A Specialized Overlay for Advanced Full-Wave Electromagnetic Simulations within 3D CAD Environment

- Linking popular Computer-Aided Design (CAD) and full-wave electromagnetic (EM) simulations (here, with our in-house conformal Finite-Difference Time-Domain method).

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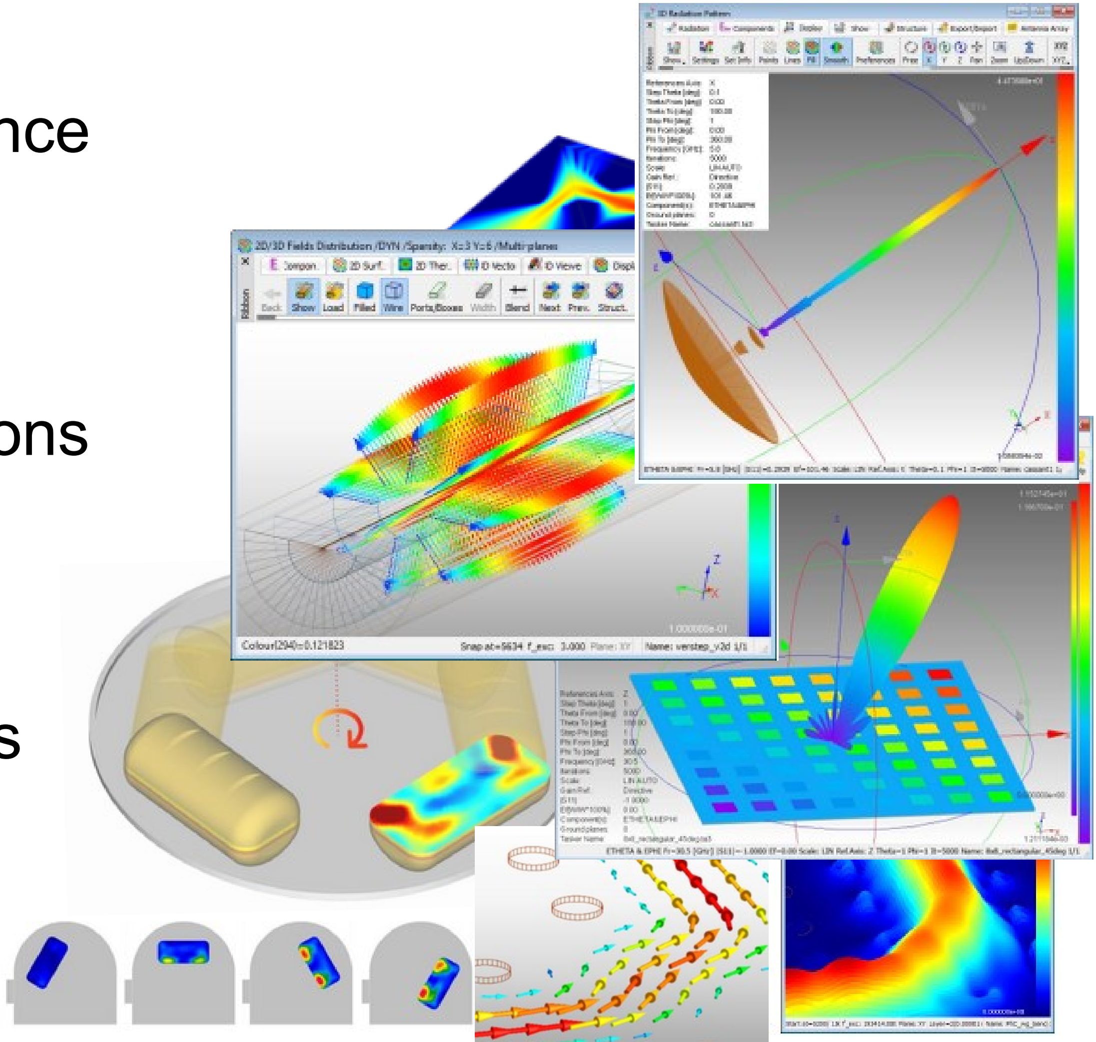
Outline

1. Introduction
2. 3D CAD for Full-Wave EM Overlay Features
3. Microstrip Line Modelling and Simulation (example of using an overlay).
4. Results – Insertion Loss versus frequency, resonators (digital twinning with overlay).
5. Conclusions

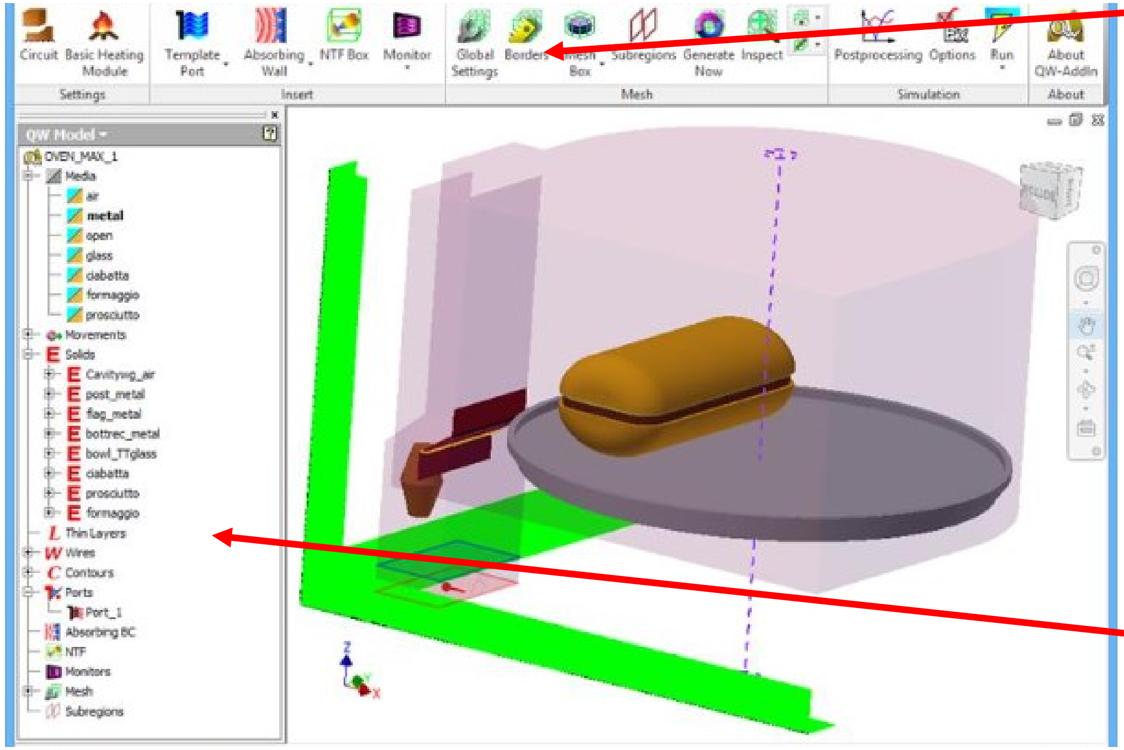
Introduction

- **Context:** The integration of CAD tools with advanced electromagnetic (EM) simulation methods is critical for designing high-performance electronic systems.
- **Solution:** Our work introduces a novel module that integrates CAD with full-wave EM simulations using an in-house conformal FDTD method.
- **Innovation:** Combines the FEA with the computational FDTD for analyzing large circuits across broad frequency ranges.

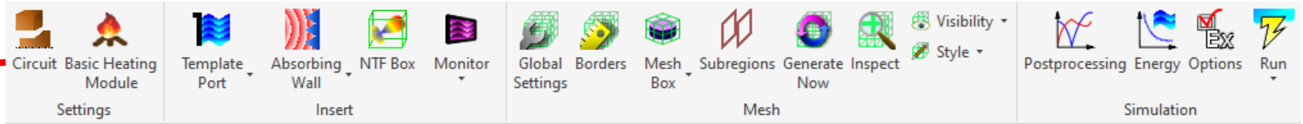
Examples of overlay use:



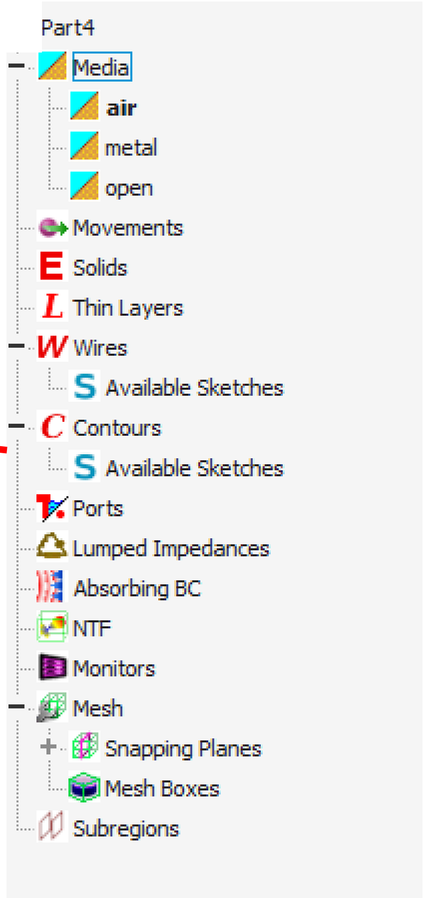
3D CAD for Full-Wave EM Overlay - Construction



Complete project using 3D CAD Overlay



Default view of 3D CAD Overlay ribbon



Default view of 3D CAD Overlay model tree

3D CAD Overlay – Work scheme

Prepare input data for simulation

Based on input data simulator extract results

3D CAD Overlay

- Integration with 3D CAD
- Handles periodic and axisymmetric (V2D) structures
- Simplifies material definitions, boundary conditions, ports, post-processing parameters, and excitation profiles.
- Parameter Management
- Automatic Meshing Generation Option based on cells per wavelength
- Adaptive Time Step Management
- Mesh-Snapping Planes
- Priority-Based Snapping Planes
- Grid Search Regime

General-purpose electromagnetic simulator based on the conformal FDTD method

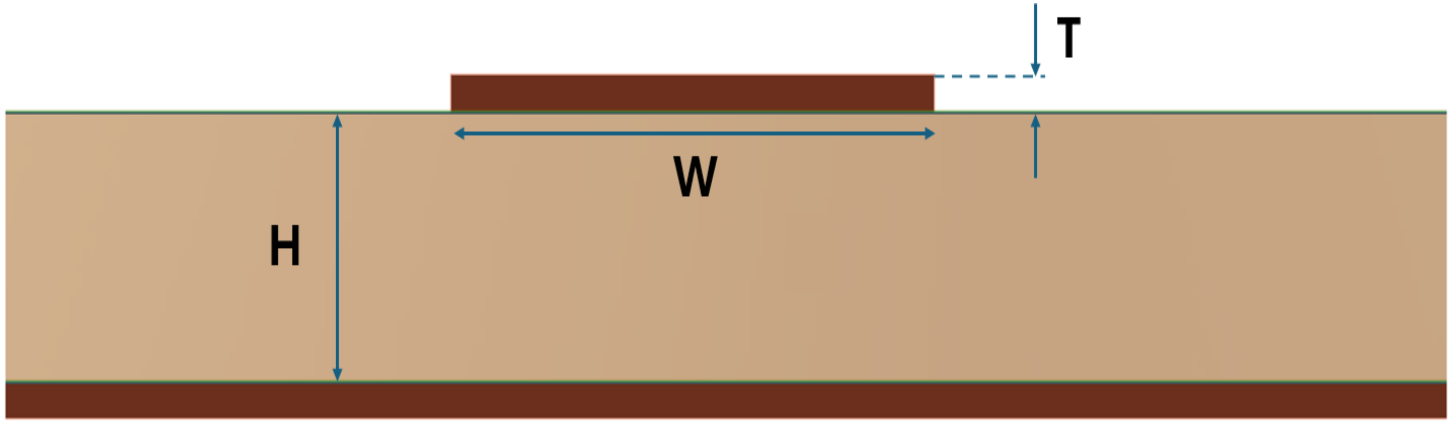
Features:

- Full 3D EM solver
- Vector 2D (BOR), solver applicable to the analysis of axisymmetrical devices.
- Heat Module, heating analysis including loads rotation and translation, frequency tuning, heat flow and material parameters modification.
- Module for high Q-factor structures analysis.
- Optimiser - Module which allows to finding an optimal solution in an automatic way.
- Multiprocessor/ multicore and MultiGPU

Results among others;

- Electric potential,
- Charges, Currents,
- Temperature, Enthalpy,
- Effective media parameters,
- Power dissipation,
- Electric fields, Magnetic fields.

Microstrip line modeling in 3D CAD Overlay



Microstrip design parameters of the model created in 3D CAD using also our overlay

Microstrip TL Test Setup Dimensions Based on iNEMI work

Geometry	Design Value
Trace Width (W1)	0.0115 in
Copper Weight (T1)	½ oz + Plating
Substrate thickness (H)	0.005 in
Panel Size	18 in x 24 in
Dk/Df	3.33/0.0018

Prepared model in Overlay based on Microstrip Test Setup

Microstrip Parameters:

- Trace Width (W): 0.0115 inches
- Substrate Thickness (H): 0.005 inches
- Copper Weight (T): ½ oz

Panel Specifications:

- Construction: 2116 56% RC

Substrate Properties:

- Dielectric Constant (Dk): 3.33
- Dissipation Factor (Df): 0.0018

Simulation Model Adjustments:

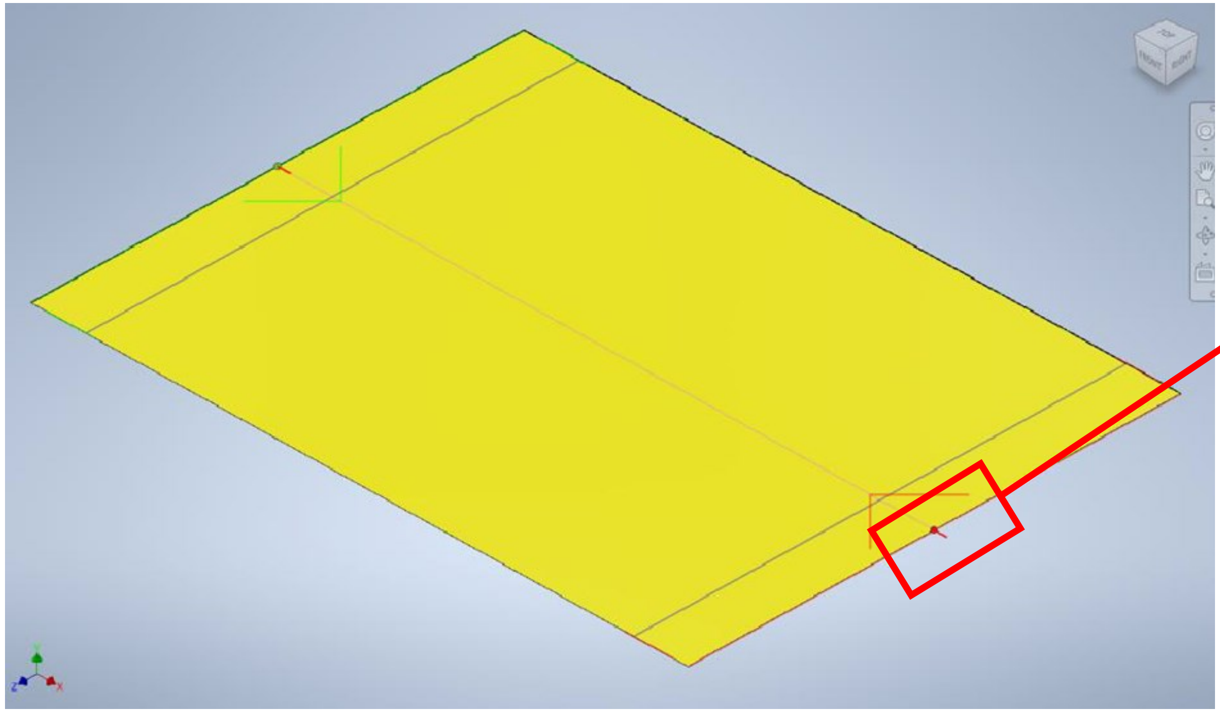
- Modified Panel Size: **3-inch by 4-inch** (to reduce cell density and shorten simulation time) -> No effect on results, significant time reduction in EM simulations

3D CAD Design:

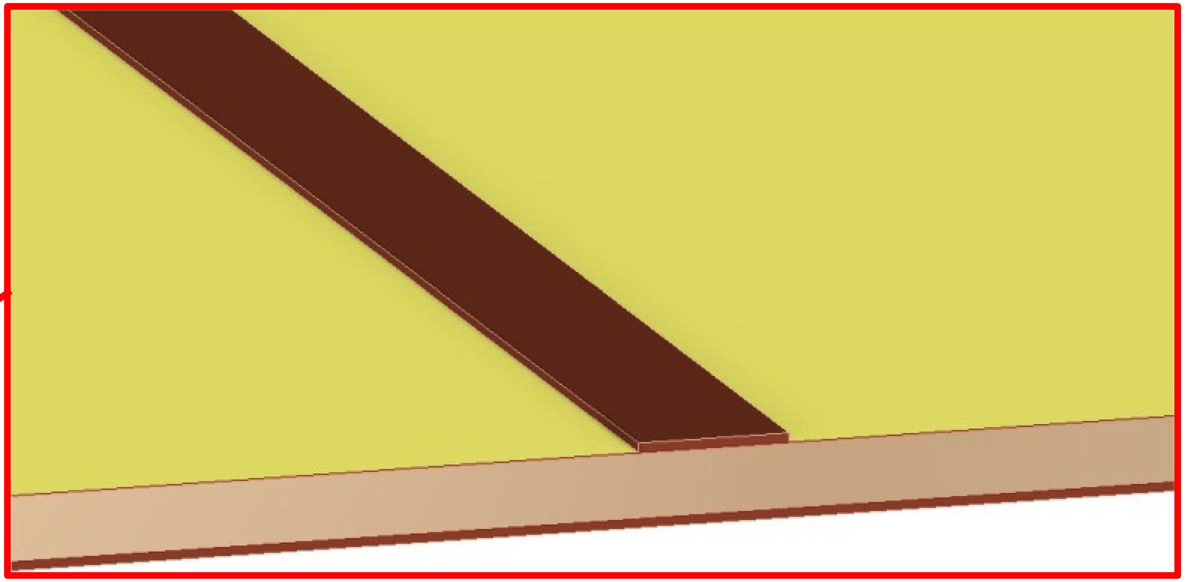
- Airbox Height: 0.02 inches above microstrip
- Metal Box Enclosure: Bottom metallization of the microstrip forms one wall

Excitation: Transverse Electromagnetic (TEM) field across a frequency range of **0 to 50 GHz**

Microstrip line model in 3D CAD Overlay



Microstip Line with shown source and load with reference planes.

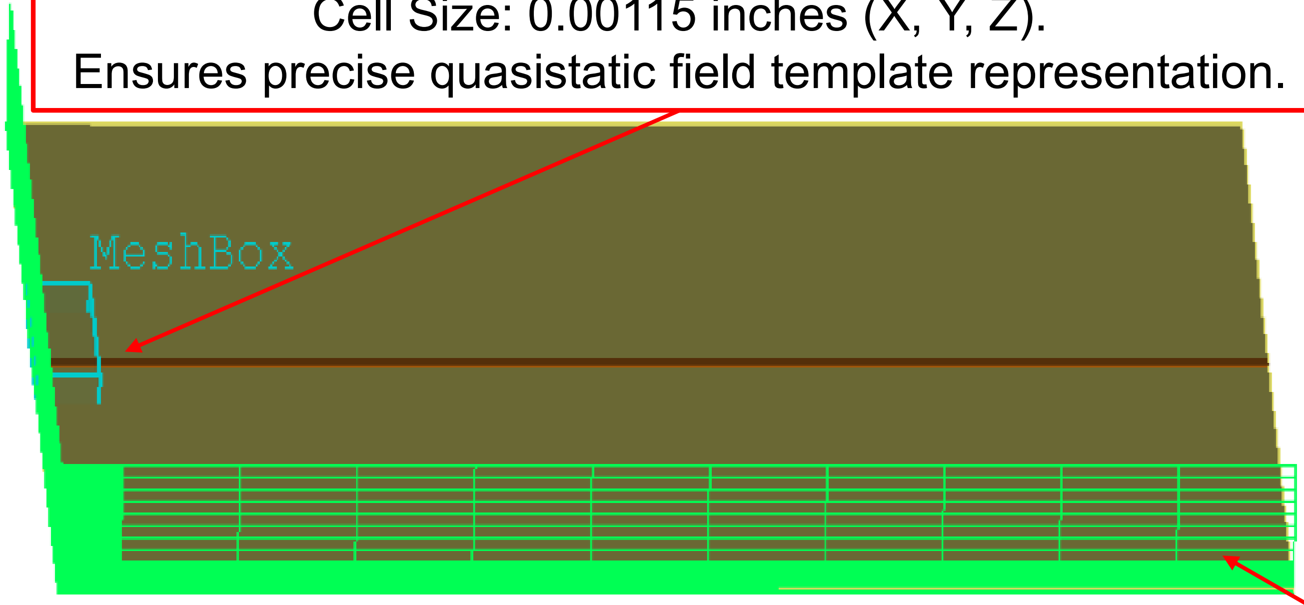


Zoom on metallization in 3D model made in our overlay

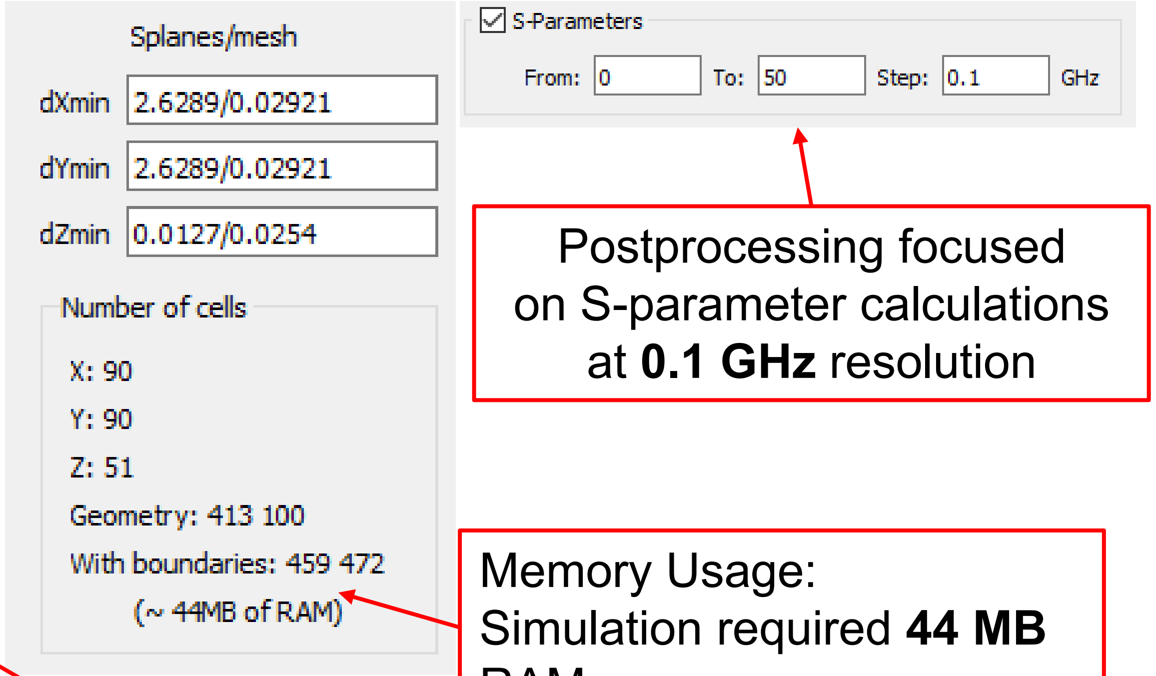
- Microstrip technology is a widely adopted method for **characterizing copper foil conductivity** in PCBs.
- Offers a practical, reliable, and cost-effective solution for signal integrity analysis, but it take a lot of time.
  - Reduced fabrication turnaround time.
  - Simplified testing process.
- Substrate Material **->** Extremely **low-loss, halogen-free** material used for consistency.

Microstrip line meshing in 3D CAD Overlay

High-Density **Mesh Box** (Excitation Point):
Cell Size: 0.00115 inches (X, Y, Z).
Ensures precise quasistatic field template representation.



Distribution of cells on prepared microstrip line model.



Postprocessing focused on S-parameter calculations at **0.1 GHz** resolution

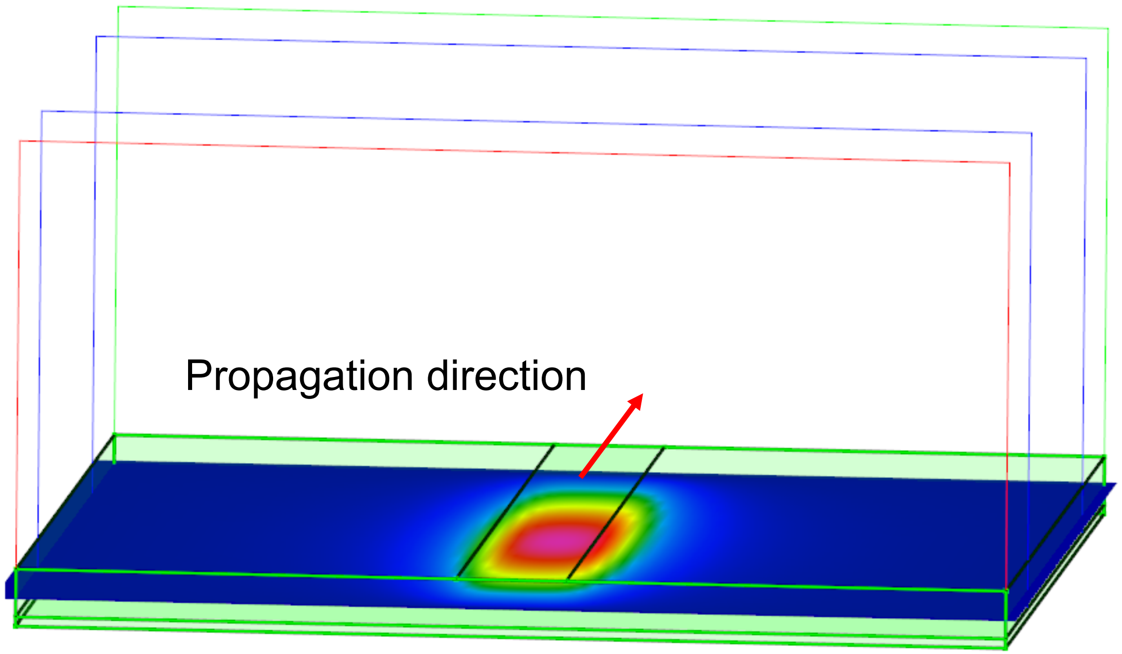
Memory Usage:
Simulation required **44 MB** RAM.

Outside Mesh Box: Cell Size: 0.1 inches (X), 0.01 inches (Y, Z).
Optimized for computational efficiency.

This approach enabled accurate copper foil conductivity characterization and demonstrated the effectiveness of microstrip-based designs for high-performance, low-loss PCBs in DOE applications.

Microstrip line – EM Theory (Simulations)

A microstrip line consists of a conducting strip above a grounded dielectric substrate. The propagation of electromagnetic waves in microstrip lines involves both the conductor and the dielectric substrate. At high frequencies, such as 35 GHz, the fields are tightly confined near the microstrip line and predominantly propagate through the dielectric substrate.

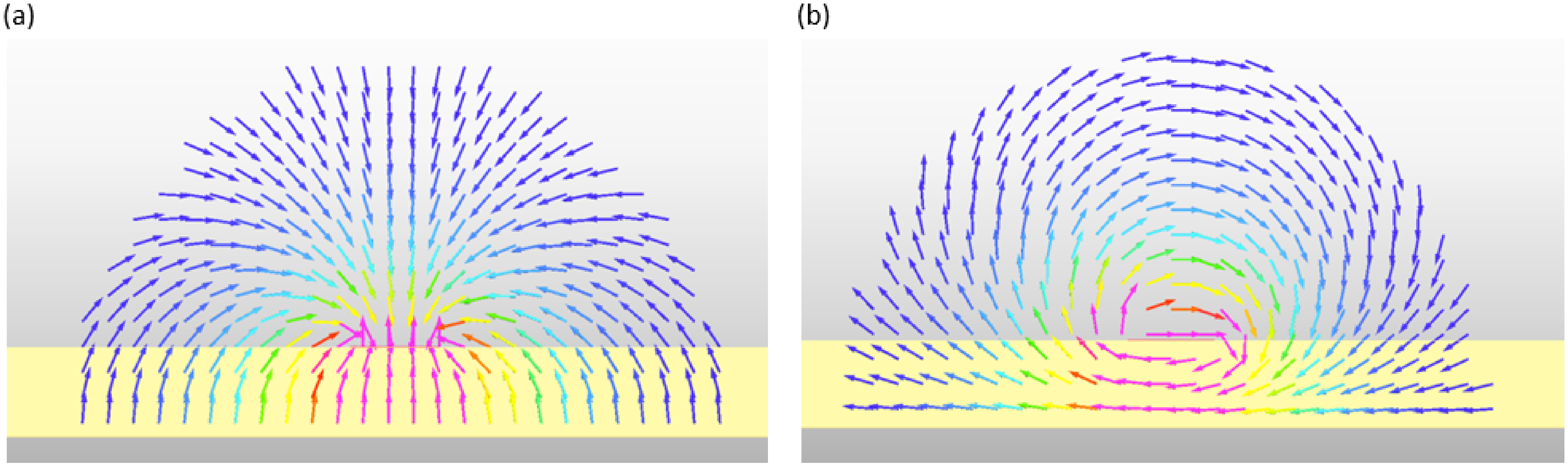


Electric Field propagets in substrate beneath microstrip line at 35 GHz.

- **Mode of Propagation**: The wave propagates in a quasi-TEM, with the electric field primarily directed along the line.
- **Field Distribution**: The electric field is not confined to the strip but extends into the substrate, creating a mixed-mode propagation where both the strip and substrate influence the wave.
- **Impedance**: The characteristic impedance of a microstrip line is determined by the geometry of the strip and the properties of the dielectric substrate. At high frequencies (like 35 GHz), the dielectric substrate's role becomes more significant as the electric field spreads beneath the microstrip, contributing to both the signal speed and loss characteristics.

Microstrip line – EM Theory (Simulations)

Full-wave simulator is used to obtain field patterns and calculate transmission losses.



Microstrip line and the (a) electric field and (b) magnetic field propagating through it.

Higher field intensity below the strip → higher contribution of the bottom side of the strip to signal losses.

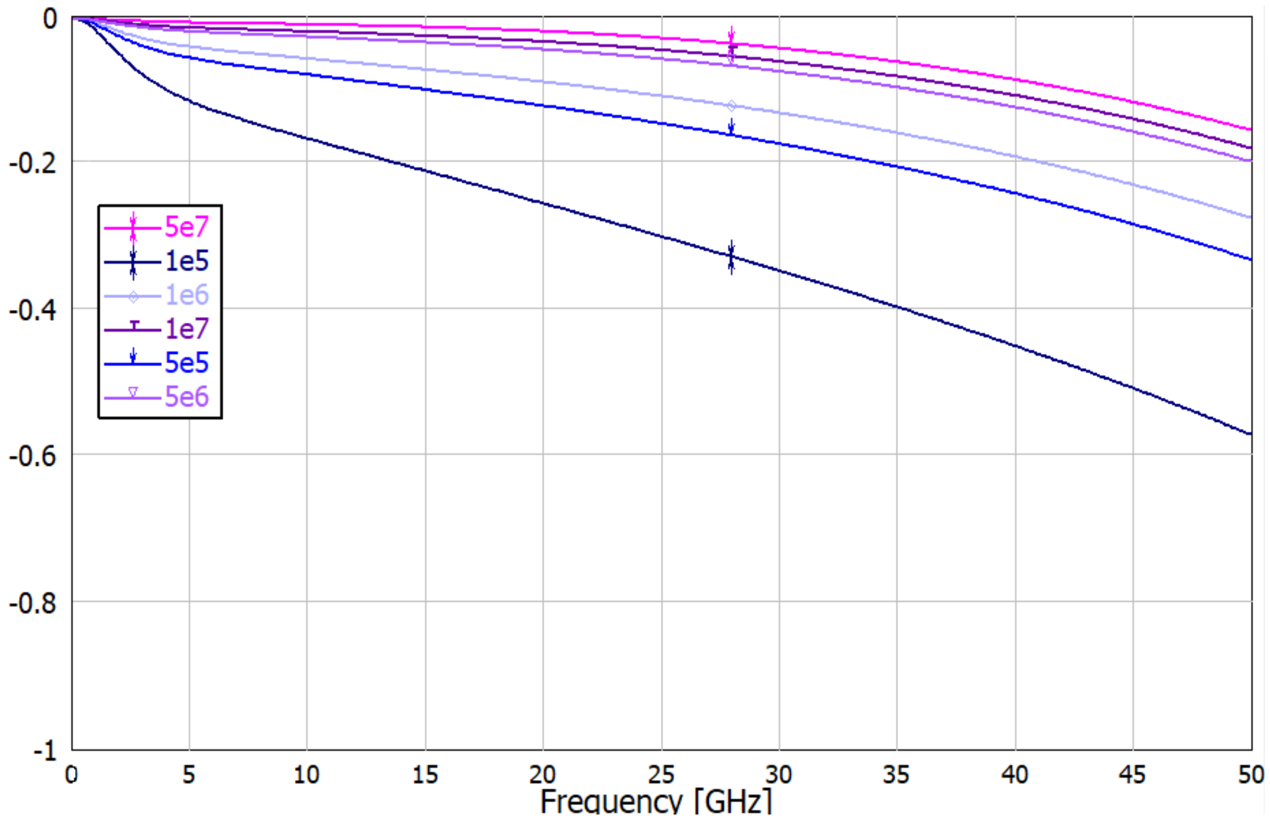
Results of consider microstrip line example

Simulation Info:

- To simulation was use Grid Search Regime for diffrent conductivity; from **1×10^5 S/m** to **5×10^7 S/m**
- The entire process took 7 minutes and 51 seconds (**00:07:51**) to complete, which included 6 simulations. During the simulations, an average of 1 383 iterations were performed per second until the required frequency resolution was achieved, after a total of 108009 iterations.

Chart interpretation:

The chart show a drastic increase in loss as conductivity decreases, following a logarithmic trend. Specifically, the sensitivity to changes in conductivity is significantly higher in the lower conductivity range, particularly at **1e5 S/m**. This highlights the critical importance of accurate measurements in regions of higher conductivity for improved correlation with simulation data.



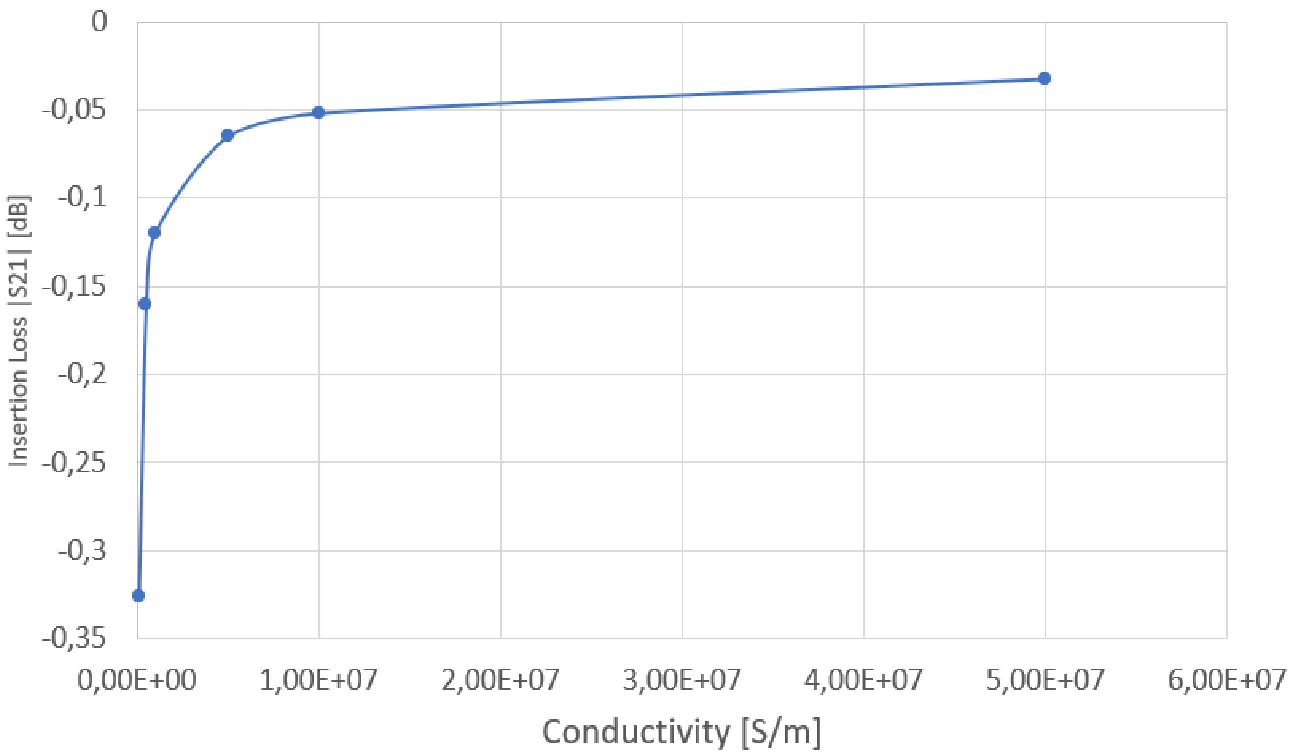
Increase in Insertion Loss |S21| versus frequency for different metal conductivities.

Results – characteristic at 28 GHz

From before characteristic a insertion loss was chosen for 28 GHz which provide information how insertion loss changes with metal conductivity.

Chart interpretation:

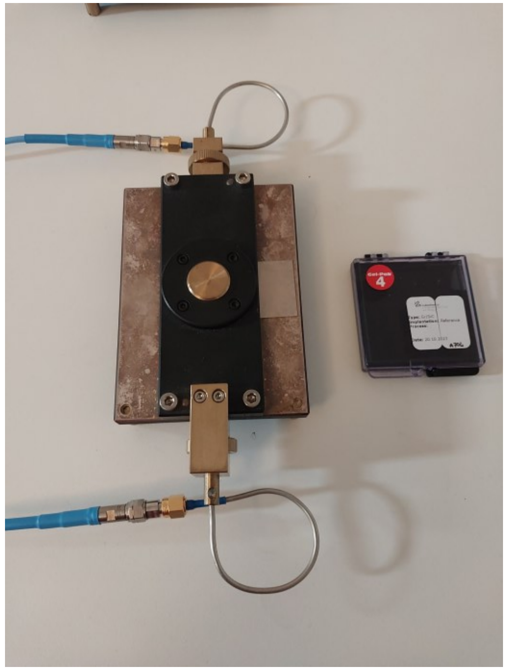
- The curve begins steeply at low conductivity values, showing significant insertion loss.
- As conductivity increases, the insertion loss rapidly decreases and flattens out.
- The relationship suggests that higher conductivity reduces insertion loss.
- The reduction in insertion loss with increasing conductivity indicates better material efficiency for signal transmission.



Insertion Loss versus metal conductivity at 28 GHz

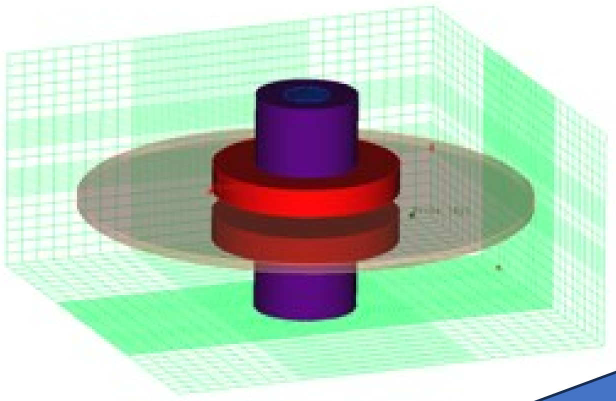
Conductivity Measurement –3D CAD Overlay used for digital twinning

Split-Post
Dielectric Resontator
(SPDR)



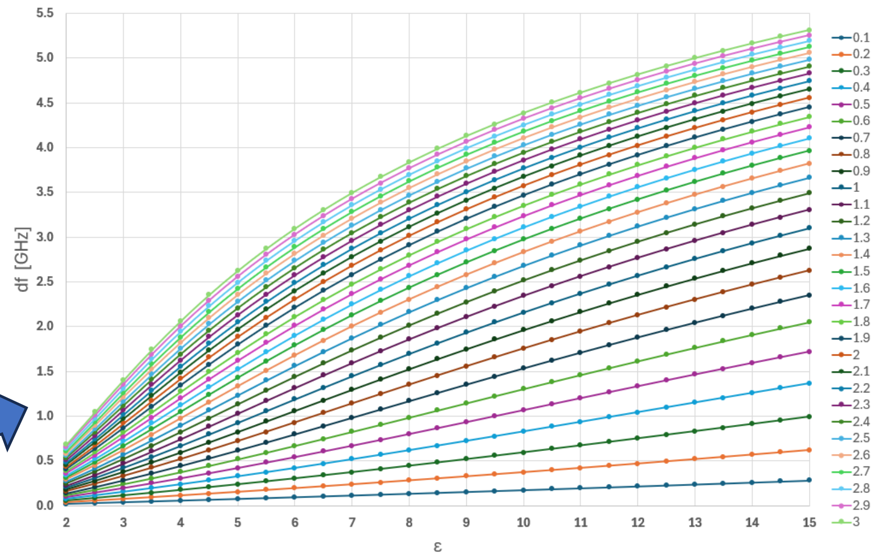
Sample during
Measurement
ε, tanδ <- ???

Transfer all
dimension
and material
parameters of SPDR
to **3D CAD Overlay**



Do a lot of EM simulations
based on 3D CAD model
where, **ε is a parameter**
in Grid Search.

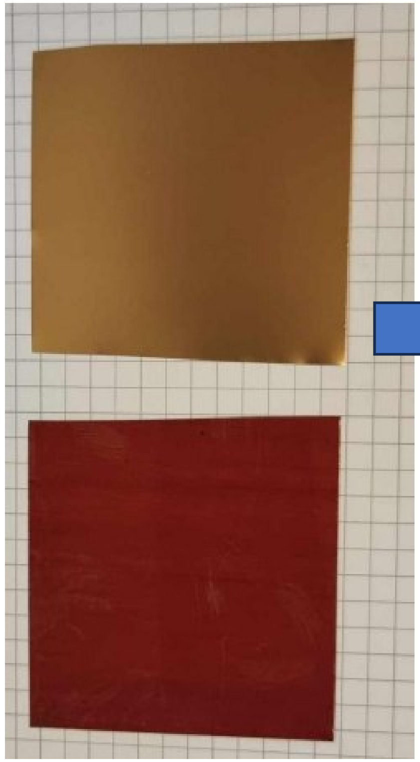
Table of possible ε based
on frequency shifts

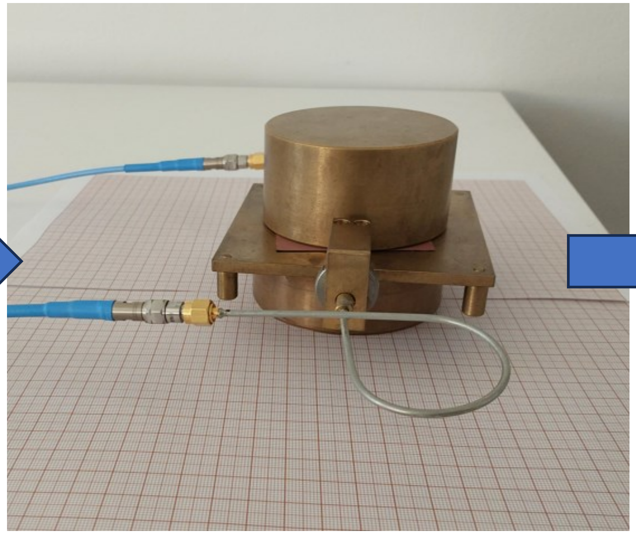


„Procedure used to calibrate a new type of Q-Choked Split Cylinder Resonator (QSCR)"

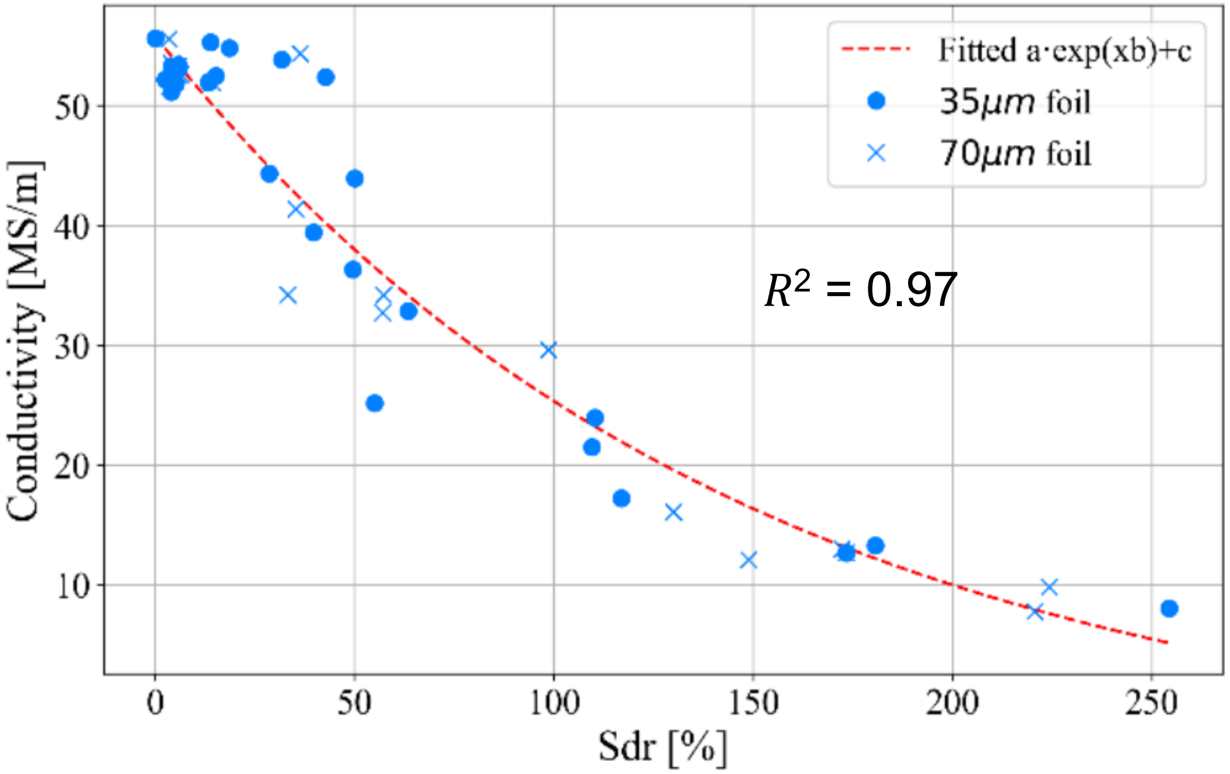
[A Novel Q-Choked Resonator for Microwave Material Measurements Alleviating Sample Thickness Limitations of Existing Techniques]
Celuch Małgorzata, Olszewska-Placha Marzena, Nowicki Łukasz *[i in.]*, IEEE Microwave and Wireless Technology Letters, 2024, vol. 34, nr 6, s.845-848. DOI:10.1109/LMWT.2024.3397912

Conductivity Measurement – Another way to characterize a copper foil using an Overlay to digital twinning





13&21 GHz
Ruby Dielectric Resonator
(RuDR)



24 types of copper foils
3 samples each give
-> **72 measured samples**

Correlation between effective conductivity (measured at 13 GHz in the RuDR) and surface roughness parameter Sdr (measured with laser interferometry).

M. Celuch, T. Devahif, T. Nalecz, J. Rudnicki, "A Systematic Study of Correlation between Surface Roughness and Microwave Effective Conductivity of Copper Foils for Ultra-Low-Loss Applications", 25th International Microwave and Radar Conference MIKON, **1-3 July 2024**, Wroclaw, Poland

Work is a part of european project: 5G Foil

Conclusions

- **CAD-EM Simulation Integration**: Utilized 3D CAD overlay module for precise and efficient analysis of complex designs (e.g., microstrip line).
- **Conformal FDTD Techniques**: Enabled signal integrity analysis with minimized computational resources.
  - Meshing strategies (mesh-snapping, mesh boxes, adaptive time-step controls, cells per wavelength).
- **Microstrip Line Example**:
  - Systematic grid search optimization for conductivity parameter.
  - Drastic increase in loss as conductivity decreases.
- **Digital Twinning** – demonstrated the use of the 3D CAD Overlay in a direct engineering process through resonator software for material measurements
- In iNEMI Project we will focus on correlating simulation results with physical measurements of microstrip lines. Future work includes thermal analysis for heating effects in PCB design (Multi-Physics Simulations)

Acknowledgment

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Funding agencies:

M-ERA.NET

eureka eurostars

NCBR National Centre for Research and Development

Wallonie | SPW Service public de Wallonie

THE GOVERNMENT OF THE GRAND-DUCHY OF LUXEMBOURG Ministry of Finance

Projects:

I4Bags

5G Foil

iNEMI International Electronics Manufacturing Initiative

Partners:

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CIRCUIT FOIL