Industrial Keynote

Accurate Materials' Testing as an Enabler for Microwave and Millimeter-Wave Industries

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Outline:

1. Introduction to IMS SC-31 (Th1E, Th2E).
2. Microwaves and Materials.
3. Material Data for Microwave Engineering.
4. QWED’s Position on the Scene.
5. Industrial Benchmarking Initiatives – iNEMI.
6. Summary and Outlook.

Introduction to IMS SC-31: Today

Emerging Technologies

28 **AI/ML for RF to mmWave —** AI/ML, algorithms implementations, and demonstrations for: spectrum sensing; mobile edge networking; MIMO and array beam operations and management; design and optimization; in-situ sensing, diagnostics, control, reconfiguration of MHz to THz communication and sensing circuits and systems

29 **Quantum devices, circuits, and systems —** Quantum devices and circuits (incl. cryogenic RF circuits); algorithms, interfaces, and systems for quantum computing and quantum sensing applications

30 **SubTHz and THz circuits and systems —** SubTHz and THz systems (300GHz to 1 THz+), incl. sub-THz architectures and implementations for passive and active sensing, 6G and Future-G communication systems.

31 **Microwave field-matter interaction, material sensing and high-power applications —** Industrial and scientific applications of microwave energy (e.g., chemistry, metallurgy, ceramic sintering, plasma generation, waste treatment, "green" materials, energy converters); MHz-to-THz sensing (from microwave microscopy to large surface/volume imaging) of materials for electronics and energy applications; multiphysics modeling of materials processing and characterization.

32 **Other innovative MHz-to-THz systems and applications —** Submissions that describe innovative contributions in new and emerging areas of interest to the MTT community not falling under the above categories are encouraged.

Th1E: Material Sensing at Microwave and mm-Wave Frequencies

Chair: Zoya Popović
Chair organization: University of Colorado Boulder
Co-chair: Pawel Kopyt
Co-chair organization: Warsaw Univ. of Technology
Location: 146C
Abstract:
Advances in material sensing and characterization techniques from S to W frequency bands are presented. Instruments based on resonators, planar transmission lines, and free-space radar are discussed.

Th2E: Near-Field Wave-Matter Interaction

Chair: Kamel Haddadi
Chair organization: Université de Lille
Co-chair: Malgorzata Celuch
Co-chair organization: QWED
Location: 146C
Abstract:
This session covers wave-material interactions ranging from microwave microscopy to high-power-density plasma generation. Near-field microscopy for high-resolution material characterization at room and cryogenic temperatures is shown using frequencies from 2 to 12GHz. Additionally, resonator-based field enhancement is shown for low-power plasma generation in the 2.45GHz ISM band.

Introduction to IMS SC-31

new knowledge

Microwave Field-Matter Interaction

new products

(1) materials' sensing with microwaves

typically different power levels

(2) materials' processing with microwaves

characterization
measurements
testing

heating
sintering
plasma generation

Introduction to IMS SC-31: Topic (2)

IMS
Connecting Minds. Exchanging Ideas.

IEEE MTT-S 2023 IMS Workshop WMG:
Recent Advances in Industrial Microwave Power Applications

Organizers:

Zoya Popović, University of Colorado Boulder, CO, USA
Vadim V. Yakovlev, Worcester Polytechnic Institute, MA, USA
Małgorzata Celuch, QWED, Warsaw, Poland

International Microwave Symposium
11-16 June 2023, San Diego, CA

The Coolest Ideas Under the Sun
SAN DIEGO 2023

IMPI

AMPERE

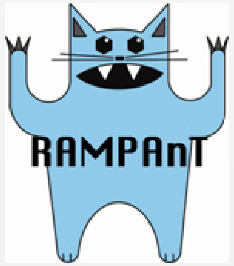
https://impi.org/ https://www.ampereeurope.org/

2009 International Microwave Symposium

7-12 June, Boston Convention & Exhibition Center
IEEE Microwave Theory and Techniques Society

Recent Advances in Microwave Power Applications and Techniques
IMS 2009 Workshop: 12 June 2009, Friday, full day

Come and stay
RAMPAnT
for new concepts and markets
in microwave theory and techniques!



IEEE
2009 IEEE MTT-S International Microwave Symposium
Highest Quality Workshop
This award is hereby presented to:
Malgorzata Celuch
For organizing the workshop
"Recent Advances in Microwave Power Applications and Techniques (RAMPAnT)"
Boston, Massachusetts
Friday, June 12, 2009

Fred Schindler
IMS2009 General Chair

Lawrence Kushner
IMS2009 Technical Program Co-Chair

Greg Lyons
IMS2009 Workshop Chair

Mark Gouker
IMS2009 Technical Program Co-Chair

IMPI/MTT-S WORKSHOP ON
INDUSTRIAL APPLICATIONS OF MICROWAVES
IEEE MTT-S International Microwave Symposium
San Francisco, CA, May 29, 1981

List of Speakers

1. H.F. Huang (DuPont) —
   Industrial and Consumer Applications of Microwaves and the Role of the International Microwave Power Institute (IMPI)
2. F. Hammersand and E. Adams (RCA) —
   Care and Operation of High Power Magnetrons for Industrial Applications
3. I. Namba and H. Sitao (Toshiba) —
   The Design and Application of Magnetrons in Microwave Ovens
4. K.L. Carr (M/A — COM) —
   Ferrite Circulators for Microwave Ovens

(LUNCHEON BREAK)

5. M.T. Long (American Microwave Technology) —
   Low-Cost Microwave Power Transistors for Microwave Ovens
6. J.P. Quine (General Electric) —
   Microwave Impedance and Heating Characteristics of Microwave Ovens
7. J.M. Osepchuk (Raytheon) —
   Safety and RFI Considerations in Microwave Power Applications.
8. Panel Discussion (All Speakers)

IEEE MTT-S IEEE MICROWAVE THEORY & TECHNOLOGY SOCIETY

Introduction to IMS SC-31: Topic (1)

IMS papers related to materials testing / sensing with microwaves are:

- not so many

- dispersed among different sessions

SC-31 aims to:

+ attract more papers

+ define coherent facilitating vivid discussions

Material World

AMi2030 ADVANCED MATERIALS INITIATIVE

https://www.ami2030.eu/

EMMC

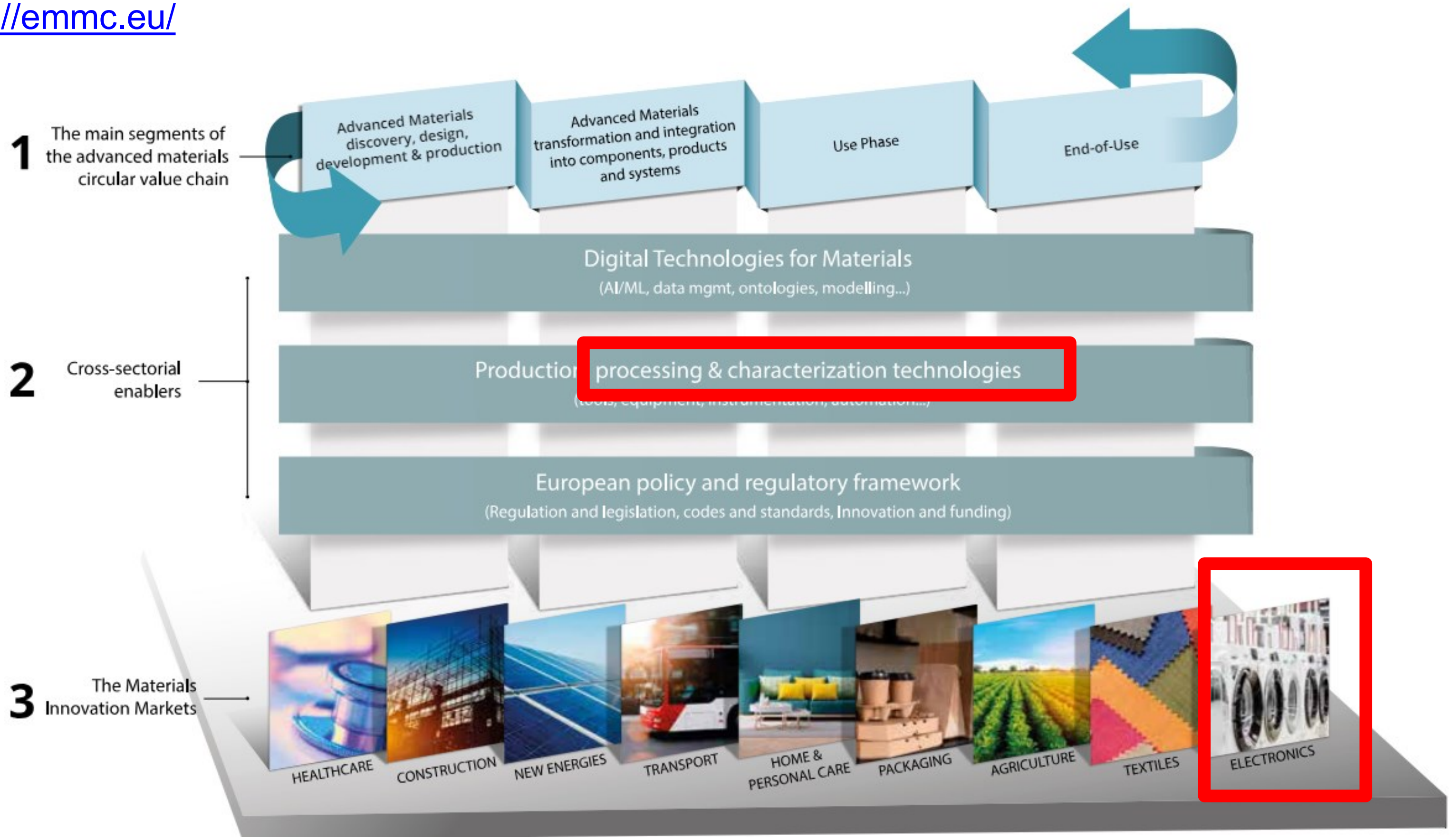
https://emmc.eu/

EMMC Roadmap

Materials Modelling and Digitalisation of the Materials Sciences

AMi2030 ADVANCED MATERIALS INITIATIVE

STRATEGIC MATERIALS AGENDA



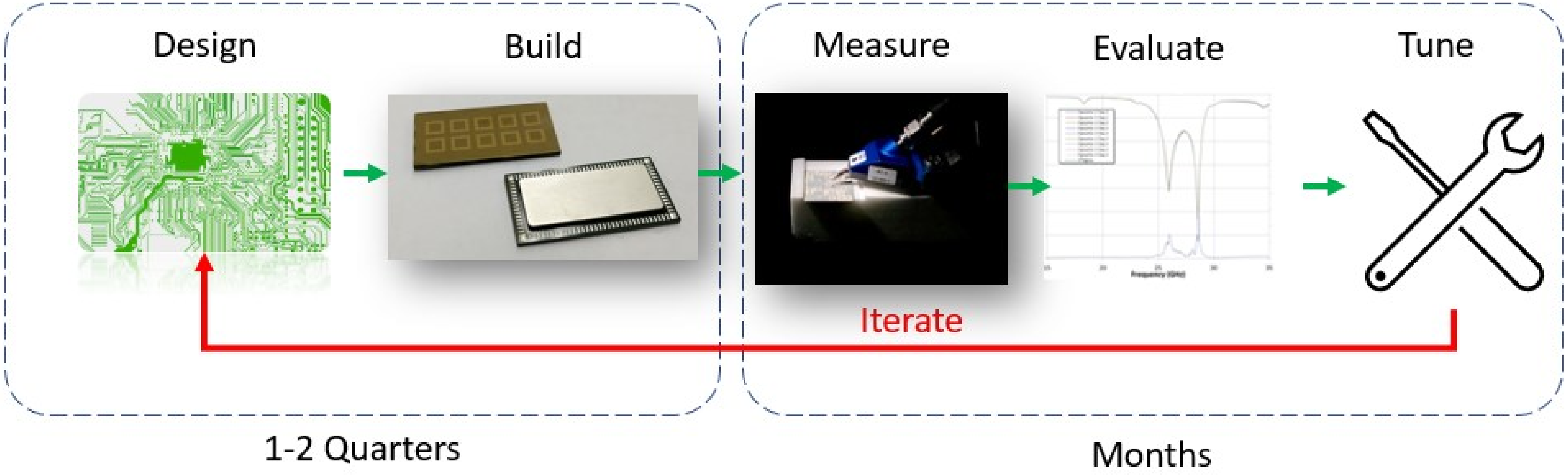
Materials in Microwave / RF Engineering

Materials come into play once you build a circuit.

CAD / CAE software can take nearly anything in.

Given contemporary CAD / CAE software capabilities, design failure is rather due to errors in materials' data.

"rubbish in, rubbish out"



*

Errors may cost $10's of millions for a single program, or worse, unexpected product failures. *

* figure and statement from https://www.inemi.org/article_content.asp?adminkey=5cc4f4100ebf2ba1f3e6fd6294749139&article=161

IMS
Connecting Minds. Exchanging Ideas.

iNEMI
International Electronics Manufacturing Initiative
www.inemi.org

QWED participates to projects evaluating:

dielectric losses

conductor losses

→ fast & precise measurement methods,

→ physical insight with computer modelling,

→ dissemination (in IEEE and EU communities).

5G/mmWave

- 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

QWED Bridging Two MTT-S Fellowships

Wojciech Gwarek (2001)
“theory and applications
of electromagnetic modeling”

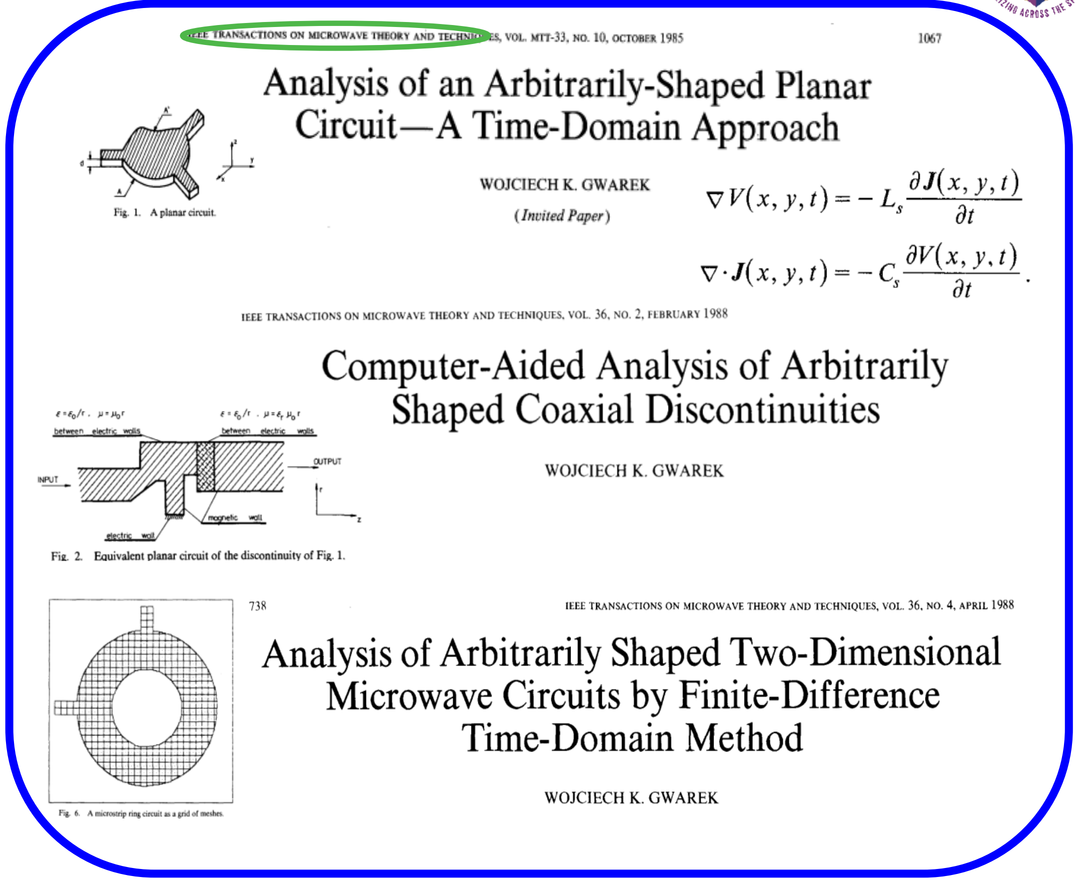
Jerzy Krupka (2012)
“high frequency measurements
of electromagnetic properties of materials”

QWED origins in Computational Electromagnetics

since 1980s...

IEEE- awarded research of Wojciech Gwarek

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

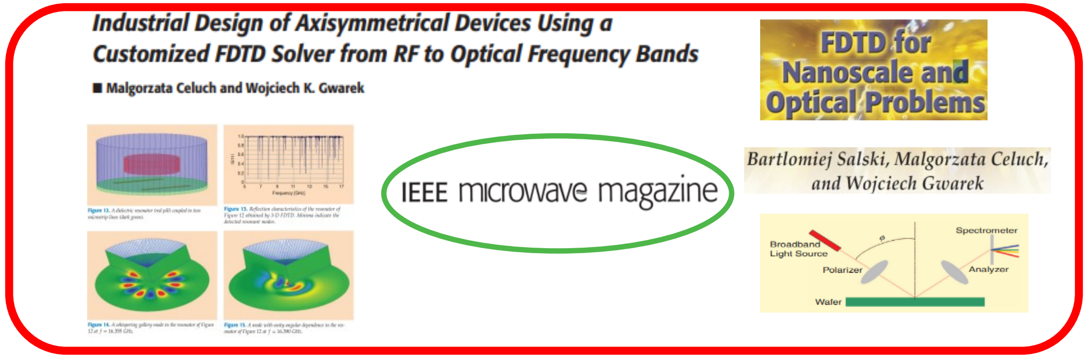
Fig. 2. Equivalent planar circuit of the discontinuity of Fig. 1.

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

+ conformal modeling of geometry
+ time-domain approach

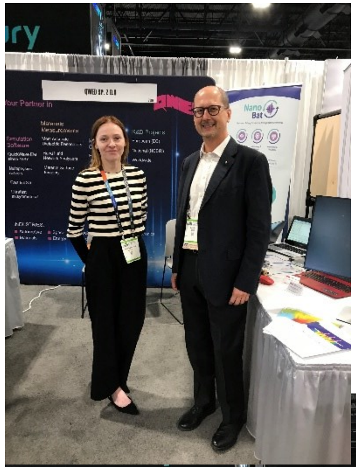
1997 first commercial licences sold by QWED

... by early 2000s, QuickWave-3D by QWED used worldwide for industrial & research applications from RF to optical bands

since 1998 annually at IEEE IMS

Anaheim, CA, 1999

San Francisco, CA, 2006

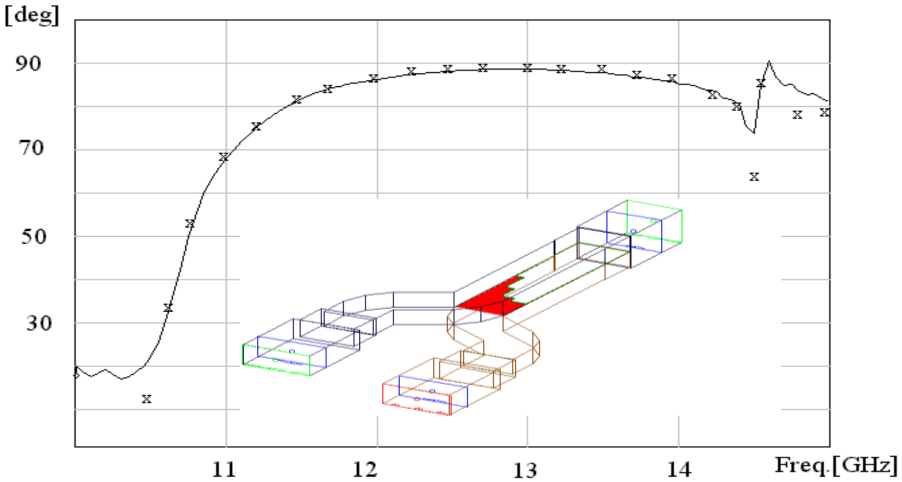


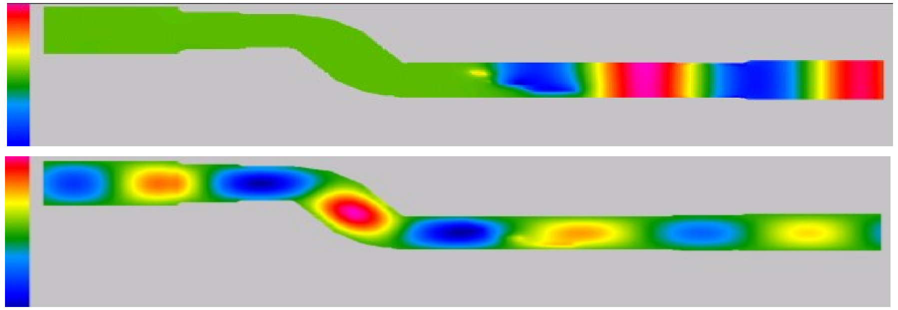
Denver, 2022

QuickWave original applications in cosmic research & SATCOM

Septum polariser by SES

design & measurements: Saab Ericsson Space
modelling: QWED, 1997
below: differential phase-shift

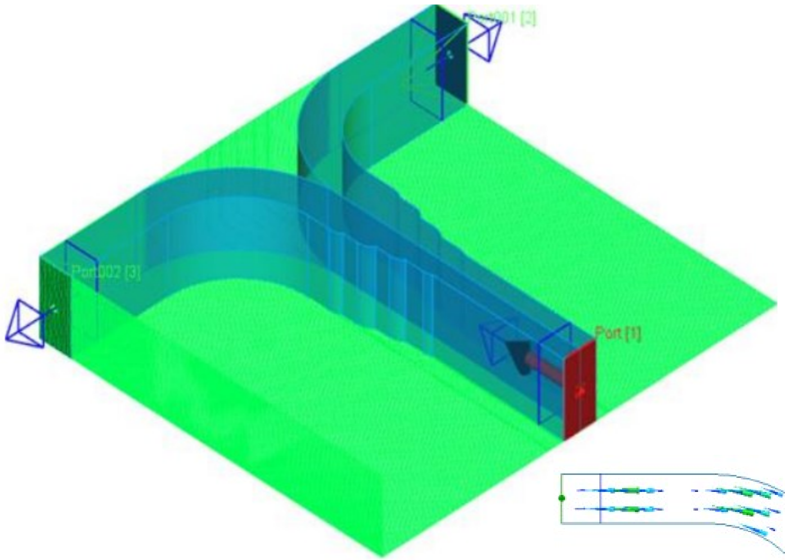


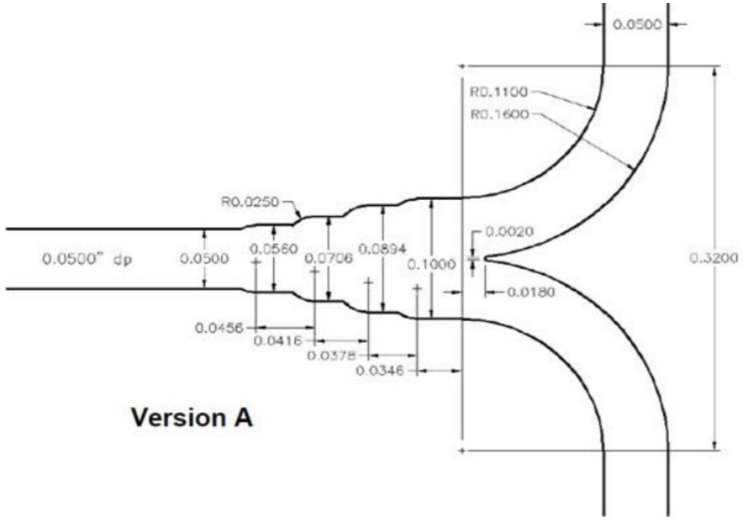


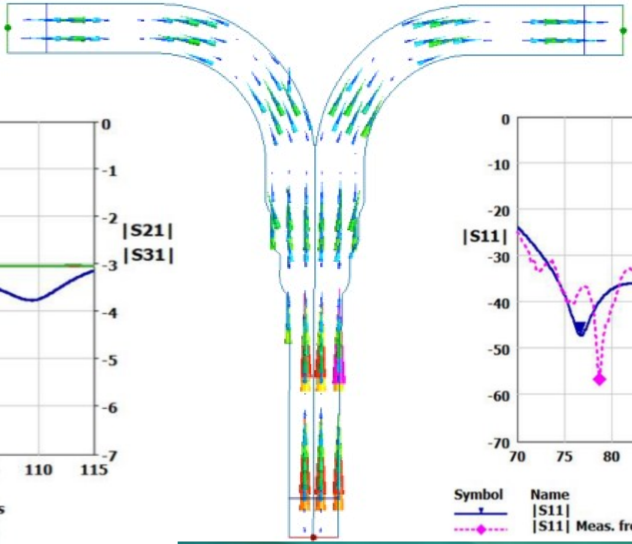
propagation of two polarisations at centre frequency

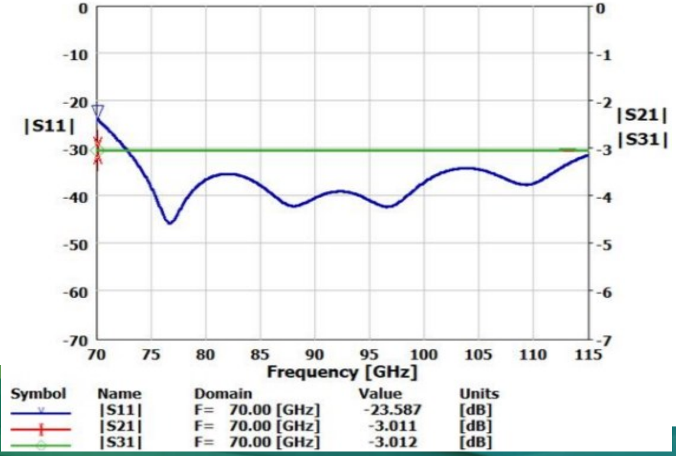
E-plane Y-junction by NRAO

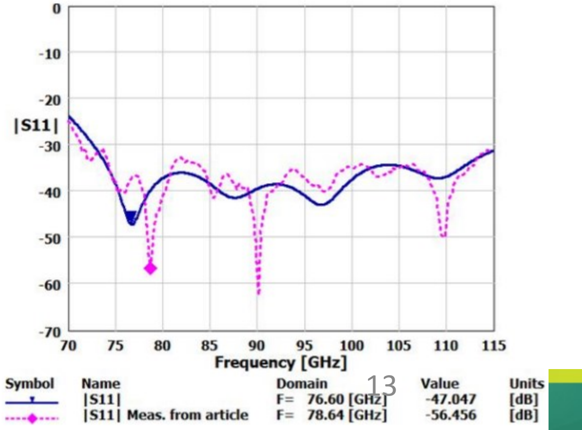
after A. R. Kerr, Elements for E-Plane Split-Block Waveguide Circuits, ALMA Memo 381







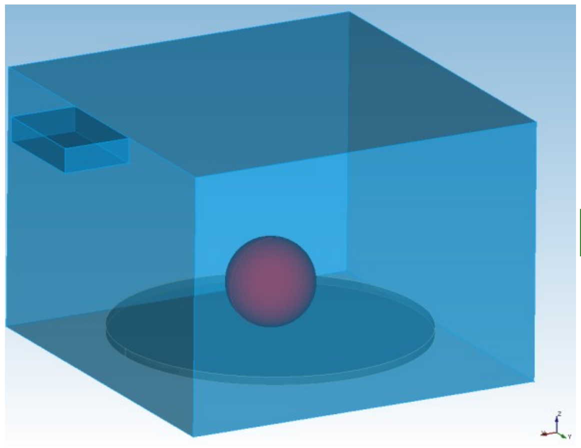




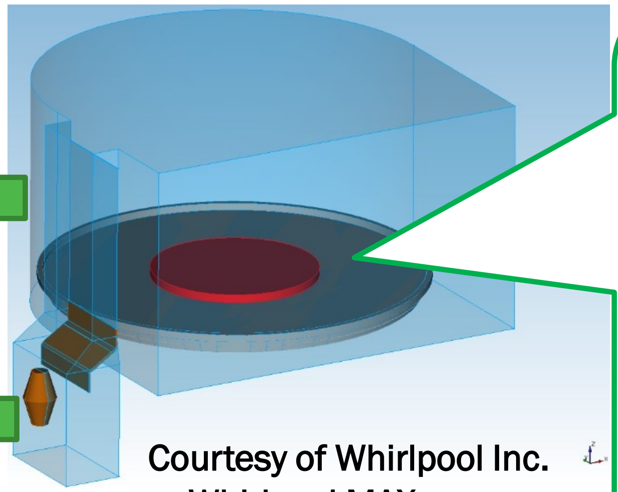
Applications for Materials Processing with Microwaves

Simple microwave heating benchmarks & microwave heating phenomena studies*

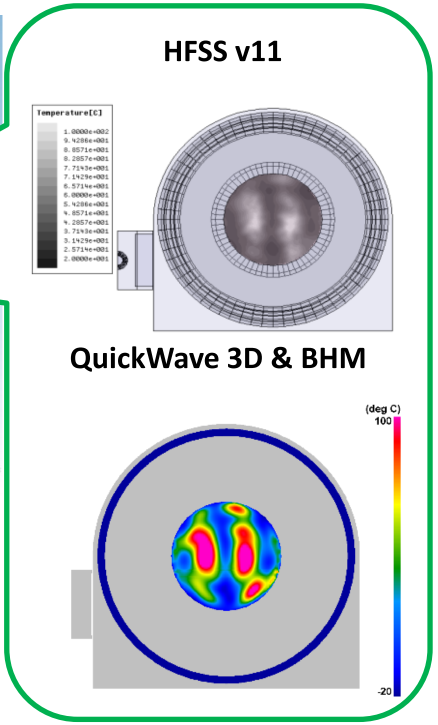
Design & analysis of real-life microwave oven cavities, incl. complicated cavity shapes and advanced feeding system*



- heat transfer & load dynamics
- Load rotation & arbitrary movement during heating
- Source parameters tuning – regime for solid state sources
- Temperature dependence of material parameters

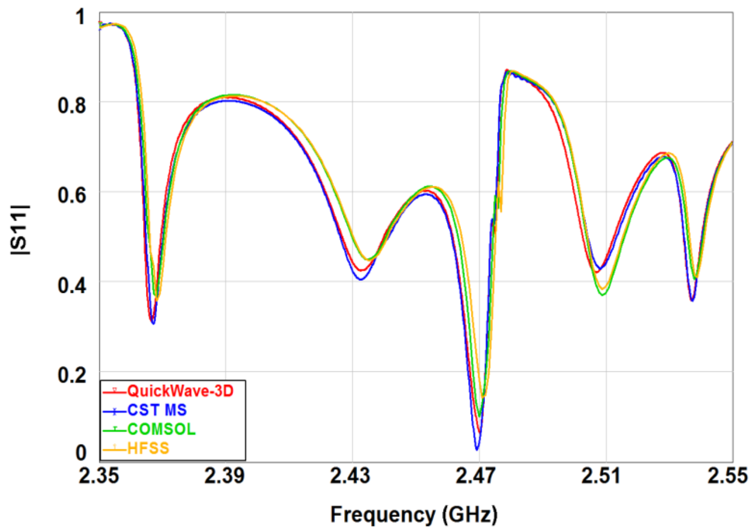


Courtesy of Whirlpool Inc. – Whirlpool MAX oven

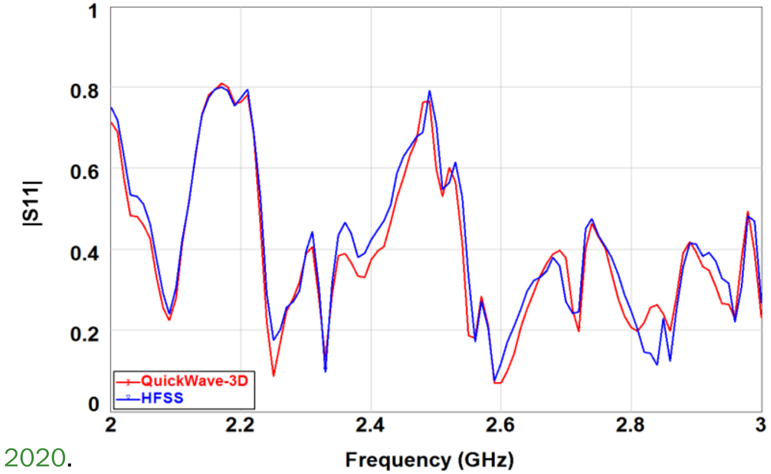


Freezing to file the state of the simulation

De-freezing on arbitrary computer & at convenient time



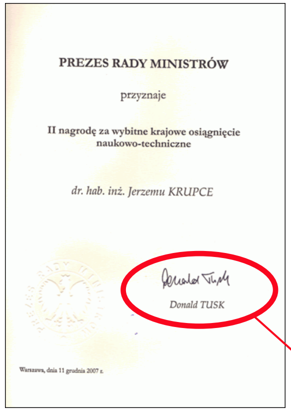
* M.Celuch, P.Kopyt & M. Olszewska-Placha in eds. M. Lorence, P. S. Pesheck, U. Erle, *Development of packaging and products for use in microwave ovens*, 2nd Ed. Elsevier 2020.

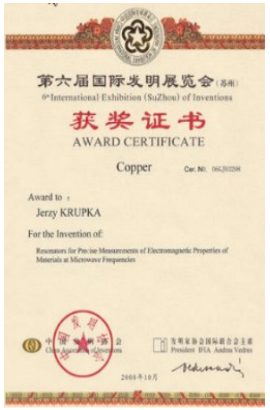


With QuickWave EM computation as fast as 1 min 18s on a low-cost video card – supporting all graphic cards with OpenCL

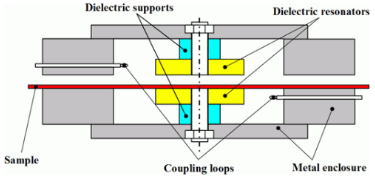
Material Measurements coming to QWED

since 1980s...
awarded research of Jerzy Krupka (IEEE Fellow) on dielectric resonators (best known: Split-Post Dielectric Resonator)

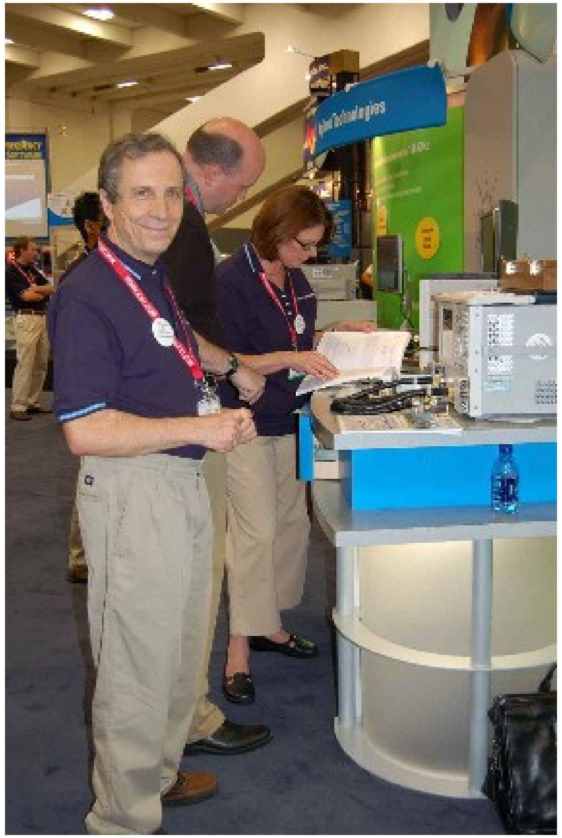




by Donald Tusk
Prime Minister of Poland 2007-2014
President of the European Council 2014-2019



... by early 2000s:
QWED commercialises the SPDRs
endorsement by Agilent / Keysight
publication of standard IEC 61189-2-721:2015



Agilent Both
IEEE IMS 2006,
San Francisco, CA

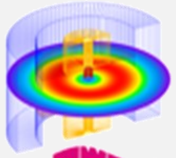
MMA-2010, Warsaw PL
co-organised by
QWED & Warsaw Univ.Tech.

Bridging Computer Modelling with Material Measurements

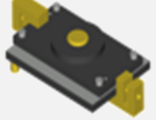
Commercial since 1997
QuickWave Simulation Software
~1000 licences implemented

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



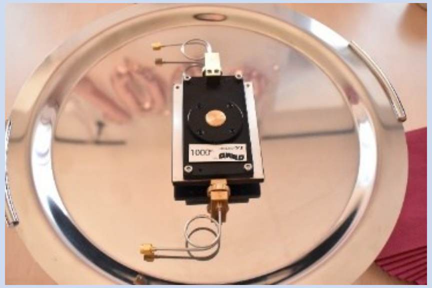
Material measurements

INNOVATION

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.

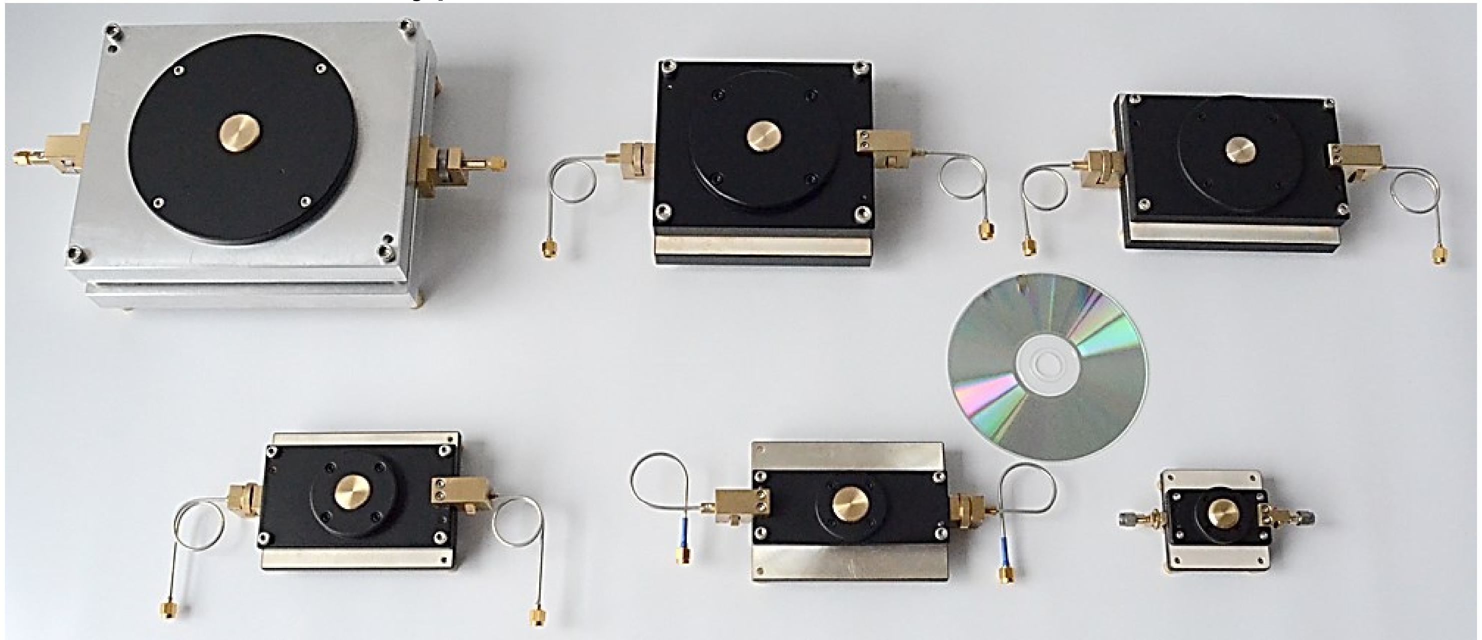
Open Platform Examples:

SMM tip presented at Numerical Electromagnetic

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

Popular Resonators Offered by QWED

SPDRs for laminar dielectric materials
typical units: 1.1 GHz -15 GHz



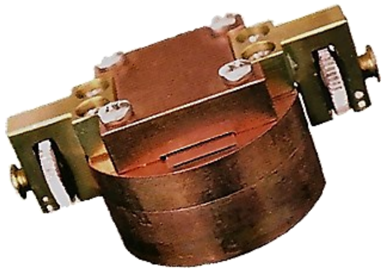
T. Karpisz, B. Salski, P. Kopyt, and J. Krupka,
doi: 10.1109/TMTT.2019.2905549.

FPOR
20 -120
GHz

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

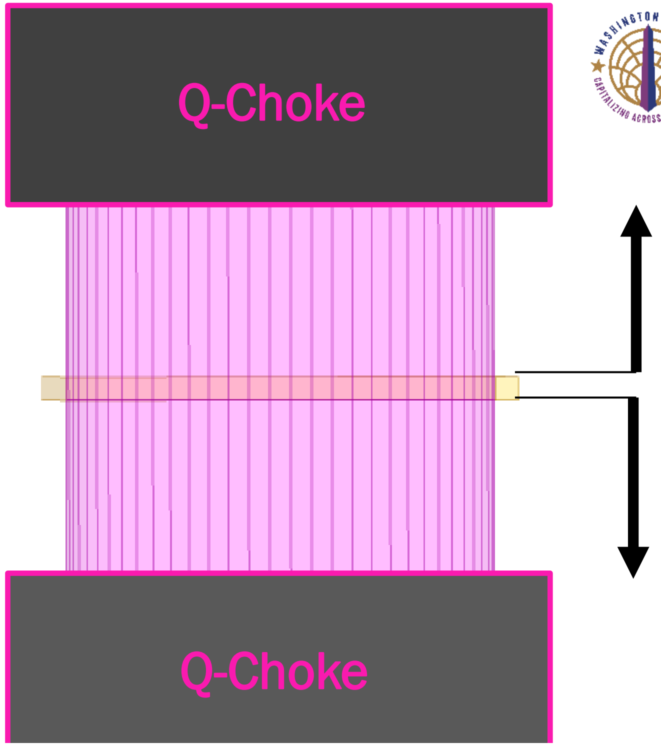
5 GHz SiPDR for resistive sheets

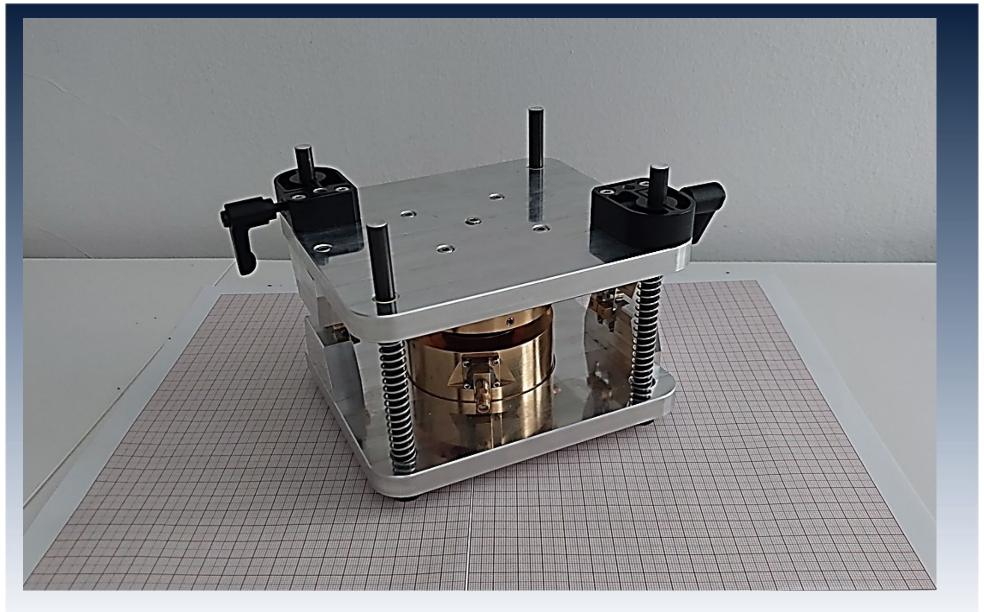
modified SiPDR for graphene

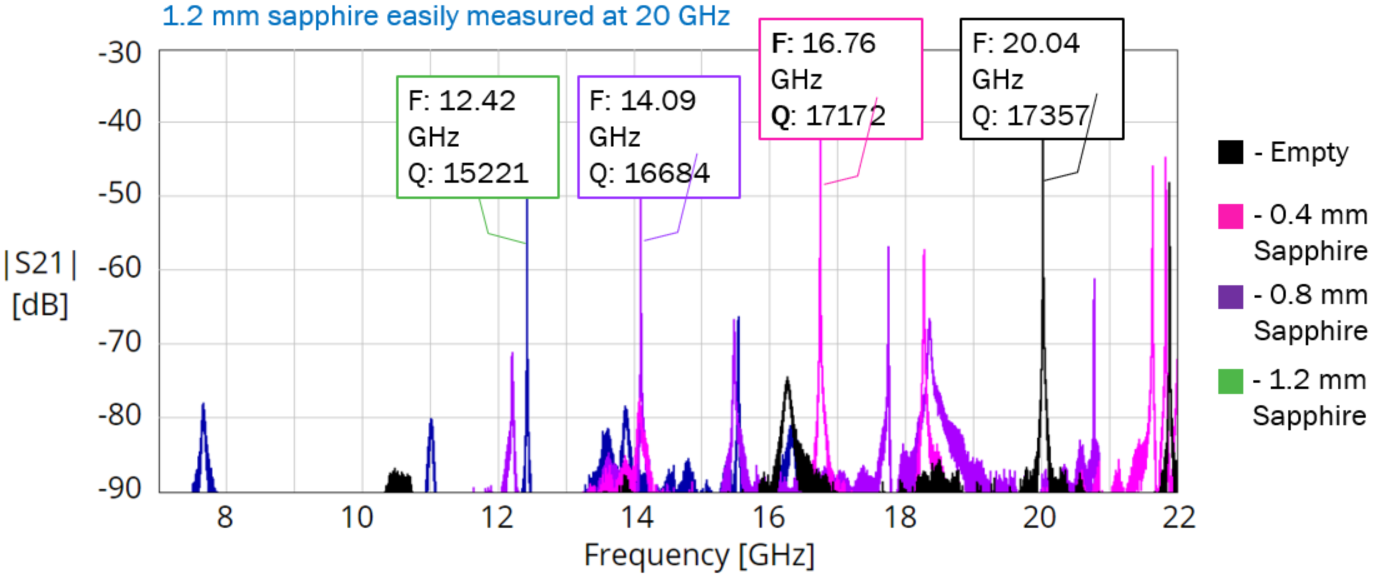


QWED's Novel SCR with Q-Choke (Th1E-2)

European patent application:
EP23461651 (Sep.2023)







First iNEMI Benchmarking Project

No standards & SRMs for mmWave Permittivity measurements >20 GHz:

- Challenges for ISO and quality control

Few vendors for mmWave Permittivity measurement equipment >10 GHz:

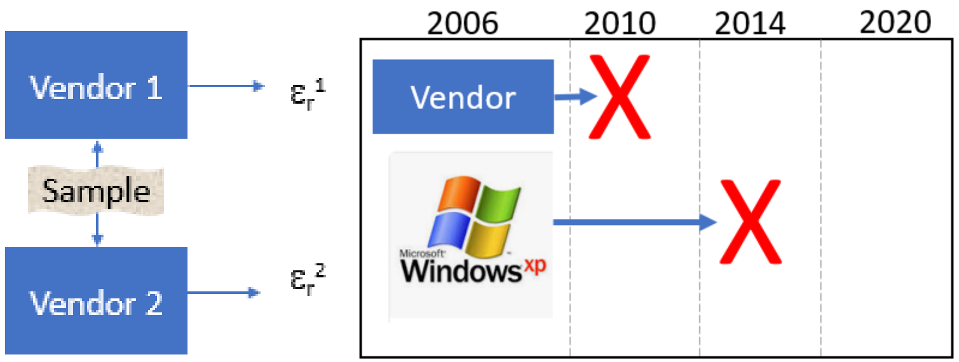
- Explain vendor to vendor differences
- Whom to trust?
- On whom to rely?

Useful 5G materials are typically **very low loss**:

- Eliminates many traditional transmission line techniques

Increasing frequency:

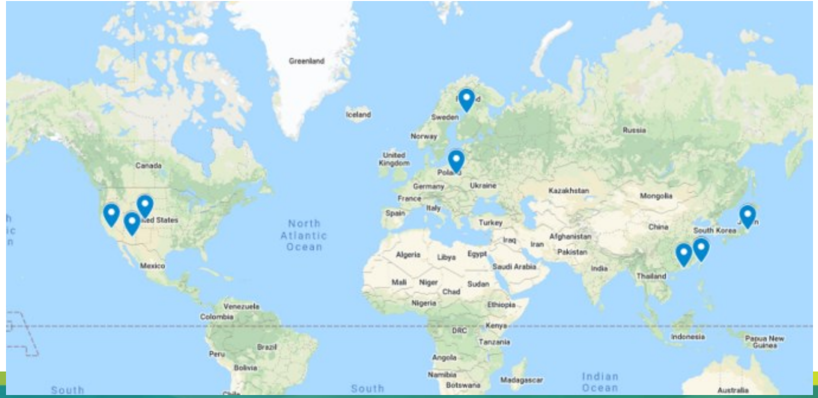
- **Incompatible** sample dimension requirements between techniques
- Higher **sensitivity to operator**



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



First Round-Robin

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

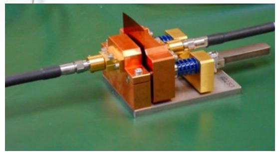
Techniques Included

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

→ Frequency Span : 10GHz – 100GHz with overlaps

10 Sample Kits Created

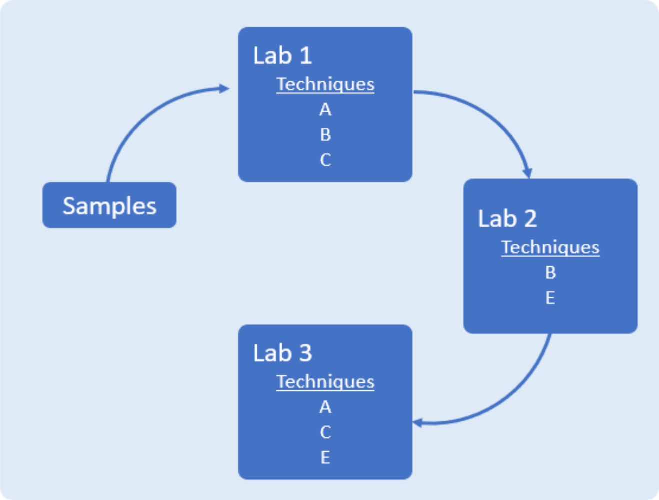
- Sample sizes 35 mm x 45 mm, 90 mm x 90 mm

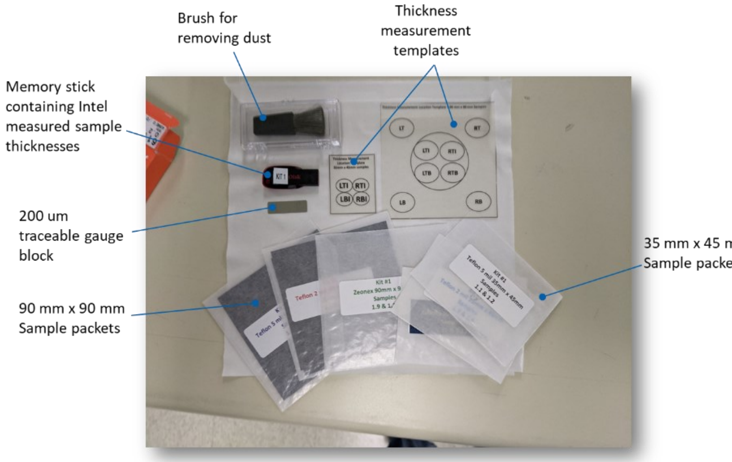




in-plane

BCDR out-of-plane

10 Laboratory Round Robin





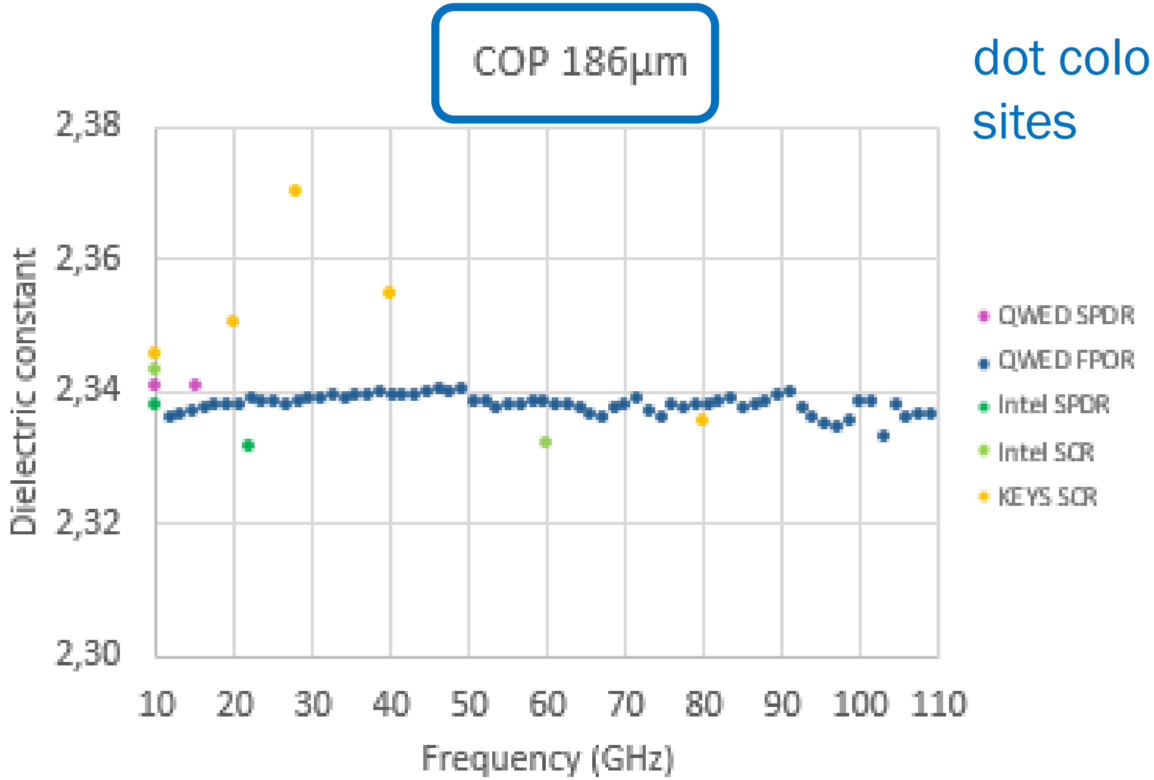
First Round-Robin Results: Consistency

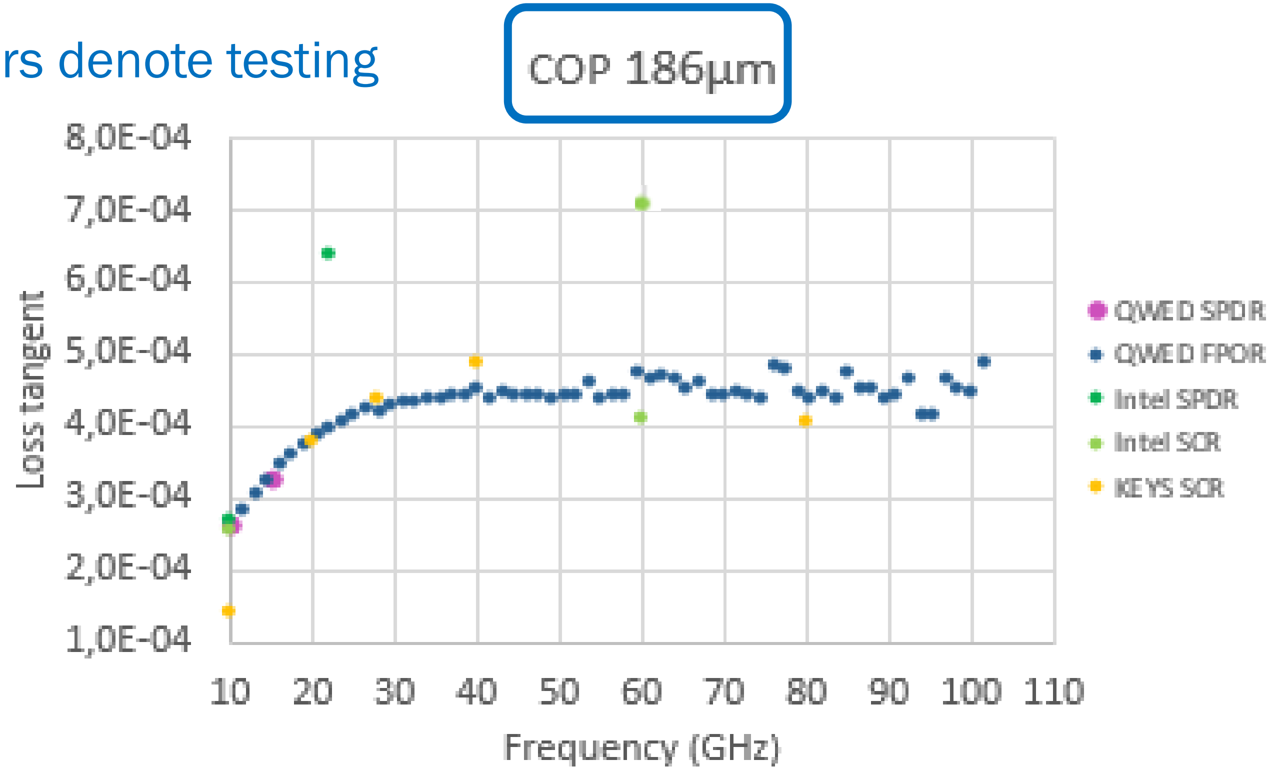
3 labs, 3 techniques
14 laboratory setups

Resonators:
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 10-110GHz

VNA, software:
Intel, Keysight – benchtop VNA with Keysight Option N1500A
QWED FPOR – benchtop VNA with customised FPOR software
QWED SPDR – handheld VNA , extraction based on abs(S21)

dot colours denote testing sites





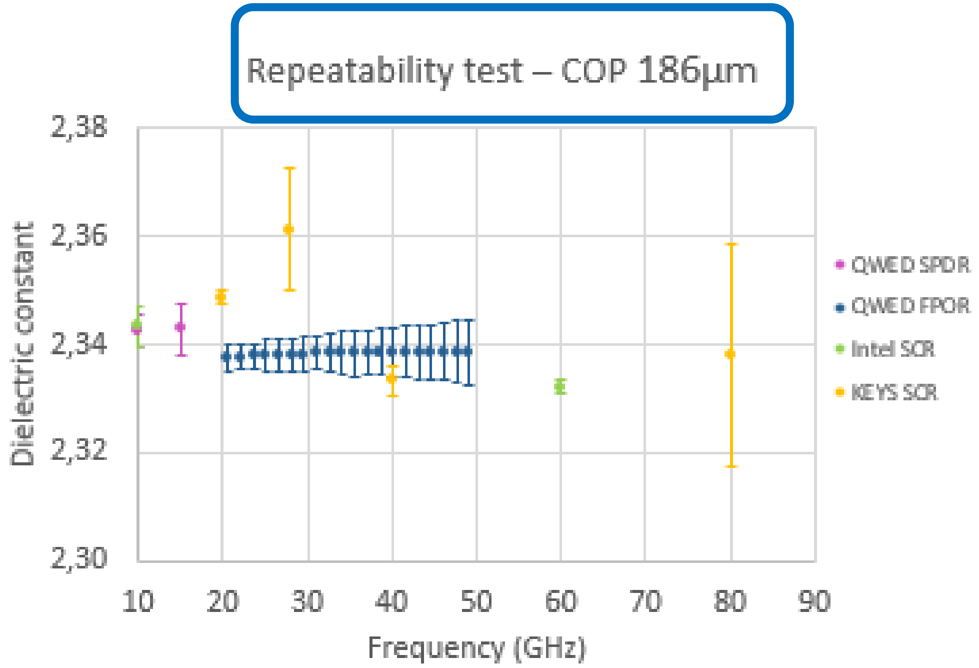
Dk spread < 1% (within ± 0.5% from average)
(< 2% incl. outliers)

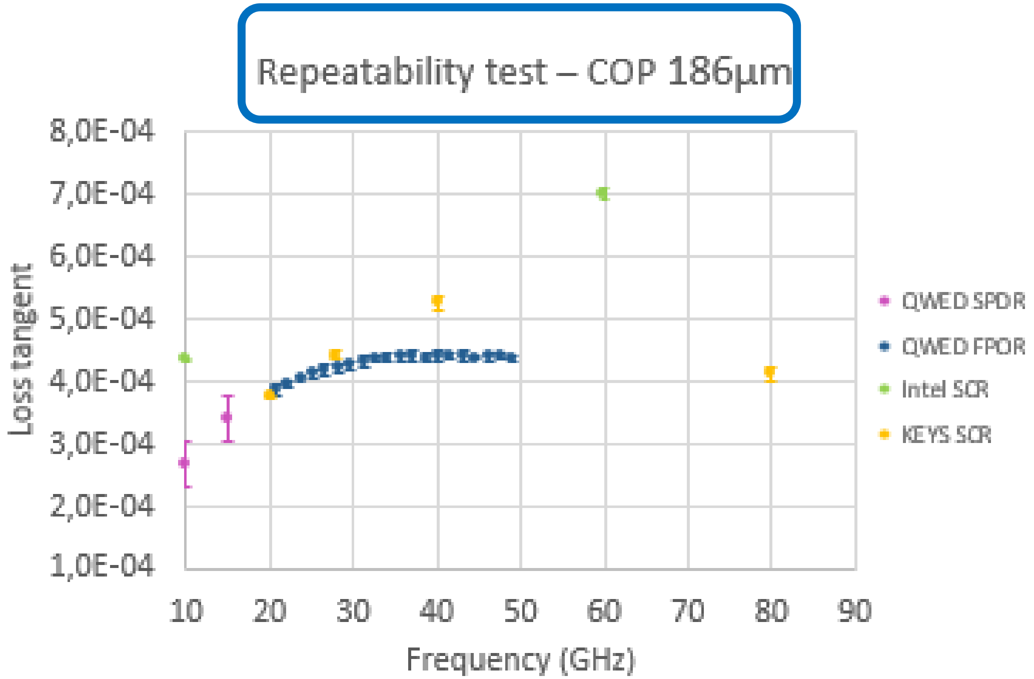
> 40GHz 2x increase in Df compared to 10GHz

First Round-Robin Results: Repeatability

3 labs, 3 techniques, 14 laboratory setups
1 operator per setup

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.





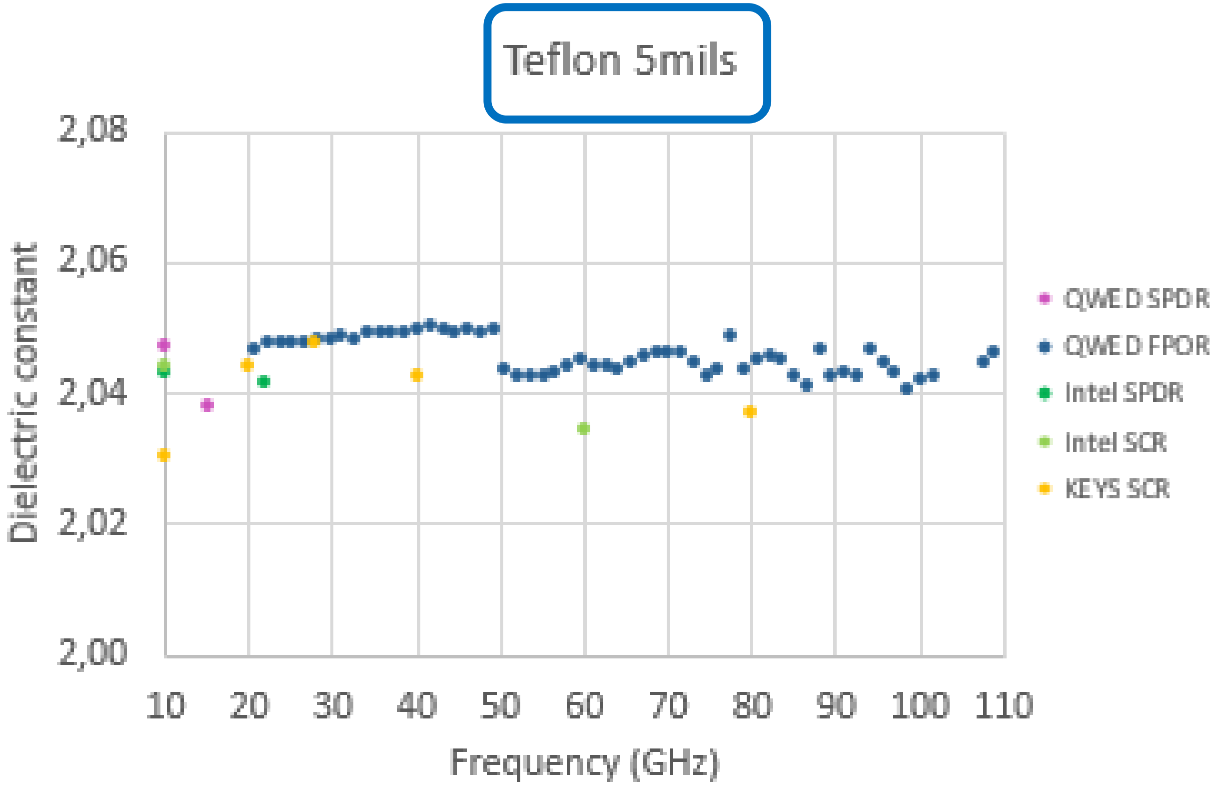
repeatability of SCR ±1%
repeatability of SPDR, FPOR better than ±0.5%

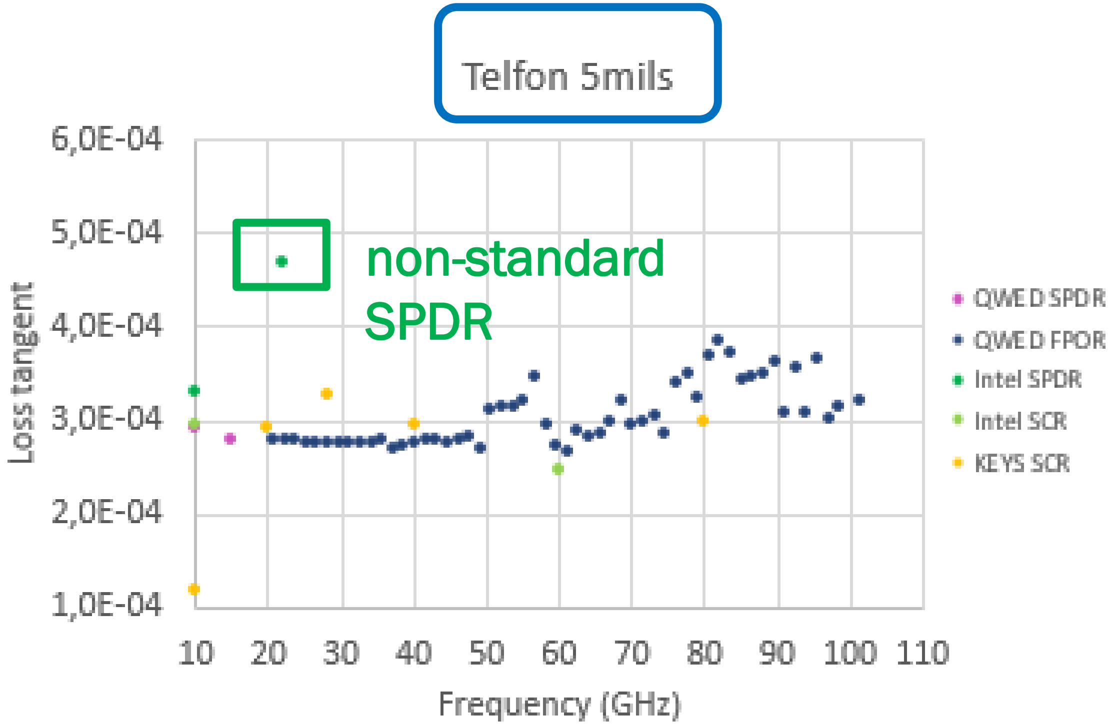
each symbol denotes an average of 16 measurements; error bar = repeatability = triple of standard deviation

Round-Robin – 2nd Material

3 labs, 3 techniques, 14 laboratory setups

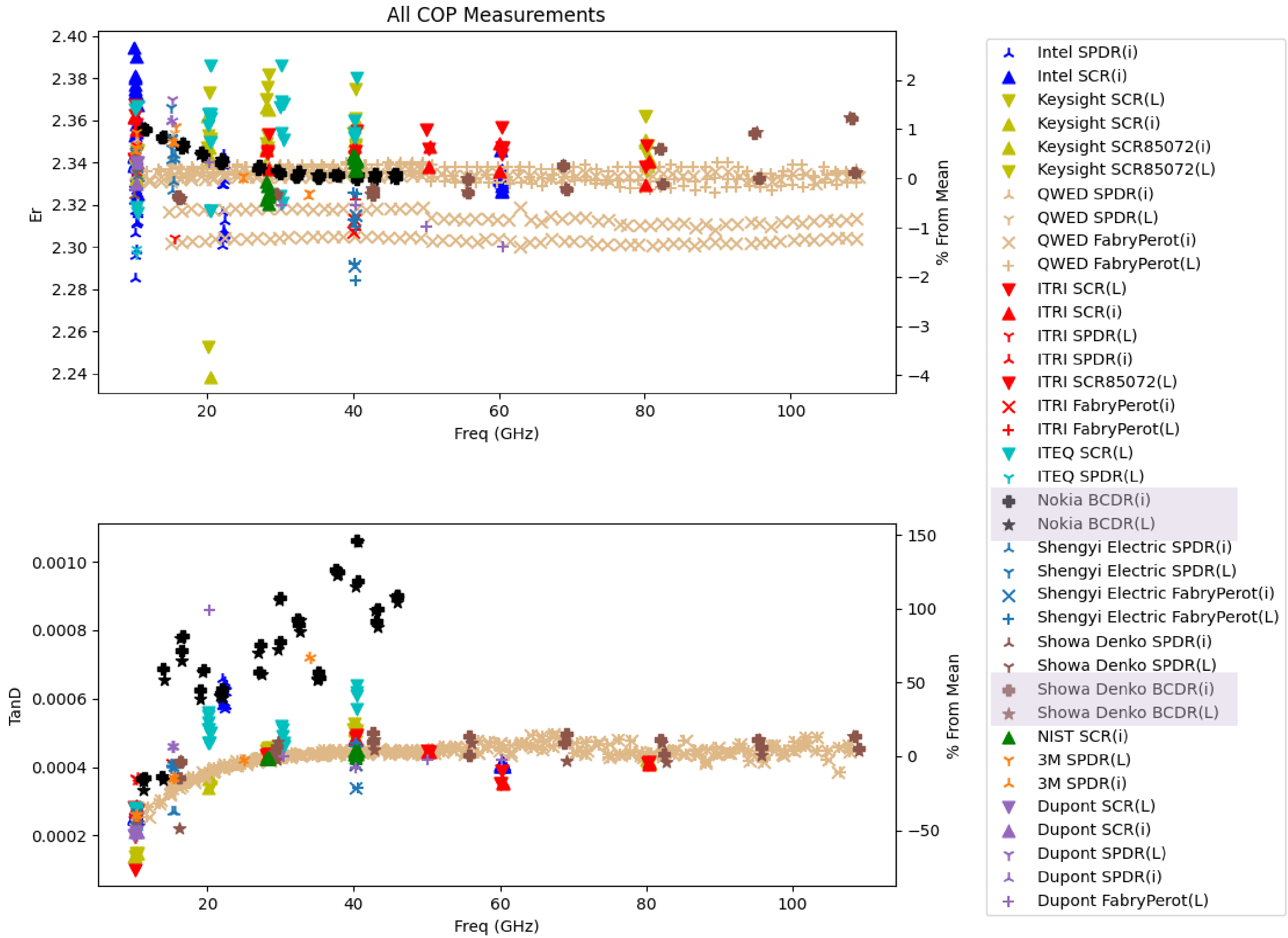
Intel - SCR at 10 / 60 GHz and SPDR at 10/ 20 GHz,
Keysight - SCR at 10 / 20 / 28 / 40 / 80 GHz
QWED - SPDR at 10/ 15 GHz and FPOR over 10-110GHz.



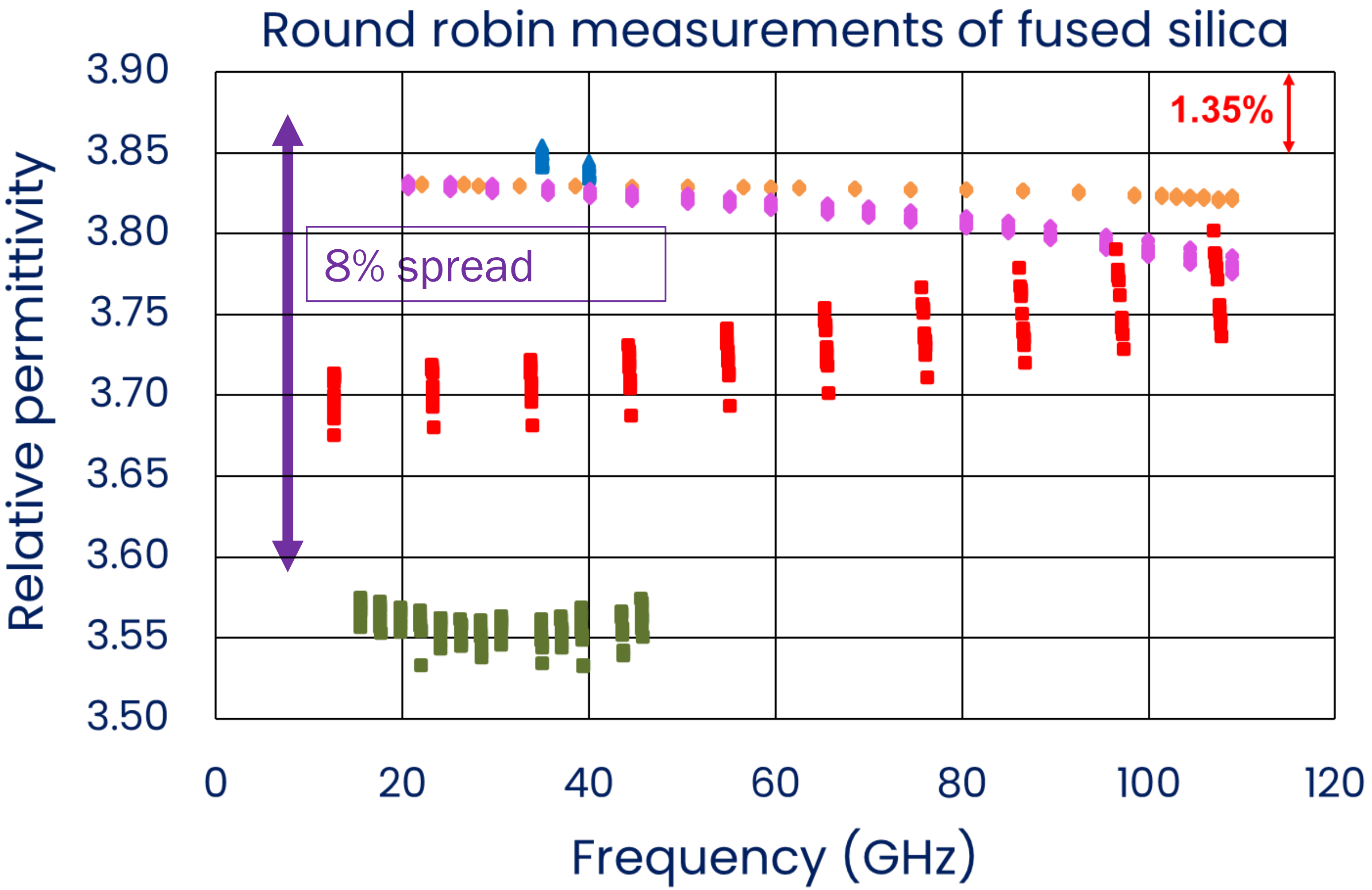


Dk spread < 1% (within ± 0.5% from average)

First Round-Robin: All Measurements for COP186 µm



Divergence of BCDR Measurements



- NIST SCR — in-plane
- Lab A FPOR — in-plane
- Lab B BCDR — out-of-plane
- Lab C FPOR — in-plane
- Lab D BCDR — out-of-plane

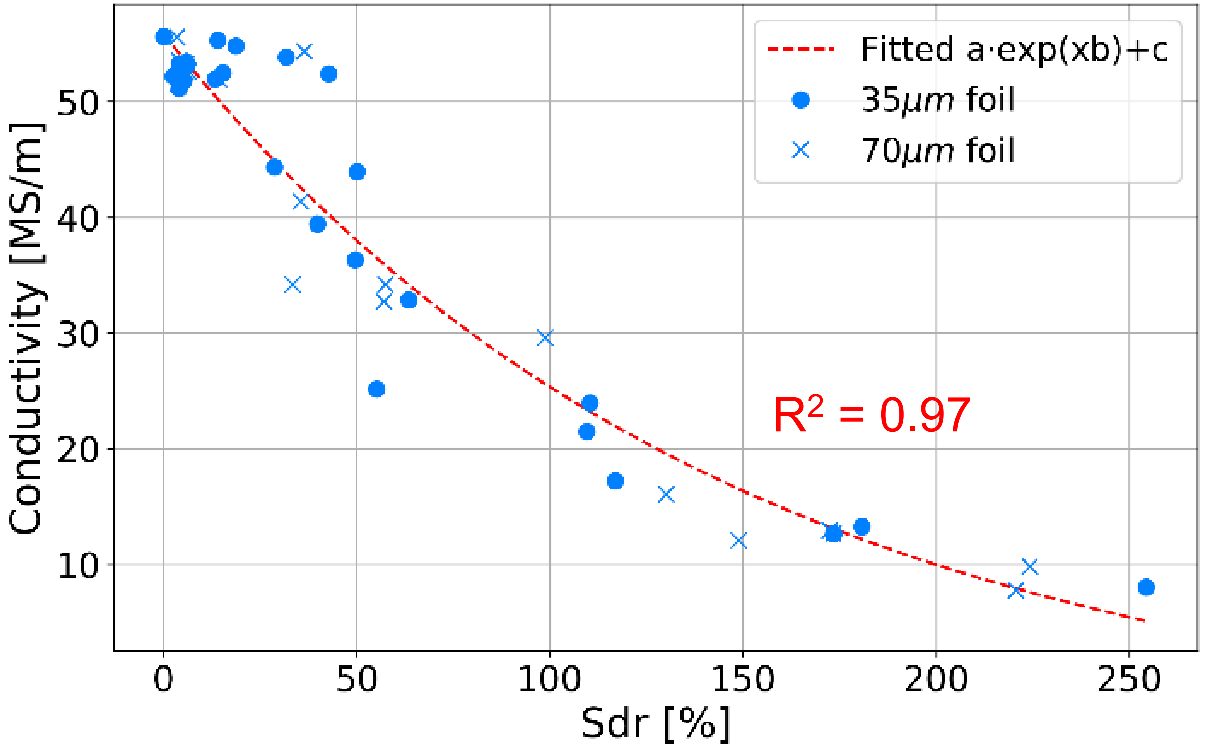
Considered causes of BCDR divergence:

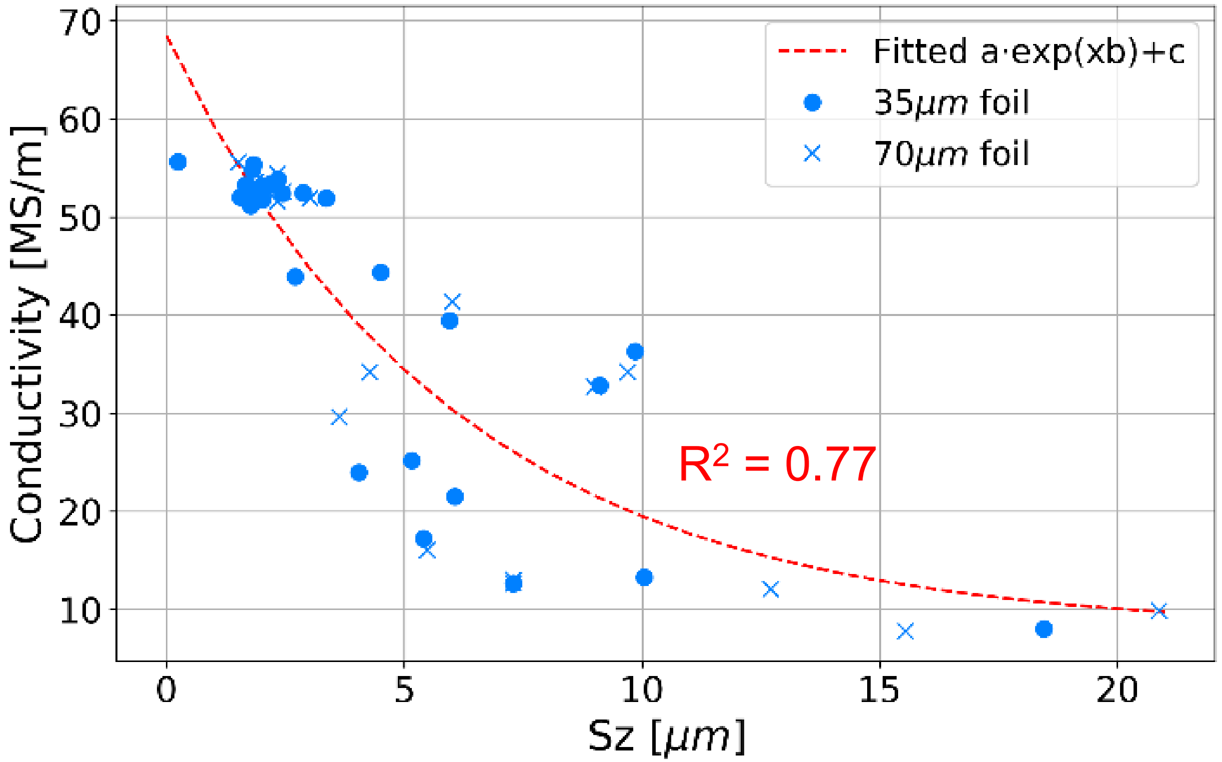
- material anisotropy,
- error inherent in out-of-plane measurement,
- error in particular BCDR instrument.

Testing of Copper Foils for 5G

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. Materials are enablers for many industrial technologies
   - novel materials are needed as well as accurate materials' data.

2. At higher MW frequencies, due to the lack of standardized testing techniques and SRMs,
   - the gap must be filled by coordinated benchmarking activities.

3. QWED contributes to such activities thanks to its combination of computer modeling and material measurement competencies.

4. Will MTT-S coordinate future benchmarking and standardization activities for FutureG materials?...

Acknowledgements

iNEMI
International Electronics Manufacturing Initiative

The author wishes to thank all the partners of the iNEMI projects for their great collaboration in the benchmarking activities.

QWED

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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**), M-ERA.NET3/2021/83/**I4BAGS**/2022, and DWM/InnovativeSMEs/176/2023 (EUREKA-Eurostars 5G_Foil project).

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