Calibration Method for Free-Space Material Measurement System in Millimeter-Wave Frequency Range

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Outline

- Introduction
- Planar Offset Short as Free-Space Reflection Standard
- Free-Space Unknown Thru Two-Port Calibration
- Free-Space Two-Tier One-Port Calibration
- Summary and Conclusions

Introduction (1/4)

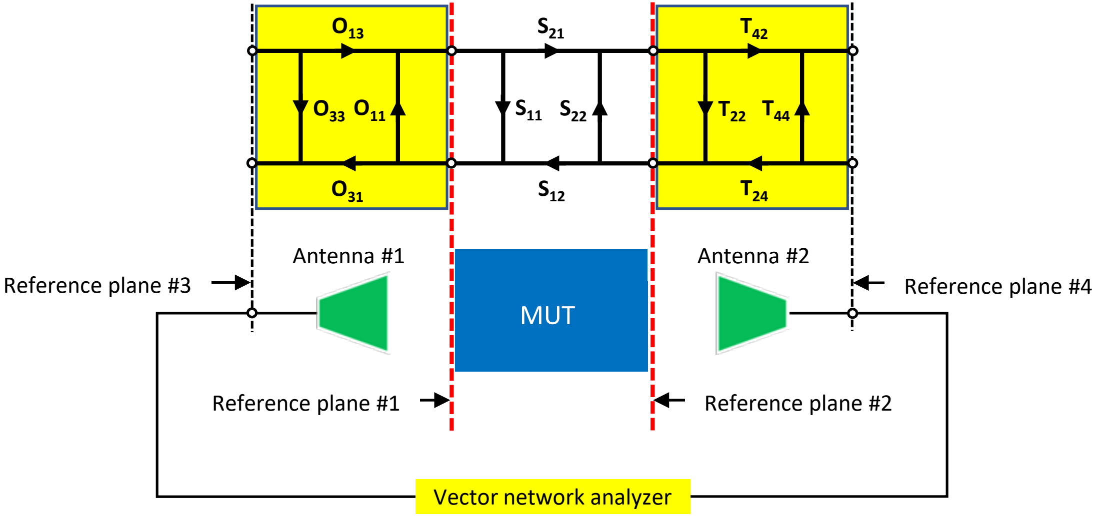
- Electrical properties of materials are requisite to design electromagnetic (EM) device and system.

- EM material measurement method

Measurement method		Advantage / disadvantage	
Reflection/transmission method	Coaxial	Broadband	Machining of MUT (Material Under Test) ⇒ Low freq. range
	Waveguide	Banded due to waveguide	
	Free space	Banded due to antenna	No machining of MUT⇒ High freq. range
Resonator method		Discrete frequency, high accuracy, no machining of MUT	

Introduction (2/4)

- Free-space transmission/reflection (T/R) material measurement
  - Measure S_{ij} of an MUT between two antennas in free space.
  - Suitable for nondestructively testing an MUT without prior machining and physical contact in high-frequency ranges



Introduction (3/4)

- General procedure of free-space T/R material measurement

  Step #1) Calibrate a material measurement system.

  Step #2) Measure S_{ij} of an MUT with the calibrated measurement system.

  Step #3) Extract material properties of the MUT from the measured S_{ij} by using EM Theory.

- Calibration method for free-space T/R material measurement

<table>
<tr><th>Calibration method</th><th>Used device/standard</th><th colspan="2">Requirement</th></tr>
<tr><td>TRM (Thru-Reflect-Match)</td><td>Reflect, match</td><td>Well-matched broadband absorber</td><td rowspan="2">Movements of RF cable</td></tr>
<tr><td>TRL (Thru-Reflect-Line)</td><td>Reflect</td><td>Precision position system</td></tr>
<tr><td>GRL (Gated-Reflect-Line)</td><td>Calibration kit, reflect</td><td colspan="2">Shift of the reference plane $\Rightarrow$ De-embedding process
Time-gating measurement</td></tr>
</table>

Introduction (4/4)

- Planar offset short proposed as a free-space calculable reflect standard (ISAP 2019)

- Free-space calibration methods using the planar offset short
  - Unknown thru two-port calibration (AMTA 2020)
  - Two-tier one-port calibration (AMTA 2021)

- This work compares the two free-space calibration methods using the planar offset short.

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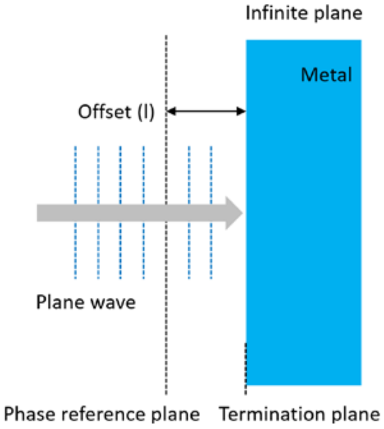
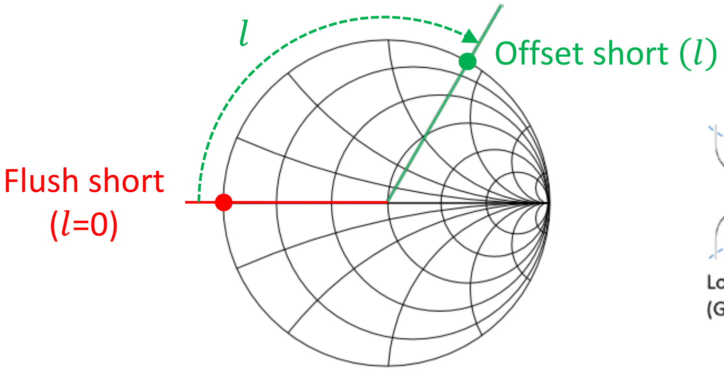
Planar Offset Short as Free-Space Reflection Standard (1/4)

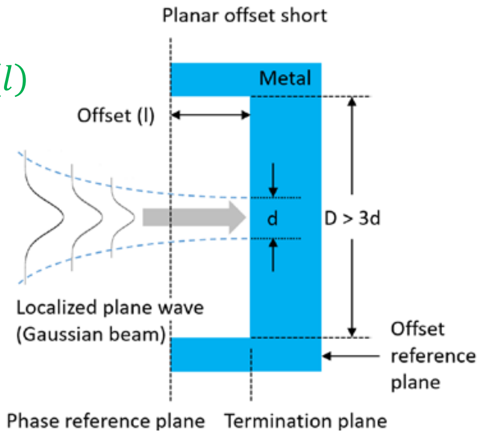
- Basic idea of planar offset short (ISAP 2019)
  - Reflection coefficient of an infinite metal plane of offset (l) illuminated by a plane wave measured at the phase reference plane



Infinite metal plane
illuminated by a plane wave



$$\Gamma(l) = -e^{-j2kl}$$



Planar offset short
illuminated by a Gaussian beam

Planar Offset Short as Free-Space Reflection Standard (2/4)

- Fabrication procedure

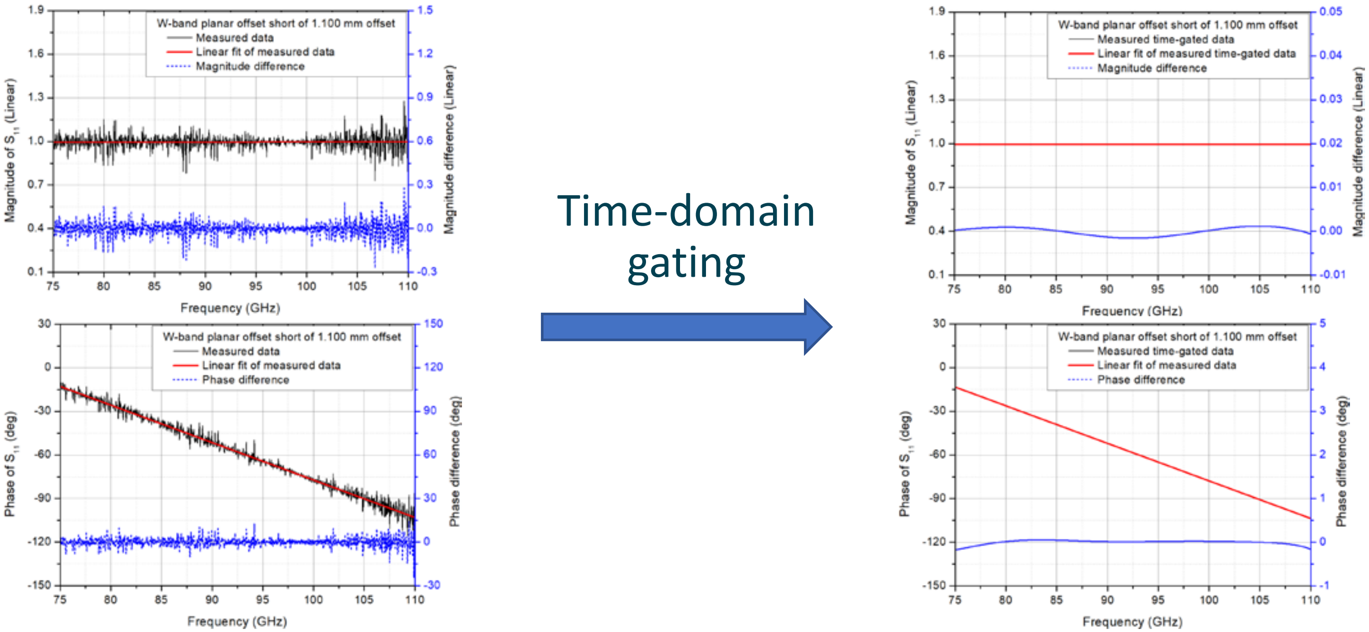
  Step #1) Fabricate an aluminum planar flush short without offset ($\boldsymbol{l}$ =0)
  of 125x125 mm^2 size and 8 mm thickness.

  Step #2) Plane away the central area (dark yellow) except the four squares (blue)
  of 10x10 mm^2 size located at the corners on one side
  of the planar flush short by the offset ($\boldsymbol{l} = \boldsymbol{l}_1 - \boldsymbol{l}_2$).

Free-space planar offset short. (Left) Step #1. (Right) Step #2.

Planar Offset Short as Free-Space Reflection Standard (3/4)

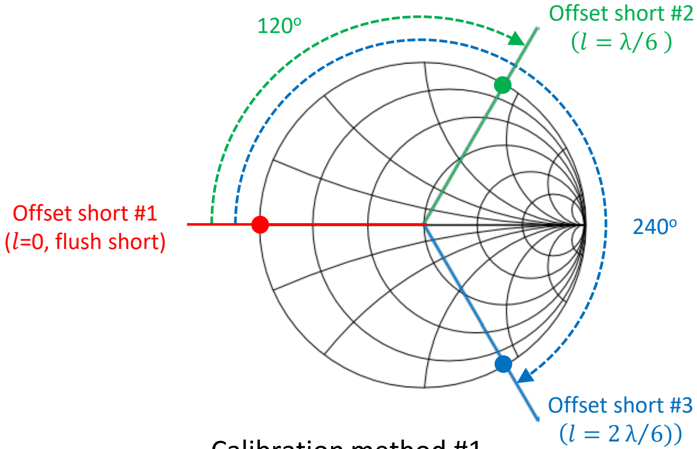
- Planar offset short of 1.100 mm offset
  - Results obtained from a measurement system calibrated by TRL method



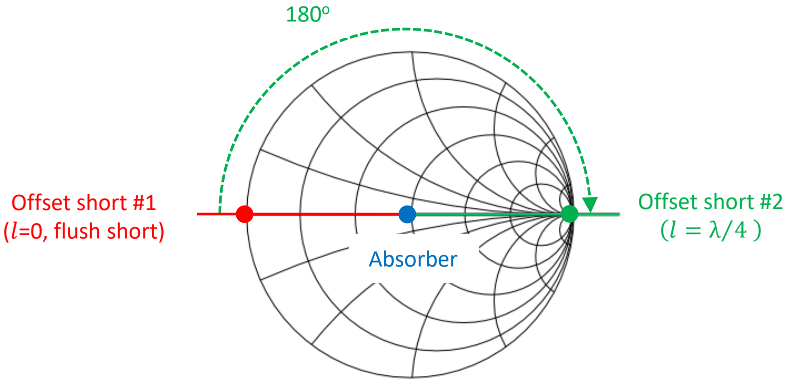
Reflection coefficient of a planar offset short of 1.100 mm offset. (Top) Magnitude. (Bottom) Phase.

Planar Offset Short as Free-Space Reflection Standard (4/4)

Standard	Calibration method #1			Calibration method #2		
	Name	Offset	Phase difference	Name	Offset	Phase difference
#1	Offset short #1	0.000 mm (0)	0	Offset short #1	0.000 mm (0)	0
#2	Offset short #2	0.550 mm $(\lambda/6)$	120 °	Offset short #2	0.825 mm $(\lambda/4)$	180 °
#3	Offset short #3	1.100 mm $(2\lambda/6)$	240 °	Flat absorber	-	-



Calibration method #1



Calibration method #2

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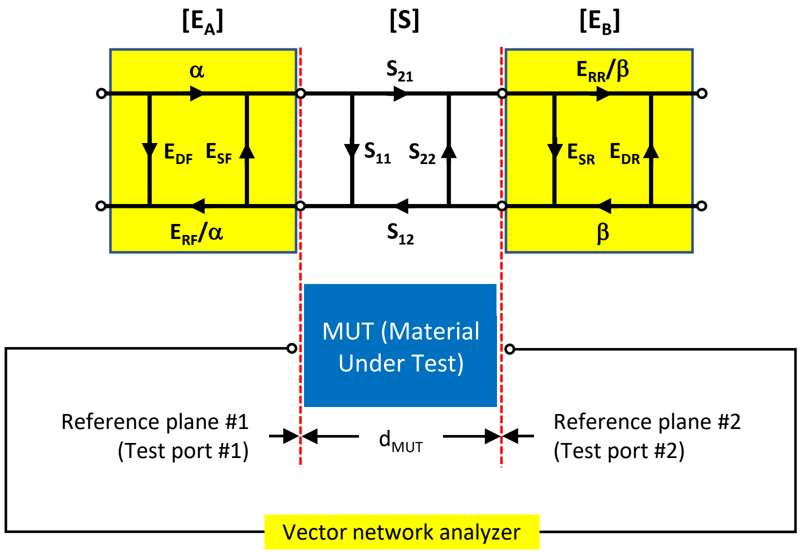
Free-Space Unknown Thru Two-Port Calibration (1/5)

- Eight-term error model of free-space T/R material measurement system
  - Two error adapters E_A & E_B between the test port of an ideal VNA and the MUT
  - Eight systematic errors: (E_{DF},E_{SF},E_{RF},α) in E_A + (E_{DR},E_{SR},E_{RR},β) in E_B



E_{DF} & E_{DR} $\Rightarrow$ Directivity
E_{SF} & E_{SR} $\Rightarrow$ Port match
E_{RF} & E_{RR} $\Rightarrow$ Tracking

α & β $\Rightarrow$ Transmission error

Free-Space Unknown Thru Two-Port Calibration (2/5)

- Representation of the eight-term error model in the cascade matrices (T)

$$[T^m] = [A][T][B]$$

$[S^m]$ $[\mathrm{E}_A]$ $[S]$ $[\mathrm{E}_B]$

where

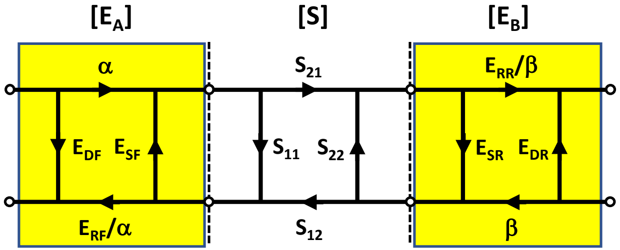
$$[T^m] = \frac{1}{S_{21}^m}\begin{bmatrix} \Delta_S^m & S_{11}^m \\ -S_{22}^m & 1 \end{bmatrix} \qquad \Delta_S^m = S_{12}^m S_{21}^m - S_{11}^m S_{22}^m = -\det(S^m)$$

$$[A] = \frac{1}{\alpha}\begin{bmatrix} \Delta_A & E_{DF} \\ -E_{SF} & 1 \end{bmatrix} \qquad [B] = \frac{\beta}{E_{RR}}\begin{bmatrix} \Delta_B & E_{SR} \\ -E_{DR} & 1 \end{bmatrix}$$

$$\Delta_A = E_{RF} - E_{DF}E_{SF} = -\det(E_A) \qquad \Delta_B = E_{RR} - E_{DR}E_{SR} = -\det(E_B)$$

$$[T^m] = \frac{\beta}{\alpha}\frac{1}{E_{RR}}\begin{bmatrix} \Delta_A & E_{DF} \\ -E_{SF} & 1 \end{bmatrix}[T]\begin{bmatrix} \Delta_B & E_{SR} \\ -E_{DR} & 1 \end{bmatrix}$$

(E_{DF}, E_{SF}, E_{RF}) + (E_{DR}, E_{SR}, E_{RR}) + β/α $\Rightarrow$ Seven unknowns!



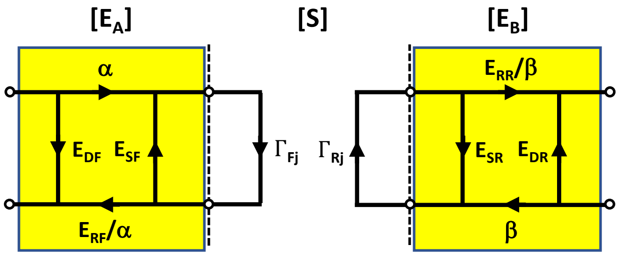
Free-Space Unknown Thru Two-Port Calibration (3/5)

- Step #1 of unknown thru calibration procedure
  - One-port calibration at (#1 & #2) for determining $(E_{Di}, E_{Si}, E_{Ri}, (i = F, R))$
    - Measure $\Gamma_{F,j}^{m}$ of three reflection standards #j of $\Gamma_{F,j}$ at (#1, $(j = 1,2,3)$).
    - Perform the one-port calibration procedure for determining (E_{DF}, E_{SF}, E_{RF}).
    - Repeat the one-port calibration procedure for determining (E_{DR}, E_{SR}, E_{RR}) at (#2, $(j = 1,2,3)$).

$$\Gamma_{i,j}^{m} = E_{Di} + \frac{E_{Ri}\Gamma_{i,j}}{1-E_{Si}\Gamma_{i,j}} \quad \text{(i=F,R, j=1,2,3)} \quad \rightarrow$$

$$\begin{bmatrix} 1 & \Gamma_{i,1}\Gamma_{i,1}^{m} & \Gamma_{i,1} \\ 1 & \Gamma_{i,2}\Gamma_{i,2}^{m} & \Gamma_{i,2} \\ 1 & \Gamma_{i,3}\Gamma_{i,3}^{m} & \Gamma_{i,3} \end{bmatrix} \begin{bmatrix} E_{Di} \\ E_{Si} \\ \Delta_k \end{bmatrix} = \begin{bmatrix} \Gamma_{i,1}^{m} \\ \Gamma_{i,2}^{m} \\ \Gamma_{i,3}^{m} \end{bmatrix} \quad \text{(i=F,R, j=1,2,3, k=A,B)}$$

3x2 measurements ⇒ 6 unknowns



Free-Space Unknown Thru Two-Port Calibration (4/5)

- Step #2 of unknown thru calibration procedure
  - Reciprocal unknown thru measurement for determining β/α

$$[T_{ut}^{m}] = \frac{\beta}{\alpha}\frac{1}{E_{RR}}\begin{bmatrix}\Delta_A & E_{DF}\\ -E_{SF} & 1\end{bmatrix}[T_{ut}]\begin{bmatrix}\Delta_B & E_{SR}\\ -E_{DR} & 1\end{bmatrix}$$

$det(T_{ut})$ =1 for reciprocal two-port device

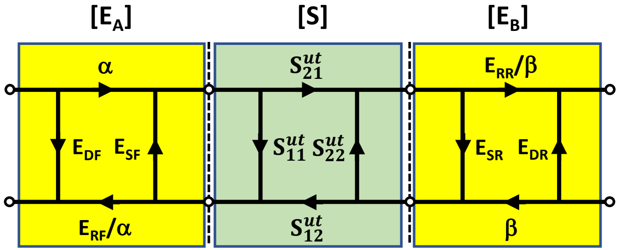
- Taking the determinant of the T matrix

Left side $\Rightarrow$ $$det(T_{ut}^{m}) = det\left(\frac{1}{S_{21}^{m}}\begin{bmatrix}\Delta_S^{m} & S_{11}^{m}\\ -S_{22}^{m} & 1\end{bmatrix}\right) = \boxed{\frac{S_{ut,12}^{m}}{S_{ut,21}^{m}}}$$

Right side $\Rightarrow$ $$\left(\frac{\beta}{\alpha}\frac{1}{E_{RR}}\right)^{2} det\begin{pmatrix}\Delta_A & E_{DF}\\ -E_{SF} & 1\end{pmatrix} det(T_{ut})\, det\begin{pmatrix}\Delta_B & E_{SR}\\ -E_{DR} & 1\end{pmatrix} = \boxed{\left(\frac{\beta}{\alpha}\frac{1}{E_{RR}}\right)^{2} E_{RF}E_{RR}}$$

$$\frac{\beta}{\alpha} = \pm\sqrt{\frac{S_{12}^{m}}{S_{21}^{m}}\frac{E_{RR}}{E_{RF}}}$$

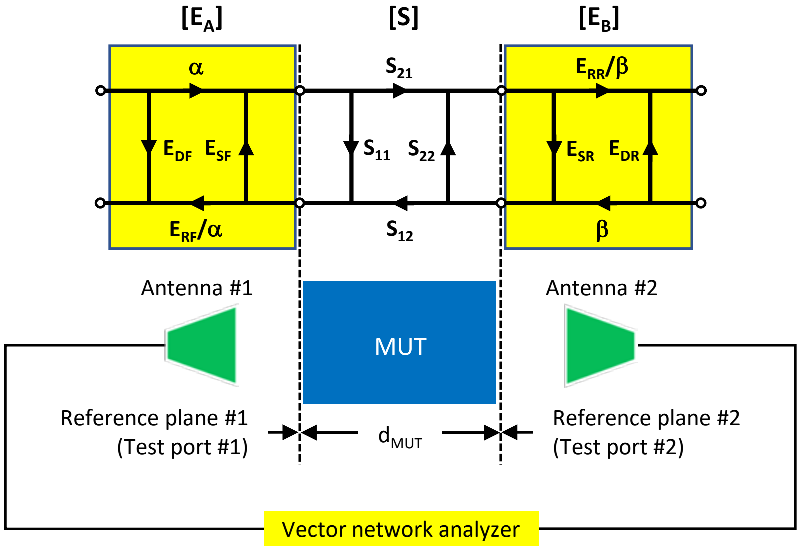
1 measurement $\Rightarrow$ 1 unknown



If an MUT is of reciprocal, the MUT can be used as an unknown thru in the calibration procedure.

Free-Space Unknown Thru Two-Port Calibration (5/5)

- MUT measurement
  - The position (i.e., #1 & #2) of an MUT is determined by the thickness of the MUT.



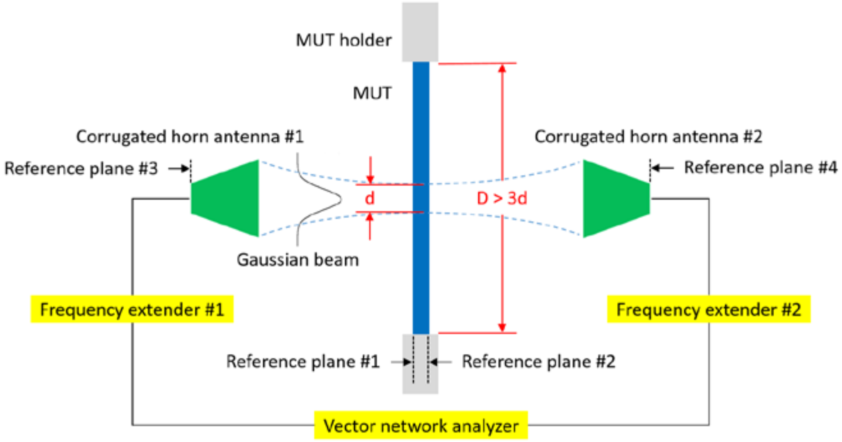
No precision position system & movements of RF cable in TRL method

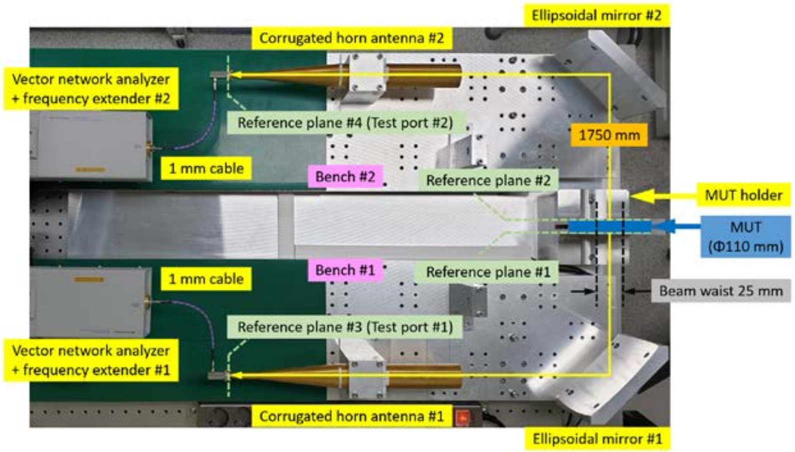
No de-embedding process & time-gating measurement in GRL method

If an MUT is of reciprocal, the MUT can be used as an unknown thru in the calibration procedure.

Measurement Results at W-band (1/4)

- Free-space material measurement system at W-band
  - Millimeter-wave S_{ij} measuring instrument
    - 67 GHz VNA + frequency extender (67-110 GHz and D-/G-/J-bands)
  - Quasi-optic based free-space instrument generating a Gaussian beam (D > 3d)





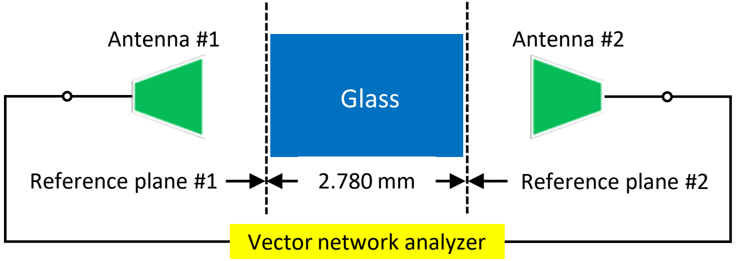
Quasi-optic based free-space material measurement system. (Left) Schematic. (Right) Photograph

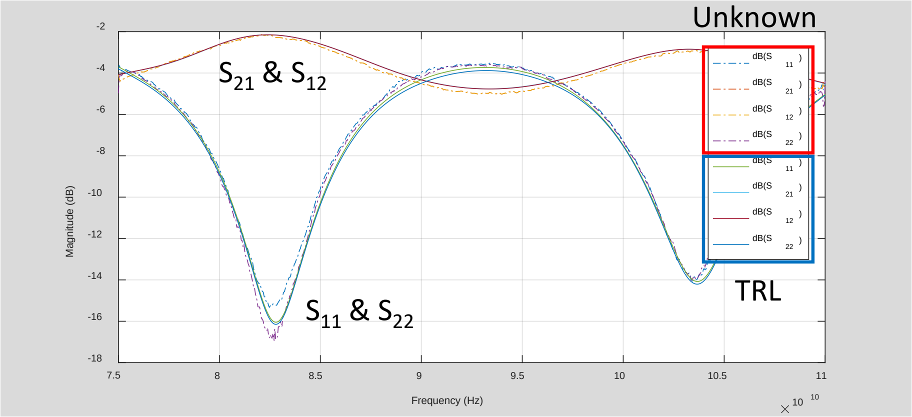
Measurement Results at W-band (2/4)

- Calibration of the free-space material measurement system at W-band
  - Unknown thru calibration using three planar offset shorts
    - One-port calibration procedure using the three planar offset 'Shorts' (l=0 mm, 0.550 mm,1.100 mm) at Reference planes #1 an #2
    - 'Reciprocal thru' measurement using an MUT as an unknown thru standard.
  - TRL calibration
    - 'Thru'
    - 'Reflect' using a metal plate of 4.671 mm thickness
    - 'Line' of 0.82 mm delay in air
    - Test port #1 of the measurement system is fixed during the calibration.
  - Measurement condition in W-band
    - 500 Hz IF bandwidth
    - 801 stepped frequency sweep points
    - 20 point smoothing

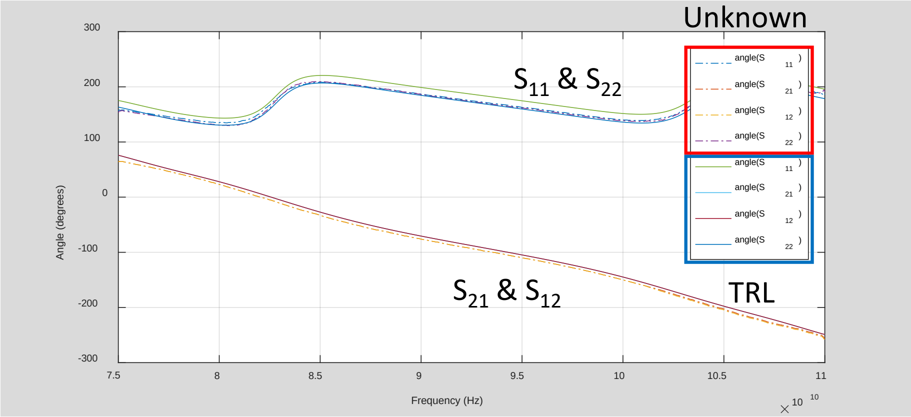
Measurement Results at W-band (3/4)

- S_{ij} of a glass of 2.780 mm thickness





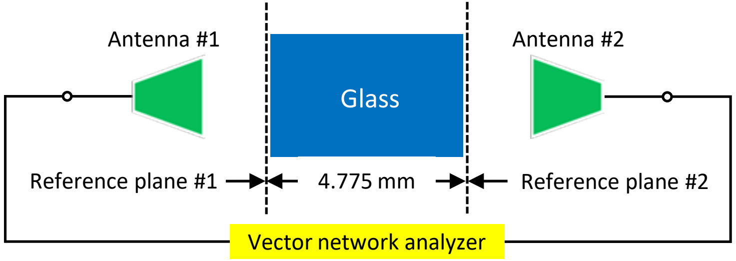
Magnitude (dB)

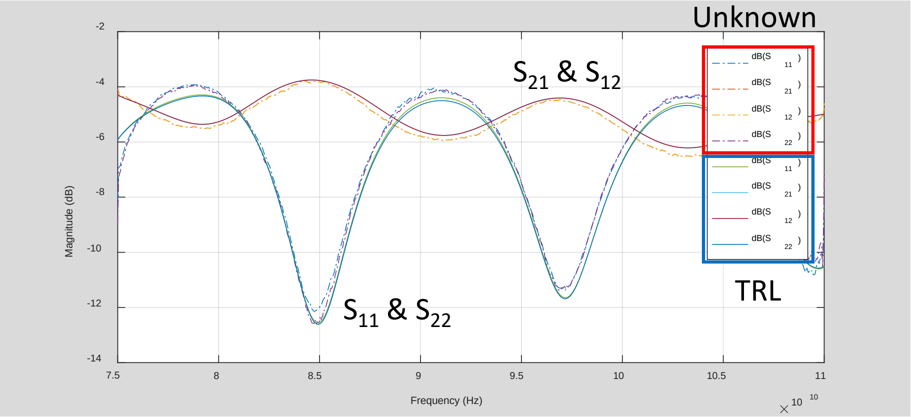


Phase (degree)

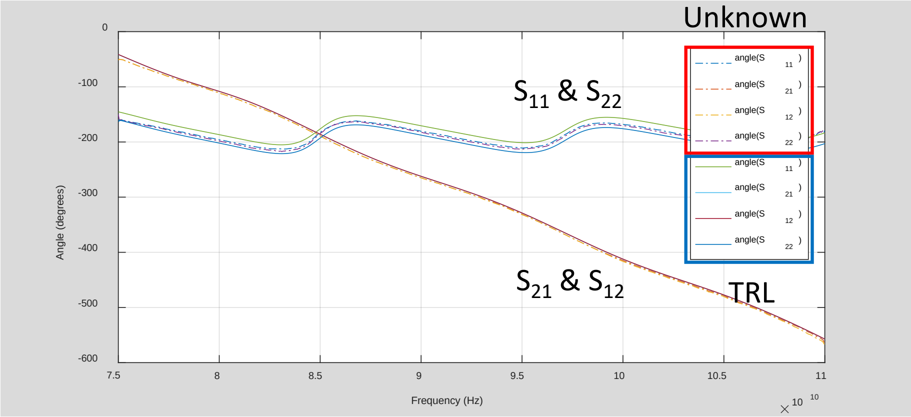
Measurement Results at W-band (4/4)

- S_{ij} of a glass of 4.775 mm thickness





Magnitude (dB)



Phase (degree)

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Introduction

- One-port material measurement based on coaxial line and waveguide
  - One-port calibration such as SOL (Short-Open-Load) method
  - Measured S_{ii} can determine either one of ε_r and μ_r.
  - Additional S_{ii} measurements for both of ε_r and μ_r measurement: An MUT at different position
    Two MUTs of different thickness

- Full S_{ij} measurement for adapter characterization
  - Two-port adapter-removal technique: Two two-port calibrations are required.
  - Two-tier one-port calibration method: Reciprocal DUT
    At least three independent reflect standards are required.
  - How to realize independent reflect standards in free space?

- In this work,
  - Free-space two-tier one-port calibration method
  - Three planar offset shorts with $\lambda/6$ offset difference as free-space calculable reflect standards
  - Full S_{ij} measurement of an MUT in free space in a millimeter-wave frequency range.

Free-Space Two-Tier One-Port Calibration

- Step 1) One-port calibration

  at Reference plane #1: $[S^e] \rightarrow [T^e]$

  Scattering matrix   Cascade matrix

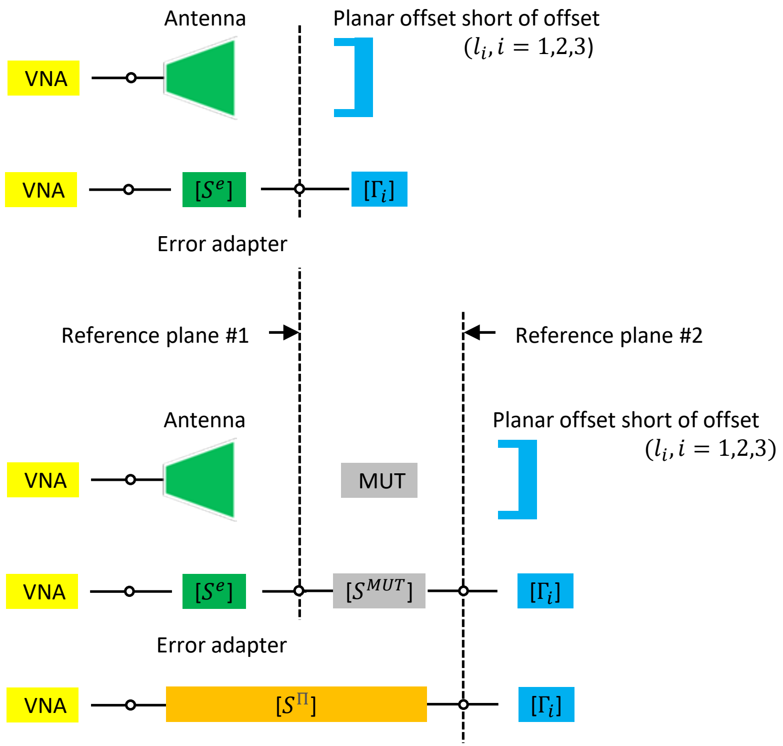
- Step 2) One-port calibration

  at Reference plane #2: $[S^\Pi] \rightarrow [T^\Pi]$

- Step 3) Determination of $[S^{MUT}]$

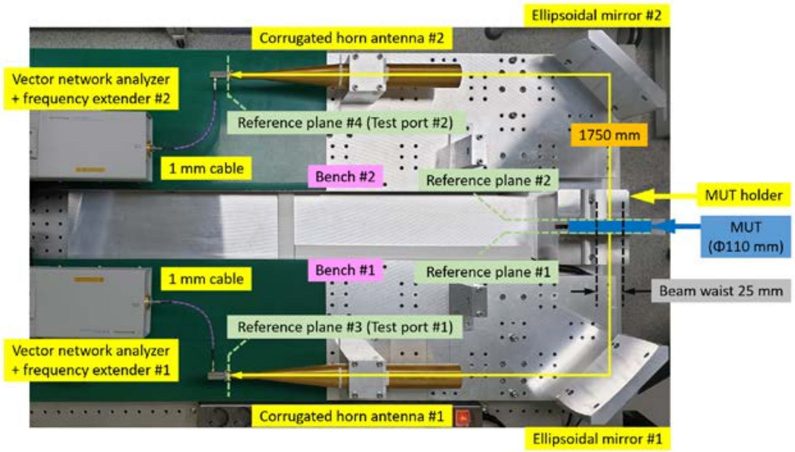
  $[T^\Pi] = [T^e][T^{MUT}]$

  $\rightarrow \boxed{[T^{MUT}] = [T^e]^{-1}[T^\Pi]} \rightarrow [S^{MUT}]$



Measurement Results at W-band (1/2)

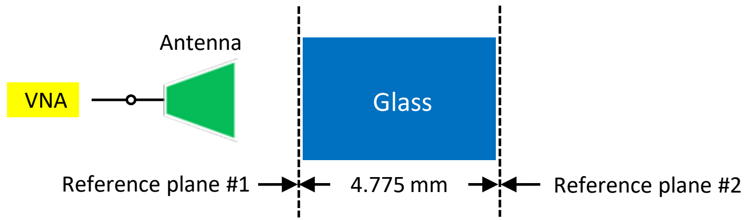
- Calibration of a free-space material measurement system at W-band
  - Two-tier one-port calibration using three planar offset shorts
    - Two successive one-port calibration at Reference planes #1 an #2
    - Three planar offset 'Shorts' (l=0 mm (0),0.550 mm $(^{\lambda}/_{6})$,1.100 mm $(^{2\lambda}/_{6})$)
  - TRL calibration
    - 'Thru'
    - 'Reflect' using a metal plate of 4.671 mm thickness
    - 'Line' of 0.82 mm delay in air
  - Measurement conditions at W-band
    - 500 Hz IF bandwidth
    - 801 stepped frequency sweep points
    - Time-domain gating & smoothing
    - Test port #1 of the measurement system is fixed during the calibration and measurement.

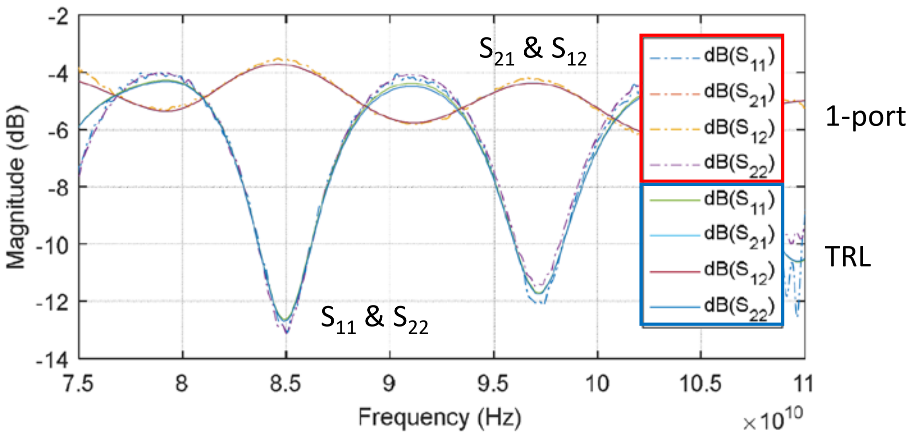


Quasi-optic based free-space material measurement system

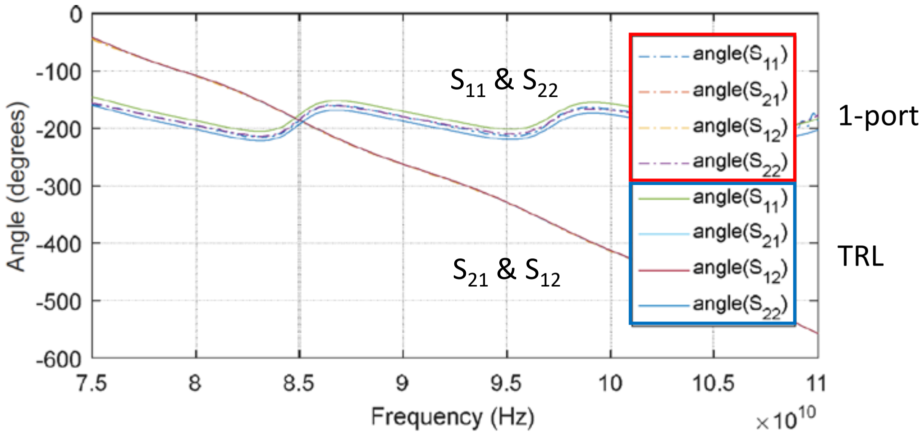
Measurement Results at W-band (2/2)

- Full S_{ij} of a glass of 4.775 mm thickness





Magnitude (dB)



Phase (degree)

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Summary and Conclusions

- Free-space calibration methods using planar offset short
  - Unknown thru two-port calibration
  - Two-tier one-port calibration

Calibration method		TRL (Thru-Reflect-Line)	TRM (Thru-Reflect-Match)	GRL (Gated-Reflect-Line)	Unknown thru	Two-tier
Number of test port		2	2	2	2	1
Used device/standard	Broadband absorber	X	O	X	X	X
	Reflect	O	O	O	X	X
	Reflect standard (Planar offset short)	X	X	X	O	O
Time-domain gating		X	X	O	X	X
De-embedding process		X	X	O	X	X
Extra calibration (Two-tier calibration)		X	X	O	X	O
Precise positioning system/Moving of RF cable		O	O	X	X	X
Traceability		O	X	X	O	O
Calibration routine/program		VNA	VNA	PC	PC	PC