iMPACT 2023

International Microsystems, Packaging,
Assembly and Circuits Technology conference

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Oct. 25-27
Taipei Nangang Exhibition Center, Hall 1

18th International Microsystems, Packaging, Assembly and Circuits Technology Conference

# Modelling-based characterisation of copper foils for mmWave applications

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IMPACT Session [S1] iNEMI
25 Oct. 2023

# 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 started in 2021 and was inntroduced to the IMPACT community at IMPACT 2021:

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IMPACT 2021
5G+
Dec. 21-23 Taipei, Taiwan

16th International Microsystems, Packaging, Assembly and Circuits Technology Conference

**TOPIC:** ***Reliability & Loss Properties of Copper Foil for 5G Applications***

**REPORTER:** ***Ed Kelley***

**AFFILIATION:** *Isola Group & Chair of iNEMI PCB & Laminate TIG*

**Email:** *ed.kelley@isola-group.com*

iNEMI

**Paper Code:** ***S1-1***

**Date:** ***Tue, Dec 21, 2021***

Project leadership & management as of Oct. 2023:

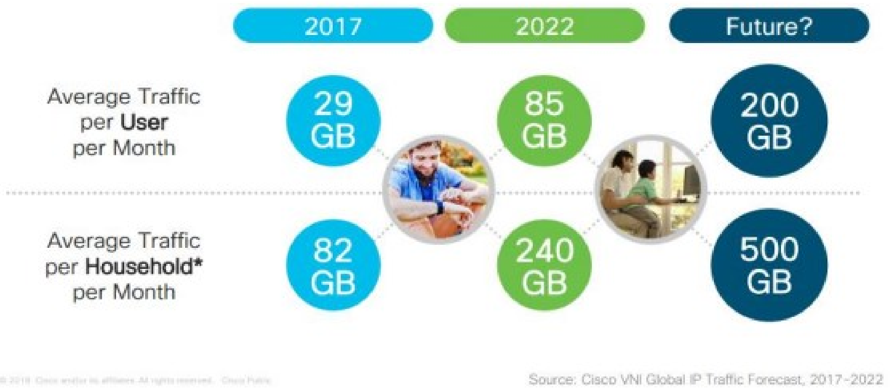
Project Leader: Steven Ethridge (Dell)

Project Manager: Steve Payne (iNEMI)

# Drivers – High Speed & High Frequency – 5G

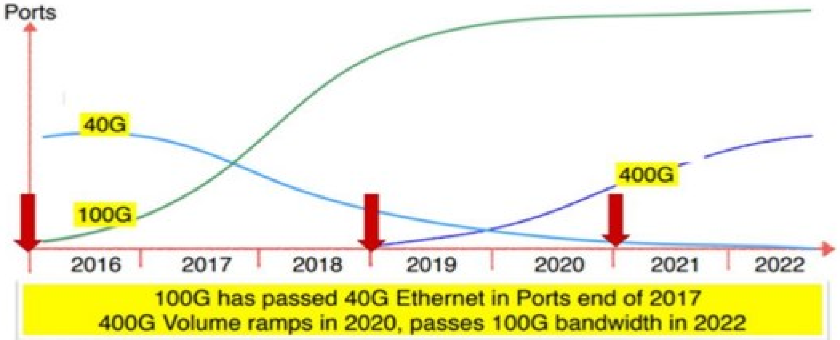
- Growth in the volume & speed of data transmission enabled by 5G telecommunications, driven by applications including:
  - Internet video, IP VOD, Web based data & gaming
  - High-speed computing, including AI and blockchain
  - Automotive ADAS
- 5G frequencies
  - Low band: typically less than 1 GHz
  - Mid-band: typically between 1 and 6 GHz
  - **High-band: 24 to 40 GHz and above**
- Drives need for low Dk/low Df base materials
  - Dielectric losses – historical focus
  - Conductor losses – become critical at high frequencies

Average Global Internet Bandwidth Usage



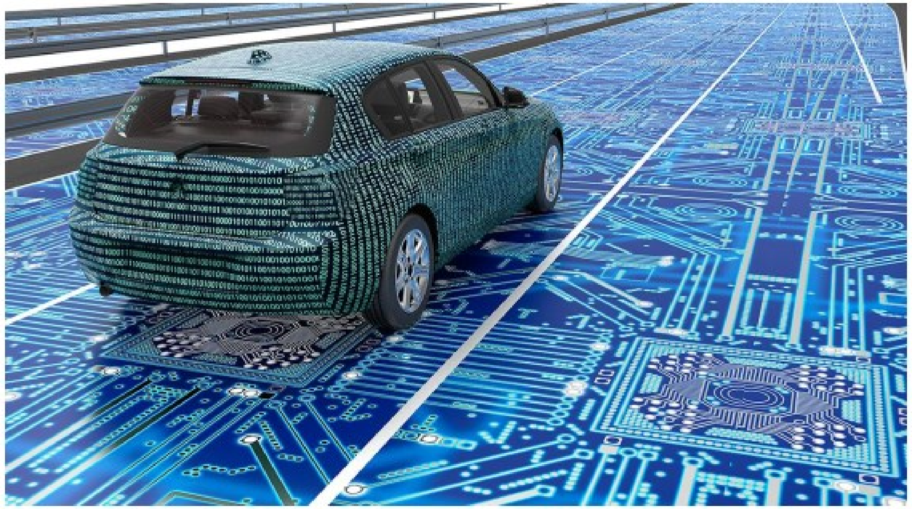
Source: Cisco VNI Global IP Traffic Forecast, 2017-2022

40G - 100G - 400G Switch Port Transition



100G has passed 40G Ethernet in Ports end of 2017
400G Volume ramps in 2020, passes 100G bandwidth in 2022

Source: Dell'Oro Group Jan 2018 Ethernet Switching Forecast



*from: Ed Kelly, IMPACT 2021*

participates to projects evaluating:

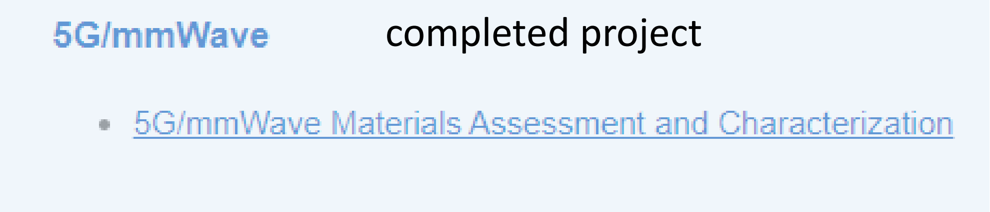
dielectric losses

conductor losses

→ fast & precise measurement methods,

→ physical insight with computer modelling,

→ dissemination (mainly in IEEE and EU communities).



completed project

**5G/mmWave**

- 5G/mmWave Materials Assessment and Characterization

ongoing projects

**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

International Electronics Manufacturing Initiative

Home / Projects / PCB & Laminates / Reliability & Loss Properties of Copper Foils for 5G Applications

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:

$$J_0 = E_0\sigma$$

→ problems common for metallic surfaces (bulk or foil)

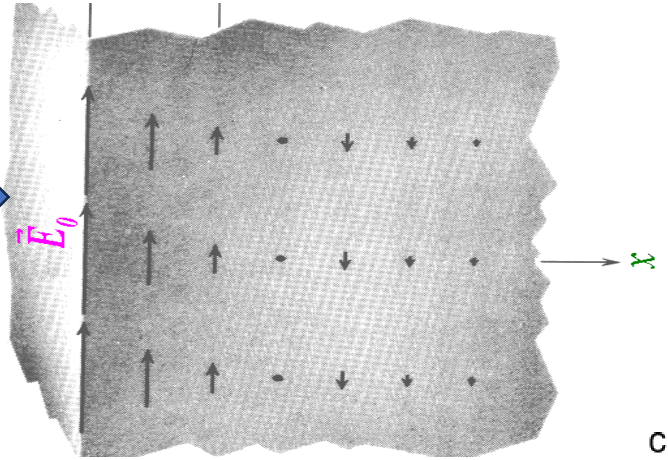
penetration depth
(fields & currents
attentuated e-times)

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

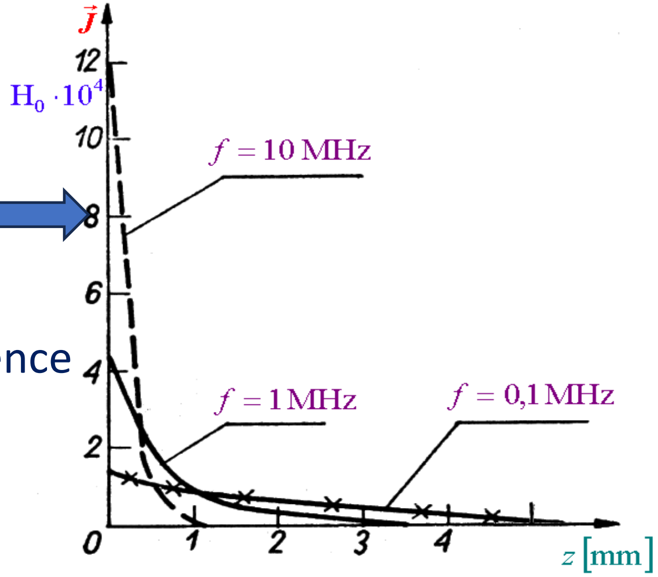
| σ [S/m] | *dp* [μm] @13.5 GHz non-magnetic metal |
|---|---|
| 1.00E+03 | 135.8309 |
| 1.00E+04 | 42.9026 |
| 1.00E+05 | 13.5588 |
| 1.00E+06 | 4.2871 |
| 1.00E+07 | 1.3556 |
| 5.00E+07 | 0.6063 |

surface resistance
(sheet resistance)

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



wave
incidence



wave
incidence

current integrated over depth
(so called surface current):

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

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

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

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
layter 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*

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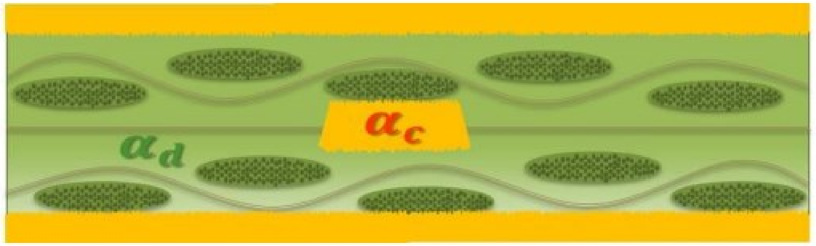
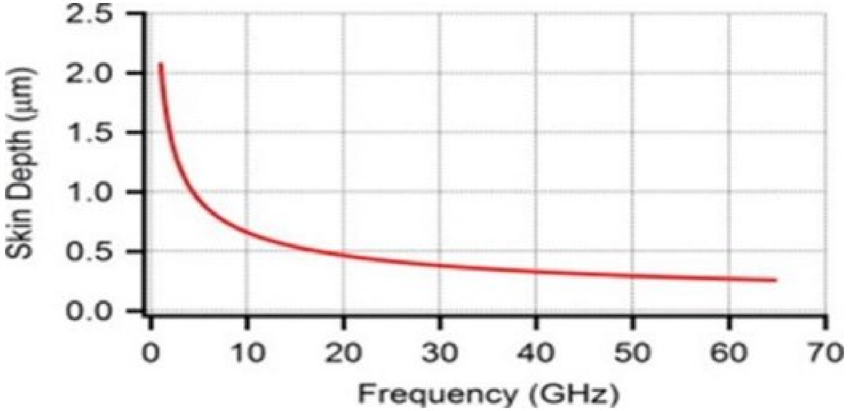
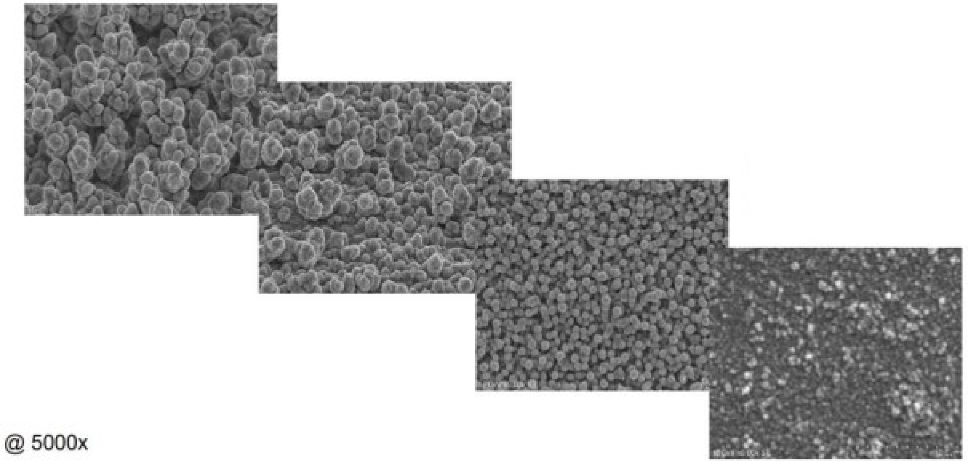
## Conductor Loss Drives Need for Ultra Low-Profile Copper

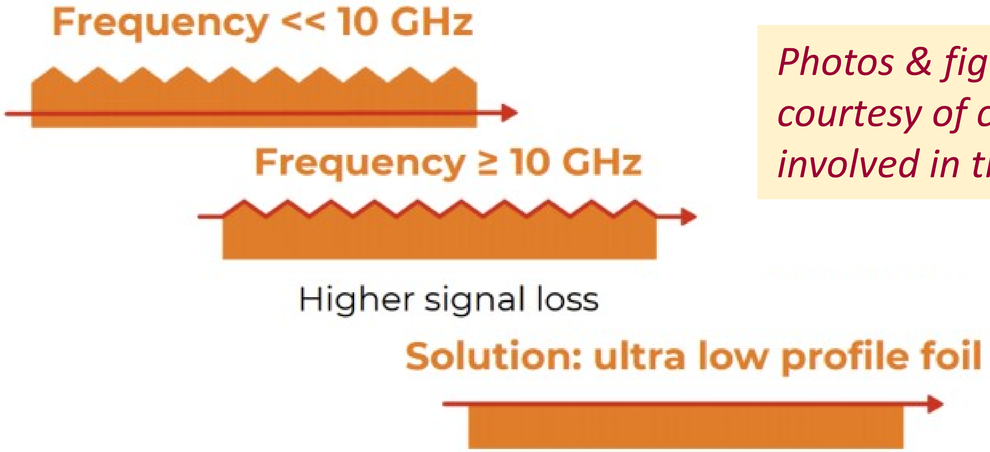


As frequency increases, skin depth decreases, and a significant amount of the current is carried in the bond treatment portion of the copper – including on the oxide alternative side





All @ 5000x



**Frequency << 10 GHz**

**Frequency ≥ 10 GHz**

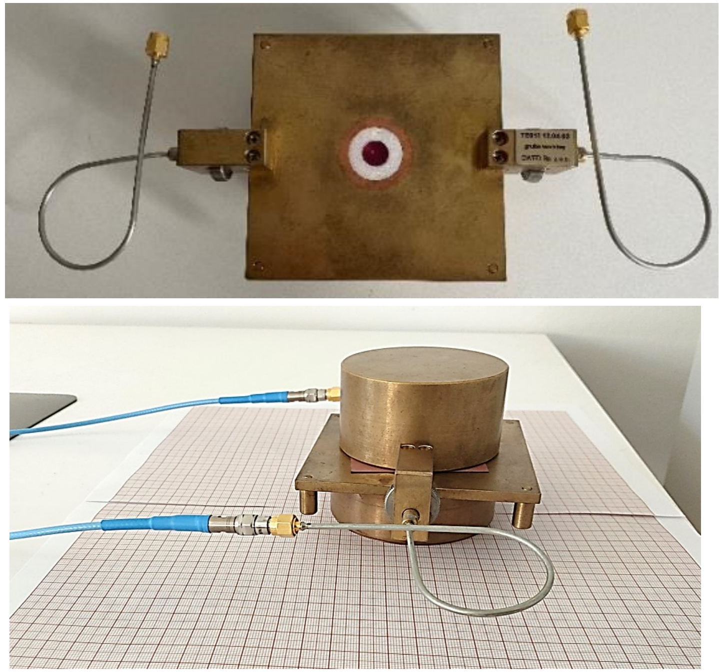
Higher signal loss

**Solution: ultra low profile foil**

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

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

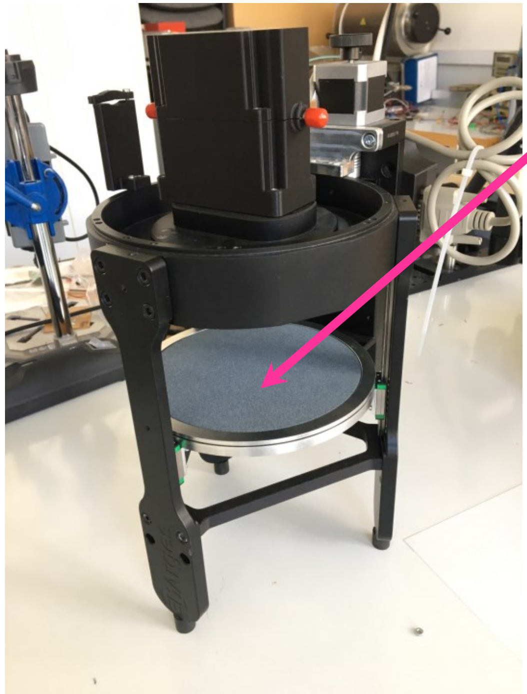
Dielectric Resonator:
Sapphire (SaDR) or Ruby (RuDD)



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

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

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



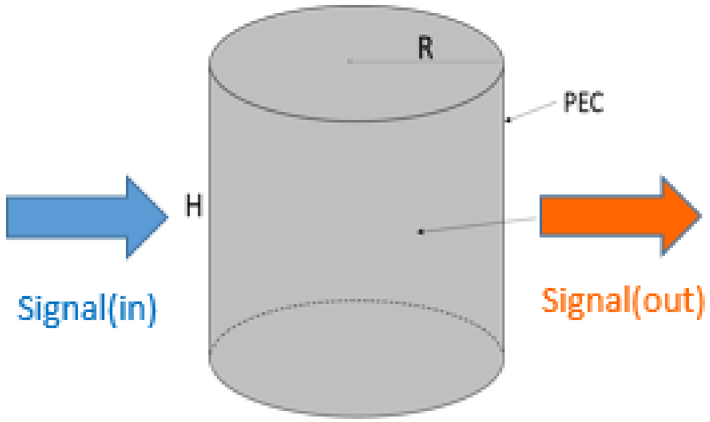
sample holder;
vacuum pump to be applied from below

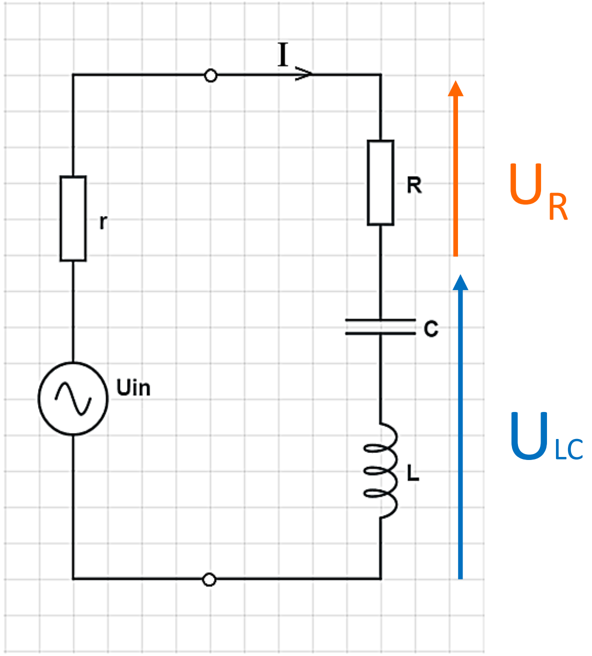
Both RuDD (SaDR) and FPOR resonators allow measuring a copper foil by itself:

- 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):





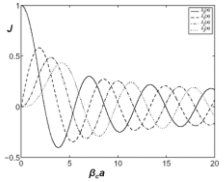
given fixed strength of Signal(in),
at resonance Signal (out) is strongest

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

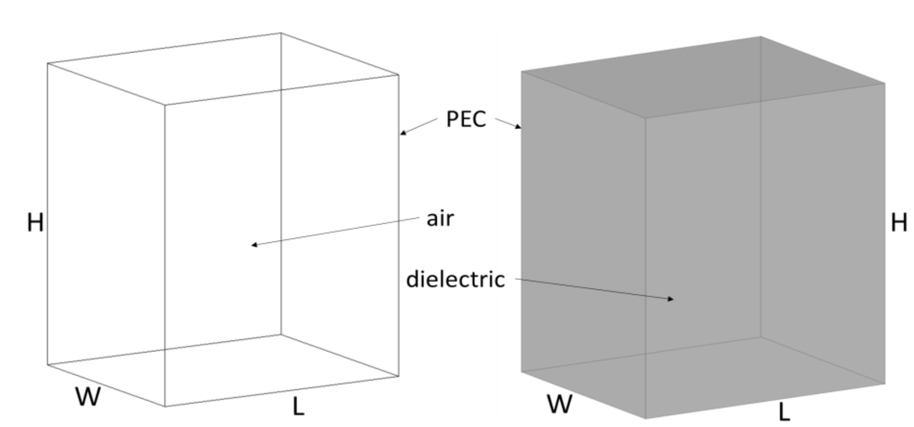
→ The resonance is sharpest (narrow-band, high-Q) when the resonator is composed of ultra-low-loss materials.

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

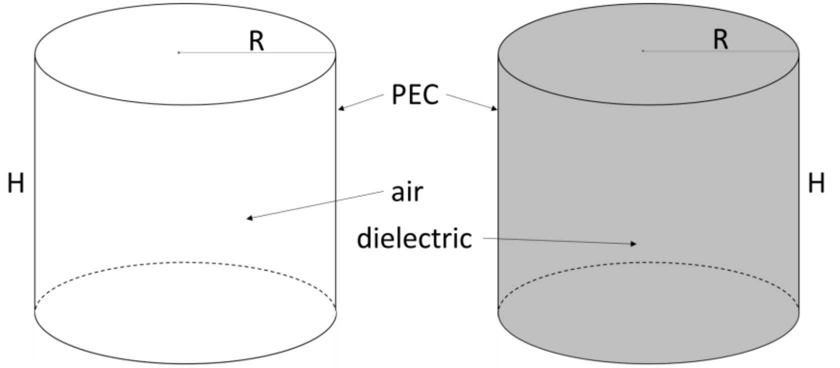
# Examples of canonical examples of resonators



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



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



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

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

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

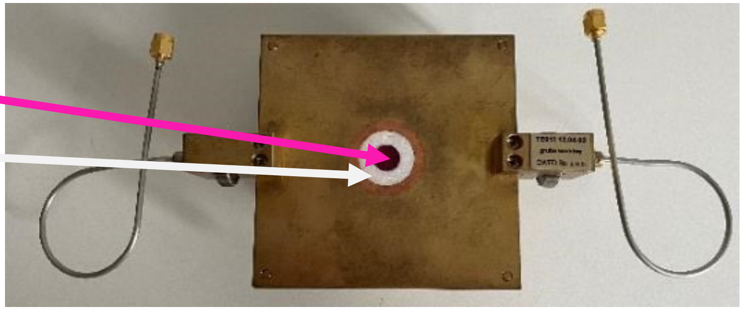
→ In classical applications for measuring dielectric materials, we minimise losses from cavity walls, to accurately capture the loss due to the dielectric filling.

→ 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

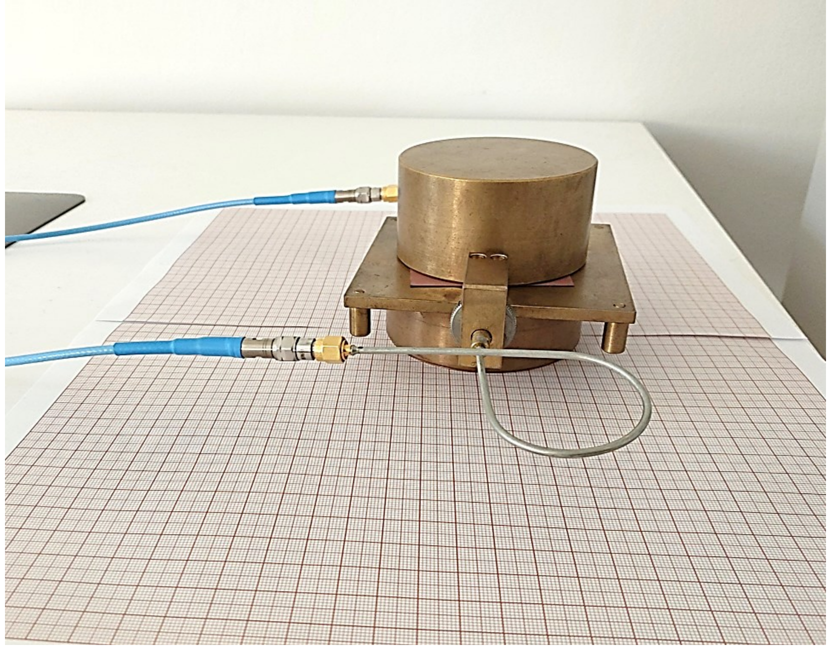
A cylinder of high-permittivity dielectric (sapphire or ruby) forms the resonator.

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:

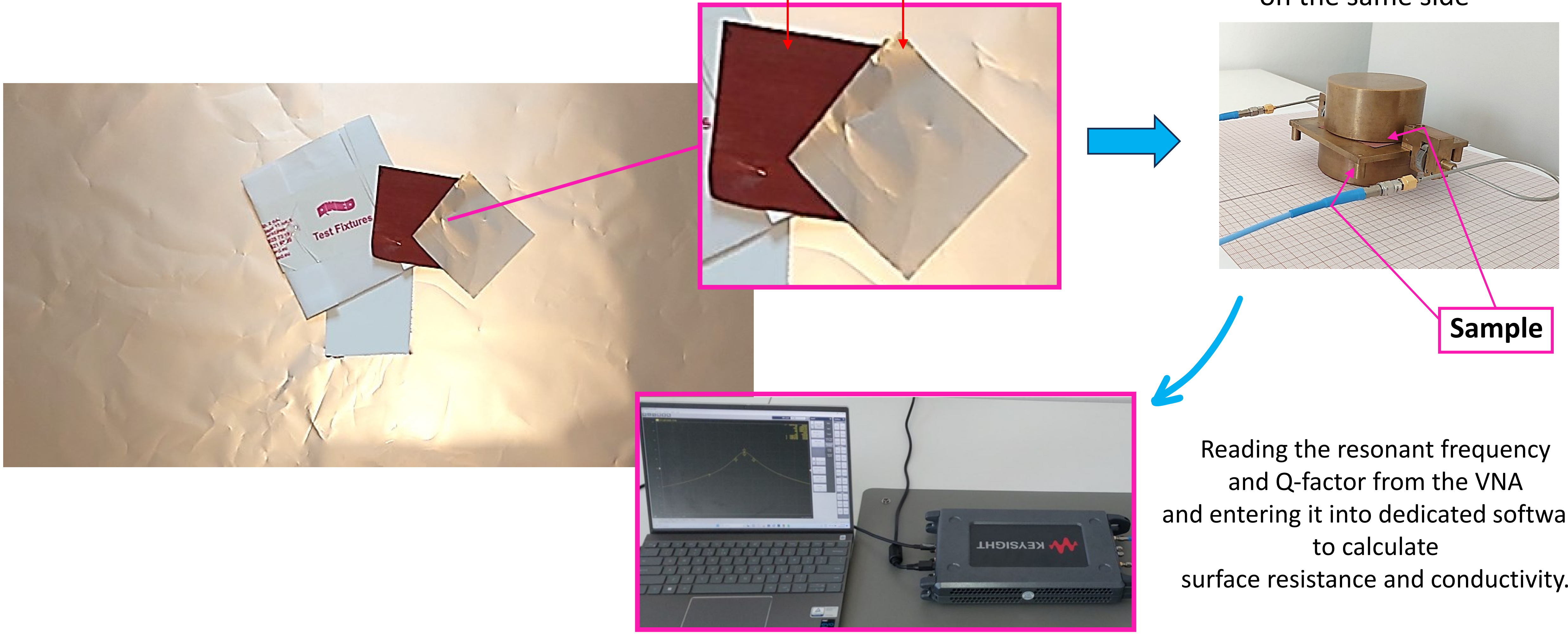
- 3 manufacturers,
- High- and Low-roughness foils,
- 6 sheets of each foil,
- to be measured on both “rough” and shiny” sides.

# Copper foils

„**Rough**” side of the sample

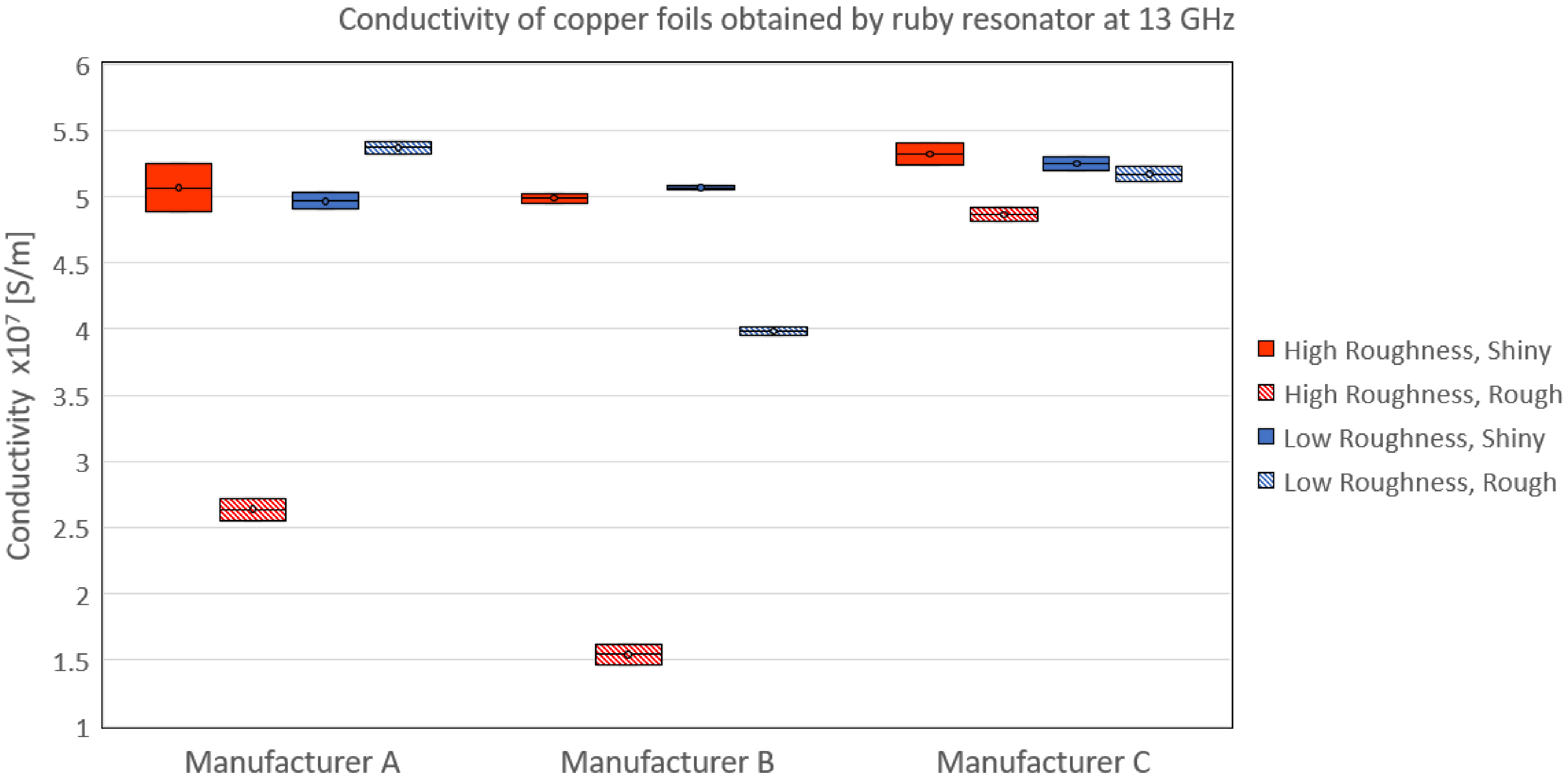
„**Shiny**” side of the sample

Samples measured
on the same side



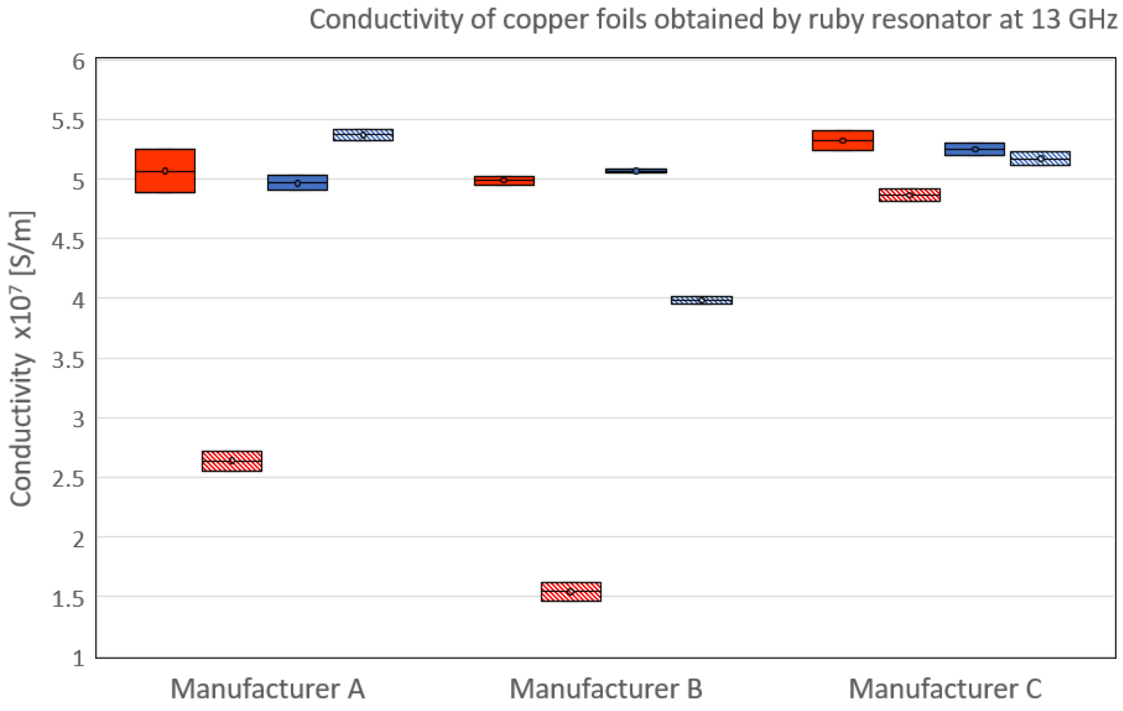
Reading the resonant frequency
and Q-factor from the VNA
and entering it into dedicated software
to calculate
surface resistance and conductivity.

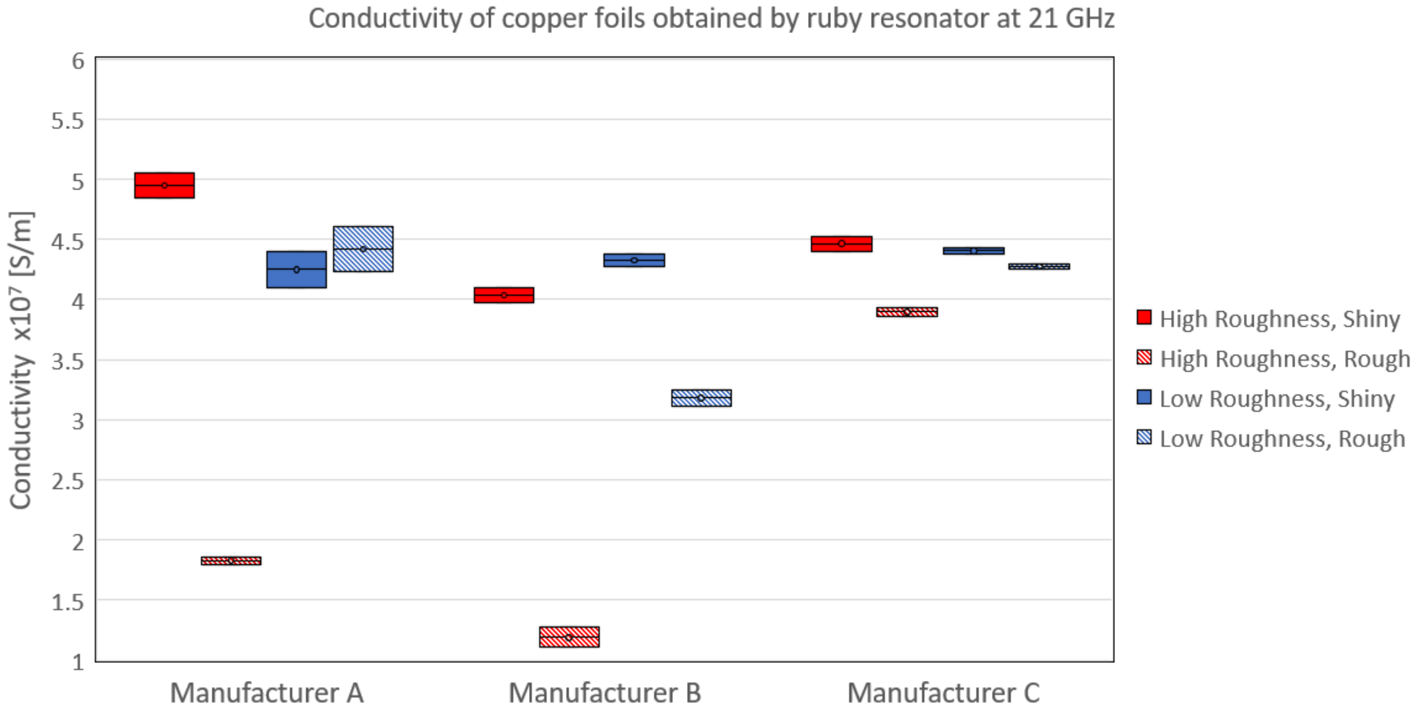
# Results



- 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


Conductivity of copper foils obtained by ruby resonator at 13 GHz


Conductivity of copper foils obtained by ruby resonator at 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

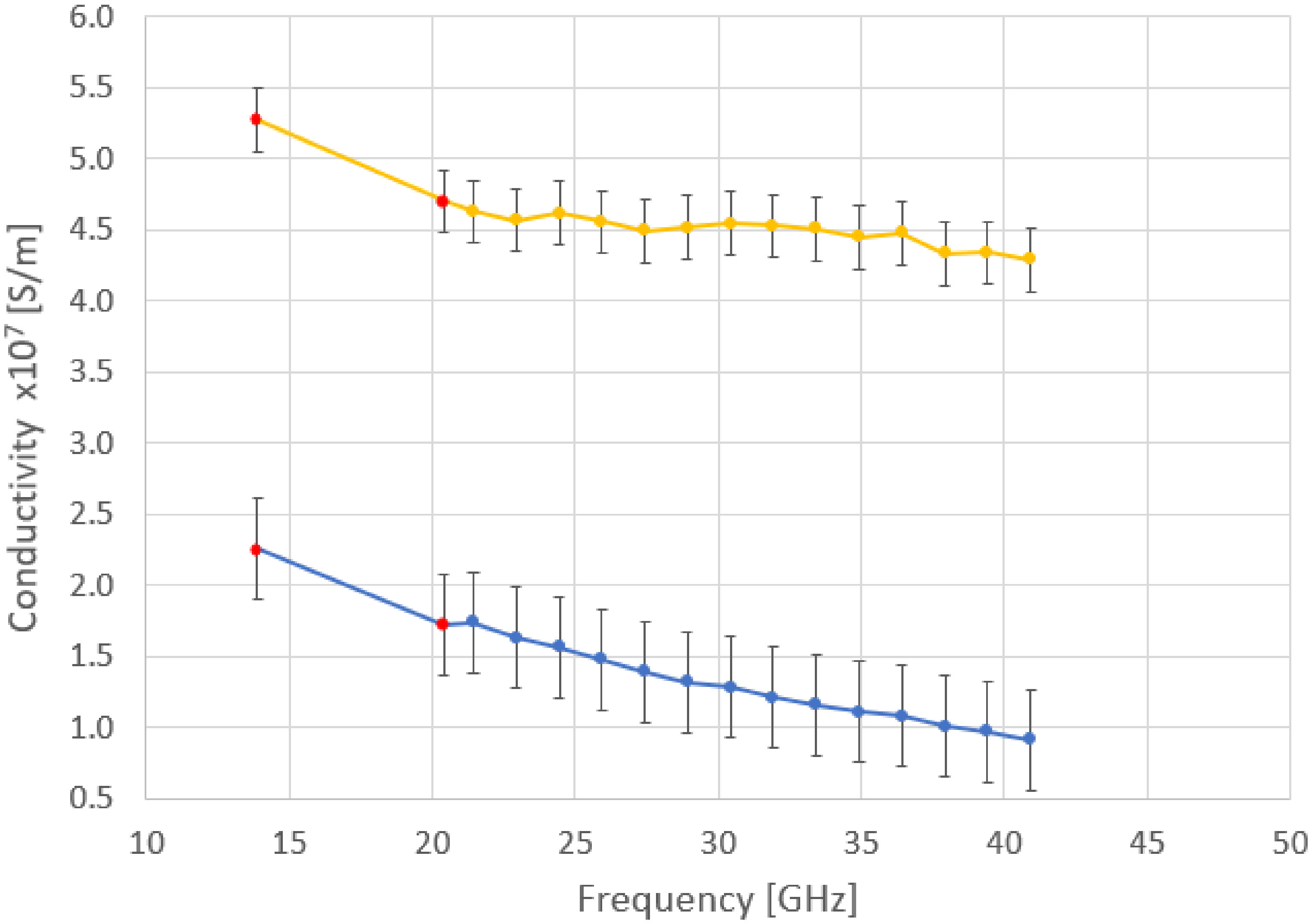
Smooth side

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 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.

# Broadband Copper Foil Measurements– FPOR & RuDD



**Manufacturer A**
– High Roughness case

● Ruby Resonator

Smooth
Rough
FPOR

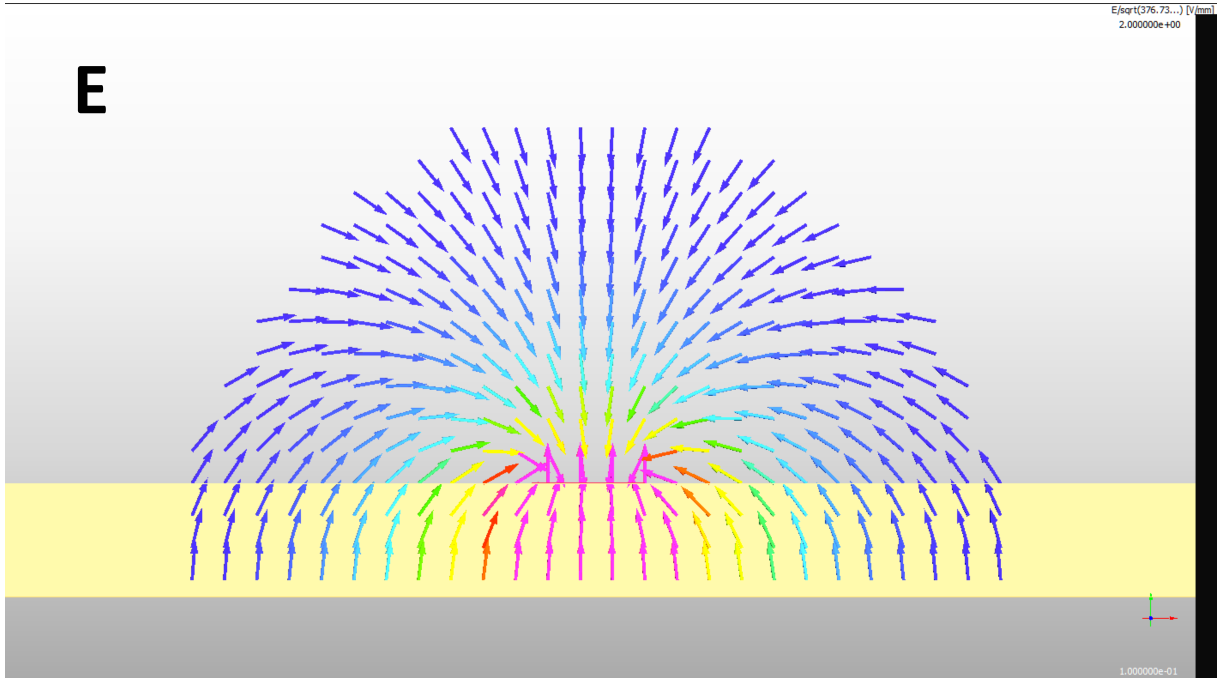
- effective conductivity decreases with frequency
  → signal loss will increase
- differences between the two sides of copper must be taken into account

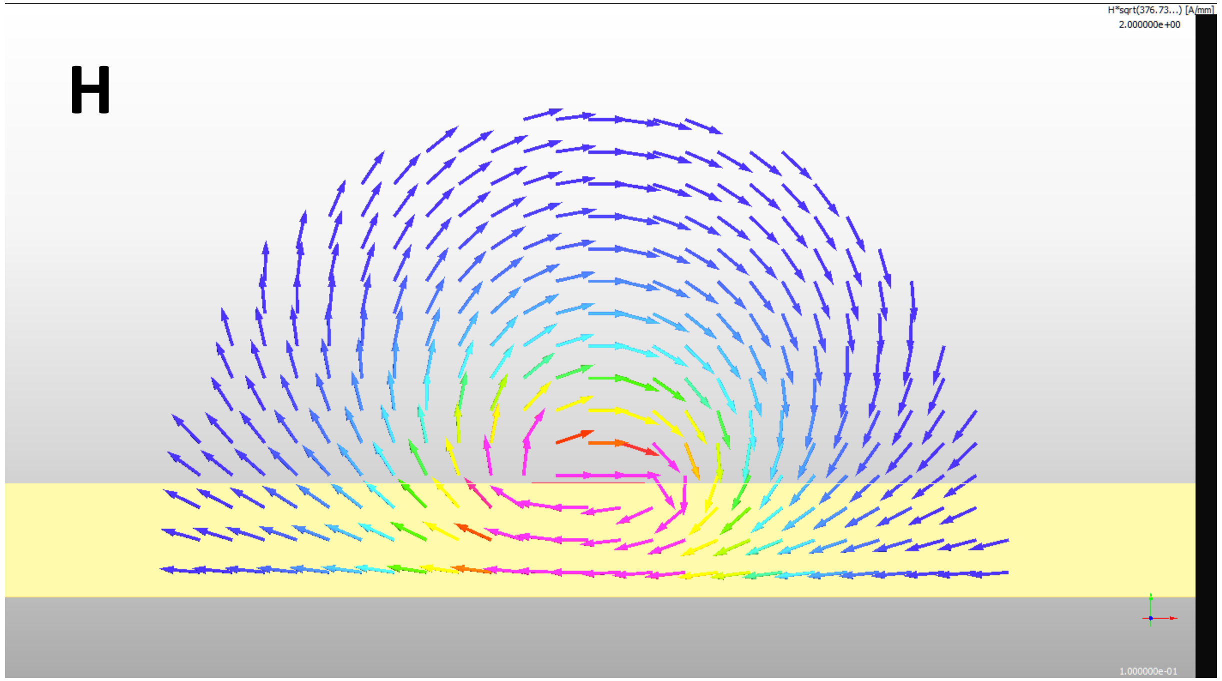
more results on the way…

# Why Both Sides of a Copper Foil Should Be Measured

We model a 50 Ohm microstrip line.

QuickWave$^{TM}$ by QWED is used to simulate field patterns and calculate transmission losses.

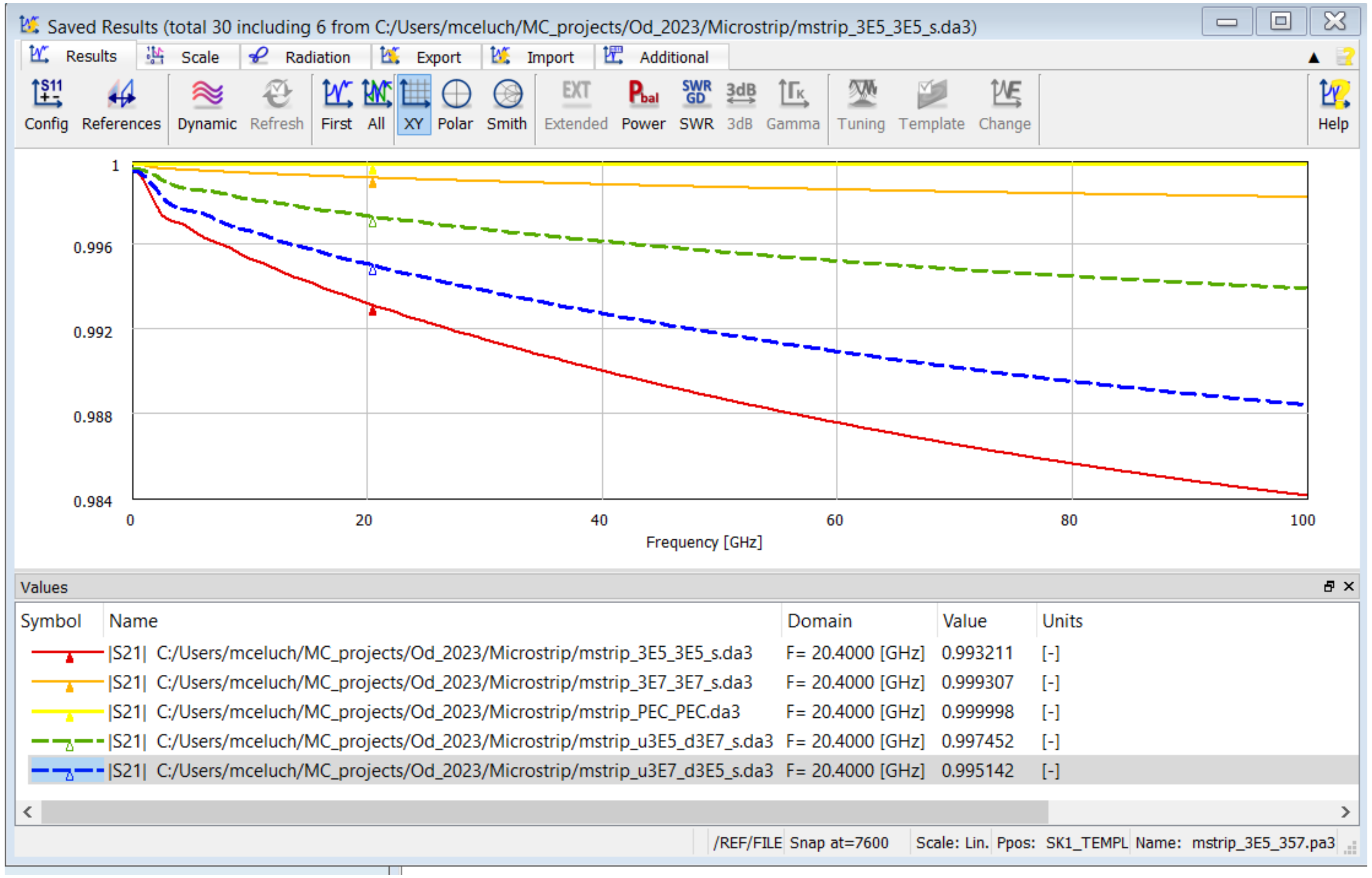




Higher field intensity below the strip → higher contribution of the bottom side of the strip to signal losses.

# Why 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).


Saved Results (total 30 including 6 from C:/Users/mceluch/MC_projects/Od_2023/Microstrip/mstrip_3E5_3E5_s.da3)

| Symbol | Name | Domain | Value | Units |
|---|---|---|---|---|
| ▲ | \|S21\| C:/Users/mceluch/MC_projects/Od_2023/Microstrip/mstrip_3E5_3E5_s.da3 | F= 20.4000 [GHz] | 0.993211 | [-] |
| ▲ | \|S21\| C:/Users/mceluch/MC_projects/Od_2023/Microstrip/mstrip_3E7_3E7_s.da3 | F= 20.4000 [GHz] | 0.999307 | [-] |
| ▲ | \|S21\| C:/Users/mceluch/MC_projects/Od_2023/Microstrip/mstrip_PEC_PEC.da3 | F= 20.4000 [GHz] | 0.999998 | [-] |
| △ | \|S21\| C:/Users/mceluch/MC_projects/Od_2023/Microstrip/mstrip_u3E5_d3E7_s.da3 | F= 20.4000 [GHz] | 0.997452 | [-] |
| △ | \|S21\| C:/Users/mceluch/MC_projects/Od_2023/Microstrip/mstrip_u3E7_d3E5_s.da3 | F= 20.4000 [GHz] | 0.995142 | [-] |

continuous lines: identical top-bottom sides

dashed lines: different top-bottom sides

PEC

$\sigma$ = 3E7 S/m

$\sigma_{top}$ = 3E5 S/m $\sigma_{bottom}$ = 3E7 S/m

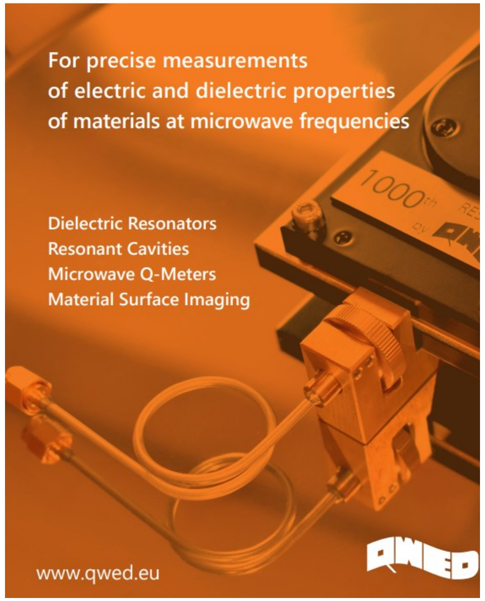
$\sigma_{top}$ = 3E7 S/m $\sigma_{bottom}$ = 3E5 S/m

$\sigma$ = 3E5 S/m

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

# The New Setups Complement QWED Resonator Product Line…

Test Fixtures and Setups



For precise measurements
of electric and dielectric properties
of materials at microwave frequencies

Dielectric Resonators
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Microwave Q-Meters
Material Surface Imaging

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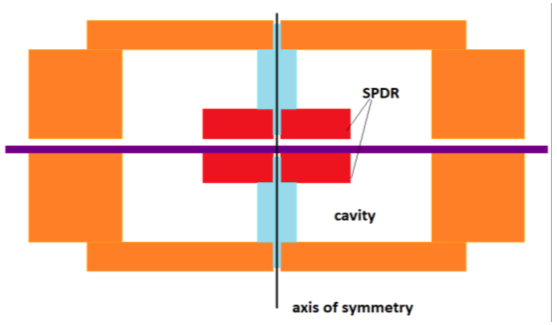
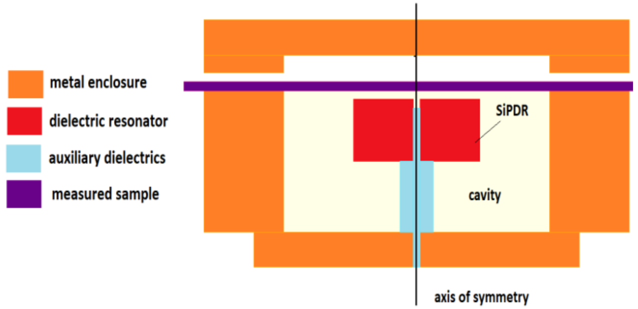
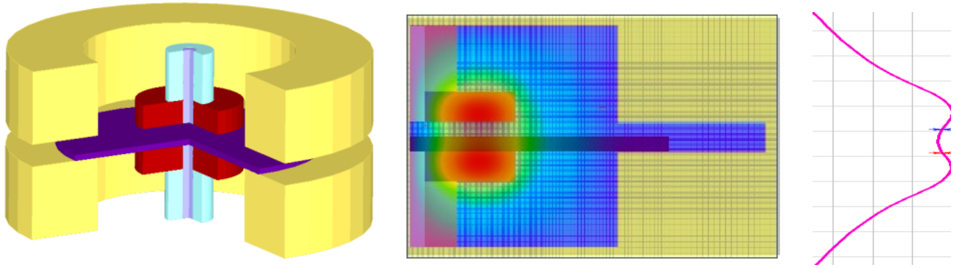
## QWED Resonators for Measuring Dielectric and Resistive Sheets

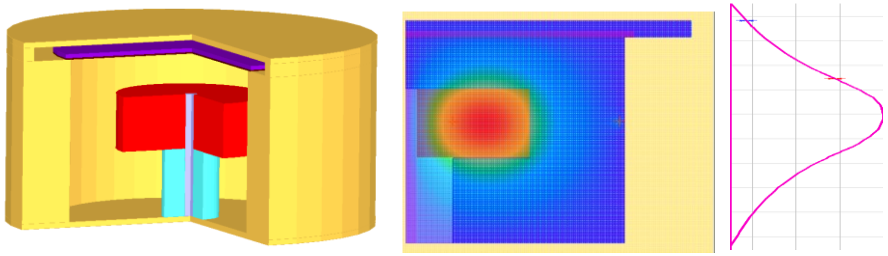
**SPDR**





**SiPDR**





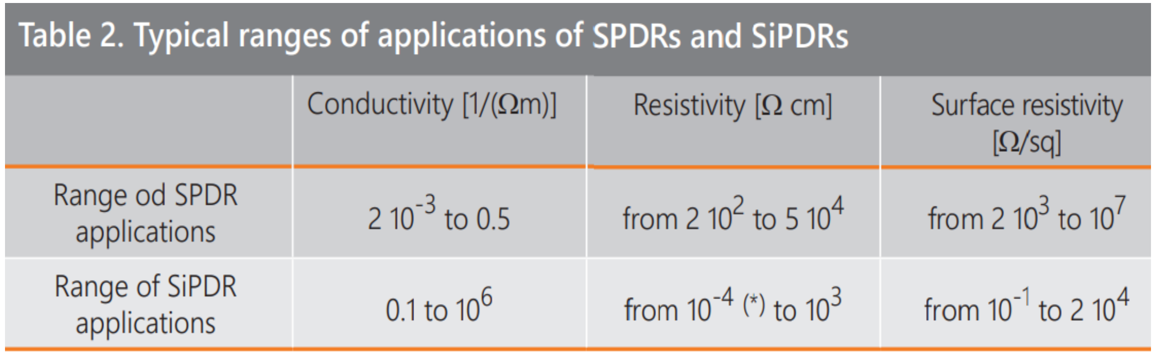


Table 2. Typical ranges of applications of SPDRs and SiPDRs

| | Conductivity [1/(Ωm)] | Resistivity [Ω cm] | Surface resistivity [Ω/sq] |
|---|---|---|---|
| Range od SPDR applications | 2 $10^{-3}$ to 0.5 | from 2 $10^{2}$ to 5 $10^{4}$ | from 2 $10^{3}$ to $10^{7}$ |
| Range of SiPDR applications | 0.1 to $10^{6}$ | from $10^{-4}$ (*) to $10^{3}$ | from $10^{-1}$ to 2 $10^{4}$ |

RuDR $> 10^6$

SPDR & SiPDR designs after:

J. Krupka and J. Mazierska, *IEEE Trans. Instr. Meas.*, 2007, doi: 10.1109/TIM.2007.903647

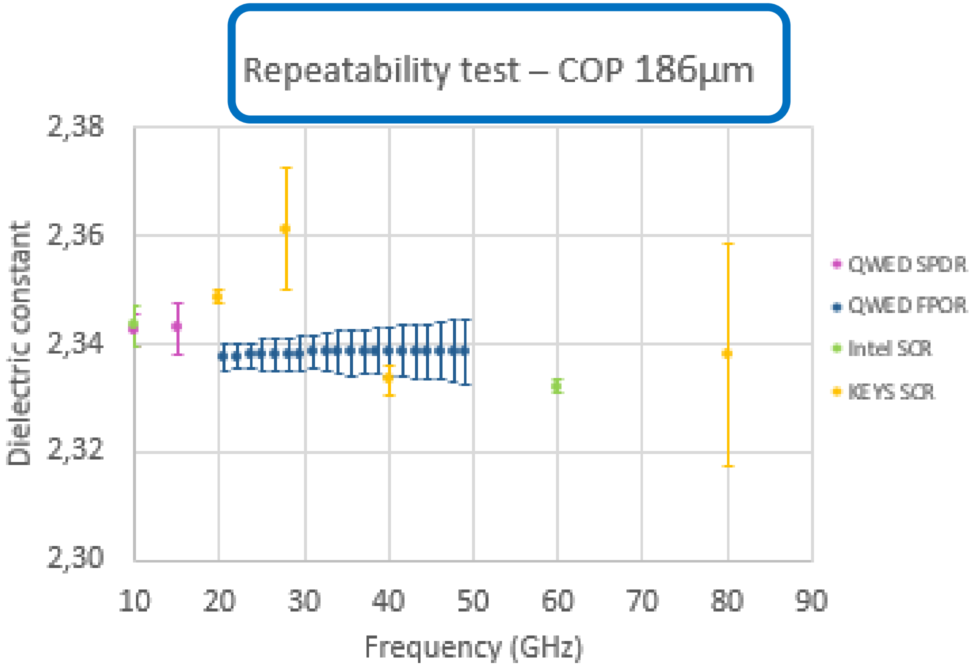
CAD models and EM field distribution:

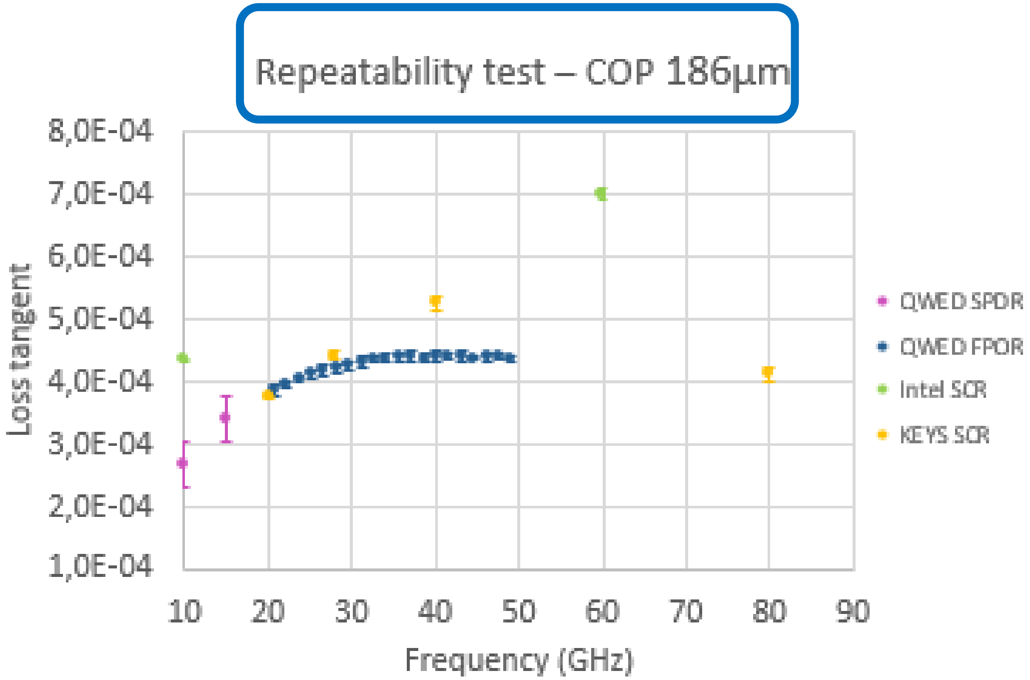
QuickWave$^{TM}$ software by QWED

# QWED Resonators for Dielectric Substrates in a previous iNEMI 5G Project*

| | |
|---|---|
| **3 labs** | Intel - SCR at 10 / 60 GHz and SPDR at 10/ 20 GHz, |
| **3 techniques** | Keysight - SCR at 10 / 20 / 28 / 40 / 80 GHz |
| **14 laboratory setups** | QWED - SPDR at 10/ 15 GHz and FPOR over 10-110GHz |

* *"5G/mmWave Materials Assessment and Characterization"*
https://www.inemi.org/article_content.asp?adminkey=5cc4f4100ebf2ba1f3e6fd6294749139&article=161





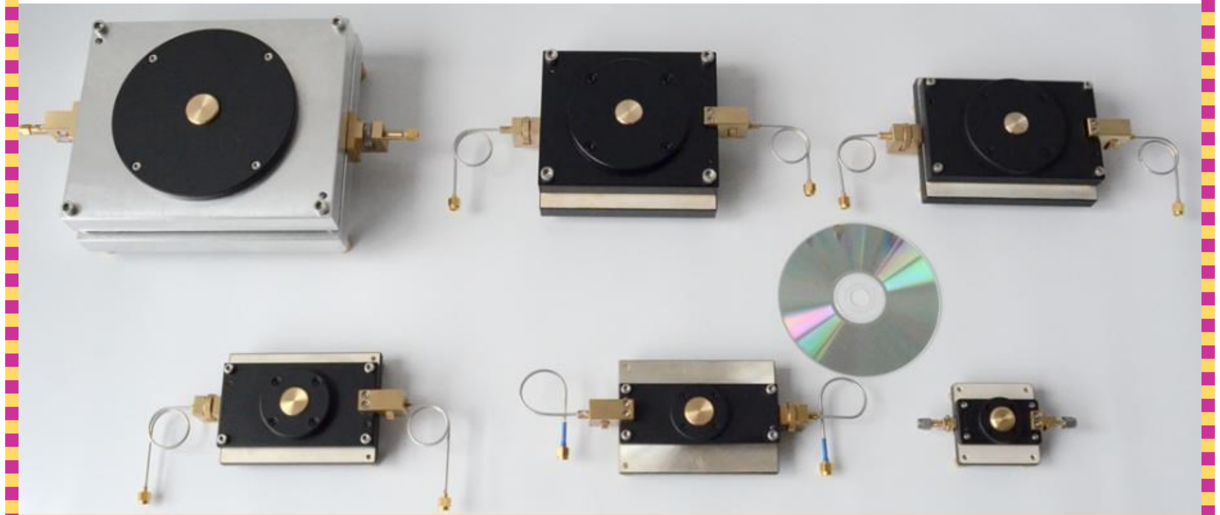
repeatability of SCR ±1%
repeatability of SPDR, FPOR better than ±0.3%

> 40GHz 2x increase in Df compared to 10GHz

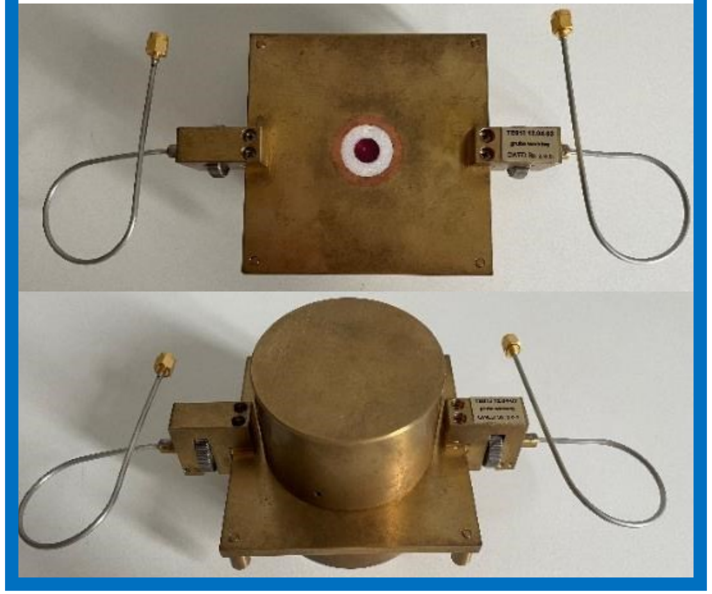
M.Celuch @ IMPACT, Taipei, 25 Oct. 2023

# QWED's Popular Dielectric Resonators

Split-Post Dielectric Resonator, typical units for 1.1 GHz -15 GHz
for laminar low-loss dielectric materials



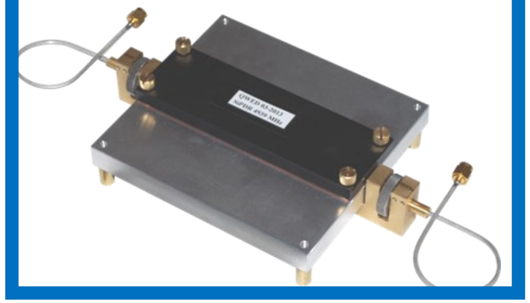
Sapphire Resonators (SaDR)
for metal foils
13.5 / 20 GHz



## more recent Fabry-Perot Open Resonator

Fabry-Perot Open Resonator
automatic span,
quasi-continuous
20 .. 120 GHz

5 GHz SiPDR
for resistive sheets



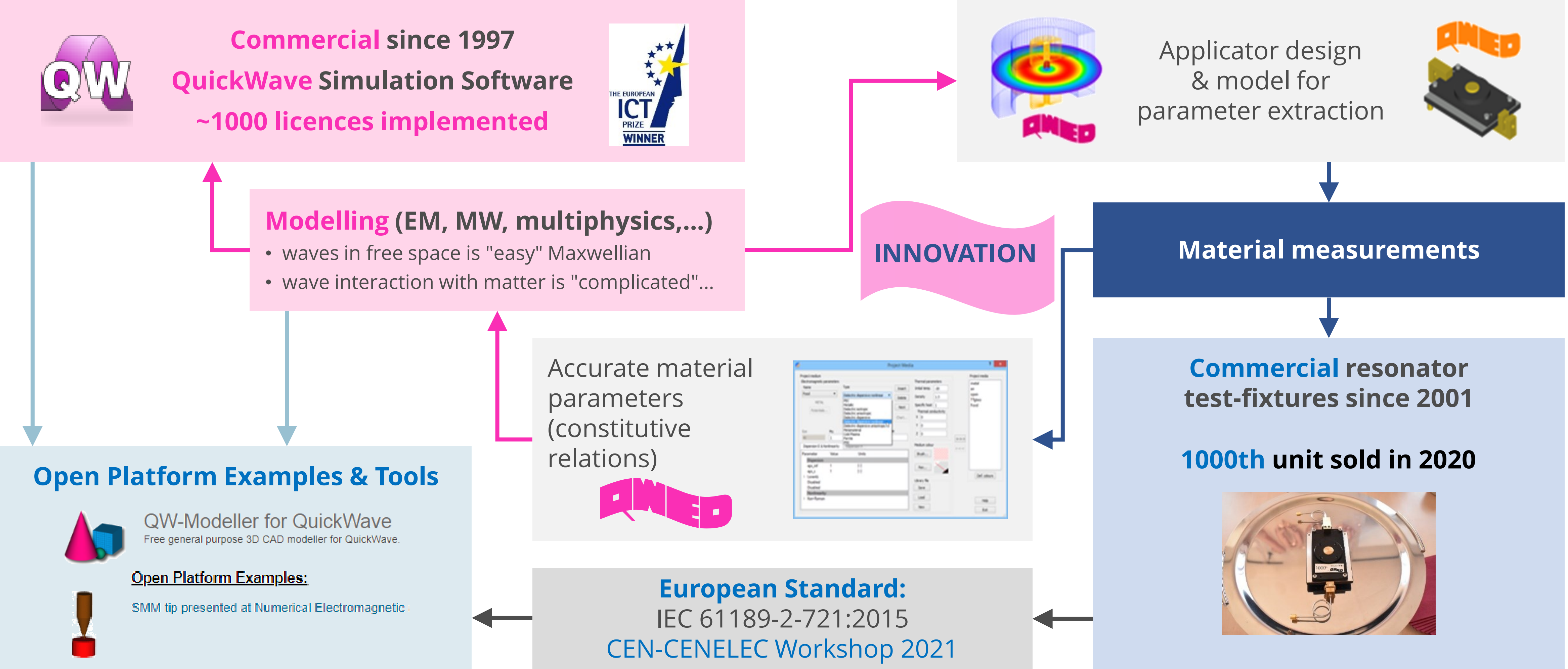
TE01δ cavities,
typically 1 GHz – 10 GHz
for bulk low-loss dielectrics

LAMINAR LOW-LOSS DIELECTRICS

METALLIC OR RESISTIVE SHEETS

APPLIED IN TEMPERATURE-VARYING CONDITIONS

# Bridging Computer Modelling with Material Measurements



**Commercial** **since 1997**
**QuickWave** **Simulation Software**
**~1000 licences implemented**

**Modelling** **(EM, MW, multiphysics,...)**
- waves in free space is "easy" Maxwellian
- wave interaction with matter is "complicated"...

Applicator design
& model for
parameter extraction

**INNOVATION**

**Material measurements**

**Commercial** **resonator test-fixtures since 2001**

**1000th** **unit sold in 2020**

Accurate material parameters (constitutive relations)

**European Standard:**
IEC 61189-2-721:2015
CEN-CENELEC Workshop 2021

**Open Platform Examples & Tools**

QW-Modeller for QuickWave
Free general purpose 3D CAD modeller for QuickWave.

Open Platform Examples:

SMM tip presented at Numerical Electromagnetic

# Summary

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!!!

# Hello from QWED

1998: Prime Minister of Poland Award

QWED' beginnning, founders (right to left):
W.Gwarek, M.Celuch, M.Sypniewski, A.Wieckowski

*Awarded by Prof. Jerzy Buzek*
*Prime Minister of Poland 1997-2002*
*President of the European Parliament 2009-2012*

Sep. 2022: 75th birthday of Prof. W.Gwarek
(cake featuring pioneering paper of 1985)

March 2020: Sale of 1000th resonator
based on designs of Prof. J.Krupka

May 2022: QWED celebrating 25 years

*I appreciate specific contributions to this presentation by:*

*Dr. Marzena Olszewska-Placha*
*Prof. Wojciech Gwarek*
*Janusz Rudnicki*
*Lukasz Nowicki*

*and special thanks to:*
*Prof. Pawel Kopyt, Warsaw Univ.Tech.*

# Acknowledgements

iNEMI
International Electronics Manufacturing Initiative

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*”

https://www.inemi.org/article_content.asp?adminkey=b5202baac78313e4914809b2f481b372&article=209

QWED R&D work is currently co-funded by the Polish National Centre for Research and Development under contracts M-ERA.NET2/2020/1/2021 (**ULTCC6G_Epac**) and M-ERA.NET3/2021/83/**I4BAGS**/2022.

NCBR
National Centre for Research and Development

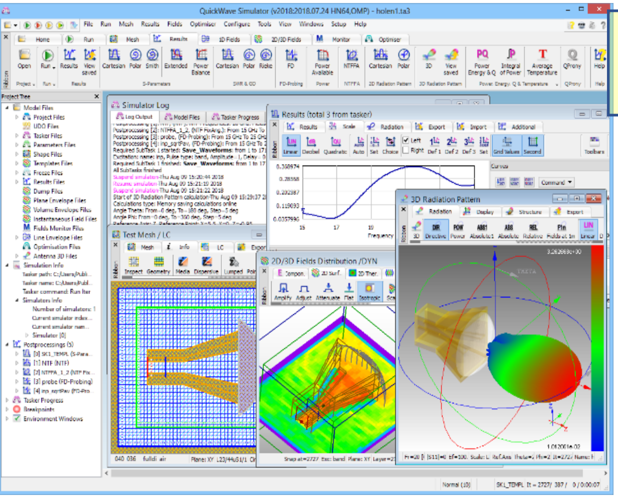
M-era.Net

ULTCC6G_EPac

I4Bags

# 26 years in a Nutshell

*presented annually at IEEE IMS Show*

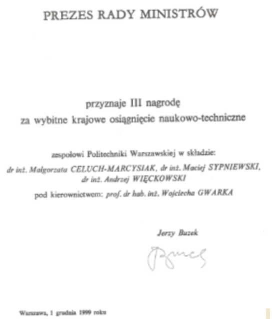


## Electromagnetic simulation & design software, 3D & BOR 2D tools

**based on 300+ publications by:**

prof.W.Gwarek, IEEE Fellow, DML, Pioneer Award

dr.M.Celuch, President of QWED



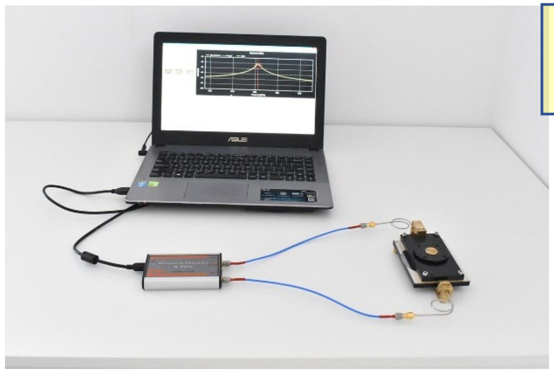
PREZES RADY MINISTRÓW

przyznaje III nagrodę
za wybitne krajowe osiągnięcie naukowo-techniczne

zespołowi Politechniki Warszawskiej w składzie:
*dr inż. Małgorzata CELUCH-MARCYSIAK, dr inż. Maciej SYPNIEWSKI,*
*dr inż. Andrzej WIĘCKOWSKI*
pod kierownictwem: *prof. dr hab. inż. Wojciecha GWARKA*

*Jerzy Buzek*

Warszawa, 1 grudnia 1999 roku



## Instruments for precise material measurements

**based on 300+ publications**

by prof.J.Krupka, IEEE Fellow

DIPLOMA

Eureka!

THE BELGIAN AND INTERNATIONAL TRADE FAIR FOR TECHNOLOGICAL INNOVATION

to

Jerzy KRUPKA

Politechnika Warszawska – Wydział Elektroniki i Technik Informacyjnych (Warsaw University of Technology - Faculty of Electronics and Information Technology)

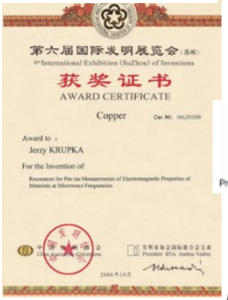
for the innovation

Résonateurs pour des mesures précises des propriétés électromagnétiques de matériaux à bande de fréquence micro-ondes.

**Médaille d'or**

THE PRESIDENT OF THE INTERNATIONAL JURY

THE PRESIDENT



第六届国际发明展览会（苏州）

6th International Exhibition (SuZhou) of Inventions

获奖证书

AWARD CERTIFICATE

Copper

Award to :

Jerzy KRUPKA

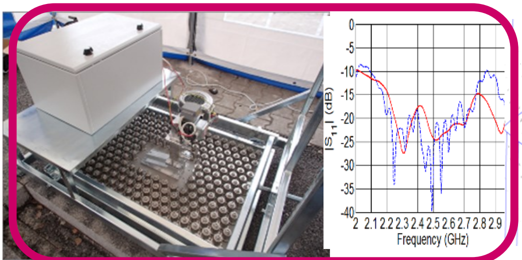
For the Invention of:

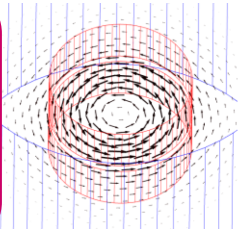
Resonators for Precise Measurements of Electromagnetic Properties of Materials at Microwave Frequencies

China Association of Inventions

President IFIA Andras Vedres

2008年10月





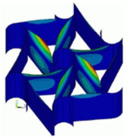
## Consultancy & design services based on EM expertise & tools

team of 10+engineers, 4 PhDs, 2 Profs

key areas: MW power appliances, customised resonators, antennas &feeds

# R&D projects

**FP6 SOCOT** – development and validation of an optimal methodology for overlay control in semiconductor industry, for the 32 nm technology node and beyond.



**FP6 CHISMACOMB** – development, modelling, and applications of chiral materials → EM validation of mixing rules

**Eureka E! 2602 MICRODEFROST MODEL** – innovative software-based product development tool for simulating and optimising heating and defrosting processes in microwave ovens

**FP7 HIRF SE** (High Intensity Radiated Field Synthetic Environment) - numerical modelling framework for aeronautic industry

**Eureka FOODWASTE** – developing new microwave treatment system for high water content waste

**ERA-NET MNT NACOPAN** – applications and modelling of nano-conductive polymer composites

**NGAM2** – designing an industrial device for thermal bonding of bituminous surfaces with the aid of microwave heating

**MMAMA** (Microwave Microscopy for Advanced and Efficient Materials Analysis and Production) – EM modelling & characterisation for the development of high efficiency solar cells

**NanoBat** - developing a novel nanotechnology toolbox for quality testing of Li-ion and beyond Lithium batteries with the potential to redefine battery production in Europe and worldwide.

M-ERA.NET

**ULTCC6G_EPac** – development & application of novel ceramics for 5G & beyond

**I4BAGS** – modelling & characterisation of ion-implanted battery & graphene-enabled devices