TUMA11

Screening of the mmWave Signal Loss Properties of Copper Foils without the Need for Test Circuit Manufacturing

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5G_Foil

ULTCC6G_EPac

Outline:

1. The iNEMI "Copper Foils" Project*.
2. Problems of Copper Foil Loss at Higher Frequencies.
3. QWED New Instruments for EM Characterisation of Copper Foils.
4. Recent iNEMI Project Results for Representative Copper Foil Samples.
5. More about QWED's Modelling-Based Materials' Characterisation.
6. Summary and Acknowledgements.

* iNEMI "Copper Foils" Project: "*Reliability & Loss Properties of Copper Foils for 5G Applications*"
https://www.inemi.org/article_content.asp?adminkey=b5202baac78313e4914809b2f481b372&article=209

The iNEMI "Copper Foils" Project

iNEMI
International Electronics Manufacturing Initiative

The iNEMI "Copper Foils" project started in 2021

participates to projects evaluating:

dielectric losses

conductor losses

→ fast & precise measurement methods,

→ physical insight with computer modelling,

→ dissemination (mainly in IEEE and EU communities).

5G/mmWave completed project

- 5G/mmWave Materials Assessment and Characterization

5G/mmWave

- mmWave Permittivity Reference Material Development
- Also see Roadmap: 5G/6G mmWave Materials and Electrical Test Technology Roadmap (5G/6G MAESTRO)

Board Assembly

- Bi-Sn Based Low-Temperature Soldering Process and Reliability
- Characterization of Third Generation High-Reliability Pb-Free Alloys
- Conformal Coating Evaluation for Environmental Protection against Corrosive Environments, Phase 3
- Connector Reliability Test Recommendations, Phase 3
- Electromigration of SiBn Solder for Second-Level Interconnect
- QFN Package Board Level Reliability

Optoelectronics

- Best Practices for Expanded Beam Connectors in Data Centers

Packaging

- Impact of Low CTE Mold Compound on Second-Level Board Reliability, Phase 2
- Low Temperature Material Discovery and Characterization for First Level Interconnect
- Moisture Induced Expansion Metrology for Packaging Polymetric Materials Project, Phase 1
- PLP Fine Pitch Substrate Inspection/Metrology, Phase 4
- RDL Adhesion Strength Measurement Project
- Warpage Characterization and Management Program
  - High Density Interconnect Socket Warpage Prediction and Characterization

PCB & Laminates

- Reliability & Loss Properties of Copper Foils for 5G Applications
- PCBA Materials for Harsh Environments, Phase 2
- Hybrid PCBs for Next Generation Applications
- PCB Characterization for CAF and ECM Failure Mitigation
- PCB Connector Footprint Tolerance

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Reliability & Loss Properties of Copper Foils for 5G Applications

Statement of Work & Project Statement

- Statement of Work (v 1.3; April 8, 2021)
- Project Statement (v 1.0; April 8, 2021)

Project Focus:

The purpose of the project is to correlate:

(non-contact) surface roughness measurements

to surface conductivity

to signal loss (through a microstrip test vehicle)

at increasing frequencies.

QWED resonant methods characterising effective conductivity of stand-alone copper foil samples

The project will also investigate durability ("strength") of the inner layer bond:

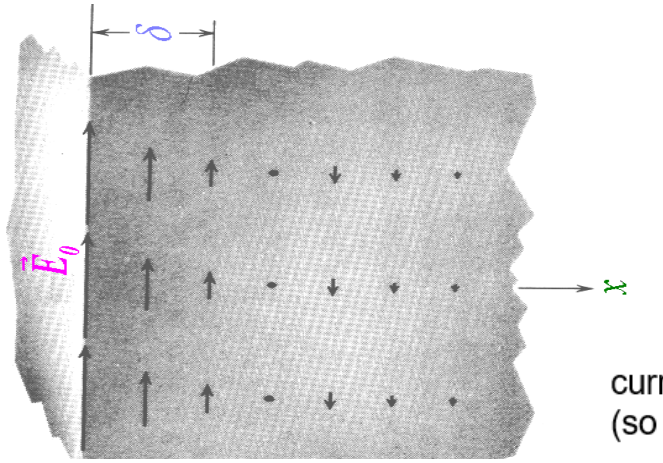
- for various copper roughness' and surface finishes,
- on ED (electrodeposited) and RA (rolled annealed) copper foil
- and also after various oxide alternative finishes.

Why Copper Loss Becomes More problematic at Higher Frequencies

current at the surface
related to E-field at the surface:

→ problems common for metallic surfaces (bulk or foil)

$$J_0 = E_0 \sigma$$



wave incidence

penetration depth (fields & currents attenuated e-times)

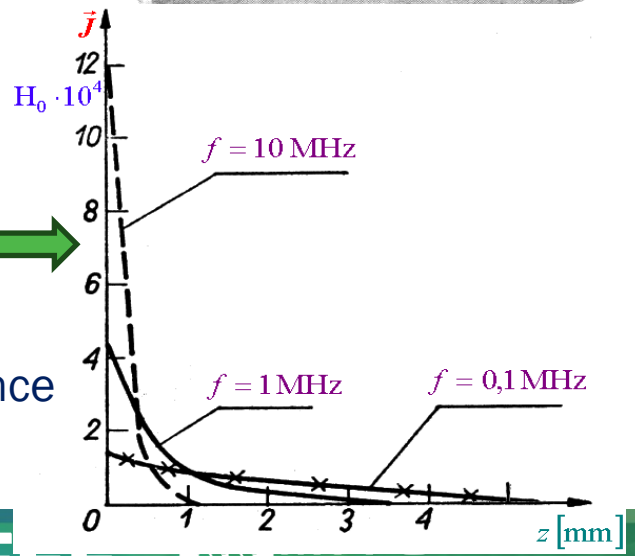
$$d_p = \sqrt{\frac{2}{\omega \mu_0 \sigma}}$$

σ [S/m]	*dp* [μm] @13.5 GHz non-magnetic metal
1.00E+03	135.8309
1.00E+04	42.9026
1.00E+05	13.5588
1.00E+06	4.2871
1.00E+07	1.3556
5.00E+07	0.6063

surface resistance (sheet resistance)

$$R_s = \frac{1}{\sigma d_p} = \sqrt{\frac{\pi f \mu}{\sigma}}$$

current integrated over depth (so called surface current):



wave incidence

$$J_{sz} = \int_0^\infty J_z dx = \frac{J_0 d_p}{1+\mathrm{j}} = \frac{E_0}{1+\mathrm{j}} d_p \sigma =$$

$$= \frac{E_0}{1+\mathrm{j}} \sqrt{\frac{2}{\omega\mu\sigma}} \sigma = \frac{E_0}{1+\mathrm{j}} \sqrt{\frac{2\sigma}{\omega\mu}} =$$

$$= \frac{E_0}{1+\mathrm{j}} \sqrt{2\mathrm{j}} \sqrt{\frac{\sigma}{\mathrm{j}\omega\mu}} = E_0 \sqrt{\frac{\sigma}{\mathrm{j}\omega\mu}} = \frac{E_0}{Z} = H_0$$

Total current ("surface current") flowing along the metallic surface is equal to the incident H-field amplitude (does not depend on frequency or metal conductivity).

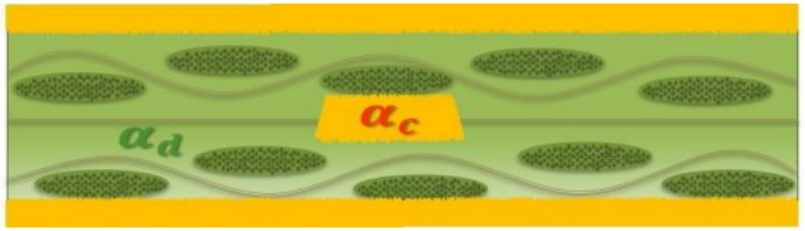
At higher frequencies, this current flows in a thinner layer below metal surface, hence, experiences a higher resistance.

Why Copper Loss Becomes More problematic at Higher Frequencies

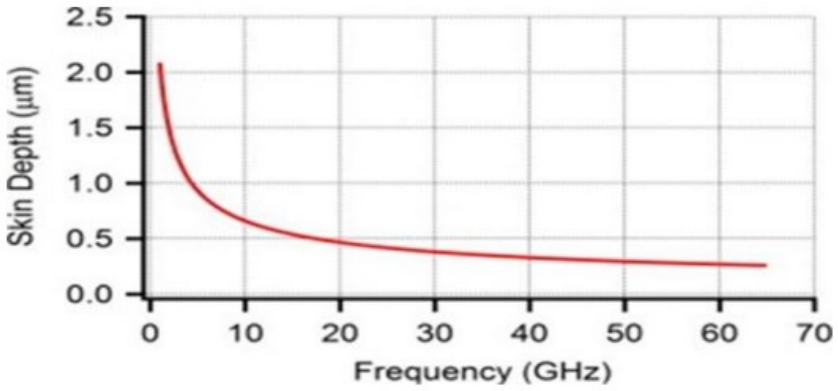
→ problems specific to foils:

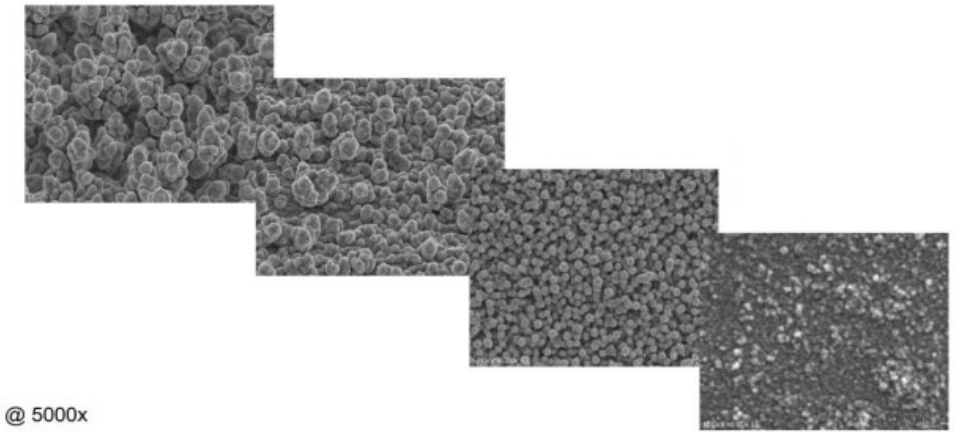
from: Ed Kelly, IMPACT 2021

Conductor Loss Drives Need for Ultra Low-Profile Copper



As frequency increases, skin depth decreases, and a significant amount of the current is carried in the bond treatment portion of the copper – including on the oxide alternative side





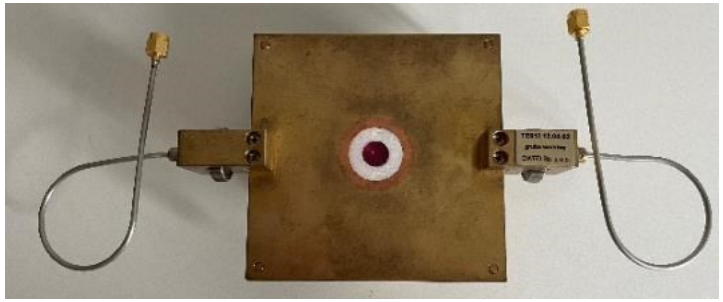
All @ 5000x

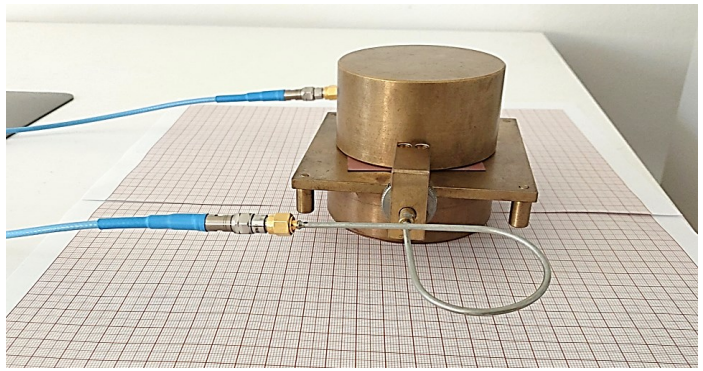
Higher signal loss

Photos & figures: courtesy of copper foil manufacturers involved in the project

Methods Proposed by QWED for Measuring Surface Resistance R_s (and *Effective* Conductivity σ_{eff} of Copper Foils)

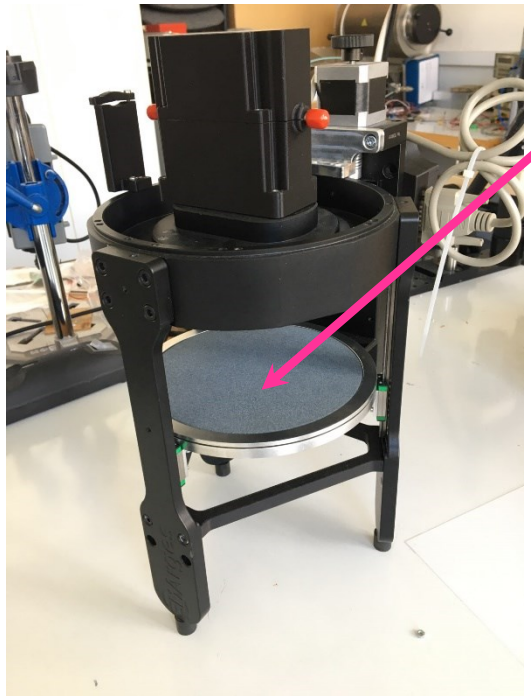
Dielectric Resonator:
Sapphire (SaDR) or Ruby (RuDD)





$$R_s = \sqrt{\frac{\pi f \mu}{\sigma_{eff}}}$$

effective parameter, lower than bulk copper, including the effects of inhomogeneity (roughness, treatment)



Fabry-Perot Open Resonator
(modified to planar-concave design)

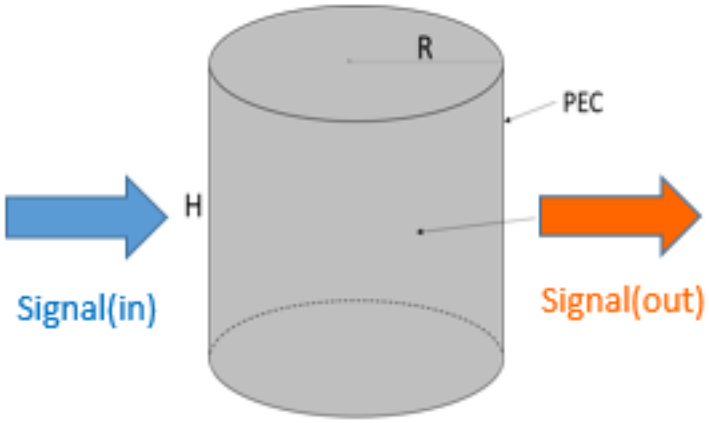
sample holder;
vacuum pump to be applied from below

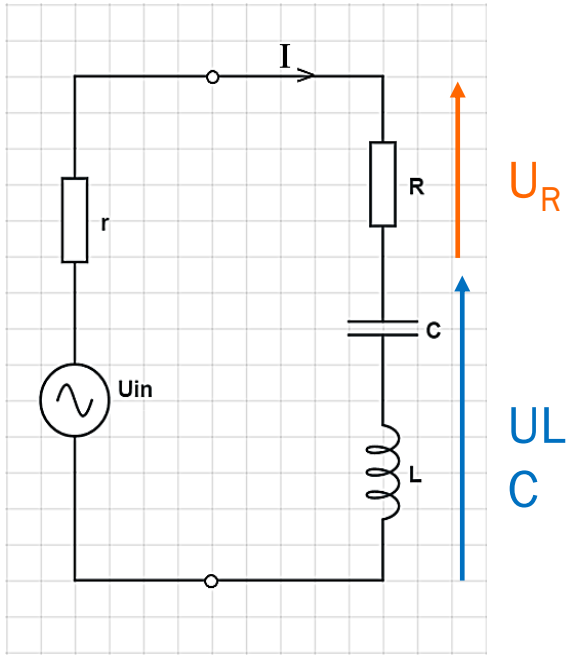
Both RuDD (SaDR) and FPOR resonators allow measuring a copper foil by itself:

- no need to fabricate a test circuit!
- loss from the foil is separated from any dielectric loss,
- the two sides of foil can be measured separately,
- foils on laminates can also be measured.

Why Resonators for Material Measurements?

Circuit theory interpretation (for newcomers to the field):





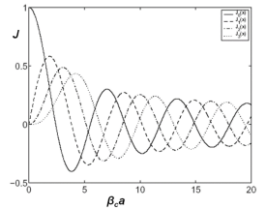
given fixed strength of Signal(in),
at resonance Signal (out) is strongest

given fixed strength of Uin,
at resonance U_R is strongest (U_{LC} =zero)

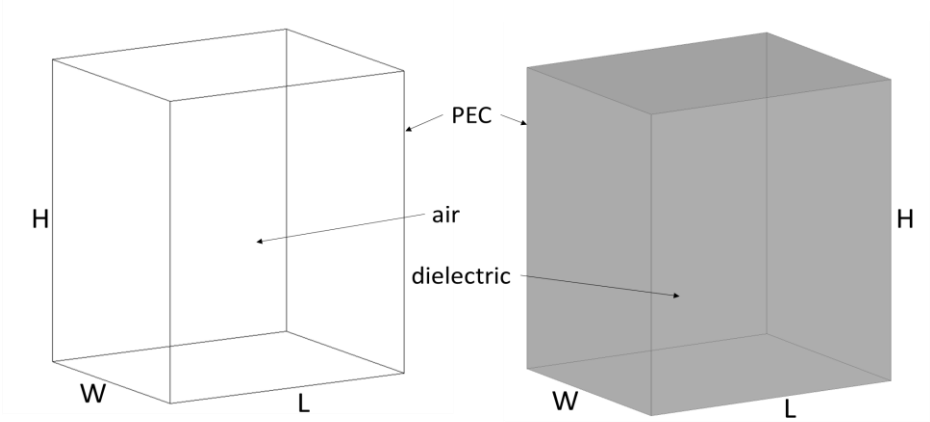
→ The resonance is sharpest (narrow-band, high-Q) when the resonator is composed of ultra-low-loss materials.

→ Hence, the resonant methods are specifically suitable for characterising 5G/mmWave materials.

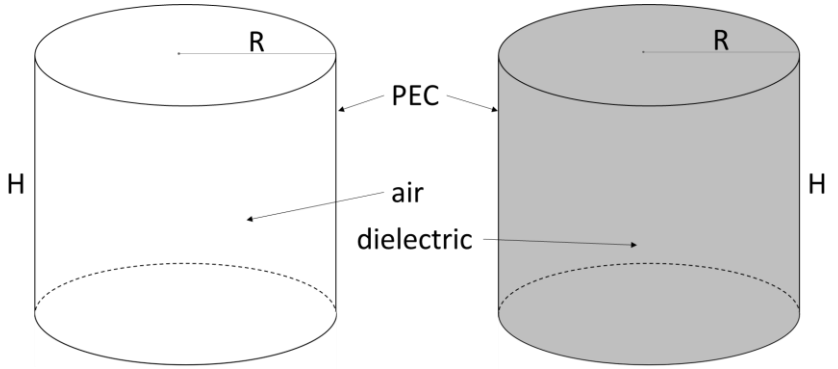
Examples of canonical examples of resonators



$$Q = 2\pi \frac{\overline{W}}{\overline{P_q} T}$$



$$Q = 2\pi \frac{\iiint_V \varepsilon \vec{E} \cdot \vec{E}^* dv}{T \iiint_V \sigma \vec{E} \cdot \vec{E}^* dv} = \frac{\omega\varepsilon}{\sigma} = \frac{1}{\tan\delta}$$



$$f_{r,mnp} = \frac{v}{2}\sqrt{\left(\frac{m}{W}\right)^2 + \left(\frac{n}{L}\right)^2 + \left(\frac{p}{H}\right)^2}$$

$$v = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{c}{\sqrt{\varepsilon_r}}$$ *in non-magnetic low-loss dielectrics*

$$f_{r,mnp} = \frac{v}{2}\sqrt{\left(\frac{\kappa_{mn}^{(,)}}{\pi R}\right)^2 + \left(\frac{p}{H}\right)^2}$$

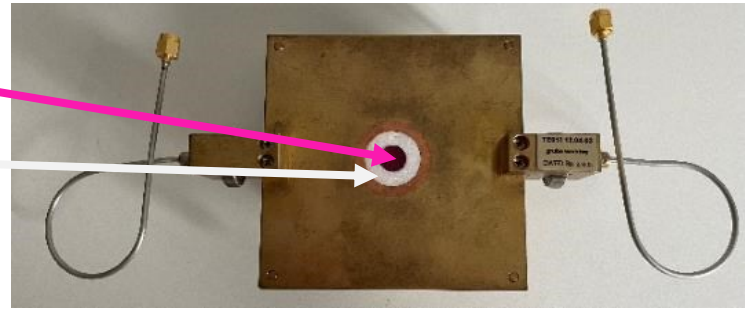
→ In classical applications for measuring dielectric materials, we minimise losses from cavity walls, to accurately capture the loss due to the dielectric filling.

→ To characterise copper foils, we minimise internal dielectric losses and apply a copper foils as a part of the cavity walls, with contribution to the overall loss of the resonator evaluated by rigorous electromagnetic modelling.

Ruby Dielectric Resonator for Measuring Conductive Layers

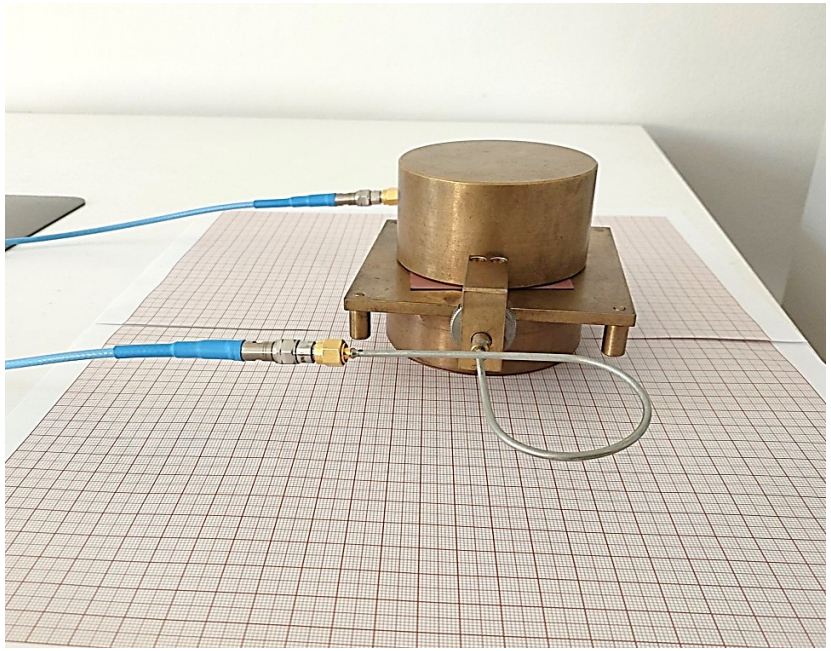
A cylinder of high-permittivity dielectric (sapphire or ruby) forms the resonator.

It is mounted in a cylindrical cavity via a teflon ring.



Losses of the resonator come from:
mainly: bottom & top plates made by the sample-under-test
(pressed with metal blocks for electrical contact & mechanical robustness),
additionally: cavity side walls & ruby itself
(minimised & calibrated out via the modelling).

- It operates at nominal frequencies of **13 GHz** and **21 GHz**.
- Two identical metallic samples are required for measurements.
- The samples should have dimensions of at least **23 mm x 23 mm.**
- The dedicated software calculates material parameters based on the measured data: resonance frequency and Q-factor (extracted through VNA).



Ruby Dielectric Resonator (RuDD) - example measurement system

The picture above shows an example of a measurement kit which consists of a laptop (running a dedicated App), VNA and ruby resonator.

Sample preparation

Package with copper foils
received by QWED from iNEMI project partners

Foils cut and sorted into samples
for RuDD measurements

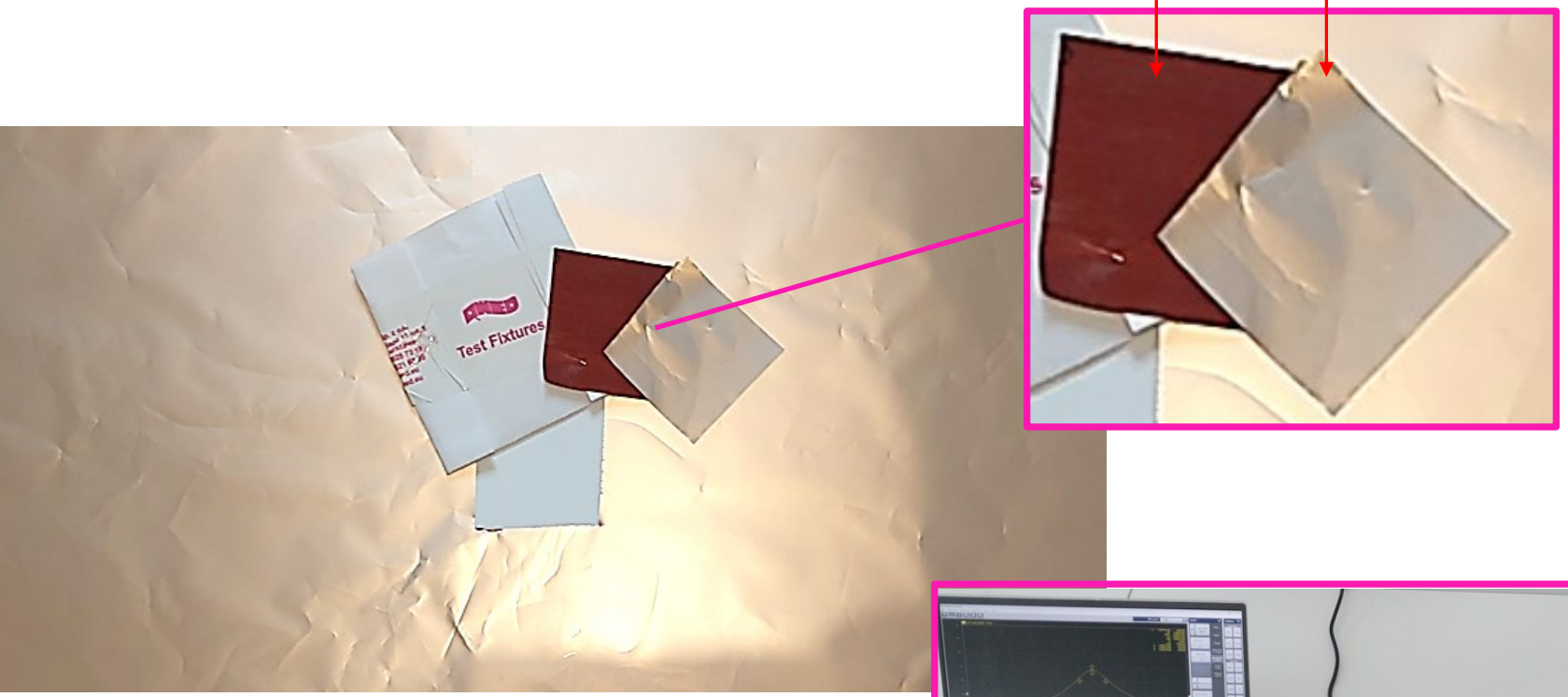
iNEMI project partners provided representative sets of copper foils:

- 3 manufacturers,
- High- and Low-roughness foils,
- 6 sheets of each foil,
- to be measured on both “rough” and shiny” sides.

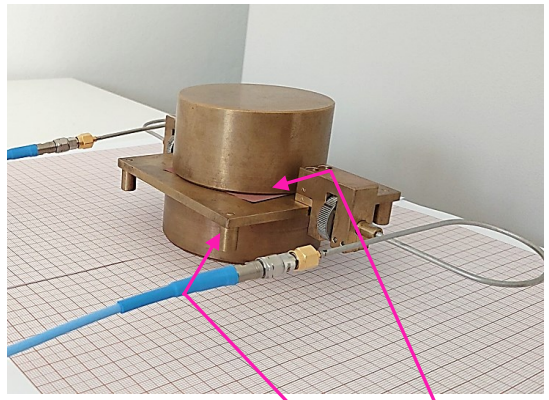
Copper foils

„**Rough**" side of the sample

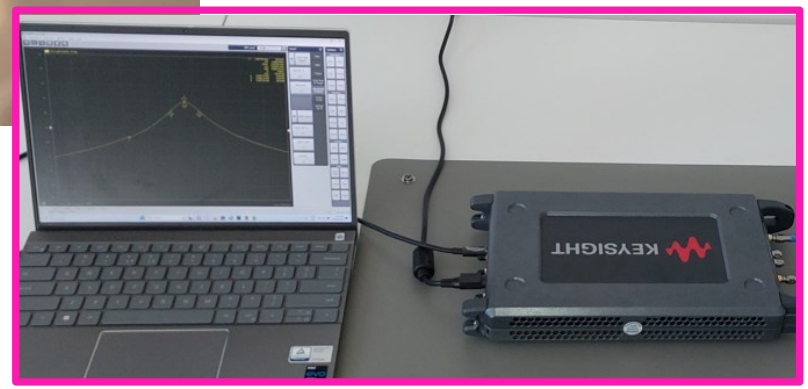
„**Shiny**" side of the sample



Samples measured on the same side

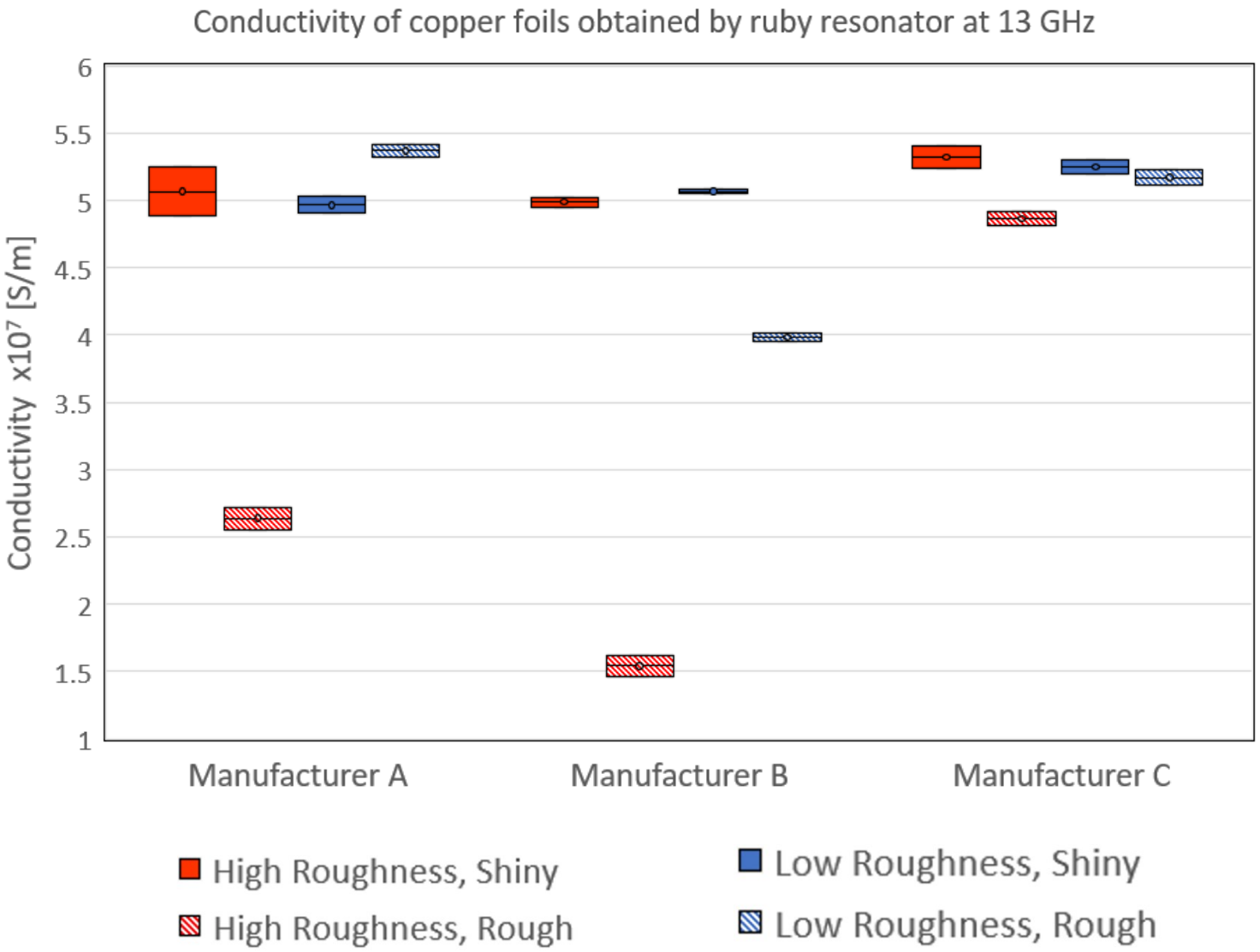


Sample



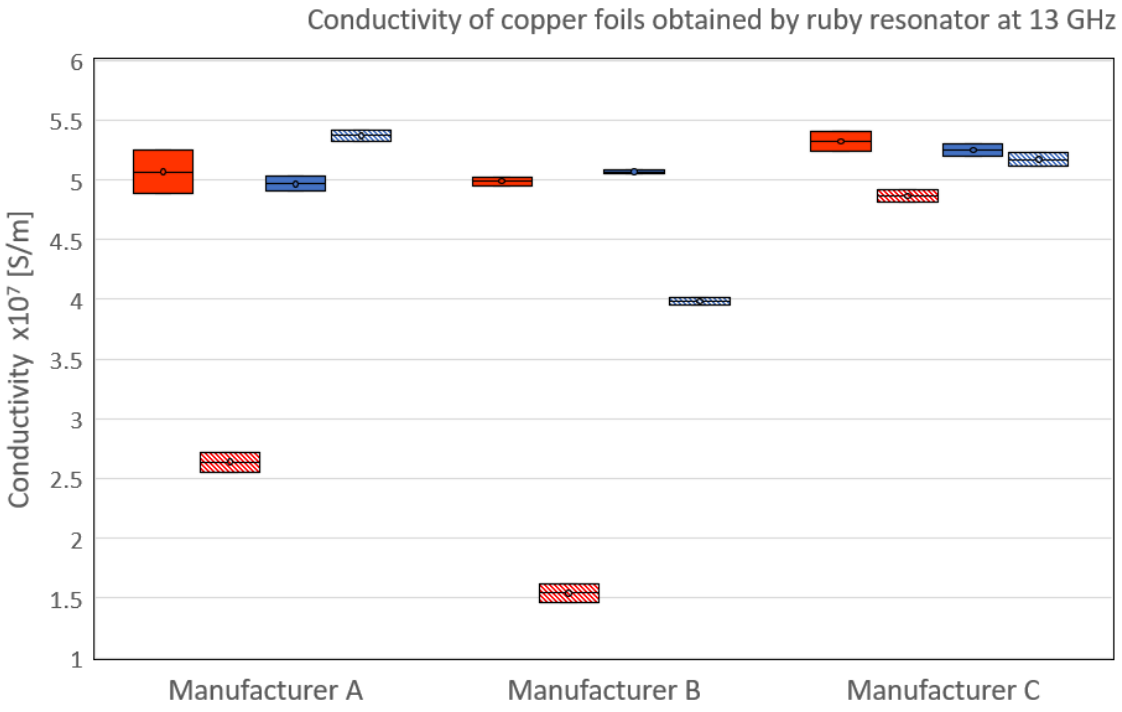
Reading the resonant frequency and Q-factor from the VNA and entering it into dedicated software to calculate surface resistance and conductivity.

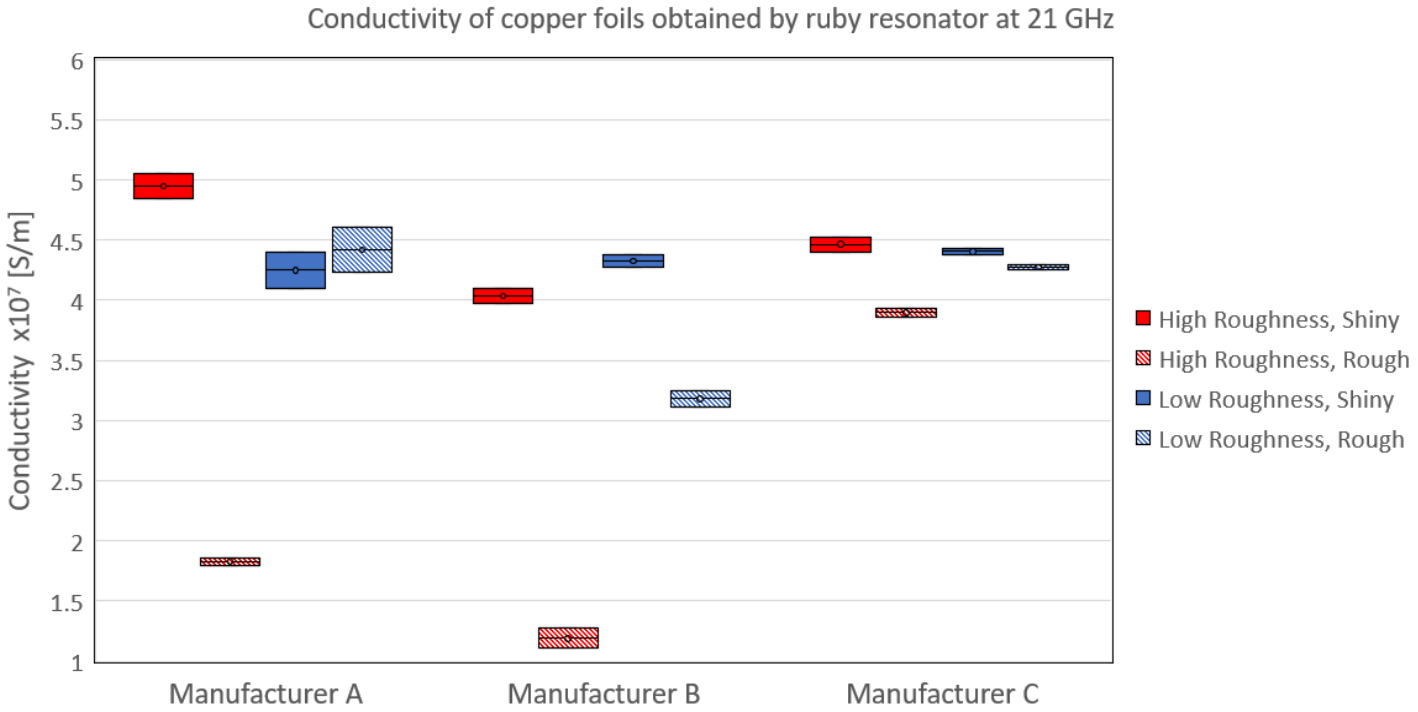
Results



- Copper foils exhibit lower effective conductivity than bulk copper.
- Copper foils from 3 different manufacturers, of both High- and Low-roughness, exhibit similar (within 10%) effective conductivities when measured on the "shiny" side (ca. 5÷5.5 x 10^7 S/m).
- "Rough" side of high-roughness foils has lower conductivity (even by a factor of 2-3, depending on the manufacturer).
- For Low-roughness foils, the difference between the "shiny" and "rough" sides is less significant (with even an anomaly for one manufacturer).

RuDD Results @ 13GHz and 21 GHz





At the higher frequency of 21 GHz:

- All measured effective conductivity values tend to be lower than at 13 GHz.
- Differences between the manufacturers become more significant.
- Copper foils from only one manufacturer, of one type (High-roughness, shiny side) maintain effective conductivity at the level of 5 x 10^7 S/m. Other ones drop below 4.5 x 10^7 S/m.

Fabry-Perot Open Resonator (FPOR) – adapted for measuring conductive films

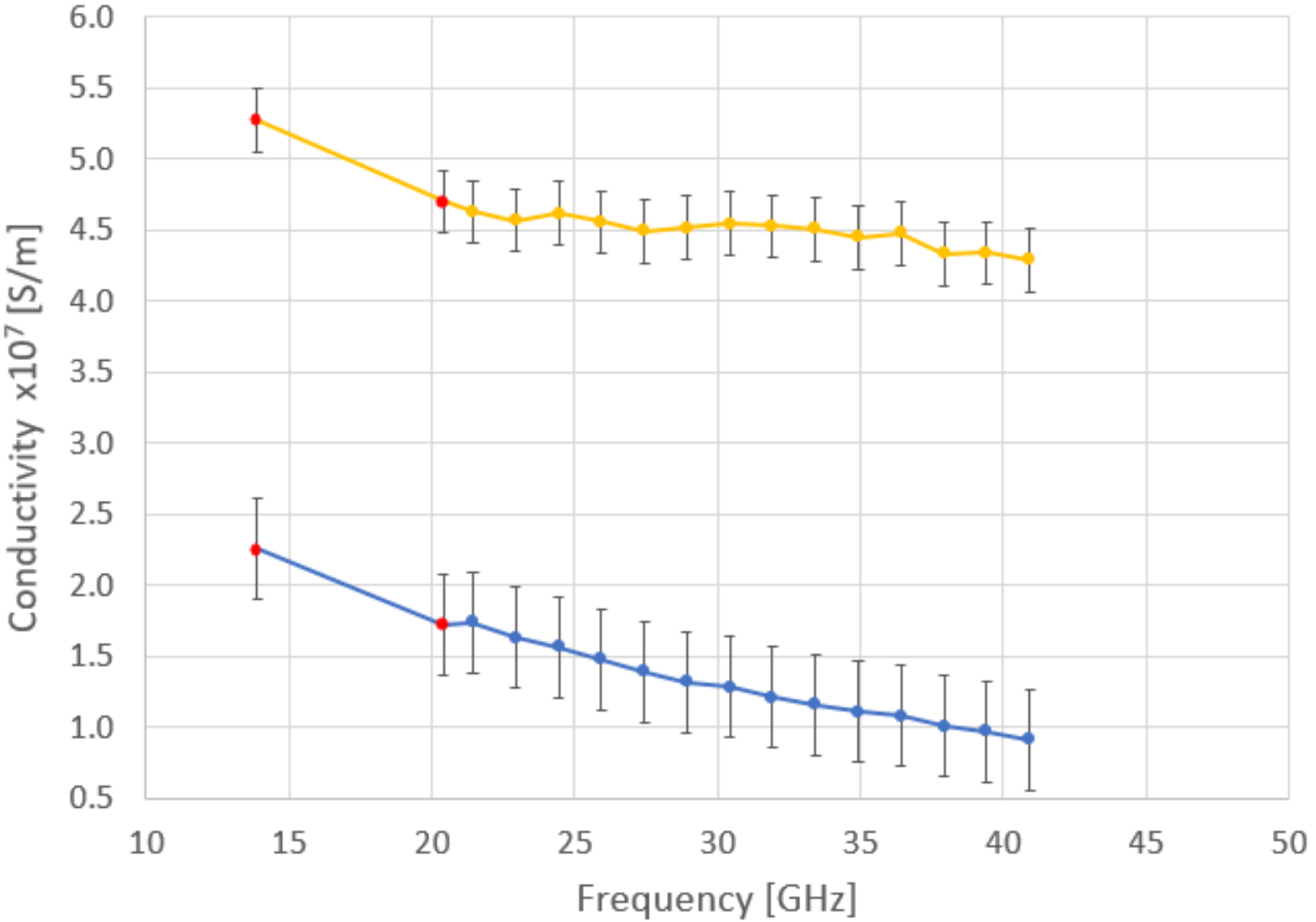
Rough side

Smooth side

sample size
90mm x 90mm

FPOR allows broadband and precise resonant measurements of electromagnetic properties of materials.
It is adapted to copper foil measurements by:
- replacing the classical double-concave mirrors with planar-concave design (the foil-under-test forms the planar mirror),
- a vacuum pump is applied for fixing the foil,
- dedicated software is developed (for converting measured resonant frequencies & Q-factors to foils' effective conductivity.

Broadband Copper Foil Measurements– FPOR & RuDD



- Ruby Resonator

Smooth
Rough
FPOR

- effective conductivity decreases with frequency → signal loss will increase
- differences between the two sides of copper must be taken into account

Conclusions

1. The iNEMI "Copper Foils" project investigates "Reliability & Loss Properties of Copper Foils for 5G Applications".
This talk has reported on the status of Task 2, where copper foils' topology is correlated to copper loss, responsible for signal loss in 5G circuits.

2. QWED has developed two resonator-based instruments for measuring effective conductivity of copper foils, based on:
- Dielectric Resonator (here: RuDD, dual-frequency: 13 GHz & 21 GHz)
- Fabry-Perot Open Resonator (in plano-concave topology, multi-mode, quasi-continuous measurement in 20..40 GHz band).
The measurements are quick & convenient, of the copper foils per se, as delivered by the manufacturer – no need to build a test circuit!

3. iNEMI project partners have provided representative sets of copper foils:
- 3 manufacturers,
- High- and Low-roughness foils (to be measured on both "rough" and shiny" sides)
- 6 sheets of each foil type (to study sample reproducibility: averages and standard deviation calculated).

4. QWED measurements show that, for higher frequencies (mmWave):
- effective conductivity of all copper foils decreases (hence, electric loss increases) with frequency,
- differences in loss due to different manufacturers and copper types increase,
- differences of signal loss due to different conductivity of the two sides of copper need to be taken into account in circuit design.

5. The iNEMI consortium will now be correlating the measured copper losses to more systematic topology measurements, as well as adding treatment and then evaluating its effects.

6. QWED is happy to design custom-made instruments and enter into joint R&D projects!!!

Acknowledgment

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5G_Foil

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