Dielectric Measurements at mm-Wave Frequencies with the Material Characterization Kit (MCK)

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Swissto12®

Outline

- Introduction and Market Need
- MCK Concept and Operational Principles
- Description of MCK Hardware and Software
- Product Advantages and Frequency Bands
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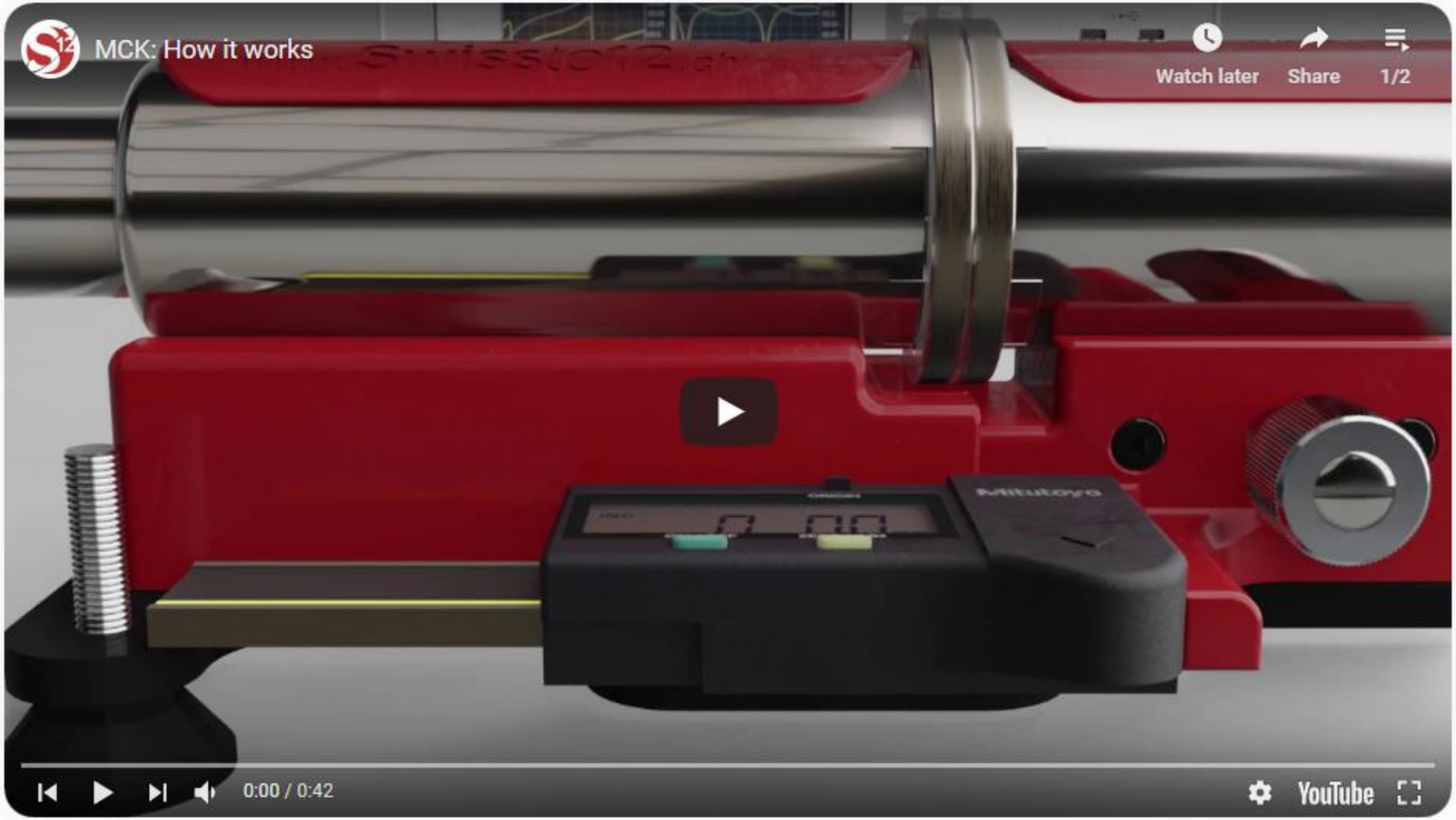
- Conclusions and Future Developments

Introduction – Market Need

- Higher data rates → frequencies **above 50 GHz**
- Dielectric properties (***ε_r*** and **tan*δ***) → simulations for design optimisation
- Material properties in **relevant frequencies** (not datasheets at 1 or 10 GHz)
- Low frequencies (**< 50 GHz**): waveguides, cavity resonators, or free-space setups
- High frequencies (**> 50 GHz**): no convenient solution in market

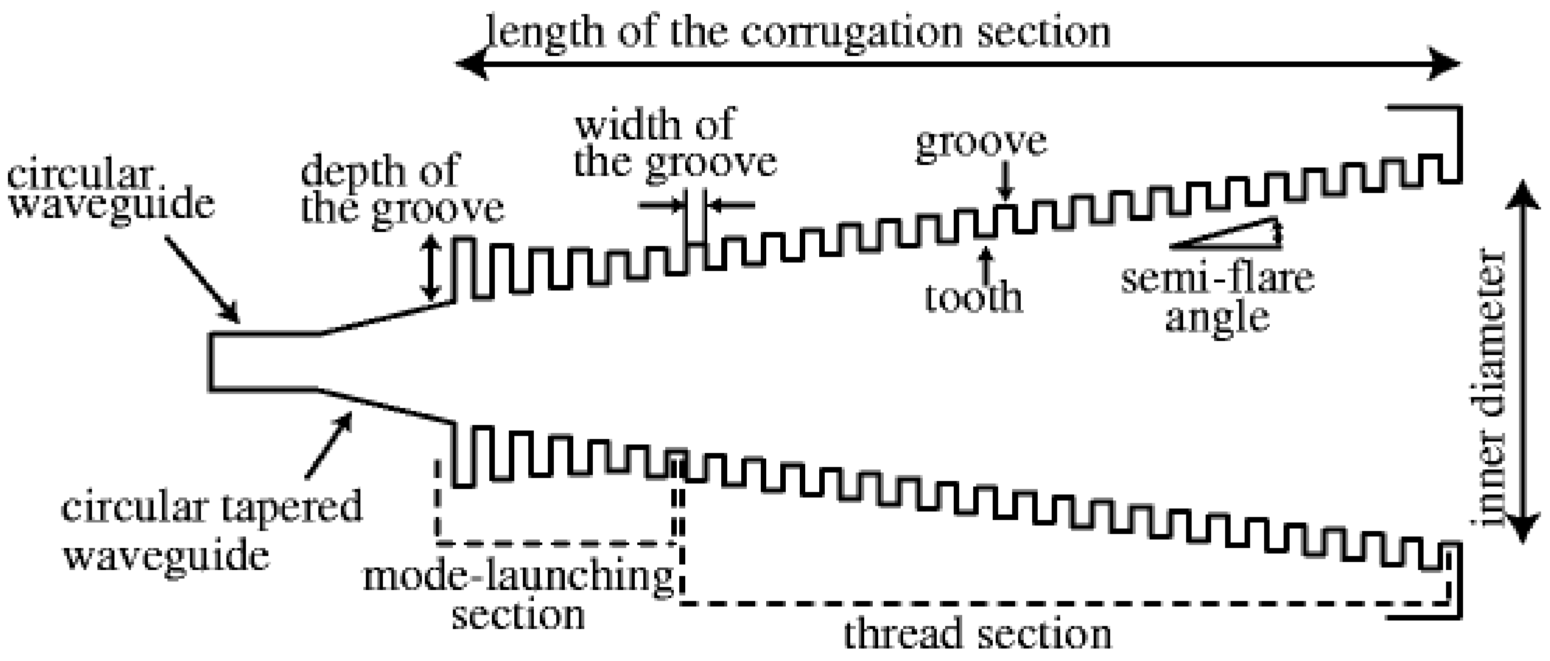
SWISSto12's solution : **Material Characterisation Kit (MCK)**

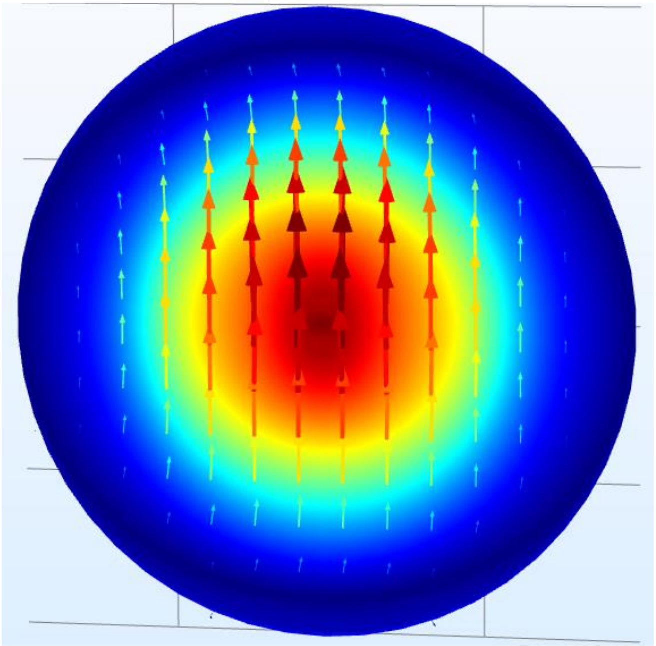
How it Works



https://www.youtube.com/watch?v=OZLNENg1Q-U

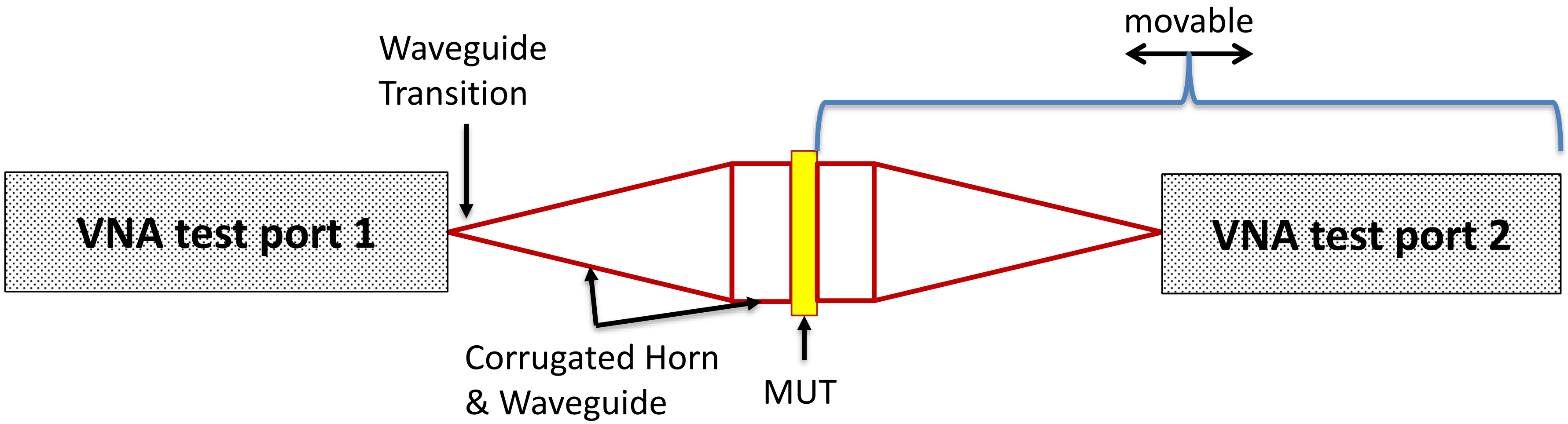
MCK Concept and Operational Principles (1/2)





- **Corrugated horns**: stack of precisely machined rings (**SWISSto12 patent**)
- Samples exposed to beam with **planar phase front**: **HE_{11} hybrid mode** (linear polarization)
- Gap does not perturb signal propagation: hybrid **“guided free-space”** approach
- RF design specs: **Return loss** > 20 dB, **HE_{11} mode purity** > 98%

MCK Concept and Operational Principles (2/2)



- **Minimum** measurement configuration: **only S_{21} and S_{11} data**
- Analytical **Fresnel formulas**: reflection/transmission of plane wave

$$S_{11} = \frac{r\left(1 - e^{-j2nk_0 d}\right)}{1 - r^2\left(1 - e^{-j2nk_0 d}\right)} \qquad S_{21} = \frac{(1 - r^2)e^{-jnk_0 d}}{1 - r^2\left(1 - e^{-j2nk_0 d}\right)}$$

$$r = \frac{z-1}{z+1} \qquad \mu = nz \qquad \varepsilon = \frac{n}{z}$$

Description of Hardware and Software (1/2)

- ✓ MCK with attached **electronic caliper**
- ✓ Metallic "**short**" calibration standard
- ✓ Set of **precision screws** adapted to the model
- ✓ Detailed **user's guide** with warranty
- ✓ Software to extract permittivity and loss tangent
- o [**Optional**] Upgrade kit for soft samples and foams
- o [**Optional**] Upgrade kit for liquid samples and powders
- o [**Optional**] Upgrade kit for coatings and multilayers

MCK ships in a properly designed **PeliCase**

Description of Hardware and Software (2/2)

- **Browser-based** (runs on VNA or computer)
- **Cross-platform** (Windows, Linux, and Mac support)
- **Compatible** with most VNA mainframes
- **Setup** & direct **data acquisition** from the VNA
- **Fast response calibration** (S_{11} and S_{21}) of the MCK
- Data analysis with **frequency independent** model
- Data analysis with **frequency dependent** model
- **Data export** in Touchstone (.s2p) format

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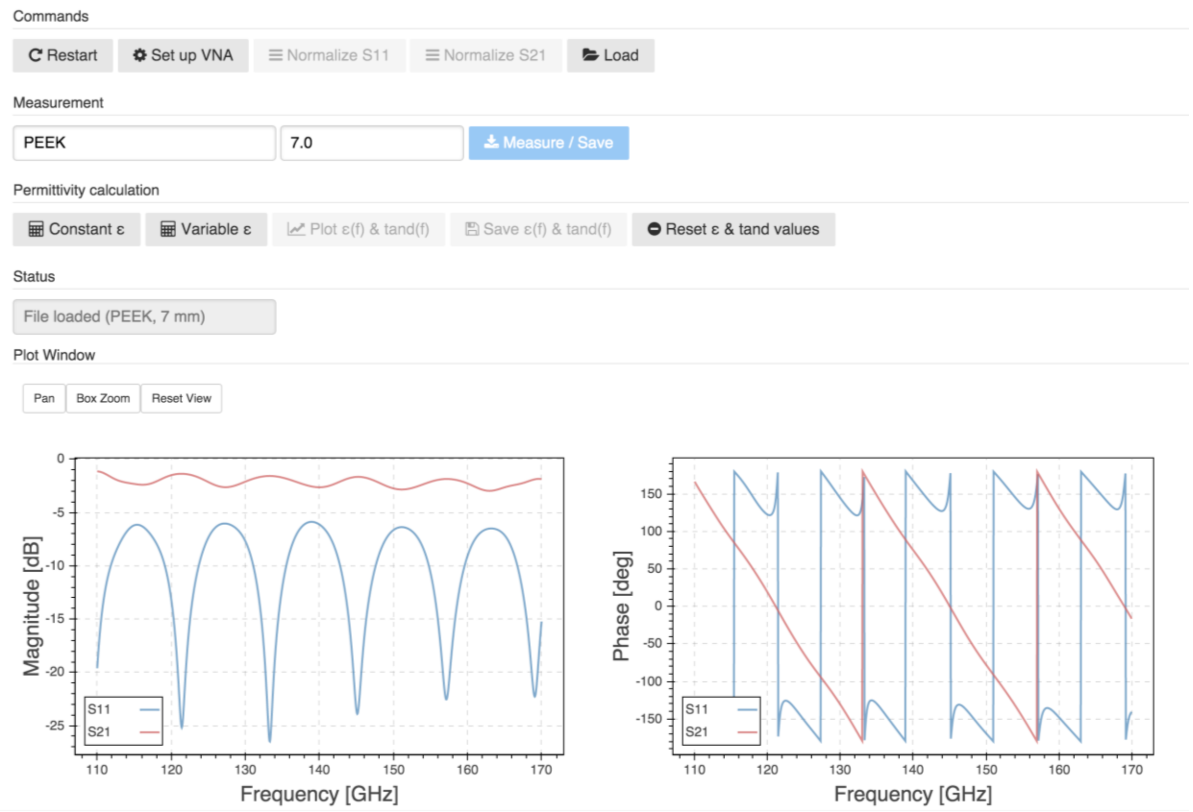


MCK Product Advantages

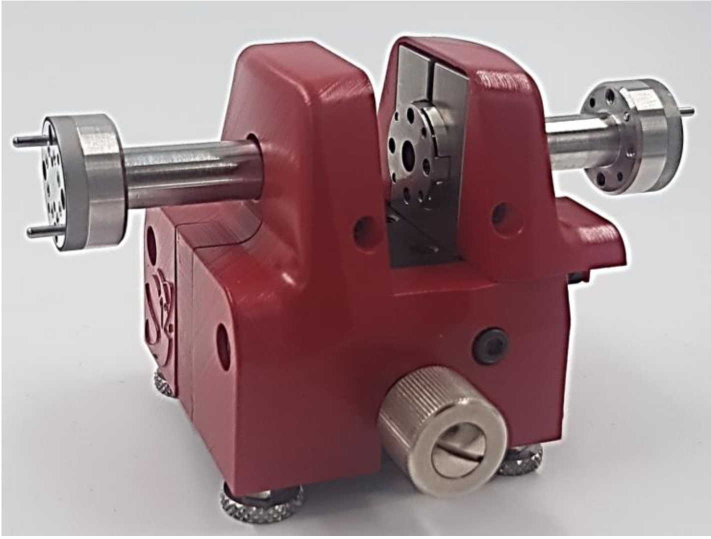
- Frequency-banded solution **from 25 GHz up to 1.1 THz**
- Connection to **standard waveguide flanges** (from WR28 to WR1.0)
- Main **advantages** of MCK:
  - ✓ **Compact** (easy to transport)
  - ✓ **Robust** (very repeatable results)
  - ✓ **Fast** (few seconds per measurement)
  - ✓ **Easy-to-use** (simple calibration)

Available Frequency Bands

Group 4	Group 3	Group 2	Group 1
WR28 (25 – 40 GHz)	WR15 (47 – 75 GHz)	WR6.5 (110 – 170 GHz)	WR2.2 (330 – 500 GHz)
WR22 (33 – 50 GHz)	WR12 (55 – 90 GHz)	WR5.1 (140 – 220 GHz)	WR1.5 (500 – 750 GHz)
WR19 (40 – 60 GHz)	WR10 (67 – 110 GHz)	WR3.4 (220 – 330 GHz)	WR1.0 (750 – 1100 GHz)

Groups 2, 3 & 4

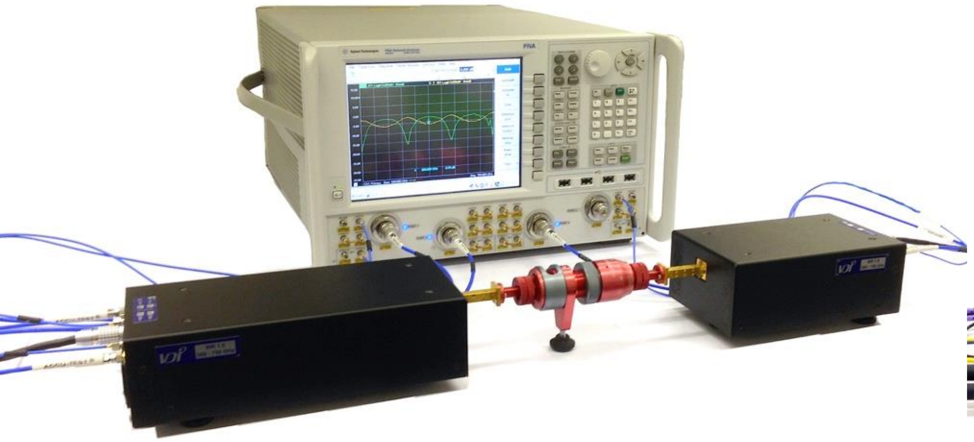
Group 1



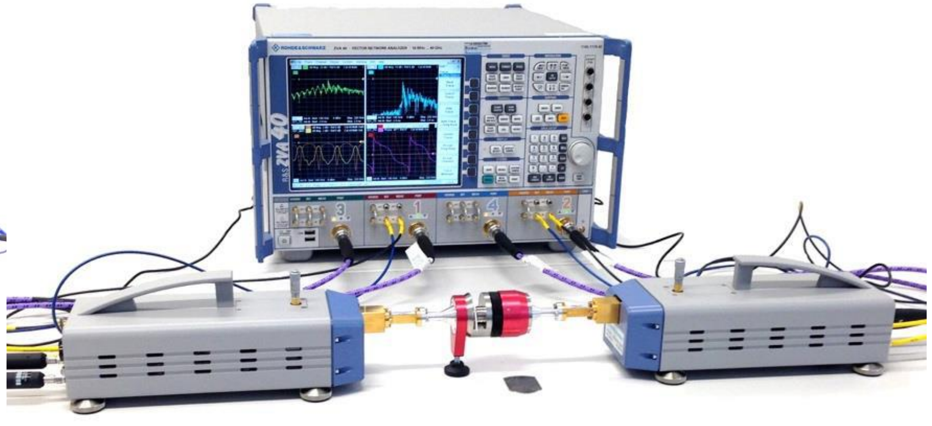
Sample Requirements

- For **solid** samples:
  - **Homogeneous** thickness (flat slab), no special issue with **surface roughness**
  - Lateral dimensions to **cover the antenna** aperture (typically 40 x 40 mm)
  - **Maximum** thickness of approximately **20 mm**
  - **No** strict **minimum** thickness, ideally a few millimeters for low loss materials
  - Possible to measure **anisotropic** materials by rotating the sample
- For **soft** samples and **foams** (upgrade kit):
  - Similar to the solid samples, special sample holder provided + upgraded software version
- For **liquid** samples and **powders** (upgrade kit):
  - **Volume** restricted from the special sample holder provided + upgraded software version
- For **coatings** and **multilayer materials** (upgrade kit):
  - **Special version** of the software customized to the needs of the customer

Measurement Setup and Connectivity



Keysight PNA + VDI extenders



Rohde & Schwarz ZVA

Anritsu Shockline E-band VNA

- VNA with **time domain option enabled** (additional software option)

➢ **If 4-port VNA**: Millimeter wave frequency extenders (up to 1.5 THz currently)

➢ **If 2-port VNA**: Coaxial-to-waveguide adapters for frequencies up to 67 GHz

➢ **If webMCK software**: Computer that connects to the VNA (Ethernet of GPIB connection)

Calibration and Measurement Procedure

Step 1: Clamp the **"short" calibration standard** between the two antennas and **normalise S_{11}**

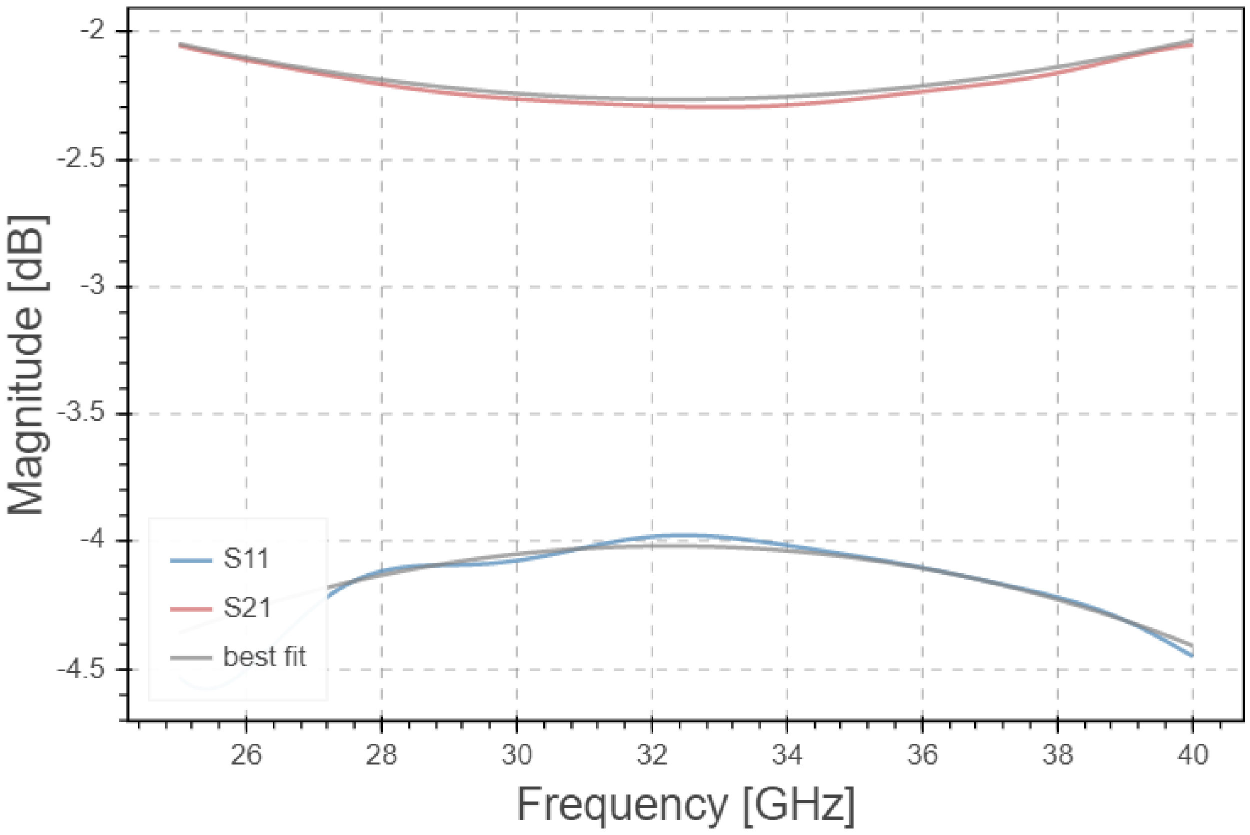
Step 2: Connect the two antennas directly without a gap between (**thru**) and **normalise S_{21}**

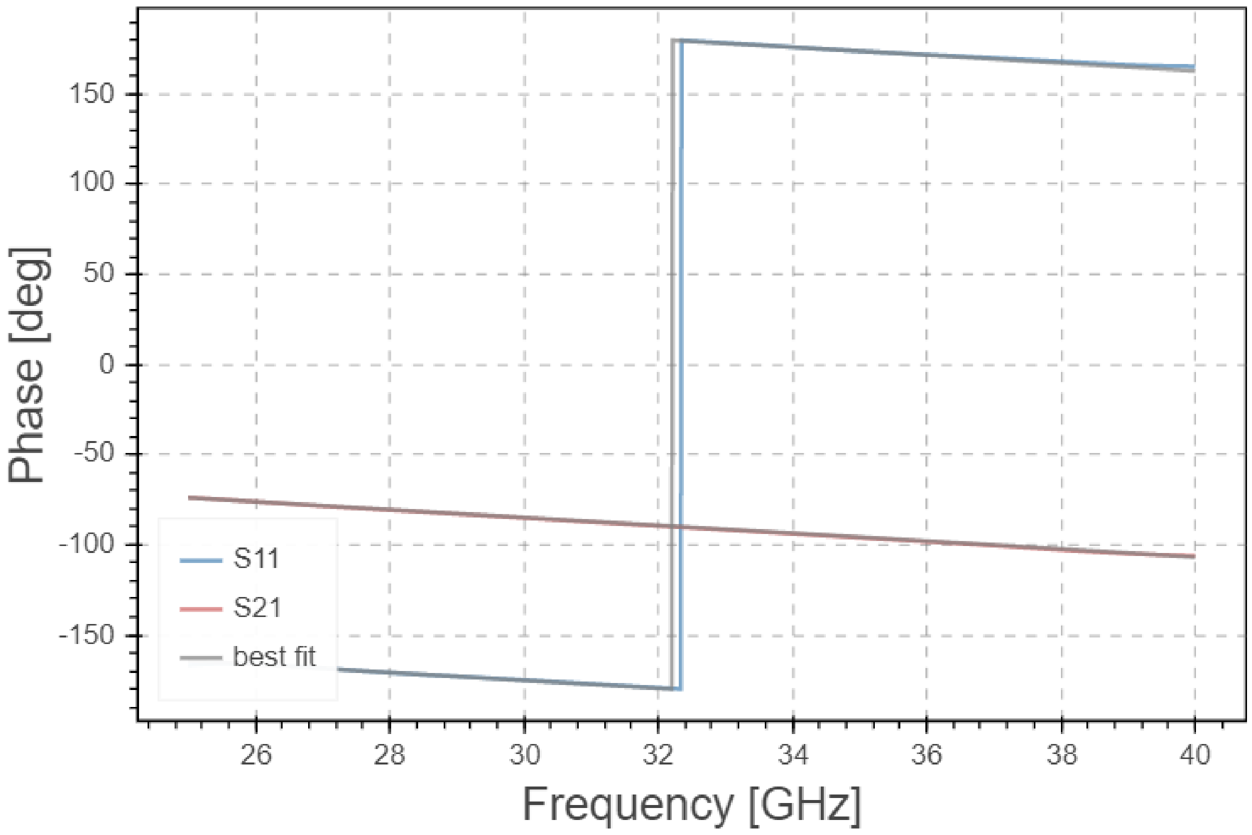
Step 3: Clamp the sample between the two antennas and measure **time-gated S-parameters**

MCK **response calibration** & **time-gating** sufficient for good measurements - **No need** for prior TRL/SOLT waveguide calibration

Measurement Examples (Const. eps)

Boronsilicate Glass (*d* = 1.1 mm) @ **WR28** (25 – 40 GHz)

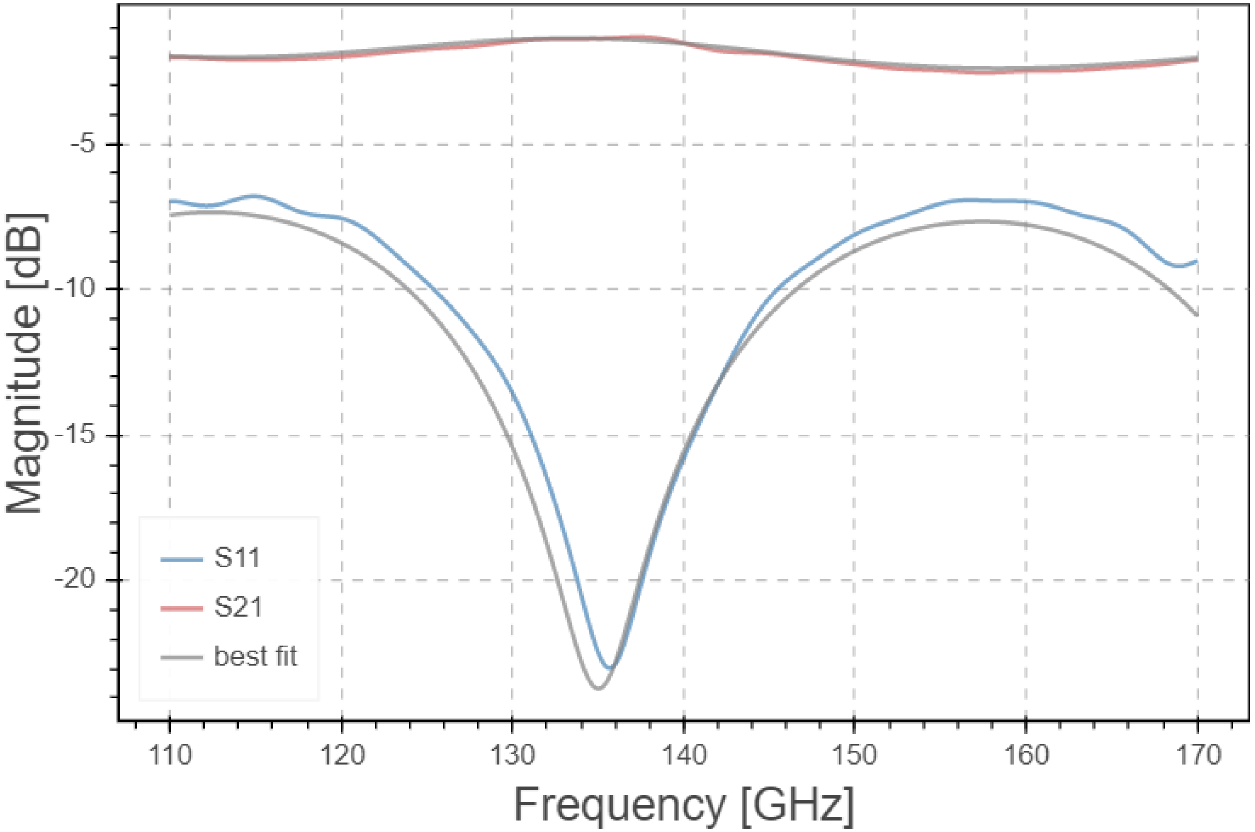


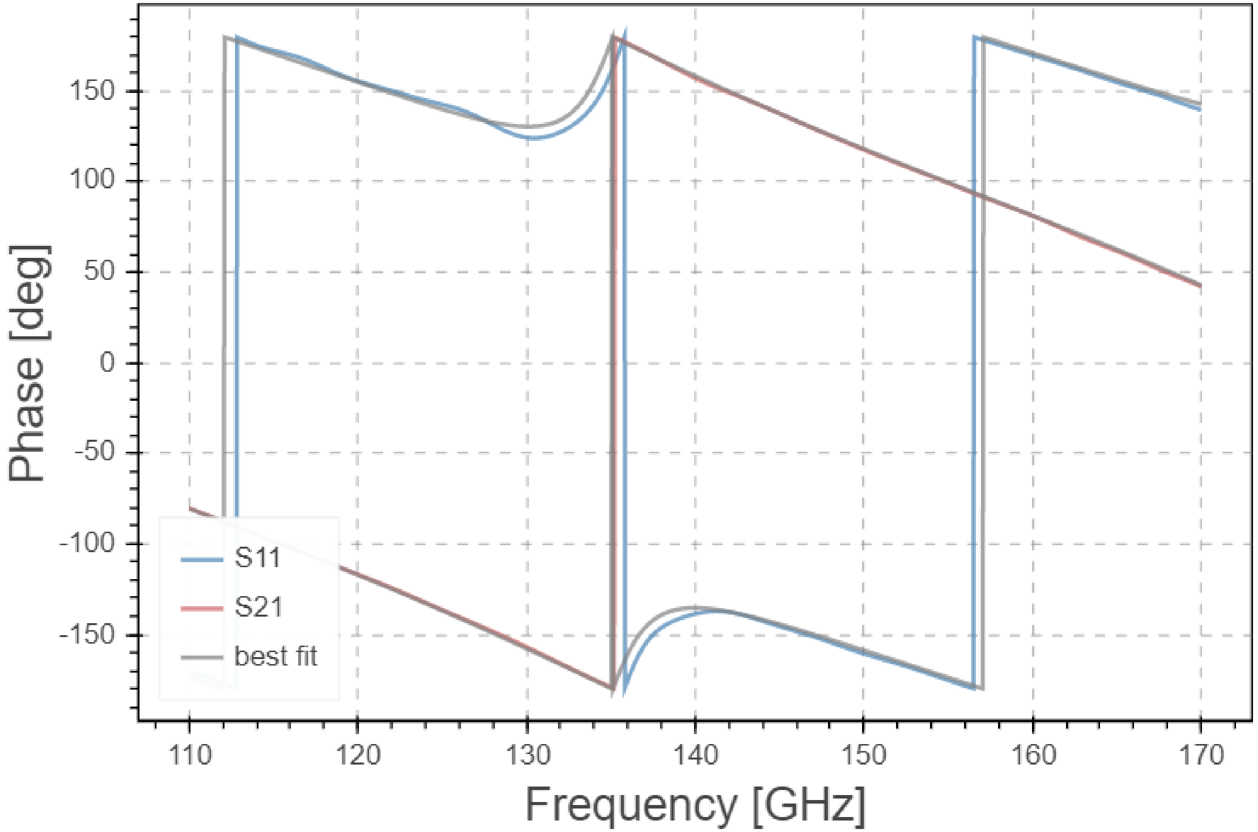


Frequency independent result: ε_r = 4.45, tanδ = 8.27 x 10^{-3}

Measurement Examples (Const. eps)

Polymer Material A (*d* = 2.0 mm) @ **WR6.5** (110 – 170 GHz)

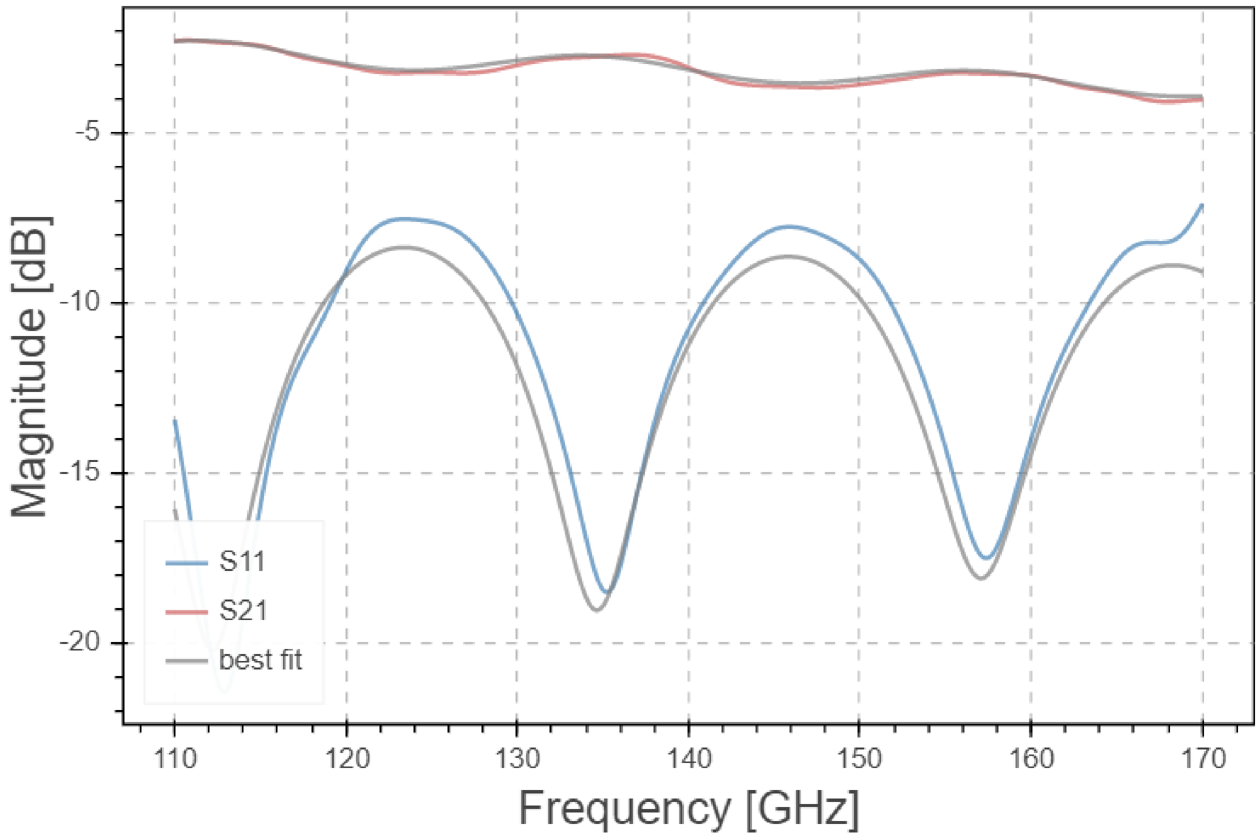


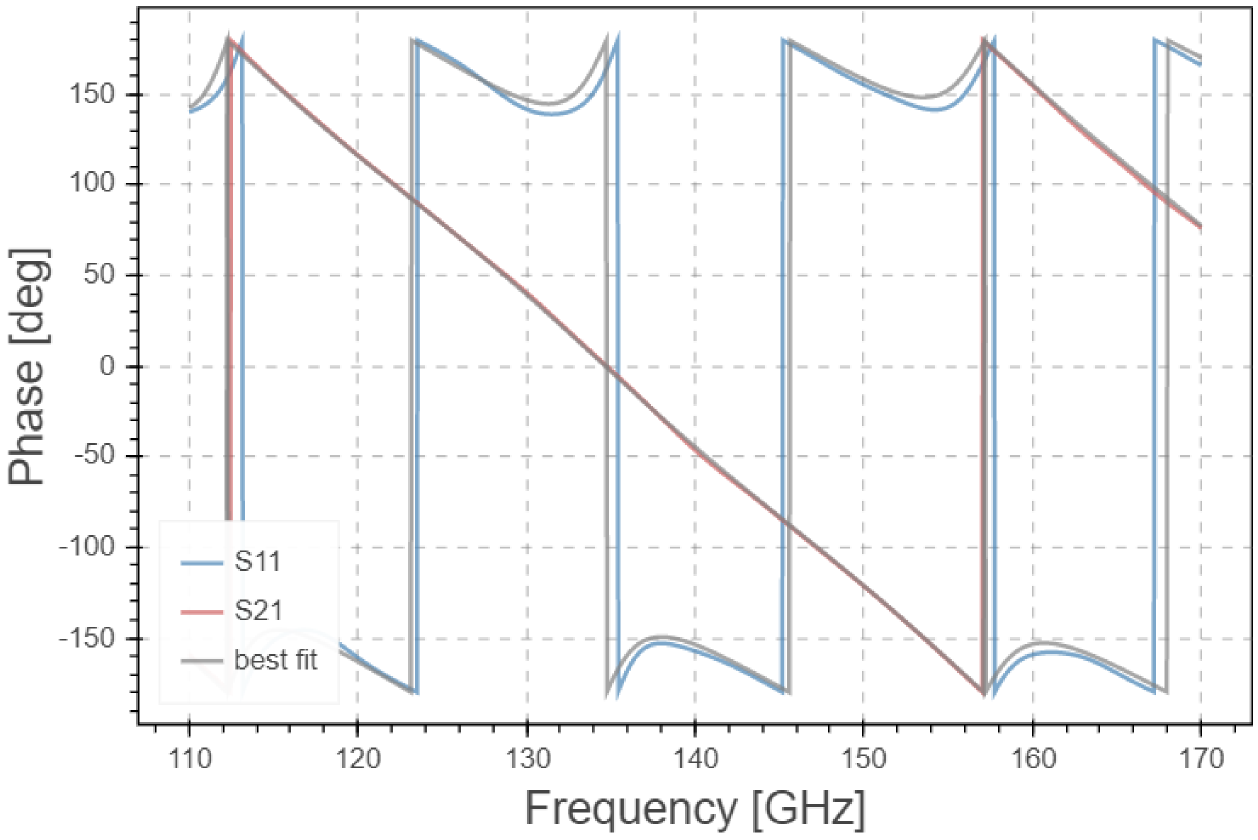


Frequency independent result: $\varepsilon_r = 2.80$, $\tan\delta = 3.01 \times 10^{-2}$

Measurement Examples (Const. eps)

Polymer Material A (d = 4.0 mm) @ **WR6.5** (110 – 170 GHz)

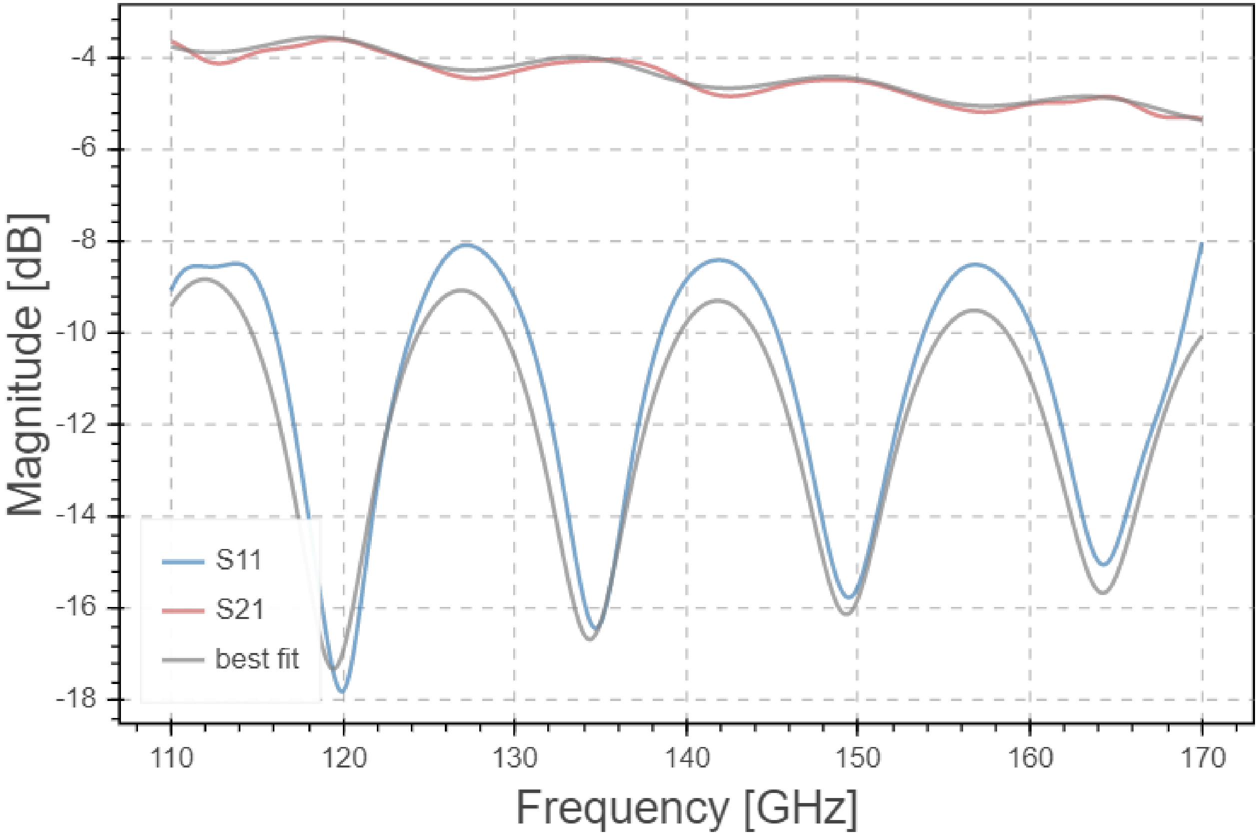


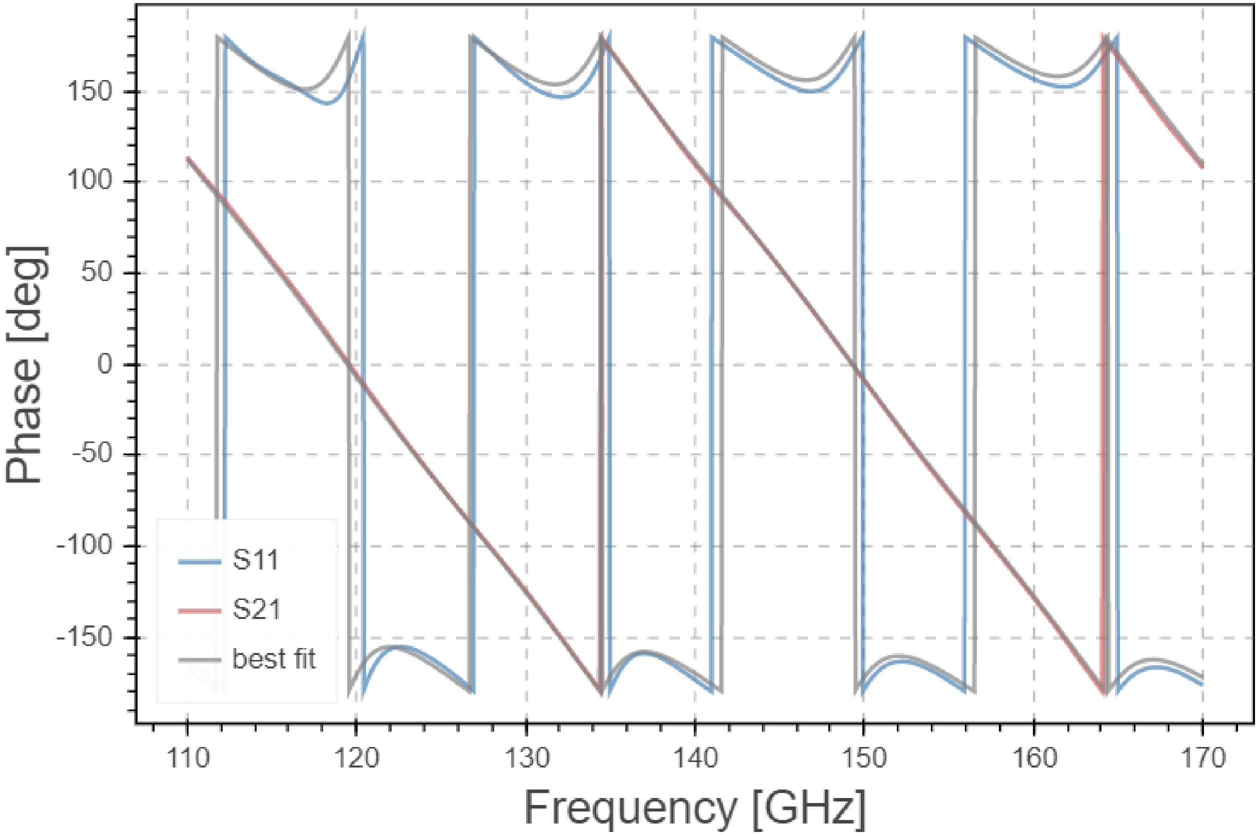


Frequency independent result: ε_r = 2.76, tanδ = 3.02 x 10^{-2}

Measurement Examples (Const. eps)

Polymer Material A (d = 6.0 mm) @ **WR6.5** (110 – 170 GHz)

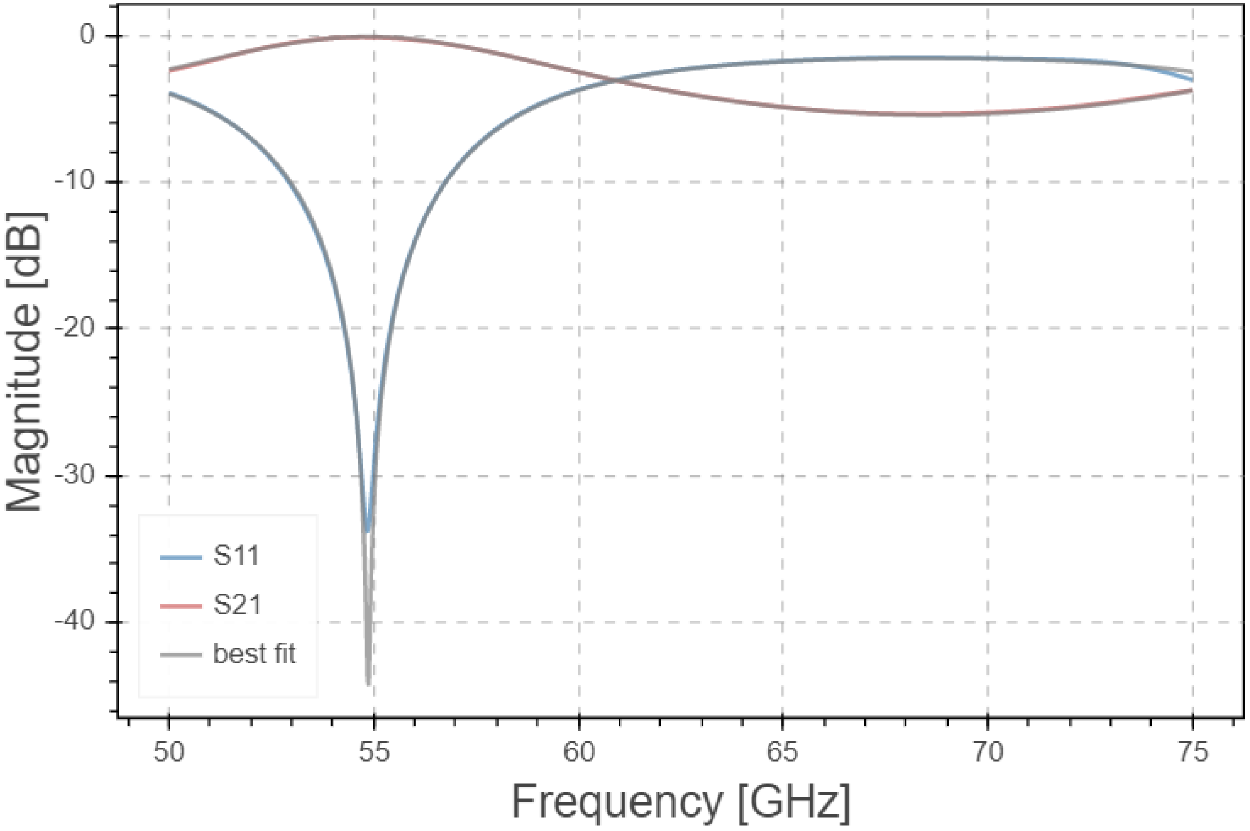


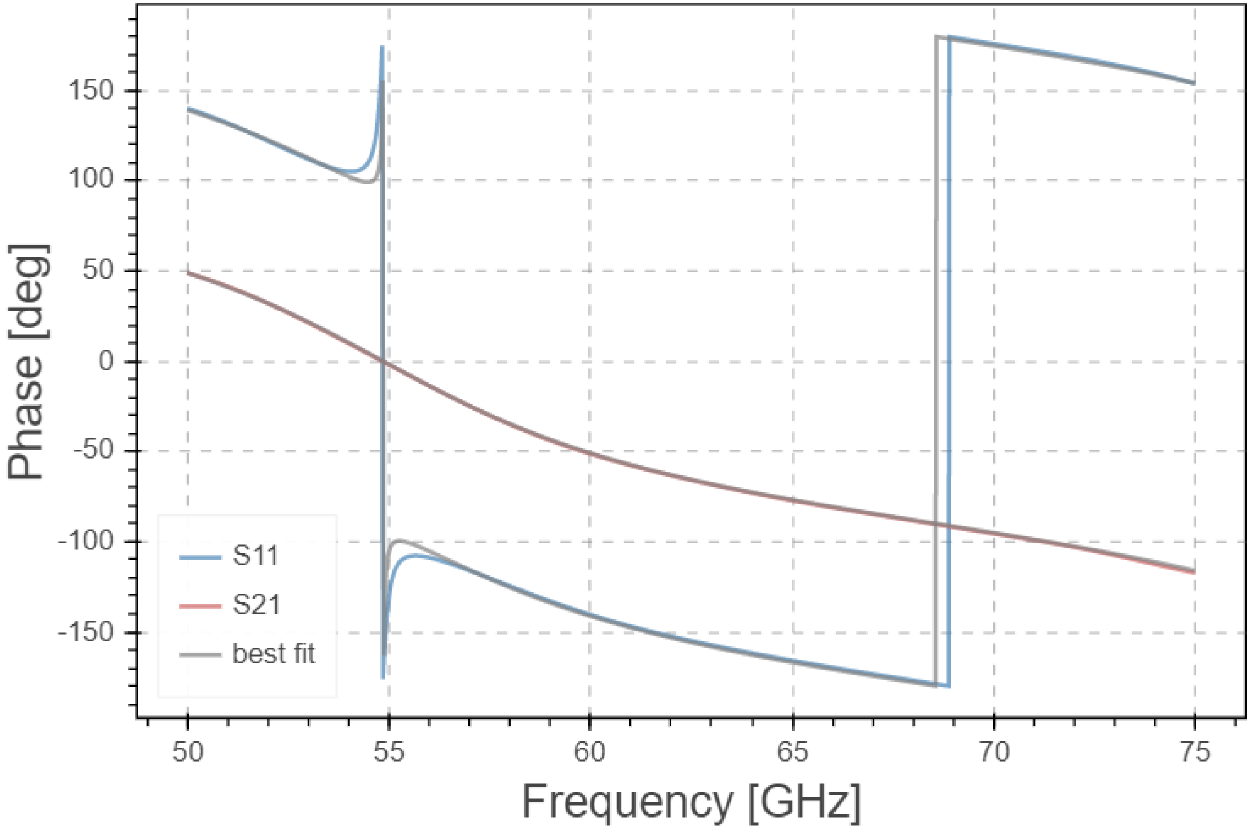


Frequency independent result: ε_r = 2.77, tanδ = 3.00 x 10^{-2}

Measurement Examples (Const. eps)

Prime FZ-Si Wafer (d = 1.6 mm) @ **WR15** (50 – 75 GHz)

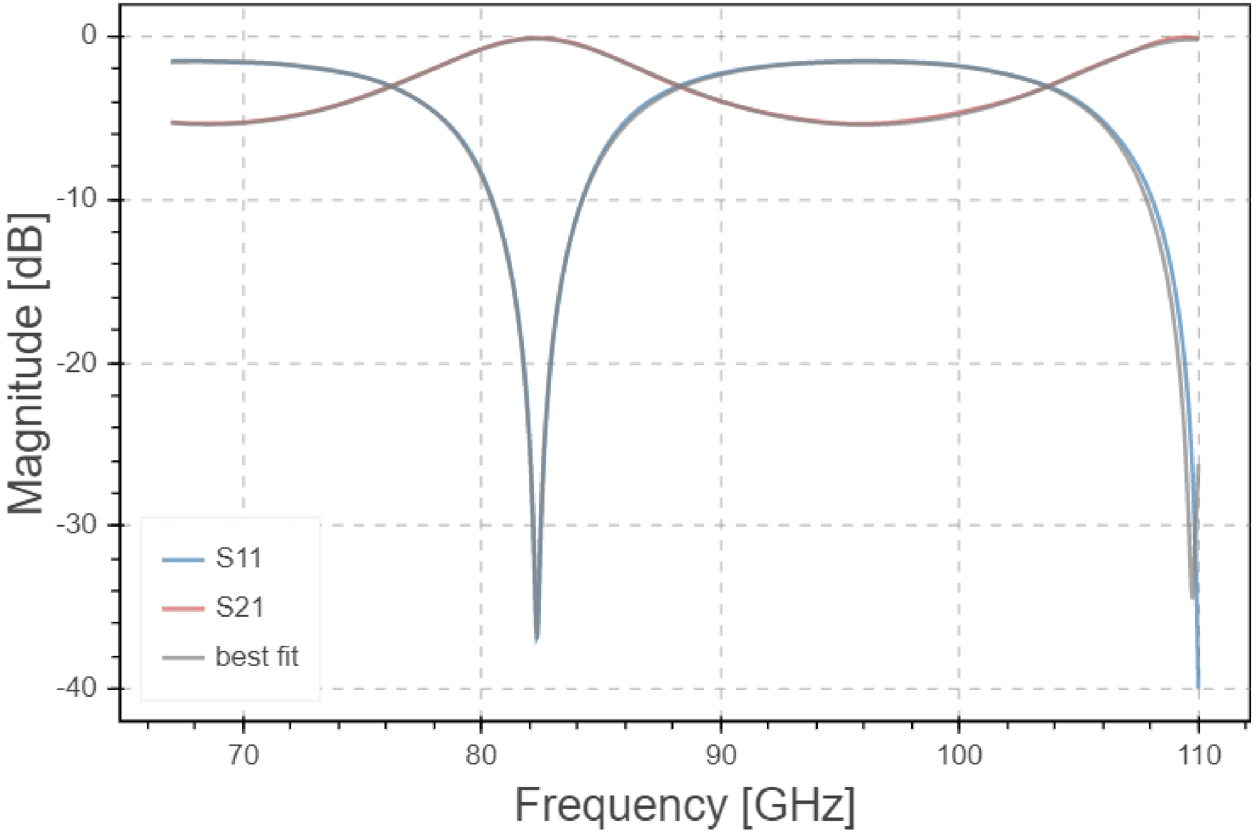


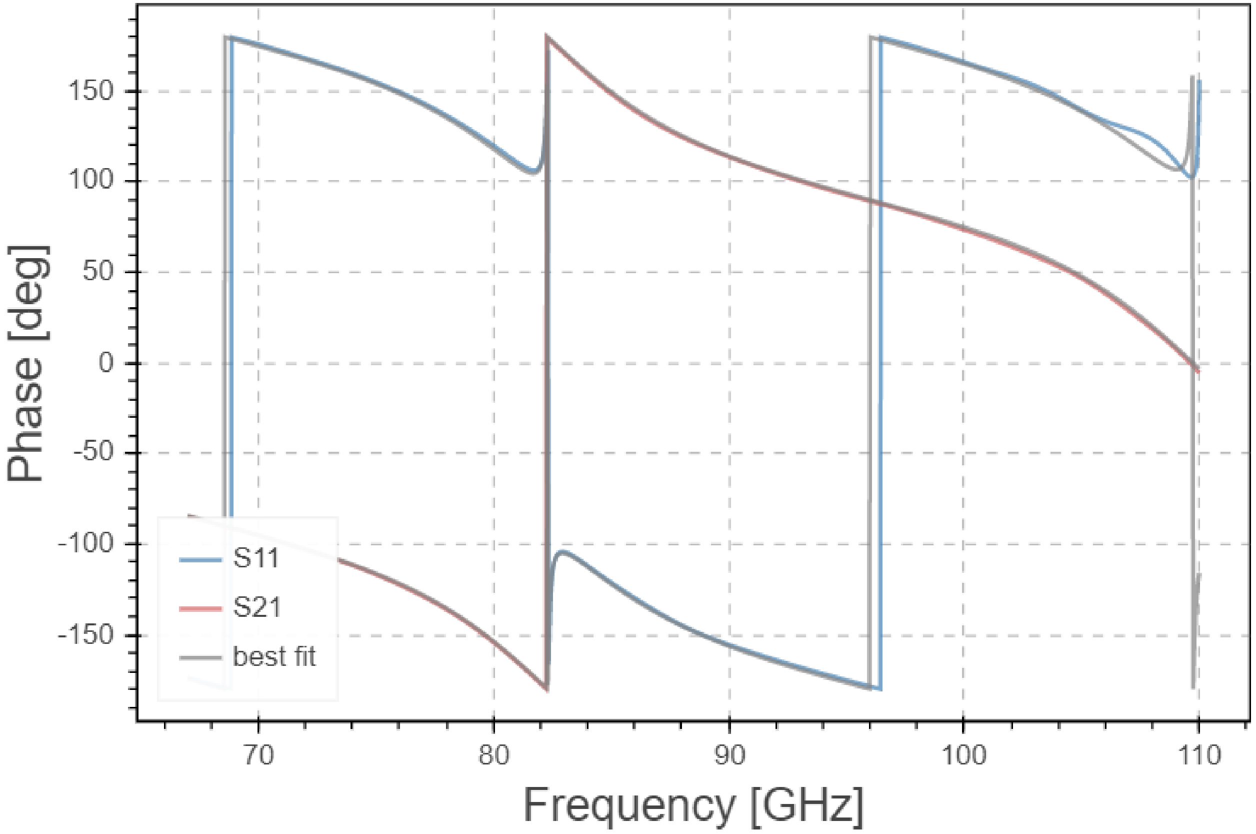


Frequency independent result: ε_r = 11.66, tanδ = 1.19 x 10^{-3}

Measurement Examples (Const. eps)

Prime FZ-Si Wafer (*d* = 1.6 mm) @ **WR10** (67 – 110 GHz)

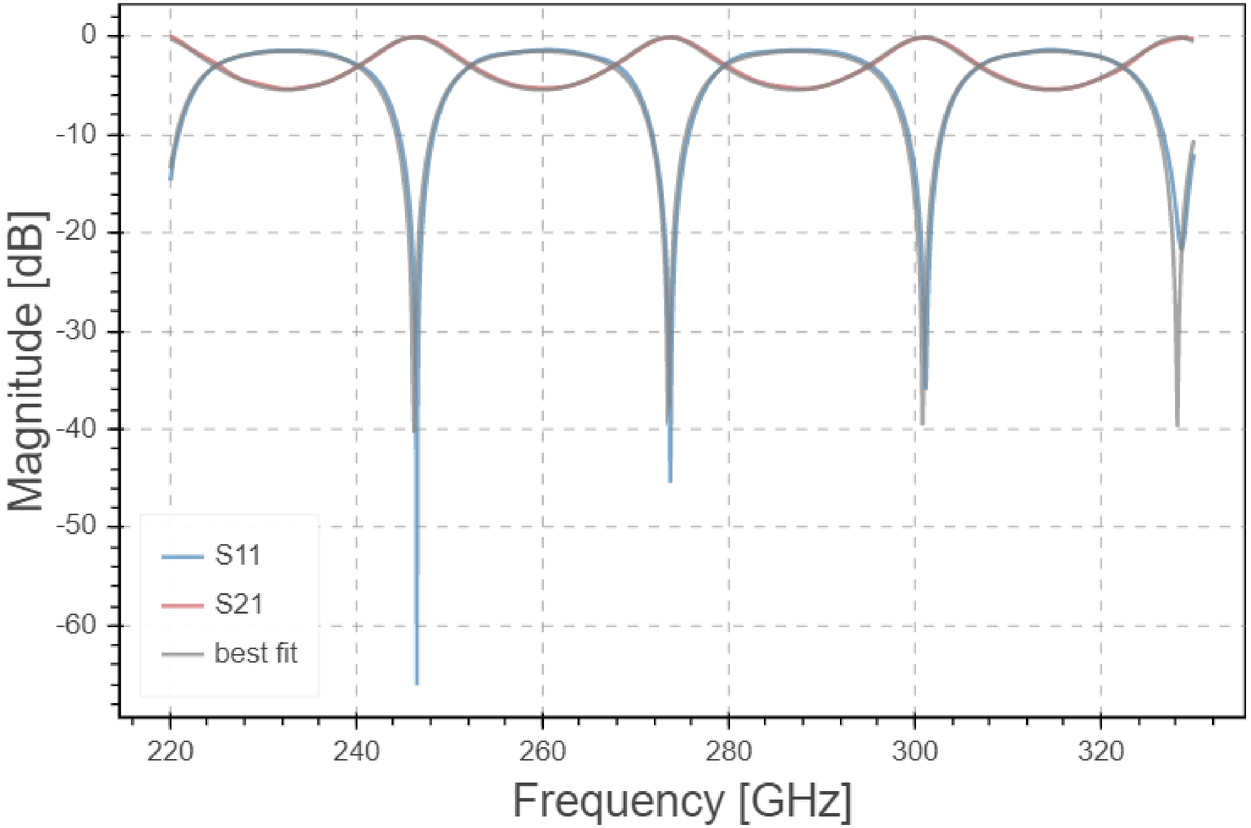


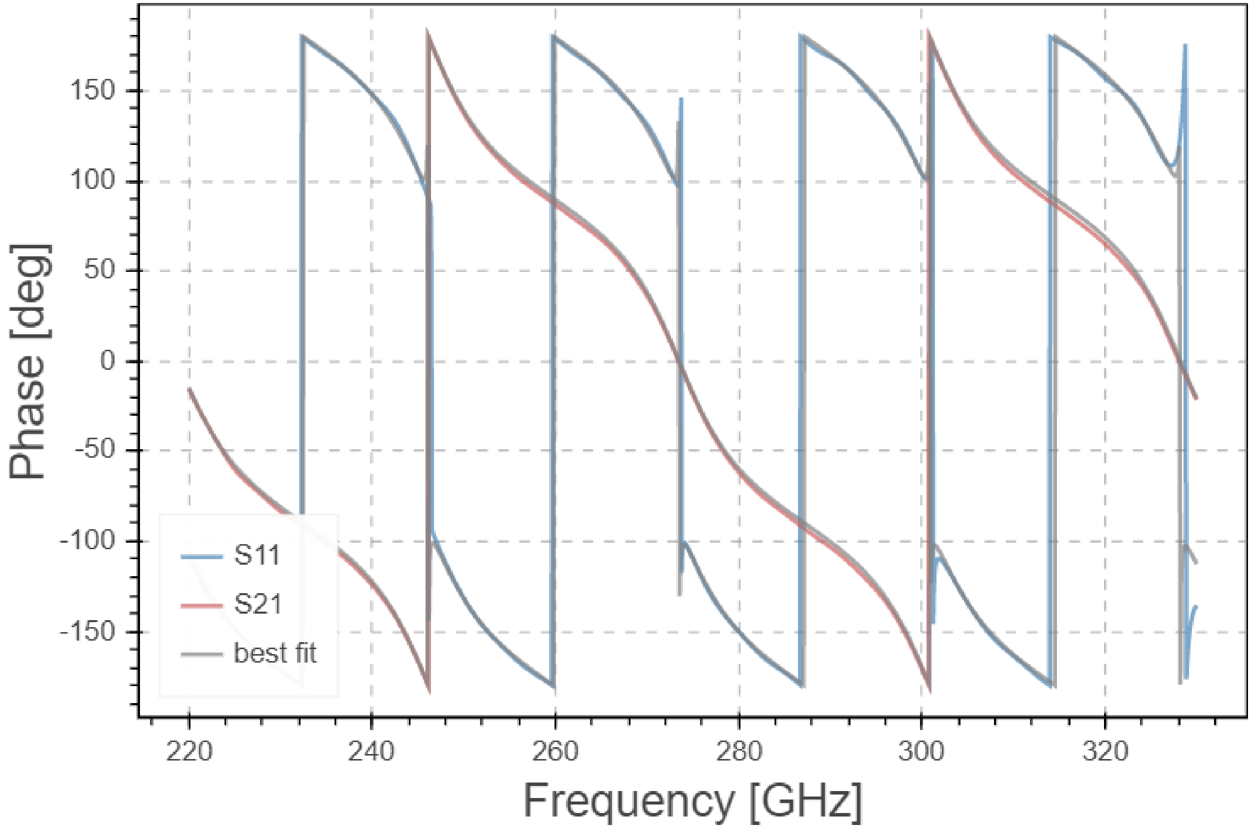


Frequency independent result: ε_r = 11.66, tanδ = 1.97 x 10^{-3}

Measurement Examples (Const. eps)

Prime FZ-Si Wafer (*d* = 1.6 mm) @ **WR3.4** (220 – 330 GHz)

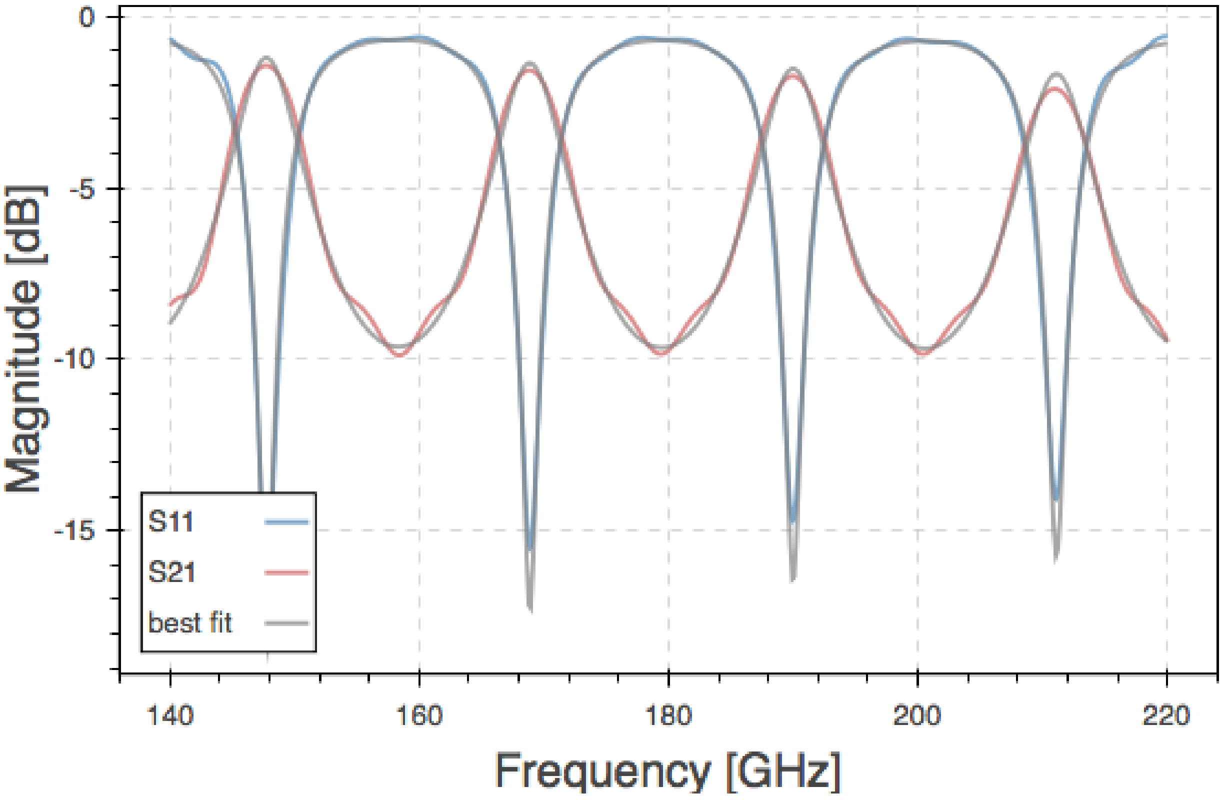


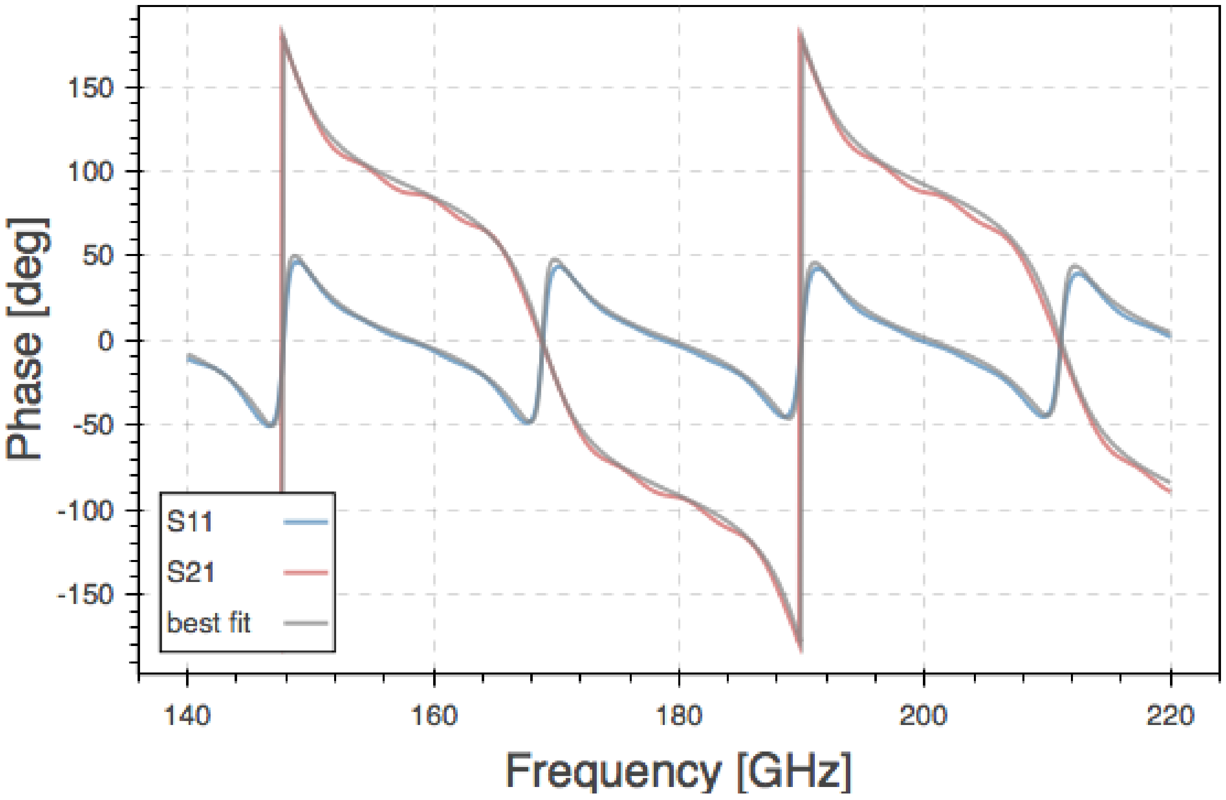


Frequency independent result: $\varepsilon_r = 11.73$, $\tan\delta = 3.52 \times 10^{-3}$

Measurement Examples (Const. eps)

$YZrO_2$ (d = 1.23 mm) @ **WR5.1** (140 – 220 GHz)

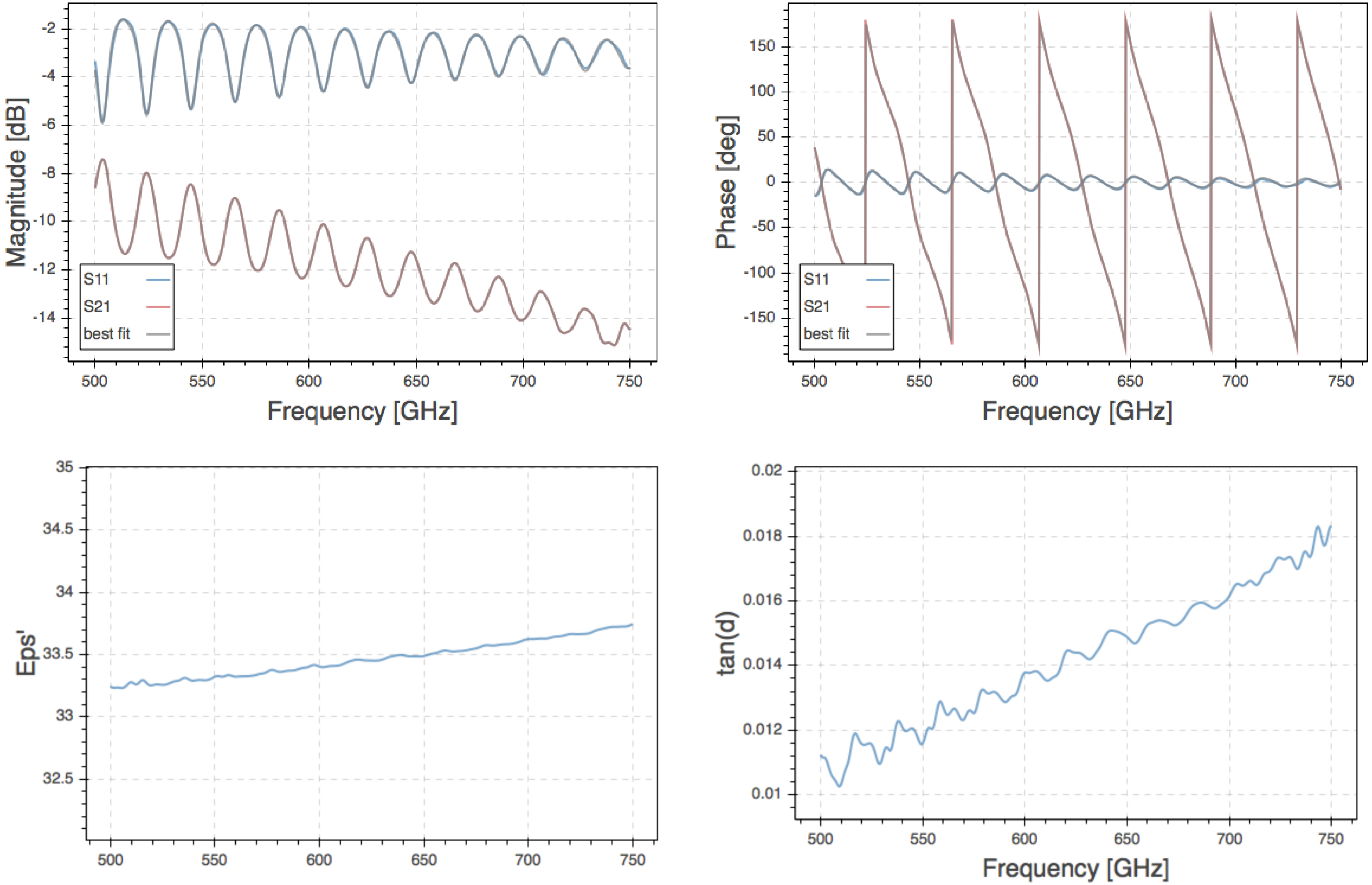




Frequency independent result: ε_r = 33.32, tanδ = 4.49 x 10^{-3}

Measurement Examples (Var. eps)

$YZrO_2$ (d = 1.23 mm) @ **WR1.5** (500 – 750 GHz)



TRL Calibration for the MCK (1/2)

Material Measurements Using VNA-based Material Characterization Kits Subject to Thru-Reflect-Line Calibration

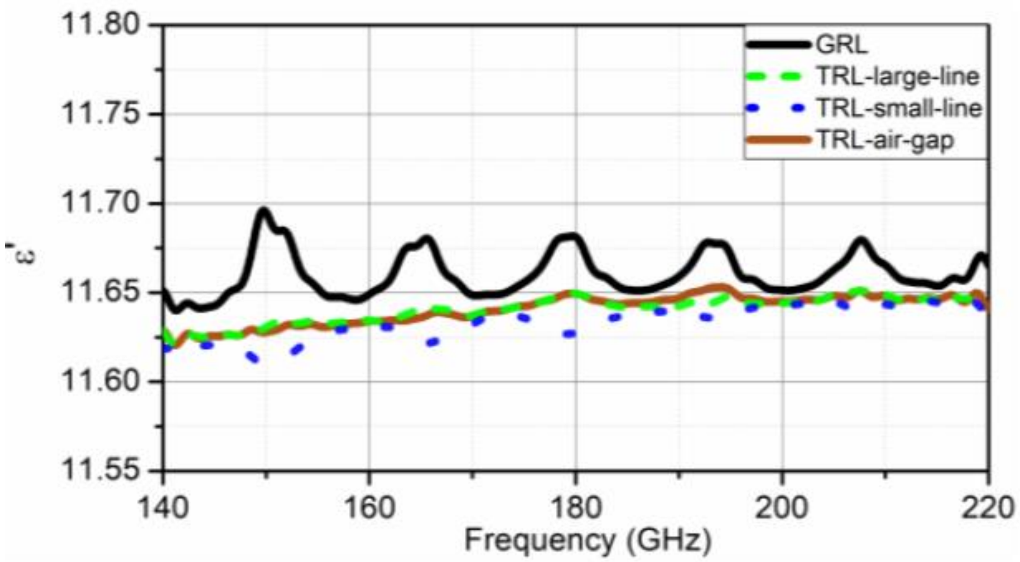
Yi Wang, *Student Member, IEEE*, Xiaobang Shang, *Senior Member, IEEE*, Nick M. Ridler, *Fellow, IEEE*, Mira Naftaly, Alexandros I. Dimitriadis, Tongde Huang, Wen Wu, *Senior Member, IEEE*

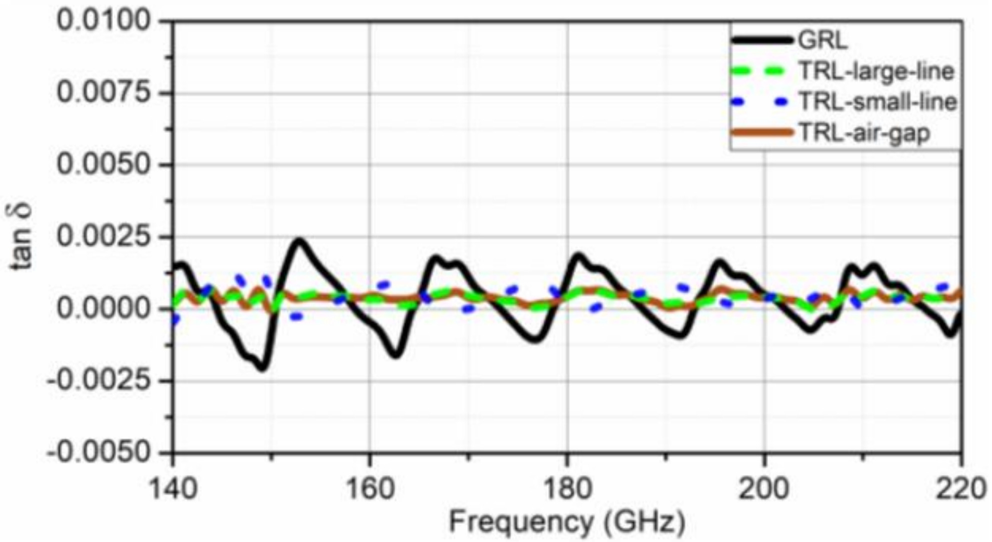
Paper submitted on 27-01-2020 to IEEE Transactions on THz Science and Technology

- Comparison of the default MCK calibration (Gated-Reflect-Line) with 3 different variants of a TRL calibration in WR5.1 band (140-220 GHz)
- An air line and two metallic lines (corresponding to the groove and tooth diameter of the corrugated waveguide) are tested and compared
- TRL calibration seems to offer improved results in some cases, like high-epsilon dielectrics

TRL Calibration for the MCK (2/2)

Fig. 2. Photograph of the machined line standards for the WR-5 band MCK. Both lines have the same thickness of 0.420 mm. The diameters of the inner holes are 9.052 mm and 8.200 mm.





- Comparison of different MCK calibrations for a Silicon sample with a thickness of 3.06 mm
- Oscillations of the dielectric properties versus frequency due to standing waves
- Results smoothened with TRL calibration

Upgrade Kits for the MCK

WR3.4 MCK and sample holder for liquids and powders

Introduced commercially in 2019:

1) Upgrade kit for soft samples and foams
2) Upgrade kit for liquid samples and powders
3) Upgrade kit for coatings and multilayers

All the upgrade kits are accompanied by an upgraded version of the webMCK software for S-parameter de-embedding

S-parameter De-embedding

Analytical procedure based on the transformation of S-matrix to T-matrix:

$$(S) = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \rightarrow (T) = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix}$$

where $T_{11} = \frac{-\det(S)}{S_{21}}$, $T_{12} = \frac{S_{11}}{S_{21}}$, $T_{21} = \frac{-S_{22}}{S_{21}}$, $T_{22} = \frac{1}{S_{21}}$, and $\det(S) = S_{11}S_{22} - S_{12}S_{21}$

Stack of materials by multiplying their corresponding T-matrices:

$$(T) = (T_1)(T_2)$$

If (T_1) is measured independently (separate sample), (T_2) equals:

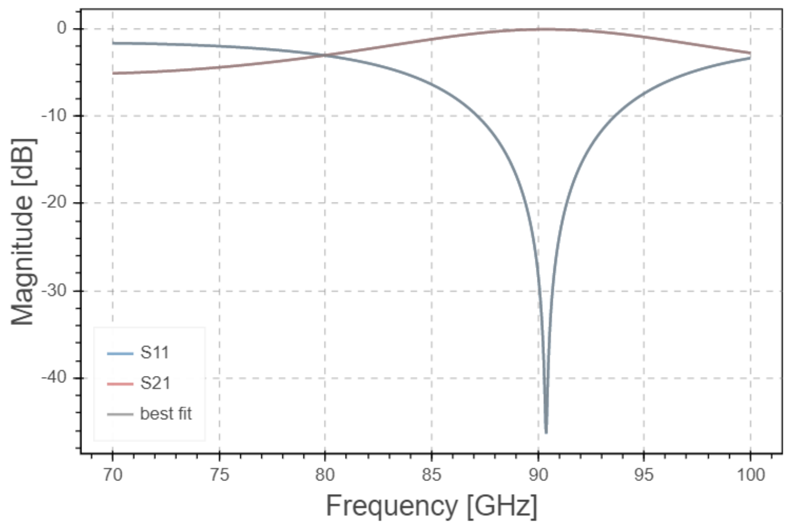
$$(T_2) = (T_1)^{-1}(T)$$

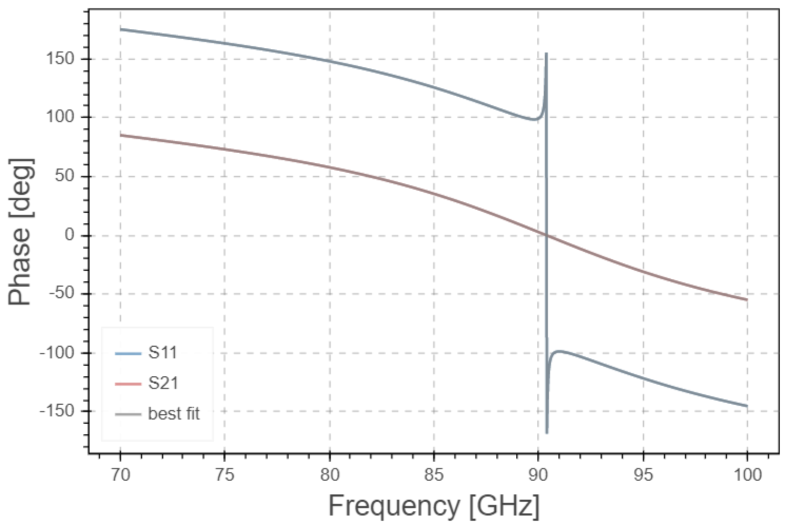
Finally, S-parameters for fitting obtained via the inverse transformation:

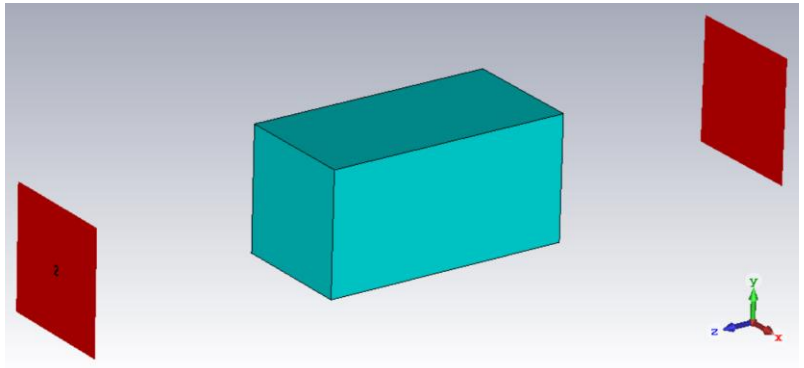
$$(T) = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \rightarrow (S) = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix}$$

where $S_{11} = \frac{T_{12}}{T_{22}}$, $S_{12} = \frac{\det(T)}{T_{22}}$, $S_{21} = \frac{1}{T_{22}}$, $S_{22} = \frac{-T_{21}}{T_{22}}$, and $\det(T) = T_{11}T_{22} - T_{12}T_{21}$

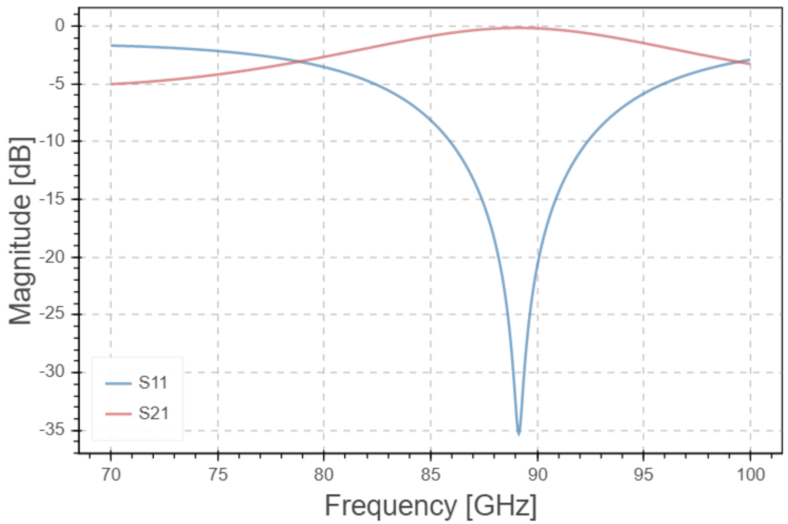
Example for Two-Layered Material (1/2)

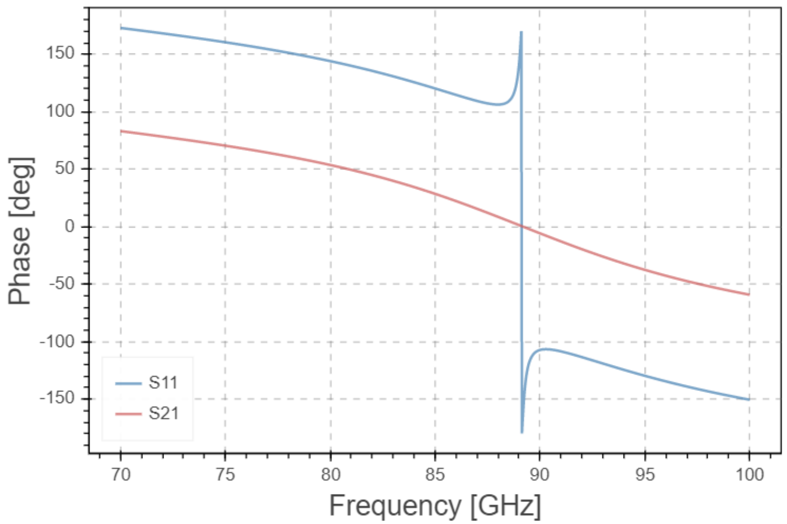


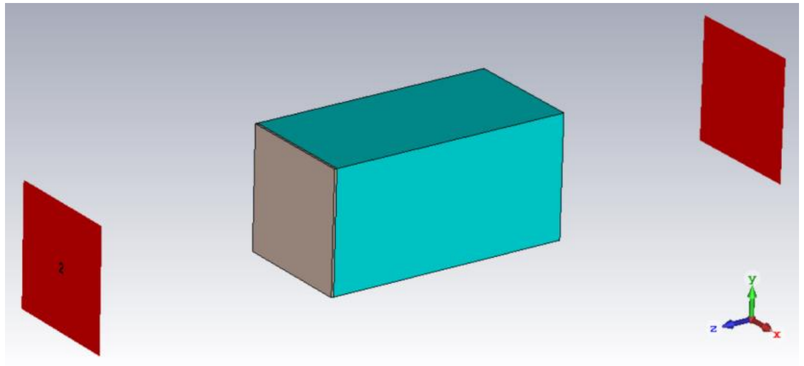




S- parameters of silicon substrate with ε' = 11.0, tanδ = 0.001, and d = 1.0 mm

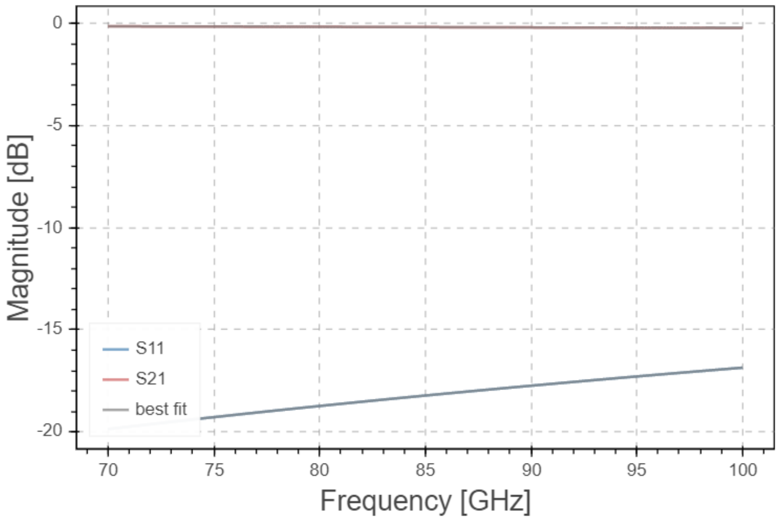


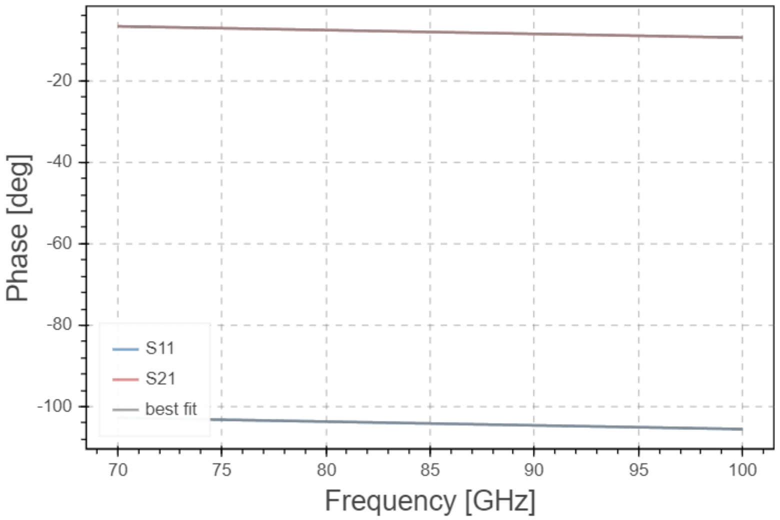


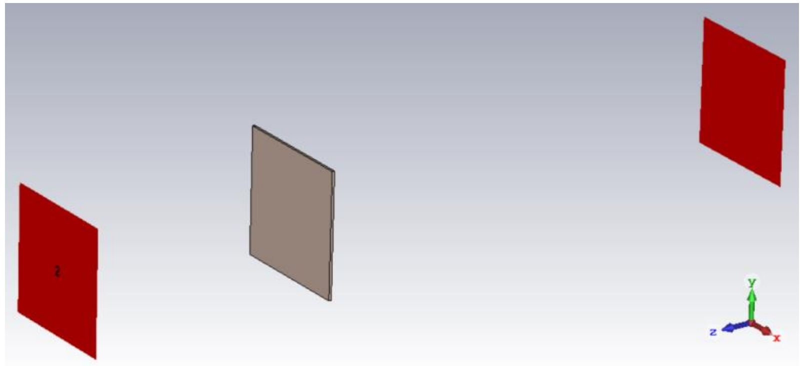


S- parameters of silicon substrate with ε' = 11.0, tanδ = 0.001, and d = 1.0 mm plus a coating layer with ε' = 15, tanδ = 0.1, and d = 10 µm

Example for Two-Layered Material (2/2)







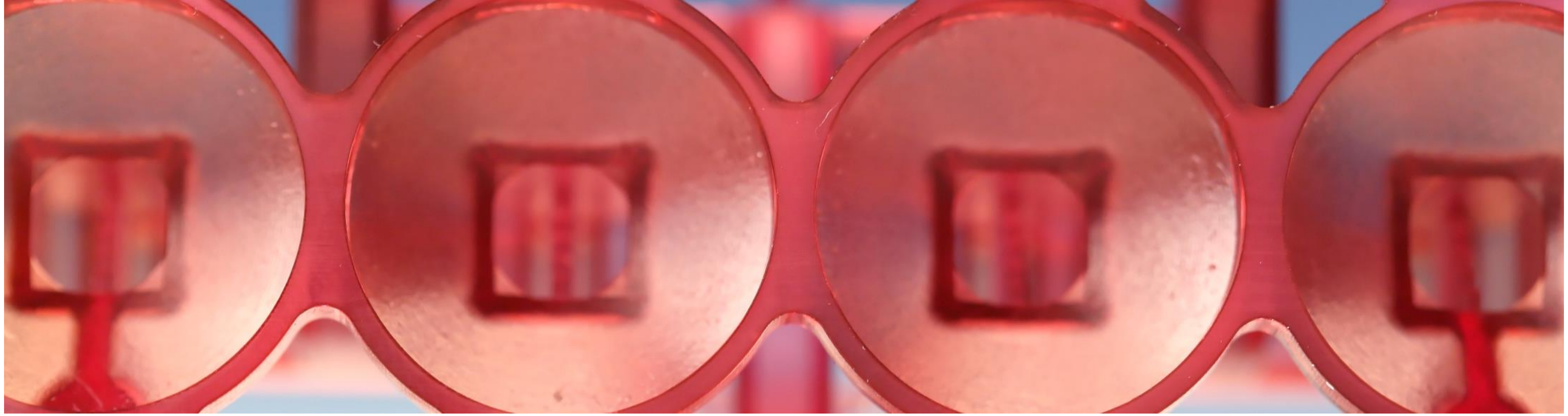
S-parameters of a coating layer with ε' = 15, tanδ = 0.1, and d = 10 µm

- De-embedded S- parameters of the coating layer provide a perfect fit with simulations for ε' = 15, tanδ = 0.1
- Similar de-embedding procedure is followed for the other upgrade kits (based on teflon sample holders)

Conclusions and Future Developments

- Fast, compact, easy-to-use, and robust instrument for dielectric measurements
- Frequency range from 25 GHz to 1.1 THz (multiple models available)
- Possibility to extend to non-solid materials and special applications with upgrade kits
- Limitation for very low-loss materials ($\tan\delta < 5e\text{-}4$) intrinsic to non-resonant approach

- Implementation of suitable algorithm for calculation of magnetic permeability
- Characterization of thin conductive films (under the TRANSPIRE project)
- Product improvements in the coming months (reference sample for easy validation, dynamometric key and hexagonal screw for better measurement repeatability etc.)
- Improved and unified software support for all the main VNAs



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