南京航空航天大學
NANJING UNIVERSITY OF AERONAUTICS AND ASTRONAUTICS

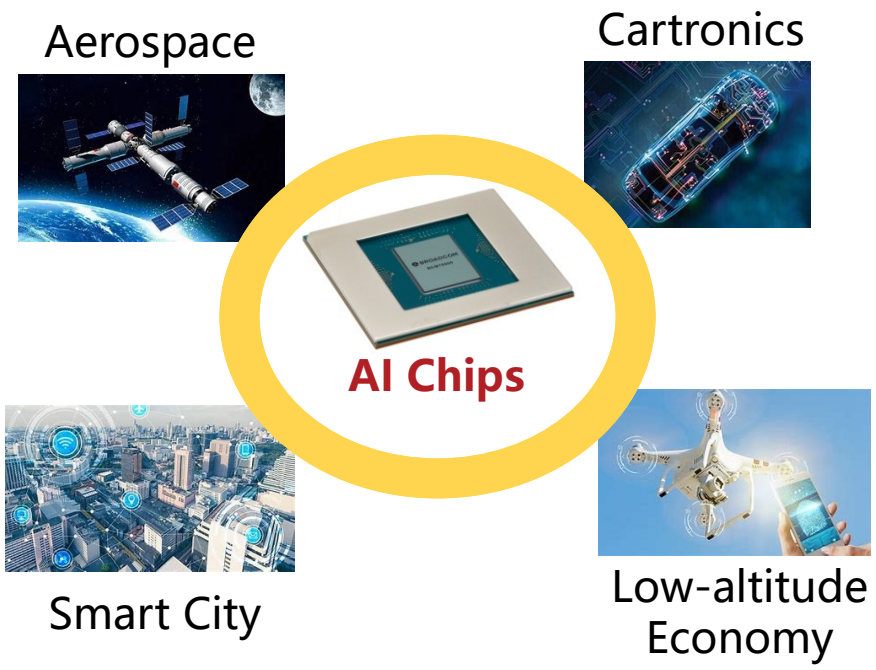
Theory and Techniques of RF Probe Calibration: From Parasitic Extraction of Calibration Standards to Calibration Algorithm

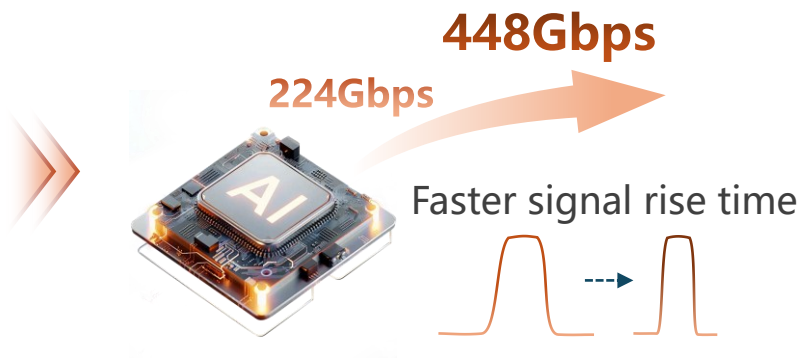
Jiefeng Zhou
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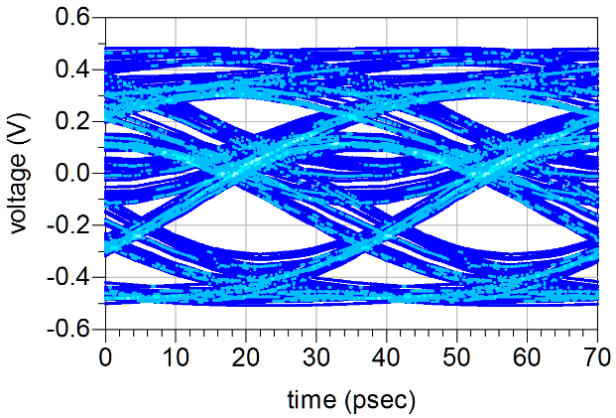
Hybrid IBIS Summit at IEEE WAI 2026
Hangzhou, China
November 6, 2026

Background

➢ **As AI advances rapidly, growing computational power is leading to signal integrity issues.**



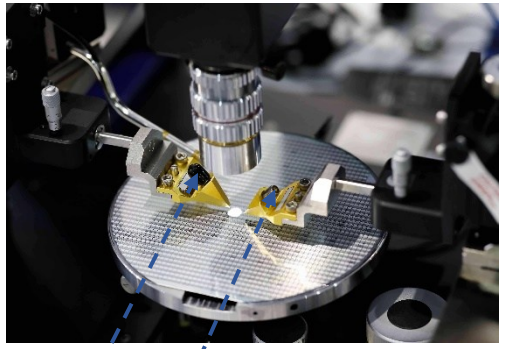


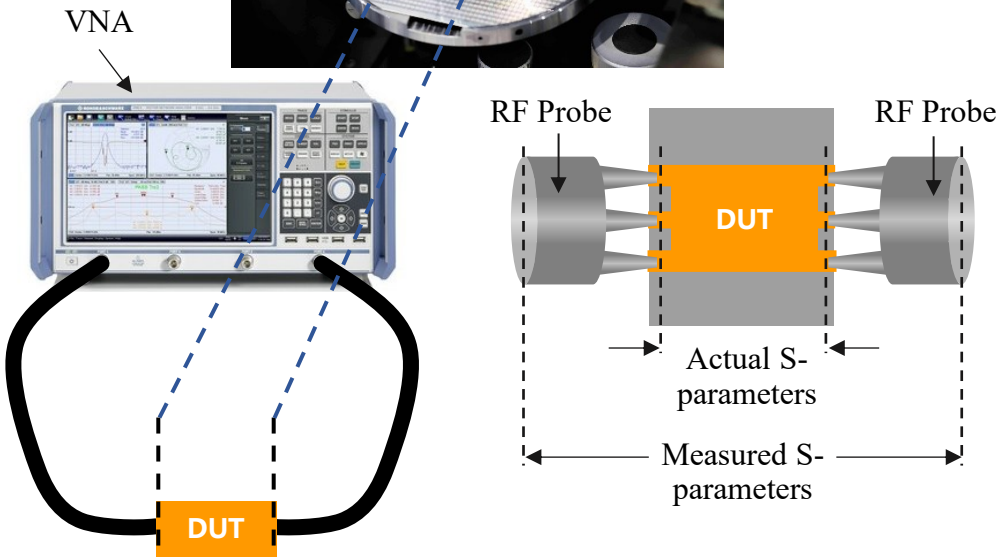


- The rapid advancement of AI is empowering industries across the board, enabling them to innovate faster, improve efficiency, and unlock new opportunities.
- The computational power is constantly increasing, and the signal integrity issue of the chip channels has become increasingly prominent, which affects the stable transmission of signals.

Background

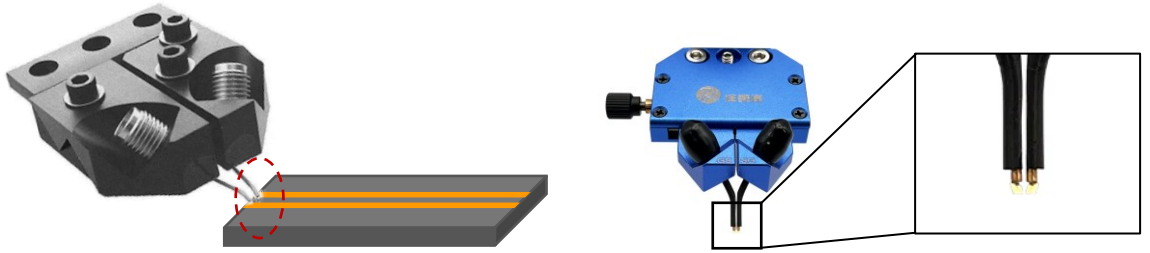
- **On-Wafer broadband S-parameter measurement is the direct and powerful tool for analyzing the signal integrity of chip channels.**



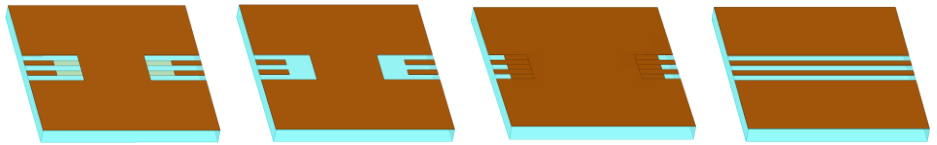


- The calibration algorithm and corresponding calibration standards are required to eliminate the errors introduced by the probes;
- The on-wafer four-port S-parameter measurement faces greater challenges!

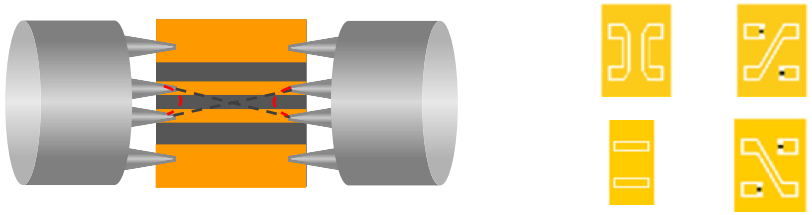
Challenge 1: **Parasitic and crosstalk effects** are significantly evident at high frequencies.



Challenge 2: When the on-chip calibration component operates at a high frequency, **the extraction of parasitic parameters becomes more challenging**.



Challenge 3: There are **numerous error terms** in the four-port probe, and the calculation process is very complicated.

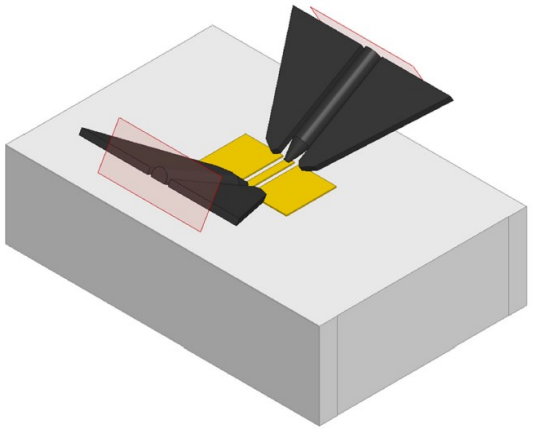


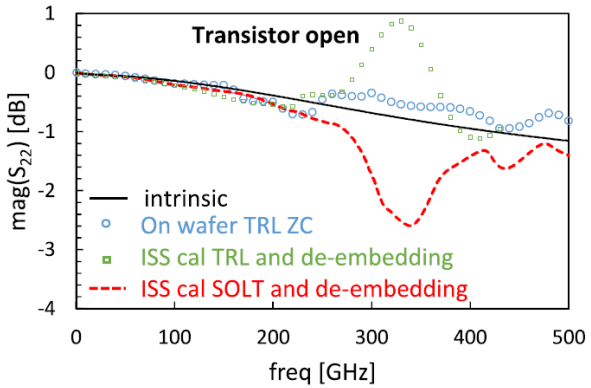
Research States

1. Two-Port Calibration Algorithm

- A calibration algorithm based on SOLT, SOLR, and TRL was formed and has been widely applied in the calibration of VNA.
- In recent years, many domestic and foreign institutions have conducted more in-depth research on the SOLT and TRL calibration algorithms. The research content has gradually shifted from board level to chip level and has made breakthroughs at higher frequencies.

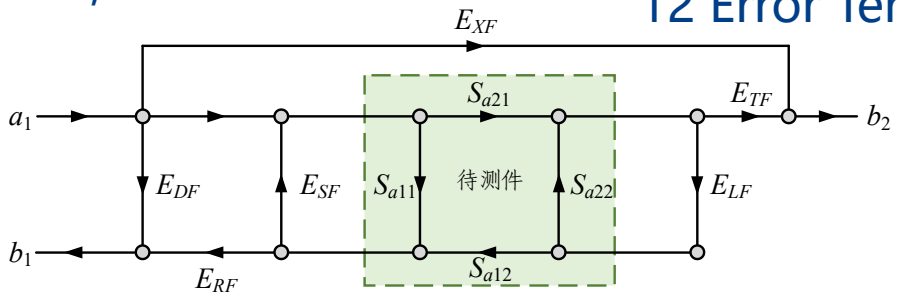
- **Disadvantages:** SOLR and TRL cannot take crosstalk into account, and on-chip S-parameter measurements are prone to errors.



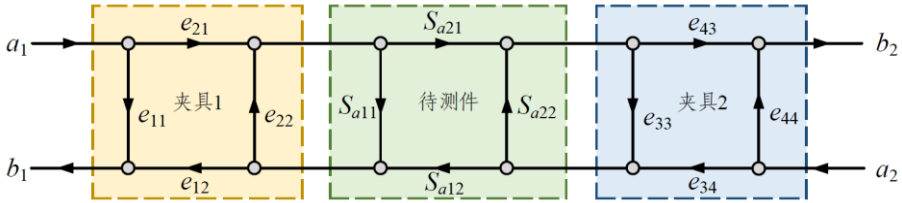


- SOLT，SOLR

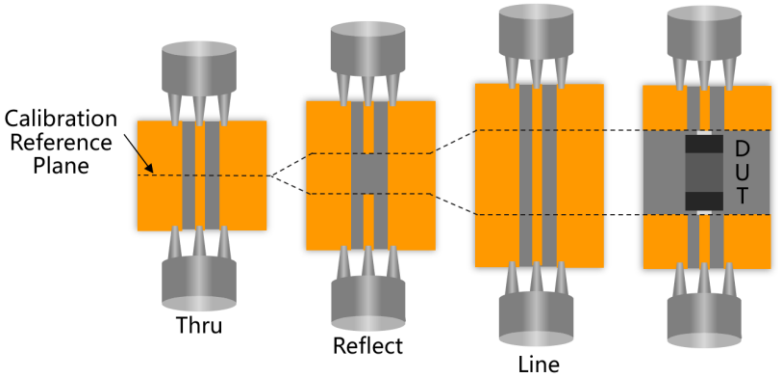
12 Error Terms



8 Error Terms



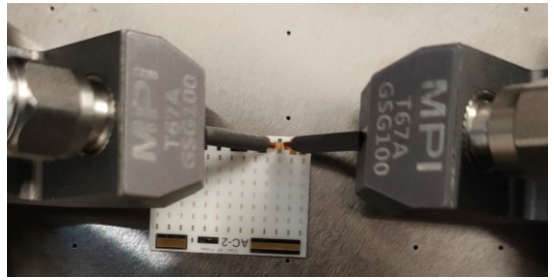
- TRL



Research States

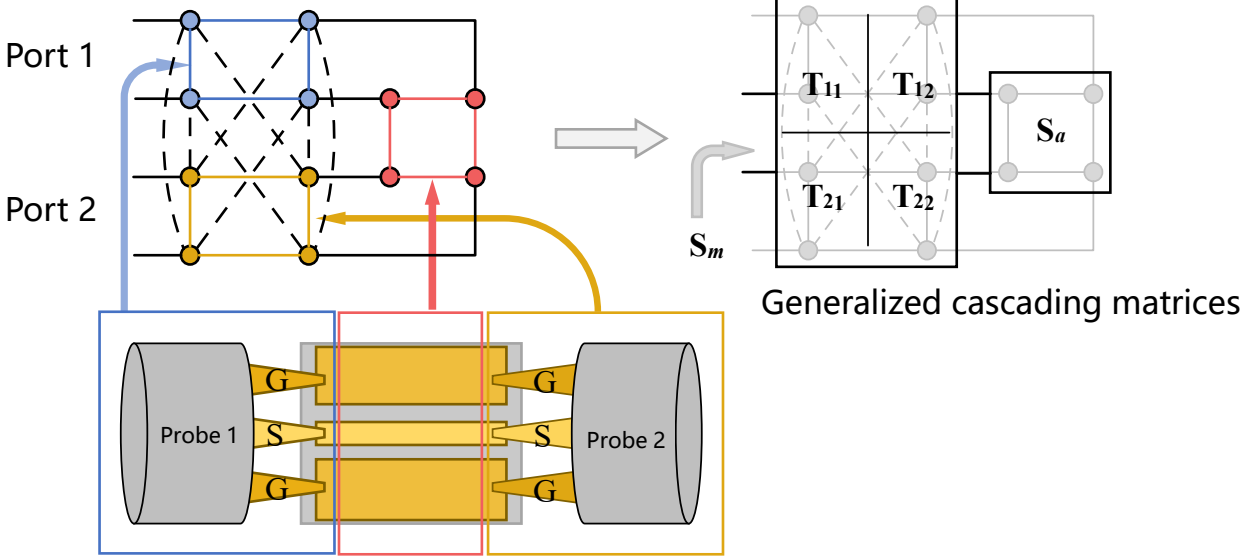
2. Two-Port Calibration Algorithm in Crosstalk System

- 16-term error model



For an on-wafer two-port S-parameter measurement system with crosstalk, its signal flow diagram can be represented in the form of including 16 error terms.

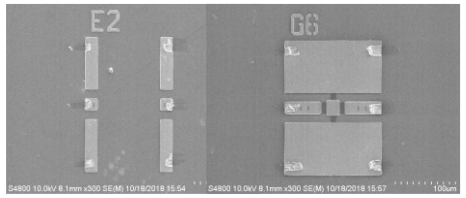
Signal diagram

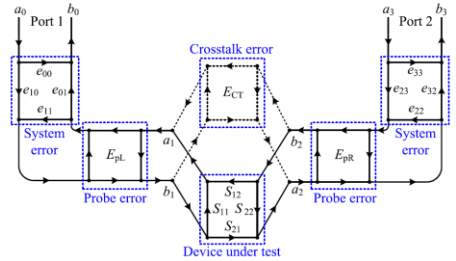


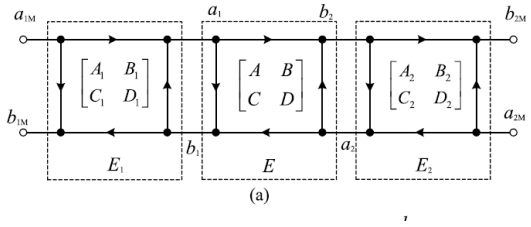
Generalized cascading matrices

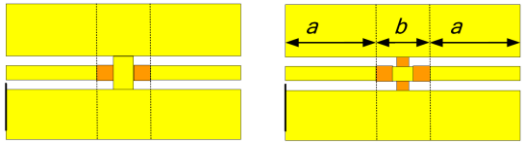
On-wafer S-parameter measurement

- Based on 16 error models, domestic and foreign units have expanded them and proposed calibration algorithms such as COF, new SOLT, and two-step SOLR.









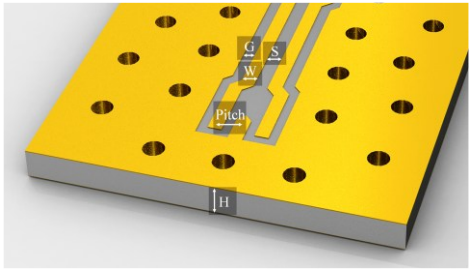
- **Disadvantage: The two-port calibration algorithm cannot be applied to a four-port network without the need for additional direct-through calibration components!**

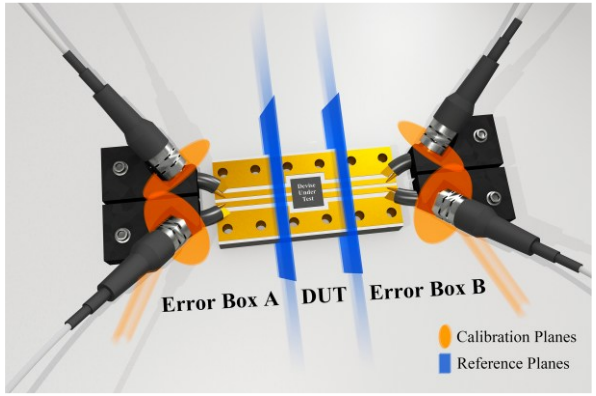


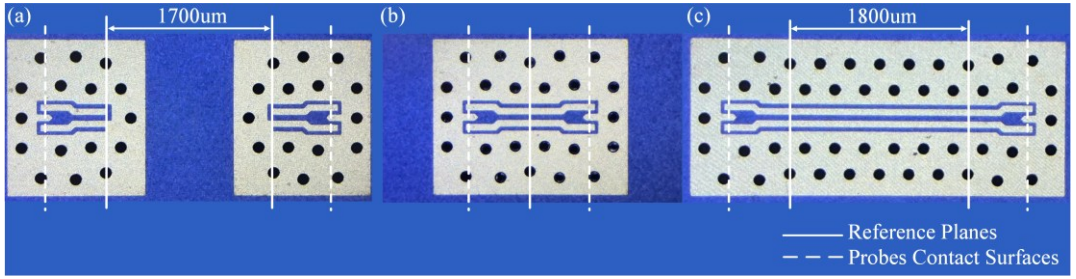
Research States

3. Four-Port Calibration Algorithm

- Multimode TRL

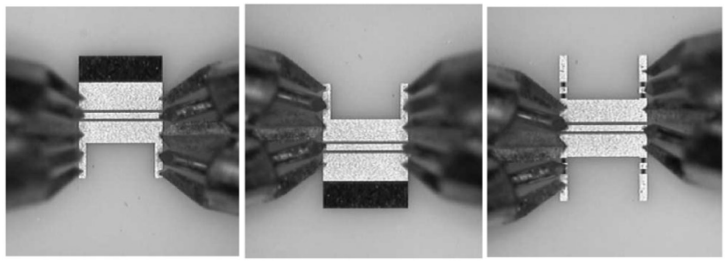


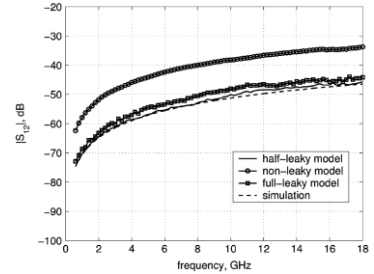




- **Disadvantage:** It requires multiple lines to expand the bandwidth, and the reference plane is not at the tip of the needle.

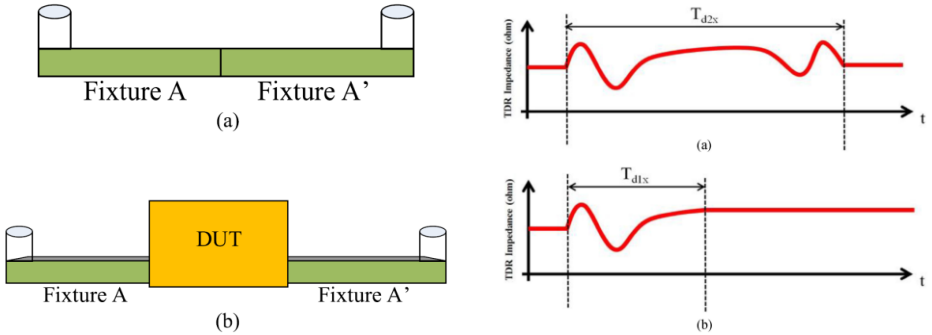
- Full-leaky/half-leaky model





- **Disadvantage:** Multiple asymmetric direct calibration pieces are required, and it is difficult to accurately obtain their S parameters.

- 2^n Ports 2×-Thru



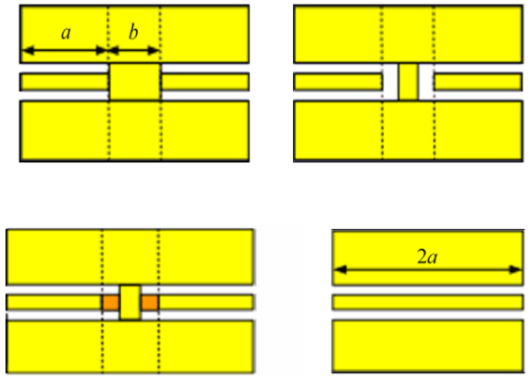
- **Disadvantages:** The probe needs to be symmetrical, and the reference plane is not at the tip of the needle. For fixtures with excessively small electrical lengths, there is a risk of incorrect cutting.

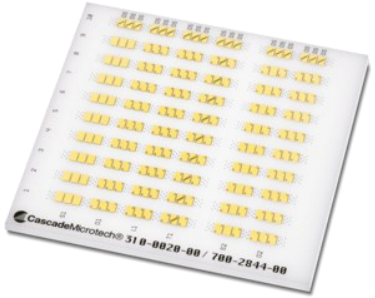
Parasitic Parameter Extraction for Calibration Standards Using an Optimization Strategy

Parasitic Parameter Extraction for Calibration Standards Using an Optimization Strategy

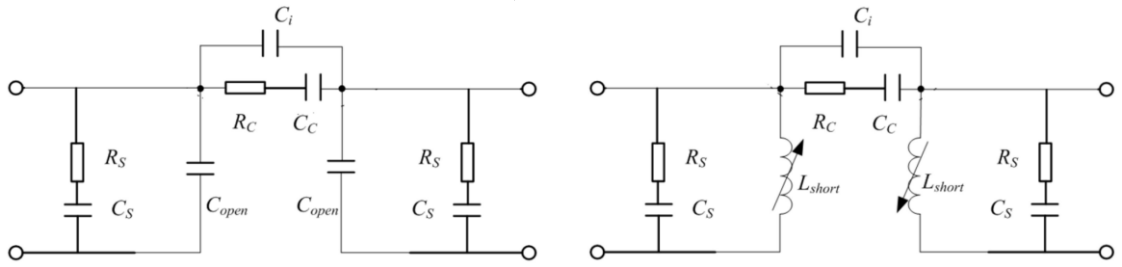
1. Overcoming the disadvantages of the traditional TRL method and integrating the advantages of 16-term error model

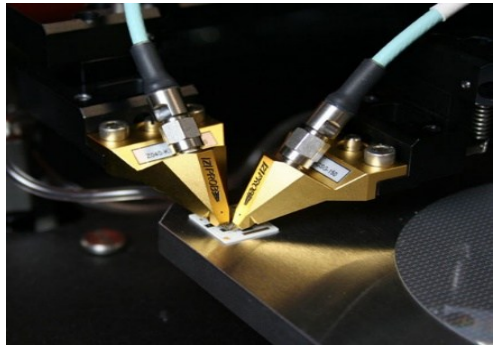
TRL method
Measuring S-parameters



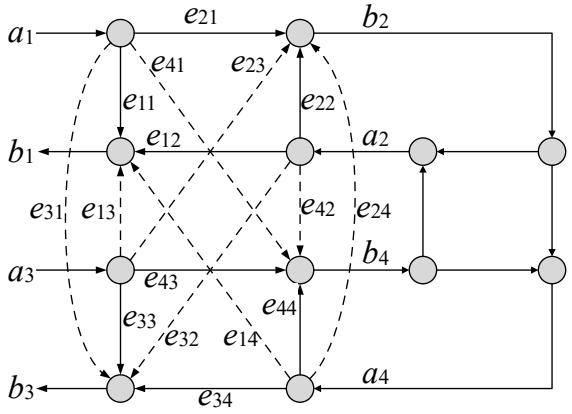


Estimation of equivalent circuit





16-term error model
Measuring S-parameters



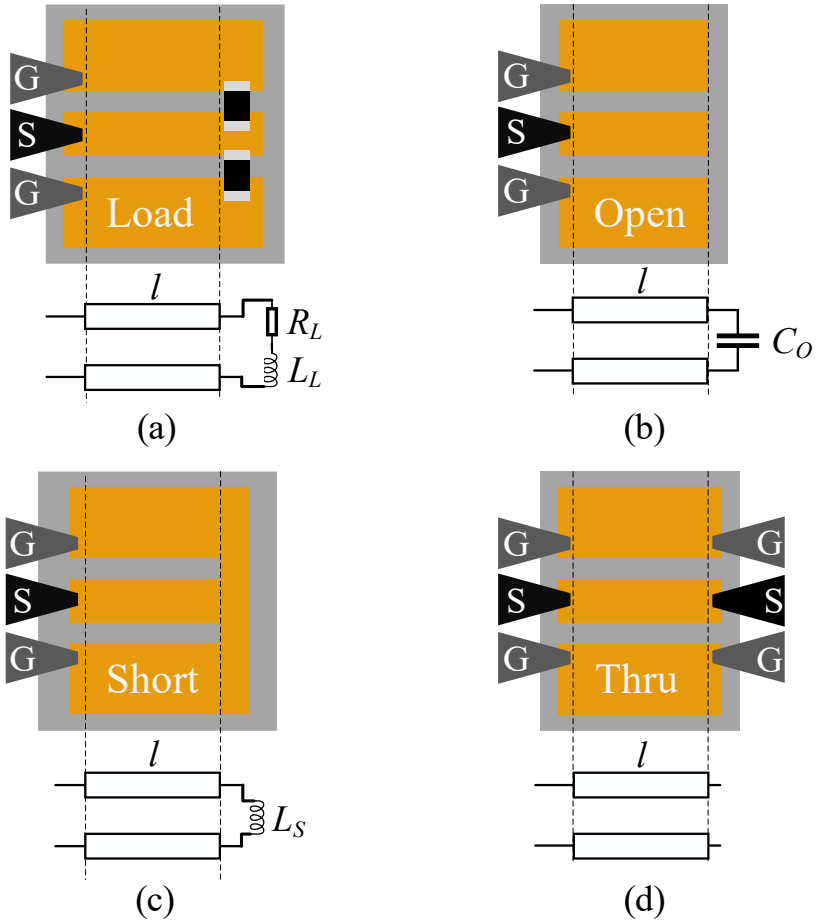
- The TRL method has **poor accuracy** under high crosstalk conditions and requires the design of additional calibration standards, making **the process cumbersome.**

- **How can we fully leverage the advantages of the 16 error models in high crosstalk systems?**

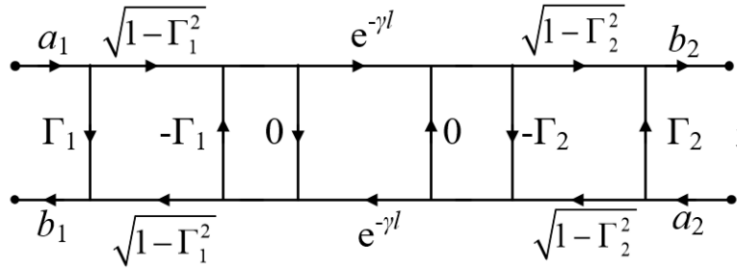
Parasitic Parameter Extraction for Calibration Standards Using an Optimization Strategy

2. Calibration standard models and transmission line S-parameter matrix

Based on the character of the calibration standards, propose their equivalent physical models



Based on the signal flow diagram of the transmission line, derive the S-parameter matrix of the transmission line



- **The S-parameters of each calibration standard can be obtained by theoretical derivation!**

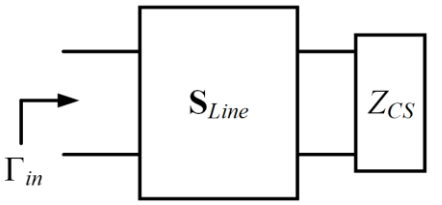
Obtain the S-parameter matrix of the transmission line

$$\mathbf{S}_{Line} = \begin{bmatrix} \dfrac{\Gamma_1(e^{\gamma l} - e^{-\gamma l})}{e^{\gamma l} - \Gamma_1^2 e^{-\gamma l}} & \dfrac{1-\Gamma_1^2}{e^{\gamma l} - \Gamma_1^2 e^{-\gamma l}} \\ \dfrac{1-\Gamma_1^2}{e^{\gamma l} - \Gamma_1^2 e^{-\gamma l}} & \dfrac{\Gamma_1(e^{\gamma l} - e^{-\gamma l})}{e^{\gamma l} - \Gamma_1^2 e^{-\gamma l}} \end{bmatrix}$$

$$\Gamma_1 = (Z_c - Z_P)/(Z_c + Z_P)$$

$$\Gamma_L = (Z_{CS} - Z_c)/(Z_{CS} + Z_c)$$

Z_c: characteristic impedance,
Z_P: reference impedance (usually 50Ω)



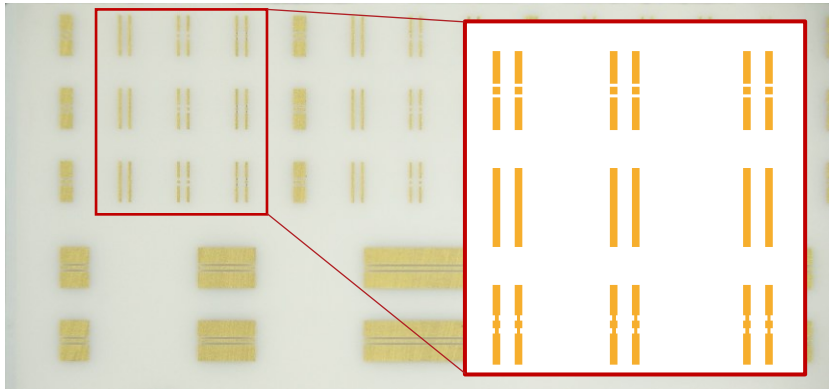
$$\Gamma_{in} = \frac{\Gamma_1(1 - e^{-2\gamma l} - \Gamma_1\Gamma_L) + e^{-2\gamma l}\Gamma_L}{1 - \Gamma_1^2 e^{-2\gamma l} - \Gamma_1\Gamma_L(1 - e^{-2\gamma l})}$$

Jiefeng Zhou, Ling Zhang, Junhui Chen, Li Jiang, Da Li, Yan Li, Hongsheng Chen, Er-Ping Li. "Parasitic Parameter Extraction for Calibration Standards Using an Optimization Strategy" **IEEE TMTT** (2023).

Parasitic Parameter Extraction for Calibration Standards Using an Optimization Strategy

3. The S-parameter matrix of lumped calibration standards

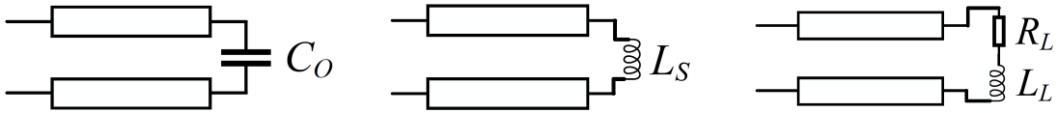
The lumped calibration standards are composed of Open, Short and Load.



The S-parameter matrix of the lumped calibration standards can be expressed as

$$\mathbf{S}_{CS} = \begin{bmatrix} \Gamma_{in1} & 0 \\ 0 & \Gamma_{in2} \end{bmatrix}$$

$$\Gamma_{in} = \frac{\Gamma_1(1-e^{-2\gamma l}-\Gamma_1\Gamma_L)+e^{-2\gamma l}\Gamma_L}{1-\Gamma_1^2 e^{-2\gamma l}-\Gamma_1\Gamma_L(1-e^{-2\gamma l})}$$



$$Z_{CS}\begin{cases} Z_O = 1/\,j\omega C_O \\ Z_S = j\omega L_S \\ Z_L = R_L + j\omega L_L \end{cases}$$

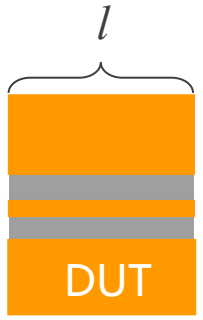
When the propagation constant γ is known, the equation contains only four unknowns: C_O, L_S, R_L, L_L

The variable to be determined: $\boldsymbol{x}=(C_O, L_S, L_L, R_L)$

- **The ultimate goal is to solve for the variable x !**

Parasitic Parameter Extraction for Calibration Standards Using an Optimization Strategy

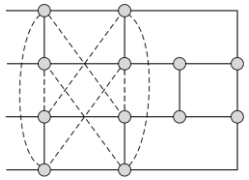
4. The Bayesian optimization algorithm for obtaining parasitic parameters



$$\mathbf{S}_{act}=\begin{bmatrix}\dfrac{\Gamma_1(e^{\gamma l}-e^{-\gamma l})}{e^{\gamma l}-\Gamma_1^2 e^{-\gamma l}} & \dfrac{1-\Gamma_1^2}{e^{\gamma l}-\Gamma_1^2 e^{-\gamma l}}\\ \dfrac{1-\Gamma_1^2}{e^{\gamma l}-\Gamma_1^2 e^{-\gamma l}} & \dfrac{\Gamma_1(e^{\gamma l}-e^{-\gamma l})}{e^{\gamma l}-\Gamma_1^2 e^{-\gamma l}}\end{bmatrix}$$

$\boldsymbol{x}=(C_O, L_S, L_L, R_L)$, random value selection

16-term error model



Update $\boldsymbol{x}$

Output the optimal $\boldsymbol{x}$

$\mathbf{S}_{cal}$ Difference between $\mathbf{S}_{cal}$ and $\mathbf{S}_{act}$

Single object optimization

Measurement problem → Optimization problem

Variables to be optimized: $\boldsymbol{x}=(C_O, L_S, L_L, R_L)$.

$$\boldsymbol{x}^* = \arg\min f(\boldsymbol{x})$$

$$s.t.\ g(\boldsymbol{x}) = (g_1(\boldsymbol{x}), g_2(\boldsymbol{x})) \le 0$$

$$\boldsymbol{x} = (C_O, L_S, R_L, L_L) \in \mathbf{X}^4$$

objective function:

$$f(\boldsymbol{x}) = \sum_{m=1}^{n}\sum_{i=1}^{4}\sum_{j=1}^{4}\sqrt{\left[re(S_{cal,ij,m}^{Ref} - S_{a,ij,m}^{Ref})\right]^2 + \left[im(S_{cal,ij,m}^{Ref} - S_{a,ij,m}^{Ref})\right]^2}$$

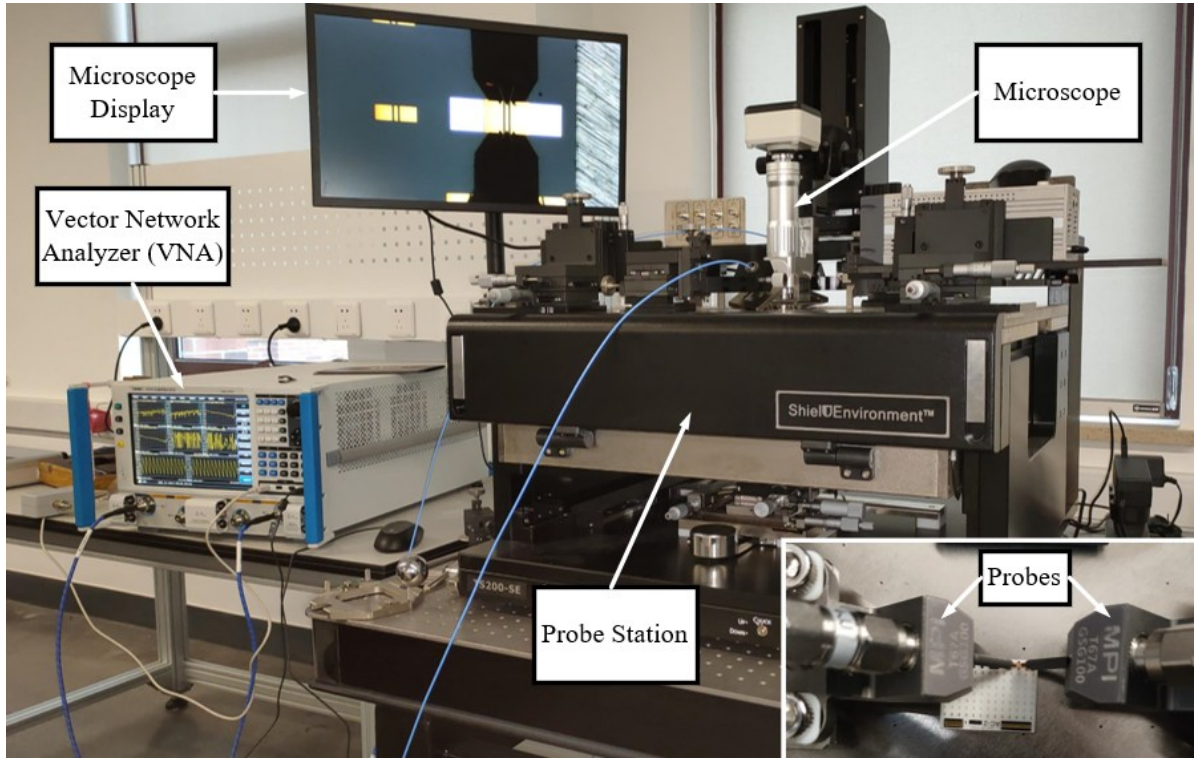
constraint conditions:

$$g_1(\boldsymbol{x}) = S_{k11}^2(\boldsymbol{x}) + S_{k21}^2(\boldsymbol{x}) - 1 \le 0,$$

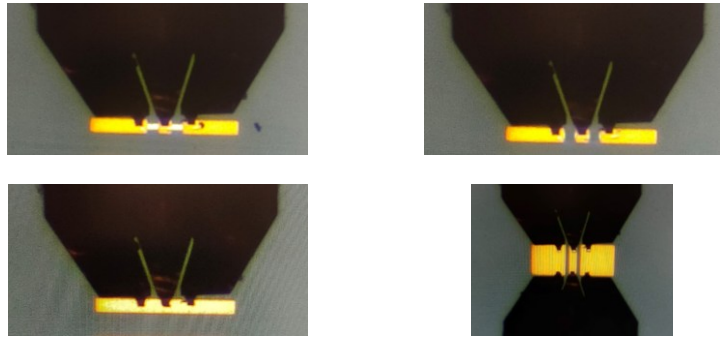
$$g_2(\boldsymbol{x}) = S_{k22}^2(\boldsymbol{x}) + S_{k12}^2(\boldsymbol{x}) - 1 \le 0.$$

Parasitic Parameter Extraction for Calibration Standards Using an Optimization Strategy

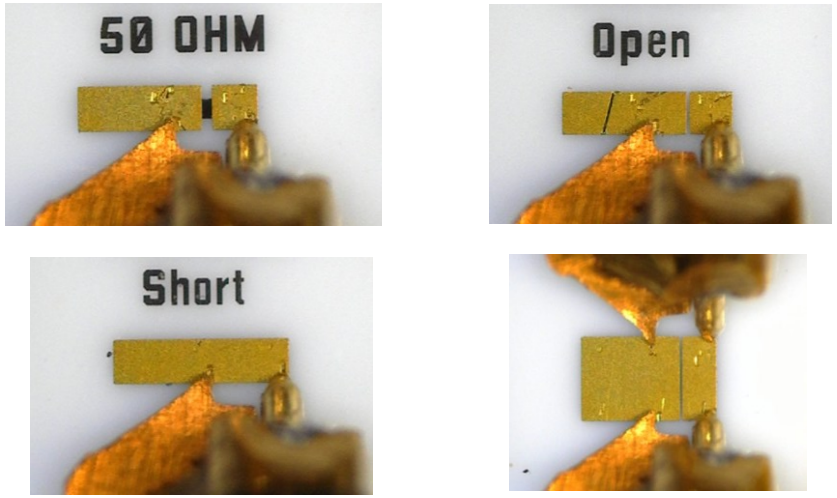
5. Measurement validation: on-wafer S-parameter measurement system



1. GSG Validation



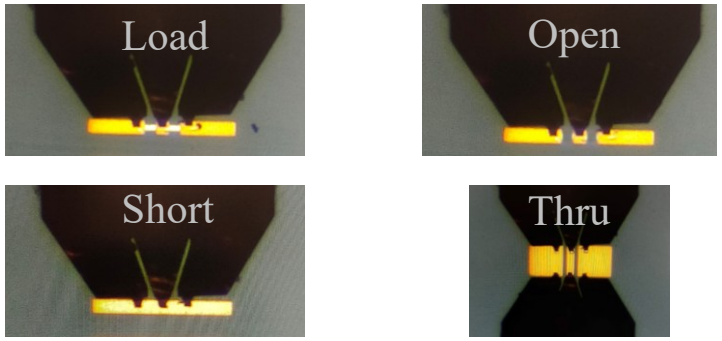
2. GS Validation



Parasitic Parameter Extraction for Calibration Standards Using an Optimization Strategy

6. Validation results in low crosstalk system

In a low crosstalk system, probes with the GSG structure are used, and the crosstalk between the probes is less than -40 dB.

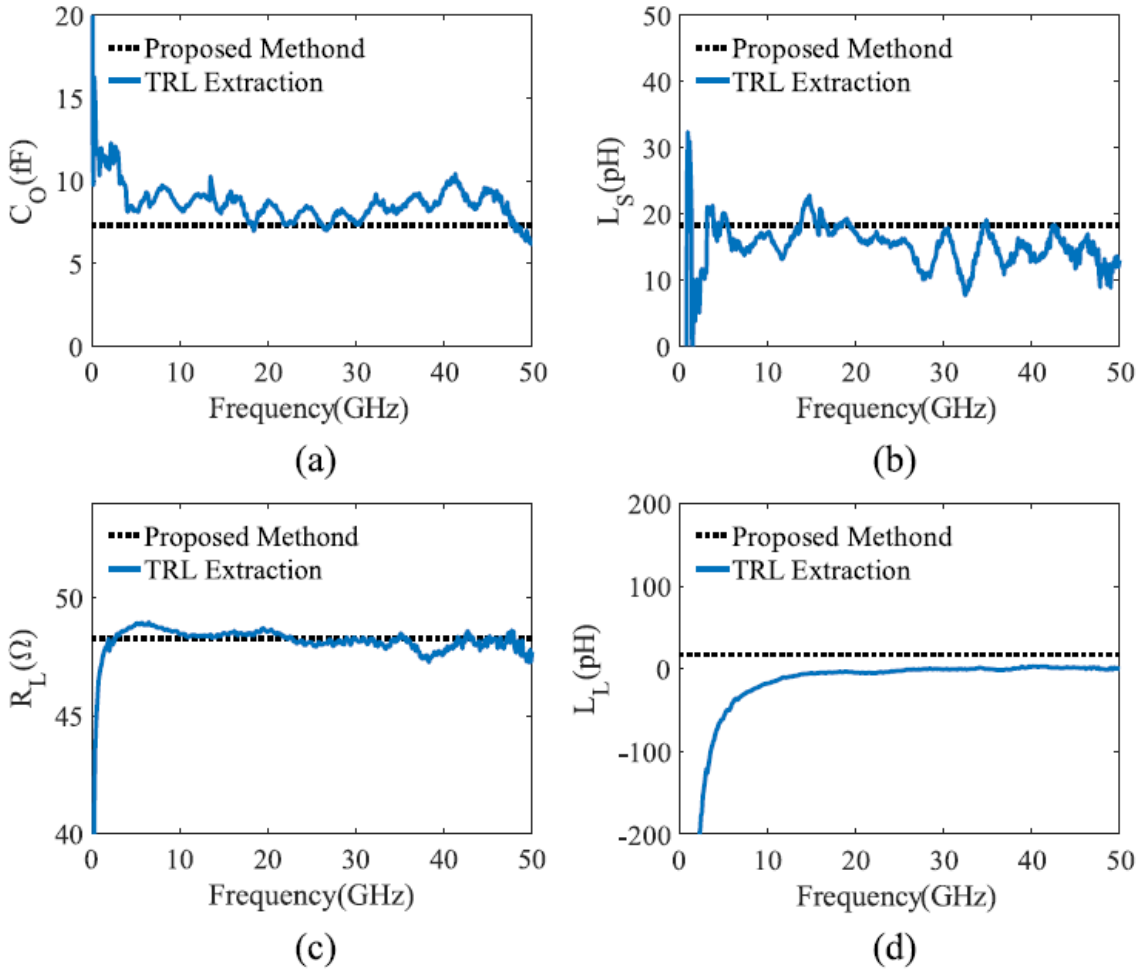


Initial sampling points: 10, Number of iterations: 100

Optimize the obtained parasitic parameters:

$C_O = 7.31$ fF, $L_S = 18.23$ pH, $R_L = 48.30\ \Omega$, $L_L = 16.92$ pH.

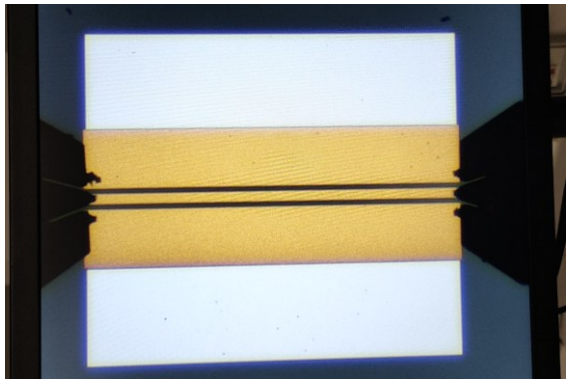
Comparison of parasitic parameter results obtained by TRL and optimization algorithms



Parasitic Parameter Extraction for Calibration Standards Using an Optimization Strategy

6. Validation results in low crosstalk system

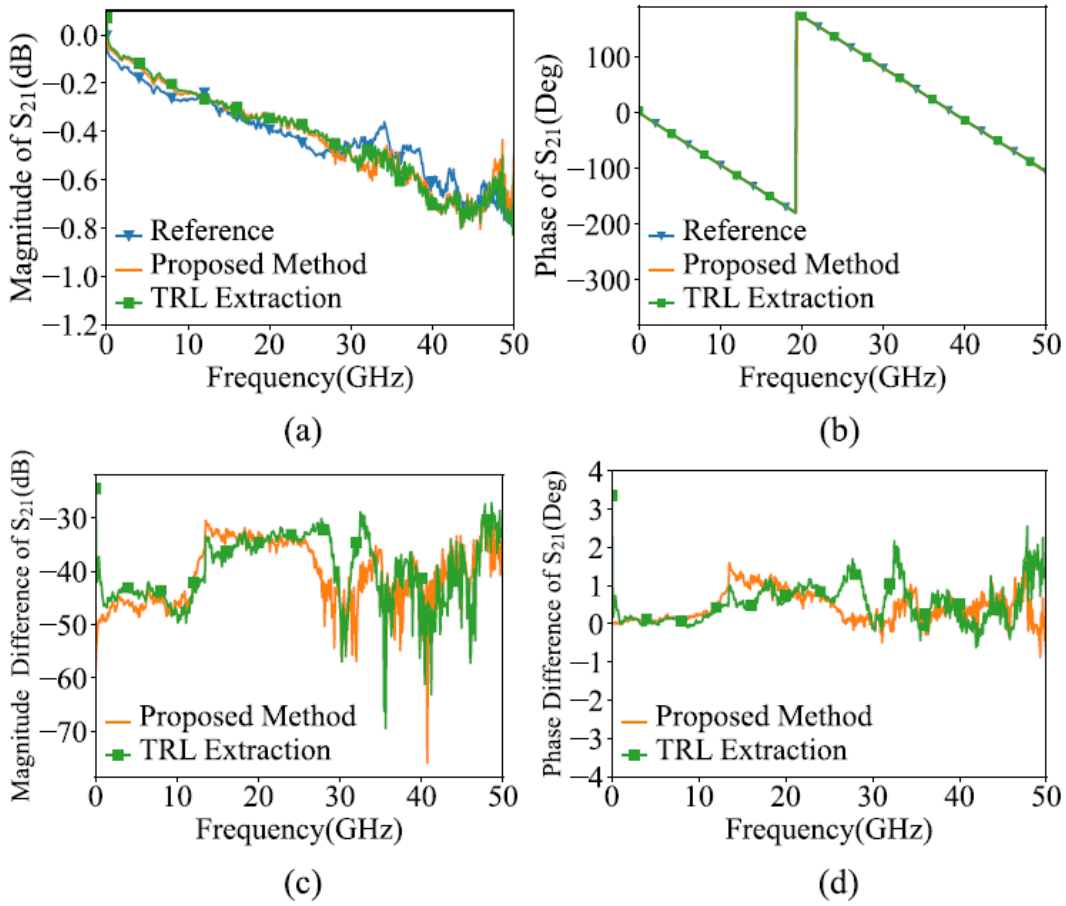
DUT: 3.5 mm CPW



- Within the frequency range of 10 MHz to 50 GHz, the amplitude difference is less than **-30.5 dB** and the phase difference is less than **1.6°**. This indicates that the proposed method can achieve high accuracy in on-wafer S-parameter measurement.

- **In low crosstalk systems, this method yields results consistent with those of the TRL method and has high accuracy!**

The 16-term error model was compared with reference values using the calibration results of two parasitic parameters.

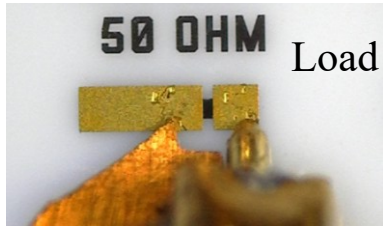


The magnitude difference is obtained by subtracting the complex values of the 16 error model calculation results from the reference result, and then calculating its dB value.

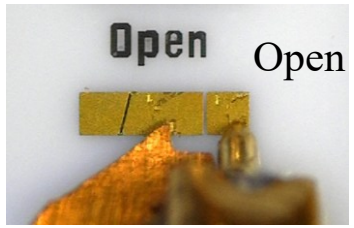
Parasitic Parameter Extraction for Calibration Standards Using an Optimization Strategy

7. Validation results in high crosstalk system

In high crosstalk systems, when using the GS structure probe, the crosstalk between the probes is greater than -30 dB.



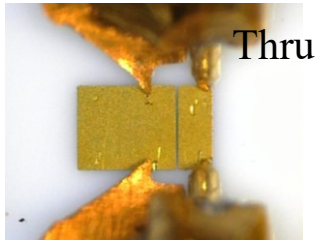
Load



Open



Short


Thru

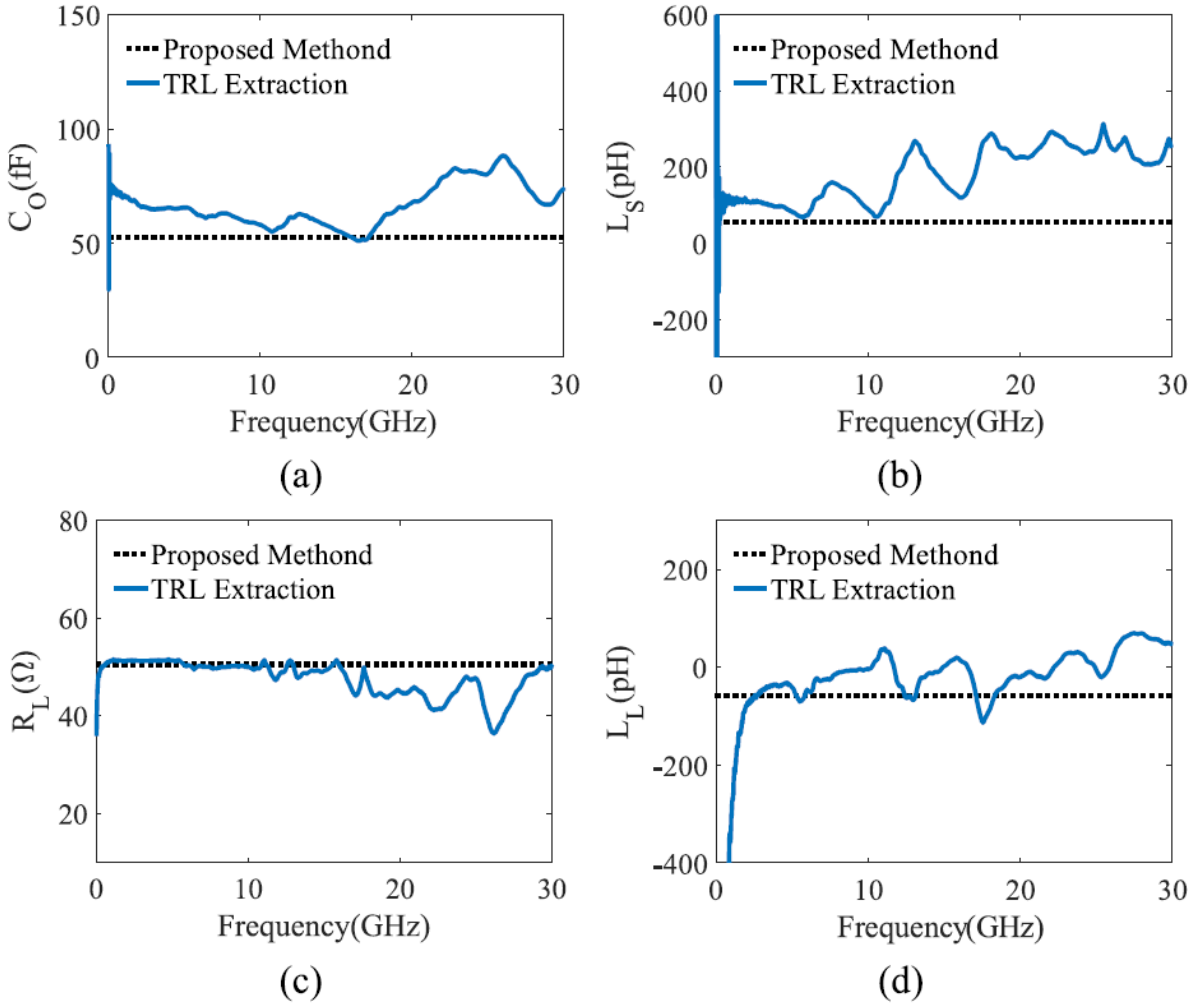
Initial sampling points: 10, Number of iterations: 100

Optimize the obtained parasitic parameters:

C_O = 52.54 fF, L_S = 54.82 pH, R_L = 50.60 Ω, L_L = -58.71 pH.

Comparison of parasitic parameter results obtained by TRL and optimization algorithms

There are significant differences between the two results!



Parasitic Parameter Extraction for Calibration Standards Using an Optimization Strategy

7. Validation results in high crosstalk system

DUT: 1.93 mm CPW

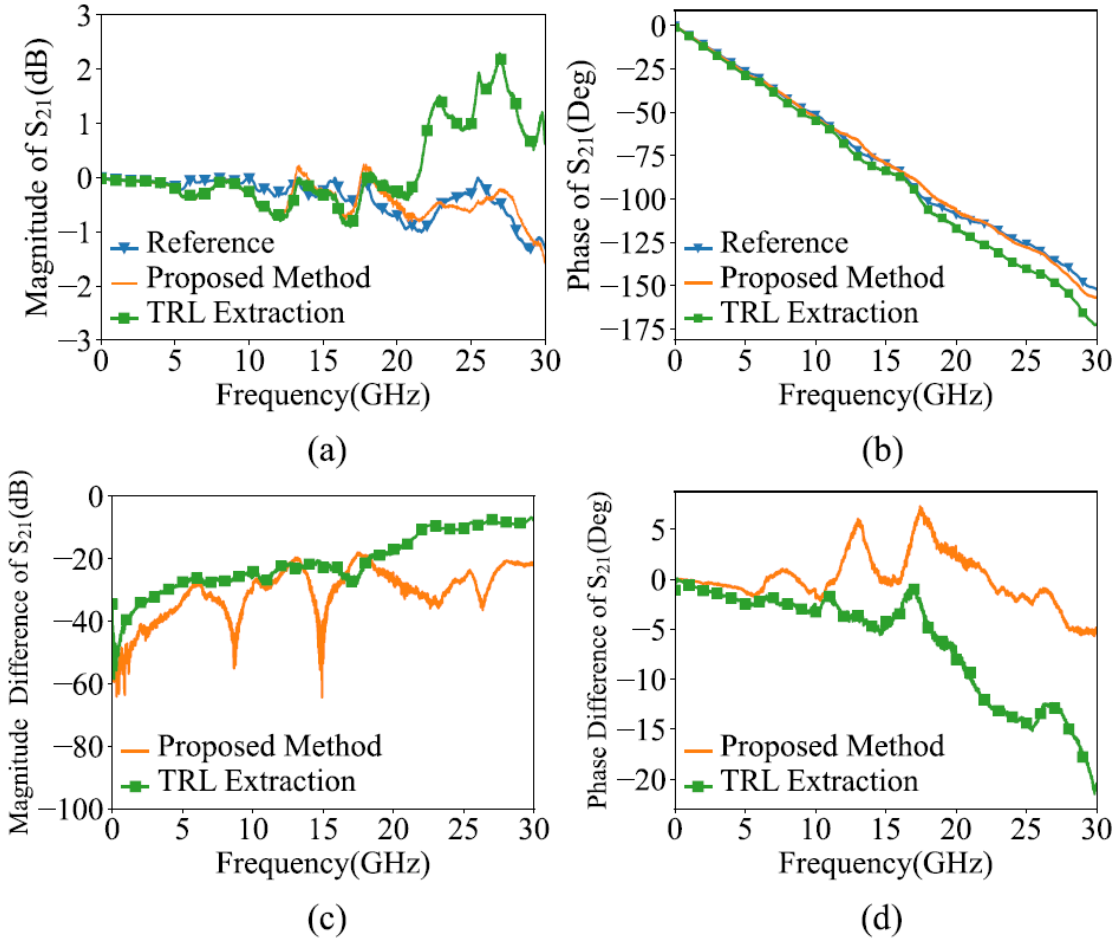
- The maximum magnitude difference of the TRL method is **-6.76 dB**, while that of this method is **-18.26 dB**. The maximum phase difference of the TRL method is **21.42°**, whereas that of this method is only **7.08°**.

- **In high crosstalk systems, the results of this method are significantly better than those of TRL!**

Innovation point:

- Transforming traditional measurement problems into optimization problems and avoiding the use of additional calibration standards **enables the acquisition of precise parasitic parameters of the calibration standards in high-interference scenarios.**

The 16-term error model was compared with reference values using the calibration results of two parasitic parameters.

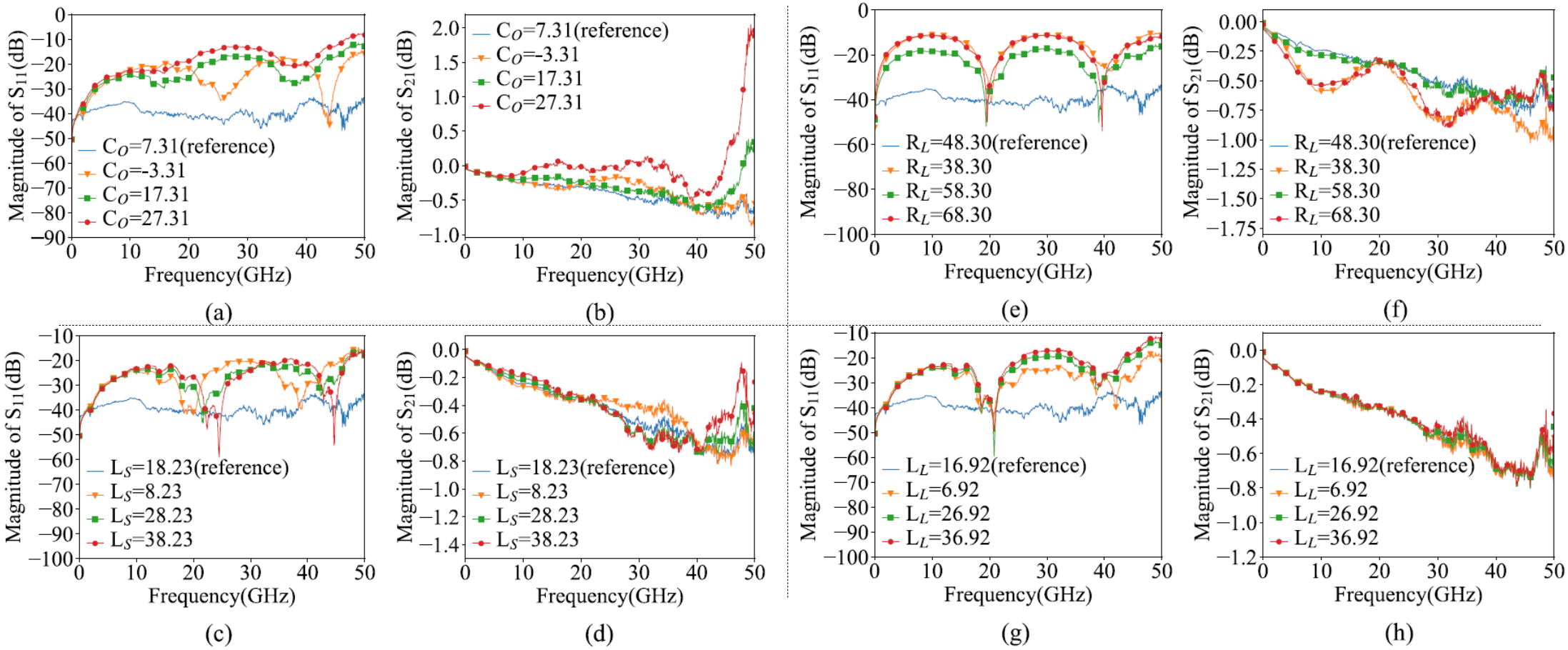


The magnitude difference is obtained by subtracting the complex values of the 16 error model calculation results from the reference result, and then calculating its dB value.

Parasitic Parameter Extraction for Calibration Standards Using an Optimization Strategy

8. Sensitivity Analysis

- Among the four parasitic parameters, C_O and R_L have a significant impact on the results. These two parameters can be **optimized multiple times by increasing the number of iterations** and gradually narrowing their value ranges to improve the optimization accuracy.



Jiefeng Zhou, Ling Zhang, Junhui Chen, Li Jiang, Da Li, Yan Li, Hongsheng Chen, Er-Ping Li. "Parasitic Parameter Extraction for Calibration Standards Using an Optimization Strategy" **IEEE TMTT** (2023).

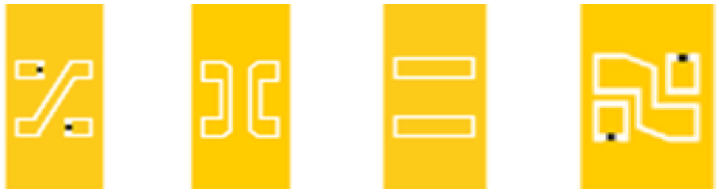
A Novel Four-Port Symmetric Probe Calibration Method for On-Wafer S-Parameter Measurement

A Novel Four-Port Symmetric Probe Calibration Method for On-Wafer S-Parameter Measurement

1. On-wafer four-port S-parameter measurement

On-wafer four-port S-parameter measurement

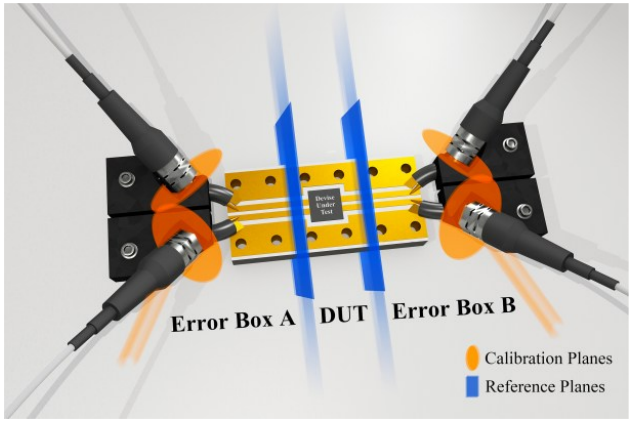




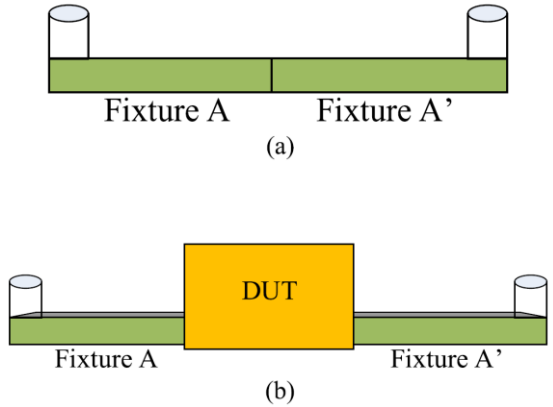
- **Challenges**
  - The **numerous error terms** of the four-port probe makes the solution process complex;
  - The two-port calibration algorithm used for calibrating the four-port probe **requires additional Thru calibration standards.**

➢ **The existing four-port calibration algorithms often have various flaws.**

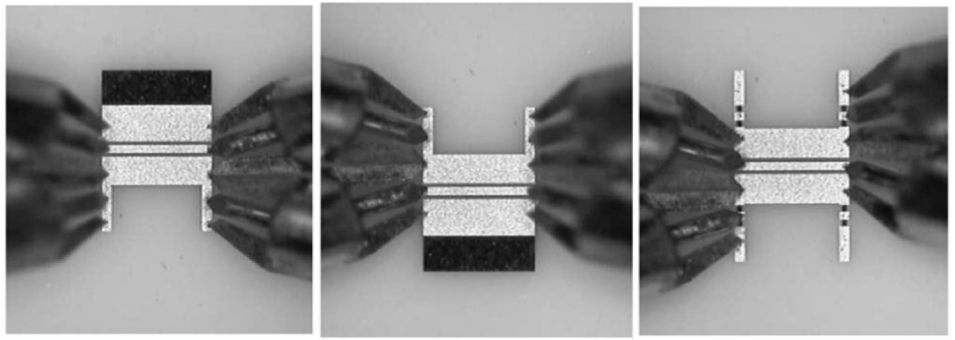
- Multimode TRL



- 2^n Port 2×Thru



- Full-leaky/half-leaky model

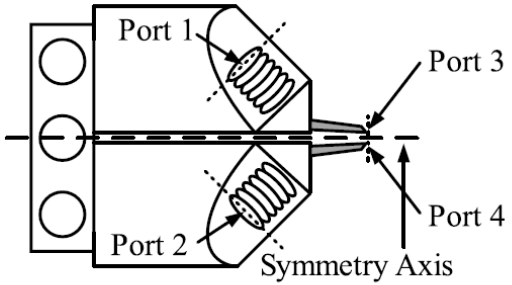


- **How to effectively reduce the error terms in the four-port network and avoid using a large number of Thru calibration standards?**

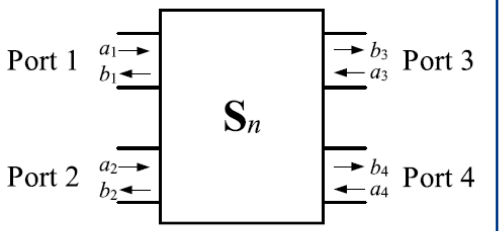
A Novel Four-Port Symmetric Probe Calibration Method for On-Wafer S-Parameter Measurement

2. Simplify the modal matrix of the symmetrical probe

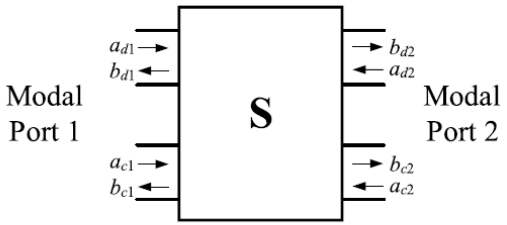
Symmetric differential probe diagram



(a)



(b)



(c)

Nodal S-parameters → Modal S-parameters

$$\begin{bmatrix} b_{d1} \\ b_{c1} \\ b_{d2} \\ b_{c2} \end{bmatrix} = \mathbf{S}_{mix} \begin{bmatrix} a_{d1} \\ a_{c1} \\ a_{d2} \\ a_{c2} \end{bmatrix} = \begin{bmatrix} S_{11}^{dd} & S_{11}^{dc} & S_{12}^{dd} & S_{12}^{dc} \\ S_{11}^{cd} & S_{11}^{cc} & S_{12}^{cd} & S_{12}^{cc} \\ S_{21}^{dd} & S_{21}^{dc} & S_{22}^{dd} & S_{22}^{dc} \\ S_{21}^{cd} & S_{21}^{cc} & S_{22}^{cd} & S_{22}^{cc} \end{bmatrix} \begin{bmatrix} a_{d1} \\ a_{c1} \\ a_{d2} \\ a_{c2} \end{bmatrix}$$

The symmetry of the probe ⇩ **Modal S-parameter matrix simplification**

$$\mathbf{S}_{mix} = \begin{bmatrix} \mathbf{S}_{11} & \mathbf{S}_{12} \\ \mathbf{S}_{21} & \mathbf{S}_{22} \end{bmatrix} = \begin{bmatrix} S_{11}^{dd} & 0 & S_{12}^{dd} & 0 \\ 0 & S_{11}^{cc} & 0 & S_{12}^{cc} \\ S_{21}^{dd} & 0 & S_{22}^{dd} & 0 \\ 0 & S_{21}^{cc} & 0 & S_{22}^{cc} \end{bmatrix}$$

The modal S-parameter matrix conforms to the transformation relationship between the S matrix and the T matrix.

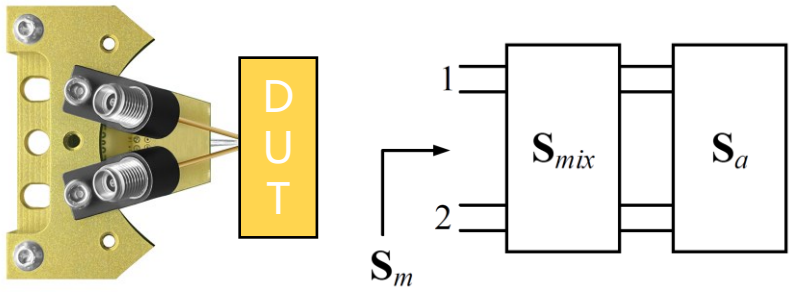
$$\mathbf{T}_{mix} = \begin{bmatrix} \mathbf{T}_{11} & \mathbf{T}_{12} \\ \mathbf{T}_{21} & \mathbf{T}_{22} \end{bmatrix} = \begin{bmatrix} \mathbf{S}_{12} - \mathbf{S}_{11}\mathbf{S}_{21}^{-1}\mathbf{S}_{22} & \mathbf{S}_{11}\mathbf{S}_{21}^{-1} \\ -\mathbf{S}_{21}^{-1}\mathbf{S}_{22} & \mathbf{S}_{21}^{-1} \end{bmatrix}$$

Jiefeng Zhou, Ling Zhang, Hanzhi Ma, Da Li, Ziyang Chen, Er-Ping Li. A Novel Four-Port Symmetric Probe Calibration Method for On-Wafer S-Parameter Measurement. **IEEE TMTT** (2024).

A Novel Four-Port Symmetric Probe Calibration Method for On-Wafer S-Parameter Measurement

3. Two-port calibration

A four-port symmetrical probe is connected to the two-port DUT



$$\mathbf{S}_a^{DUT} = (\mathbf{S}_m^{DUT}\mathbf{T}_{21} - \mathbf{T}_{11})^{-1}(\mathbf{T}_{12} - \mathbf{S}_m^{DUT}\mathbf{T}_{22})$$

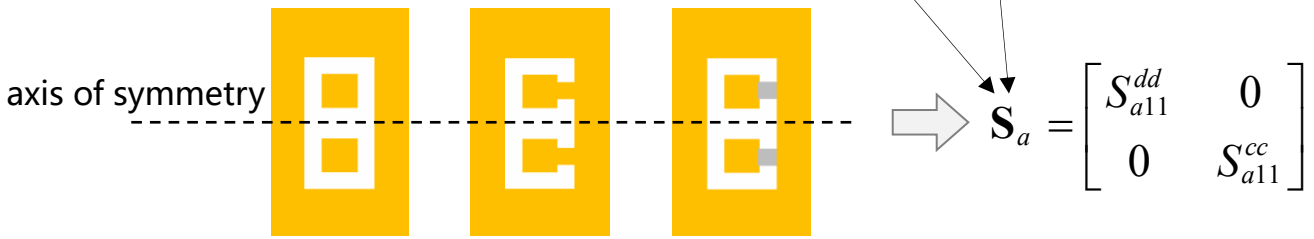
expand

Unknown variables

S_{11}^{cc}	S_{11}^{dd}
S_{22}^{cc}	S_{22}^{dd}
$S_{12}^{cc} \times S_{21}^{cc}$	$S_{12}^{dd} \times S_{21}^{dd}$

The probe is connected to the calibration standard,

$$\mathbf{S}_m = \begin{bmatrix} S_{m11}^{dd} & S_{m11}^{dc} \\ S_{m11}^{cd} & S_{m11}^{dd} \end{bmatrix} = \mathbf{S}_{11} + \mathbf{S}_{12}\mathbf{S}_a(\mathbf{I} - \mathbf{S}_{22}\mathbf{S}_a)\mathbf{S}_{21}$$



When the calibration standards also satisfy symmetry, two equations can be obtained.

$$S_{a11}^{dd}(S_{12}^{dd}S_{21}^{dd} - S_{11}^{dd}S_{22}^{dd}) + S_{11}^{dd} + S_{m11}^{dd}S_{a11}^{dd}S_{22}^{dd} = S_{m11}^{dd}$$

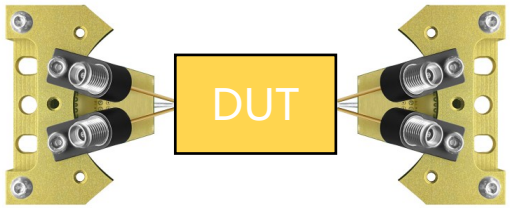
$$S_{a11}^{cc}(S_{12}^{cc}S_{21}^{cc} - S_{11}^{cc}S_{22}^{cc}) + S_{11}^{cc} + S_{m11}^{cc}S_{a11}^{cc}S_{22}^{cc} = S_{m11}^{cc}$$

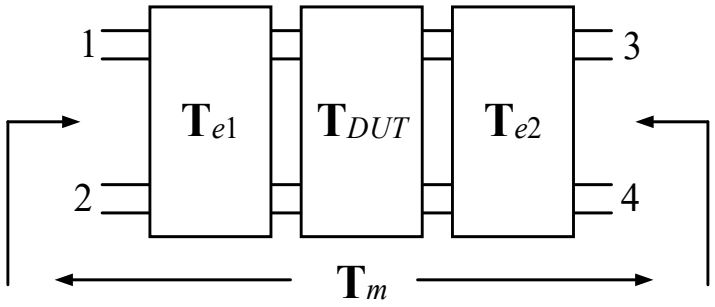
- **By connecting the three calibration standards, you can solve for the six unknowns!**

A Novel Four-Port Symmetric Probe Calibration Method for On-Wafer S-Parameter Measurement

4. Four-port calibration

Two four-port symmetrical probes are connected to the four-port DUT.





$$\mathbf{T}_a^{DUT} = \mathbf{T}_{e1}^{-1}\mathbf{T}_m^{DUT}\mathbf{T}_{e2}^{-1}$$

expand

$$T_{a13}^{DUT} = \frac{-S_{11e2}^{dd}T_{m11}^{DUT} + S_{11e1}^{dd}S_{11e2}^{dd}T_{m31}^{DUT} + (S_{11e2}^{dd}S_{22e2}^{dd} - S_{12e2}^{dd}S_{21e2}^{dd})(S_{11e1}^{dd}T_{m33}^{DUT} - T_{m13}^{DUT})}{S_{12e1}^{dd}S_{12e2}^{dd}}$$

$$T_{a33}^{DUT} = \frac{S_{11e2}^{dd}(S_{11e1}^{dd}S_{22e1}^{dd} - S_{12e1}^{dd}S_{21e1}^{dd})(T_{m31}^{DUT} + S_{22e2}^{dd}T_{m33}^{DUT}) + S_{12e2}^{dd}S_{21e2}^{dd}S_{22e1}^{dd}(T_{m13}^{DUT} - S_{11e1}^{dd}T_{m33}^{DUT})}{S_{12e1}^{dd}S_{12e2}^{dd}} +$$

$$\frac{S_{12e1}^{dd}S_{12e2}^{dd}S_{21e1}^{dd}S_{21e2}^{dd}T_{m33}^{DUT} - S_{11e2}^{dd}S_{22e1}^{dd}(T_{m11}^{DUT} - S_{22e2}^{dd}T_{m13}^{DUT})}{S_{12e1}^{dd}S_{12e2}^{dd}}$$

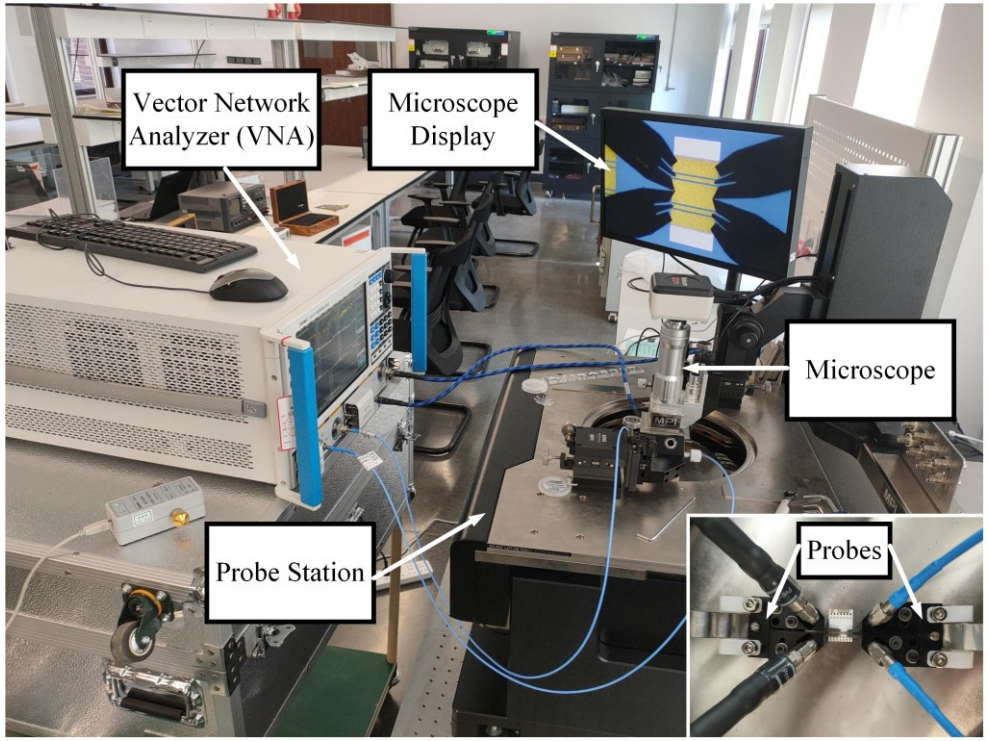
TERMS TO CALCULATE

$\mathbf{S}_{e1}$	S_{11e1}^{dd} (#1)	S_{22e1}^{dd} (#2)	$S_{12e1}^{dd} \times S_{21e1}^{dd}$ (#3)	$S_{12e1}^{dd} \times S_{12e1}^{cc}$ (#13)
	S_{11e1}^{cc} (#4)	S_{22e1}^{cc} (#5)	$S_{12e1}^{cc} \times S_{21e1}^{cc}$ (#6)	
$\mathbf{S}_{e2}$	S_{11e2}^{dd} (#7)	S_{22e2}^{dd} (#8)	$S_{12e2}^{dd} \times S_{21e2}^{dd}$ (#9)	$S_{12e2}^{dd} \times S_{12e2}^{cc}$ (#14)
	S_{11e2}^{cc} (#10)	S_{22e2}^{cc} (#11)	$S_{12e2}^{cc} \times S_{21e2}^{cc}$ (#12)	
Other	$S_{12e1}^{dd} \times S_{12e2}^{dd}$ (#15)	$S_{12e1}^{cc} \times S_{12e2}^{cc}$ (#16)	$S_{12e1}^{cc} \times S_{12e2}^{dd}$ (#17)	$S_{12e1}^{dd} \times S_{12e2}^{cc}$ (#18)

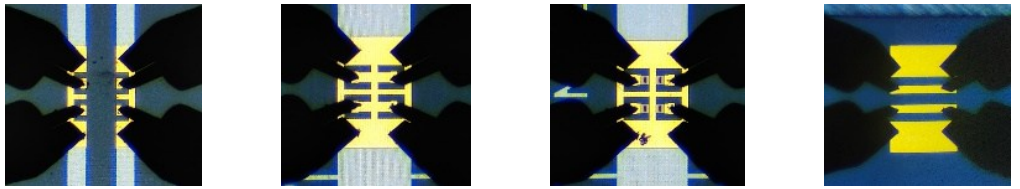
A Novel Four-Port Symmetric Probe Calibration Method for On-Wafer S-Parameter Measurement

5. Configuration of on-wafer four-port S-parameter measurement system

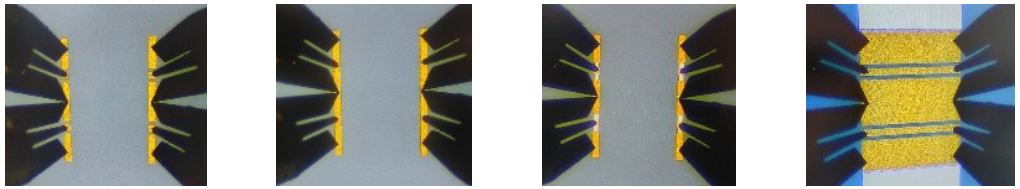
On-wafer four-port S-parameter measurement system



1. GSSG Validation

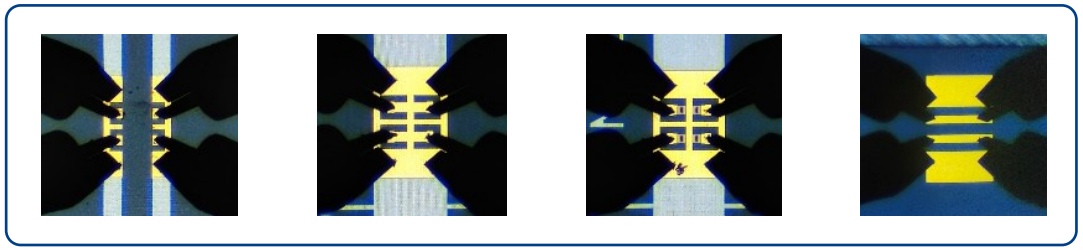


2. GSGSG Validation

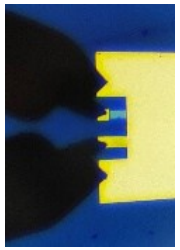


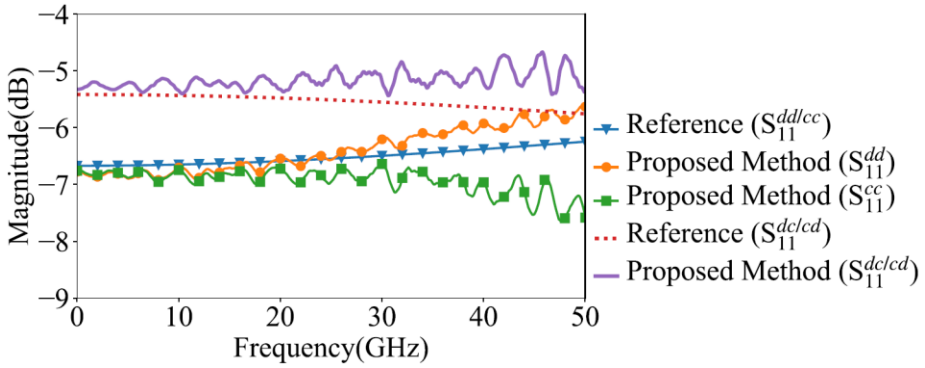
A Novel Four-Port Symmetric Probe Calibration Method for On-Wafer S-Parameter Measurement

6. Measurement validation: GSSG probe



DUT：Short-Load



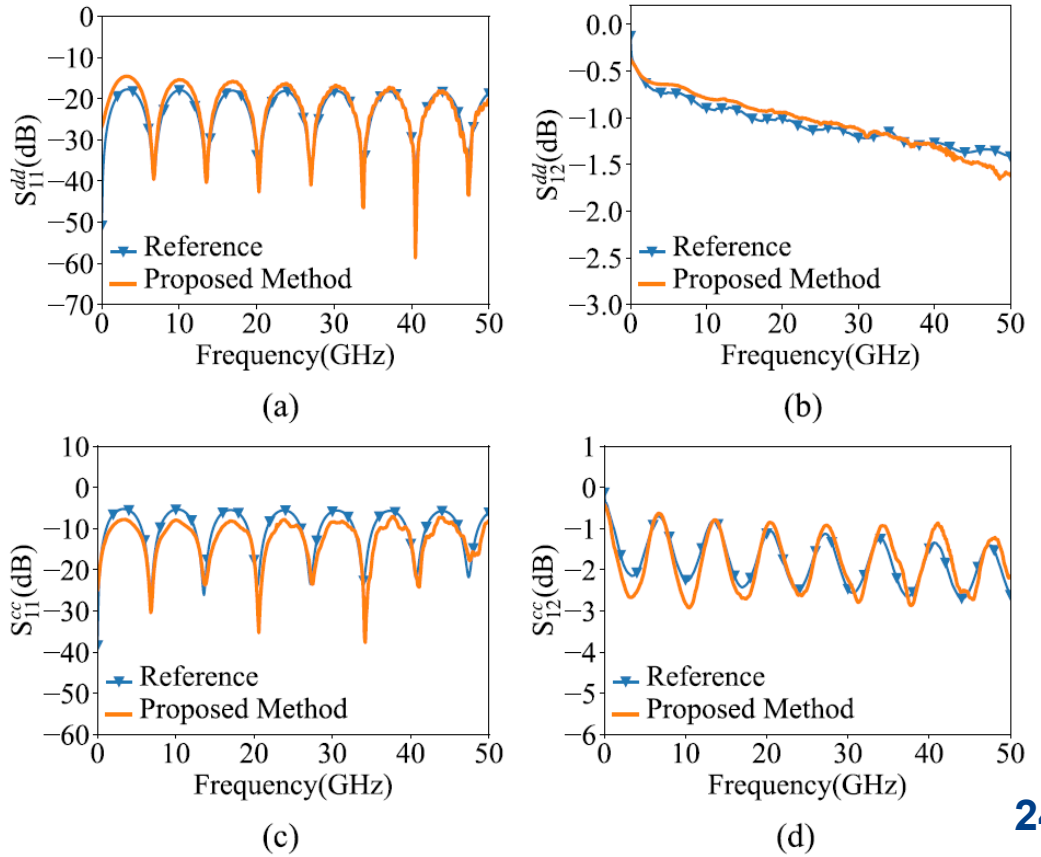


- Using the IEEE-P370 standard, the similarity measurement was **less than -23.10 dB**, which proved that this method has high accuracy in the calibration of two-port networks.

DUT：10.16 mm GSSG Transmission Line

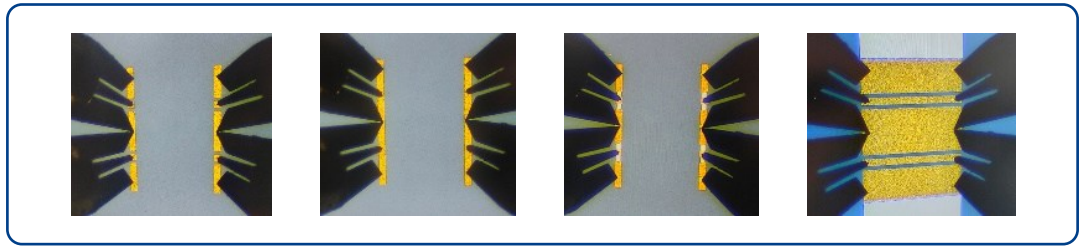


- The similarity measurement is **less than -21.94 dB**, which proves that this method has high accuracy in the calibration of four-port networks.

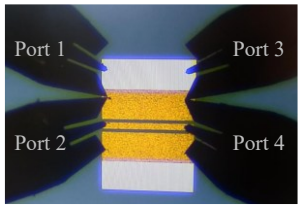


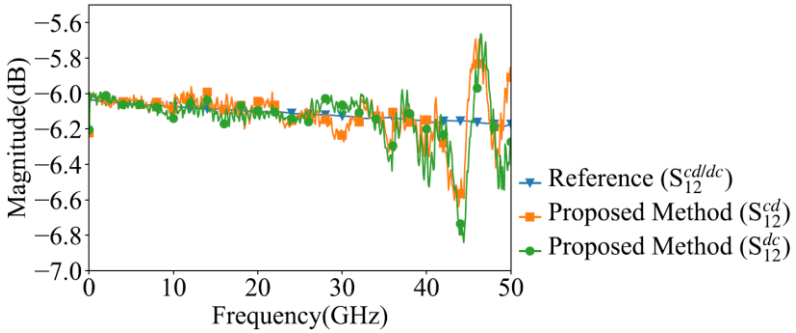
A Novel Four-Port Symmetric Probe Calibration Method for On-Wafer S-Parameter Measurement

7. Measurement validation: GSGSG probe

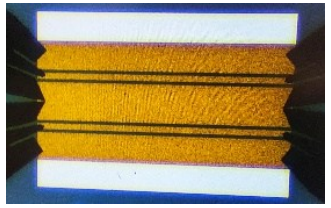


DUT: Single-channel transmission line

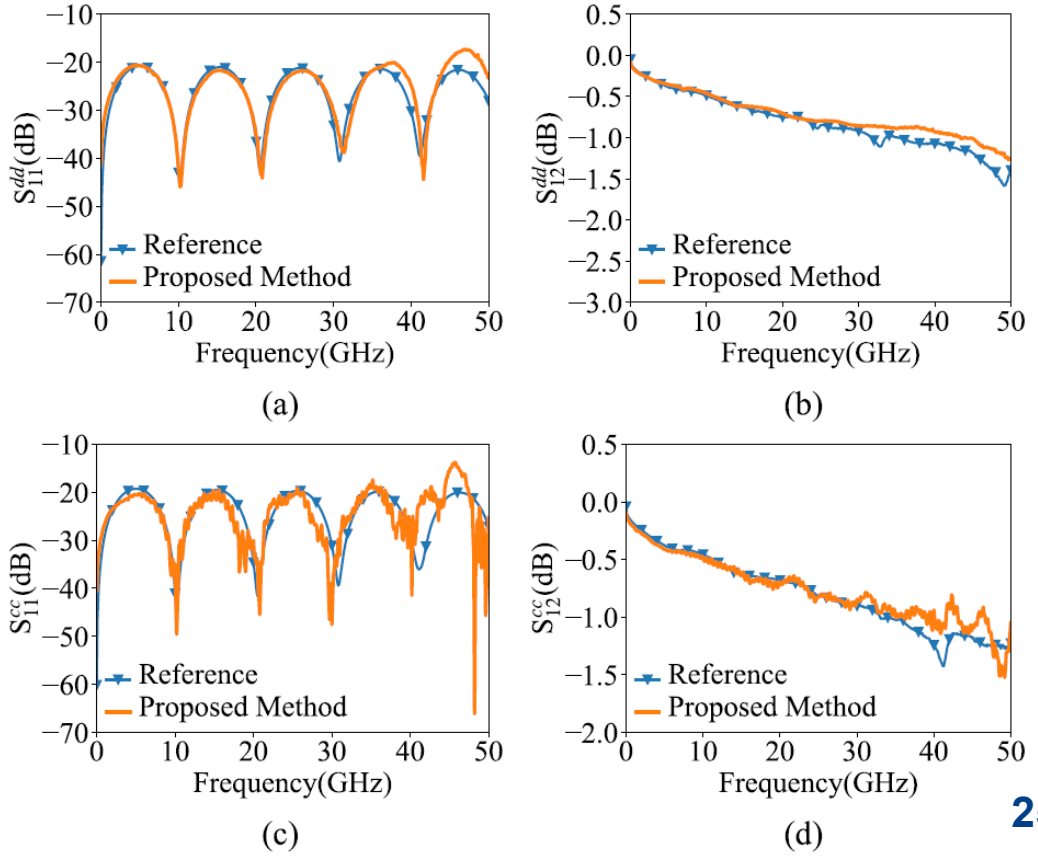




DUT: 6.60 mm GSGSG Transmission Line



- The similarity metric between this method and the reference value is less than −28.40 dB.

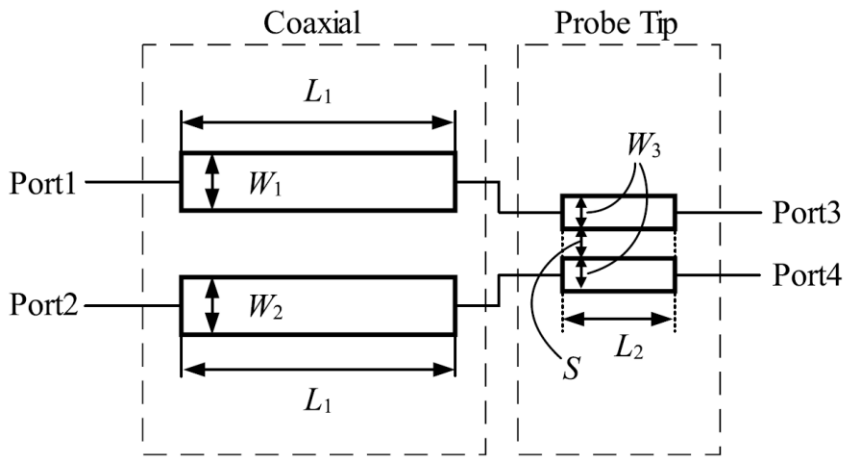


Innovation point:

- By making use of the symmetry of the probe and the properties of the mixed-mode S parameters, the number of **the error terms to be calculated is effectively reduced.** Only four calibration standards are needed to complete the four-port calibration, and the phase information of the Thru calibration standard is used to determine the sign of the error terms, without using the S-parameters of the known Thru calibration standard.

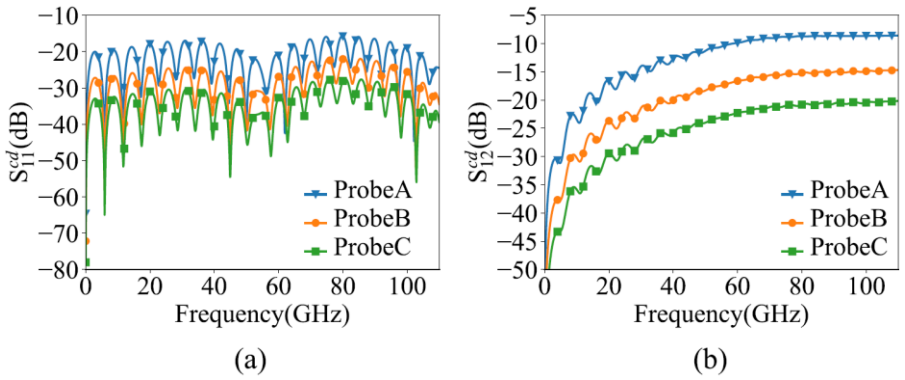
A Novel Four-Port Symmetric Probe Calibration Method for On-Wafer S-Parameter Measurement

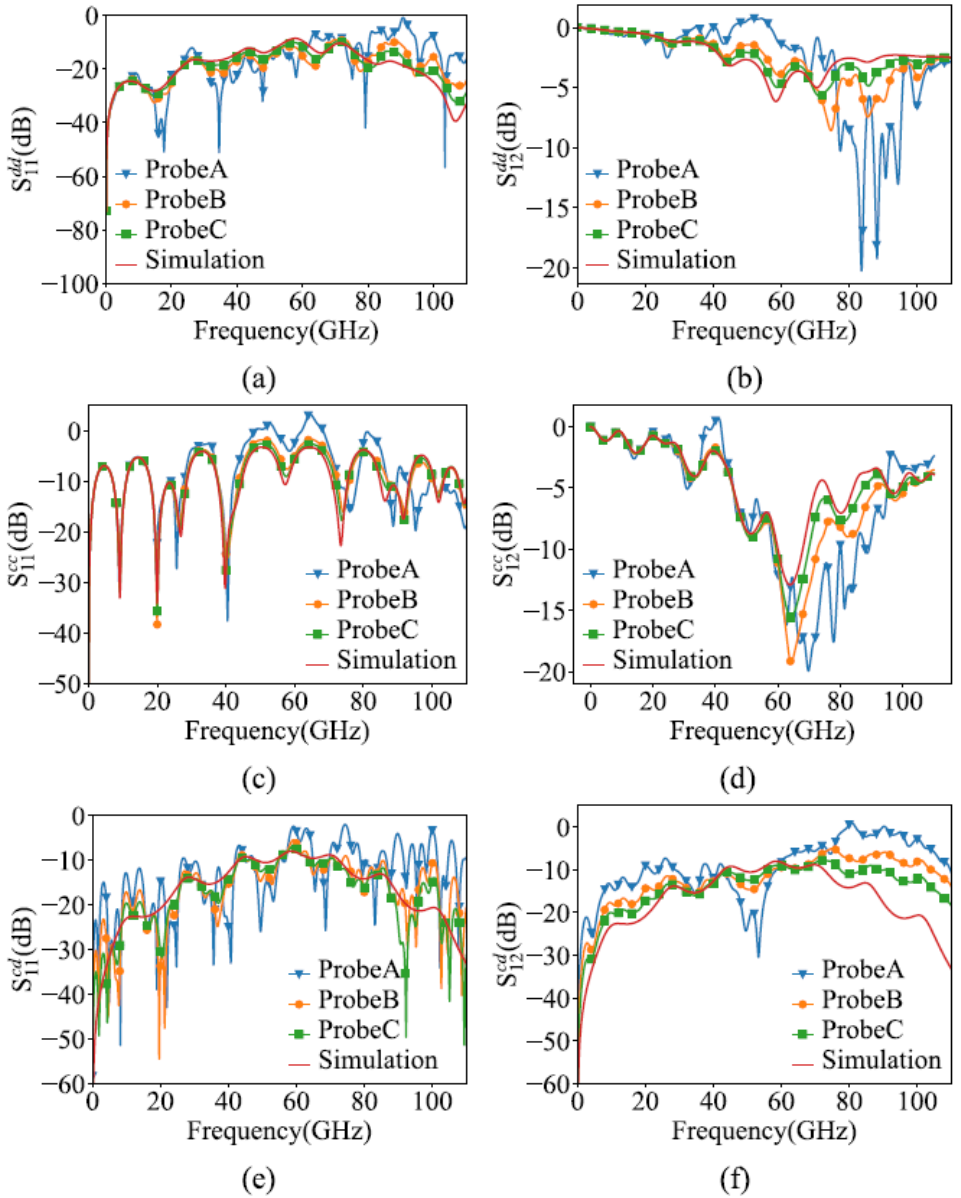
8. Sensitivity Analysis of Asymmetric Probe



L_1=10.00 mm, W_2=0.20 mm, W_3=0.075 mm, S=0.125 mm, L_2=1.00 mm
ProbeA: W_1=0.30 mm, ProbeB: W_1=0.24 mm, ProbeC: W_1=0.22 mm

The modal S-parameters of probes A, B, and C





- The S_{12}^{cd} of probe should be less than -15 dB, and the S_{11}^{cd} of probe should be less than -25 dB to prevent significant errors in the calibration results.

- **As the frequency increases, how should we deal with the failure of the probe's symmetry?**

Jiefeng Zhou, Ling Zhang, Hanzhi Ma, Da Li, Ziyang Chen, Er-Ping Li. A Novel Four-Port Symmetric Probe Calibration Method for On-Wafer S-Parameter Measurement. **IEEE TMTT** (2024).

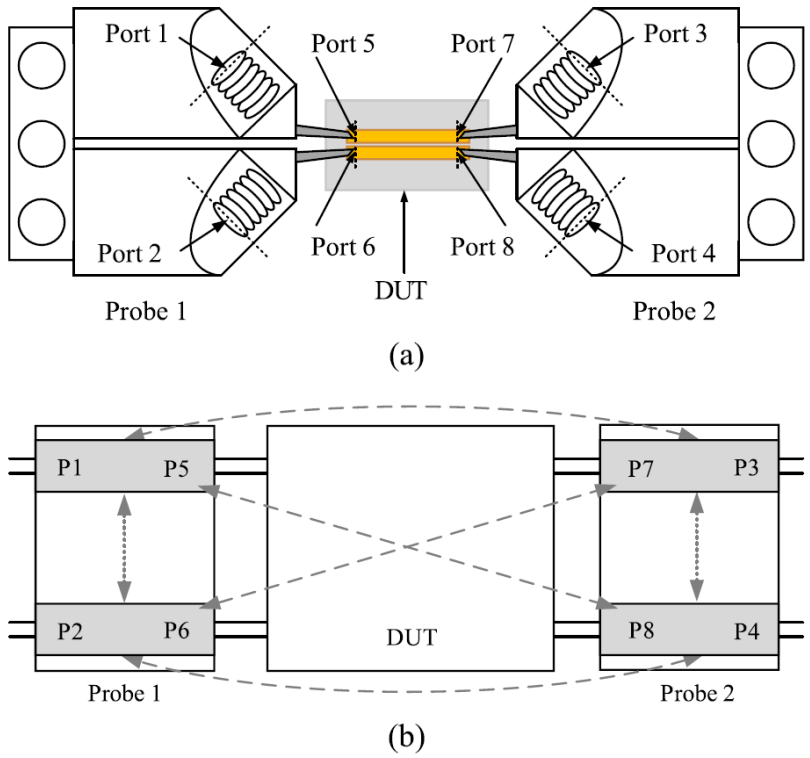
Four-Port Probe Calibration Using 64-Term Error Model for On-Wafer S-Parameter Measurement up to 110 GHz



Four-Port Probe Calibration Using 64-Term Error Model for On-Wafer S-Parameter Measurement up to 110 GHz

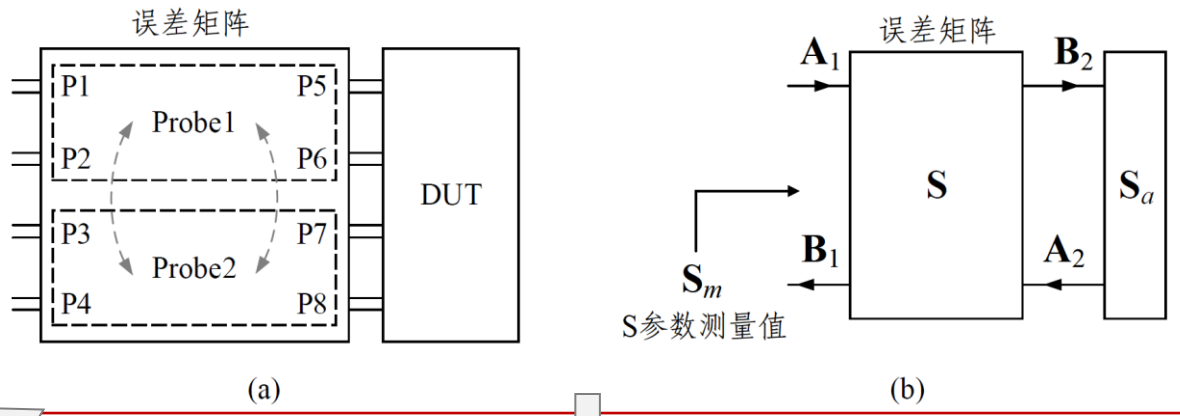
1. 64-term error model construction

On-wafer four-port S-parameter measurement system



- **Including 48 crosstalk errors and 16 inherent errors**

All the error terms can be regarded as an 8×8 error matrix.



Generalized Cascade Matrix Theory

$$\mathbf{T}_{11}\mathbf{S}_a + \mathbf{T}_{12} - \mathbf{S}_m\mathbf{T}_{21}\mathbf{S}_a - \mathbf{S}_m\mathbf{T}_{22} = \mathbf{0}$$

By connecting n calibration standards, a homogeneous equation of 16×n rows and 64 columns can be obtained.

$$\mathbf{A}t = \mathbf{0}$$

This homogeneous system of equations can be solved using the Singular Value Decomposition (SVD) method. Once **T** is determined, the actual value of the object to be measured can be calculated based on its measured value.

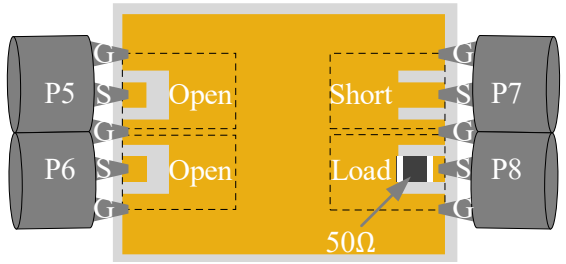
$$\mathbf{S}_a = (\mathbf{T}_{11} - \mathbf{S}_m\mathbf{T}_{21})^{-1}(\mathbf{S}_m\mathbf{T}_{22} - \mathbf{T}_{12})$$

Jiefeng Zhou, Ling Zhang, Ziyang Chen, Da Li, Jun Fan, Er-Ping Li. Four-Port Probe Calibration Using 64-Term Error Model for On-Wafer S-Parameter Measurement of Microwave Circuits up to 110 GHz. **IEEE TCASI** (2025).

Four-Port Probe Calibration Using 64-Term Error Model for On-Wafer S-Parameter Measurement up to 110 GHz

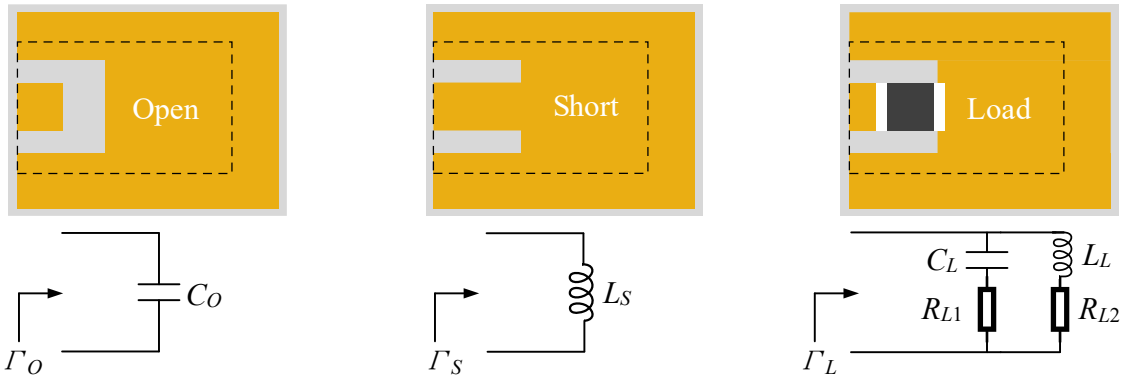
2. Calibration standards design and parasitic parameters extraction

- Lumped calibration standards (taking OOSL as an example)



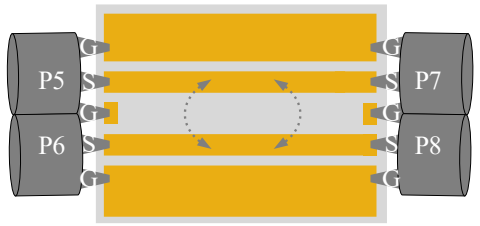
$$\mathbf{S}_a^{\mathrm{OOSL}} = \begin{bmatrix} \Gamma_O & 0 & 0 & 0 \\ 0 & \Gamma_O & 0 & 0 \\ 0 & 0 & \Gamma_S & 0 \\ 0 & 0 & 0 & \Gamma_L \end{bmatrix}$$

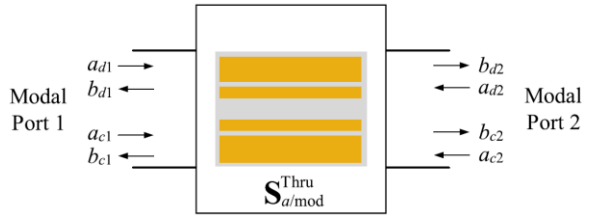
- Parasitic Parameter Model



- **The parasitic parameters of the calibration standards can be obtained through the optimization method proposed in the research one!**
- **The selection of the calibration standard combination can be achieved by the method proposed in the research two!**

- Thru calibration standard





$$\begin{bmatrix} b_{d1} \\ b_{c1} \\ b_{d2} \\ b_{c2} \end{bmatrix} = \mathbf{S}^{\mathrm{Thru}}_{a/\mathrm{mod}} \begin{bmatrix} a_{d1} \\ a_{c1} \\ a_{d2} \\ a_{c2} \end{bmatrix} = \begin{bmatrix} S_{11}^{dd} & S_{11}^{dc} & S_{12}^{dd} & S_{12}^{dc} \\ S_{11}^{cd} & S_{11}^{cc} & S_{12}^{cd} & S_{12}^{cc} \\ S_{21}^{dd} & S_{21}^{dc} & S_{22}^{dd} & S_{22}^{dc} \\ S_{21}^{cd} & S_{21}^{cc} & S_{22}^{cd} & S_{22}^{cc} \end{bmatrix} \begin{bmatrix} a_{d1} \\ a_{c1} \\ a_{d2} \\ a_{c2} \end{bmatrix}$$

The S-parameters of the Thru calibration standard can be obtained from its propagation constant.

$$S_{11}^{dd} = \frac{\Gamma_d (e^{\gamma_d l} - e^{-\gamma_d l})}{e^{\gamma_d l} - \Gamma_d^2 e^{-\gamma_d l}},\ S_{12}^{dd} = \frac{1 - \Gamma_d^2}{e^{\gamma_d l} - \Gamma_d^2 e^{-\gamma_d l}}$$

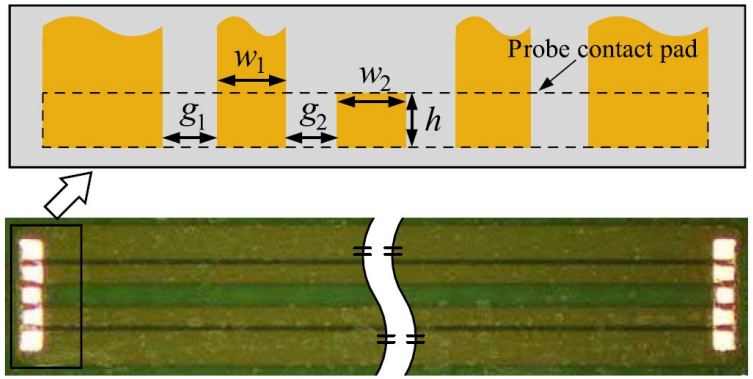
$$S_{11}^{cc} = \frac{\Gamma_c (e^{\gamma_c l} - e^{-\gamma_c l})}{e^{\gamma_c l} - \Gamma_c^2 e^{-\gamma_c l}},\ S_{12}^{cc} = \frac{1 - \Gamma_c^2}{e^{\gamma_c l} - \Gamma_c^2 e^{-\gamma_c l}}$$

Four-Port Probe Calibration Using 64-Term Error Model for On-Wafer S-Parameter Measurement up to 110 GHz

3. Calibration standard design

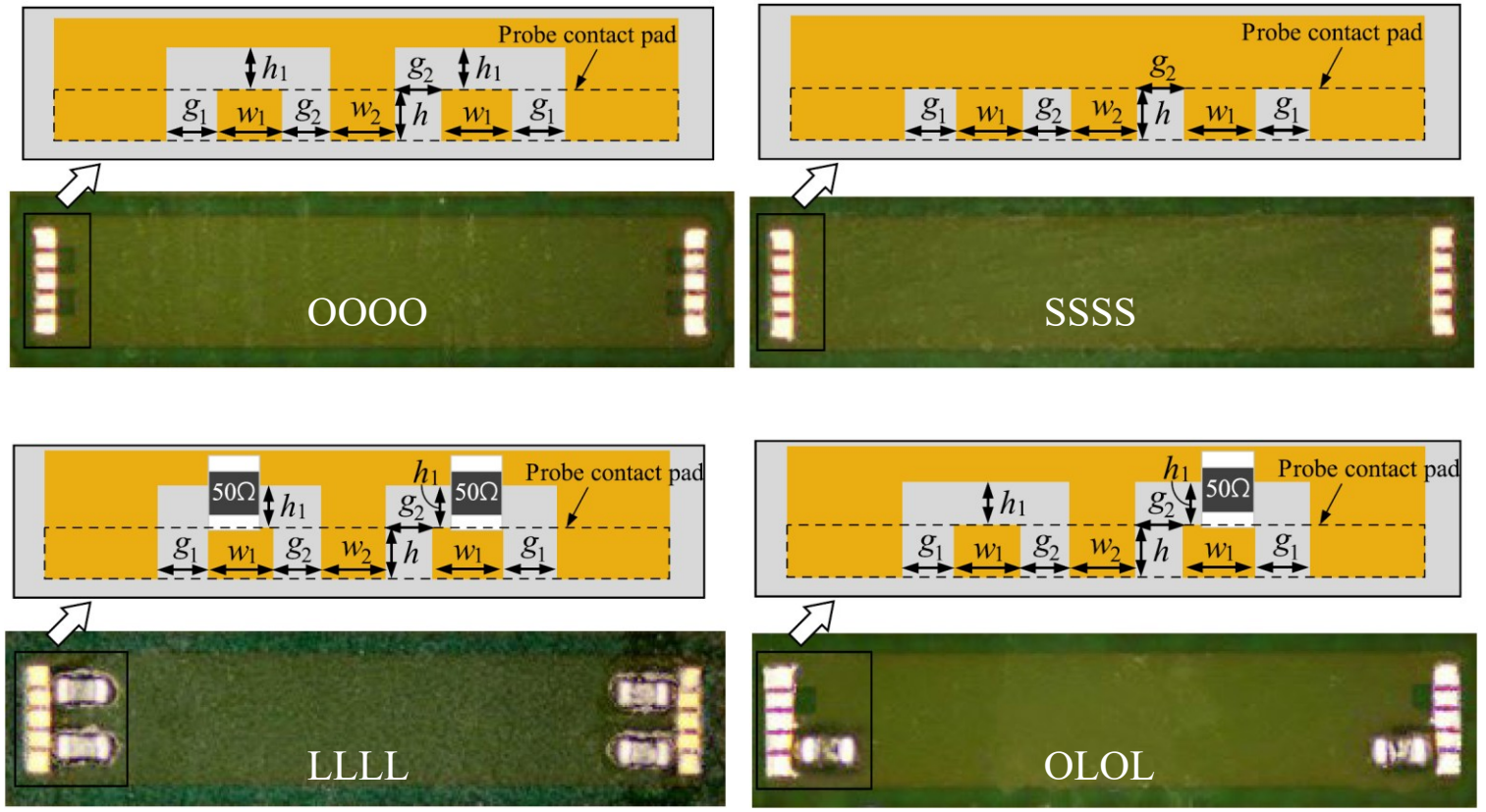
Thickness: 0.076 mm, relative dielectric constant: 3.2

- Thru calibration standard



Geometric parameters:
$g_1 = 0.05$ mm, $g_2 = 0.05$ mm, $w_1 = 0.11$ mm, $w_2 = 0.12$ mm, $h = 0.12$ mm

- Lumped calibration standards

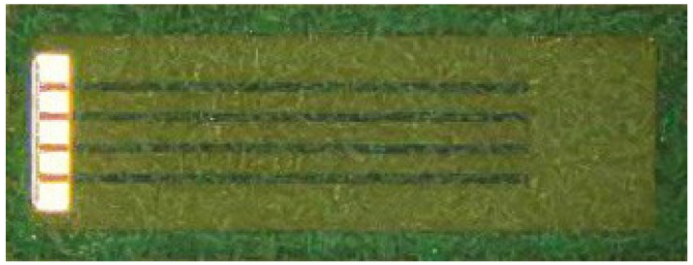


Geometric parameters:
$g_1 = 0.05$ mm, $g_2 = 0.05$ mm, $w_1 = 0.11$ mm, $w_2 = 0.12$ mm, $h = 0.12$ mm, $h_1 = 0.12$ mm

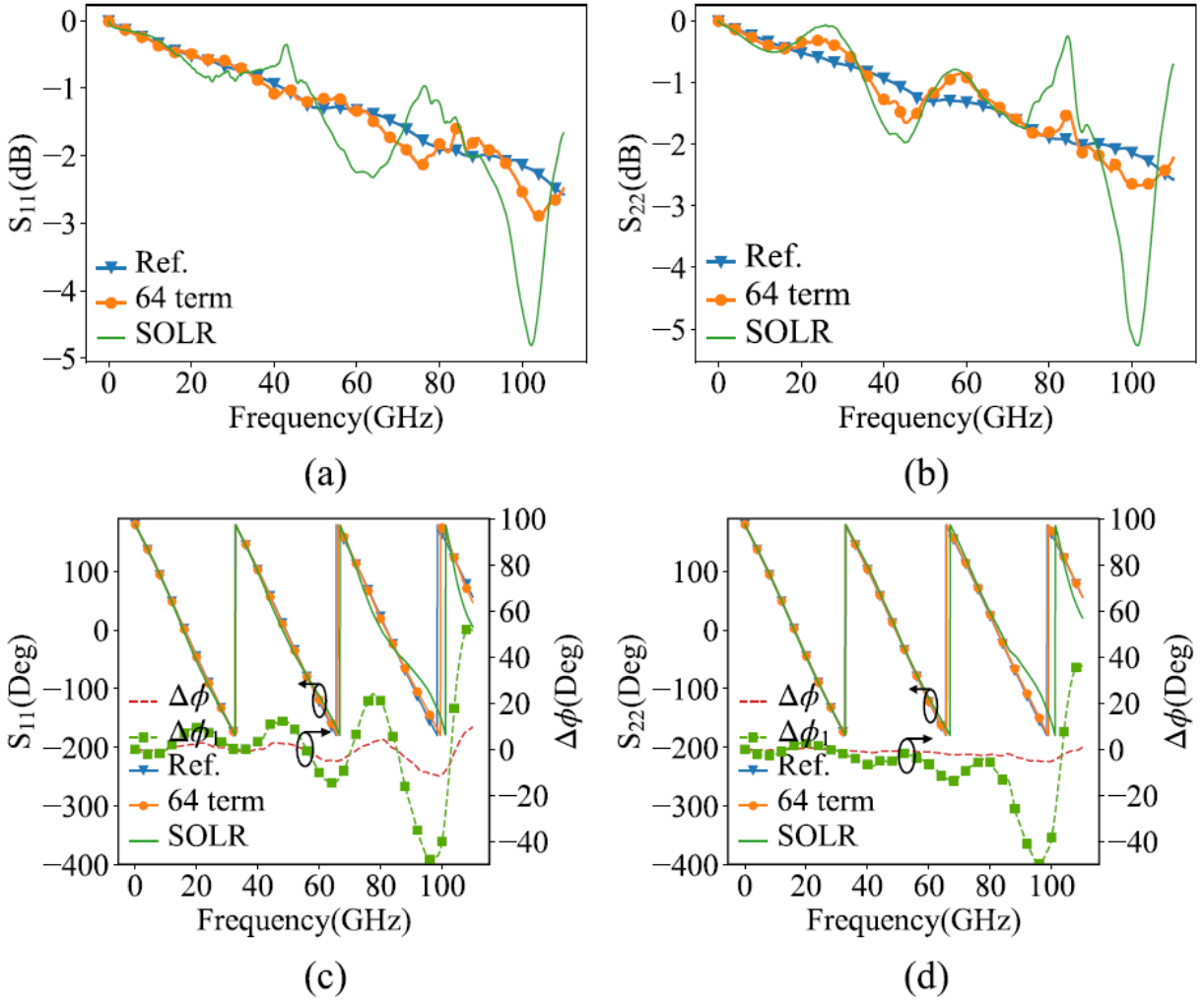
Four-Port Probe Calibration Using 64-Term Error Model for On-Wafer S-Parameter Measurement up to 110 GHz

4. Measurement validation

DUT: 2.50 mm GSGSG differential line with short end



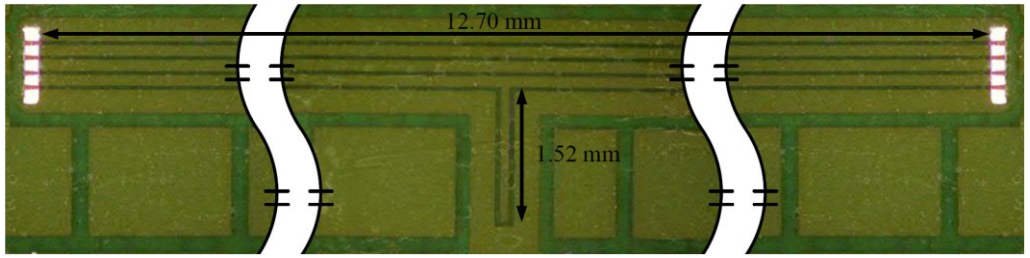
- The results show that the maximum amplitude difference between this method (64term) and the reference value (Ref.) is 0.62 dB, and SOLR is 3.07 dB;
- The verification results indicate that the maximum phase difference between this method and the reference value is 11.5°, and SOLR is 52.4°;
- In the frequency range of 10 MHz - 110 GHz, the similarity measurement using the IEEE-370 standard is less than -26.30 dB.



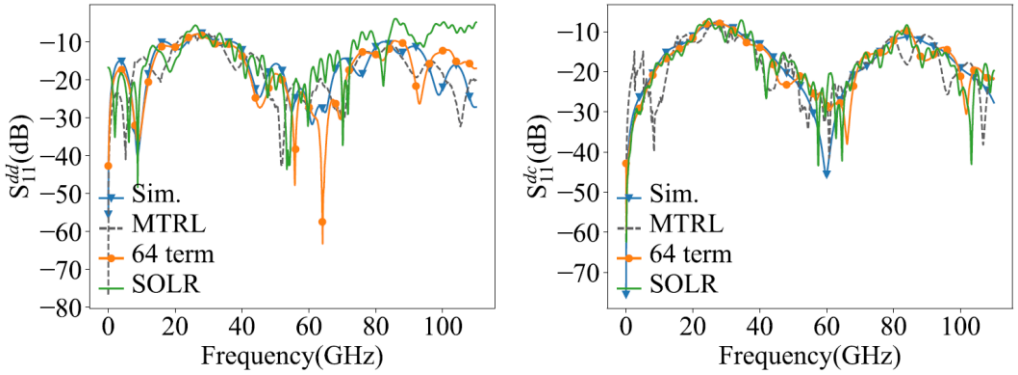
Four-Port Probe Calibration Using 64-Term Error Model for On-Wafer S-Parameter Measurement up to 110 GHz

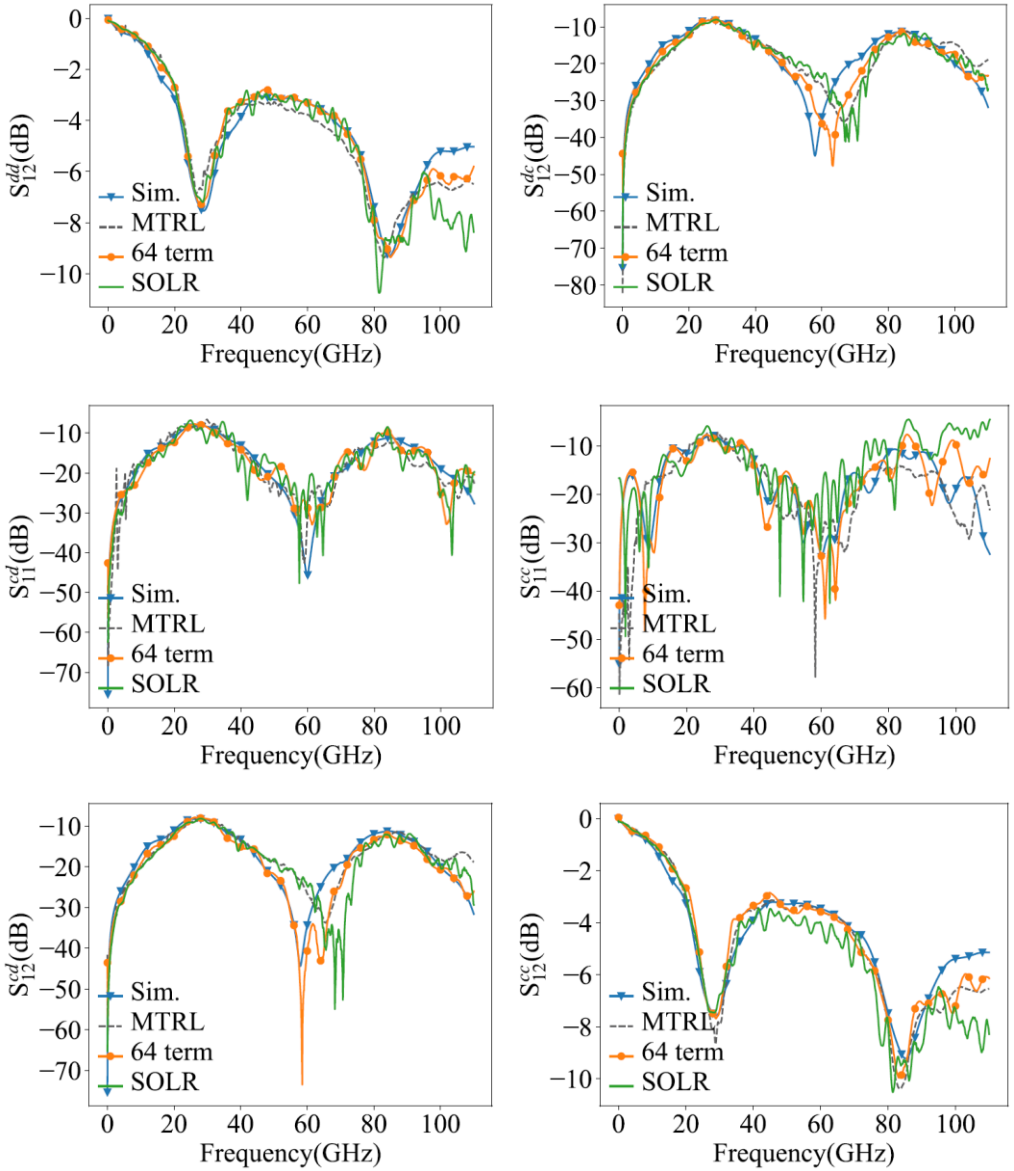
4. Measurement validation

DUT: 12.70 mm GSGSG transmission line (with a 1.52 mm open-ended branch at the middle position of one of the channels)



The S parameters of the asymmetric DUT were obtained respectively through EM full-wave simulation, SOLR, multimode TRL, and the proposed 64-term error model.

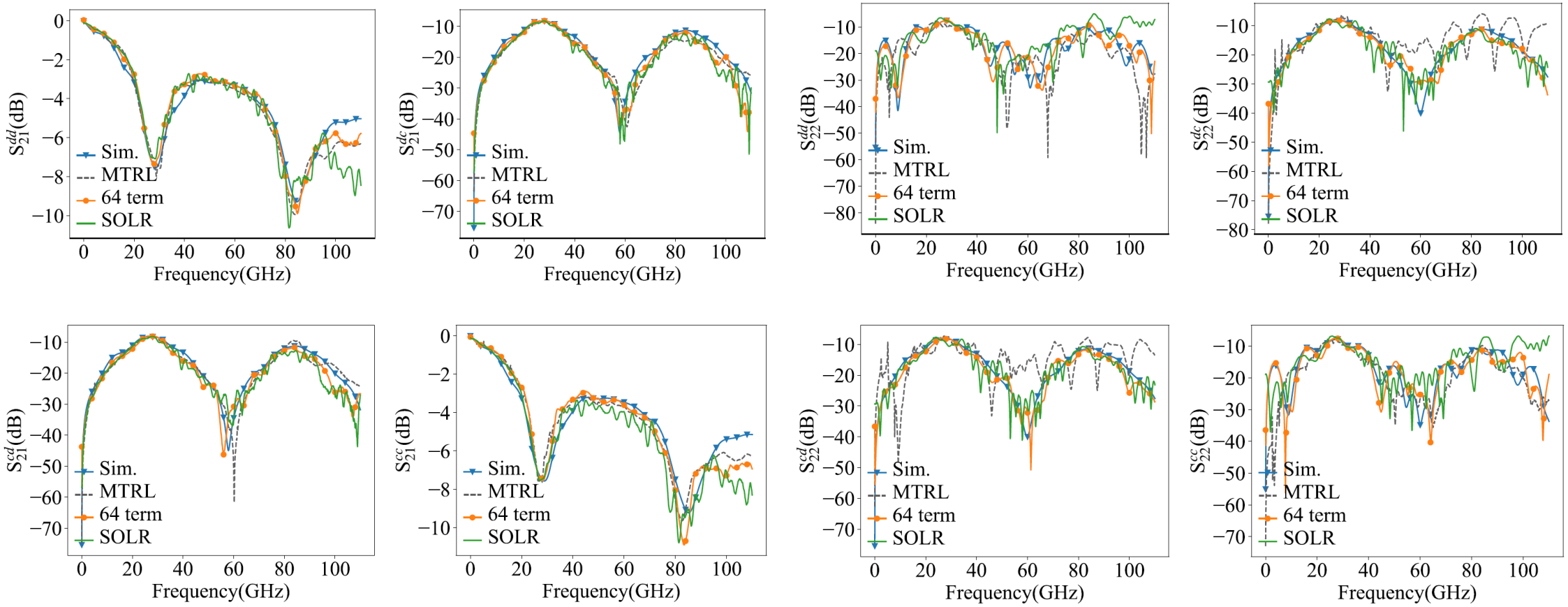




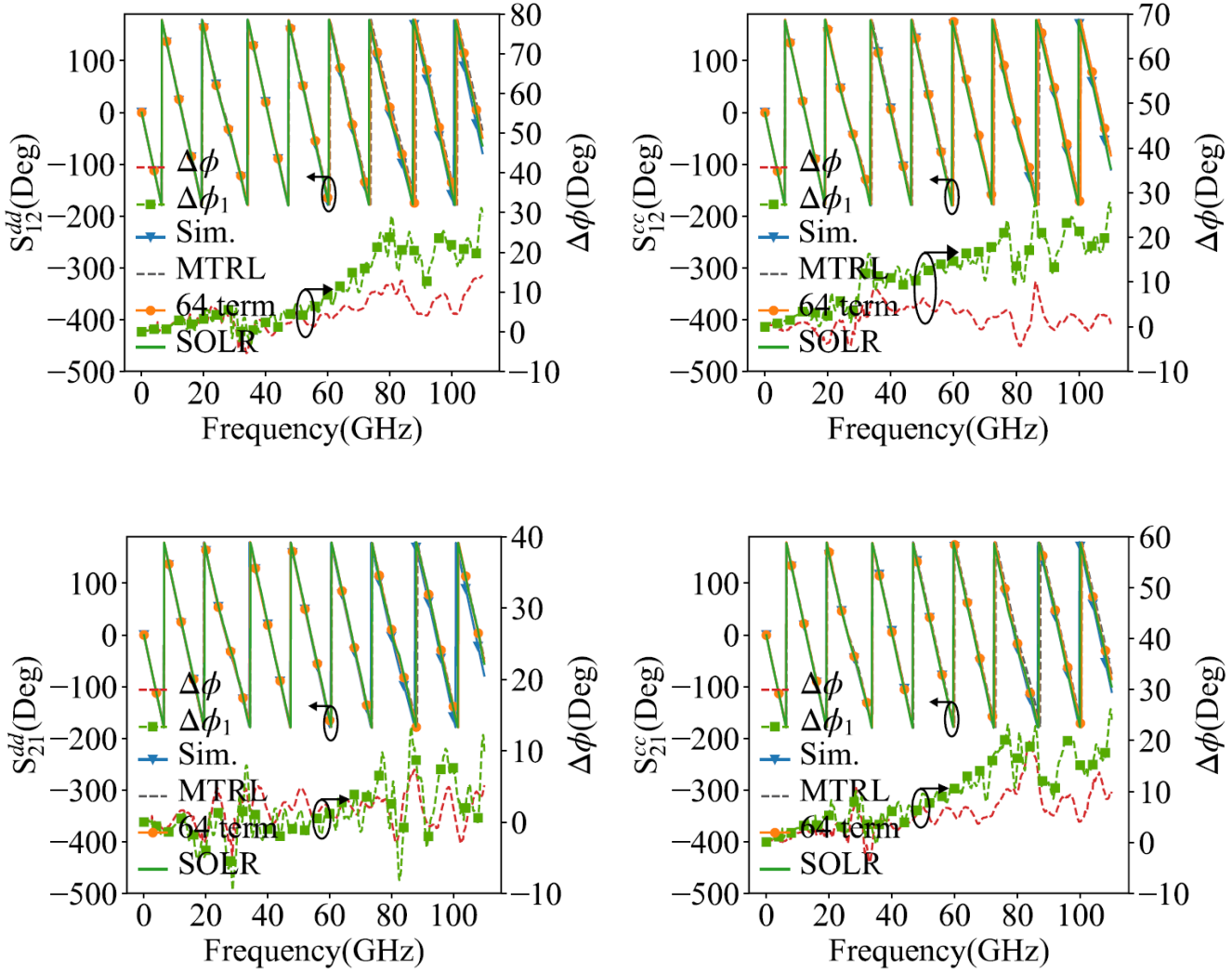
Four-Port Probe Calibration Using 64-Term Error Model for On-Wafer S-Parameter Measurement up to 110 GHz

4. Measurement validation

The results show that for $S_{12/21}^{dd/cc}$ and the mode conversion parameters $S_{12/21}^{dc/cd}$, the calculation results of the method in this chapter, the multimode TRL, and the simulation results are highly consistent; the calculated values of $S_{11/22}^{dd/cc}$ and the mode conversion S parameters $S_{11/22}^{dc/cd}$ in the 64 error model are more accurate than those calculated by the multimode TRL. Since the two-port SOLR cannot take into account the crosstalk between ports, the accuracy of this method is higher than that of the two-port SOLR.



Four-Port Probe Calibration Using 64-Term Error Model for On-Wafer S-Parameter Measurement up to 110 GHz



- The maximum phase difference between the two-port SOLR and the multimode TRL is 31.2°, and the maximum phase difference between the 64-term error model and the multimode TRL is 19.8°.

Innovation point:

- The crosstalk term between the probes and the inherent error are regarded as an error matrix. **All the error terms can be solved at once**, and the calibration of the four-port probe can be completed with only six calibration standards. This method does not need to consider the symmetry of the probe and can move the calibration reference plane to the tip position. Compared with multi-mode TRL, it does not require the design of additional calibration standards to expand the bandwidth.

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Conclusion

➢ **Provide theoretical and technical support for the key measurement and simulation technologies of signal integrity for ultra-high-speed chip channels!**

- By transforming the traditional measurement problem into an optimization problem and avoiding the use of additional calibration standards, it is possible to obtain the precise parasitic parameters of the calibration standards in high crosstalk scenarios.
- It effectively reduces the number of the error terms to be calculated. Only the phase information of the Thru calibration standard is needed to determine the sign of the error terms, without the need for the S-parameters of the known Thru calibration standard.
- All the error terms can be solved at once, and the calibration of the four-port probe can be completed with just six calibration standards. This method does not need to consider the symmetry of the probe and can move the calibration reference plane to the tip position. Compared with multimode TRL, it does not require the design of additional calibration standards to expand the bandwidth.

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Thanks for Your Attention

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