TUMA11

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

Malgorzata Celuch

QWED Sp. z o.o., Warsaw, Poland

mceluch@qwed.eu

with contributions from:
M. Olszewska-Placha, L. Nowicki, T. Nalecz (QWED)
P. Kopyt, J. Cuper (Warsaw University of Technology)

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eureka eurostars
iNEMI International Electronics Manufacturing Initiative

Outline:

1. Problems of Copper Foil Loss at Higher Frequencies.
3. QWED New Instruments for EM Characterisation of Copper Foils
   without the Need for Test Circuit Manufacturing.
4. iNEMI Project:
   Results for Representative Copper Foil Samples from 3 Vendors.
5. EUREKA-Eurostars Project:
   Influence of Copper Foil Manufacturing Parameters on Effective Conductivity.
6. Summary and Acknowledgements.

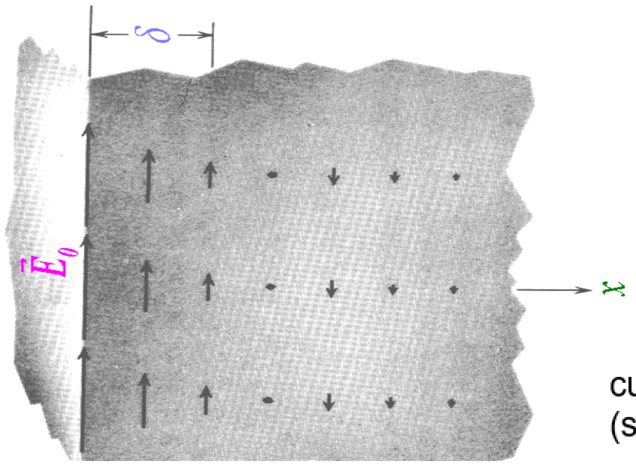
iNEMI "Copper Foils" Project: "*Reliability & Loss Properties of Copper Foils for 5G Applications*"
https://www.inemi.org/article_content.asp?adminkey=b5202baac78313e4914809b2f481b372&article=209

EUREKA-Eurostars "5G_Foil" Project: https://qwed.eu/5g_foil.html

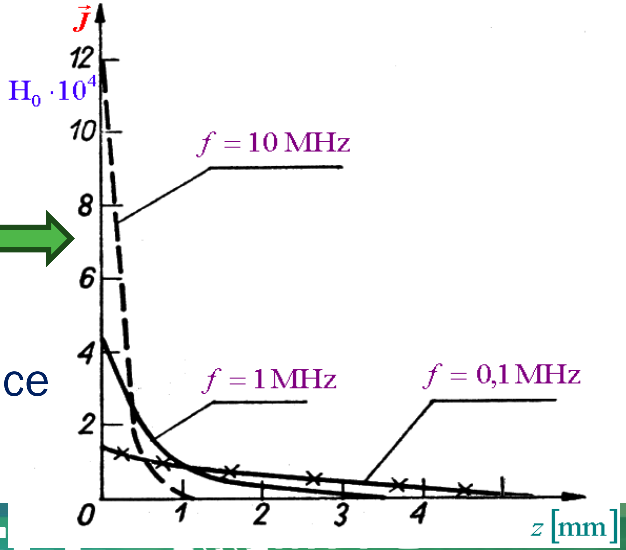
Why Copper Loss Becomes More problematic at Higher Frequencies

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

$J_0 = E_0\sigma$



wave incidence



wave incidence

→ problems common for metallic surfaces (bulk or foil)

penetration depth (fields & currents attenuated e-times)

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

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):

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

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

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

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.

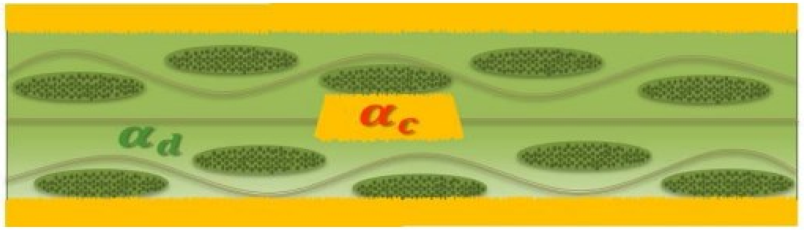
Why Copper Loss Becomes More problematic at Higher Frequencies

IMPACT
International Microsystems , Packaging, Assembly and Circuits Technology conference

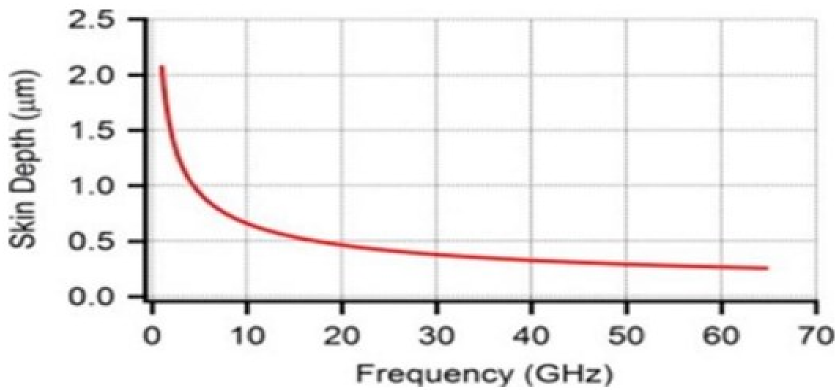
from: Ed Kelly, IMPACT 2021

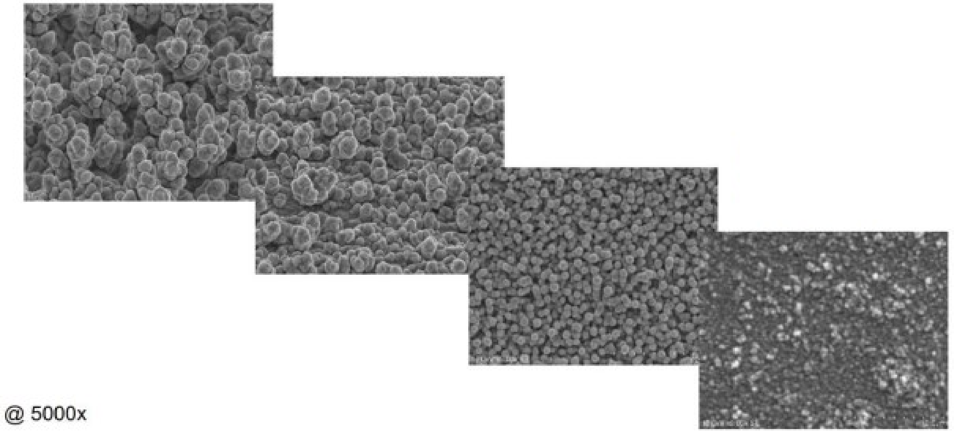
iNEMI
International Electronics Manufacturing Initiative

Conductor Loss Drives Need for Ultra Low-Profile Copper

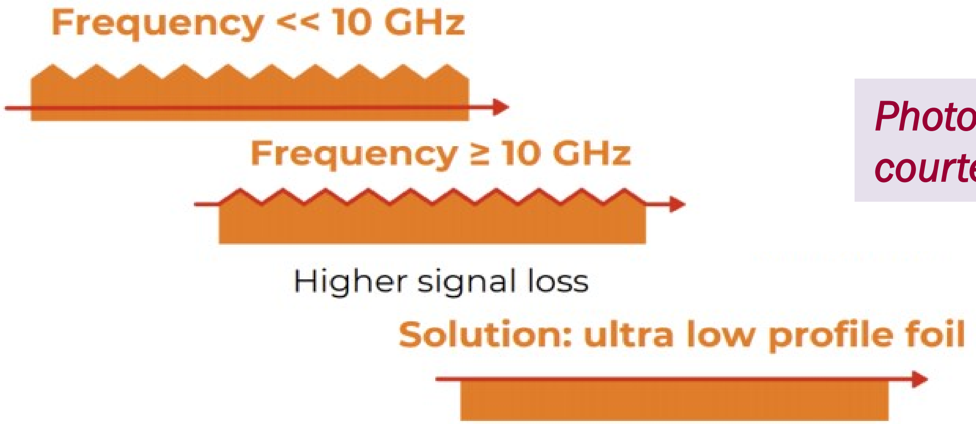


As frequency increases, skin depth decreases, and a significant amount of the current is carried in the bond treatment portion of the copper – including on the oxide alternative side





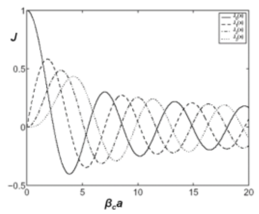
All @ 5000x



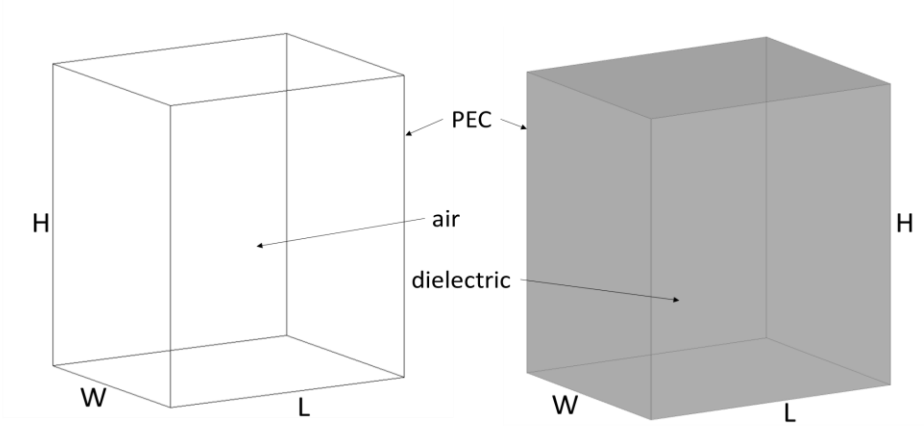
Photos & figures: courtesy of CFL

CIRCUIT FOIL

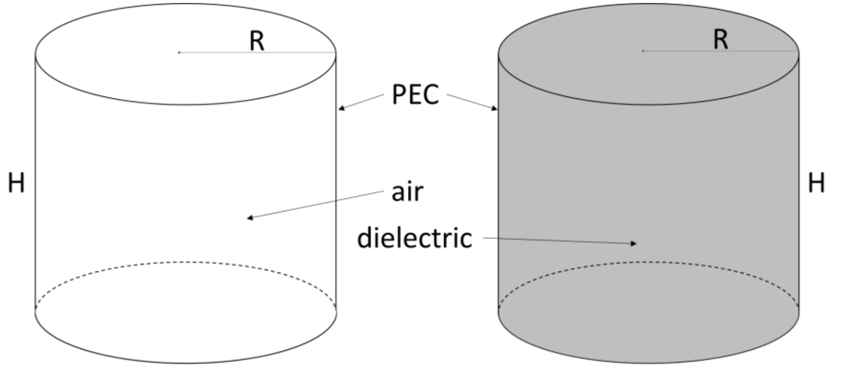
Resonant Methods for Material Measurements



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



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



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

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

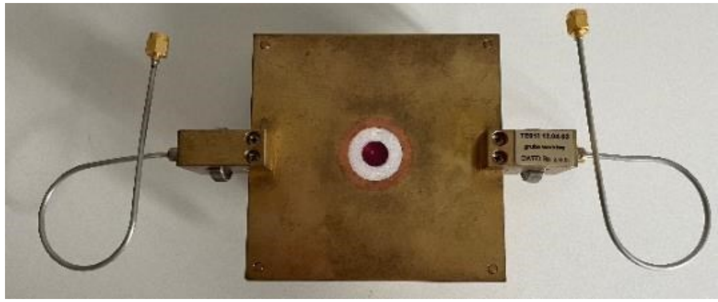
$$f_{r,mnp} = \frac{v}{2}\sqrt{\left(\frac{\kappa_{mn}^{(,)}}{\pi R}\right)^2 + \left(\frac{p}{H}\right)^2}$$

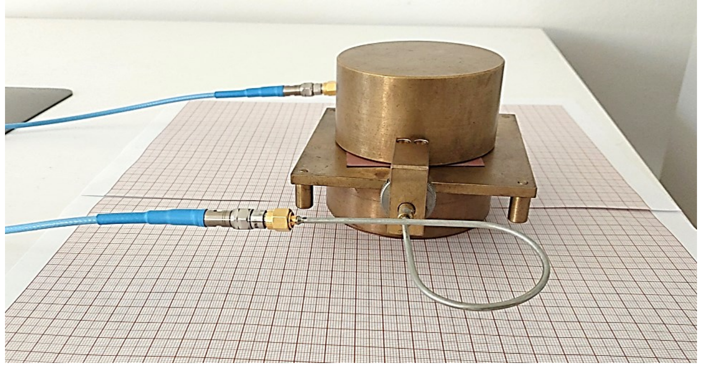
→ In classical applications for measuring dielectric materials, we minimise losses from cavity walls, to accurately capture the loss due to the dielectric filling.

→ 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 EM modelling.

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

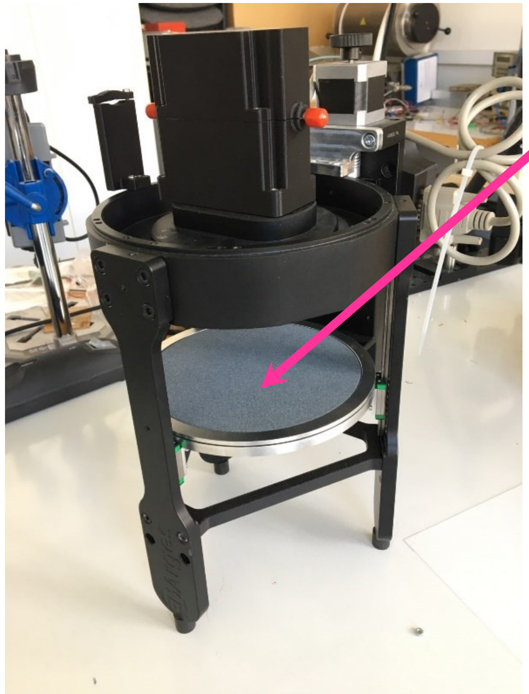
Dielectric Resonator:
Sapphire (SaDR) or Ruby (RuDD)





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

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

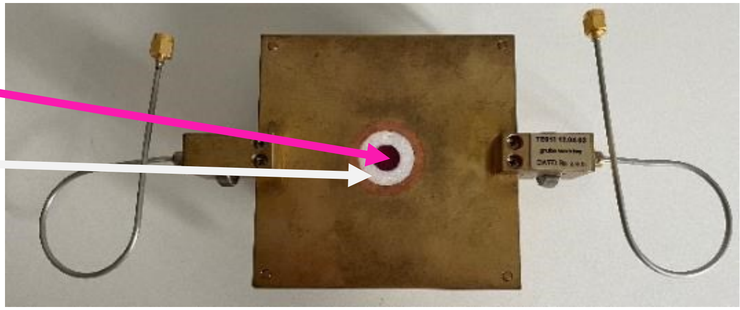
Both RuDD (SaDR) and FPOR resonators allow measuring a copper foil by itself:

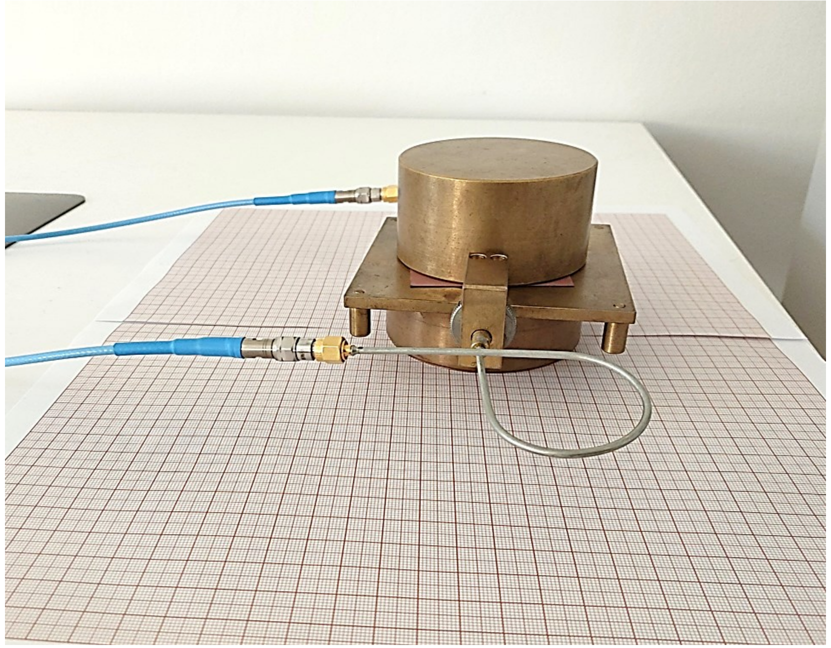
- no need to fabricate a test circuit!
- loss from the foil is separated from any dielectric loss,
- the two sides of foil can be measured separately,
- foils on laminates can also be measured.

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.





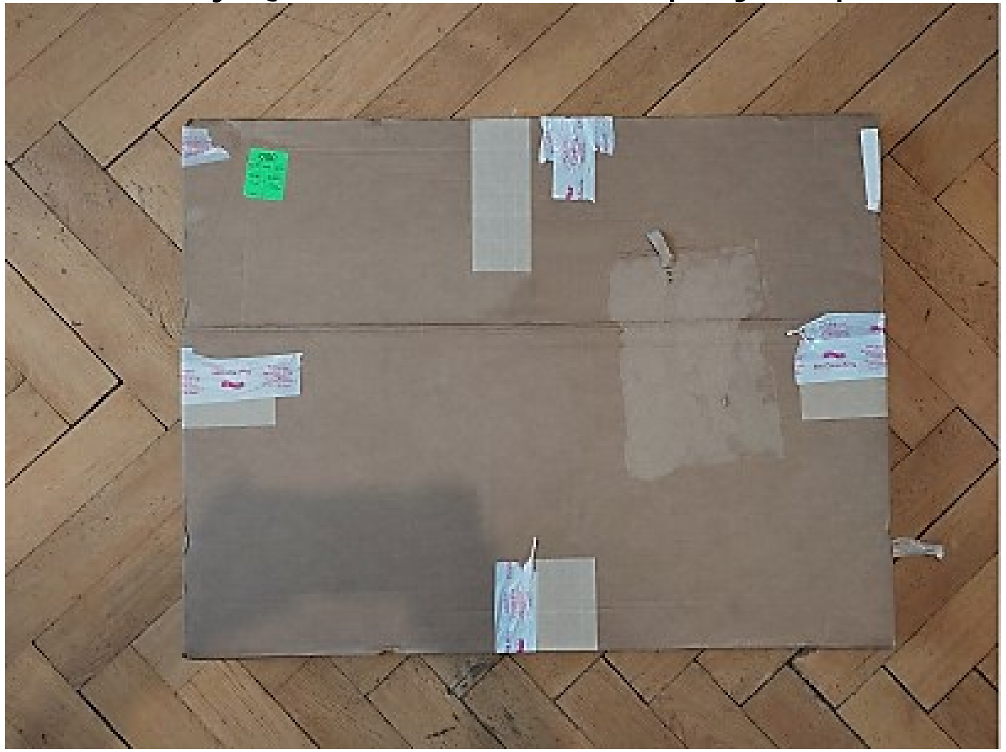
- It operates at nominal frequencies of 13 GHz and 21 GHz.
- Two identical metallic samples are required for measurements.
- The samples should have dimensions of at least 23 mm x 23 mm.
- The dedicated software calculates material parameters based on the measured data: resonance frequency and Q-factor (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.
Either VNA firmware or a dedicated App extract resonance frequency and Q-factor.
App provided with the resonator calculates material parameters.

Sample preparation

Package with copper foils
received by QWED from iNEMI project partners



Foils cut and sorted into samples
for RuDD measurements

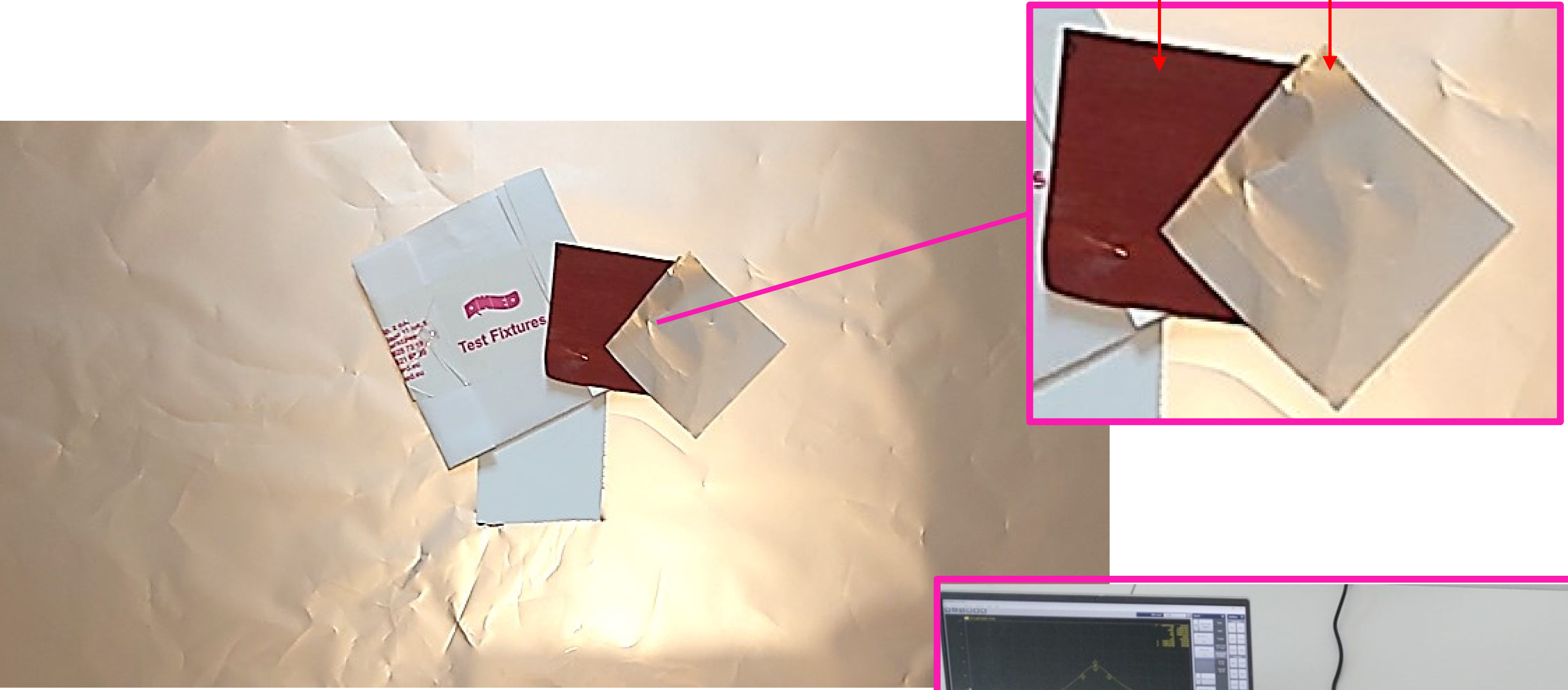
iNEMI project partners provided representative sets of copper foils:

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

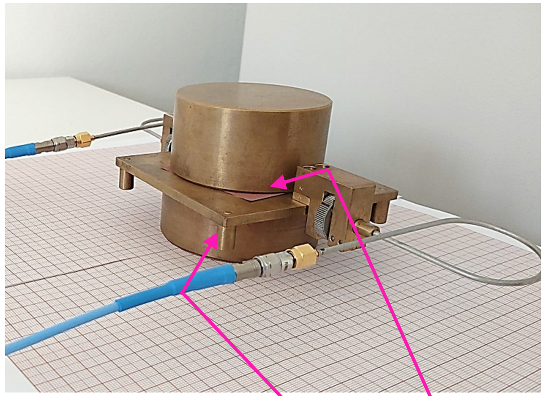
Copper foils

„**Rough**” side of the sample

„**Shiny**” side of the sample



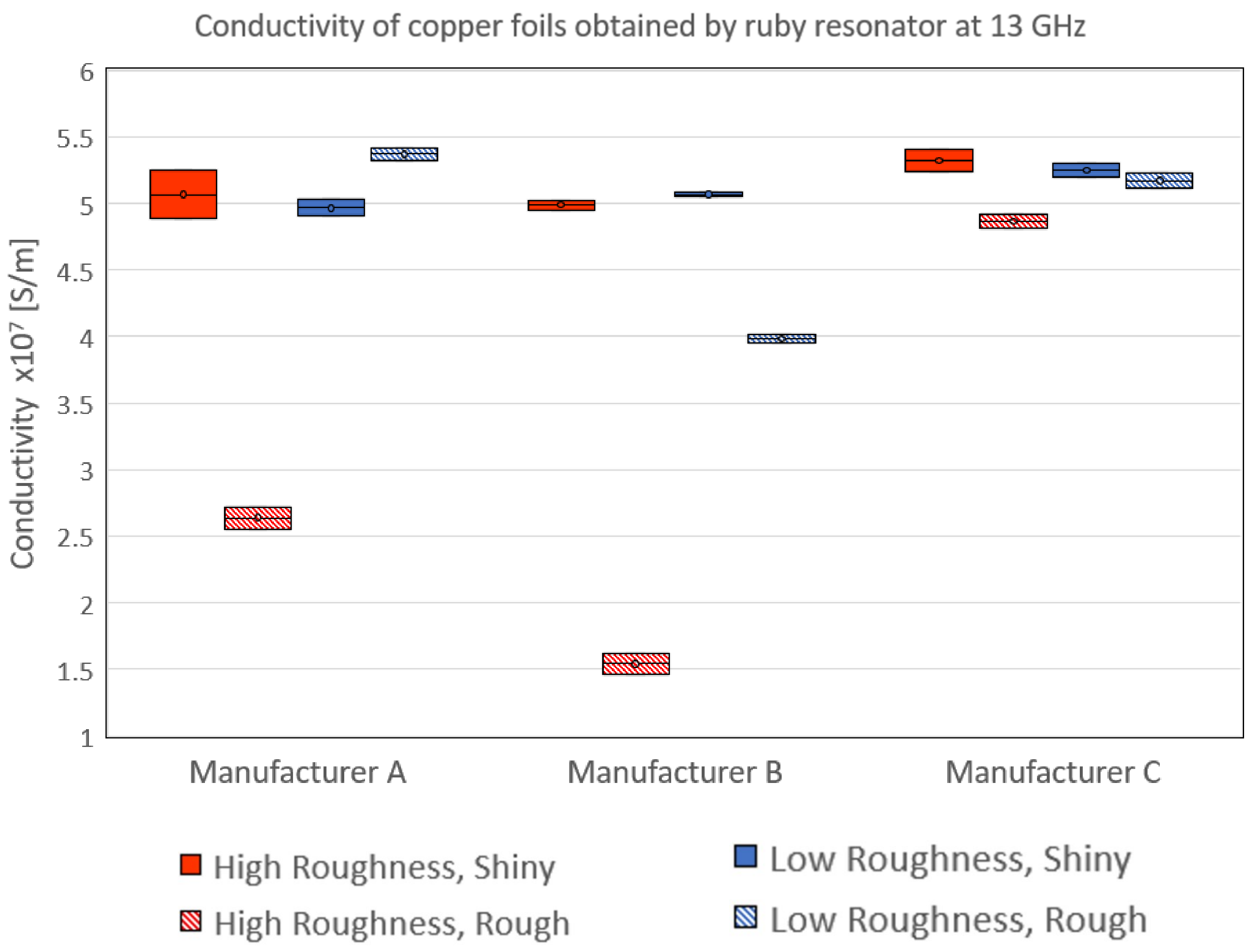
Samples measured on the same side



Sample

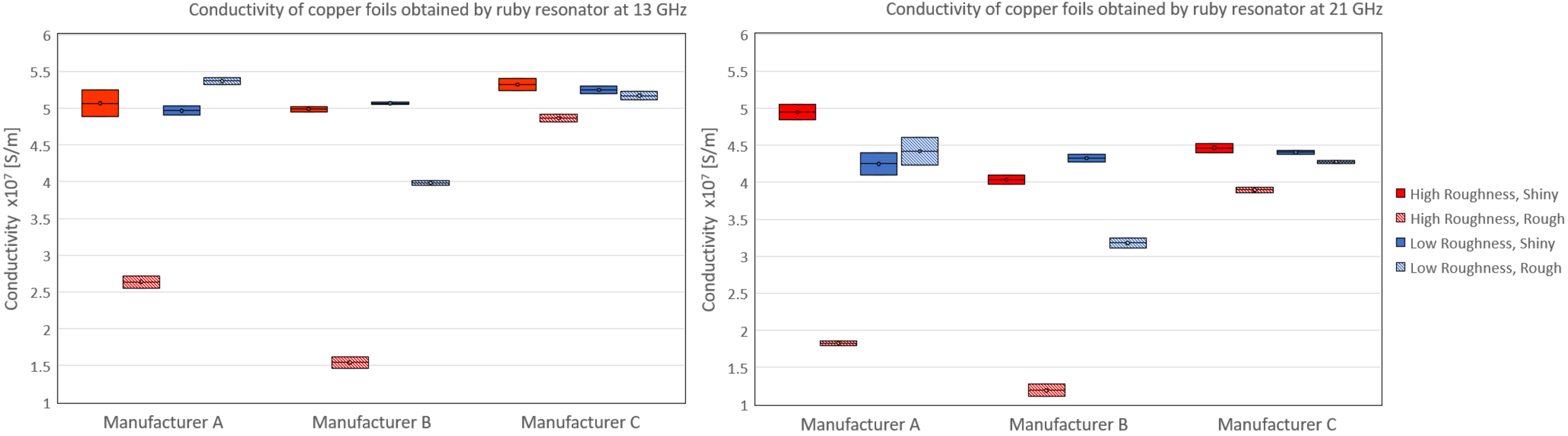
Reading the resonant frequency and Q-factor from the VNA and entering it into dedicated software to calculate surface resistance and conductivity.

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

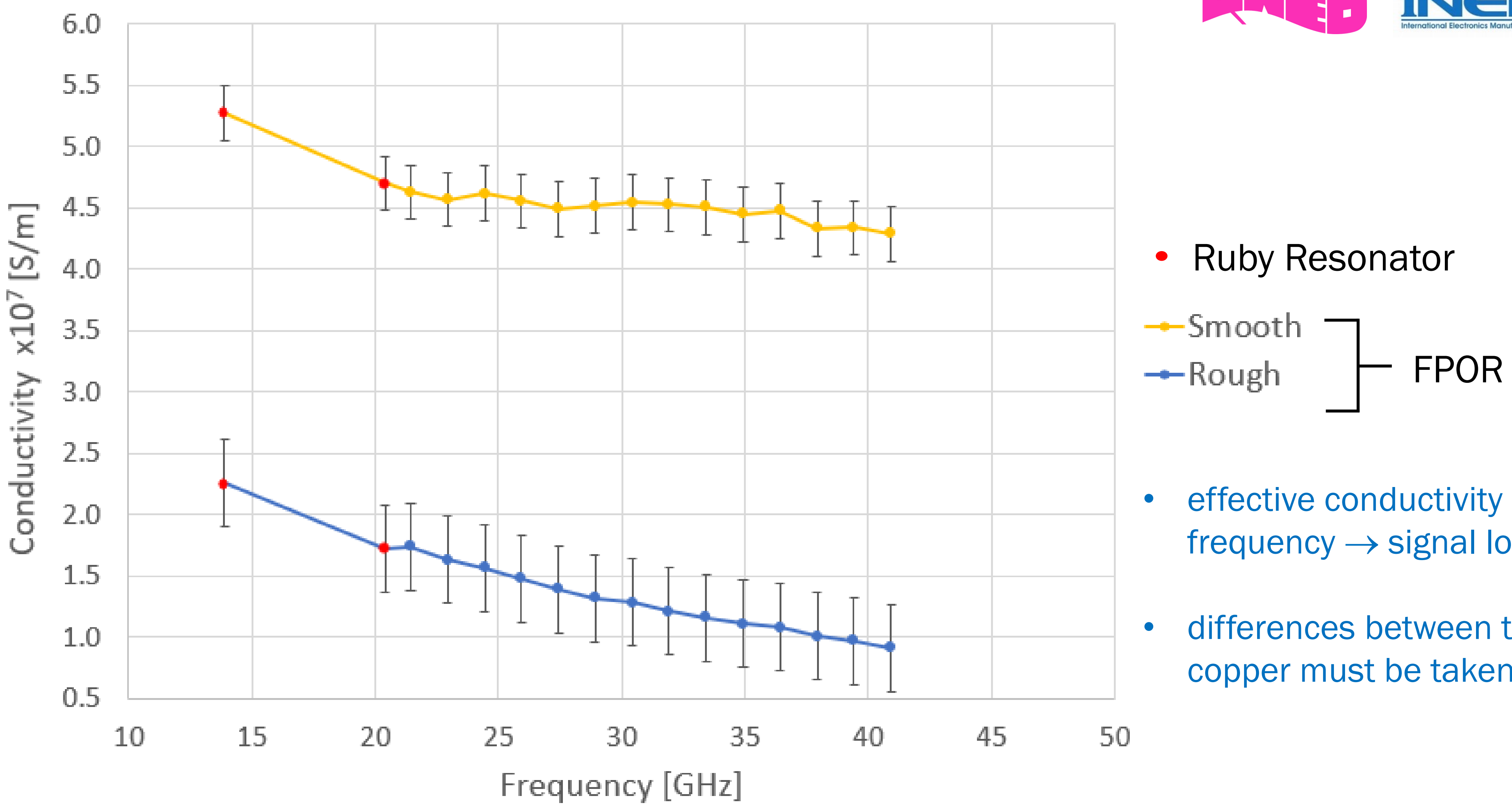
Rough side

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

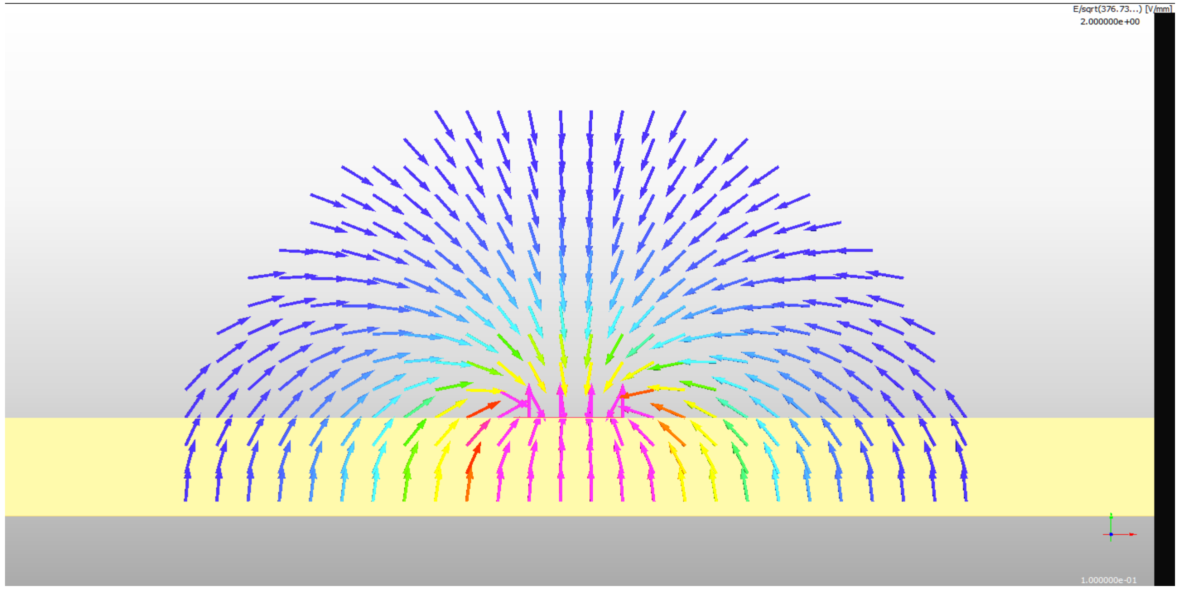


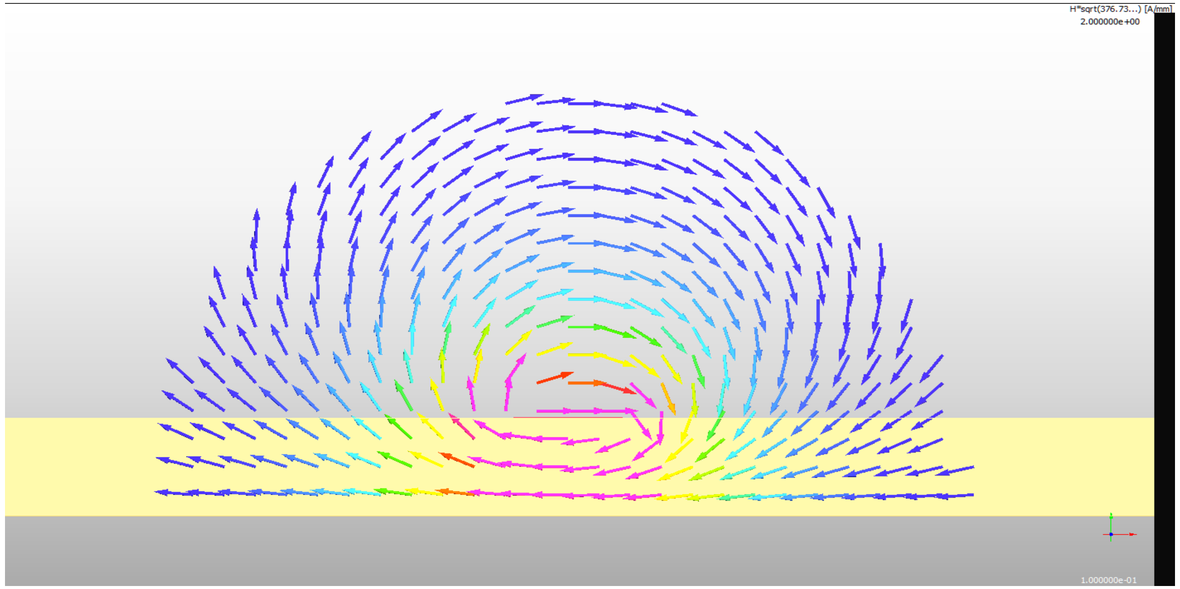
- effective conductivity decreases with frequency → signal loss will increase
- differences between the two sides of copper must be taken into account

Why Do We Need to Measure Both Sides of Copper

We model a 50 Ohm microstrip line.

QuickWave™ by QWED is used to simulate field patterns and calculate transmission losses.

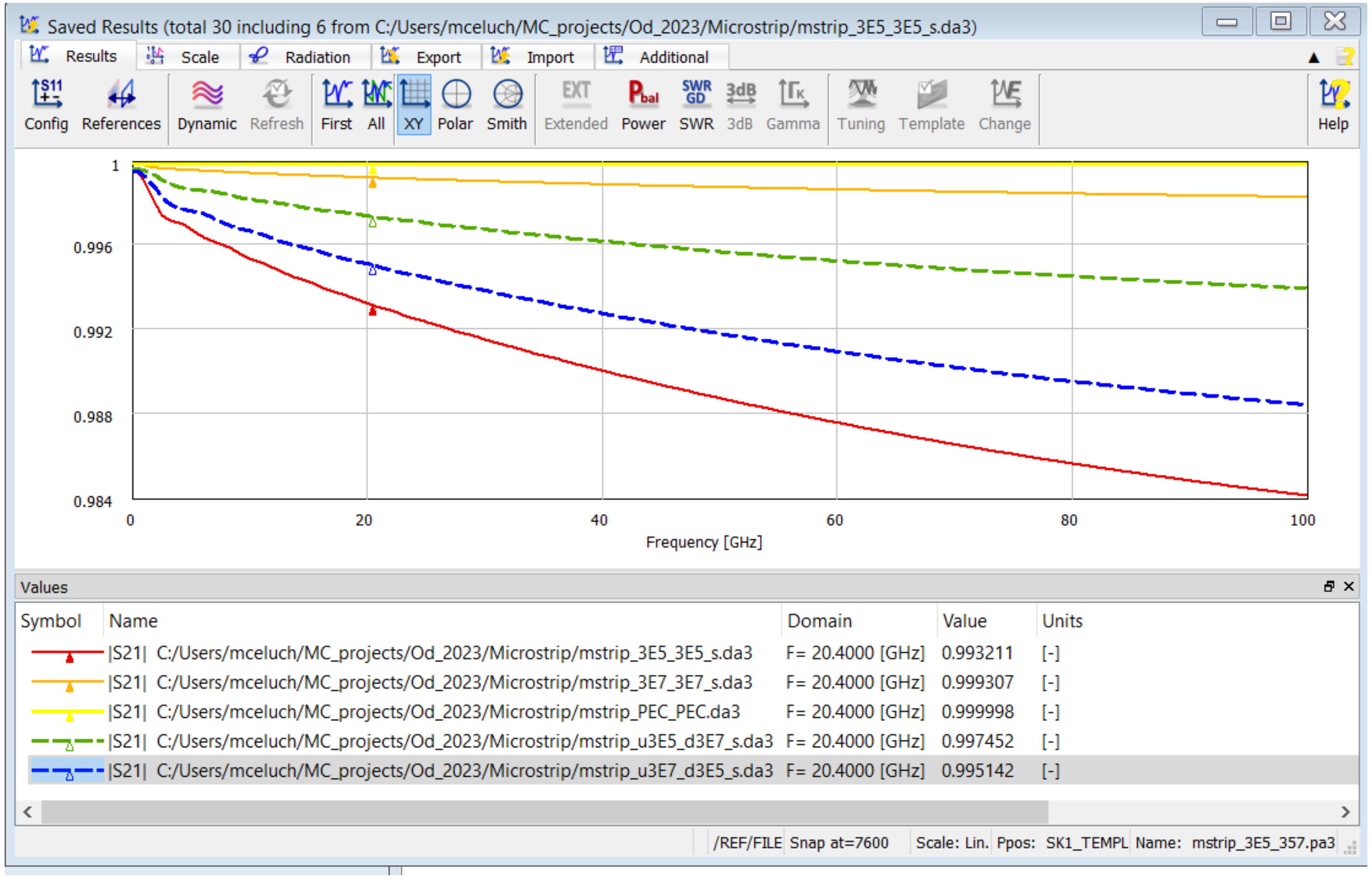




Higher field intensity below the strip → higher contribution of the bottom side of the strip to signal losses.

Why Do We Need to Measure Both Sides of Copper

Predictions based on field patterns are confirmed by simulating a segment of the line, with a dual-side microstrip (conductivities to the bottom and upper side assigned independently in the model).



continuous lines: identical top-bottom sides

dashed lines: different top-bottom sides

PEC

σ = 3E7 S/m

σ_{top} = 3E5 S/m σ_{bottom} = 3E7 S/m

σ_{top} = 3E7 S/m σ_{bottom} = 3E5 S/m

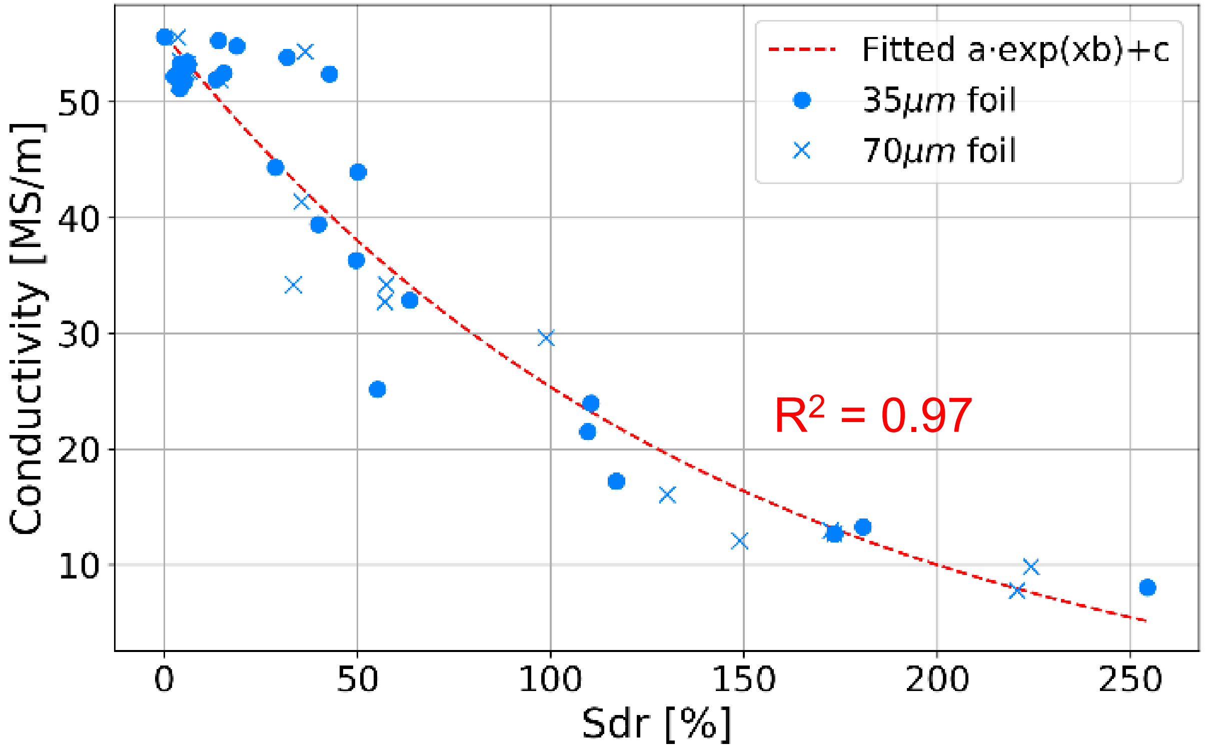
σ = 3E5 S/m

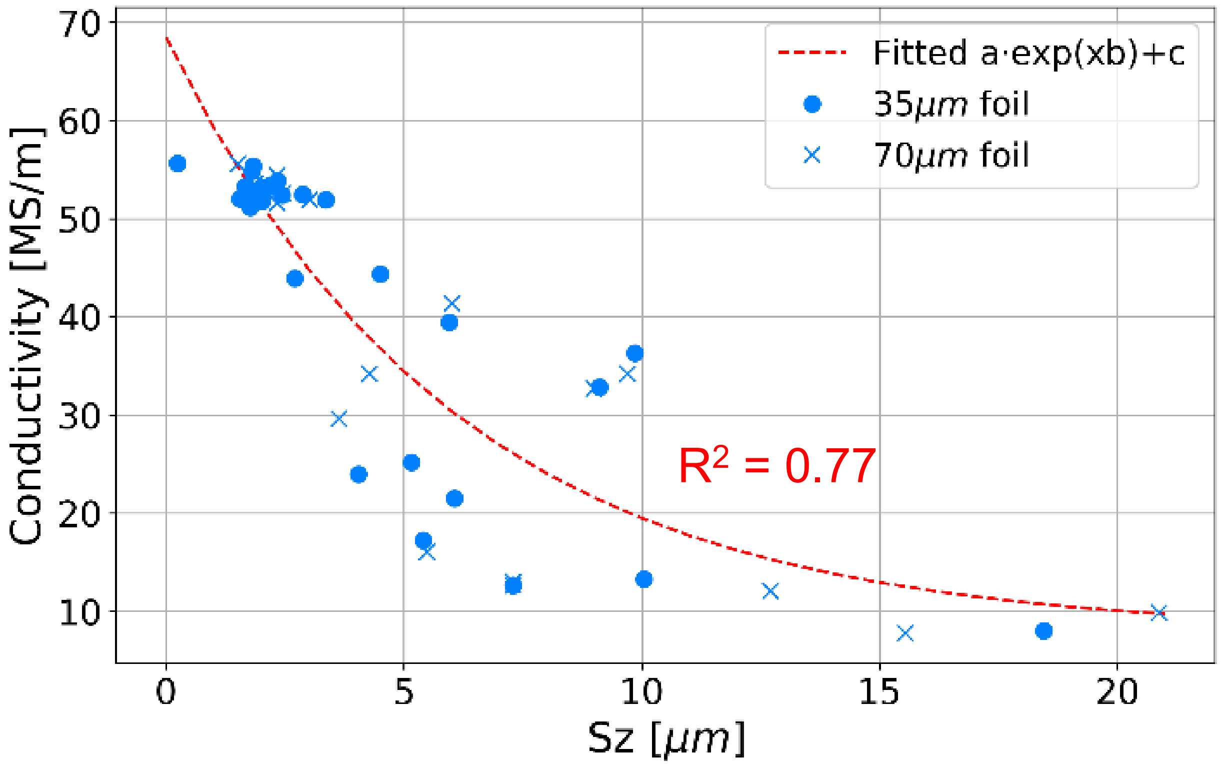
Note:
differences in bottop-top conductivities are exaggerated, to capture differences in transmission loss along a short segment of the line.

Results

Correlating effective conductivity to different surface roughness parameters

foils of 35μm and 70 μm thickness, both sides of each foil





correlation with Sdr (averages) is stronger than with Sz (roughness "amplitudes")
Sz, Sdr both obtained with noncontact laser interferometry
correlation is weaker with Rz, Ra obtained with stylus profilometer

Conclusions

1. 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. The initial testing was in the iNEMI project "Copper Foils", where the 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. Further developments and testing continue in the EUREKA-Eurostars project "5G_Foil".

5. QWED measurements show consistently 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,
    -

6. Foil roughness (preferably expressed as Sdr) is a major but not the only factor influencing the effective conductivity. The ongoing work concerns influences of grain size, oxide teratment, and other manufacturing factors.

Acknowledgment

The work was initiated in the iNEMI ‘Reliability & Loss Properties of Copper Foils for 5G Applications’ project of the International Electronics Manufacturing Initiative.

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