Pan-European
PEDC
Electronics Design Conference

Enhanced Modeling and Characterization of Copper Foils for PCB Design

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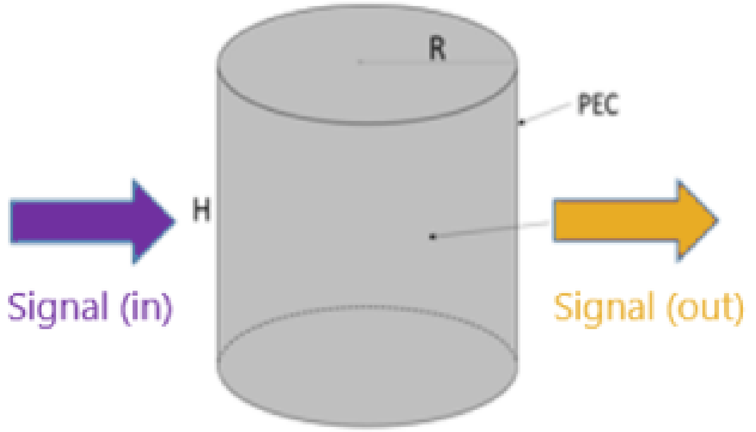
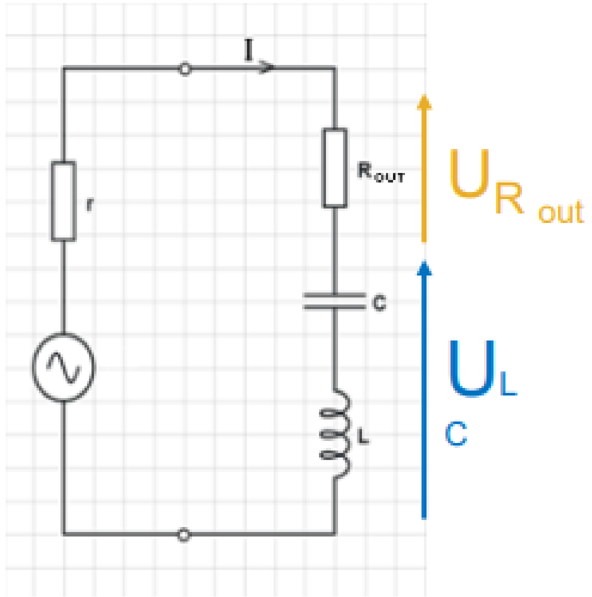
Outline

1. The iNEMI "Copper Foils" Project*.
2. Introduction - Electromagnetic Insight.
3. Problems of Copper Foil Loss at Higher Frequencies.
4. Experimental Methodology – Sapphire/Ruby Dielectric Resonator & plano-concave Fabry-Perot Open Resonator.
5. Sample preparation & measurement systems.
6. Results – Effective conductivities of copper foils & Correlation with Surface Roughness.
7. 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

Electromagnetic Insight
- Why Resonators for Material Measurements?





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} =zer

→ 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.

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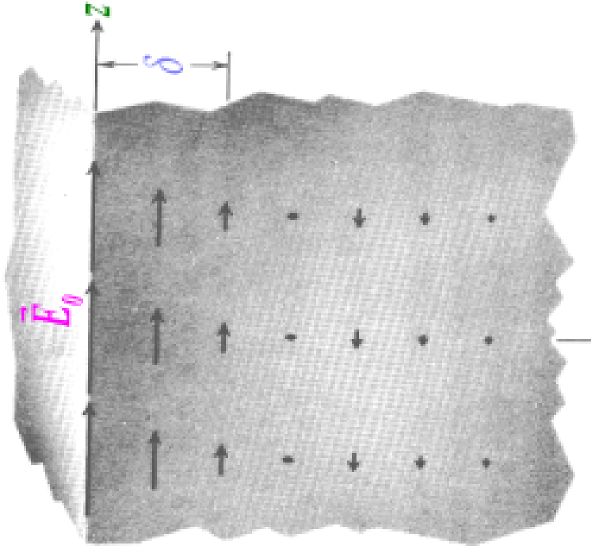
Why Copper Loss Becomes More problematic at Higher Frequencies

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

$J_0 = E_0\sigma$

→ problems common for metallic surfaces (bulk or foil)

wave incidence



penetration depth
(fields & currents attentuated e-times)

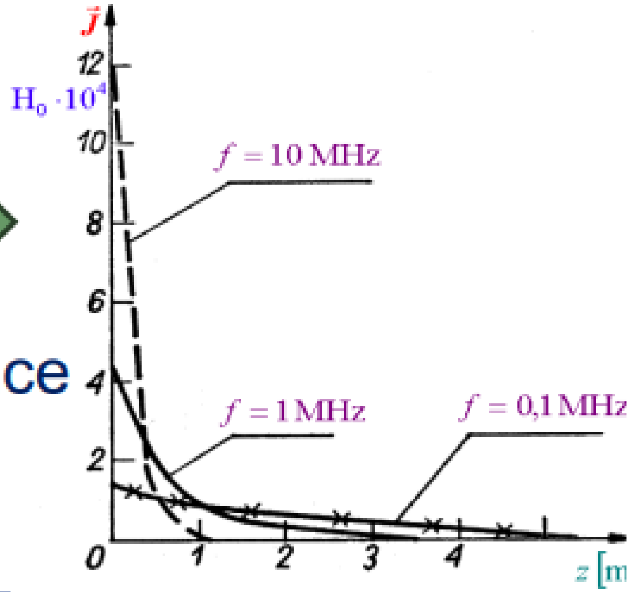
$$d_p = \sqrt{\frac{2}{\omega\mu_0\sigma}}$$

σ [S/m]	d_p [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)

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

wave incidence



current integrated over depth
(so called surface current):

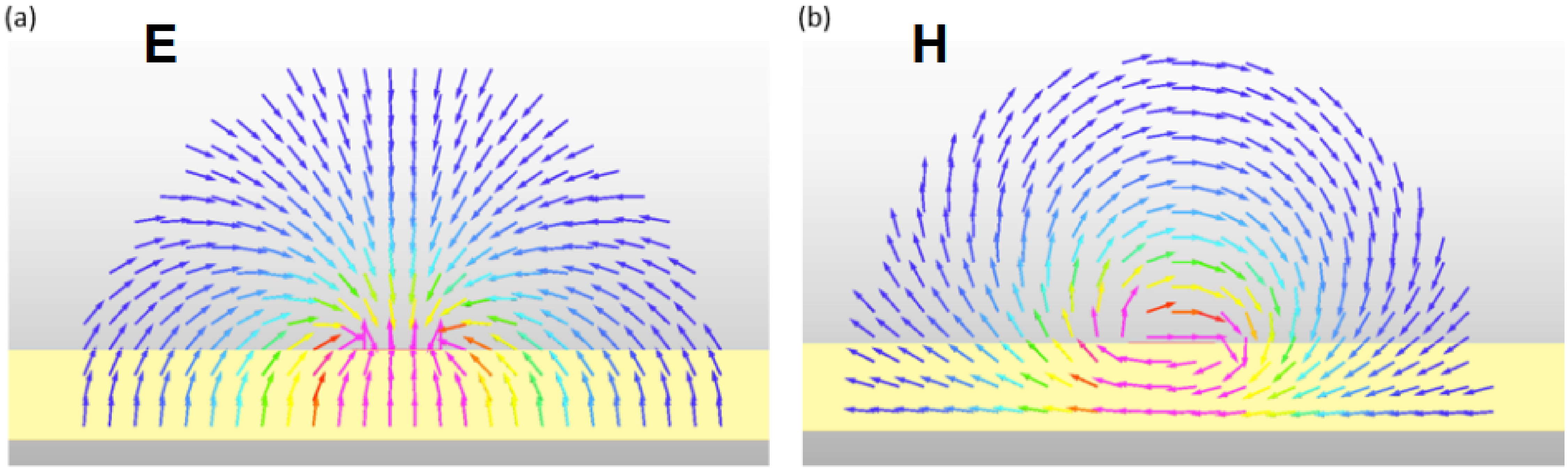
Total current ("surface current")
flowing along the metallic surface
is equal to the incident H-field amplitude
(does not depend on frequency or metal conductivity).

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

Why Both Sides of a Copper Foil Should Be Measured

We model a 50 Ohm microstrip line.

FDTD symulator is used to simulate field patterns and calculate transmission losses.

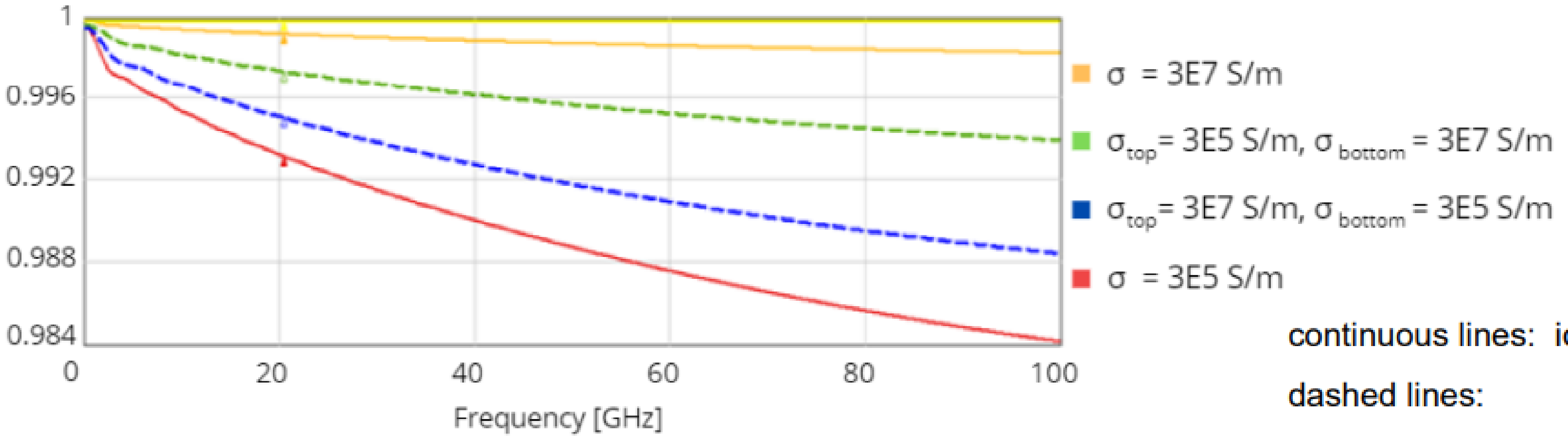


A 50 Ohm microstrip line and the (a) electric field and (b) magnetic field propagating through it.

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

Why Both Sides of a Copper Foil Should Be Measured

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

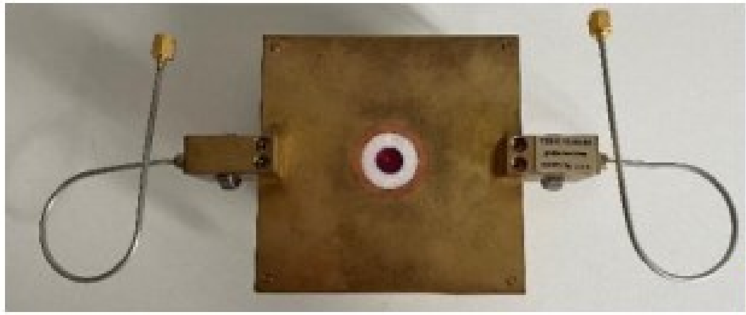
dashed lines: different top-bottom sides

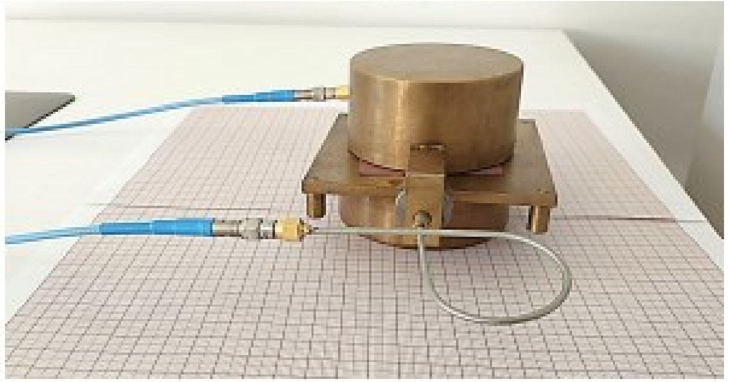
Segment of the line, with a dual-side microstrip - conductivities to the bottom and upper side assigned independently in the model

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

Experimental Methodology – Sapphire/Ruby Dielectric Resonator & Fabry-Perot Open Resonator

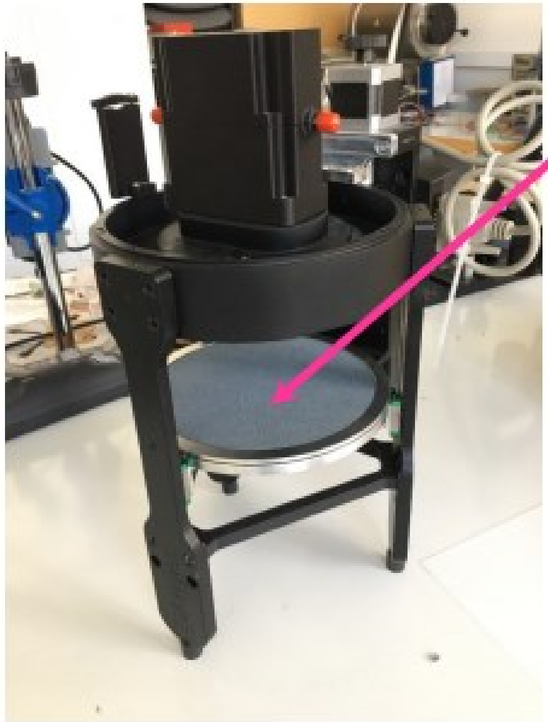
Dielectric Resonator:
Sapphire (SaDR) or Ruby (RuDR)





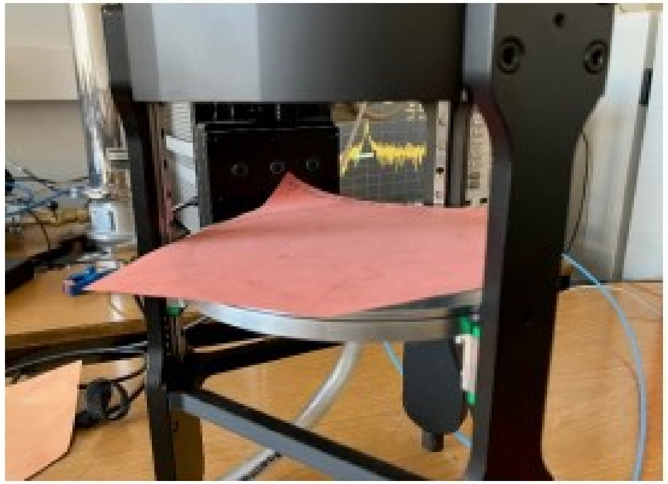
$$R_s = \sqrt{\frac{\pi f \mu}{\sigma_{eff}}}$$

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



Fabry-Perot Open Resonator
(modified to planar-concave desig

sample holder;
vacuum pump to be applied from below



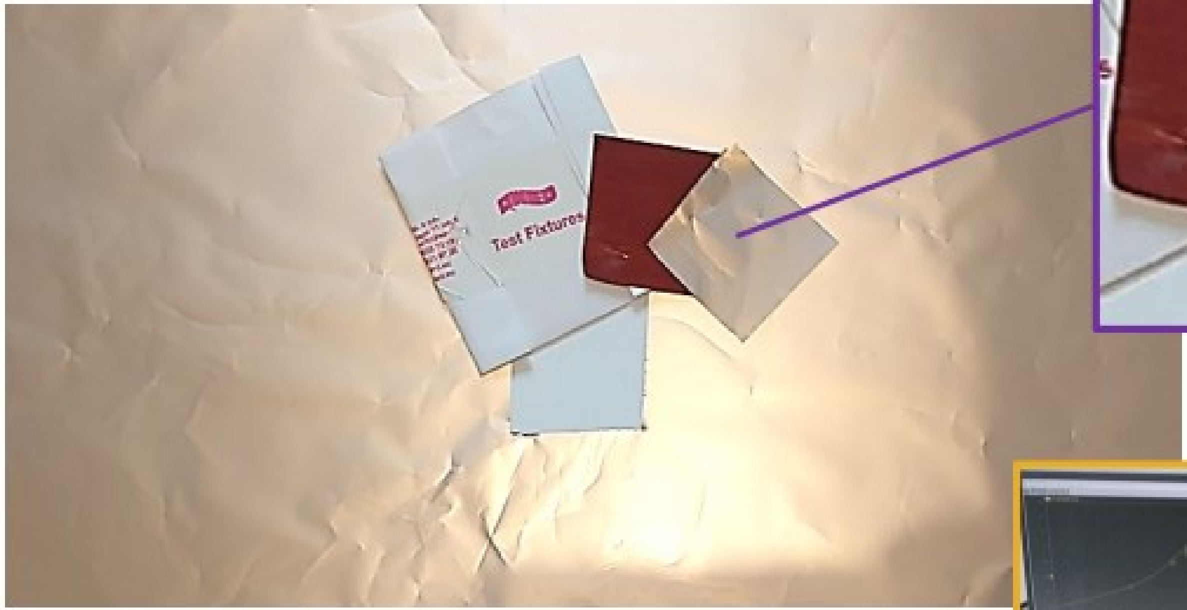
Both RuDR (SaDR) and FPOR resonators allow measuring a copper foil by itself:

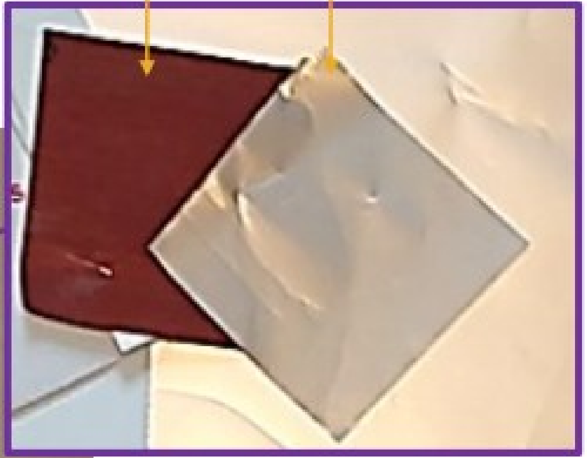
- no need to fabricate a test circuit!
- loss from the foil is separated from any dielectric loss,
- the two sides of foil can be measured separately,
- foils on laminates can also be measured.

Sample preparation – Copper foils

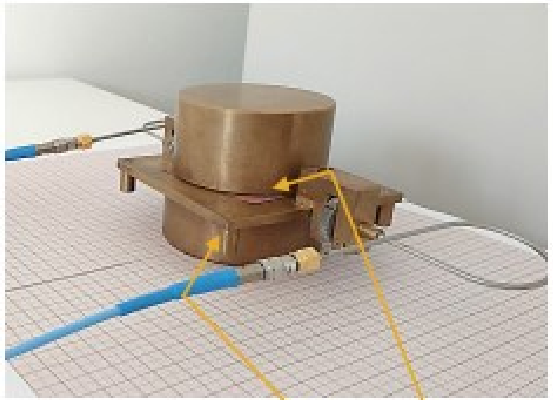
„**Rough**” side of the sample

„**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.

Measurement systems

example
of a measurement kit

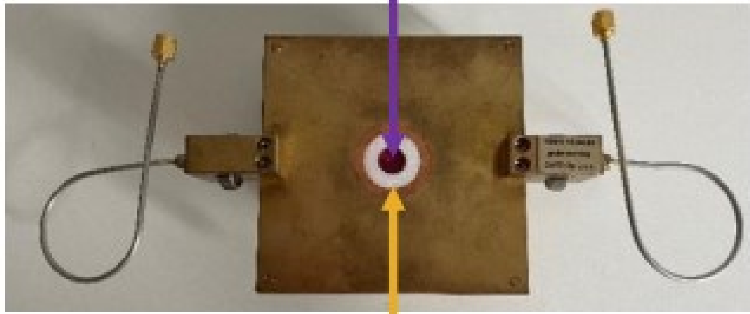
Losses of the resonator come from:

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).

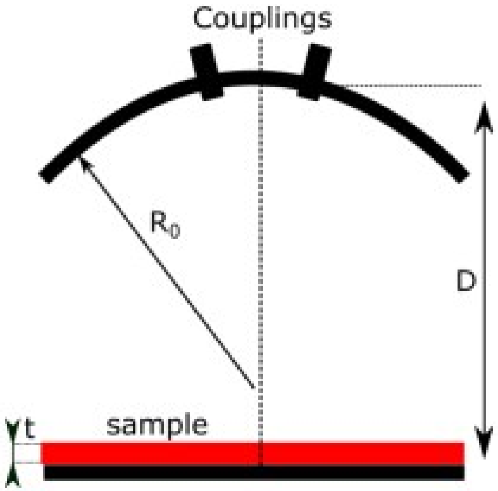
- It operates at nominal frequencies of **13 GHz** and **21 GHz**.
- Two identical metallic samples are required for measurements.
- The samples should have dimensions of at least **23 mm x 23 mm.**
- The dedicated software calculates material parameters based on the measured data: resonance frequency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

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



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

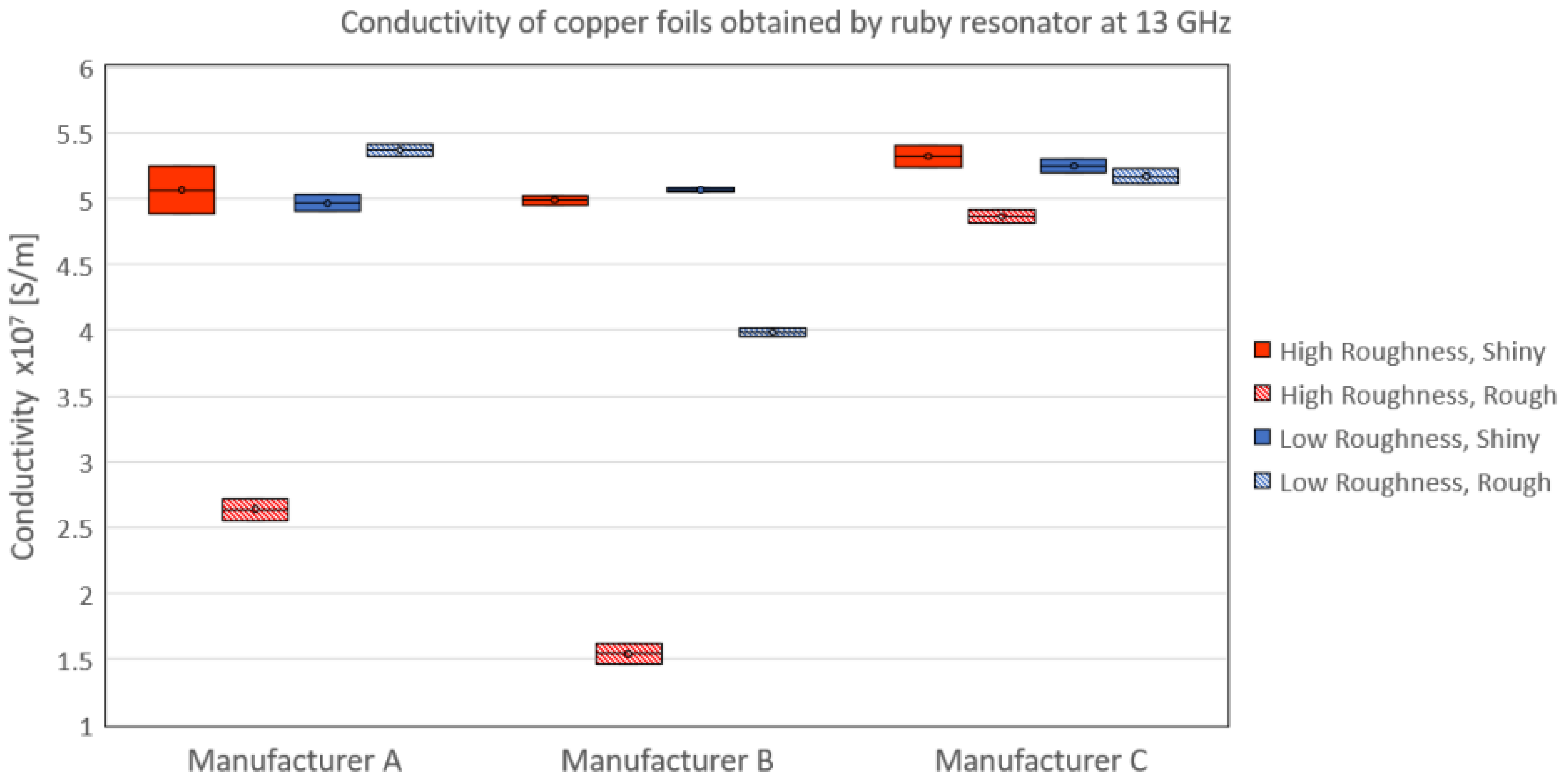
Measurement systems



sample size
90mm x 90mm

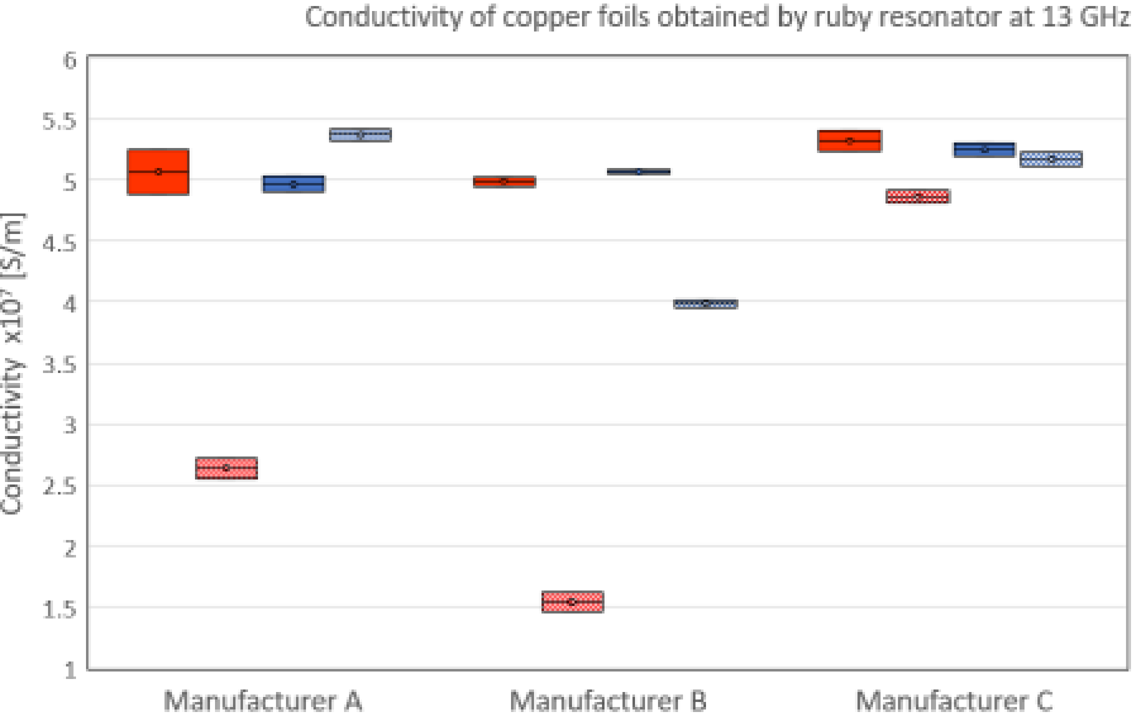
FPOR allows broadband and precise resonant measurements of electromagnetic properties of materials.
It is adapted to copper foil measurements by:
- replacing the classical double-concave mirors with planar-concave design (the foil-under-test forms the planar mirror),
- a vacuum pump is applied for fixing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

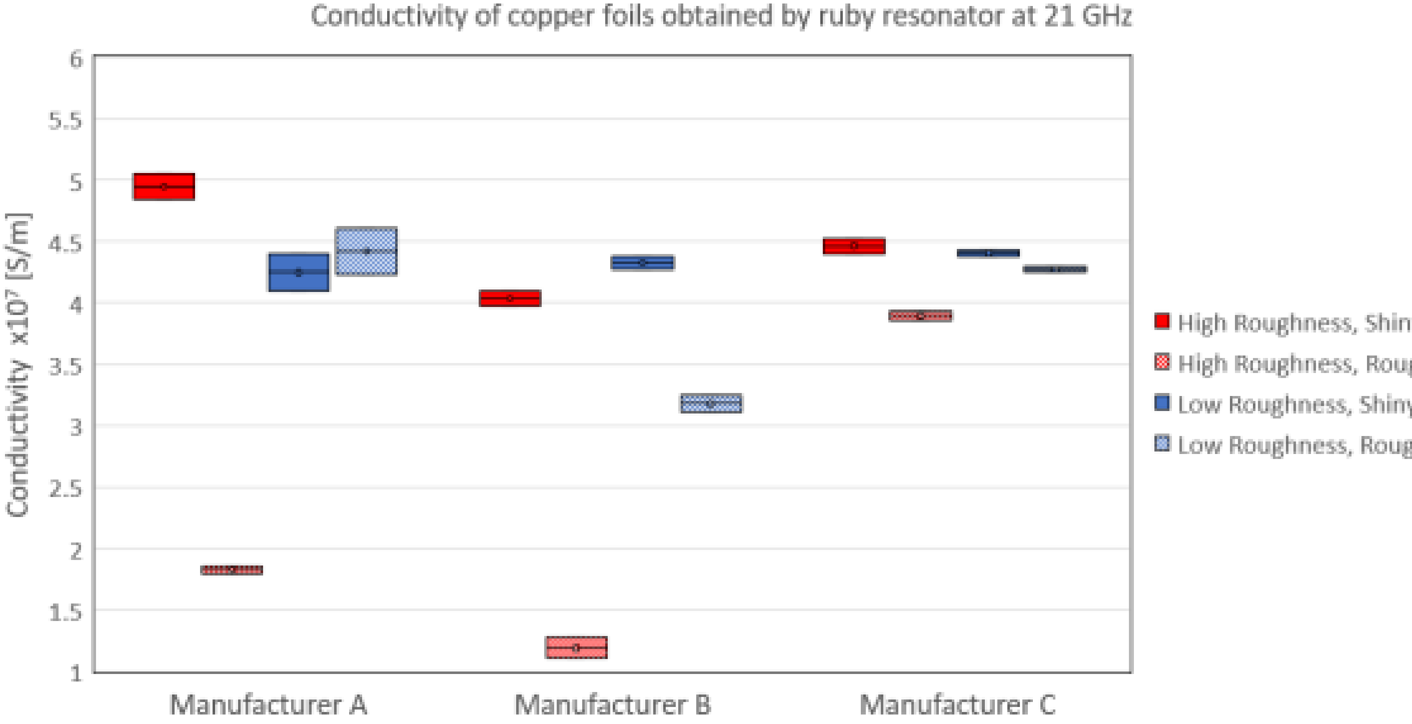
Results – Effective conductivities of copper foils



- 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).

Results – Effective conductivities of copper foils

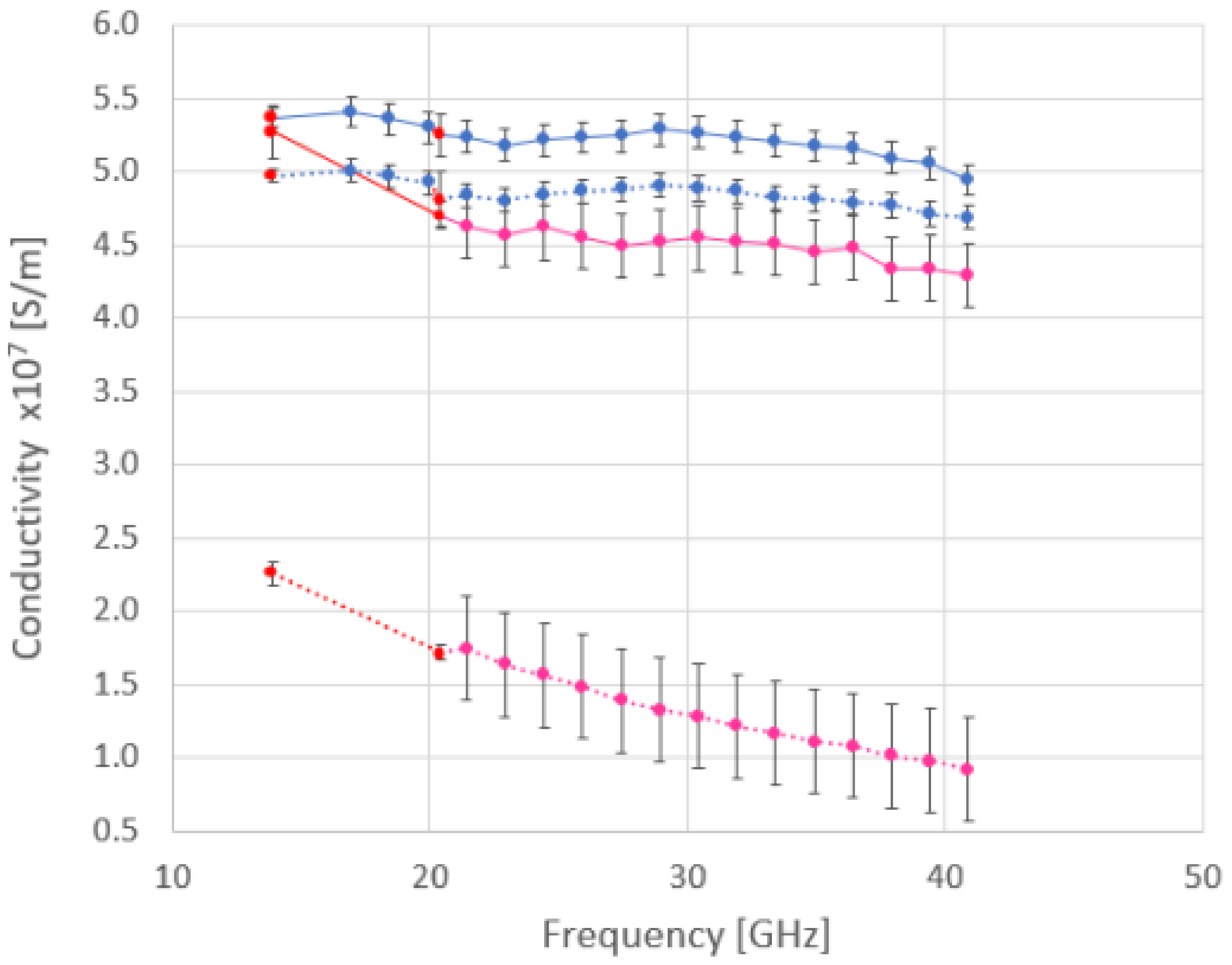




At the higher frequency of 21 GHz:

- 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.

Results – Effective conductivities of copper foils



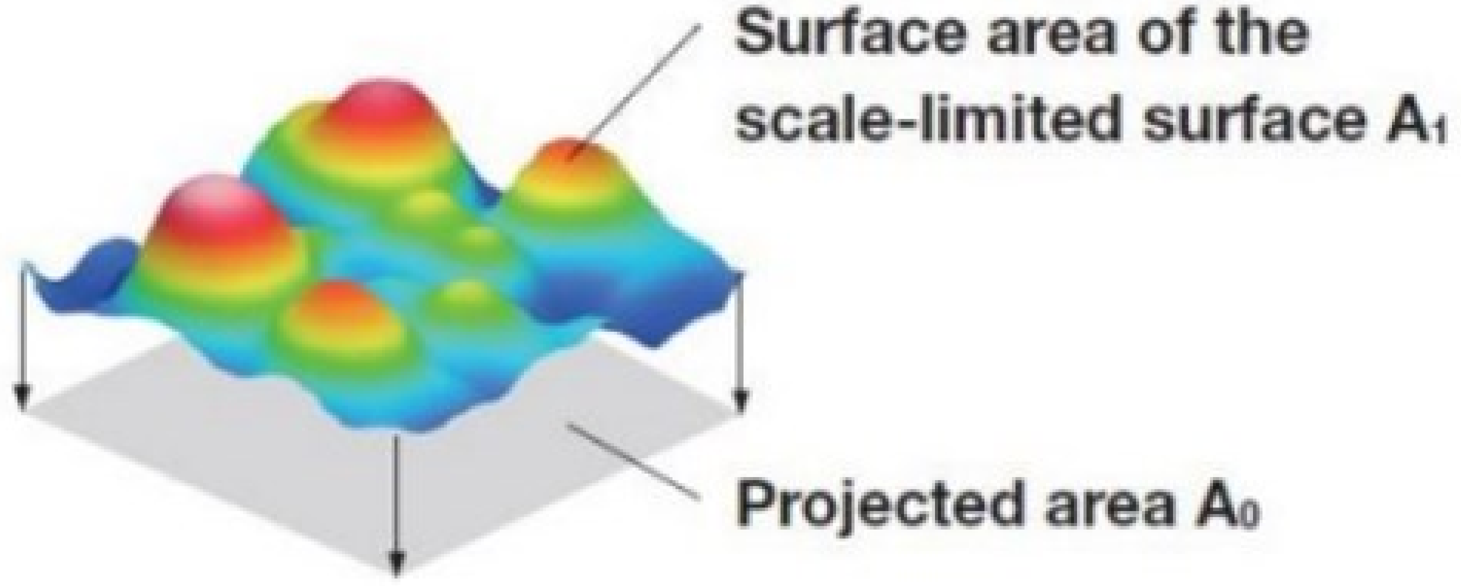
Manufacturer A
– Low&High Roughness case

- Ruby Resonator RuDR

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

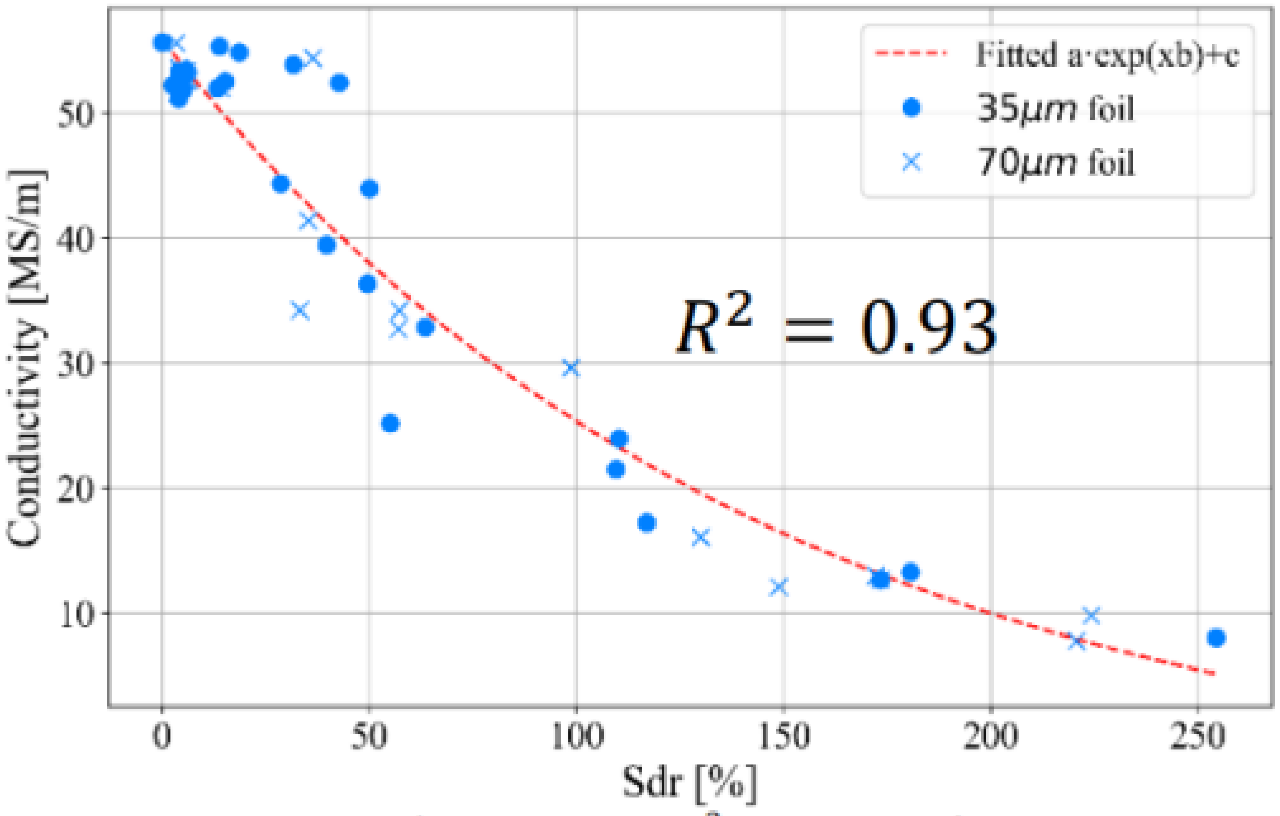
Roughness parameters (contact stylus profilometre)

Developed interfacial area ratio (Sdr)

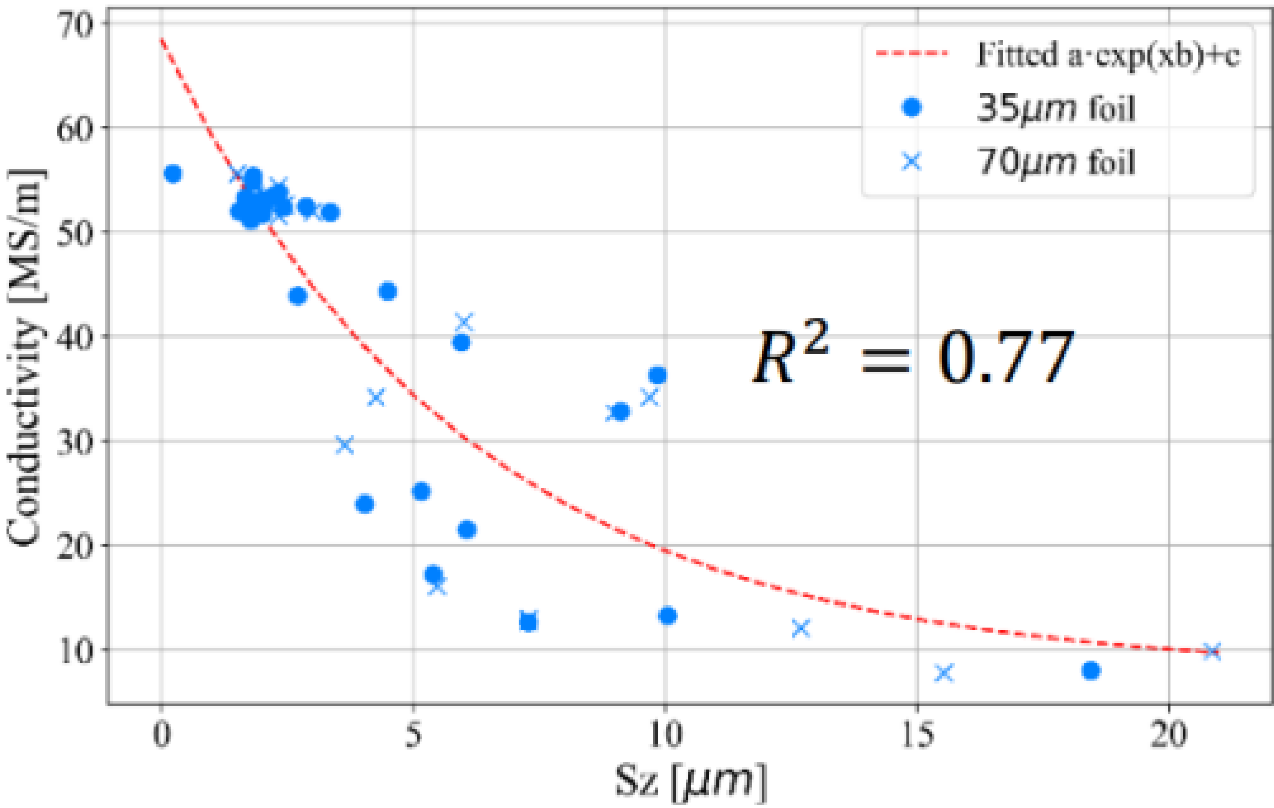


* https://www.olympus-ims.com/en/metrology/surface-roughness-measurement-portal/parameters/#!cms[focus]=cmsContent14708

Correlation Between Effective Conductivity and Surface Roughness



(a=61.4 MS/m, b=-6.87*10^{-3}, c=-5.59 MS/m)



(a=60.7 MS/m, b=-0.16 1/um, c=-7.82 MS/m)

Better fit with noncontact pamateres
But still not perfect fit.

Summary

- Measurements are conducted on copper foils in their delivered state from three manufacturers, covering high- and low-roughness variants. The study includes both "rough" and "shiny" sides of each foil type, with six sheets per type, enabling a comprehensive analysis of sample and measurement reproducibility. Averages and standard deviations are calculated.

- 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.

We have confirmed that increasing roughness leads to higher loss.

- However we have also shown that roughness-to-loss is not represented by a closed-form formula.

- Sz or Sdr (from non-contact roughness measurement) give higher correlation to loss, than Rz (from contact measurement).

It is recommended to measure foils before their application in mm-Wave circuit design.

As further expected in view of the electromagnetic considerations, foil thickness is irrelevant.

Acknowledgment

QWED team wishes to thank all the partners, of all the iNEMI "5G" projects,

for their great collaboration in the benchmarking activities.

With this presentation, we specifically acknowledge the collaboration in the iNEMI "Copper Foils" Project:

"Reliability & Loss Properties of Copper Foils for 5G Applications"

- This work was supported by the Polish National Centre for Research and Development, within the M-ERA.NET I4Bags project (under contract M-ERA.NET3/2021/83/I4BAGS/2022), ULTCC6G_Epac (M-ERA.NET2/2020/1/2021) EUREKA-Eurostars 5G_Foil project (DWM/InnovativeSMEs/176/2023).

NCBR National Centre for Research and Development M-era.Net ULTCC6G_EPac I4Bags 5G Foil

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