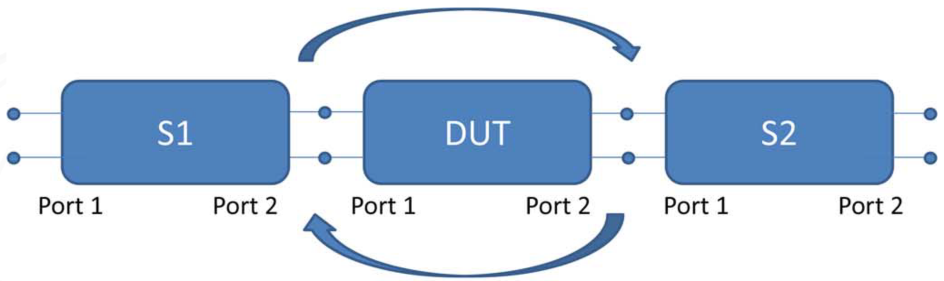
The two tier interior model

"S1" and "S2" can be calibrated out using TRL

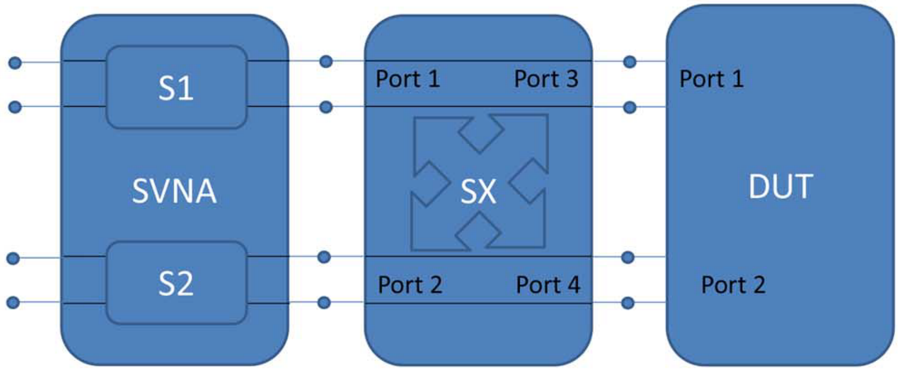
$$SX_{13} = SX_{31} = SX_{24} = SX_{42} = 1$$

$$SX_{11} = SX_{22} = SX_{33} = SX_{44} = 0)$$

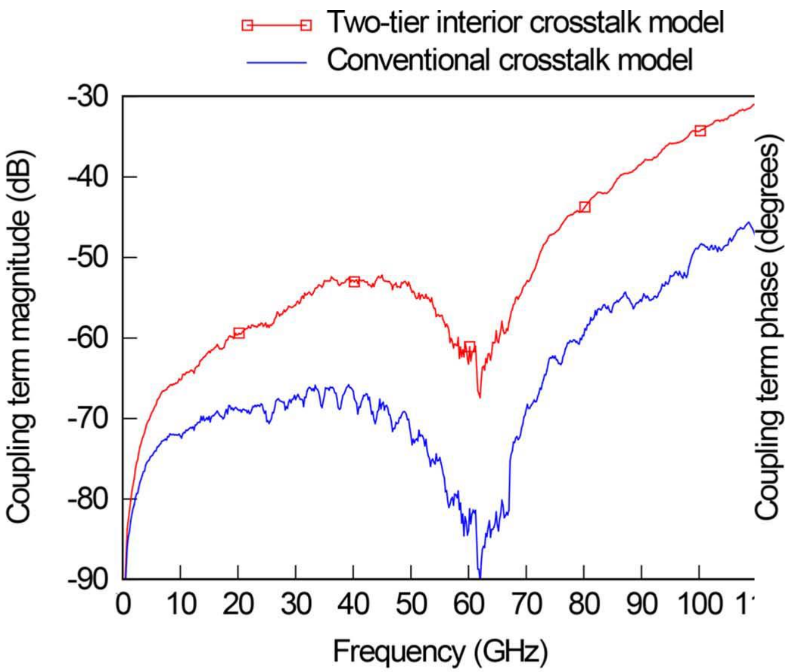
$$SX_{12}, SX_{21}, SX_{43}, SX_{34}, SX_{14}, SX_{41}, SX_{23}, \text{ and } SX_{32}$$

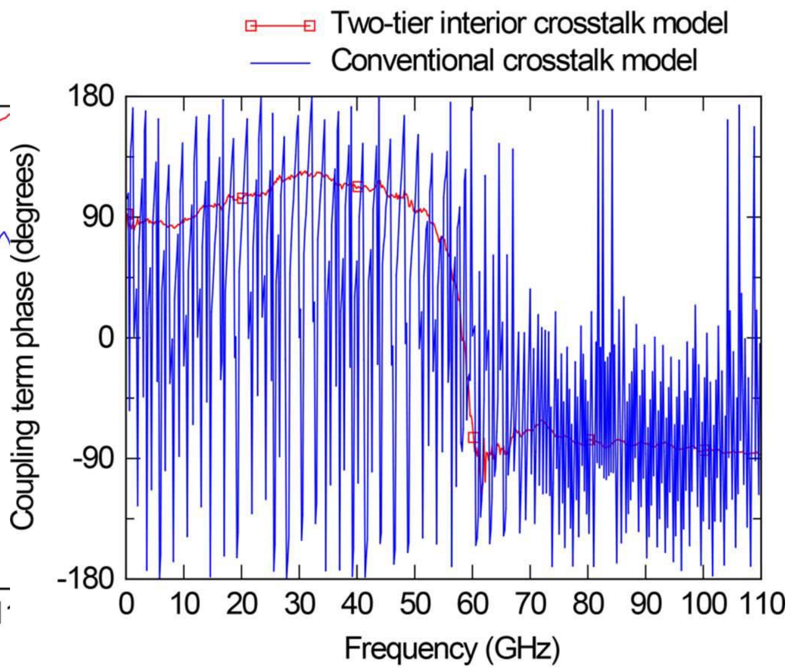


Strictly speaking, it is an approximation, is not completely physical, and is not precisely passive.



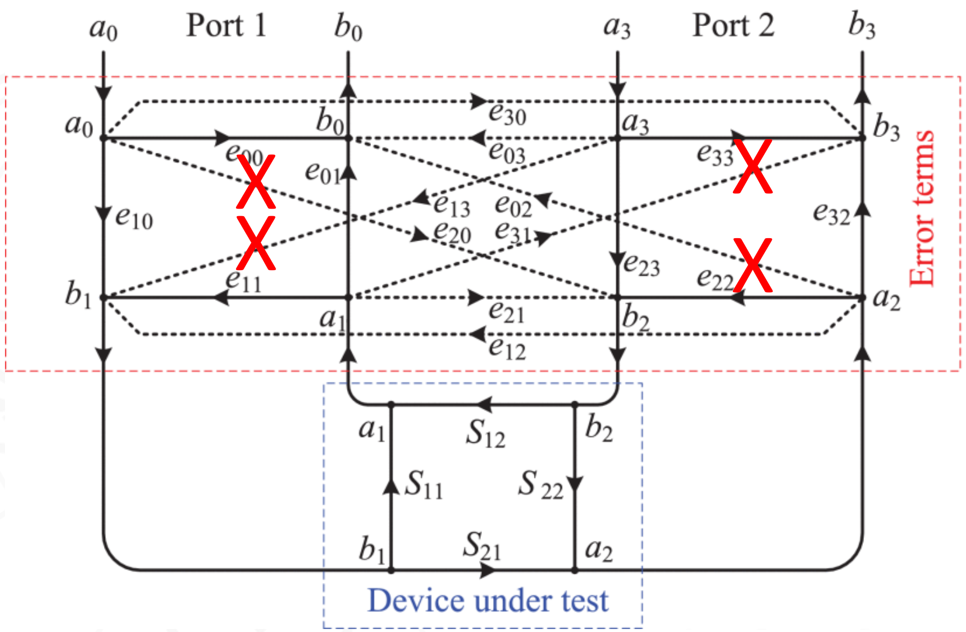
Williams et al IEEE MTT 2014

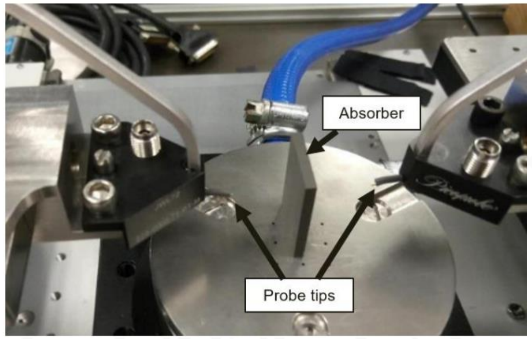


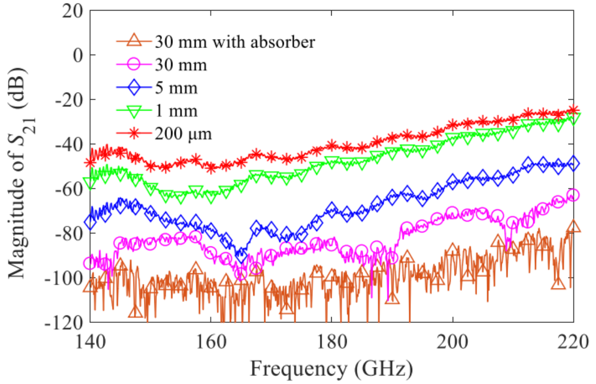


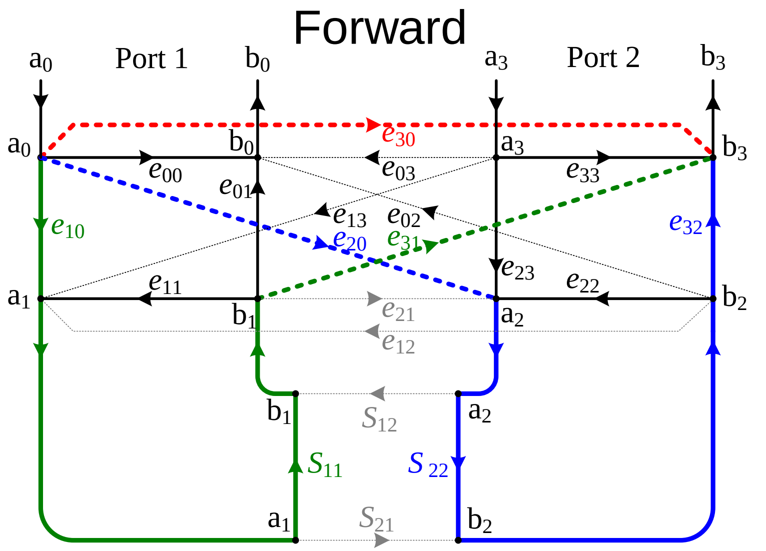
The 10 term error model

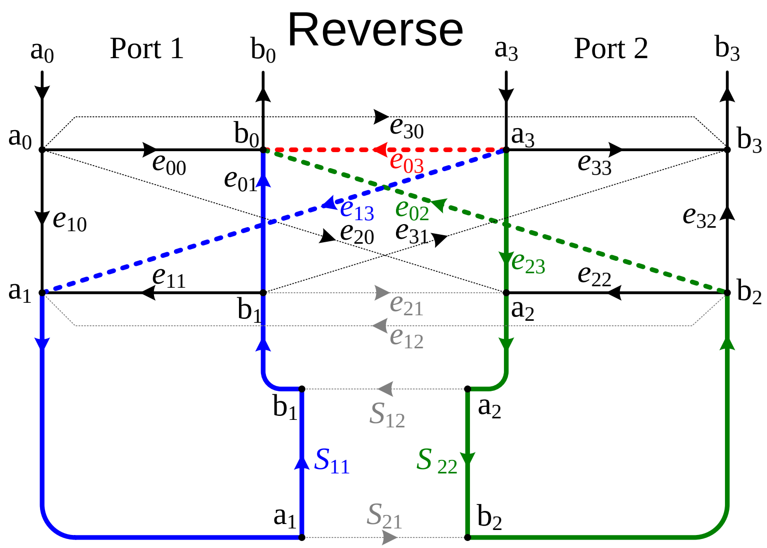
Liu et al IEEE MTT 2018











The 10 term error model

$$T=\begin{bmatrix} E_2-E_1E_3^{-1}E_4 & E_1E_3^{-1} \\ -E_3^{-1}E_4 & E_3^{-1} \end{bmatrix}$$

$$=\frac{1}{x}\begin{bmatrix} xe_{01}+x_1e_{00}+x_2e_{03} & xe_{02}+x_3e_{00}+x_4e_{03} & e_{00}e_{23}-e_{03}e_{20} & e_{03}e_{10}-e_{00}e_{13} \\ xe_{31}+x_1e_{30}+x_2e_{33} & xe_{32}+x_1e_{30}+x_2e_{33} & e_{30}e_{23}-e_{33}e_{20} & e_{33}e_{10}-e_{30}e_{13} \\ x_1 & x_3 & e_{23} & -e_{13} \\ x_2 & x_4 & -e_{20} & e_{10} \end{bmatrix}$$

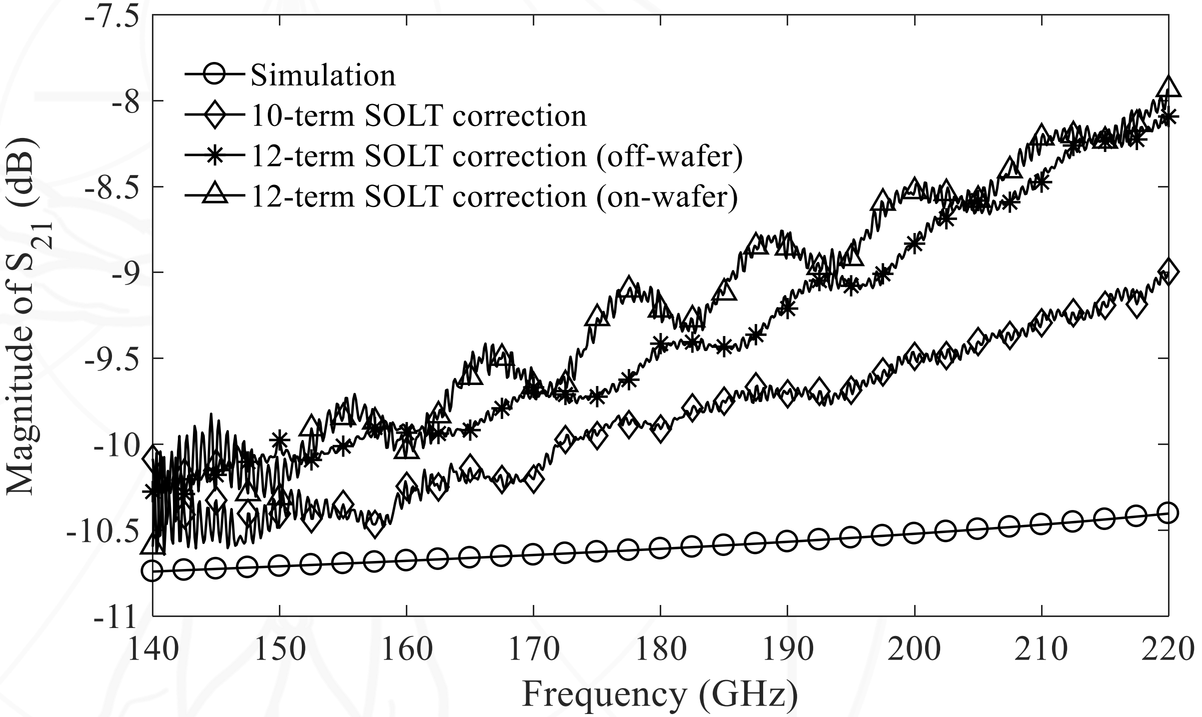
$$x=e_{10}e_{23}-e_{13}e_{20}$$
$$x_1=e_{13}e_{21}-e_{23}e_{11}$$
$$x_2=e_{20}e_{11}-e_{10}e_{21}$$
$$x_3=e_{13}e_{22}-e_{23}e_{12}$$

$$T=\begin{bmatrix} e_{01}-e_{00}e_{11}/e_{10} & -e_{00}e_{12}/e_{10} & e_{00}/e_{10} & 0 \\ -e_{21}e_{33}/e_{23} & e_{32}-e_{22}e_{33}/e_{23} & 0 & e_{33}/e_{23} \\ -e_{11}/e_{10} & -e_{12}/e_{10} & 1/e_{10} & 0 \\ -e_{21}/e_{23} & -e_{22}/e_{23} & 0 & 1/e_{23} \end{bmatrix}$$

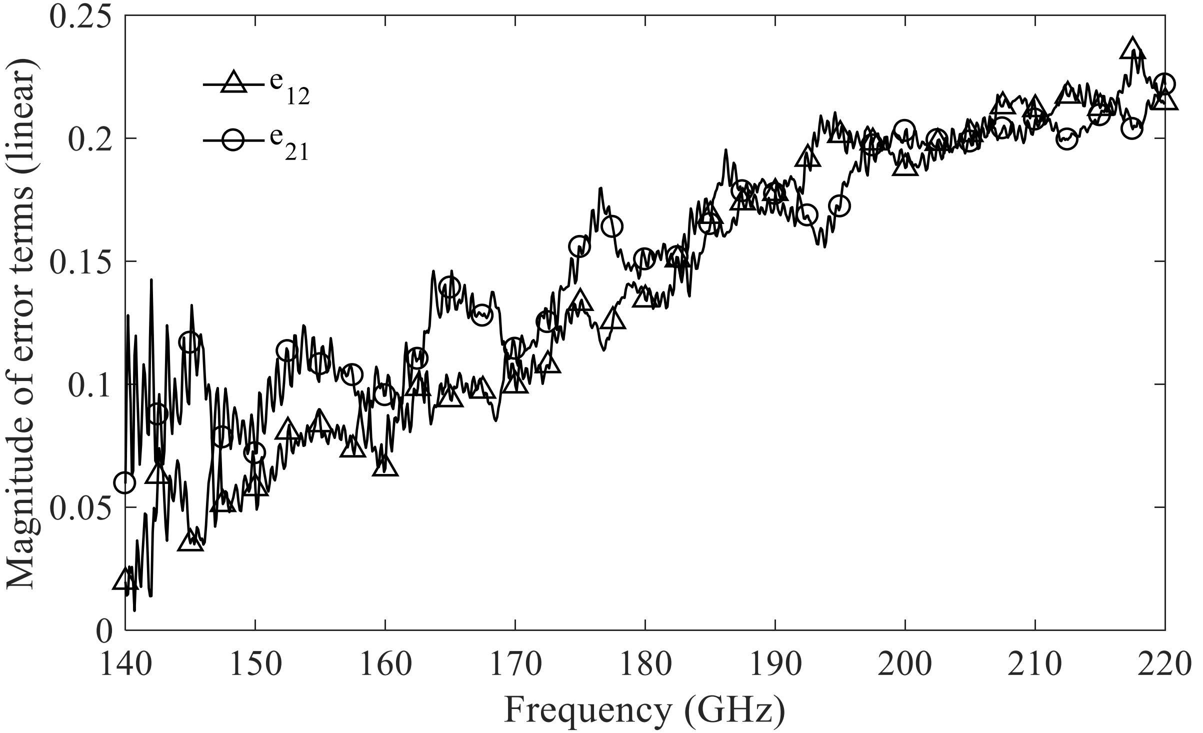
10 term Errors in T matrix

The 10 term error model

Attenuator transmission measured w & w/o crosstalk corrections

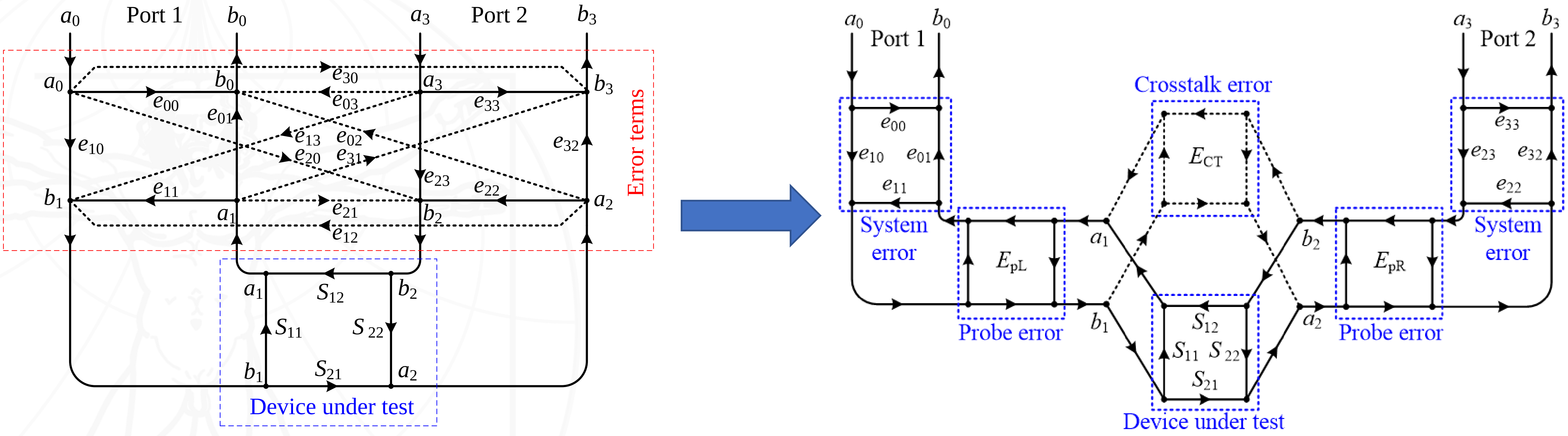


Magnitude of e_{12} and e_{21} terms. To some extent, these error terms represent crosstalk between probes.



The calibration on fly (CoF) method

A novel 12-term error term model separating the leakage from the intrinsic device-under-test (DUT) for calibration and actual device measurements; suitable for DUT with different length from calibration standards



Wu et al IEEE MTT 2020

The calibration on fly (CoF) method

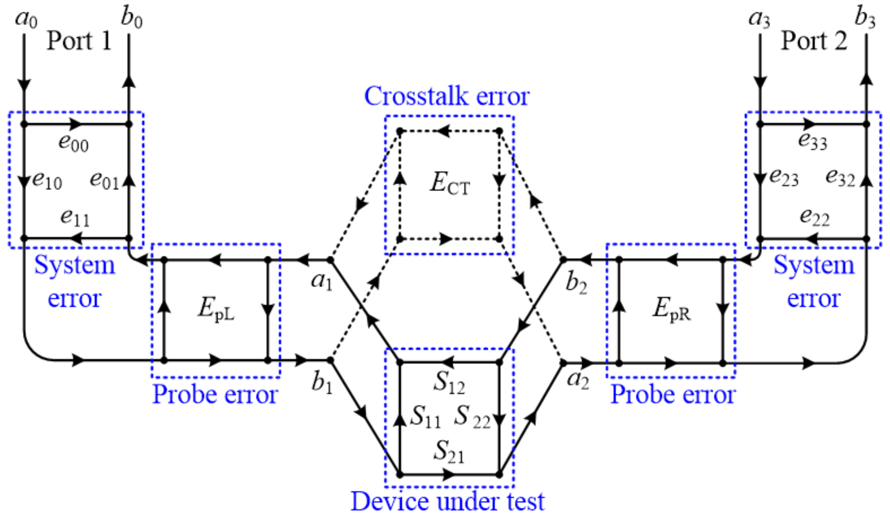
$$Y_{CT} = Y_{open||CT} - Y_{open}$$

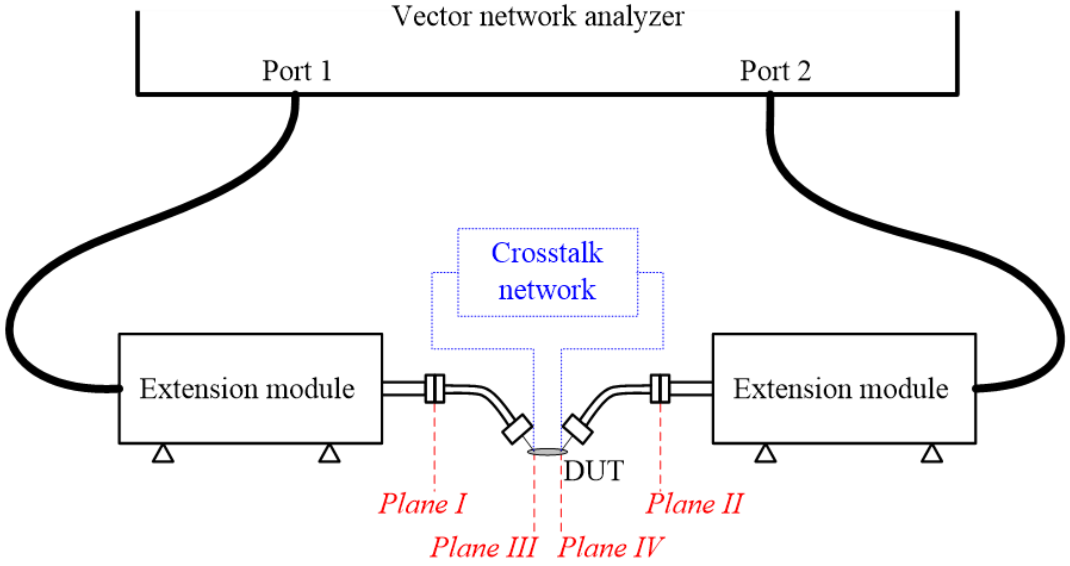
$$\Delta_Y S = (1 + S_{11})(1 + S_{22}) - S_{21}S_{12}$$

$$\Delta Y = (Y_0 + Y_{11})(Y_0 + Y_{22}) - Y_{21}Y_{12}$$

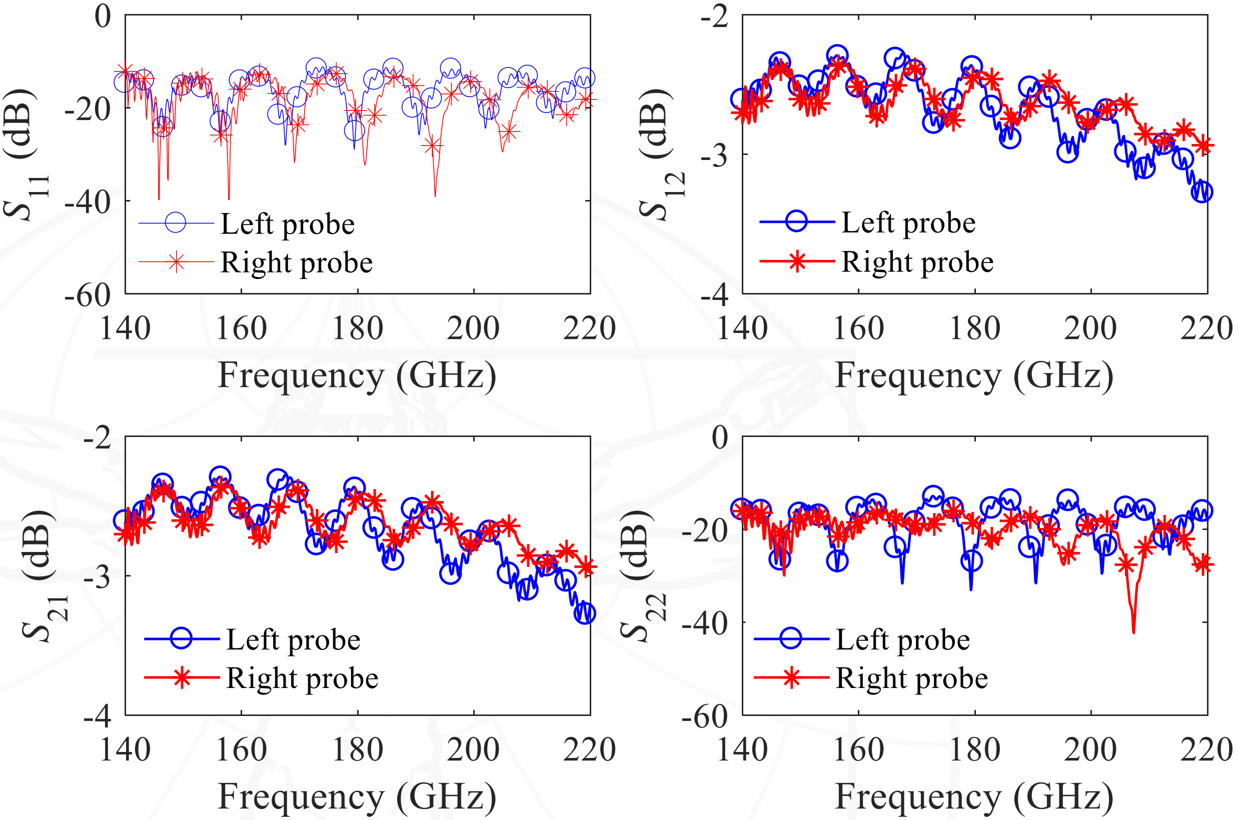
1. Calibrate the system at waveguide ports e.g. 2-port TRL
2. Extract probes' S-parameters using SOL
3. Measure a dummy pair e.g. Open-Open or Load-Load but not Short-Short having the same distance as a DUT
4. Extract the cross-talk matrix

Wu et al IEEE MTT 2020

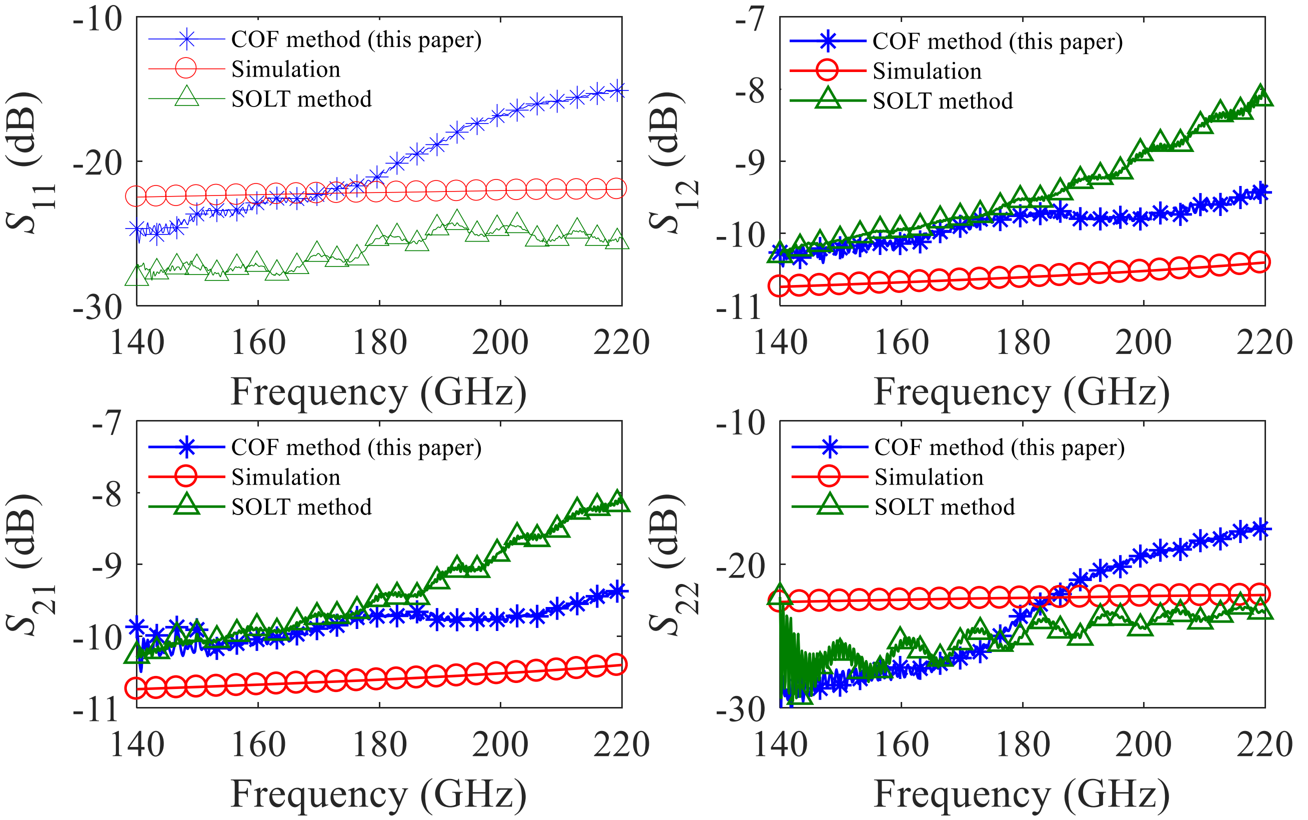




The calibration on fly (CoF) method

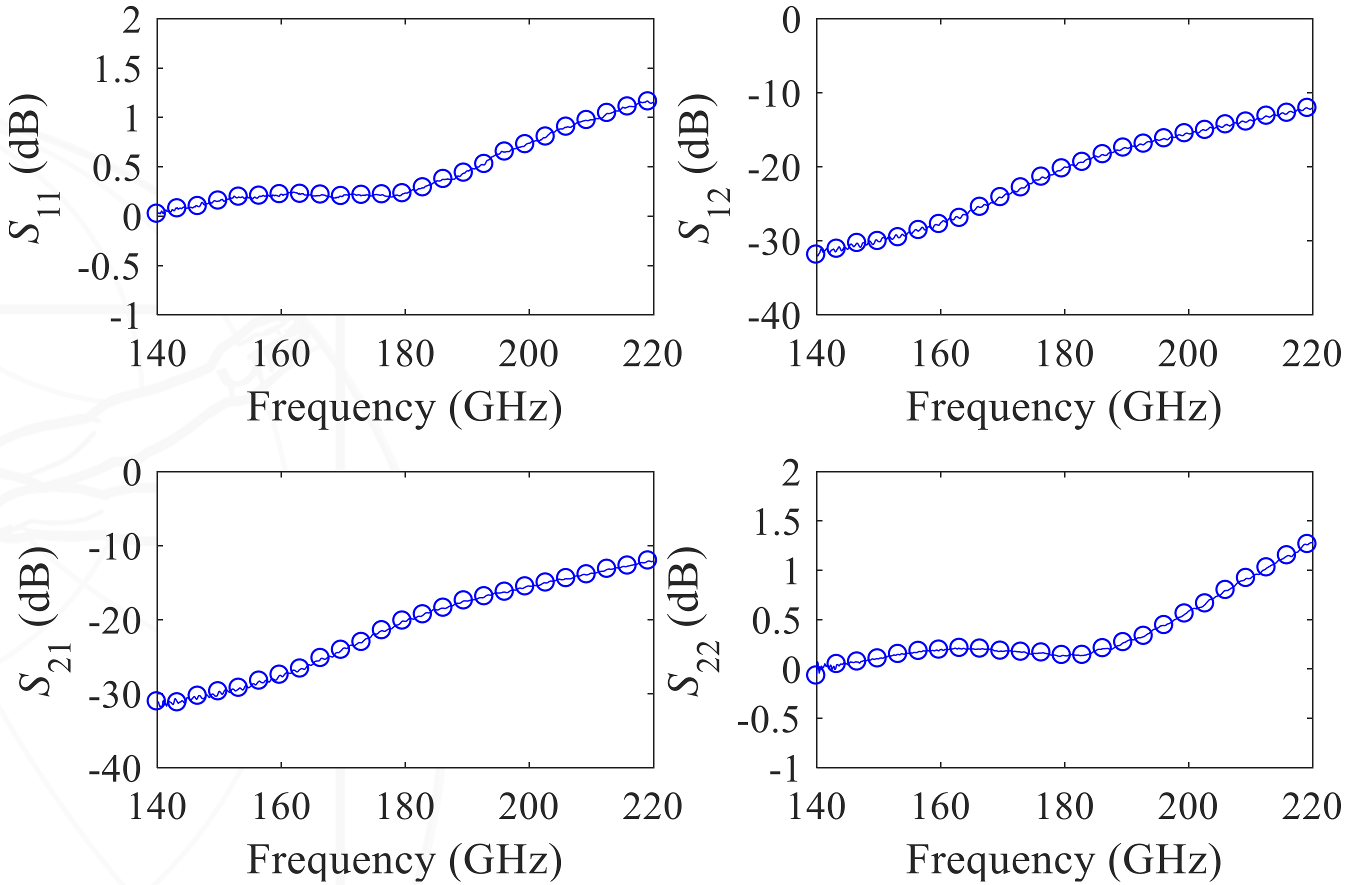


S-parameters of microwave probe pair on each side. Port 1 is a coaxial port of each probe, and port 2 is a probe tip port of each probe.



S-parameters of a 10-dB attenuator after the calibration of this paper, compared with both of simulation results and that after the calibration of SOLT (conventional 12-term error model).

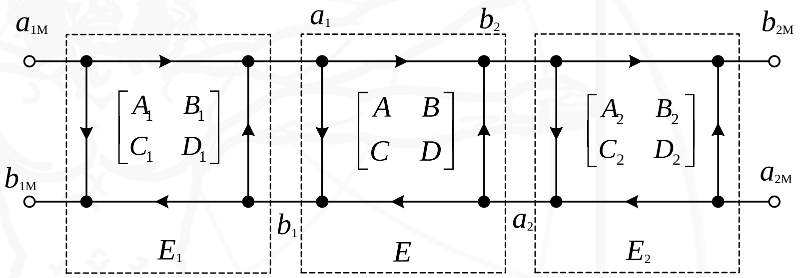
The calibration on fly (CoF) method

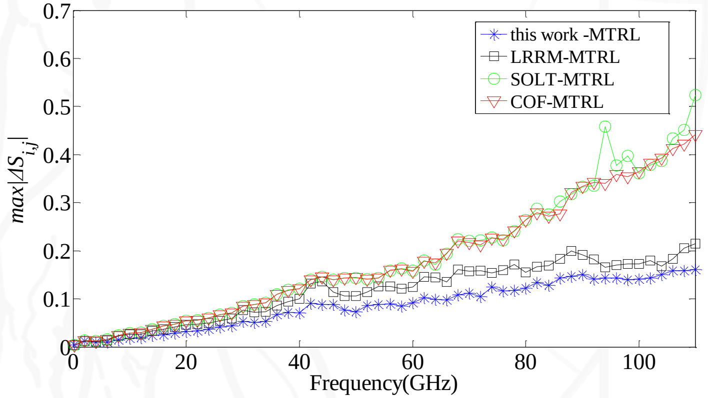


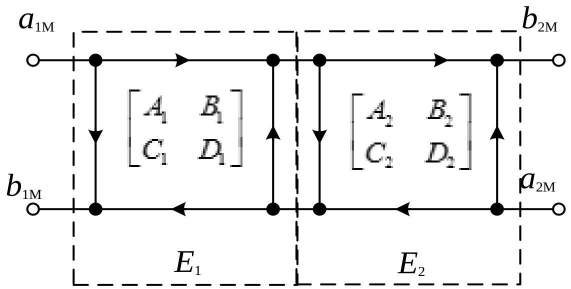
S-parameters of the crosstalk network. The magnitude of S_{11} and S_{22} are greater than 1, which is possible due to the probe launch difference between calibration and measurement.

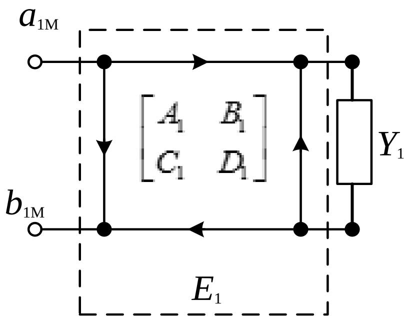
An improved CoF method

- A new 12-term error model
- Only two calibration steps required
- Taking calibration planes to the access of DUTs on chip
- Less stringent standards including an undefined Thru, two undefined Reflect pairs i.e. Open-Open and Short-Short and one defined Load pair







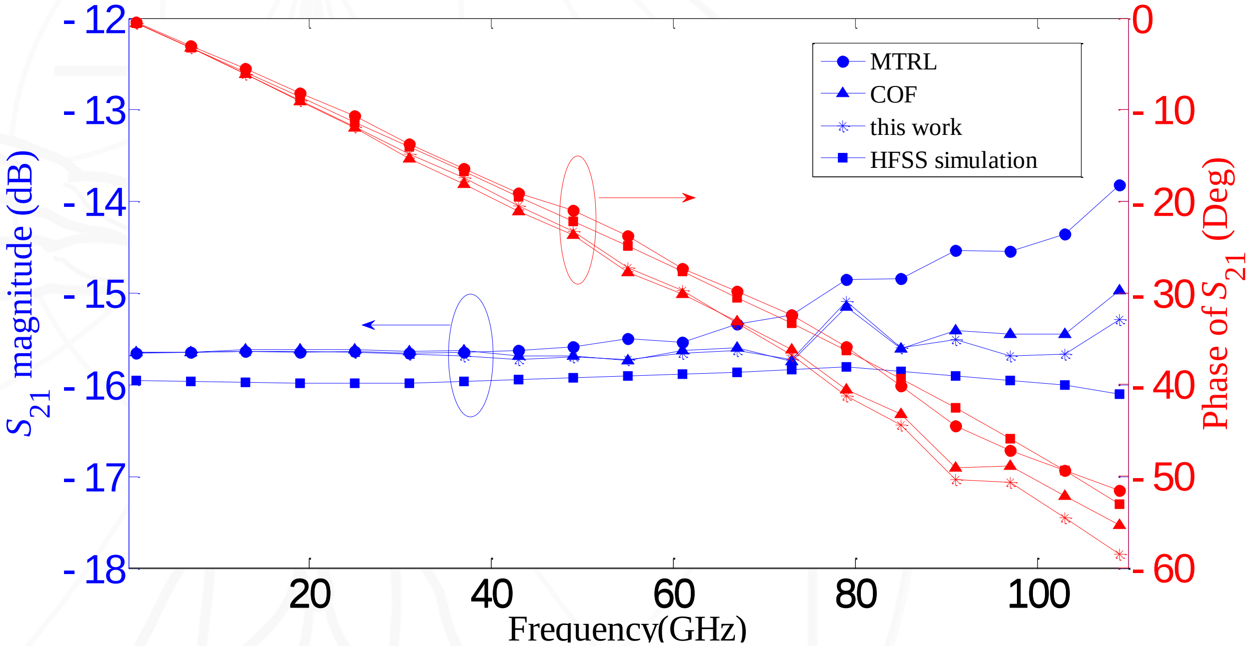


Type	Description	Definition	Quantity
Thru	Matched straight line	not required	1
Open-Open	Identical Open pair	not required	1
Short-Short	Identical Short pair	not required	1
Load-Load	Match pair	Required	1

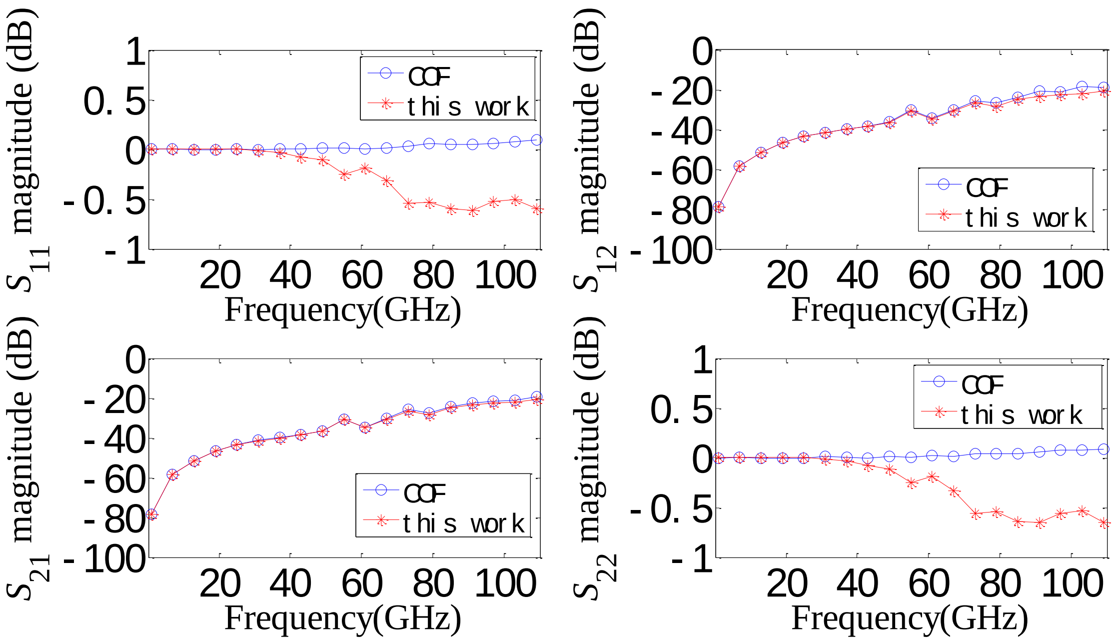
Wang et al. IEEE MTT 2022 Early Access

The improved CoF method

Magnitude and phase of S_{21} of the mismatched attenuator corrected using different methods.



S-parameters of the crosstalk network between COF and the new method



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Summary & future work

- Probe-probe crosstalk/leakage contributes more significantly at mm-Wave
- Accurate error models and calibration algorithms are desperately required
- Calibration standards should be further investigated
- New £2.6M (€3M) test cluster to be launched in April 2023
  - AWG: 128/256 GSa/s, 4/2 channels (67 GHz; extended to 330 GHz)
  - RT Oscilloscope: 128 GSa/s 4 channels (70 GHz; extended to 330 GHz)
  - 50GHz PNA-X: SA, NF, TD etc
  - Noise tuners: 2 GHz-43.5 GHz
  - Loadpull: full band
  - Frequency extender modules to (10 MHz-1.1 THz)
  - 10 inch autoprober

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Acknowledgement

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- Mr. Aihua Wu (HSRI)
- Mr. Chen Liu (HSRI)
- Mr. Yibang Wang (HSRI)

Thank you!