discover accurate EM modelling

Evaluation and extensions of resonator techniques for the characterization of ceramics and energy materials relevant to 6G applications

Marzena Olszewska-Placha, Malgorzata Celuch, Lukasz Nowicki, Janusz Rudnicki

QWED Sp. z o.o., Warsaw, POLAND, www.qwed.eu

KEYNOTE

Electronic Materials and Applications 2023

S21: Materials, Devices, and Applications in 6G Telecommunications

19 January 2023

Outline

1. The two perspectives of this work:
    from research to commercialisation,
    from computer modelling to material measurements.

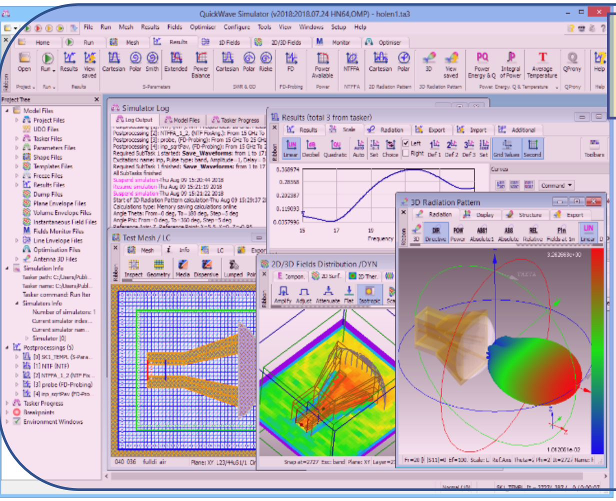
2. Our microwave & mmWave resonators (as presented at EMA 2020 - 2022).

3. Recent extension to temperature-dependent characterisation for ULTCCs.

4. Extensions to surface imaging of energy materials.

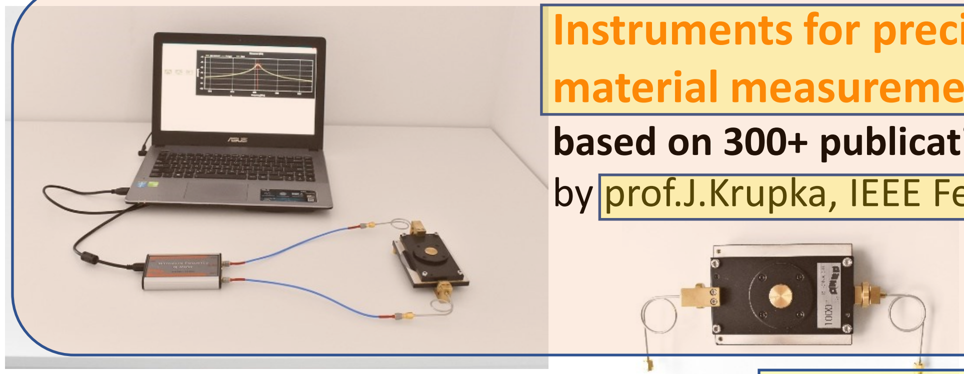
5. Acknowledgments & collaborative offer.

25 years in a Nutshell



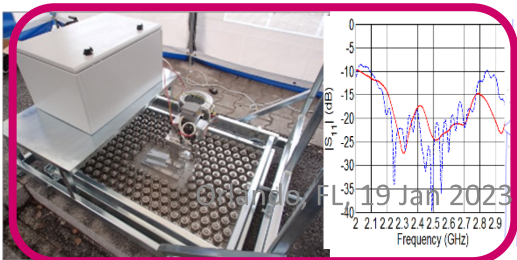
Electromagnetic simulation & design software, 3D & BOR 2D tools

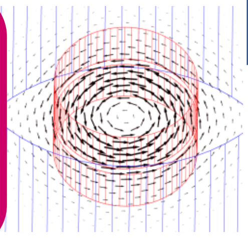
based on 300+ publications by:
prof.W.Gwarek, IEEE Fellow, DML, Pioneer Award
dr.M.Celuch, President of QWED



Instruments for precise material measurements

based on 300+ publications by prof.J.Krupka, IEEE Fellow

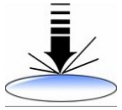




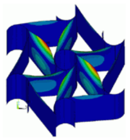
Consultancy & design services based on EM expertise & tools

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

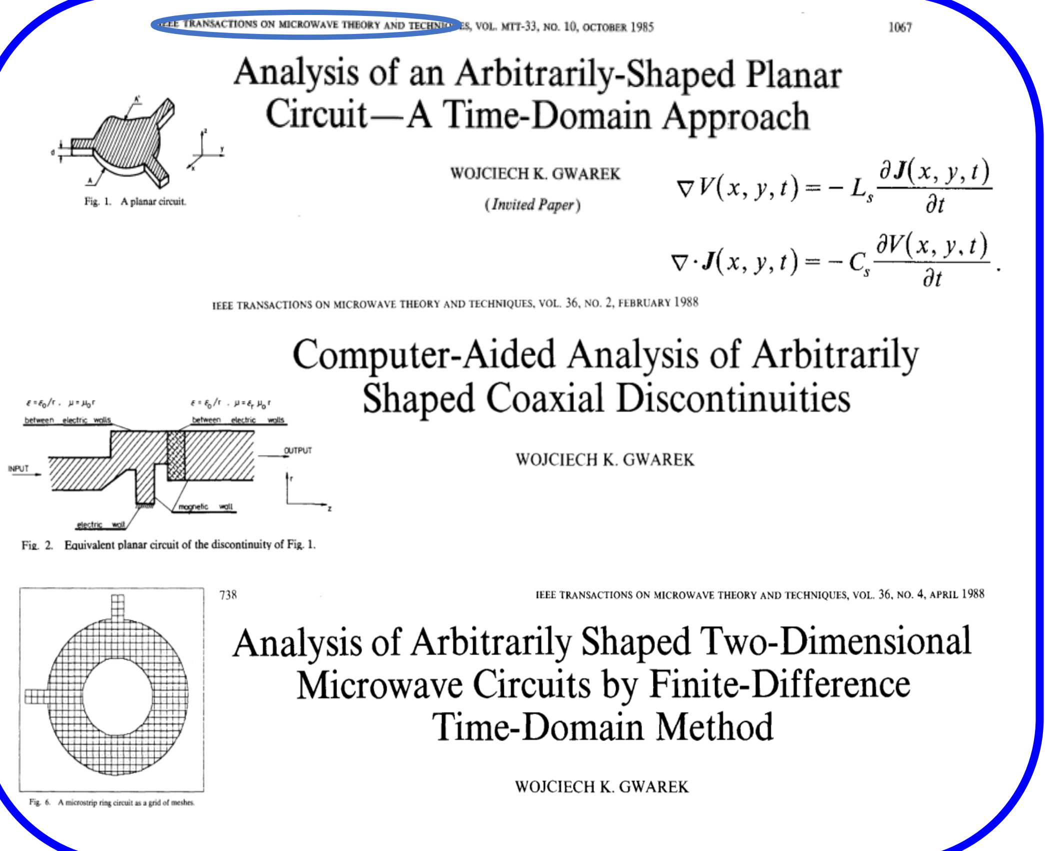
I4BAGS – modelling & characterisation of ion-implanted battery & graphene-enabled devices

Origins of QWED Computer Modelling

since 1980s…

IEEE- awarded research of Prof. Wojciech Gwarek
on 2D FDTD modelling (with novel conformal meshing)

Fellow, Pioneeer Award, DML



IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. MTT-33, NO. 10, OCTOBER 1985 1067

Analysis of an Arbitrarily-Shaped Planar Circuit—A Time-Domain Approach

WOJCIECH K. GWAREK (Invited Paper)

Fig. 1. A planar circuit.

$$\nabla V(x,y,t) = -L_s \frac{\partial J(x,y,t)}{\partial t}$$

$$\nabla \cdot J(x,y,t) = -C_s \frac{\partial V(x,y,t)}{\partial t}.$$

IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 36, NO. 2, FEBRUARY 1988

Computer-Aided Analysis of Arbitrarily Shaped Coaxial Discontinuities

WOJCIECH K. GWAREK

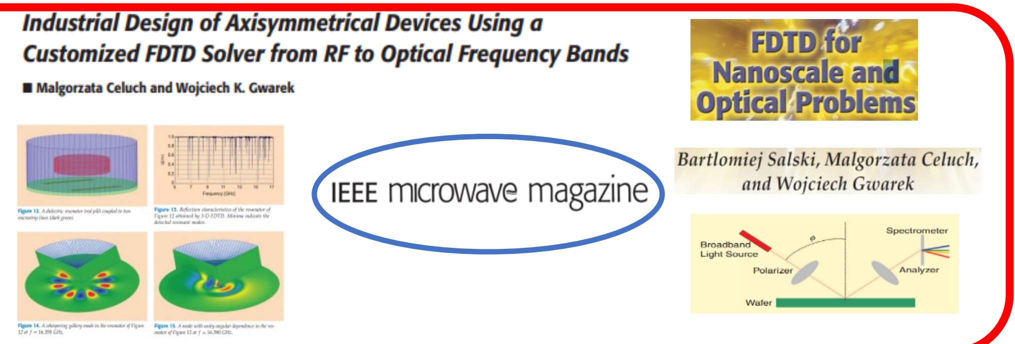
Fig. 2. Equivalent planar circuit of the discontinuity of Fig. 1.

738 IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 36, NO. 4, APRIL 1988

Analysis of Arbitrarily Shaped Two-Dimensional Microwave Circuits by Finite-Difference Time-Domain Method

WOJCIECH K. GWAREK

Fig. 6. A microstrip ring circuit as a grid of meshes.



Industrial Design of Axisymmetrical Devices Using a Customized FDTD Solver from RF to Optical Frequency Bands

Malgorzata Celuch and Wojciech K. Gwarek

IEEE microwave magazine

FDTD for Nanoscale and Optical Problems

Bartlomiej Salski, Malgorzata Celuch, and Wojciech Gwarek

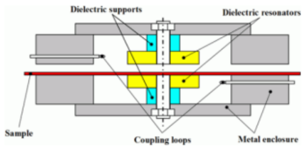
… by early 2000s:

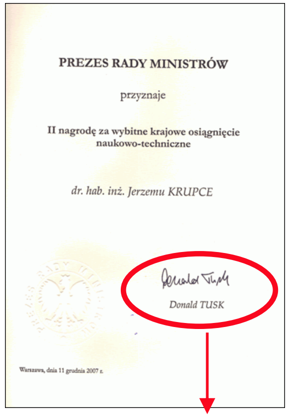
QWED commercialises & continues the development
licences for QuickWave-3D by QWED used worldwide
industrial applications from RF to optical bands

Origins of QWED Material Measurements

since 1980s…

awarded research of Prof. Jerzy Krupka (IEEE Fellow)
on dielectric resonators (best known: Split-Post Dielectric Resonator)





PREZES RADY MINISTRÓW

przyznaje

II nagrodę za wybitne krajowe osiągnięcie naukowo-techniczne

dr. hab. inż. Jerzemu KRUPCE

Donald TUSK

by Donald Tusk
Prime Minister of Poland 2007-2014
President of the European Council 2014-2019

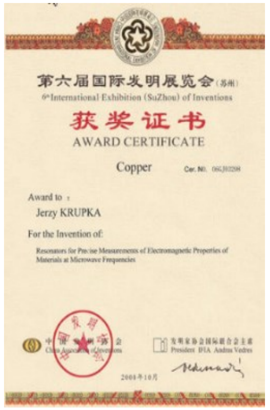
DIPLOMA

Eureka!

THE BELGIAN AND INTERNATIONAL TRADE FAIR FOR TECHNOLOGICAL INNOVATION

Jerzy KRUPKA

Médaille d'or



第六届国际发明展览会

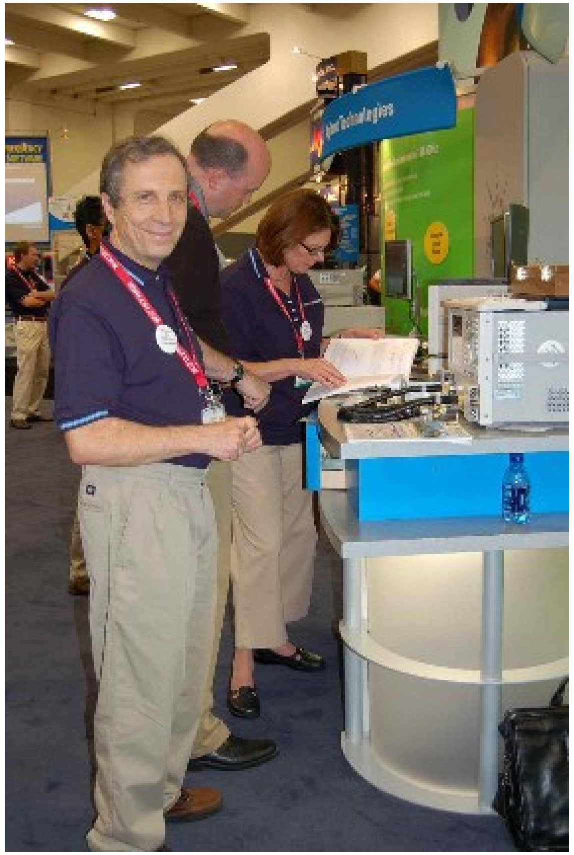
获奖证书

AWARD CERTIFICATE

Copper

Award to: Jerzy KRUPKA

For the Invention of:



Agilent Both
IEEE IMS 2006, San Francisco, CA

MMA-2010, Warsaw PL
co-organised by QWED & Warsaw Univ.Tech.

… by early 2000s:

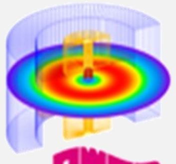
QWED commercialises the SPDRs
endorsement by Agilent / Keysight
publication of standard IEC 61189-2-721:2015

Current Work: Bridging Computer Modelling with Material Measurements

Commercial since 1997
QuickWave Simulation Software
~1000 licences implemented

THE EUROPEAN ICT PRIZE WINNER

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



Applicator design & model for parameter extraction

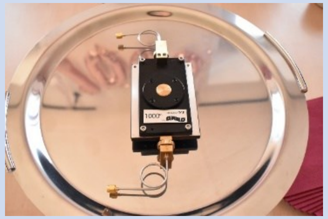
INNOVATION

Material measurements

Accurate material parameters (constitutive relations)

Commercial resonator test-fixtures since 2001

1000th unit sold in 2020



Open Platform Examples & Tools

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

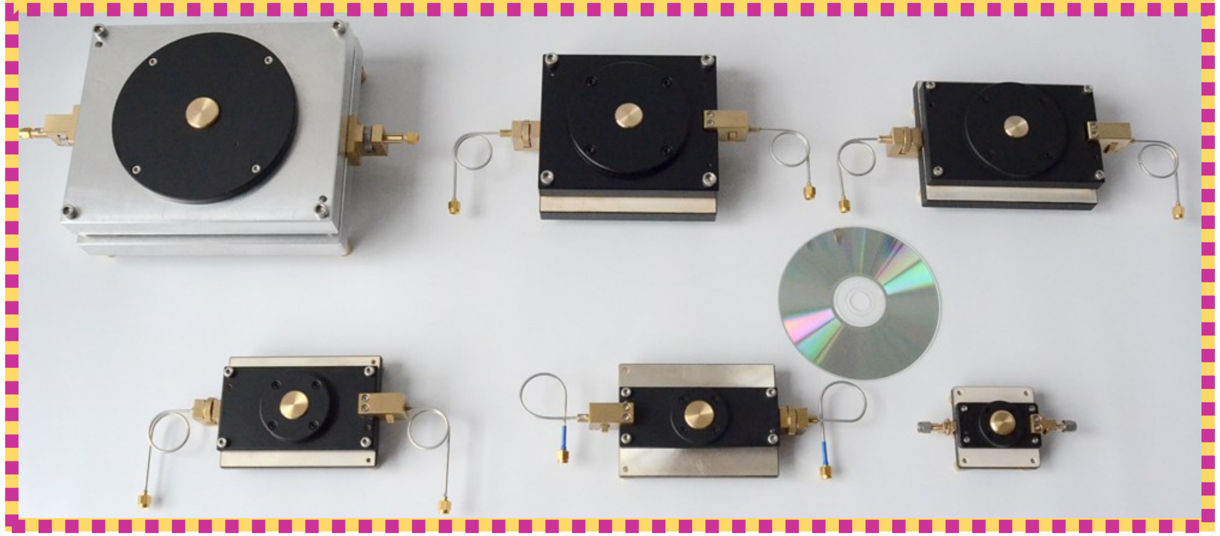
Open Platform Examples:

SMM tip presented at Numerical Electromagnetic

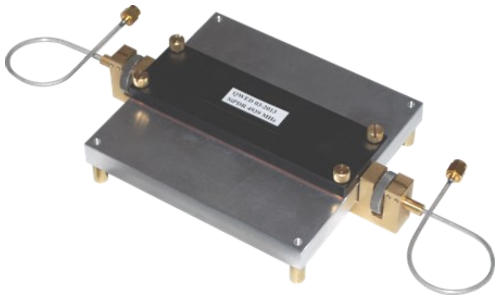
European Standard:
IEC 61189-2-721:2015
CEN-CENELEC Workshop 2021

QWED's Popular Dielectric Resonators and more recent FPOR

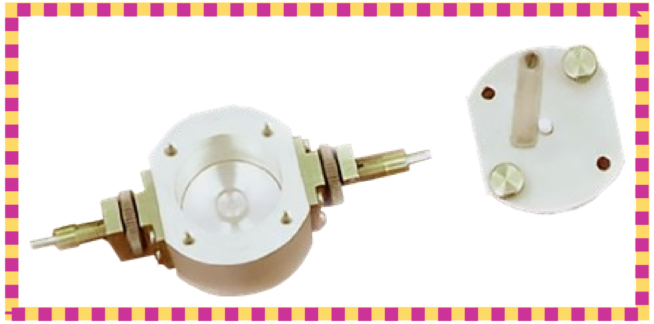
Split-Post Dielectric Resonator, typical units for 1.1 GHz -15 GHz
for laminar low-loss dielectric materials



5 GHz SiPDR
for resistive sheets



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

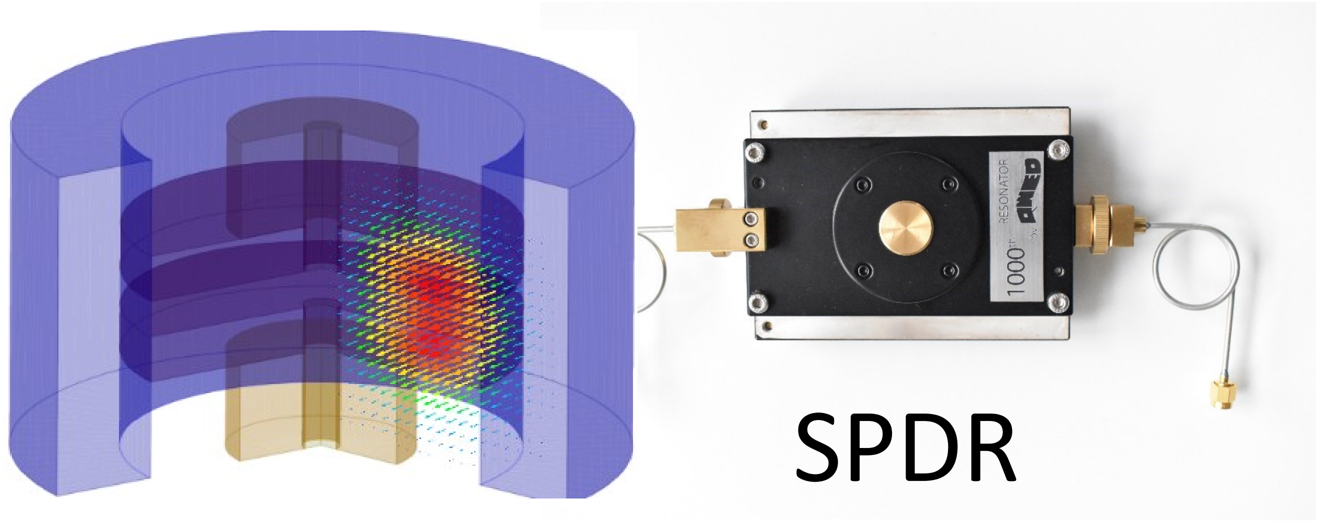


Fabry-Perot Open Resonator
automatic span, quasi-continuous 20 .. 120 GHz

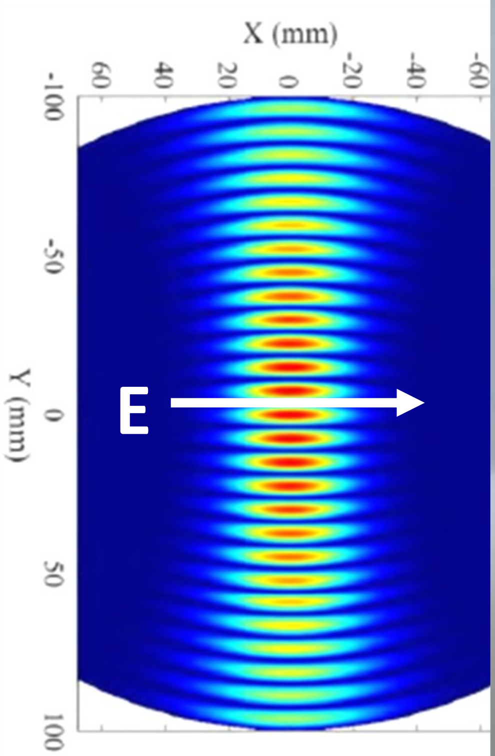
APPLIED TO CERAMICS FOR 5G & 6G

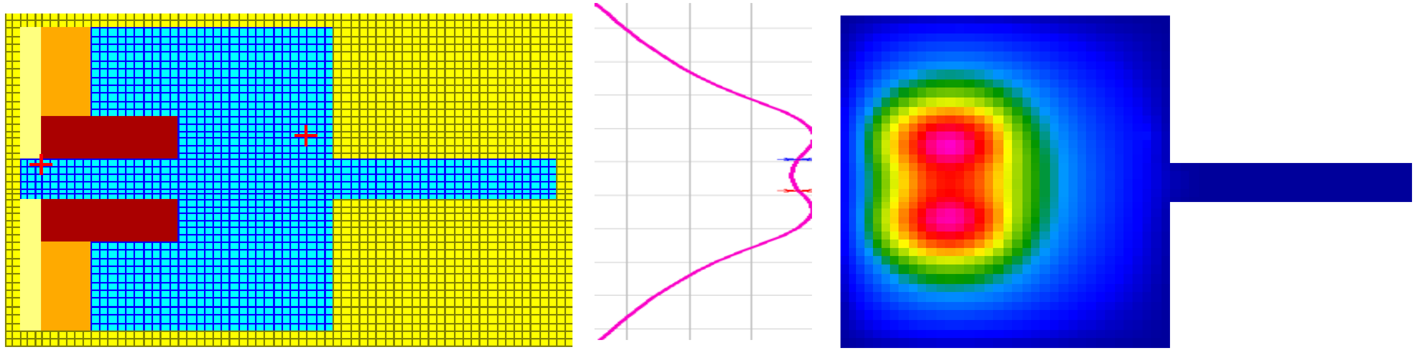
APPLIED IN TEMPERATURE-VARYING CONDITIONS

Some Physics behind our Resonators



FPOR



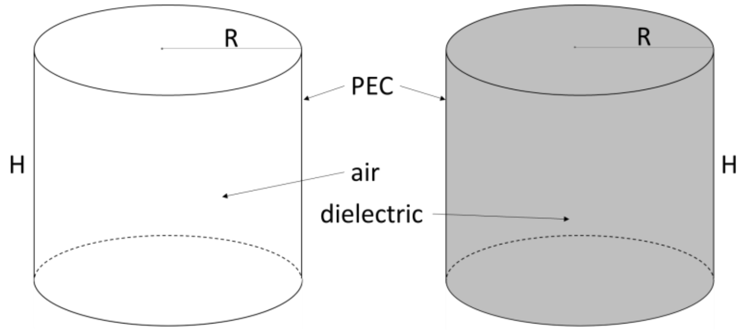


Field distributions obtained from full-wave EM simulations (QuickWave^{TM} software by QWED).
Accurate design & calibration of resonator test-fixtures facilitated by accurate EM modelling!

Why Resonators: Well Controlled Sensitivity to Material Properties

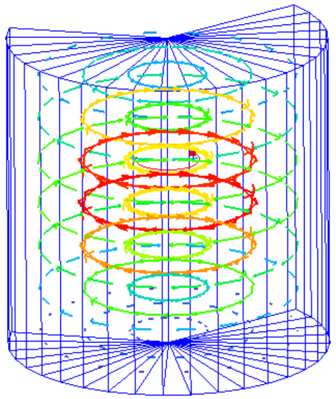
Resonance in theory: non-zero electromagnetic fields exist in isolated structures (no excitation).
Field properties are well-defined and **linked to material properties.**

E.g. for cylindrical cavities:

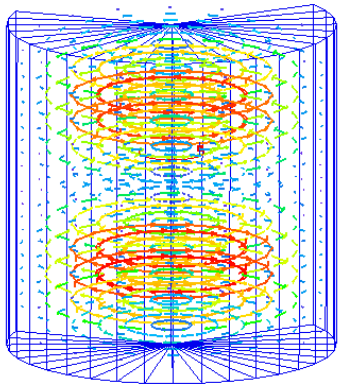


$$f_{r,mnp} = \frac{c}{\sqrt{Dk}} \sqrt{\left(\frac{\kappa^{(,)}_{mn}}{\pi R}\right)^2 + \left(\frac{p}{H}\right)^2}$$

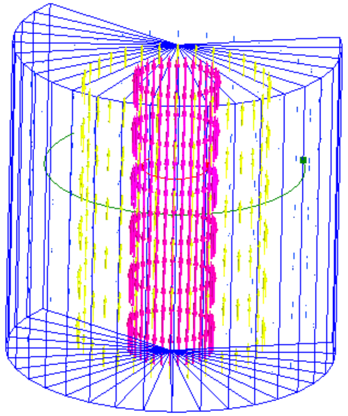
in non-magnetic low-loss dielectrics



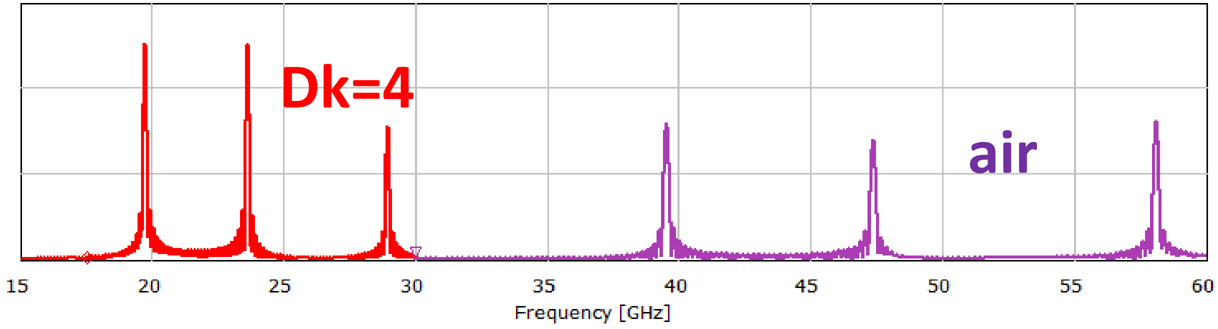
TE011



TE012



TM010



For filled cavities of any shape:

$$f_{r,mnp} = \frac{c}{\sqrt{Dk}} K(\text{modal\_index, cavity dimensions})$$

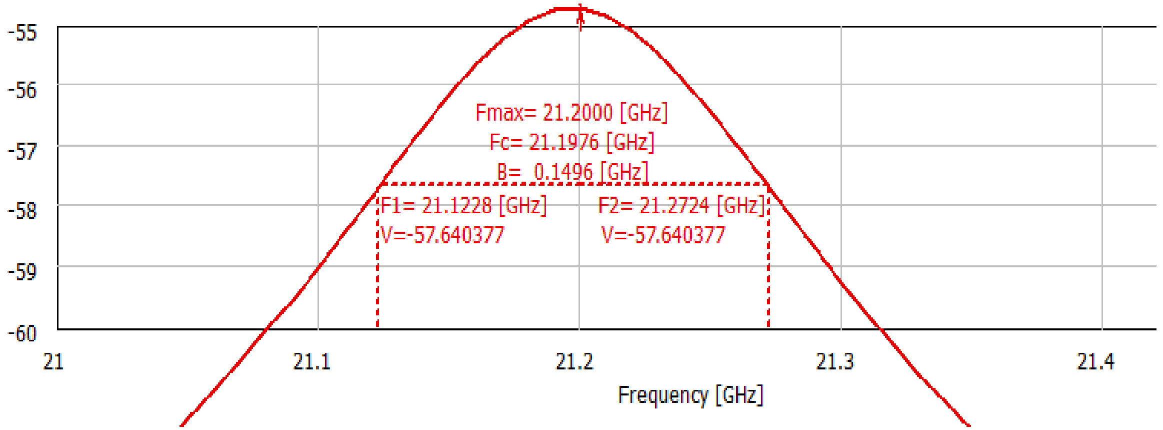
Why Resonators: High Sensitivity to Material Losses

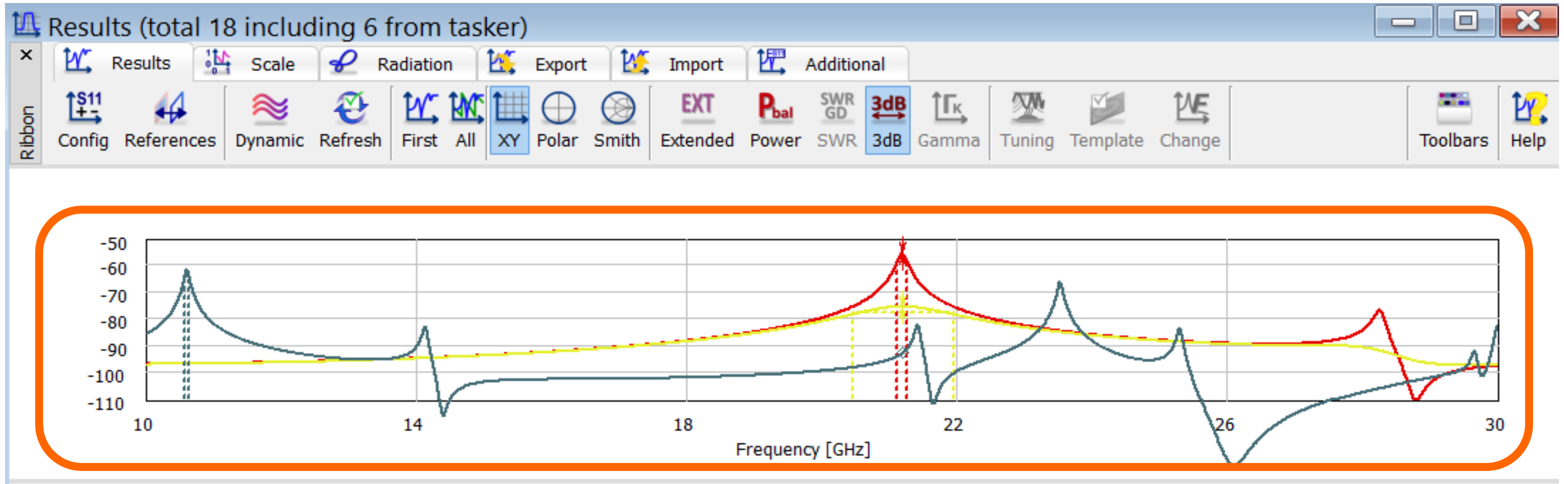
in non-magnetic
low-loss dielectrics

2* electric_energy_stored

$$Q = 2\pi \frac{\iiint_V \varepsilon \vec{E} \cdot \vec{E}^* dv}{T \iiint_V \sigma \vec{E} \cdot \vec{E}^* dv} = \frac{\omega\varepsilon}{\sigma} = \frac{1}{Df} \approx \frac{fres}{\Delta f} = (\tan\delta)^{-1}$$

electric_dissipated_power





ε_r=1 σ=0.00833 S/m
@21.2GHz:
tanδ=0.071
Q_{SUT}= 1 / 0.0071 = 141
Q_{S21}=21.2/0/1496= 141

ε_r=1 σ=0.0833 S/m

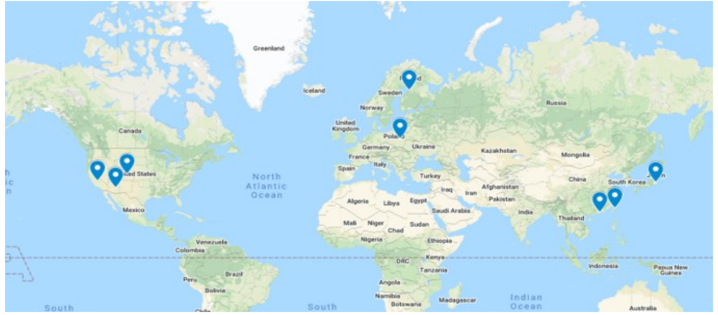
ε_r=4 σ=0.0166 S/m

iNEMI 5G Round Robin Overview

previously presented at: EuMW 2021 United in Microwaves EXCEL, LONDON 2-7 APRIL 2022 www.eumw2021.com

Our project: iNEMI

- 3M
- AGC-Nelco
- Ajinomoto USA
- AT&S
- Centro Ricerche FIAT-FCA
- Dell
- Dupont
- EMD Electronics (Co-Chair)
- Flex
- Georgia Tech
- Showa Denko Materials
- IBIDEN Co Ltd
- IBM
- Intel
- Isola
- ITRI (Co-Chair)
- Keysight (Co-Chair)
- MacDermid-Alpha
- Mosaic Microsystems
- NIST
- Nokia
- Panasonic
- QWED
- Shengyi Technology Company
- Sheldahl
- Unimicron Technology Corp
- Zestron



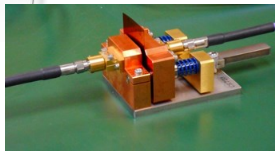
Sample Material Requirements
- Stable, Low loss
- Low moisture absorption / temperature dependency
- Isotropic
- Good mechanical & handling properties

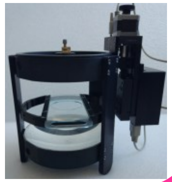
1st Project Stage
- Precision Teflon
- Cyclo Olefin Polymer

2nd Project Stage
- Rexolite
- Fused Silica

Industrial
- Automotive

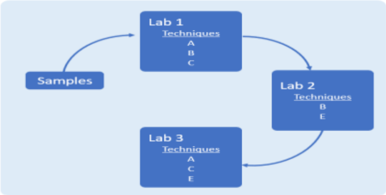
Techniques Included
- Split Post Dielectric Resonator
- Split Cavity Resonator
- Fabry-Perot
- Balanced Circular Disk Resonator

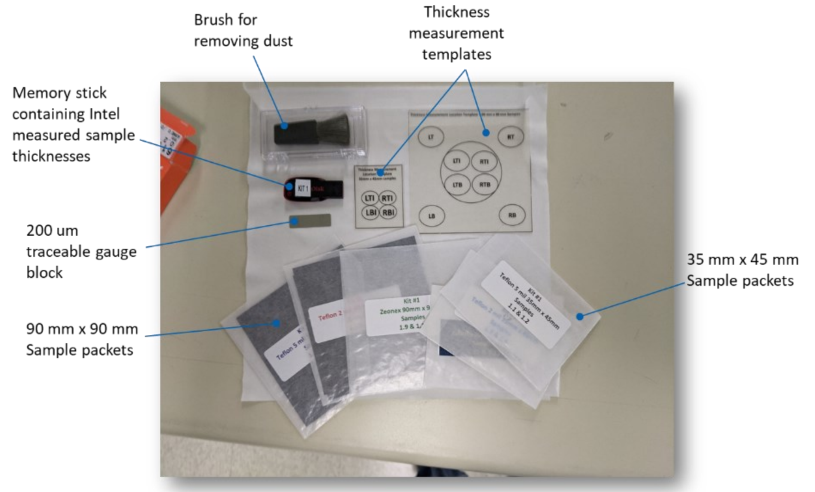




→ Frequency Span : 10GHz – 100GHz with overlaps

10 Laboratory Round Robin





10 Sample Kits Created
- Sample sizes 35 mm x 45 mm, 90 mm x 90 mm
- circulated between 10 labs

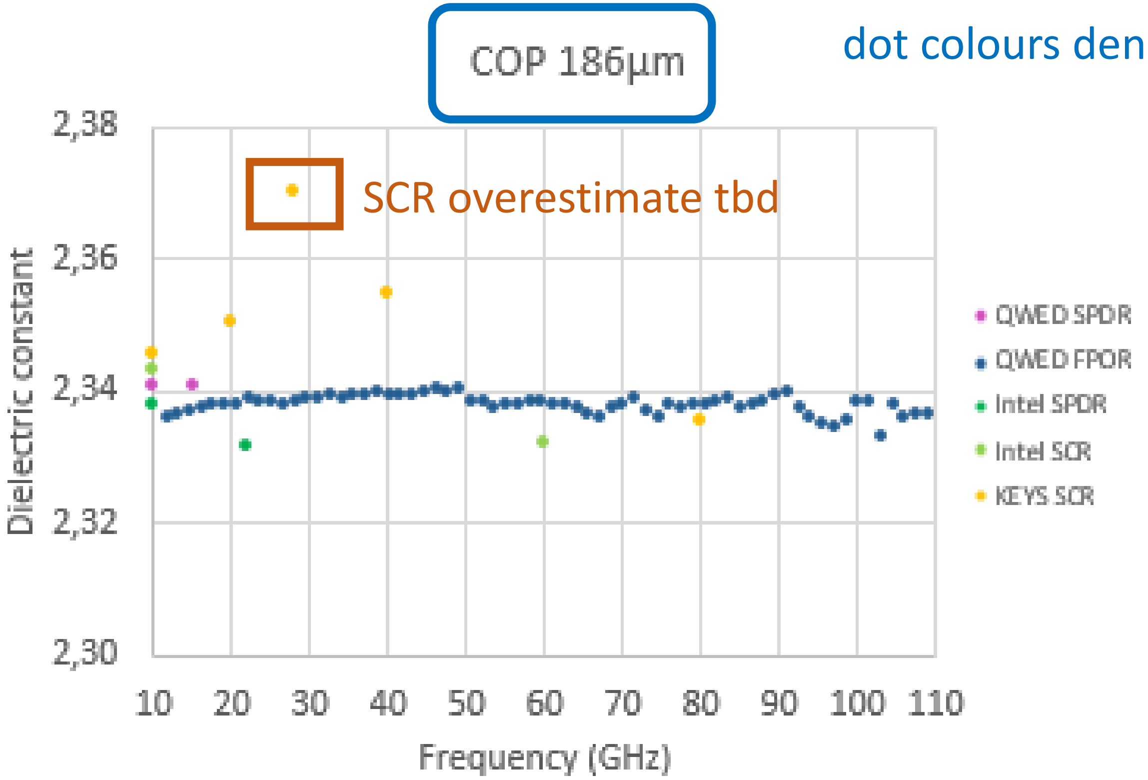
Characterisation Results - Consistency

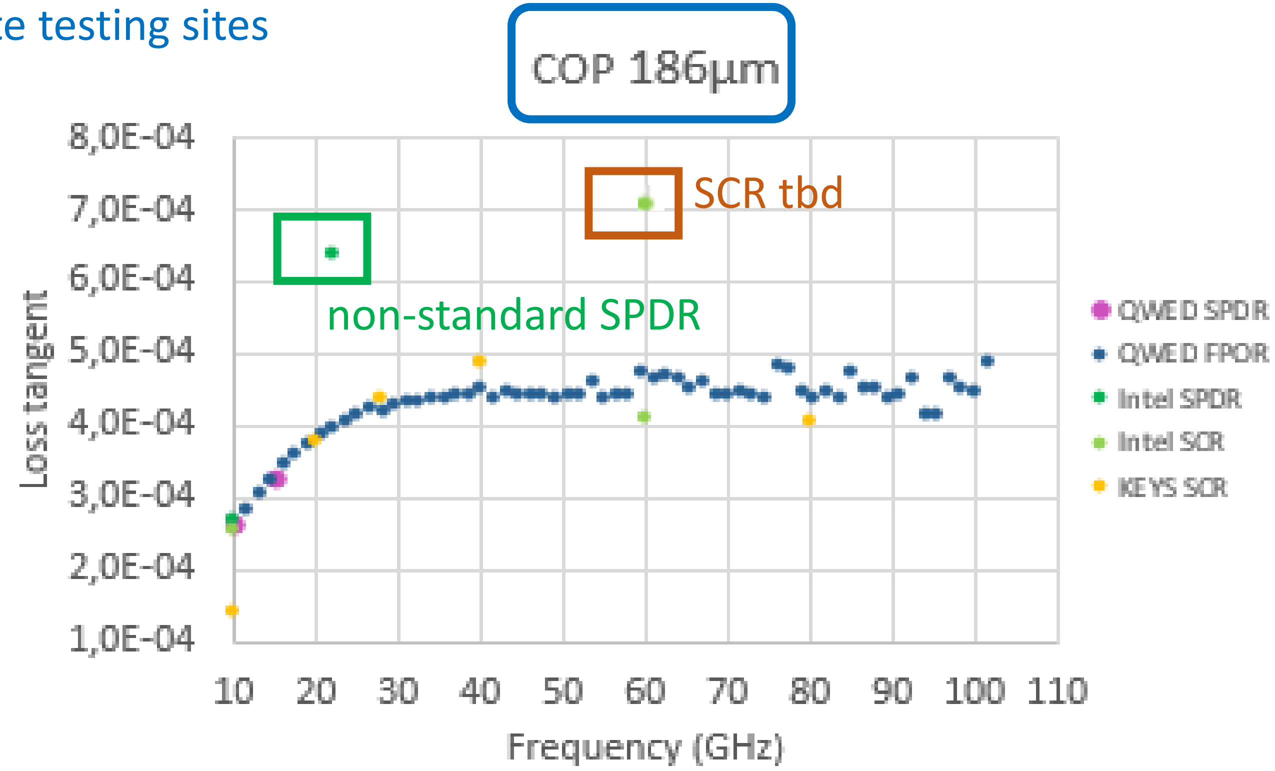
previously presented at: EXCEL, LONDON 2-7 APRIL 2022 EuMW 2021 United in Microwaves www.eumw2021.com

3 labs, 3 techniques, 14 laboratory setups

Intel - SCR at 10 / 60 GHz and SPDR at 10/ 20 GHz,
Keysight - SCR at 10 / 20 / 28 / 40 / 80 GHz
QWED - SPDR at 10/ 15 GHz and FPOR over 10-110GHz.

dot colours denote testing sites





Dk spread < 1% (within ± 0.5% from average)
(< 2% incl. outliers)

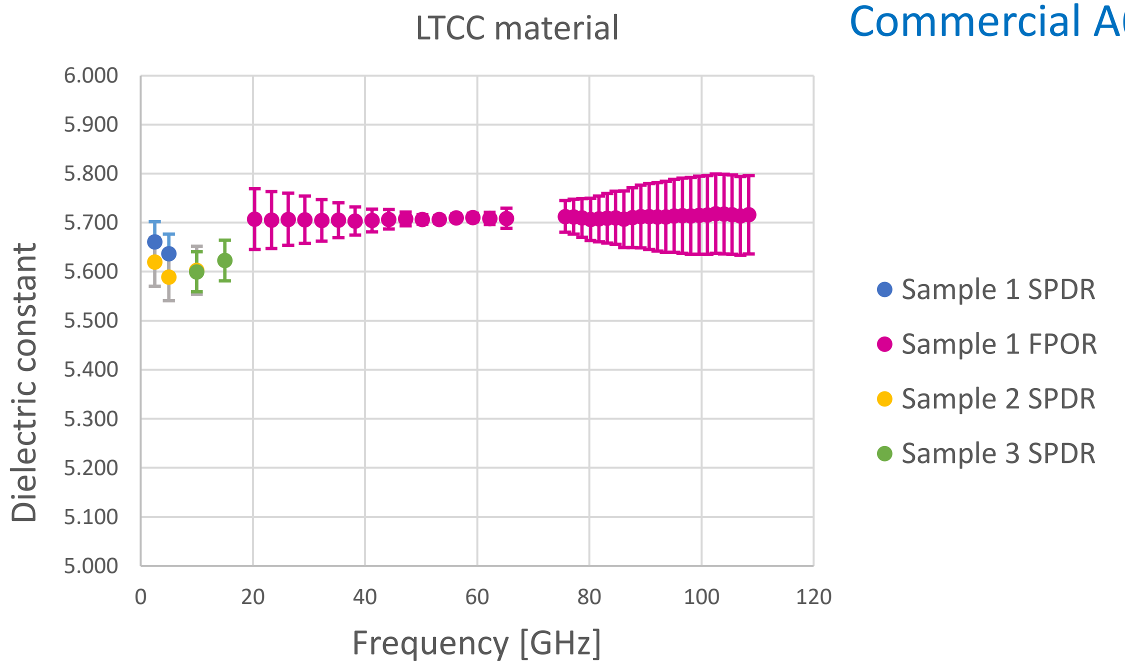
> 40GHz 2x increase in Df compared to 10GHz

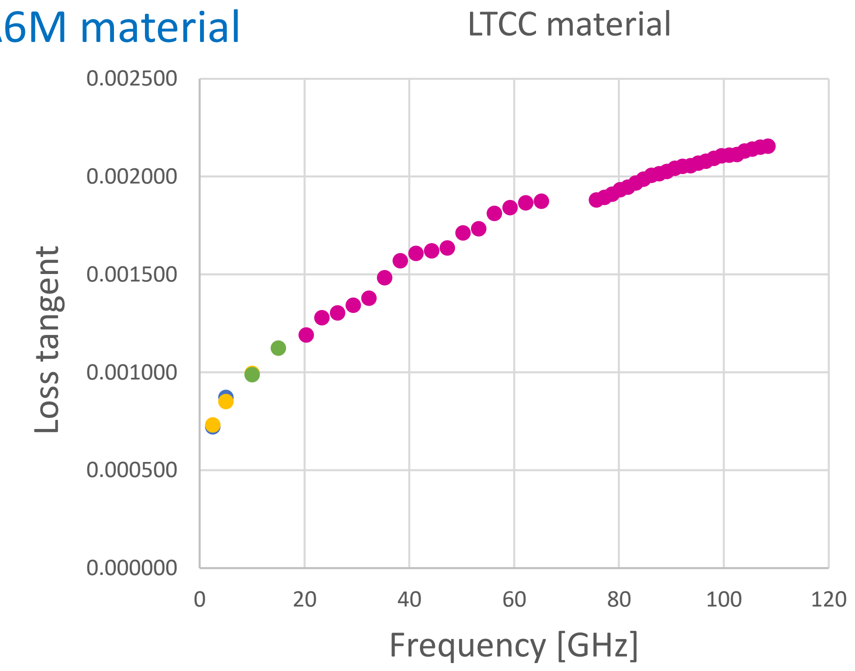
Recent Applications to ULTCC Materials: test of commercial A6M ceramic

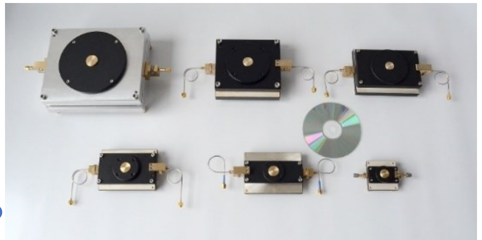
Ultra-Low Temperature Co-fired Ceramics for 6th Generation Electronic Packaging **(ULTCC6G_EPac under M-ERA.NET 2)**

ULTCC6G_EPac project is co-financed by the National Centre for Research and Development under M-ERA.NET2/2020/1/2021 contract.

Commercial A6M material







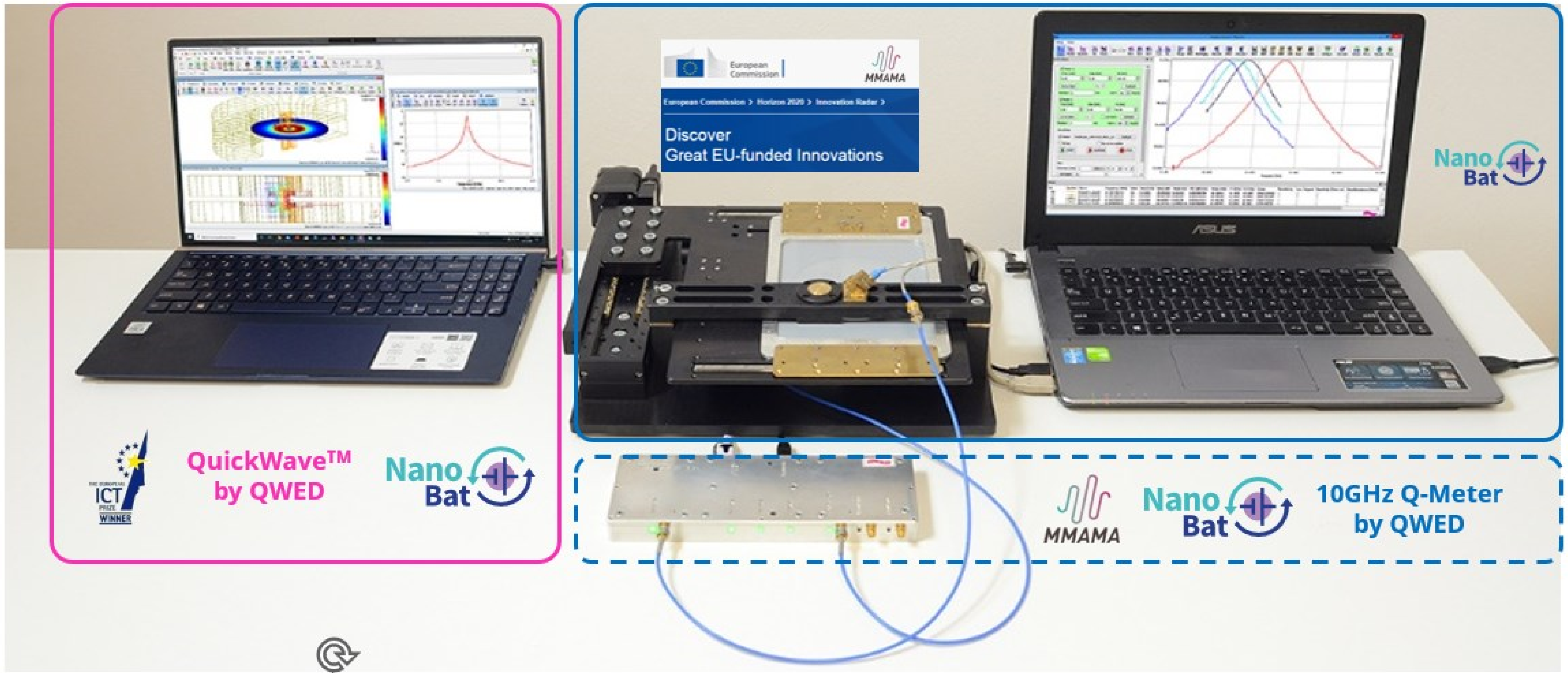
SPDRs

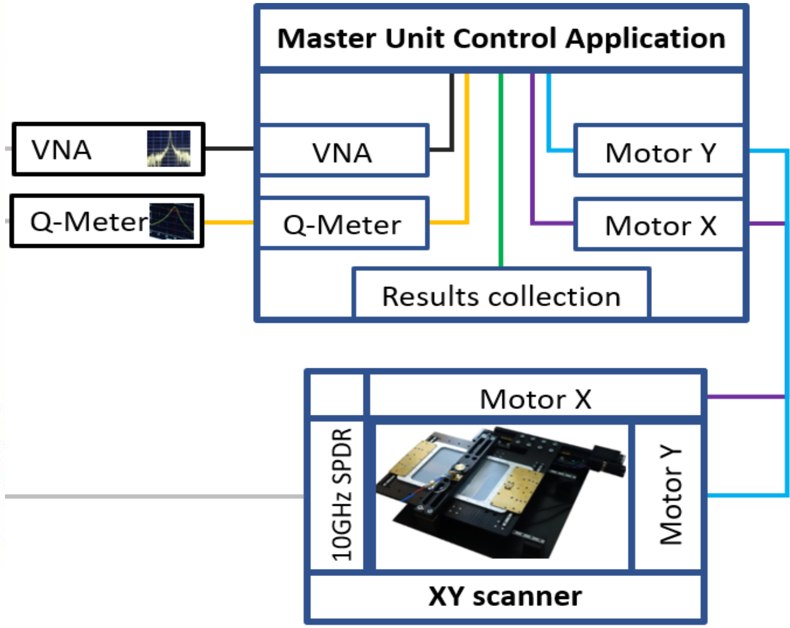
FPOR

SPDRs and FPOR results consistent within uncertainty bounds – related to thickness variation

Extension of the SPDR Method to 2D Imaging of Planar Samples

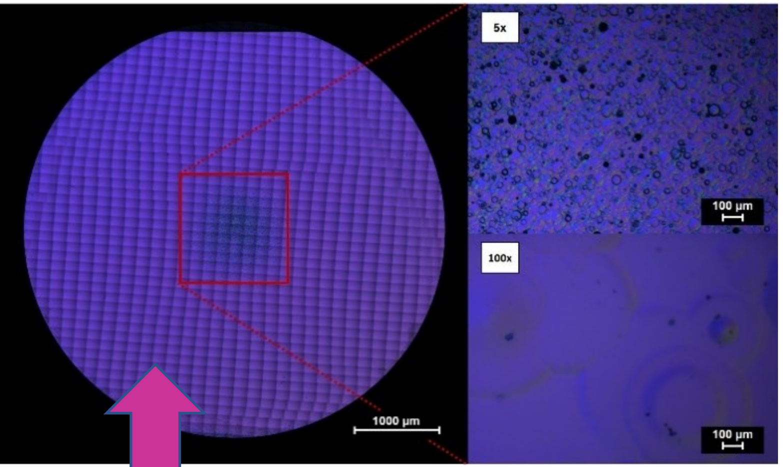
2D scanner designed with a modified 10 GHz SPDR





Finalist of the European Innovation Radar Prize 2021

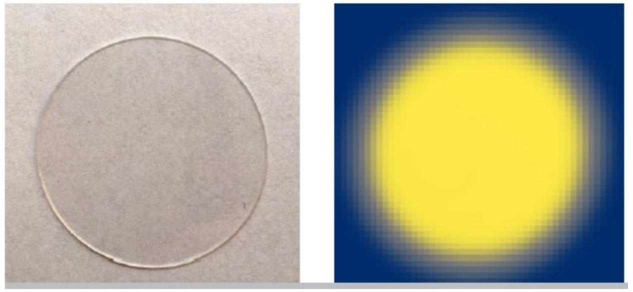
2D SPDR Imaging of HR- GaN for Light & Power Electronics Devices

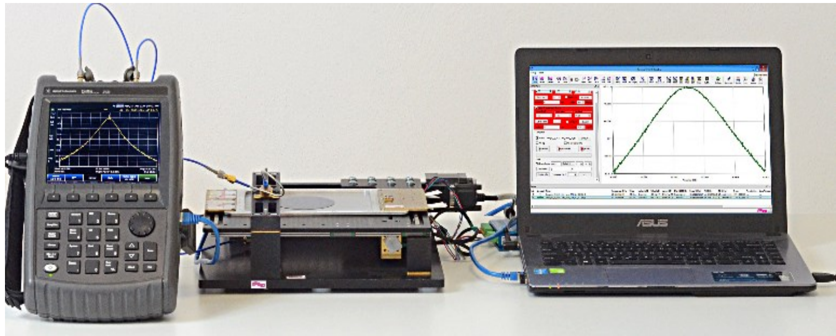


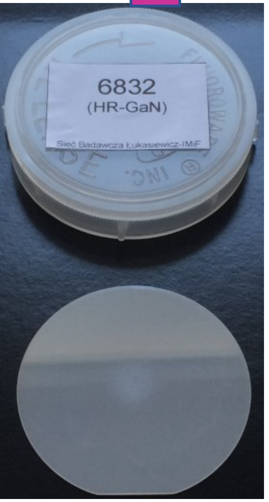
Optical microscopy image at L-IMiF reveals morphology inhomogeneity in the central area:

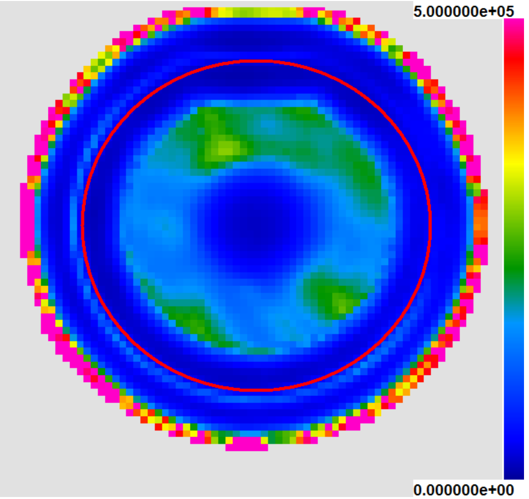
- in qualitative terms only,
- attributed to the growtch non-uniformity,
- only the central part appears unuseful for making devices.

2D map of quartz wafer









SPDR image:

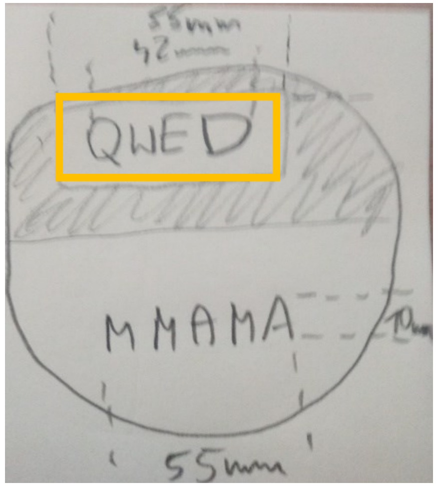
- shows this whole GaN template unuseful,
- quantitative evaluation:
  - edge ring inherent to so-called edge effect,
  - ca. $2 \cdot 10^4$ Ωcm in the centre (dark blue),
  - ca. $5 \cdot 10^4$ Ωcm along the inner ring (light blue),
  - up to $1.2 - 3 \cdot 10^5$ Ωcm across outer SUT's area (blue-green),
  - edge effect along the circumference.

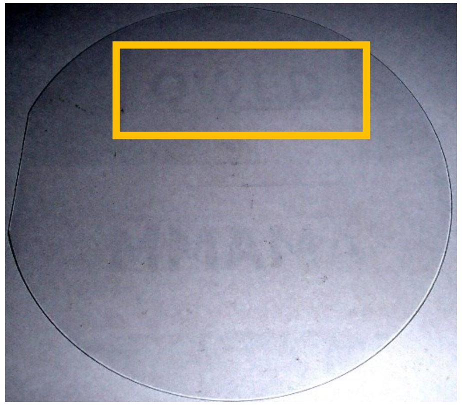
The National Centre for Research and Development

M-ERA.NET

Łukasiewicz IMiF

2D Imaging of Organic Semiconductors for Solar Cells

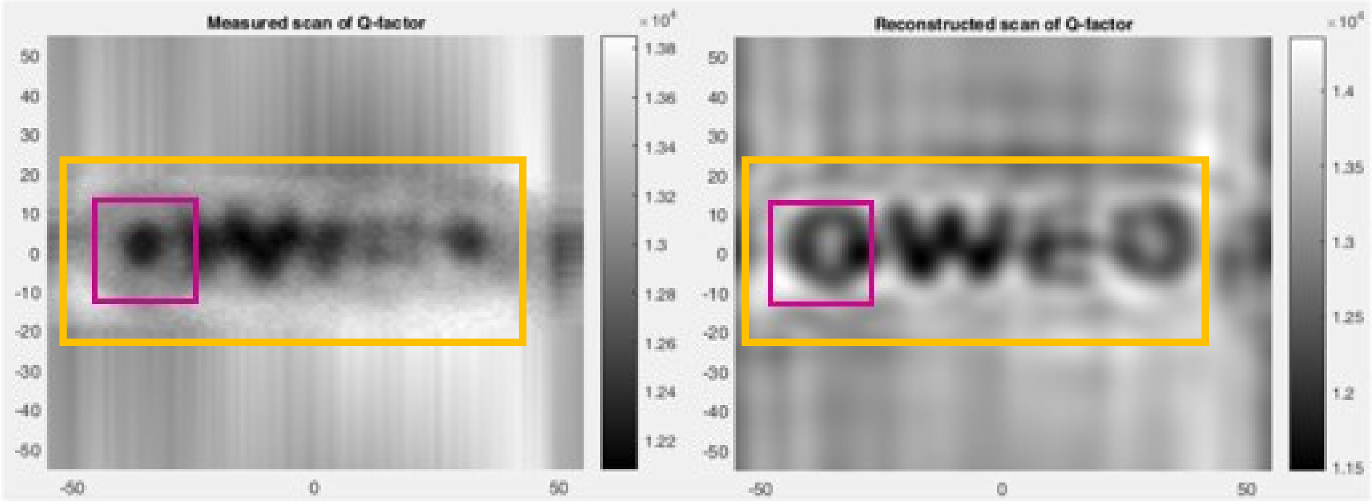




Patterned PEDOT:PSS sample
courtesy MateriaNova, Belgium

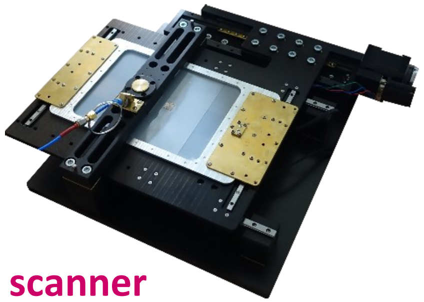
MMAMA MATERIA NOVA

Modelling-Based Resolution Enhancement of Surface Images

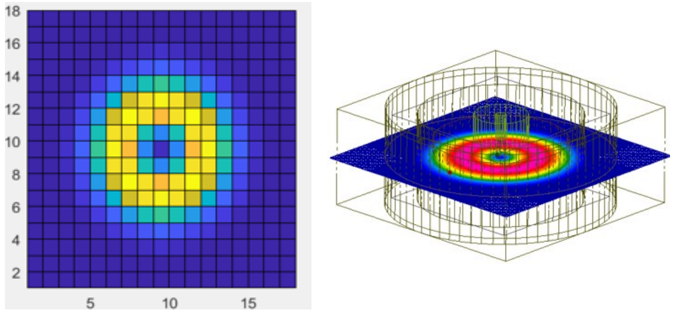


raw image of sample resistivity
(measured Q-Factor)

image further deconvolved
using SPDR field pattern
pre-simulated in QuickWave

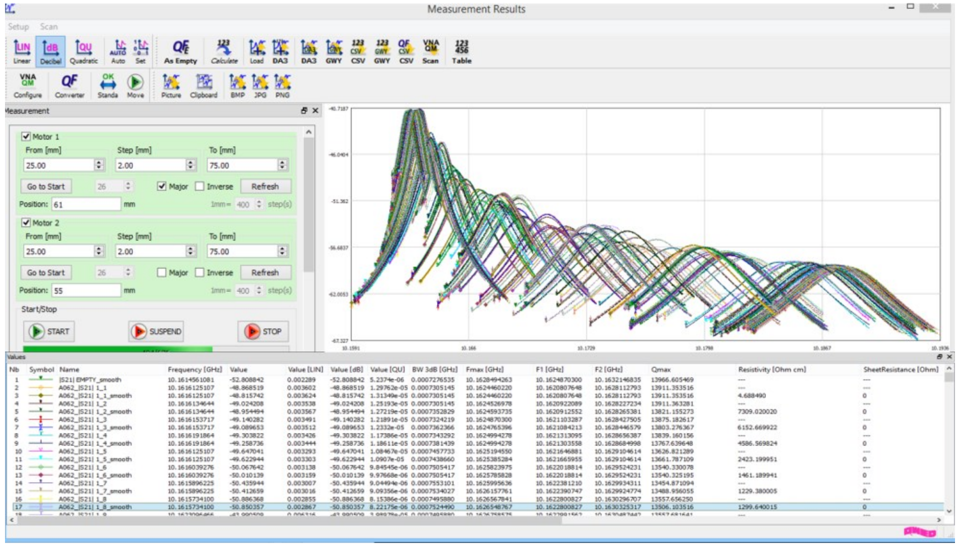


2D SPDR scanner

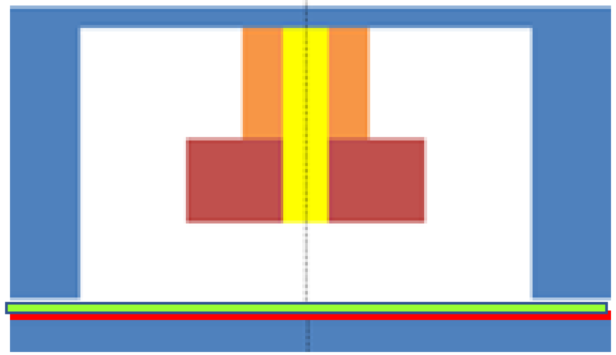


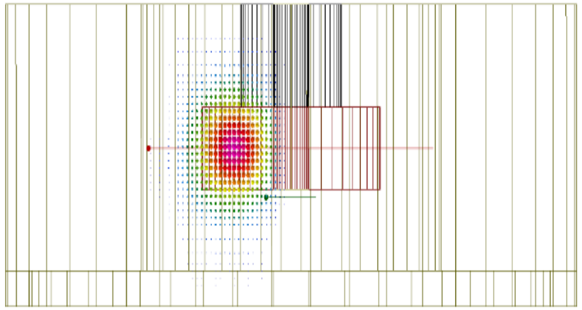
The National Centre for Research and Development
M-ERA.NET
QWED

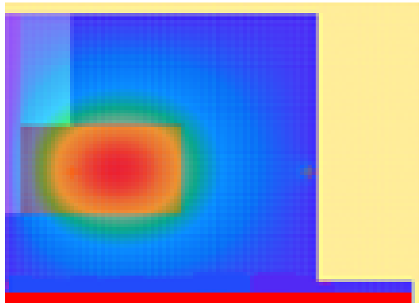
2D Imaging of Conductive Films – 10 GHz iSiPDR Scanning Setup

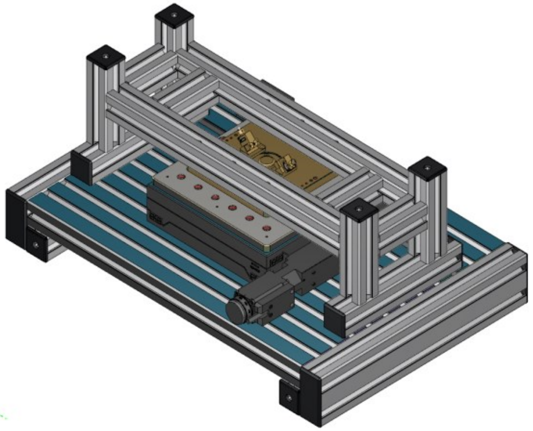


2D SiPDR scanner   Keysight FieldFox   Control App





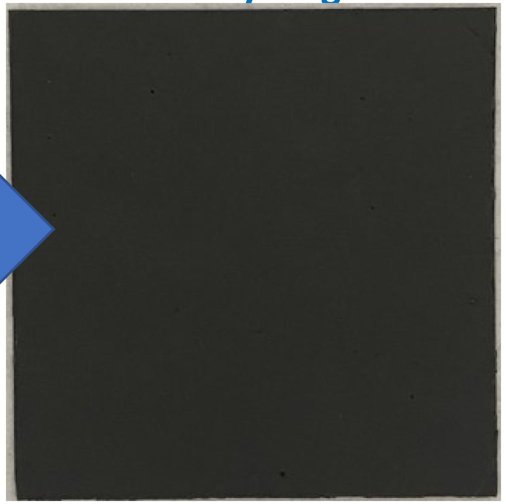




2D Imaging of Conductive Films – Graphene Anodes Before & After Cycling

Copper electrode

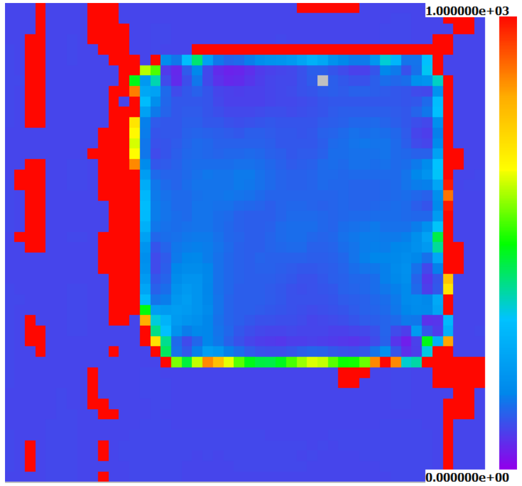
Graphene –based battery anode before cycling



Scanning range: 80 x 80 mm, scanning step: 2mm
Measurement points: 1681
Scanning time: ca. 2h

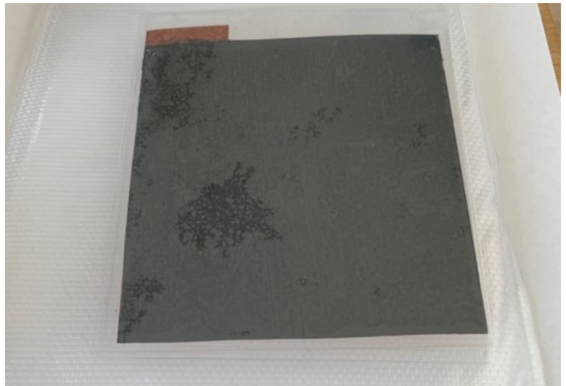
2D map of Rs [Ω/sq.]

values of Rs [Ω/sq.]



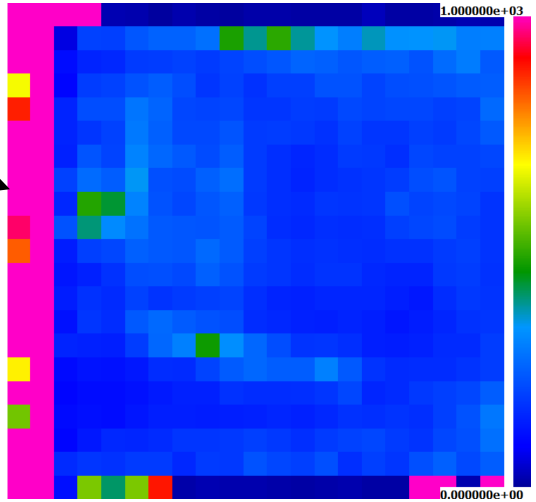
85 – 160 [Ω/sq.]

**courtesy PLEIONE Energy, Greece*



Graphene –based battery anode after battery cycling (ca. 100 cycles)

Sample edge (protecting foil)



110 – 340 [Ω/sq.]

increase indicates SEI formation

Acknowledgements

The presented work has received funding from:

the *European Union's Horizon 2020* research and innovation programme under grant agreement *NanoBat No 861962*.

the *Polish National Centre for Research and Development* under contracts *M-ERA.NET2/2020/1/2021* and *M-ERA.NET3/2021/83/I4BAGS/2022*.

M-ERA.NET 3 has received funding from the *European Union's Horizon 2020* research and innovation programme under grant agreements *No 958174*.

We kindly acknowledge the collaborations with our partners in the above projects, and especially L-IMIF (PL), Fraunhofer (DE), Pleione (EL), and Materianova (BE), for providings the samples presented herein.

We further acknowledge KEYSIGHT TECHNOLOGIES (US & AT) for the long-term collaborations as well as all partners in the iNEMI "5G" projects for joint round-robin experiments and discussions.

Summarising…

1. Resonator-based techniques provide unbeatable accuracy
for the characterisation of low-loss materials relevant to 5G and 6G.

2. The using higher frequency bands, 5G / 6G become a “moving target”
requiring developments of resonators for ever higher frequencies.
→ FPOR has been proven a practical solution up to 120 GHz
and further increase of its operating frequencies requires enhancement (calibration) on the VNA side.

3. In the ongoing M-ERA.NET ULTCC6G_EPac project the use of SPDRs and cavities has been extended
to controlled environmental conditions, providing feedback for the ULTCC process developments.

4. In the H2020 MMAMA & NanoBat, and M-ERA.NET I4BAGS projects the use of SPDRs and SiPDRs has been
extended to 2D imaging of energy materials, providing feedback for process quality control.

5. QWED team is open to undertake new challenges in the field of material measurements, including 6G,
and new collaborations, especially where our modelling competencies can fill existing knowledge gaps.