Th1E-1

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

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NCBR
National Centre for Research and Development
ULTCC6G_EPac
M-era.Net
I4Bags
QWED
iNEMI
International Electronics Manufacturing Initiative

All photos © QWED.

(1) QWED celebrating 25 years in May 2022

(1), (2) featured in IEEE Microwave Magazine, Dec. 2022, by R.Henderson, IEEE MTT-S President, "Let Them Eat Cake"

Prime Minister of Poland Award for QWED 1998

(2) 75th birthday of W.Gwarek at MIKON 2022 (cake featuring pioneering paper of 1985)

Sale of 1000th resonator based on designs of J.Krupka

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

Outline:

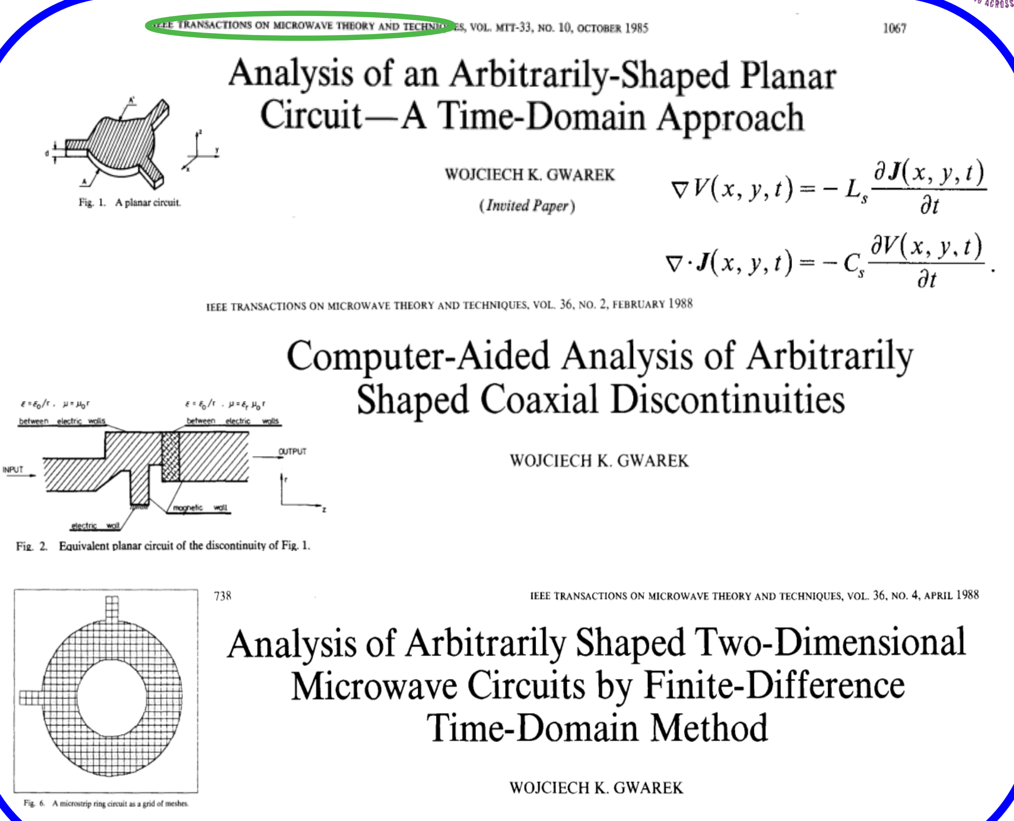
1. QWED: from Computational Electromagnetics to Modelling-Based Materials' Characterisation.
2. iNEMI: Setting-Up 5G/mmWave Benchmarking Projects.
3. Resume of Round-Robin Results of Resonator-Based Techniques for Characterising 5G Substrates.
4. Modelling: Interpretation of Measurements and Design of New Instruments.
5. Summary.
6. Invitations and Acknowledgements.

QWED origins in Computational Electromagnetics

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

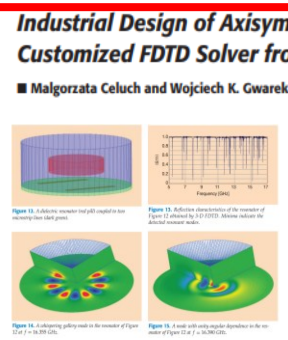
Fig. 6. A microstrip ring circuit as a grid of meshes.

M.Celuch joins the above research, leading to PhD in 1996

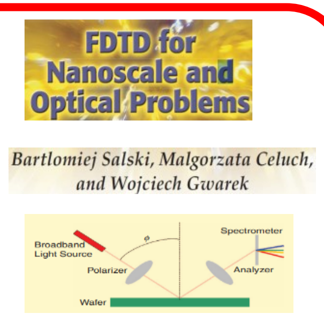
1996 Beta-Version of QuickWave at Univ. Chalmers, Kent, Helsinki

1997 first commercial licences sold by QWED

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



IEEE microwave magazine

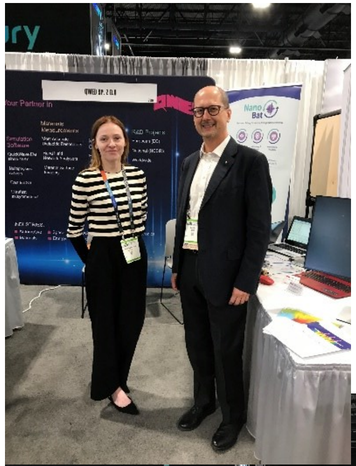


IMS
Connecting Minds. Exchanging Ideas.

since 1998 annually at IEEE IMS

Anaheim, CA, 1999

San Francisco, CA, 2006

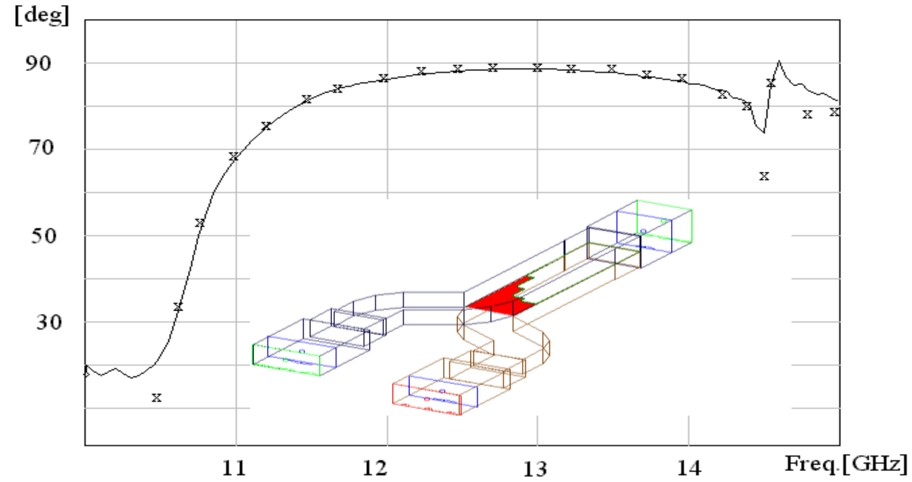


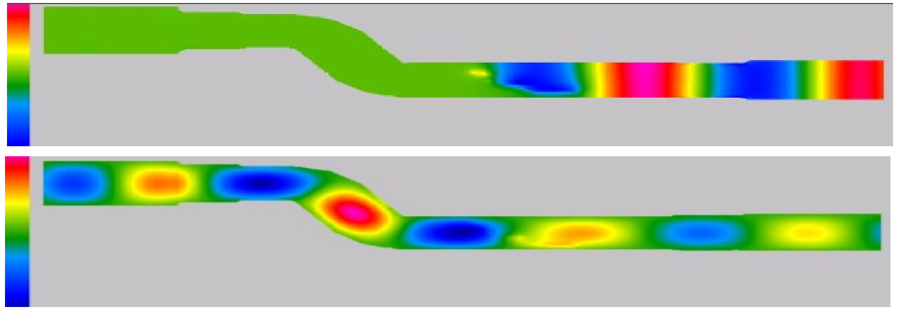
Denver, 2022

QuickWave original applications in cosmic research & SATCOM

Septum polariser by SES

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

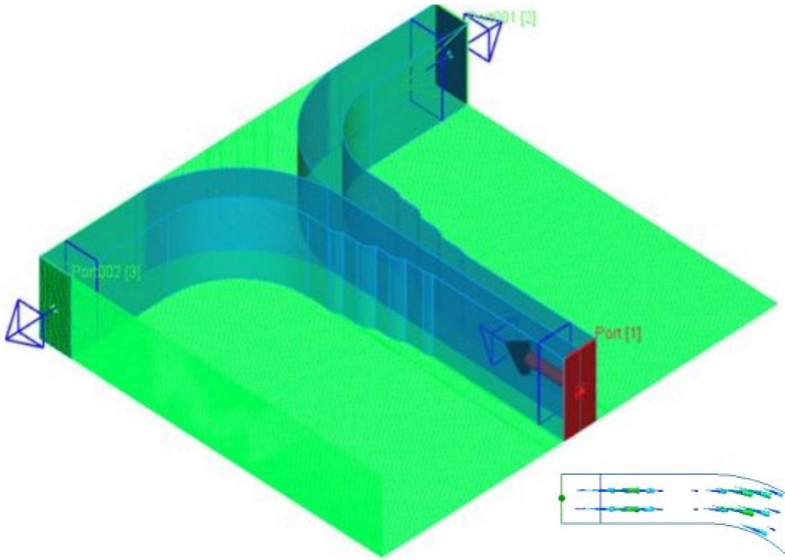


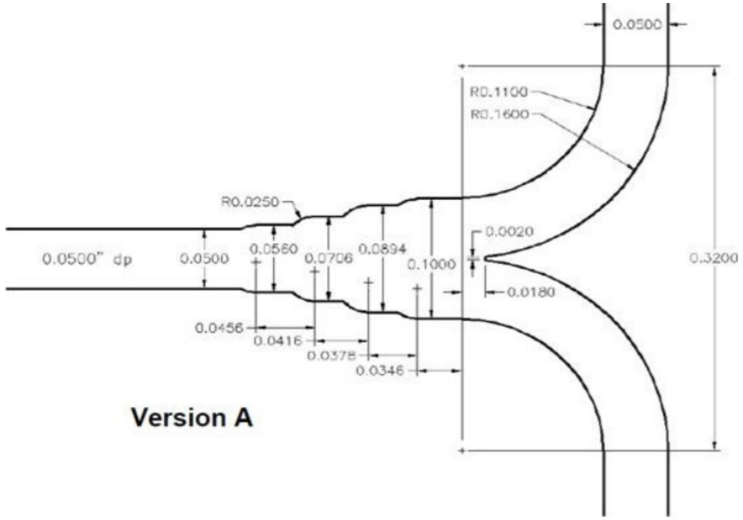


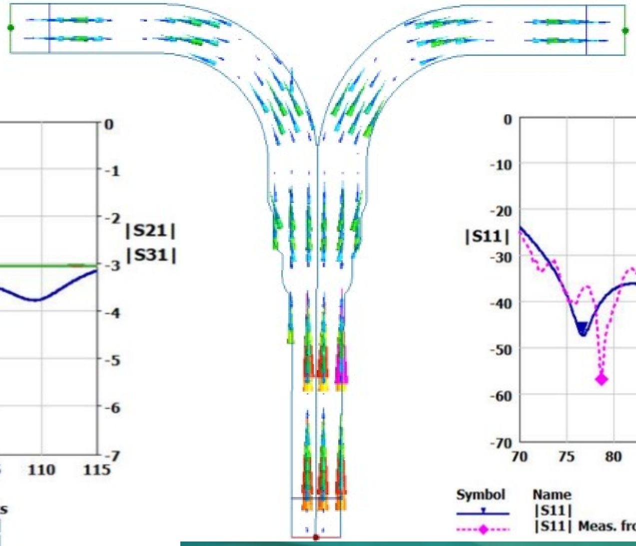
propagation of two polarisations at centre frequency

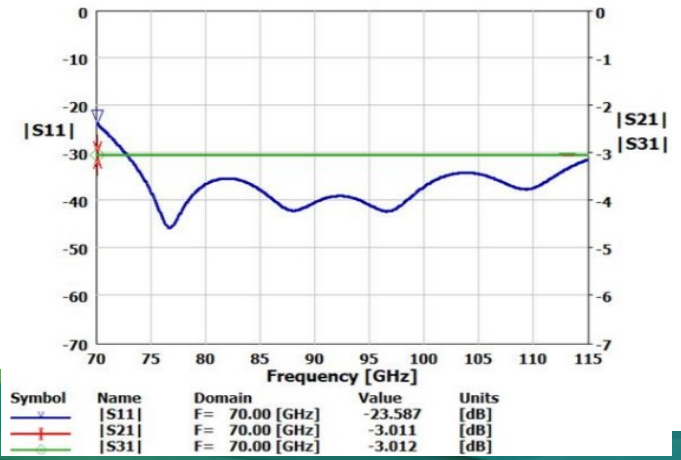
E-plane Y-junction by NRAO

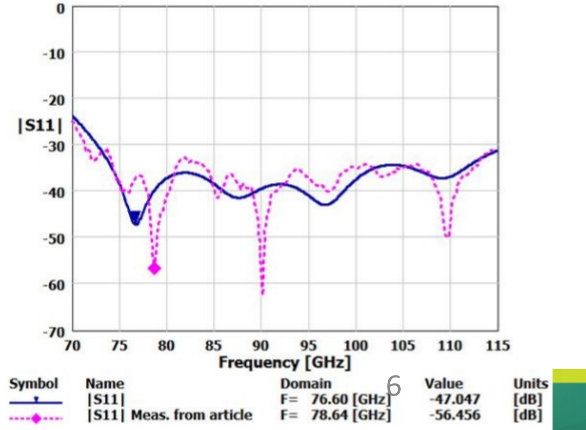
after A. R. Kerr, Elements for E-Plane Split-Block Waveguide Circuits, ALMA Memo 381







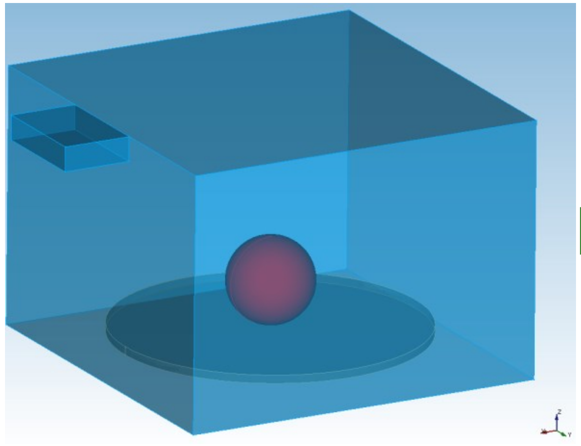




Applications for Materials Processing with Microwaves

Simple microwave heating benchmarks & microwave heating phenomena studies*

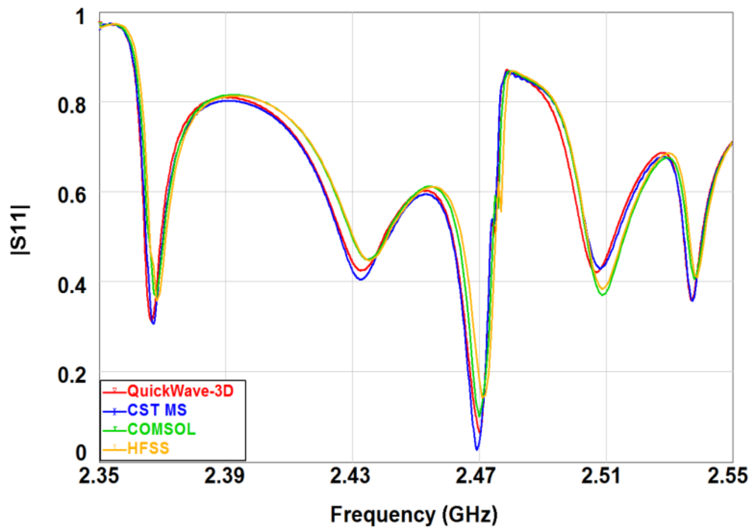
Design & analysis of real-life microwave oven cavities, incl. complicated cavity shapes and advanced feeding system*

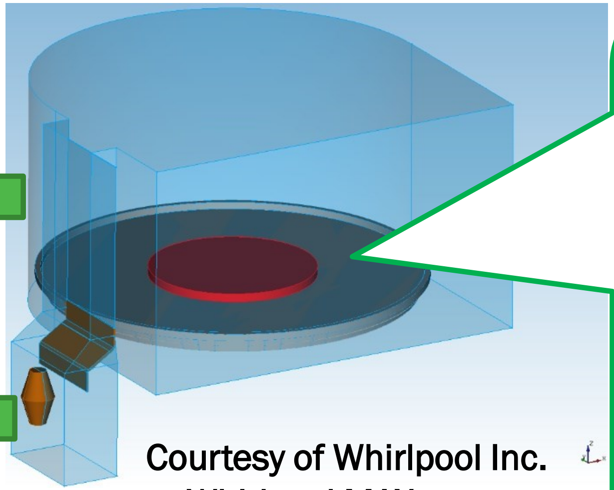


- heat transfer & load dynamics
- Load rotation & arbitrary movement during heating
- Source parameters tuning – regime for solid state sources
- Temperature dependence of material parameters

Freezing to file the state of the simulation

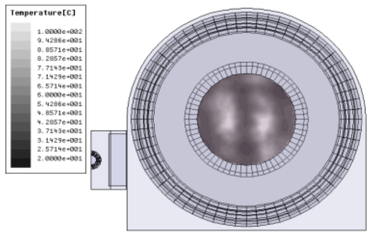
De-freezing on arbitrary computer & at convenient time



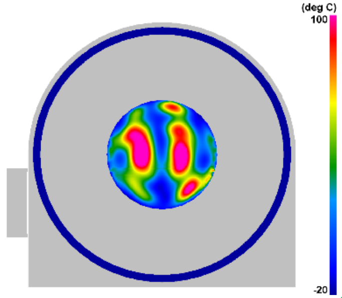


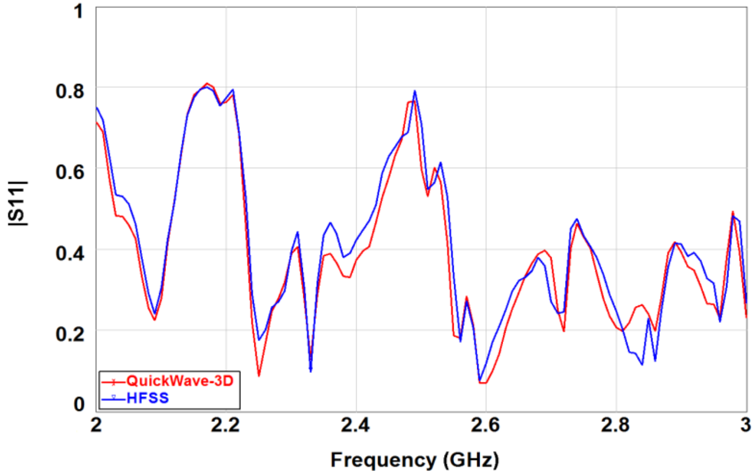
Courtesy of Whirlpool Inc. – Whirlpool MAX oven

HFSS v11



QuickWave 3D & BHM





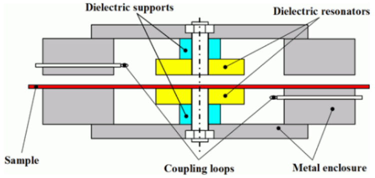
With QuickWave EM computation as fast as 1 min 18s on a low-cost video card – supporting all graphic cards with OpenCL

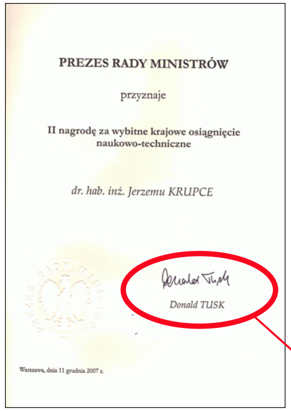
* M.Celuch, P.Kopyt & M. Olszewska-Placha in eds. M. Lorence, P. S. Pesheck, U. Erle, *Development of packaging and products for use in microwave ovens*, 2nd Ed. Elsevier 2020.

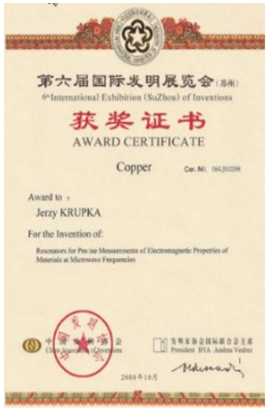
Material Measurements coming to QWED

since 1980s...

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



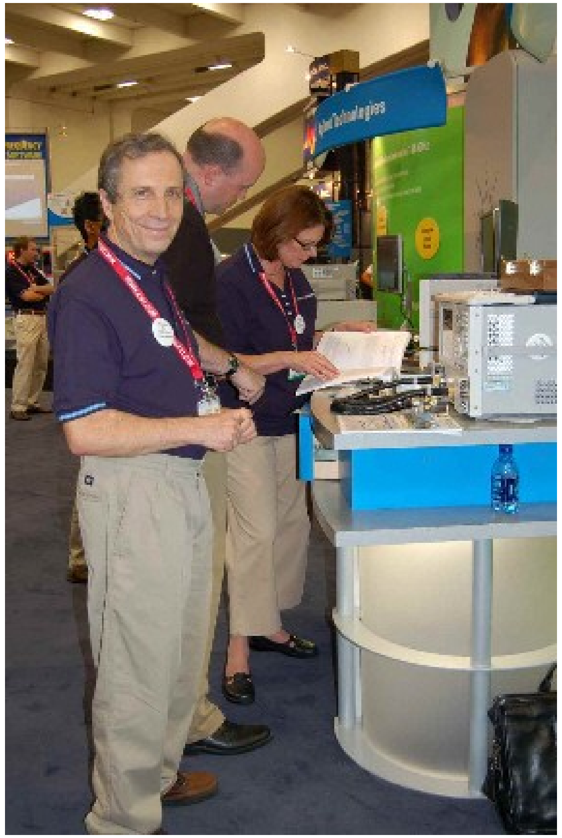




by Donald Tusk
Prime Minister of Poland 2007-2014
President of the European Council 2014-2019

... by early 2000s:

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

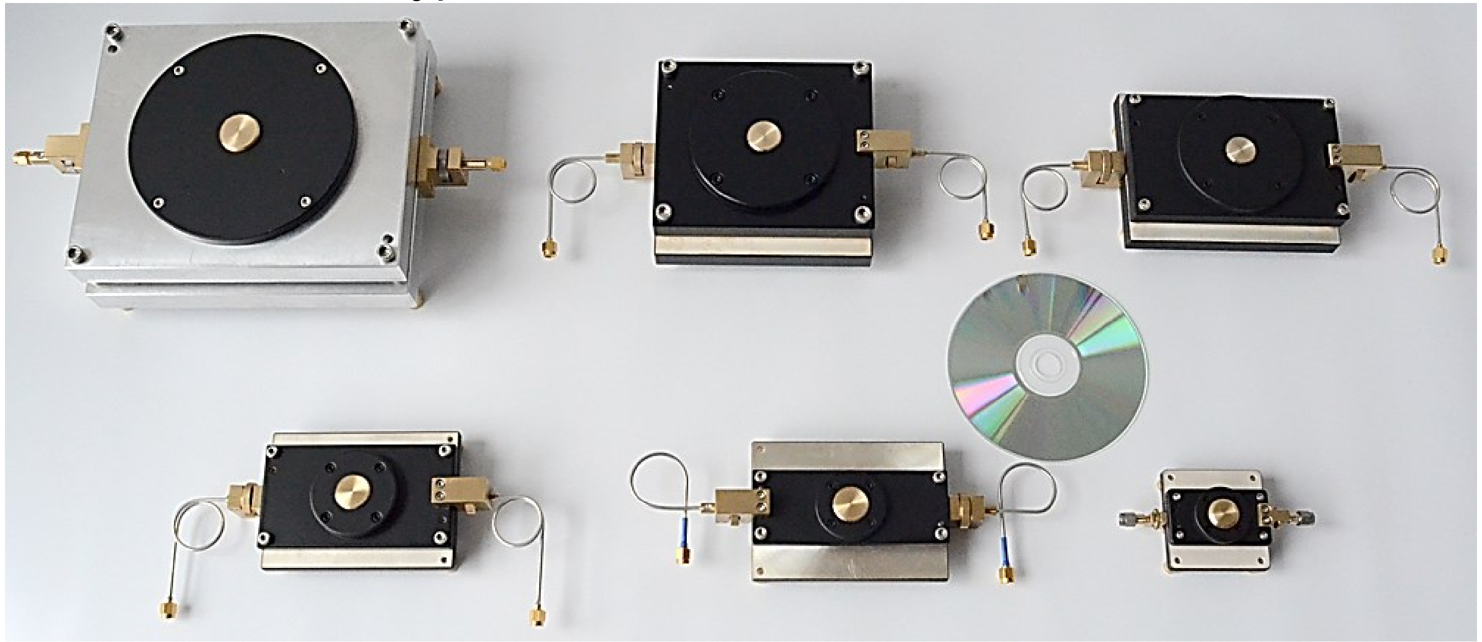


Agilent Both
IEEE IMS 2006,
San Francisco, CA

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

Popular Resonators Offered by QWED

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



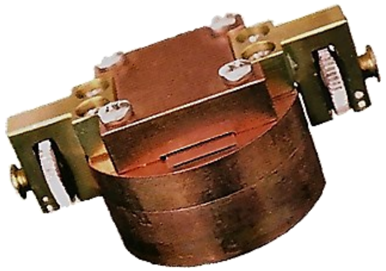
T. Karpisz, B. Salski, P. Kopyt, and J. Krupka,
doi: 10.1109/TMTT.2019.2905549.

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

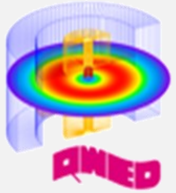


Bridging Computer Modelling with Material Measurements

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

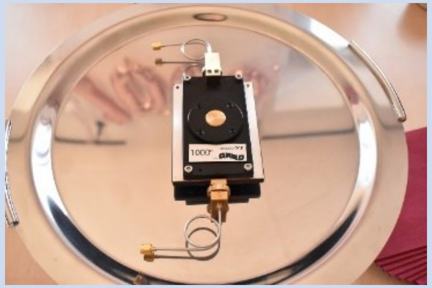
Material measurements

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.

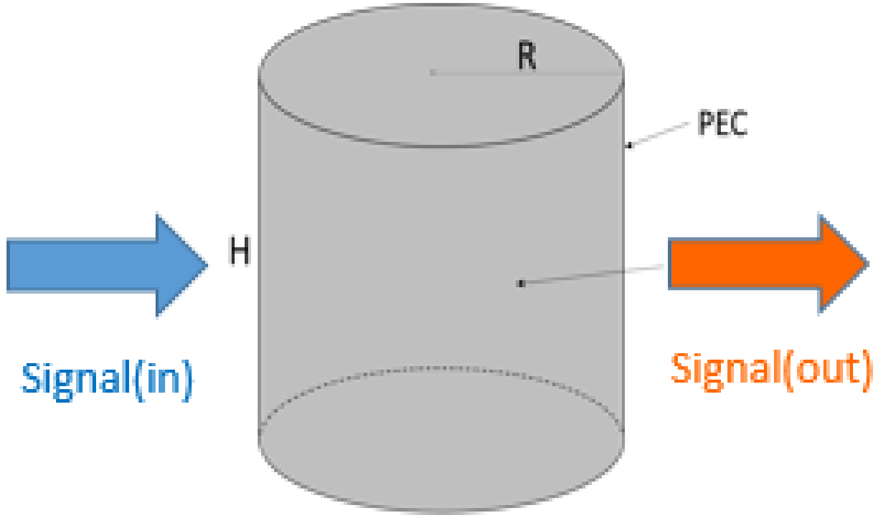
Open Platform Examples:

SMM tip presented at Numerical Electromagnetic

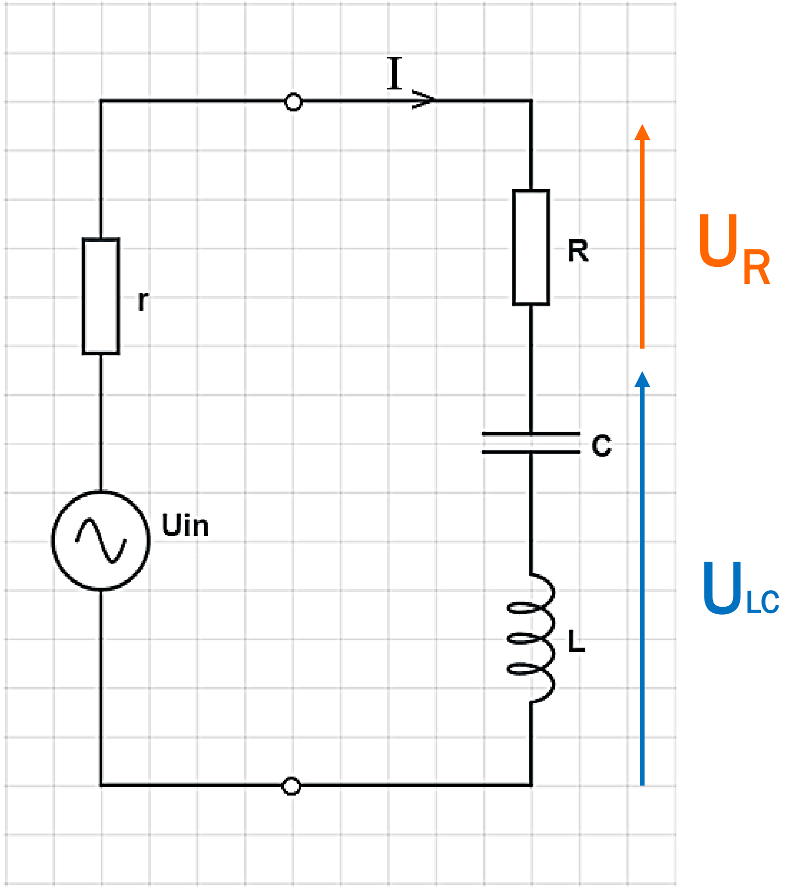
European Standard:
IEC 61189-2-721:2015
CEN-CENELEC Workshop 2021

Why Resonators for Material Measurements?

Circuit theory interpretation (for newcomers to the field):



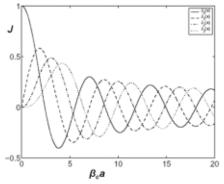
given fixed strength of Signal(in),
at resonance Signal (out) is strongest



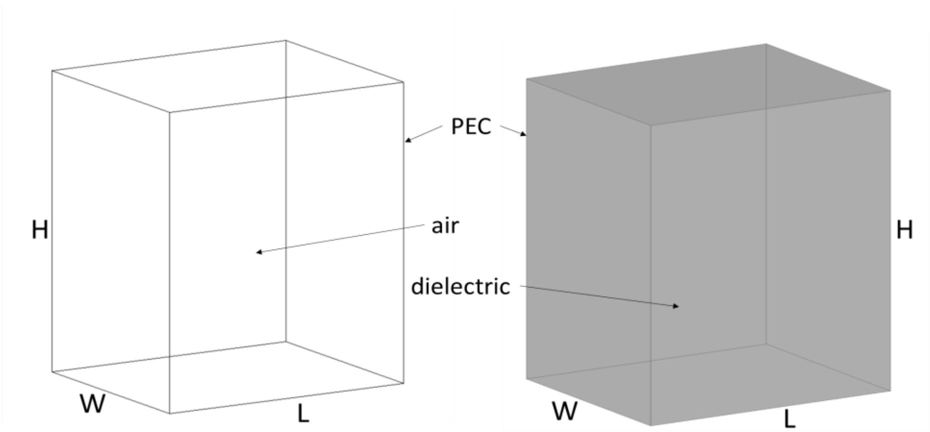
given fixed strength of Uin,
at resonance U_R is strongest (U_{LC} =zero)

Examples of canonical examples of resonators (*for newcomers to the field*)

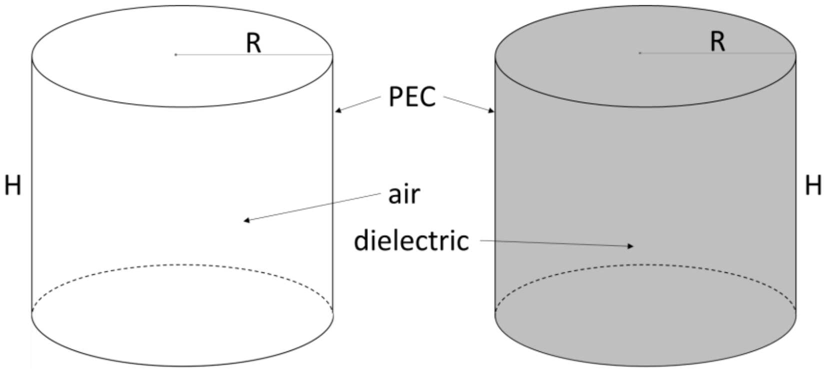
Eigenvalue problems: analytical solutions exist for cuboidal and cylindrical cavities:



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



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



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

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

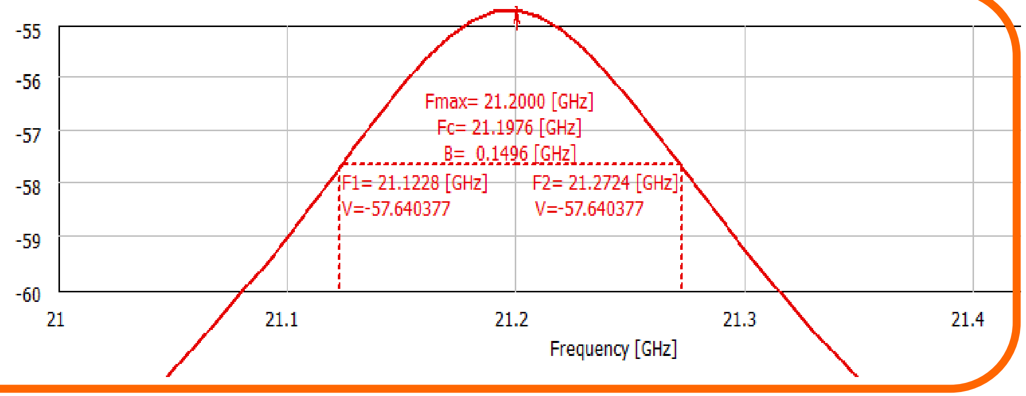
$$f_{r,mnp} = \frac{v}{2}\sqrt{\left(\frac{\kappa_{mn}^{(,)}}{\pi R}\right)^2 + \left(\frac{p}{H}\right)^2}$$

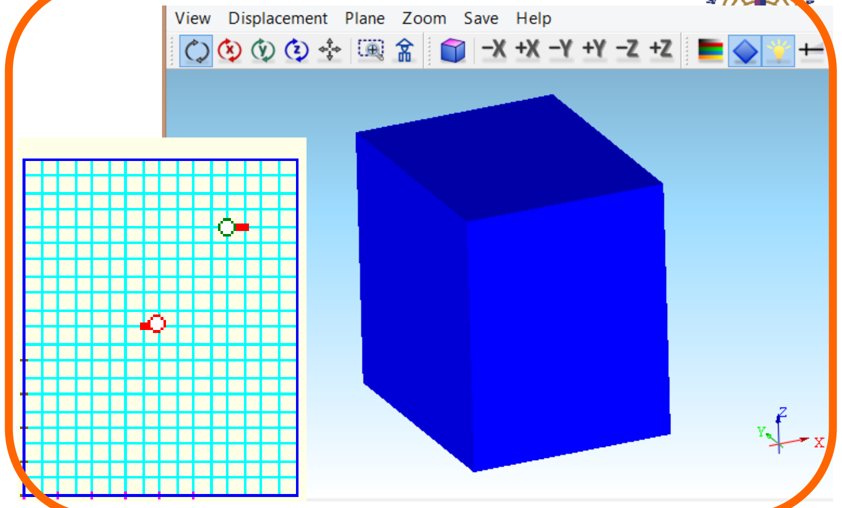
→ application of cavities to Dk measurements appears straightforward!

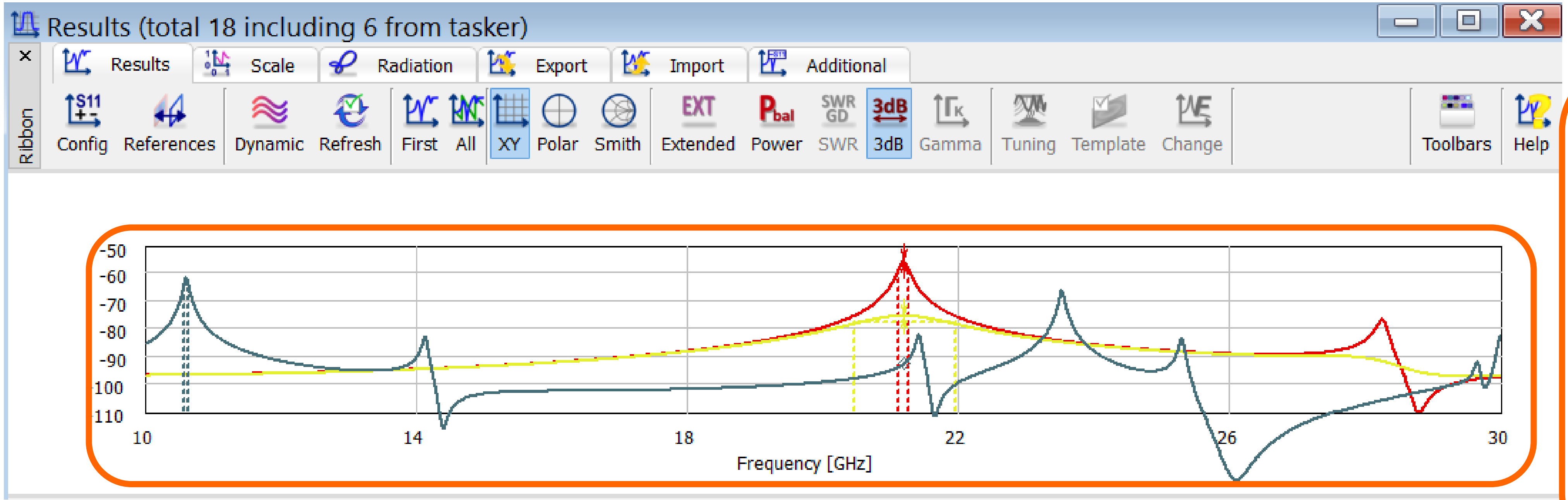
(but cavity losses should be minimised & 100% filling factor is difficult to achieve)

QuickWave Modelling of a Cuboidal Cavity

Transmission |S21| simulated between weakly coupled source and probe in a cube 8x10x10 [mm]







ε_r=1 σ=0.00833 S/m @21.2GHz:

tanδ=0.071

Q_{SUT}= 1 / 0.0071 = 141

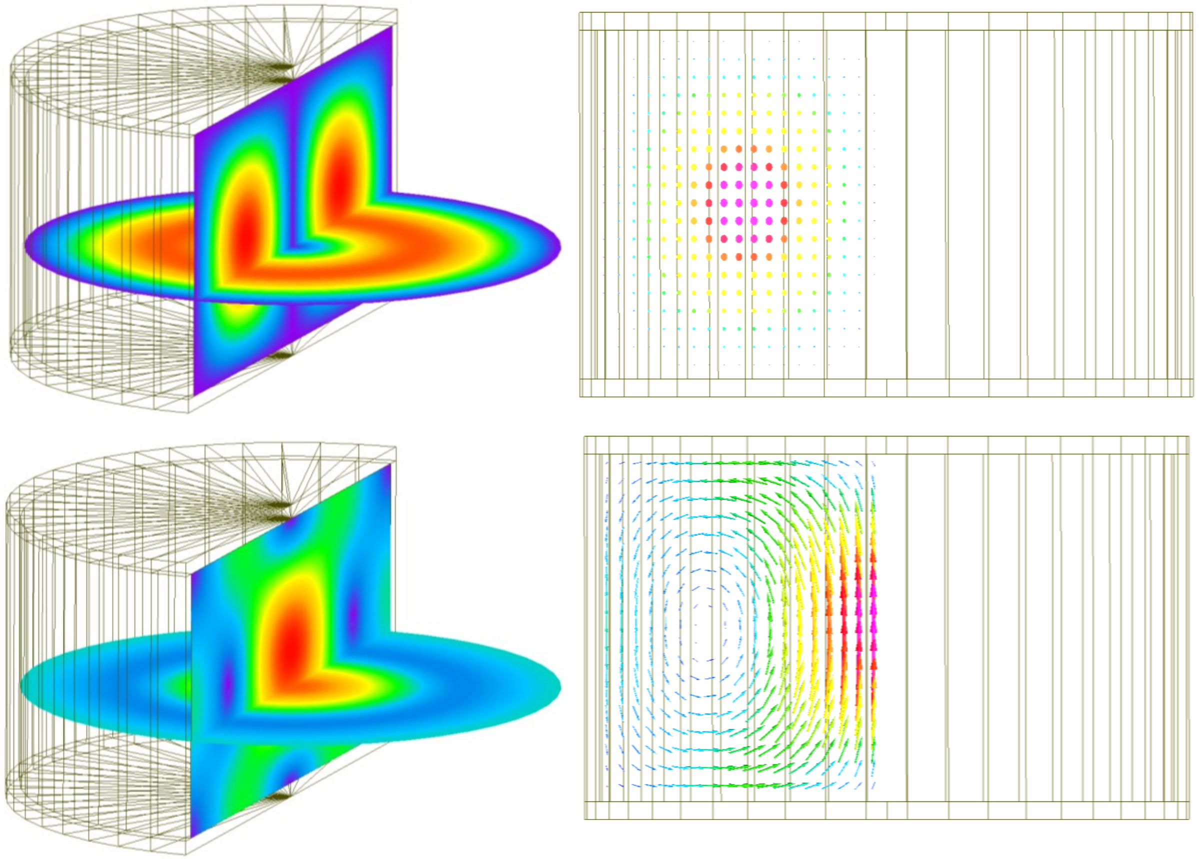
Q_{S21}=21.2/0/1496= 141

ε_r=1 σ=0.0833 S/m

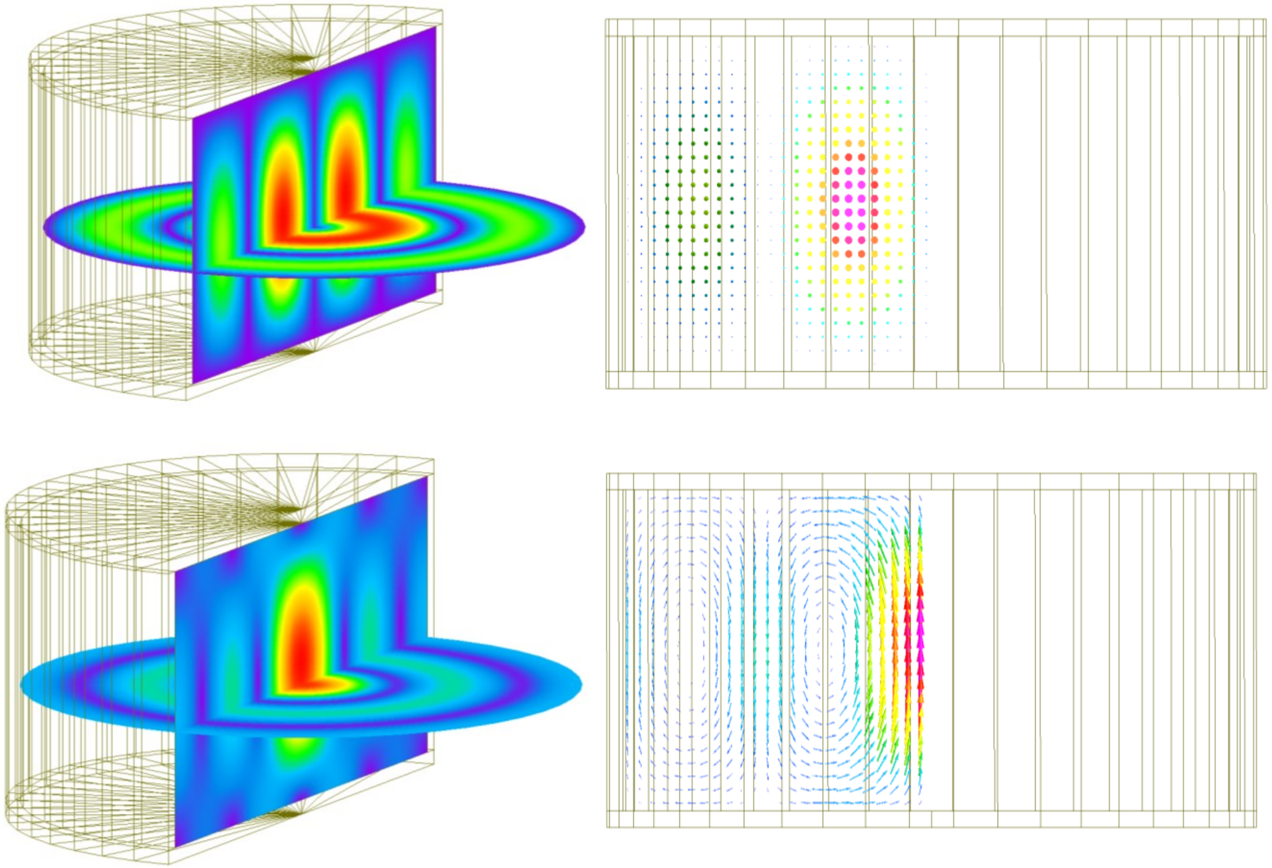
ε_r=4 σ=0.0166 S/m

QuickWave model of a cylindrical cavity

TM011 mode



TM021 mode

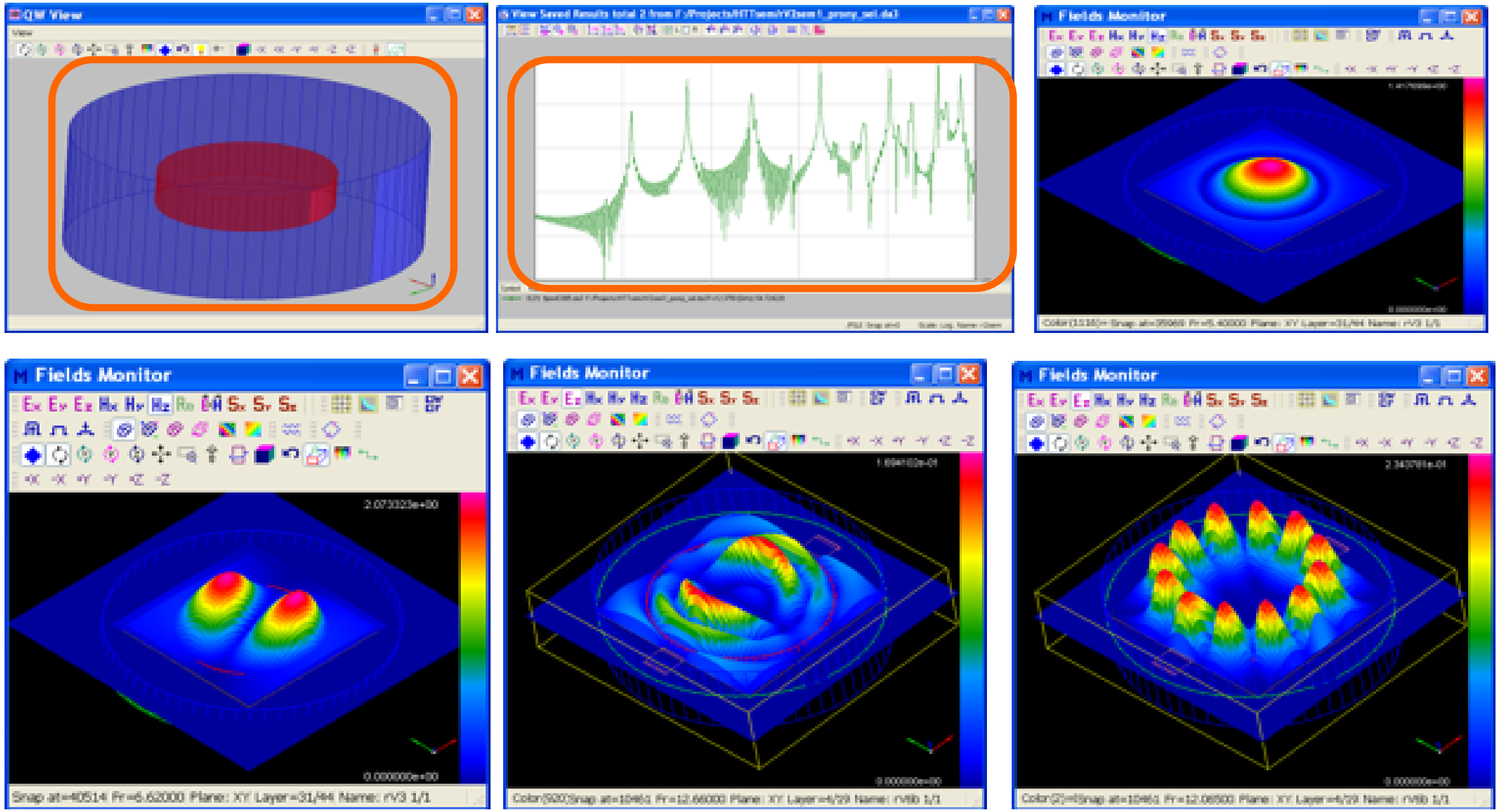


compared to rectangular (cuboidal) cavities, typically:

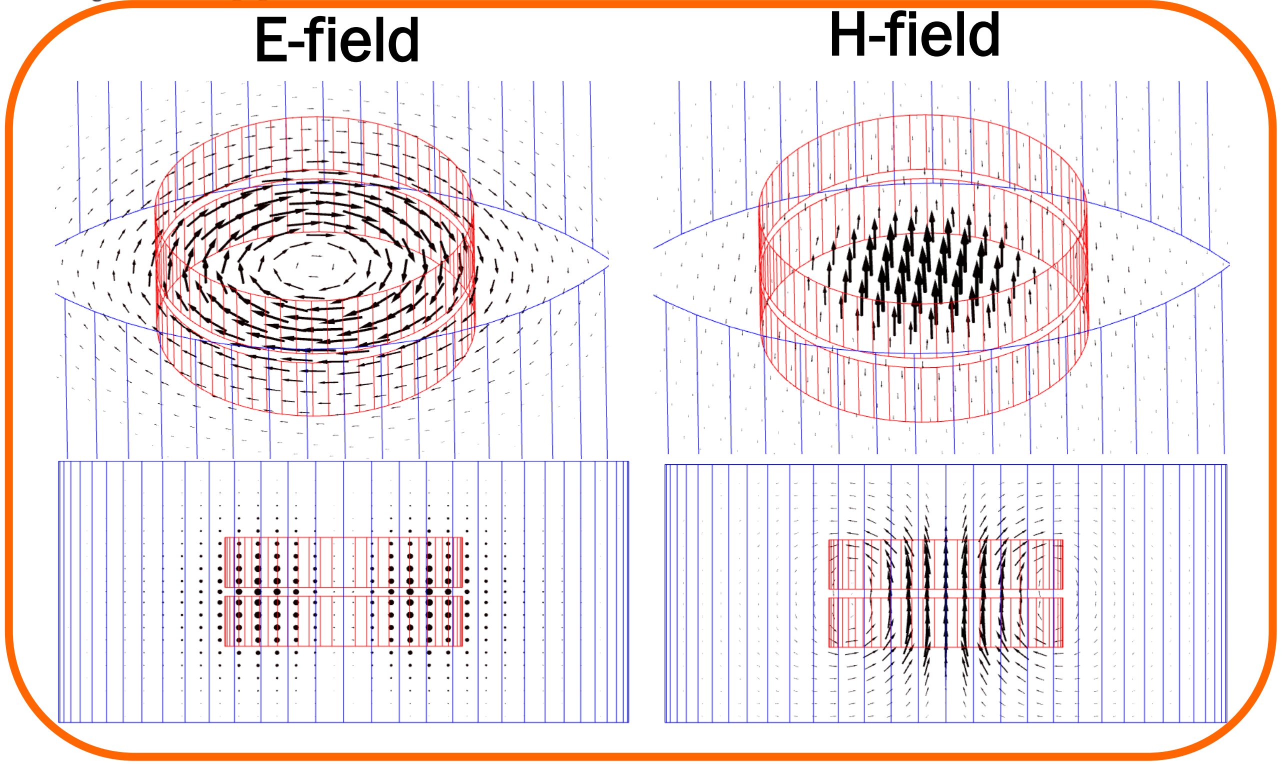
- lower contribution of wall losses
- easier standard manufacturing

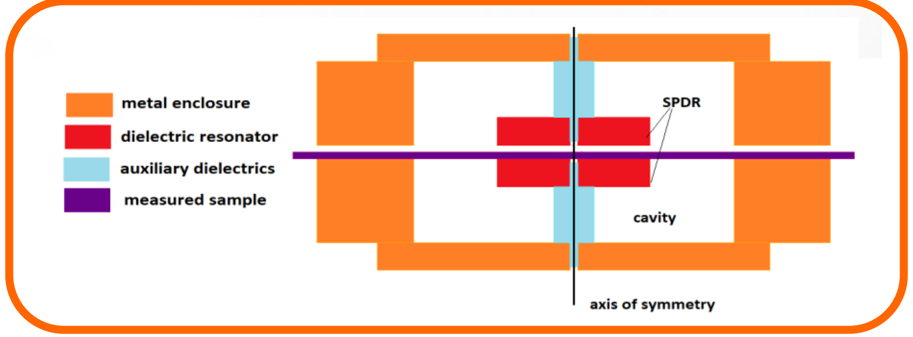
How do dielectric resonators work (*with QuickWave illustration*)

Dielectric resonator (top left)
As a multimode device (see transmission diagramme, top centre)
Including TE01 mode (top right) **and many higher modes** (lower row)



Split-Post Dielectric Resonator method – as illustrated by QucikWave

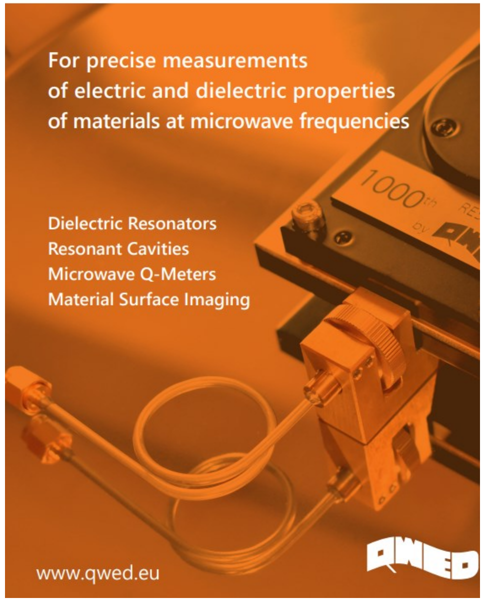


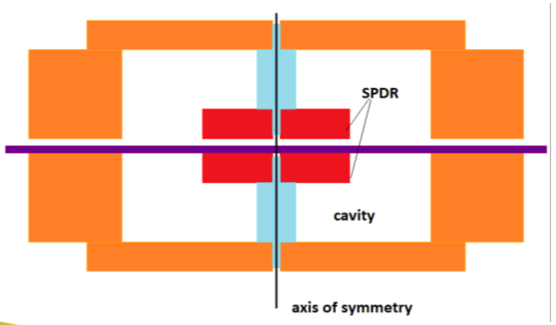


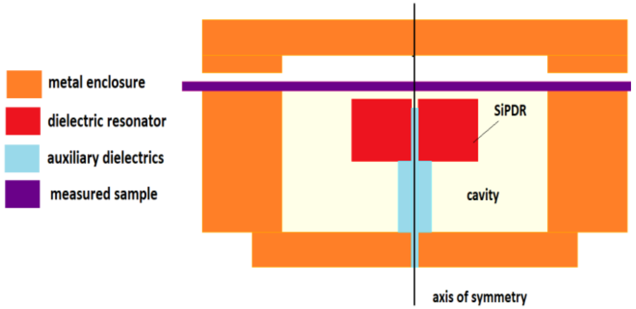
- resonant mode with EM fields mostly confined in and between those ceramic posts ⟶ minimial losses in metal enclosure
- H-field is only vertical at the side wall of the enclosure ⟶ only circumferential currents in side wall ⟶ no radiation through slot
- E-field tangential to SUT ⟶ air slots between SUT and posts have negligible effect
- **easy SUT insertion through slot, no dismatling, NDT method**

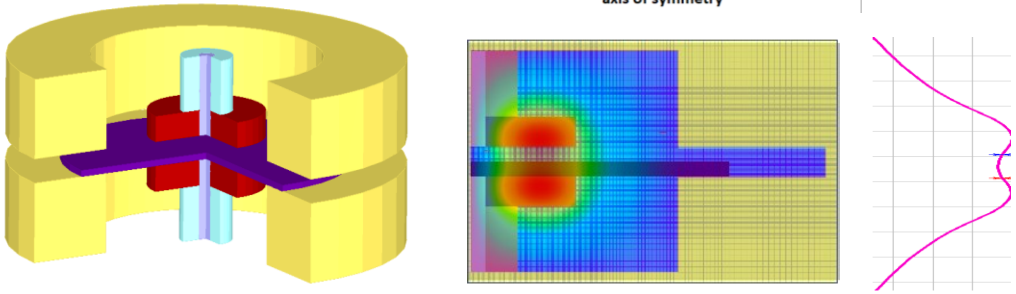
Which Scanner: SPDR or iSiPDR

Test Fixtures and Setups









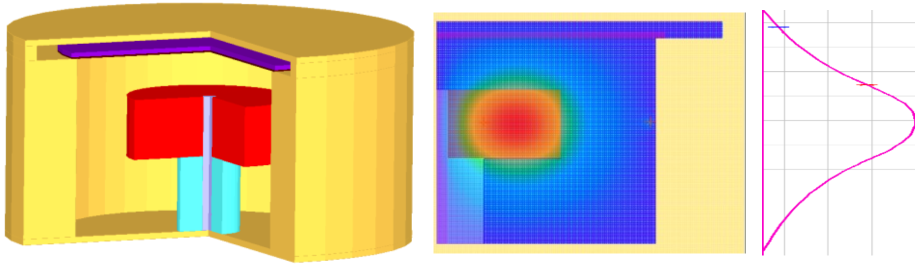


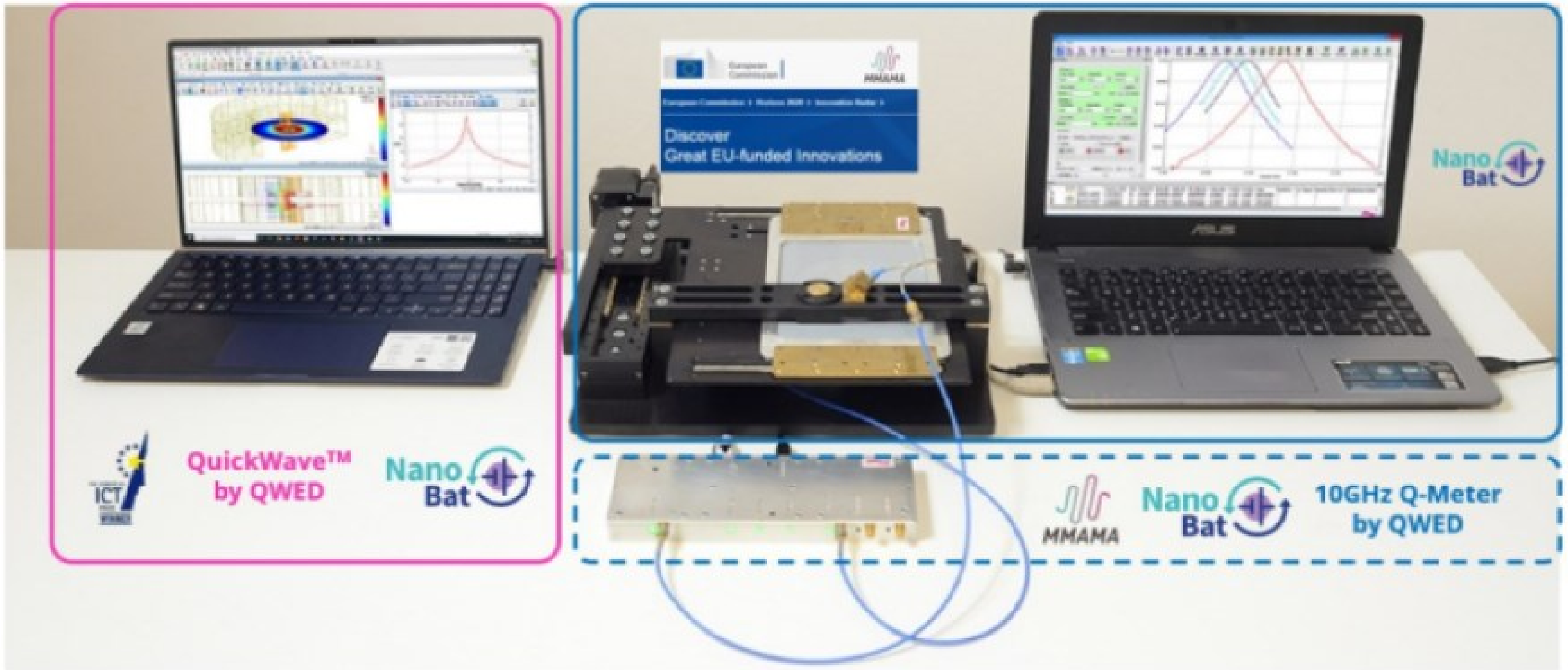
Table 2. Typical ranges of applications of SPDRs and SiPDRs			
	Conductivity [1/(Ωm)]	Resistivity [Ω cm]	Surface resistivity [Ω/sq]
Range od SPDR applications	2 10^{-3} to 0.5	from 2 10^{2} to 5 10^{4}	from 2 10^{3} to 10^{7}
Range of SiPDR applications	0.1 to 10^{6}	from 10^{-4} (*) to 10^{3}	from 10^{-1}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

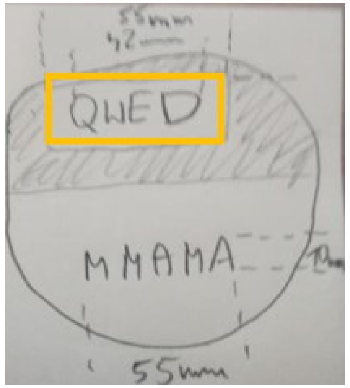
Resonator designs after:
J. Krupka and J. Mazierska, *IEEE Trans. Instr. Meas.*, 2007,
doi: 10.1109/TIM.2007.903647

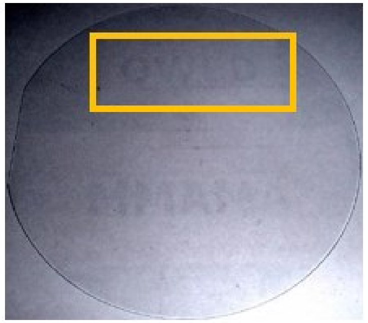
CAD models and EM field distribution:
QuickWave™ software by QWED

2D 10 GHz SPDR Scanner for Low-Loss Dielectrics

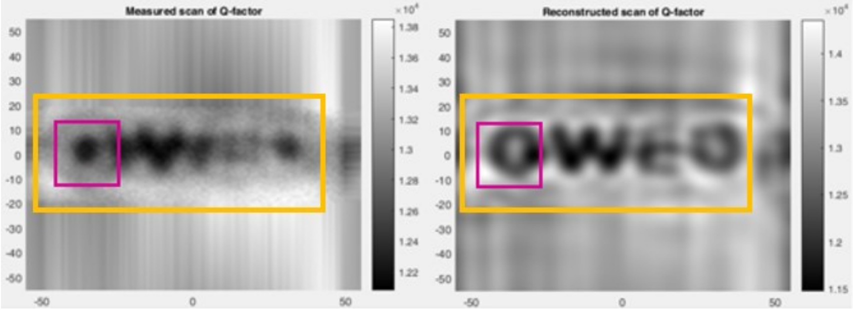
Modelling-Based Materials' Characterisation Setup

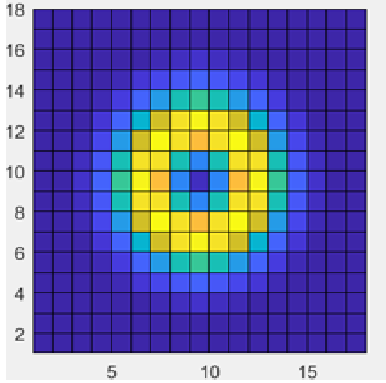


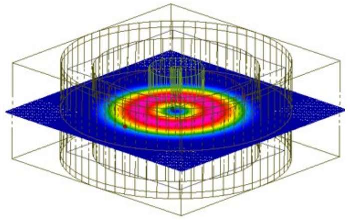




Patterned PEDOT:PSS sample
courtesy MateriaNova, Belgium







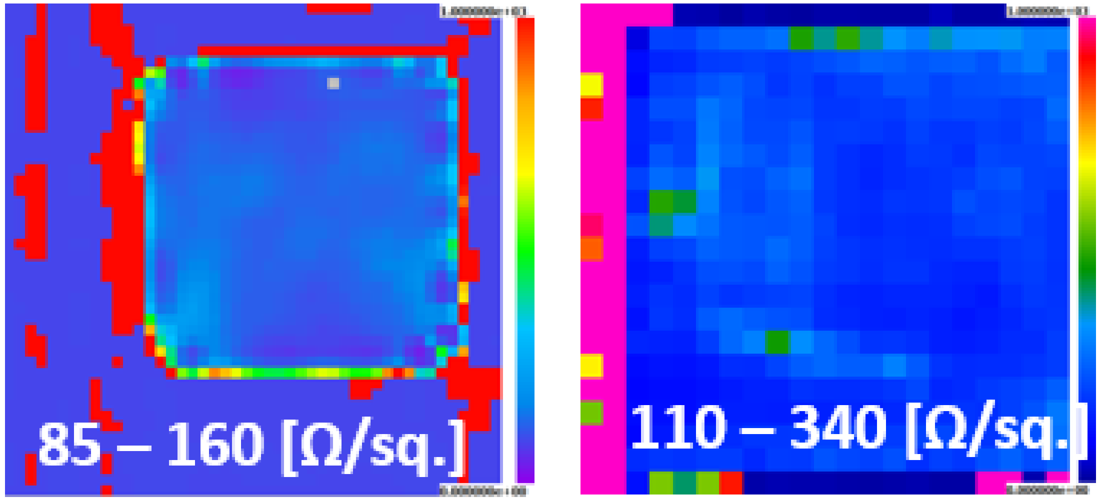
2D scanner designed with a modified 10 GHz SPDR

Finalist of the European Innovation Radar Prize 2021

2D 10 GHz iSiPDR Scanner for Resistive Sheets

Modelling-Based Materials' Characterisation Setup

2D iSiPDR scanner based on inverted 10 GHz SiPDR



Example application:
battery anodes before & after cycling (SEI formation).

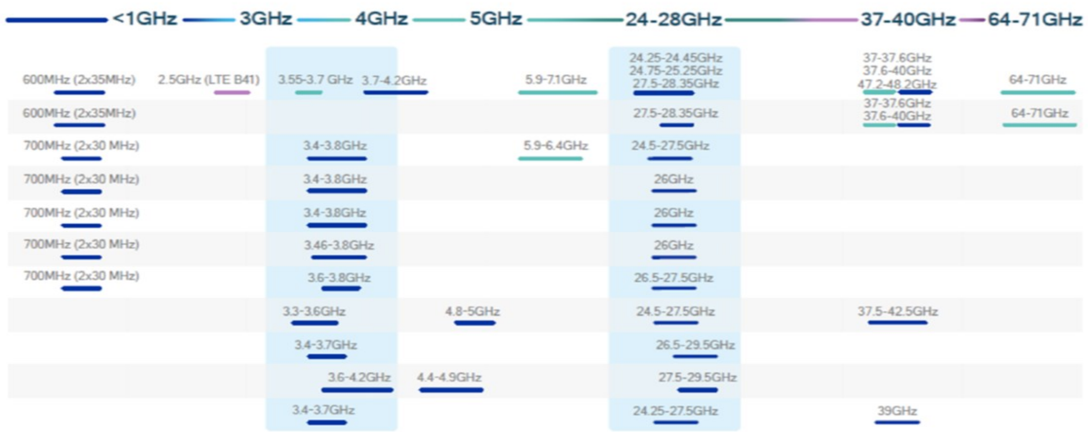
Now coming to iNEMI projects…

5G/mmWave Materials Assessment and Characterization

further referred to as “5G Dielectrics” our “5G Substrates” project

- 5G: Common to only think in terms of ‘radio’ applications
- ‘5G’ extends beyond wireless applications

CPU Clock Speeds　　High Speed I/O

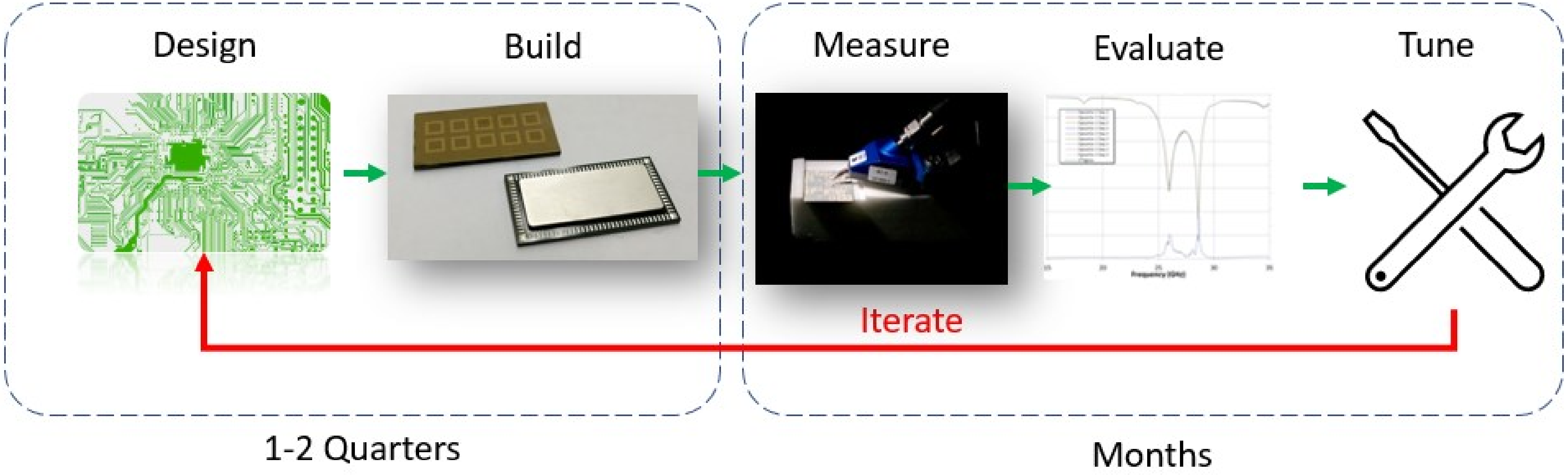


Src: Urmi Ray, 5G/High Frequency Materials Characterization Challenges and Opportunities, EMA 2021, S13

- Many forward-looking wired applications need material data spanning DC to 100+GHz
- Dielectric constant measurements are key enables for many different industries & technologies

Industrial Motivation

- Traditional methods of microwave design rely on trimming & tuning difficult to tolerate in today's environment…
- Faster & less costly "virtual prototyping" is achieved with today's modelling & simulation tools…
- …but accurate material data is still required
- …errors in materials' characterisation limit accuracy of modelling resulting in time consuming iterations



"errors may cost $10's of millions for a single program, or worse, unexpected product failures"

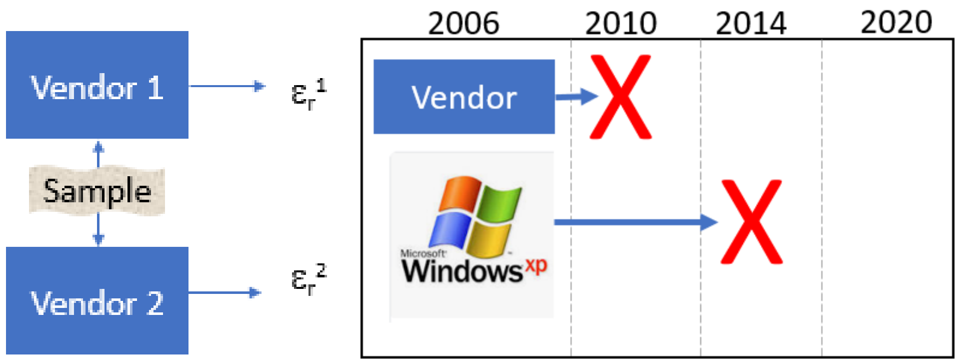
Gaps & Practical Challenges

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**:

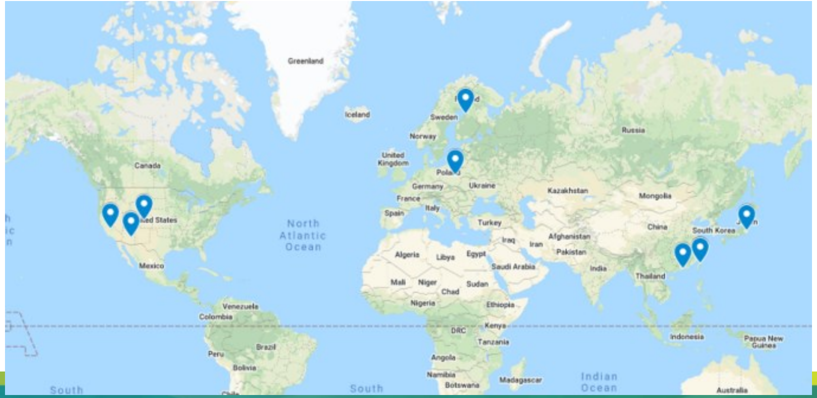
- Eliminates many traditional transmission line techniques

Increasing frequency:

- Severe limitations on **sample thicknesses**
- **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

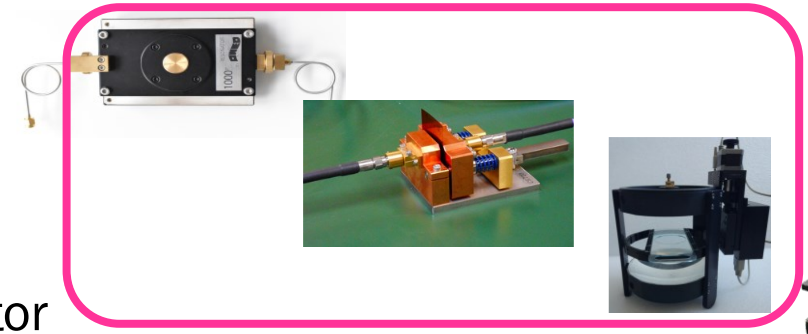
1st Project Stage
- Precision Teflon
- Cyclo Olefin Polymer

2nd Project Stage
- Rexolite
- Fused Silica

Industrial
- Automotive

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

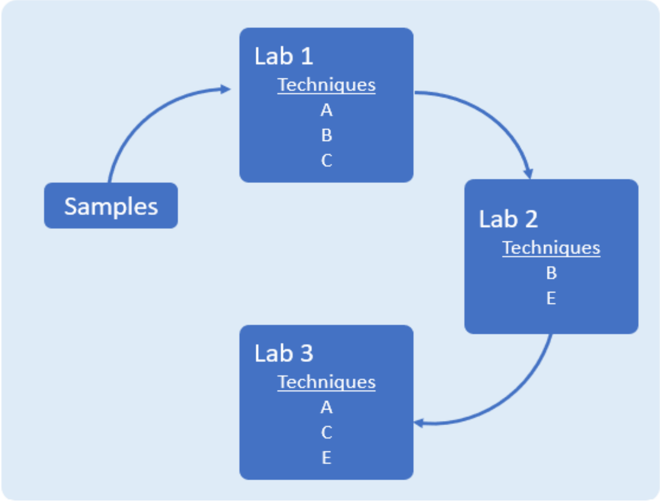
→ Frequency Span : 10GHz – 100GHz with overlaps



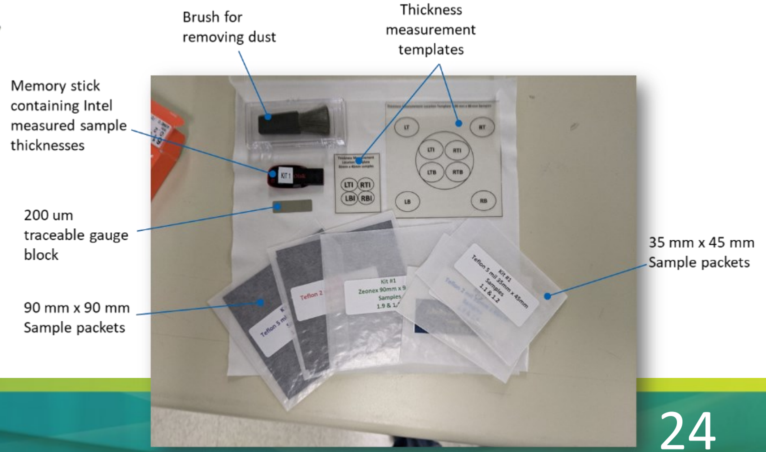
10 Sample Kits Created
- Sample sizes 35 mm x 45 mm, 90 mm x 90 mm

BCDR results & concerns reported herein.

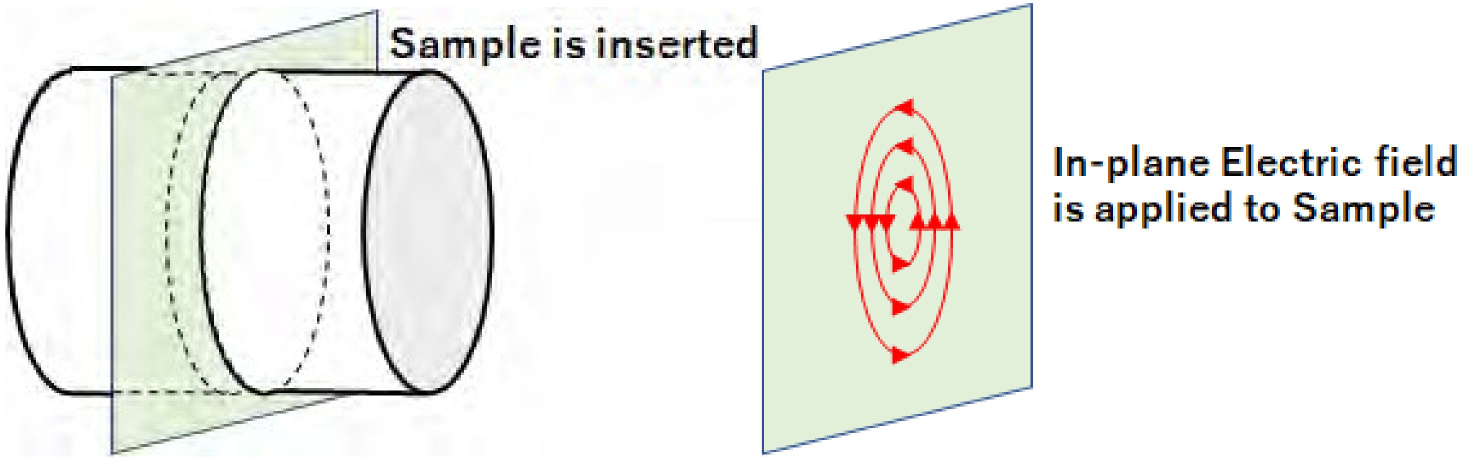
10 Laboratory Round Robin

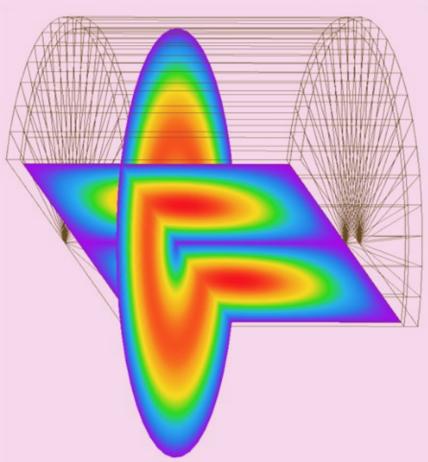


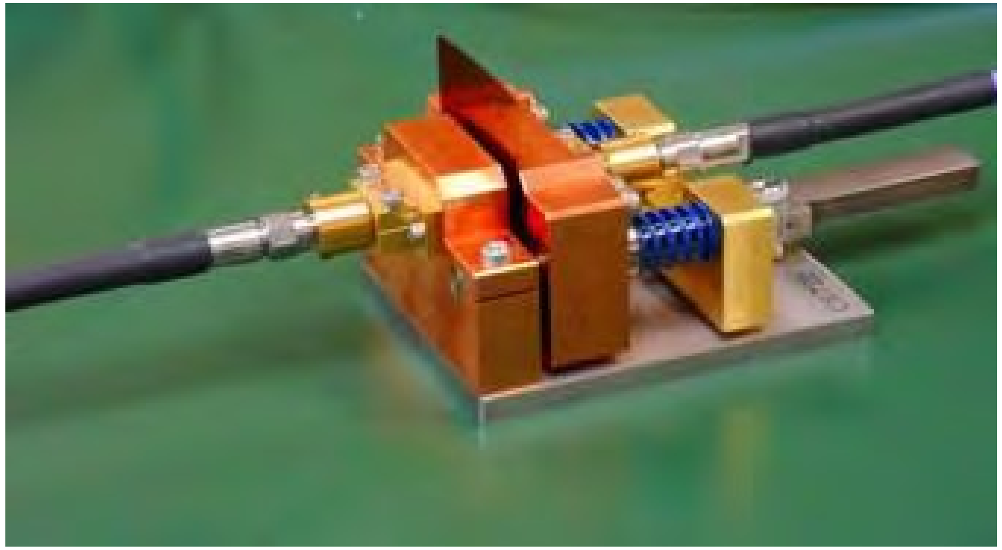
Results for in-plane measurements first reported at EuMW 2021
3 resonator techniques
2 sample kits
3 labs, each using 2+ techniques



Split Cylinder Resonator (SCR) - Basics

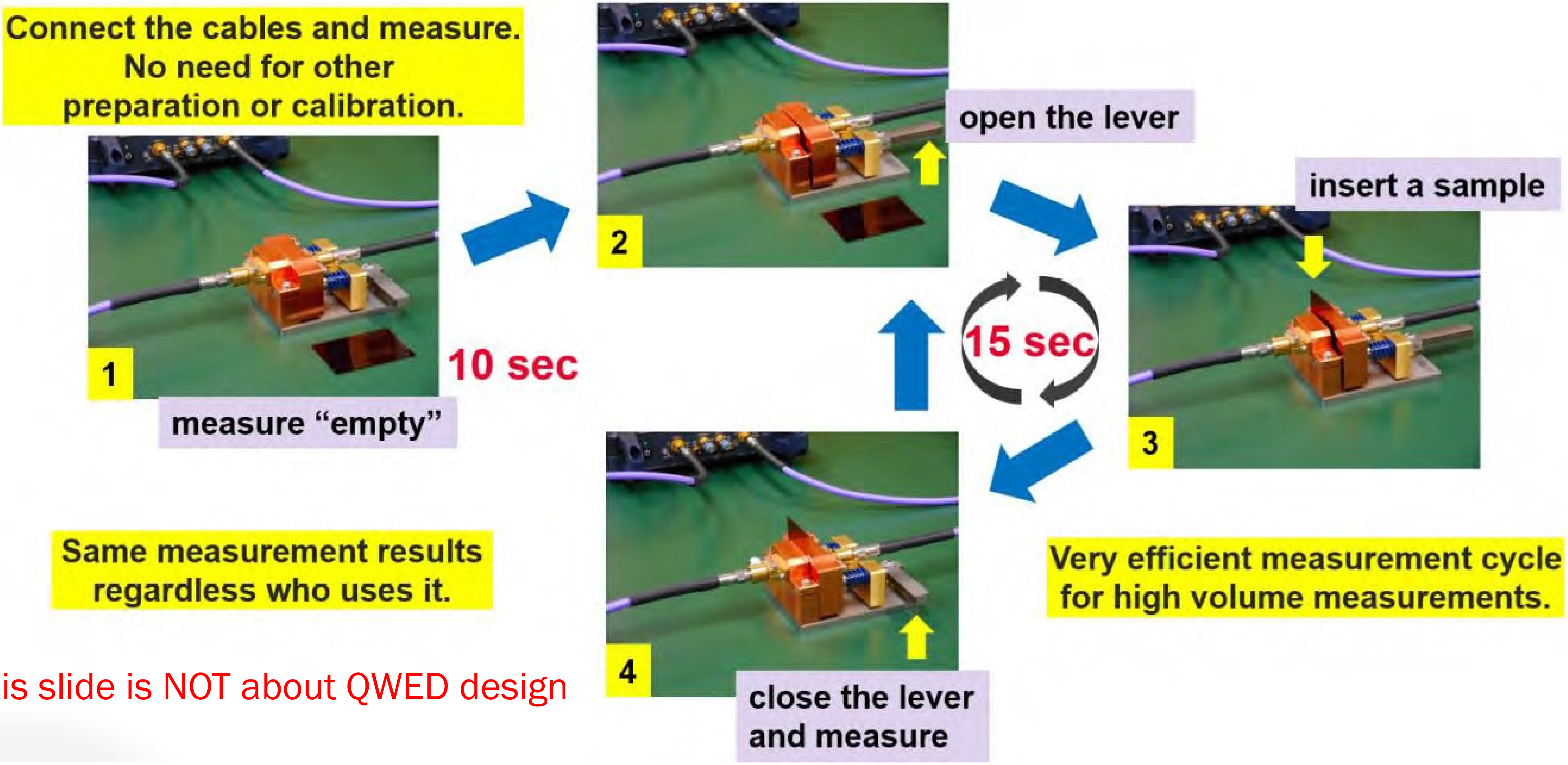






Split cylinder resonator (SCR)	Discrete frequency points from 10 GHz up to 80 GHz	• High measurement precision • Can be sensitive to many user errors • Typically interpolated to 5G mmWaves • Typically in-plane component of permittivity • Typical sample thicknesses around 100 um • Support temperature sweep measurement • IPC-TM-650 2.5.5.13 • https://www.keysight.com/us/en/assets/7018-06384/brochures/5992-3438.pdf

Measurement Procedure: SCR

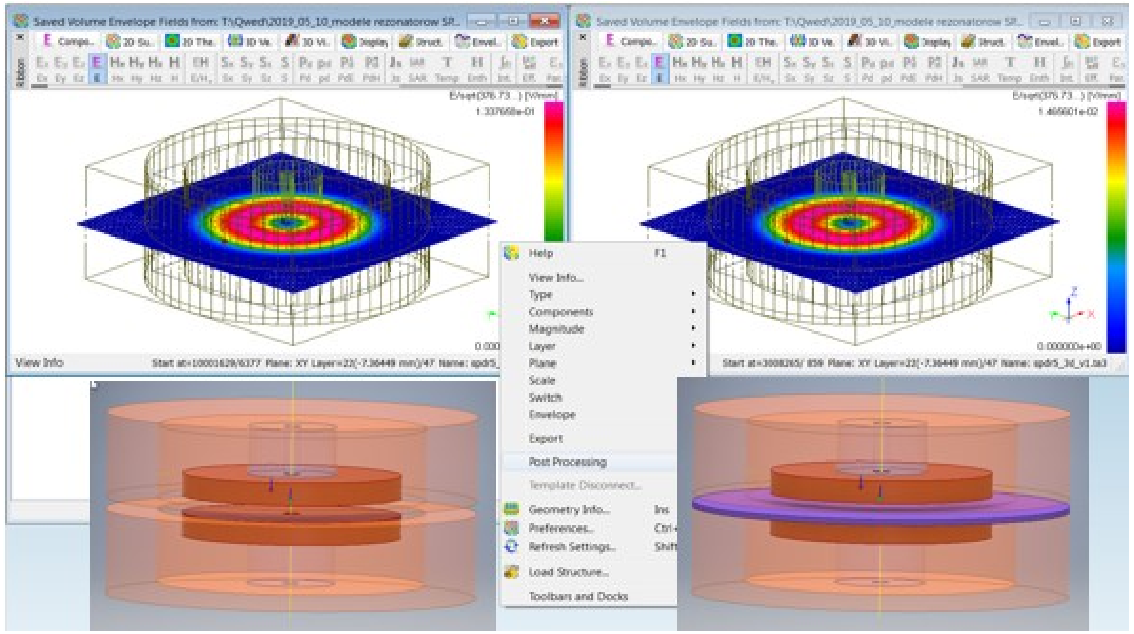


Disclaimer: this slide is NOT about QWED design

The photos and figures on this slide concern:

https://www.keysight.com/us/en/assets/7018-06384/brochures/5992-3438.pdf

Split-Post Dielectric Resonator (SPDR): Basics & Standard



- resonant mode with EM fields mostly confined in and between those ceramic posts

→ minimial losses in metal enclosure

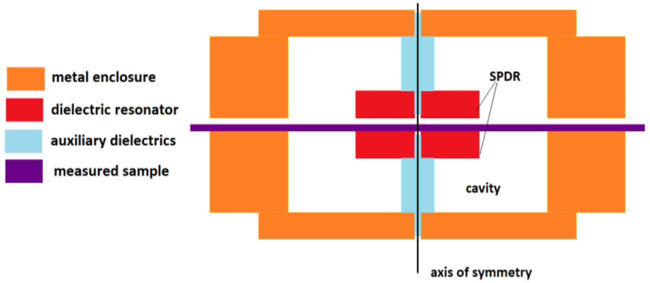
- H-field is only vertical at the side wall of the enclosure
  → circumferential currents

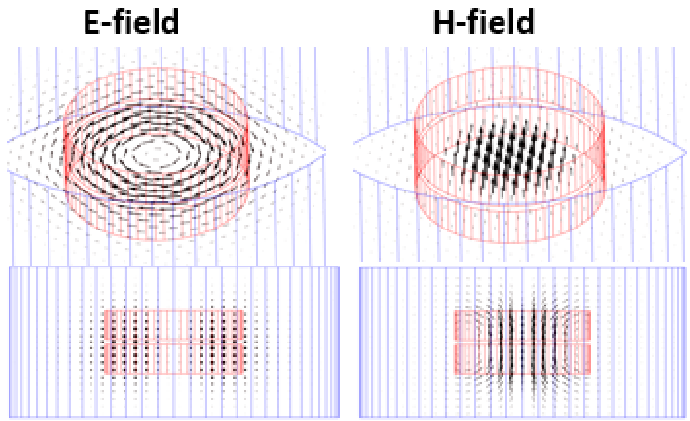
→ no radiation through slot

- E-field tangential to SUT

→ air slots between SUT and posts have negligible effect

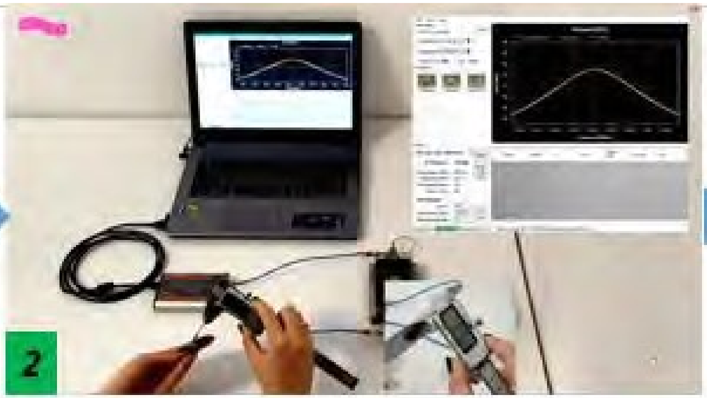
- **easy SUT insertion through slot, no dismatling**





Split-post dielectric resonator (SPDR)	Discrete frequency points from 1 GHz up to 15 GHz	• High measurement precision • Easy to use • Insensitive to many user errors • Typically in-plane component of permittivity • Typically extrapolated to 5G mmWaves • Typical sample thicknesses less than 1 mm • IEC 61189-2-721:2015 • https://www.qwed.com.pl/resonators_spdr.html • https://www.keysight.com/us/en/assets/7018-01416/application-notes/5989-5384.pdf

Measurement Procedure: SPDR

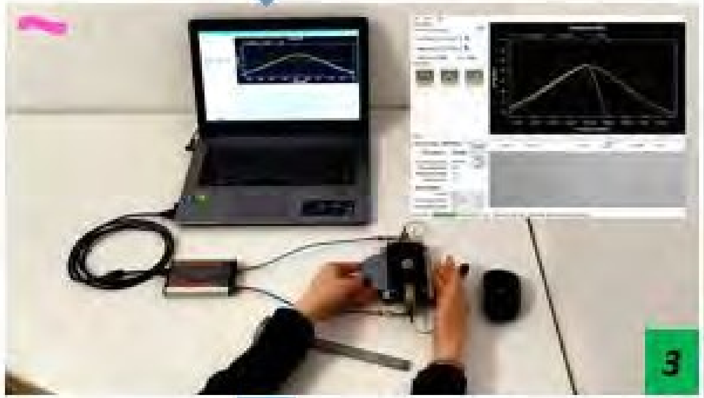


2. Measure thickness of the sample

0. Connect the SPDR to Q-Meter using SMA cables.
Connect Q-Meter to PC using USB cable.

1. Measure "empty SPDR" – app invoked measurement.

Total measurement time: 30sec

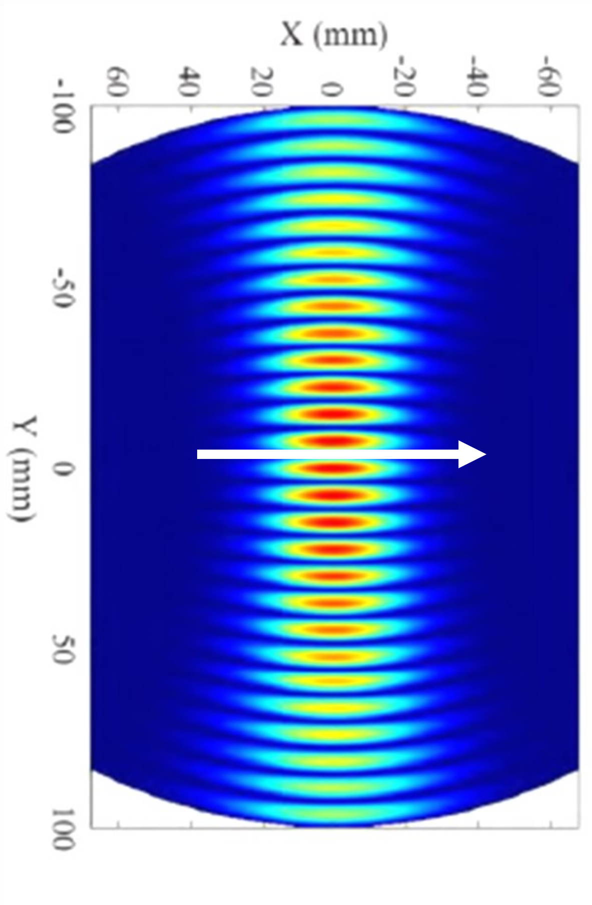


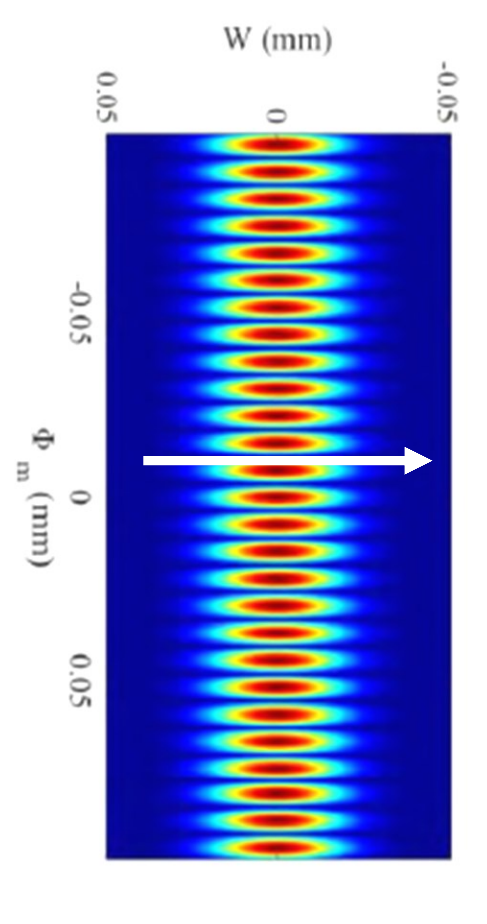
3. Insert the sample into SPDR

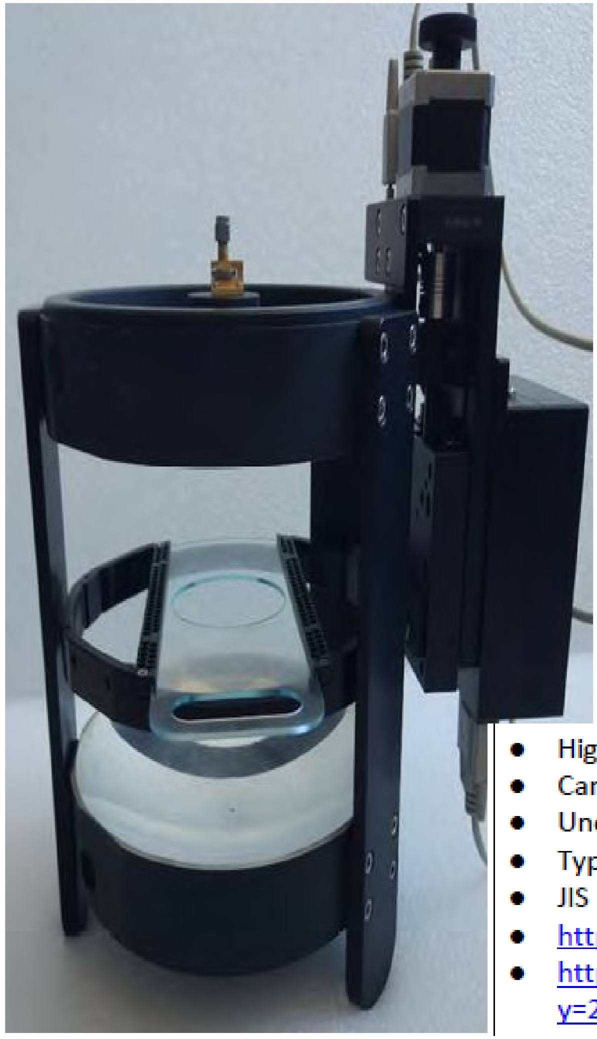
5. Material parameters are extracted automatically

4. Insert the sample thickness into the PC app

Fabry-Perot Open Resonator (FPOR): Basics & Standard







Fabry-Perot open resonator (FPOR, also called open-cavity)

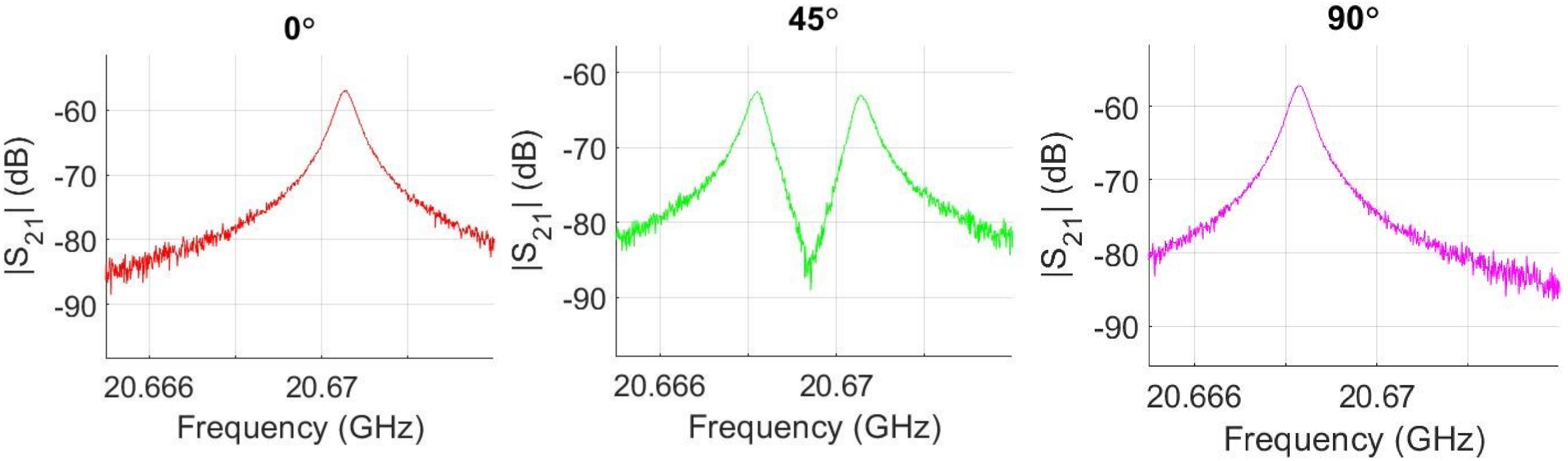
Discrete frequencies between 20 GHz up to 110 GHz

- High measurement precision
- Can be sensitive to many user errors
- Uncertainty increases with increasing frequency
- Typically in-plane component of permittivity
- JIS R1660-2
- https://www.qwed.com.pl/resonators.html#ResonatorFPOR
- https://www.keysight.com/main/editorial.jspx?cc=US&lc=eng&ckey=2276755&nid=null&id=2276755

T. Karpisz, B. Salski, P. Kopyt, and J. Krupka, "Measurement of Dielectrics From 20 to 50 GHz With a Fabry–Pérot Open Resonator," *IEEE Trans. Microw. Theory Tech.*, May 2019, doi: 10.1109/TMTT.2019.2905549.
T. Karpisz, B. Salski, P. Kopyt, and J. Krupka, "Coordinate transformation approach to the solution of the Fabry-Perot open resonator," in *2018 22nd International Microwave and Radar Conference (MIKON)*, May 2018, doi: 10.23919/MIKON.2018.8405291.

Fabry-Perot Resonator Open Resonator

Measuring in-plane anisotropy:



Resonances detected for BoPET sample (t = 0.100 mm), turned in xy plane.

T.Karpisz et al, " Measurement of in-plane anisotropy of dielectric materials with a Fabry-Perot open resonator", Proc. MIKON 2020.

Measurement Procedure: FPOR

1. *Connect the FPOR to VNA and PC with control app.*

2. *Measure "empty FPOR" (resonant frequency and Q-factor at M..N modes)*

3. *Insert the sample into FPOR*

4. *Automatic procedure finds M..N modes of sample-loaded FPOR*

5. *Material parameters at consecutive frequencies (modes) are extracted automatically*

PC app invoked and controlled measurement – fully automatic

Total measurement time: 10min

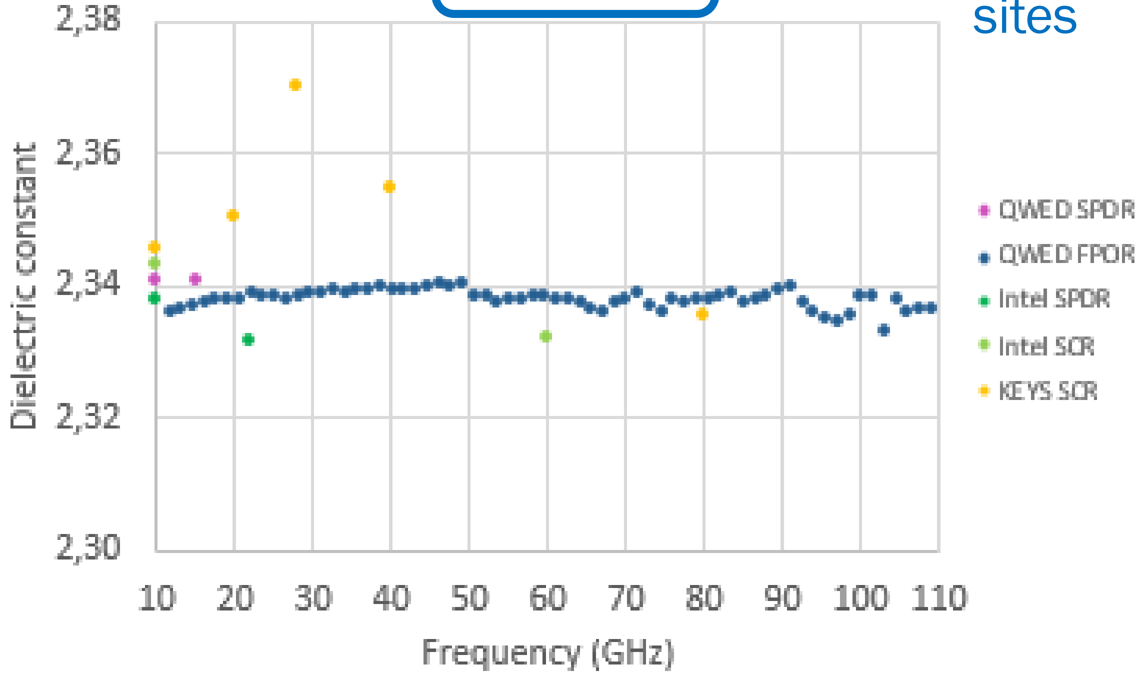
First Round-Robin Results: Consistency

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 over 10-110GHz

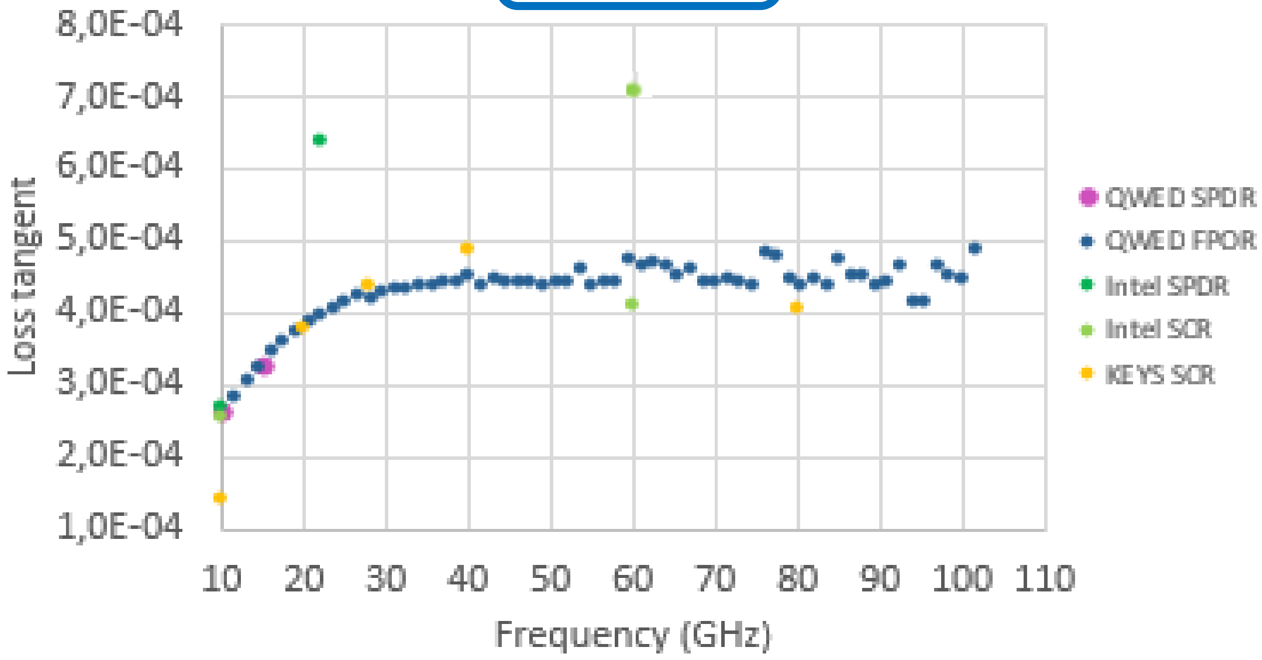
VNA, software:
Intel, Keysight – benchtop VNA with Keysight Option N1500A
QWED FPOR – benchtop VNA with customised FPOR software
QWED SPDR – handheld VNA , extraction based on abs(S21)

COP 186µm



dot colours denote testing sites

COP 186µm

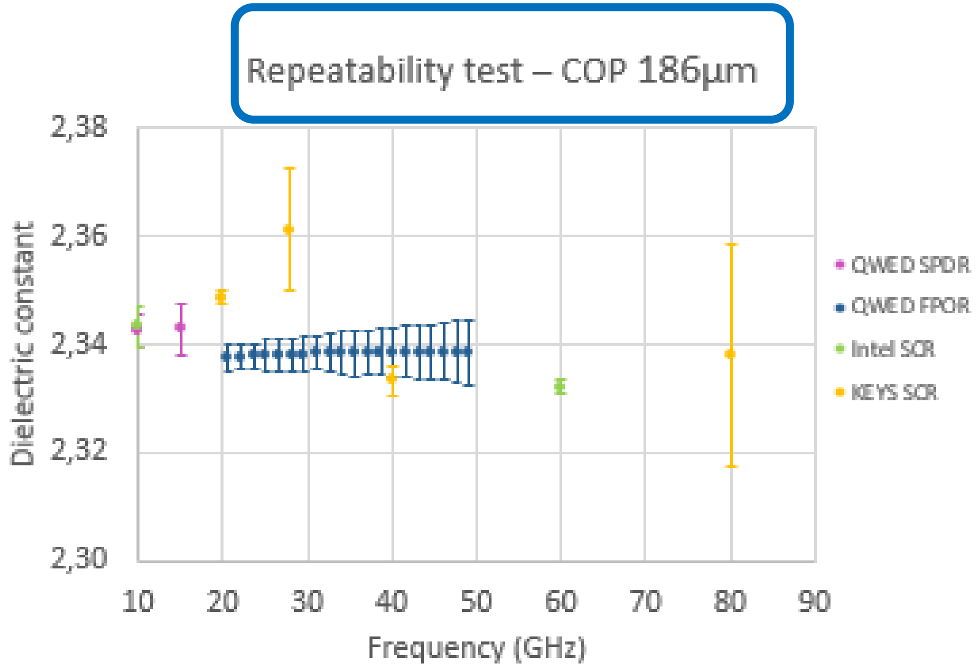


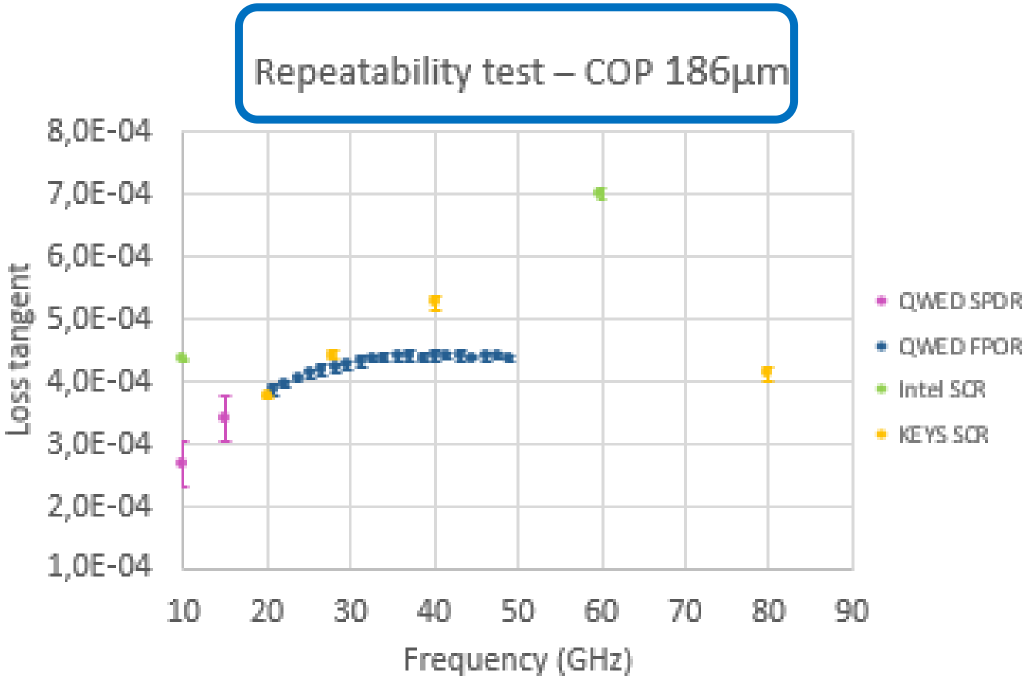
visually good results, with reference to standards and practices in the microwave range (e.g. IEC 61189-2-721:2015 for SPDRs < 20GHz dictates 0.3% for Dk assuming perfect determination of thickness, relaxed to 1% in industrial practice)

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%

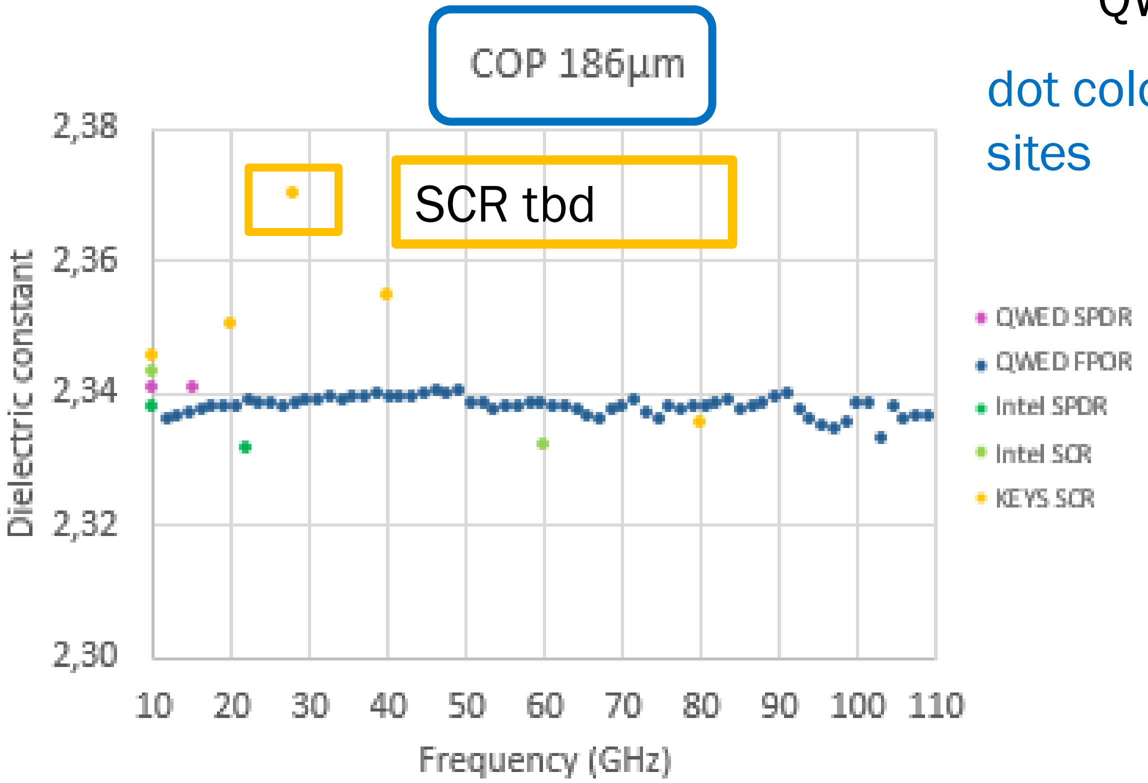
each symbol denotes an average of 16 measurements; error bar = repeatability = triple of standard deviation

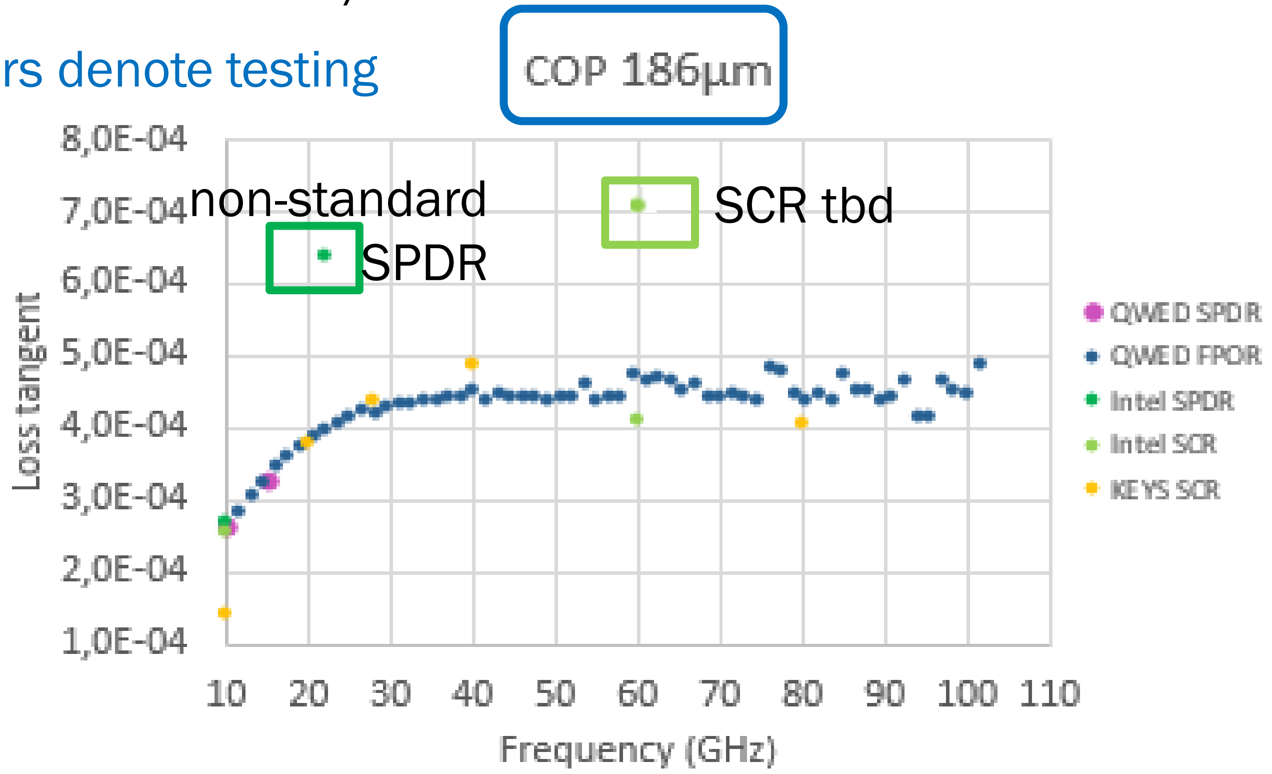
First Round-Robin Results: Discussion

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





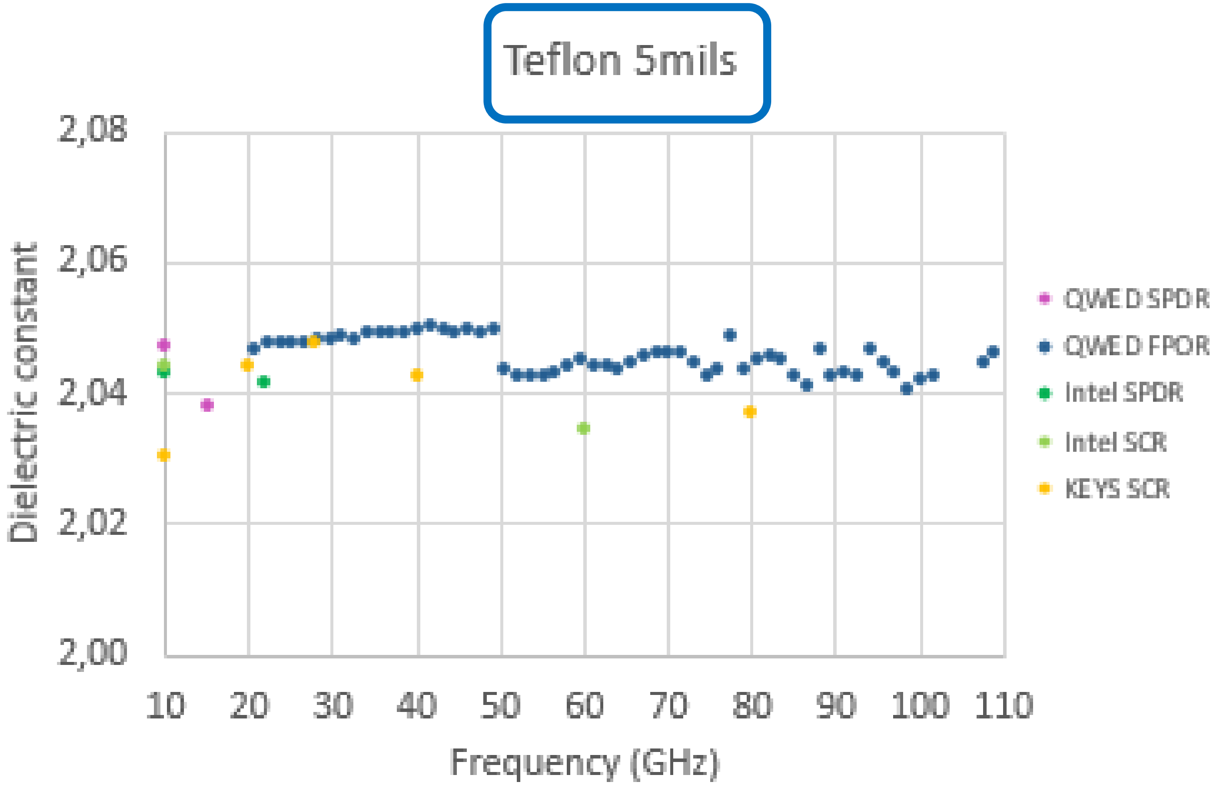
Dk spread < 1% (within ± 0.5% from average)
(< 2% incl. outliers)

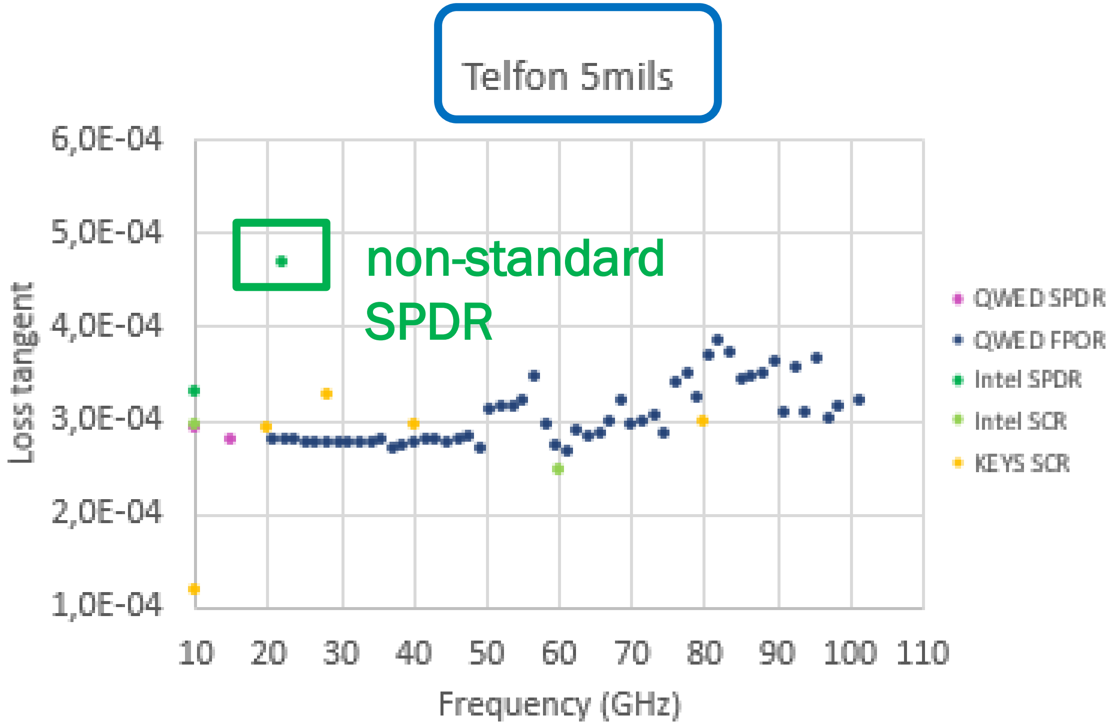
> 40GHz 2x increase in Df compared to 10GHz

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.

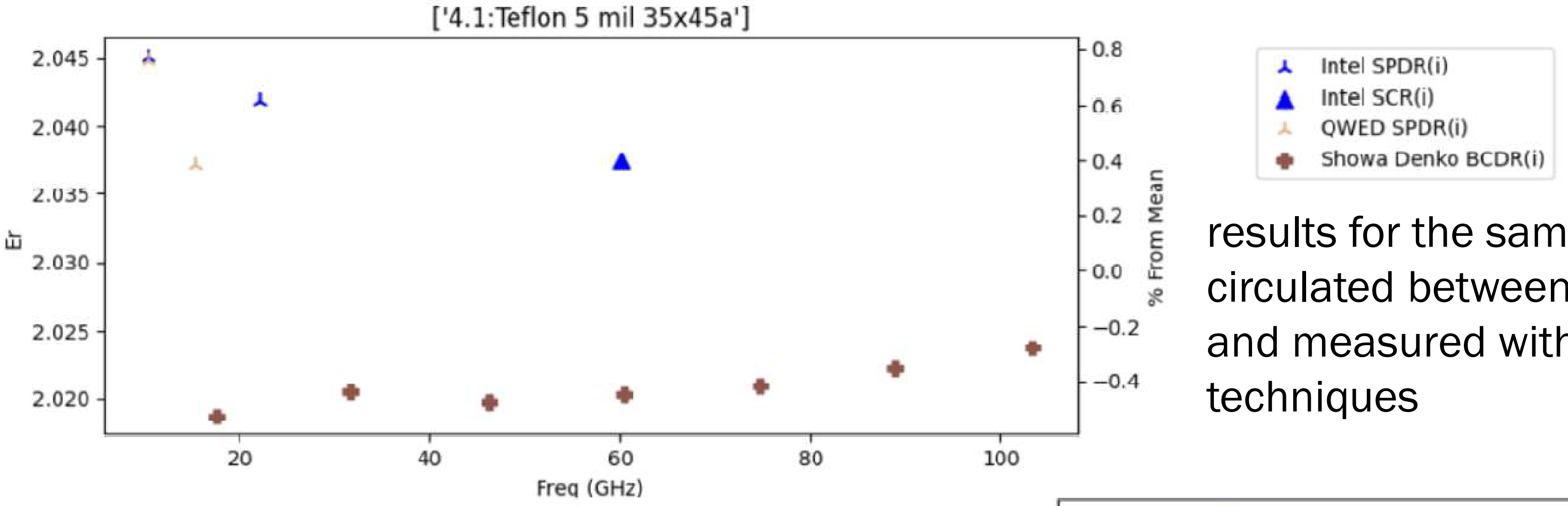




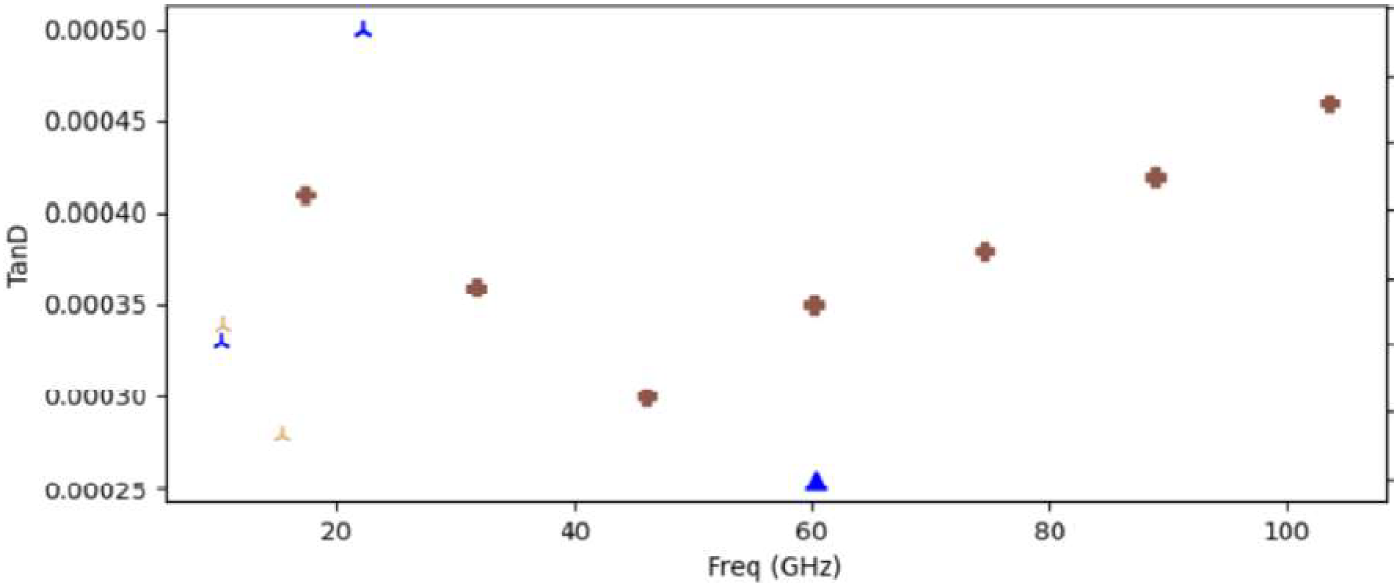
Dk spread < 1% (within ± 0.5% from average)

IMS
Connecting Minds. Exchanging Ideas.

Round Robin – 4th Lab & 4th Technique



results for the same sample circulated between 3 labs and measured with in-plane and out-of-plane techniques

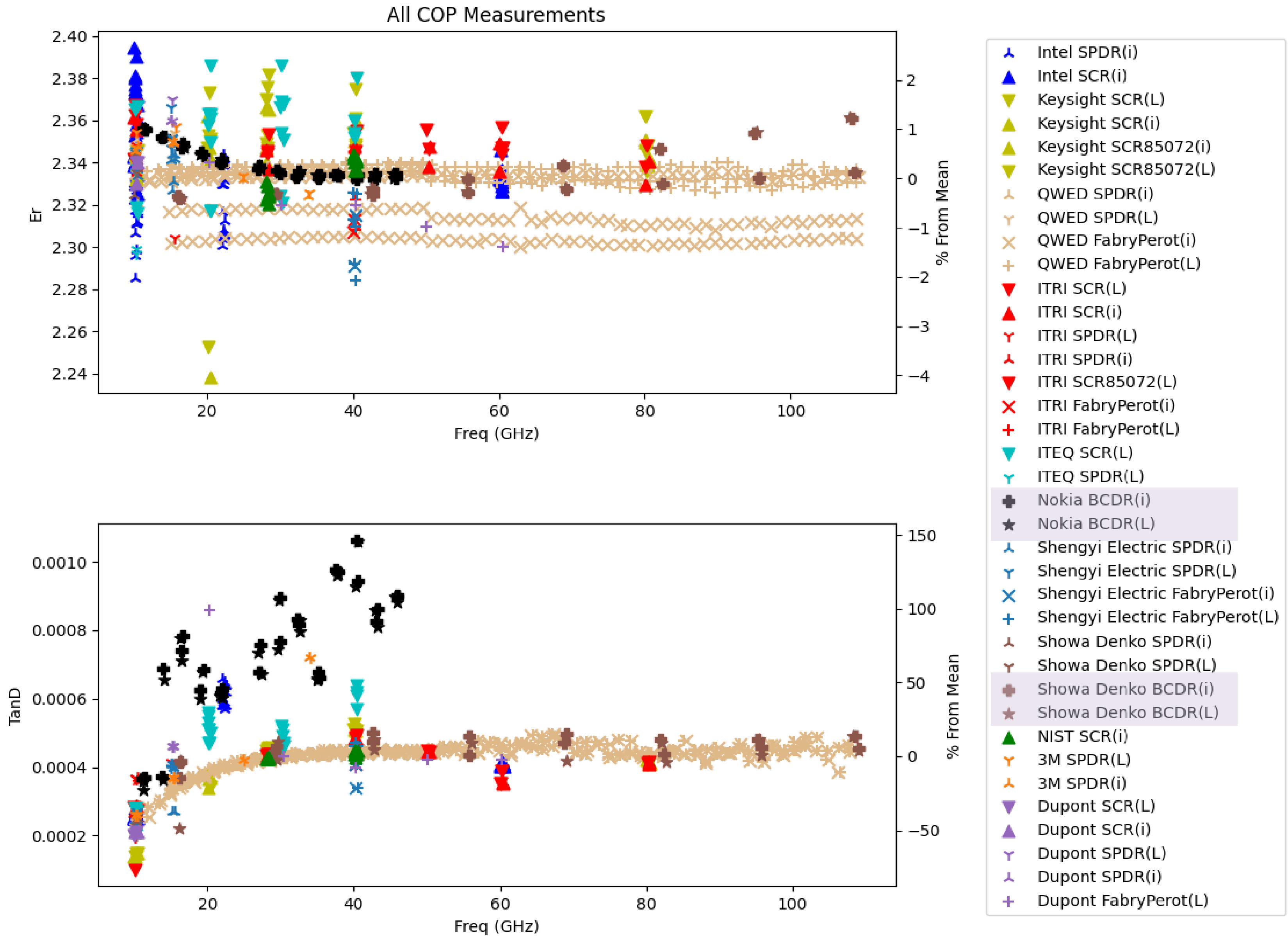


BCDR measures out-of-plane component of complex permittivity

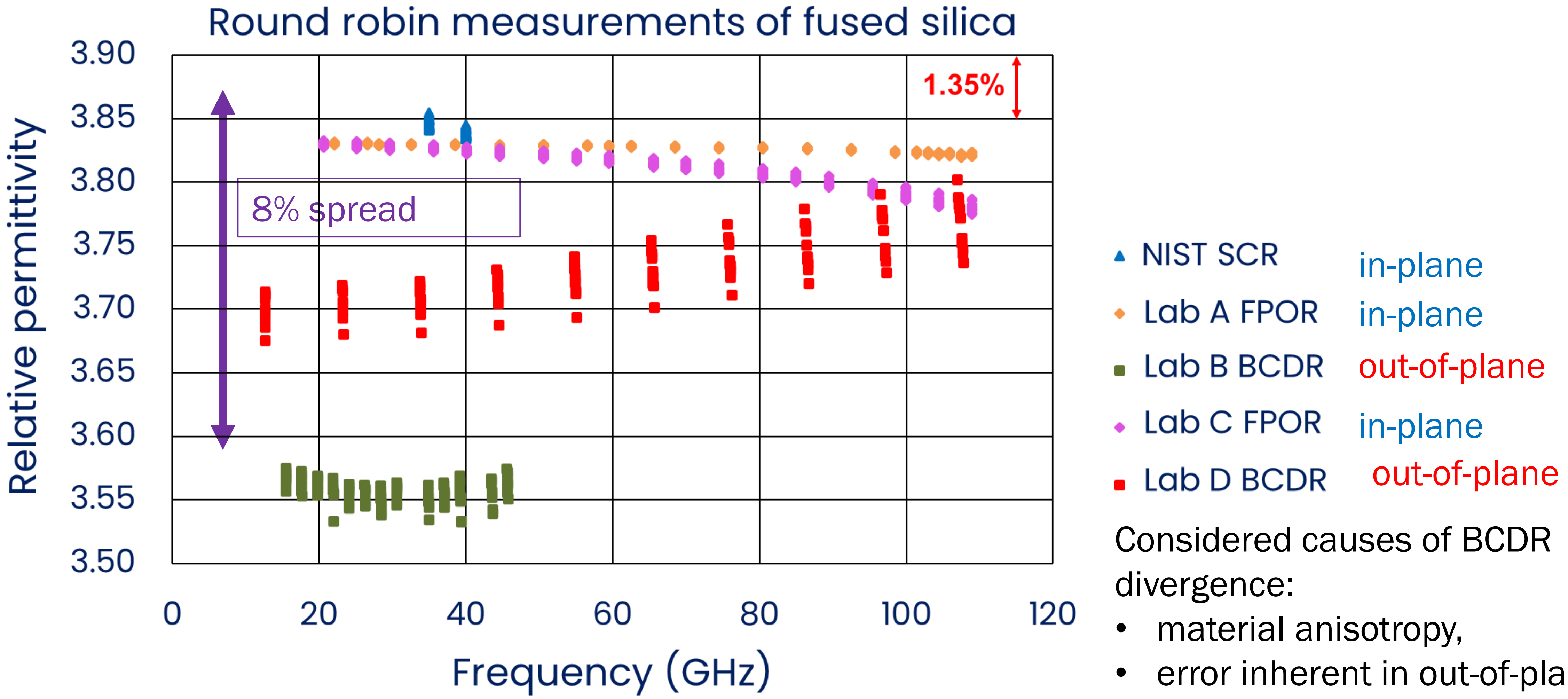
averaged BCDR results remain within 1% of averaged SCR & SPDR results

this sample is THIN

First Round-Robin: All Measurements for COP186 µm



Divergence of BCDR Measurements More Pronounced for Fused Silica*

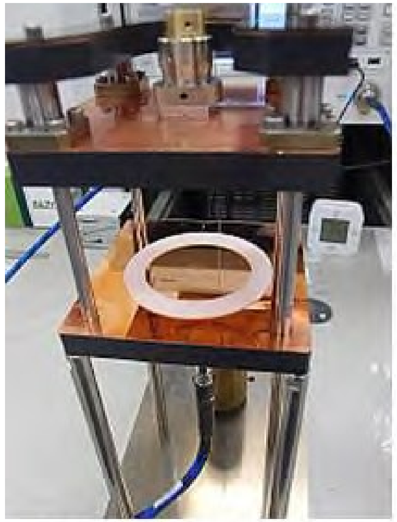


Considered causes of BCDR divergence:

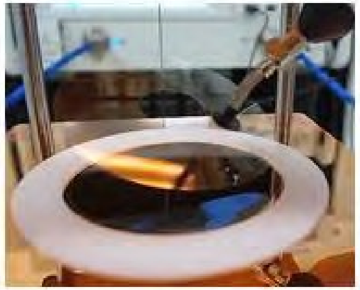
- material anisotropy,
- error inherent in out-of-plane measurement,
- error in particular BCDR instrument.

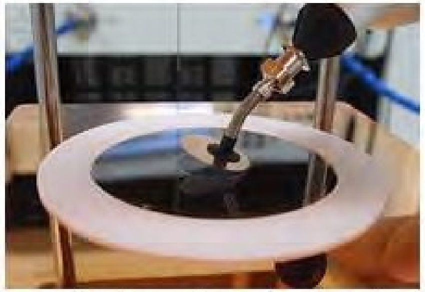
Notes on BCDR

Note: in the iNEMI benchmarking, different BCDRs are used by two project partners. The photos and figures on this slide concern:
https://www.keysight.com/us/en/assets/7120-1214/flyers/N1501AE11-67-Balanced-Type-Circular-Disk-Resonator-BCDR.pdf

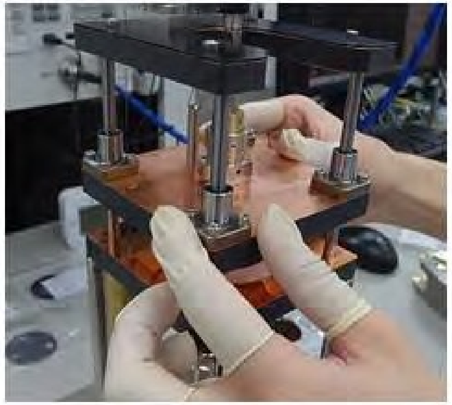

Open the resonator


Set lower side sample

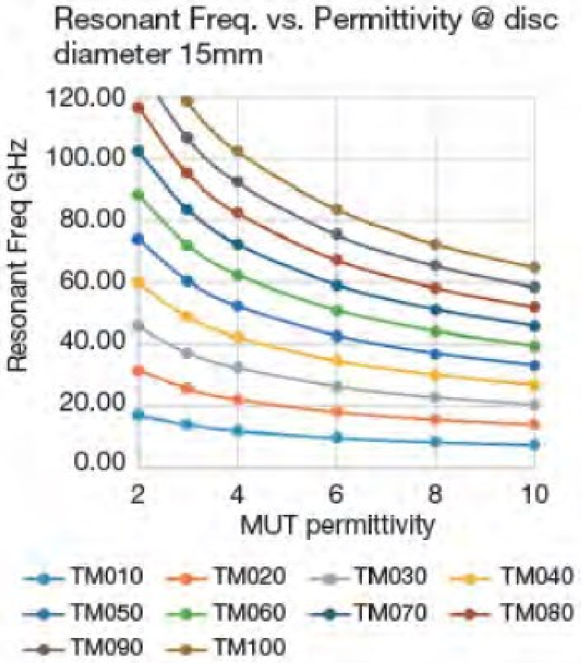

Set shim sheet


Set center electrode


Set upper side sample

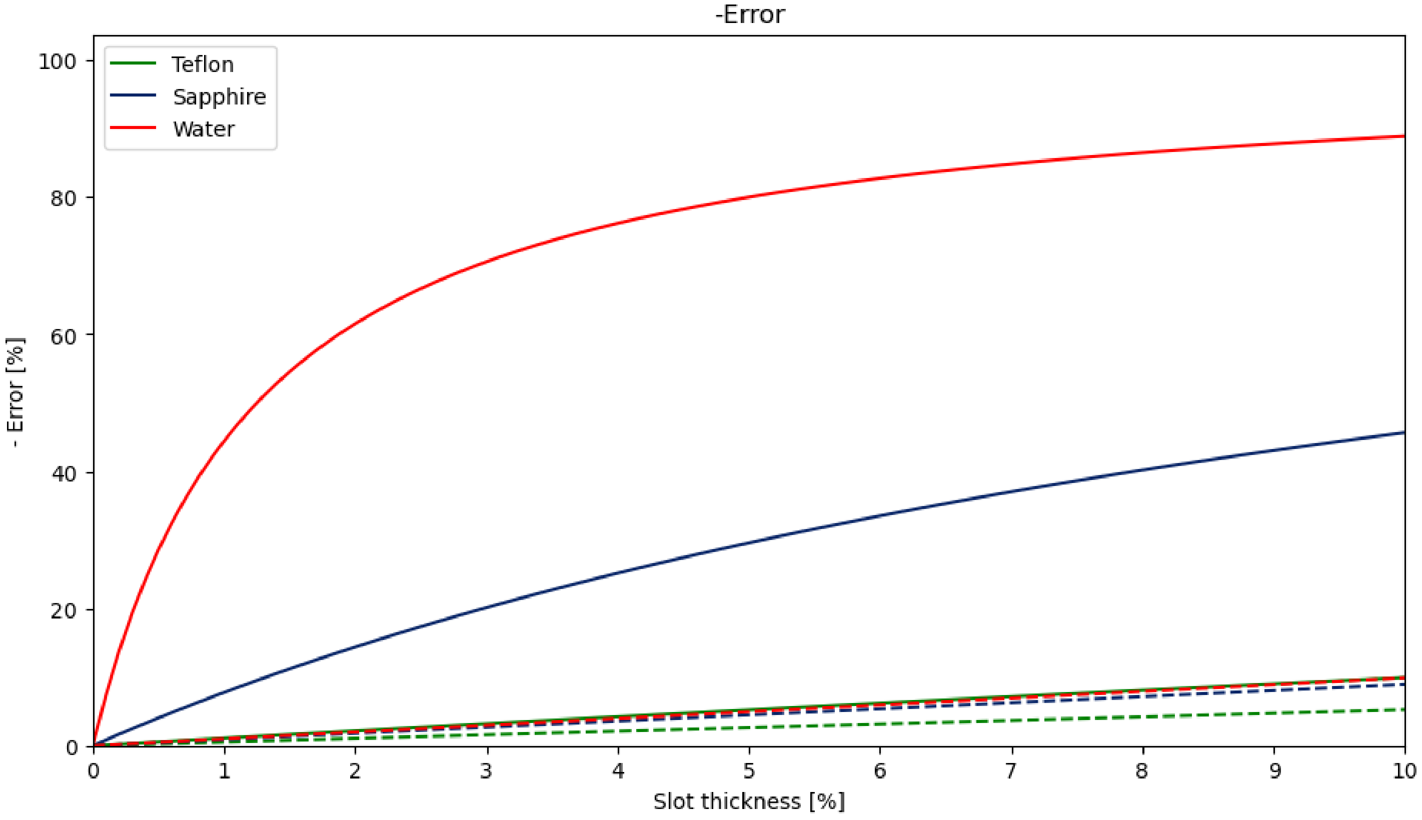

Close the resonator


Clamp and measure



Disclaimer: this slide is NOT about QWED designs

Notes on BCDR: Air slots in In-Plane and Out-of-Plane Measurements
– Small Air Slot in a Paralel-Plate Capacitor



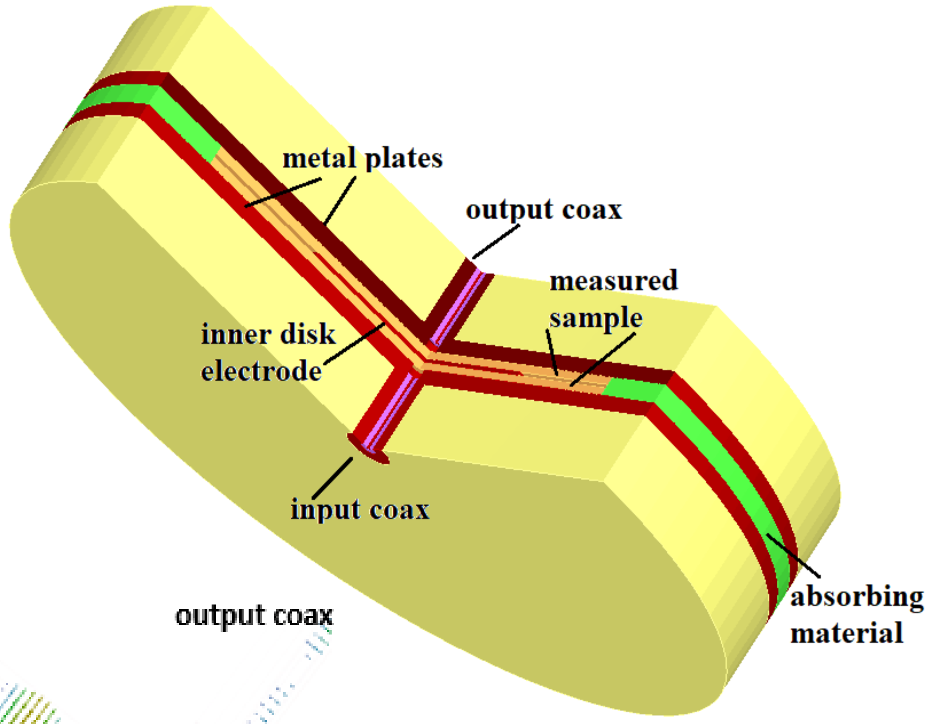
Colour – material:
- Water
- Sapphire
- Teflon

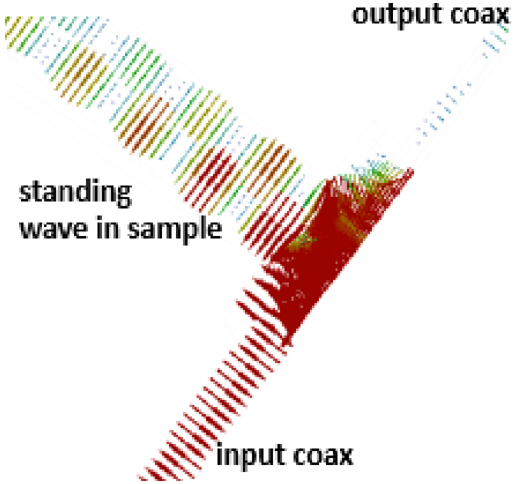
Dashed lines: in-plane
slot tangential to E-Field

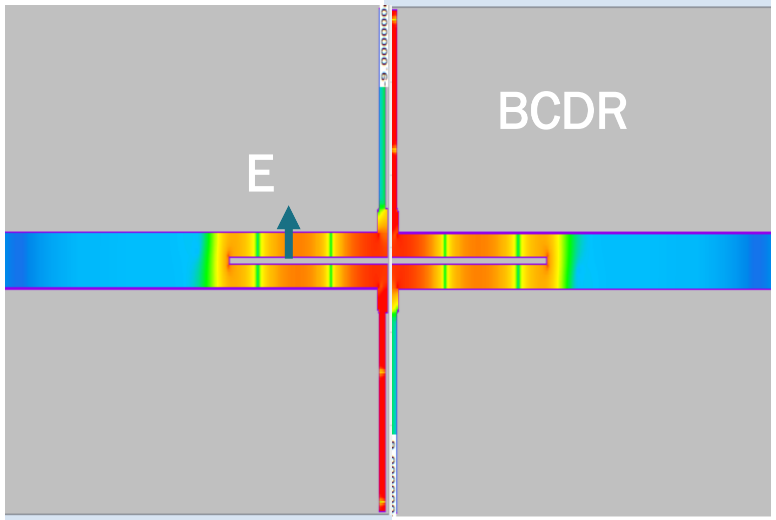
Continuous lines: out-of-plane
slot perpendicular to E-Field

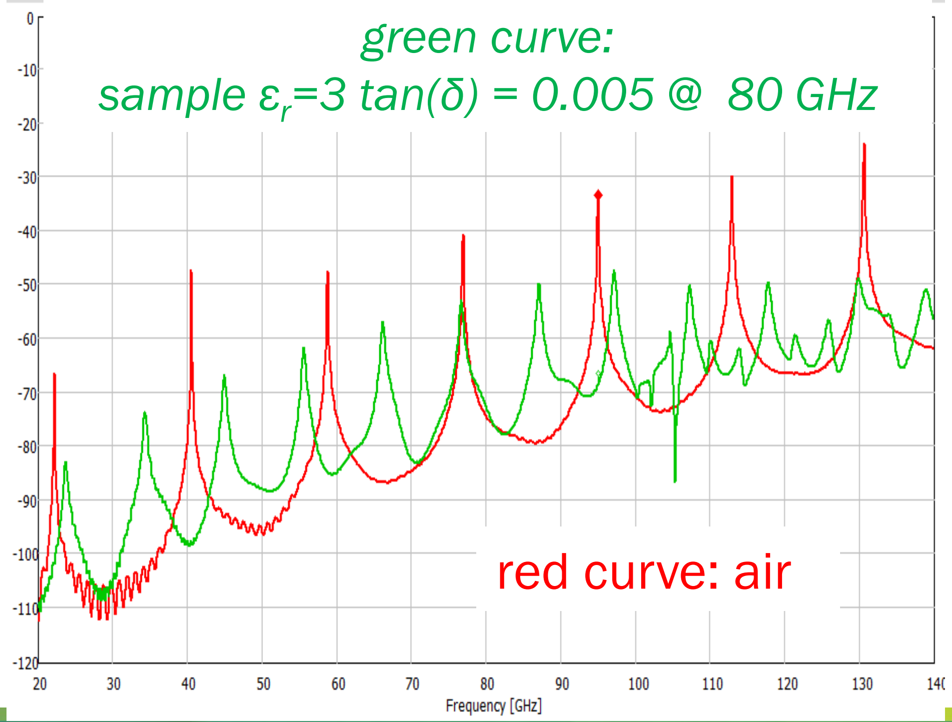
in-plane: even for high Dk dielectrics, % error in Dk is significantly smaller that % of air gap
out-of-plane: % error in Dk increases faster than linearly with % air gap (here, 10% gap –> ~40% error in Dk of sapphire)

Notes on BCDR: QWED’s Electromagnetic Insight

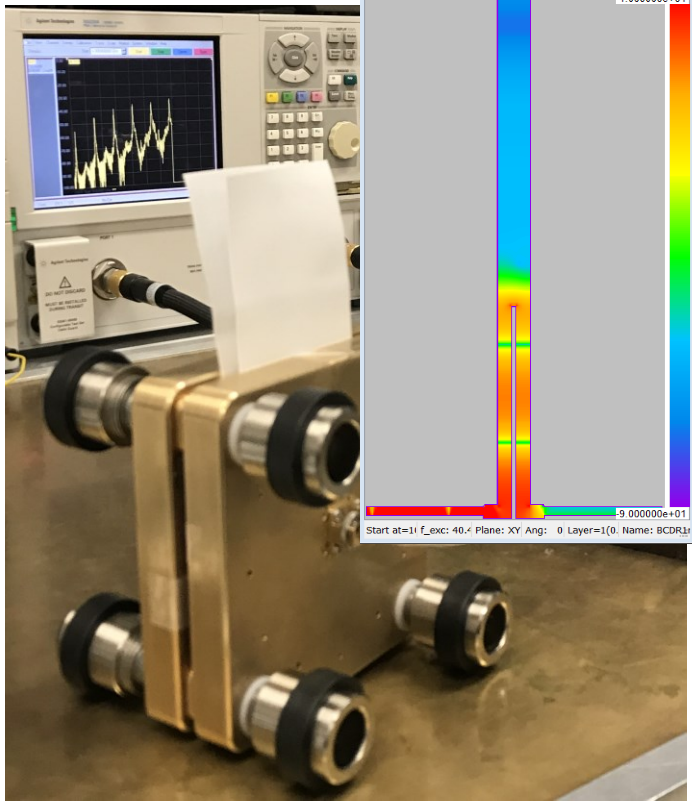


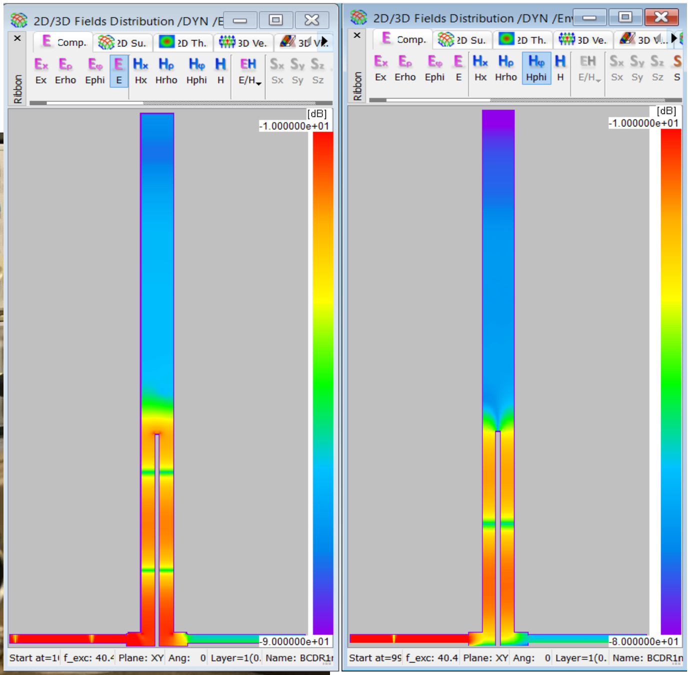




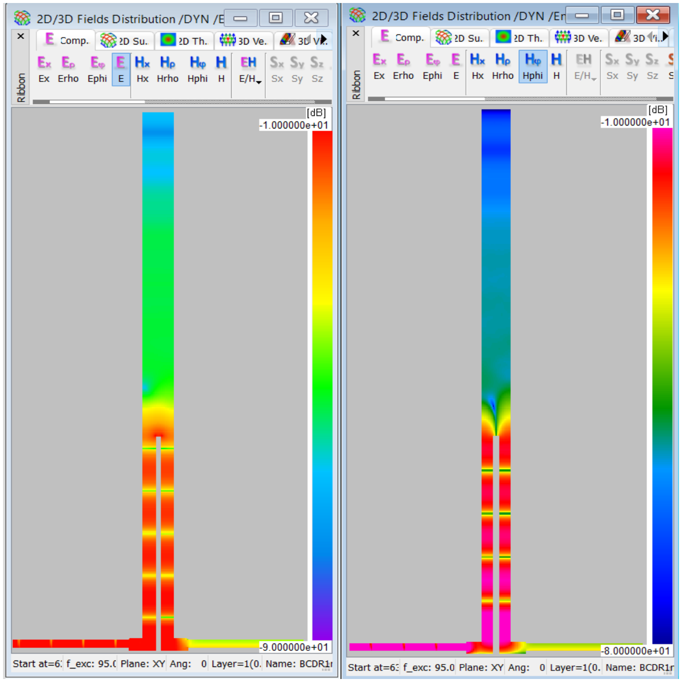


Notes on BCDR: QWED’s Test Design

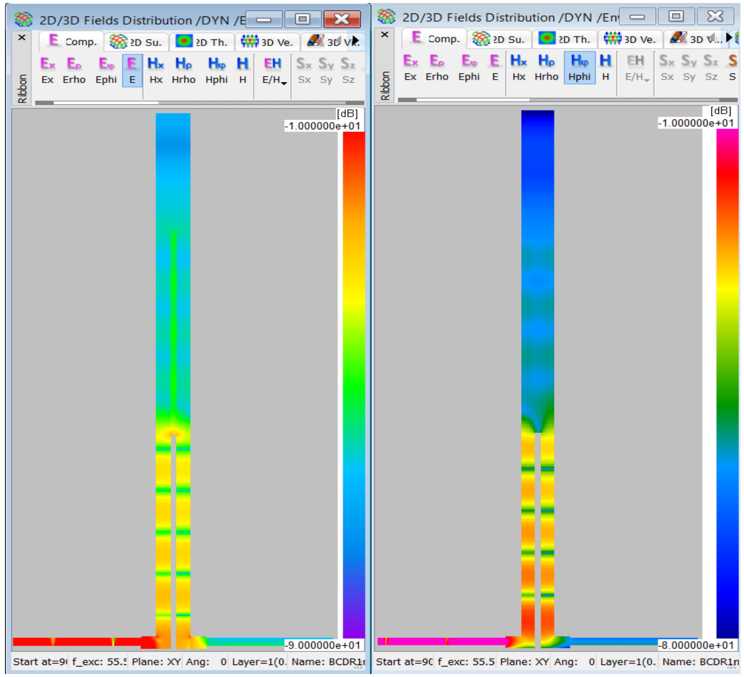




@ 40.49 GHz, air



@ 95.06 GHz, air



@ 55.57 GHz, sample

Envelope of |E| and Hphi fields in log scale (-10 to -80 dB)

Our BCDR prototype has been manufactured and works.

Measurements confirm BCDR sensitivity to air gaps, even small, caused by roughness of metallic surfaces (electrodes). This is not a problem in SPDR (and other standard out-of-plane measurements)!

QWED's Novel Design for Thick Samples

Patent: W. Gwarek, "Electromagnetic resonating structure and a method of measuring of a material parameter", European Patent Application **EP23461651**, Sep. 18, 2023.

Challenges in Measuring (Thick) Industrial Samples

Relevant industrial samples, provided in iNEMI 5G Dielectrics" project for testing for automotive radar applications, could NOT be measured at mmWaves – they were only measured with low frequency SPDR(@1.1GHz).
This is because **all the available resonator techniques** impose limits on sample thickness:

- mechanical – related to design of a particular instrument,
- electromagnetic – due to undesired modes appearing in the measurement band.

Typically:

- SPDR allows thicker samples that SCR, for given frequency,
- but SPDRs are offered only for lower frequencies.

Typically: sample needs to be thinner when:

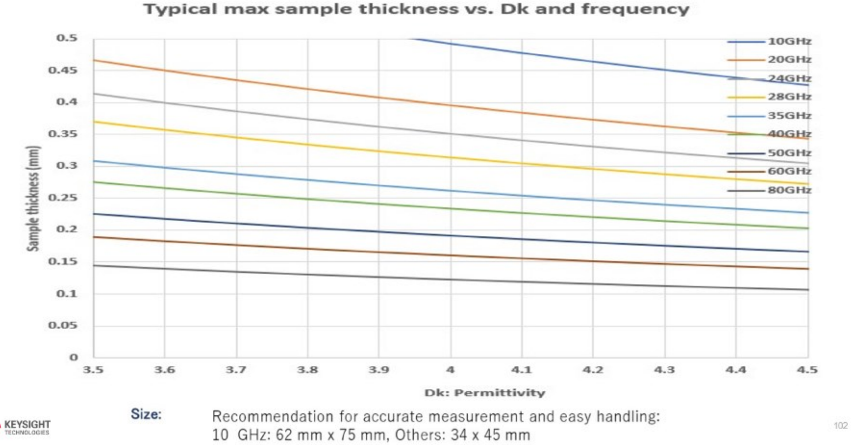
- Dk is higher,
- frequency is higher.

Example:

In 15GHz SPDR, slot 0.6mm, 0.6mm sapphire can be measured.

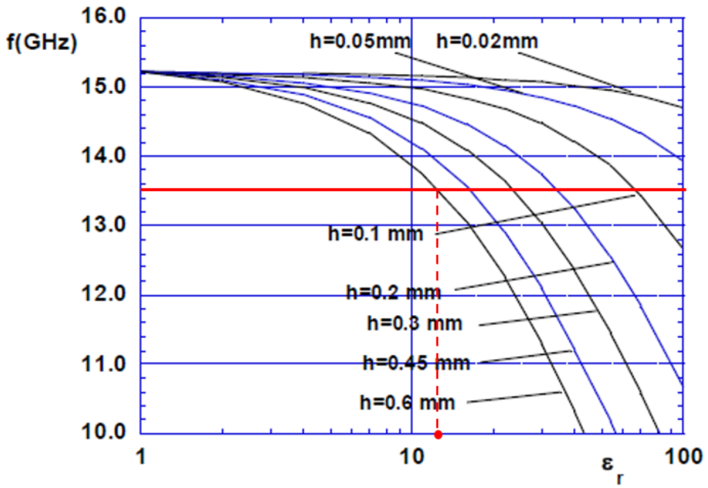
In SCR even 10GHz, sapphire sample would need to be < 0.4mm

Sample Thickness - SCR



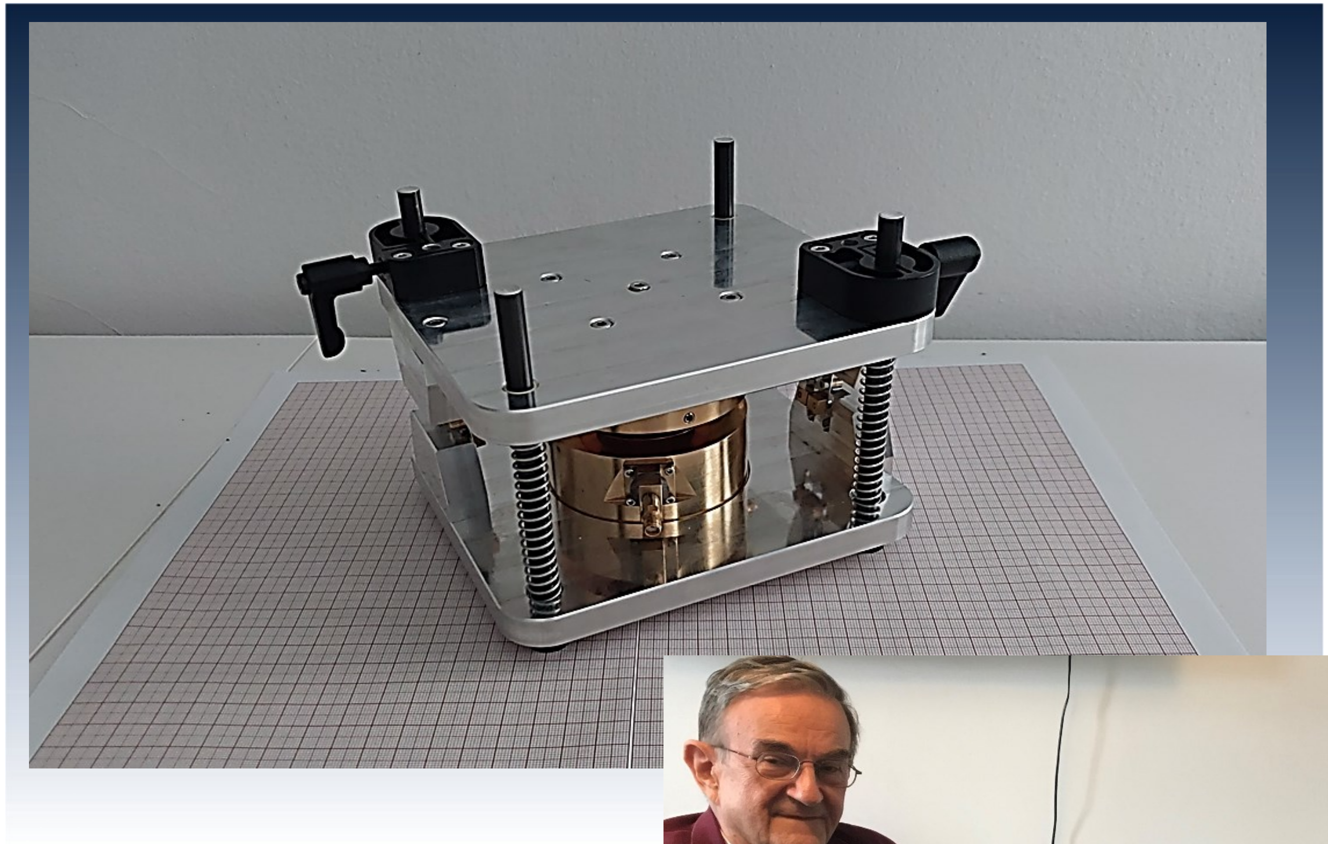
Nominal frequency [GHz]	Maximum thickness of s
1.1	6.0
2.45 / 2.5	3.1
5 / 5.1	1.95
10	0.95
15	0.6

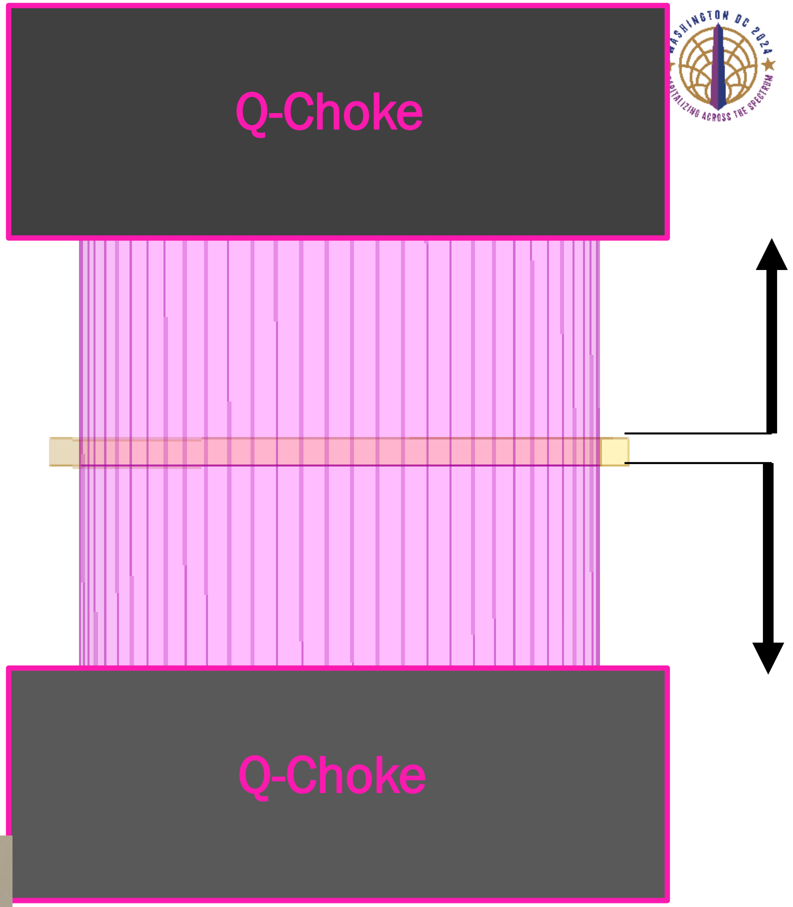
SPDR f [GHz] and slot [mm]



SPDR 15 GHz

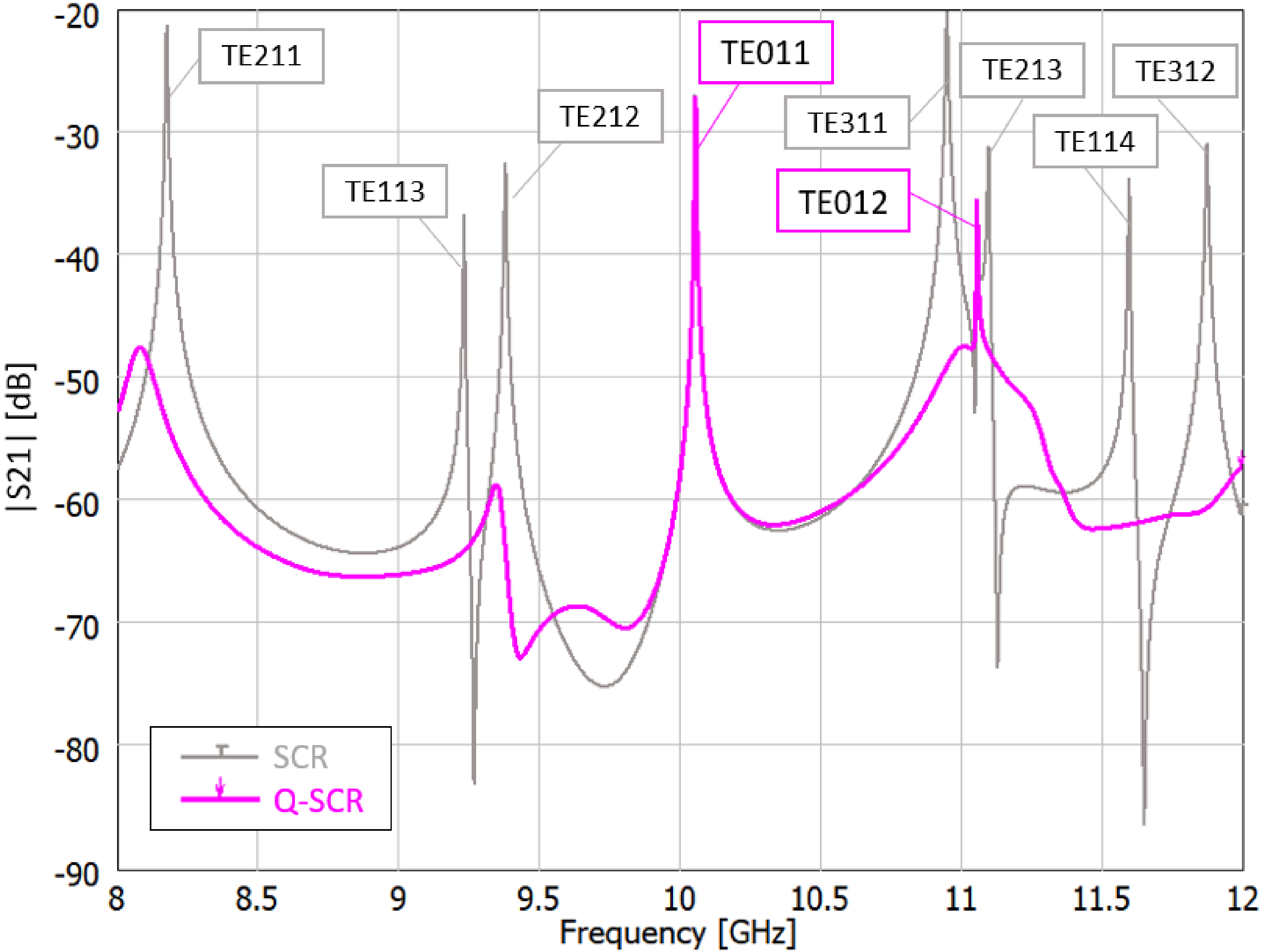
QWED's Novel SCR with Q-Choke





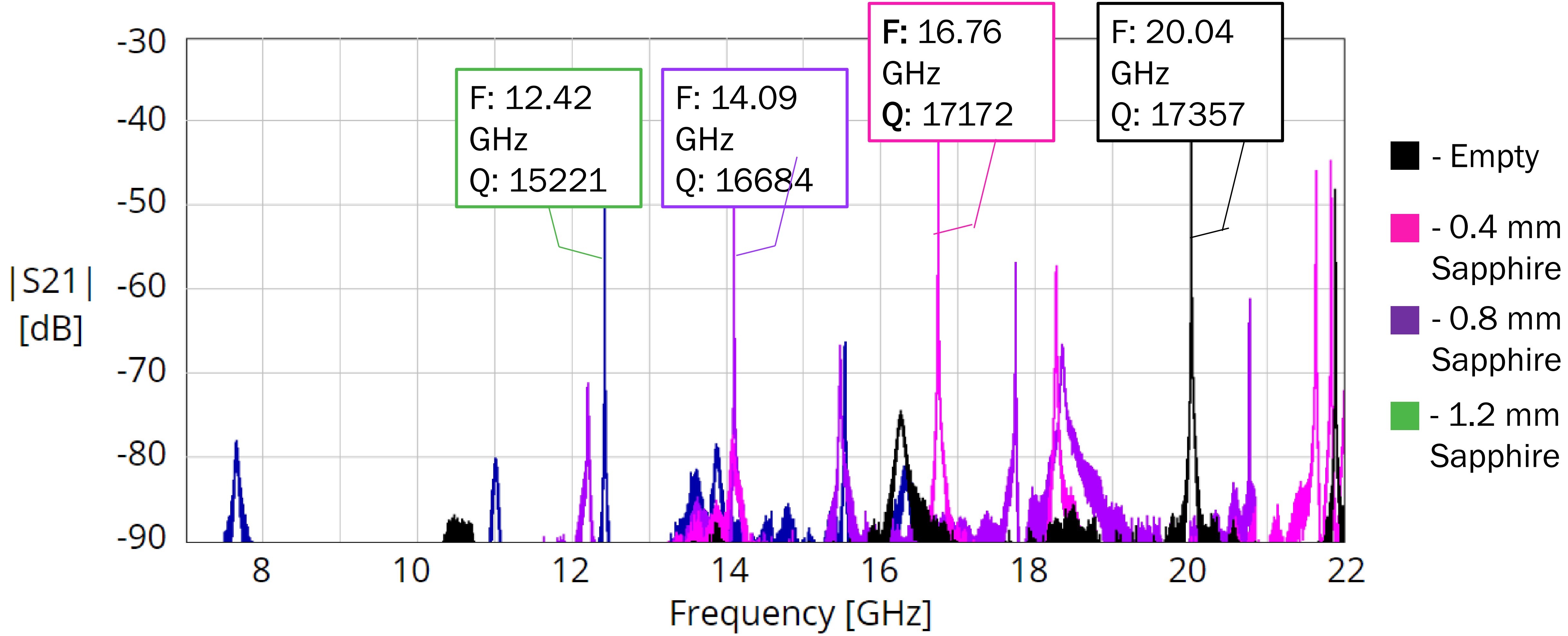
European patent number: **EP23461651**

Modelling of SCR without and with Q-Choke



10 GHz Q-SCR

Measurements in Q-Choked SCR



1.2 mm sapphire easily measured at 20 GHz

Conclusions

1. The talk has reported on iNEMI projects concerning assessement of materials and benchmarking of material measurement techniques for 5G/mmWave applications.

2. The “5G Substrates” project initiated rigorous benchmarking for substrate materials:
- assembled tens of thousands of measurements by 11 labs with 4 techniques (in different implementations),
- techniques: 3 for in-plane (SPDR, SCR, FPOR) and 1 for out-of-plane (BCDR) permittivity measurement,
- samples: 2 sample sizes that cover all the techniques: 35mm x 45 mm and 90mm x 90mm,
- materials: started with COP (186 μm) and Teflon (126 μm, 50 μm) ; then fused silica, rexolite, and industrial (automotive, electronics,..).

3. For inter-lab, inter-technique comparisons, average of 16 measurements (at a given lab by a given technique for a given sample) was used.

For in-plane techniques:
- Dk spread (between the 3 metrologies) < 1% (2% incl. non-standard outliers),
- QWED’s SPDR and FPOR well consistent, SCR and other FPORs are sometimes outliers,
- sample-to-sample variation more significant than lab-to-lab or technique-to-technique (presumably sample thickness variations),
- for COP at f > 40GHz, 2x increase in Df demonstrated compared to 10GHz loss.

For out-of-plane (BCDR), Dk measurements:
- diverges from in-plane for (presumably) isotropic samples (up to 3-7% for fused silica),
- vary in frequency,

the effects remain to be explained by BCDR designers / vendors or by use of other out-of-plane measurements.

4. The work continues in ongoing projects, including on “5G Copper Foils” and “5G SRMs”.

Conclusions

1. QWED material measurement methods and instruments have been presented:
- for different frequency bands (within 1.1 -120 GHz),
- for different materials (substrates, coper foils, liquids, 2D materials,...)

2. Insight into the physics behind the applied methods and instruments has been provided, by modelling in QuickWave^{TM} simulation software by QWED.

3. In both qulitative and quantitative terms, the presented methods and instruments prove advantageous, in the context of the international benchmarking inititaives coordinated by iNEMI.

4. Recent developments have been indicated:
- 2D imagining of dielectric surfaces of resistive films with 2D SPDR or iSiPDR scanners,
- BCDR for out-of-plane measurements (and testing of the BCDR concept),
- Q-Choked SCR for 20 GHz (scheduled 304, 40, 50 GHz) alleviating the existing limits on sample thickness.

5. QWED is happy to design custom-made instruments and enter into joint R&D projects!!!

Invitations & Acknowledgements.

9/26/2023 to 9/27/2023 EDT

26 SEP **Packaging Tech Topic Series: Toward The Physical Reliability Of 3D-Integrated Systems**
9:00 AM to 10:00 AM EDT

27 SEP **INEMI Keynote At MMA Conference**
8:30 AM to 9:30 AM CET

27 SEP **RESCHEDULED: Seminar On Humidity Robustness And Isolation Coordination For E-Mobility**
9:00 AM to 4:30 PM CET

13 OCT **INEMI Workshop: Reliability And Standards For Automotive Electronics**
8:30 AM to 5:30 PM HKT

View All Events

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

IMS
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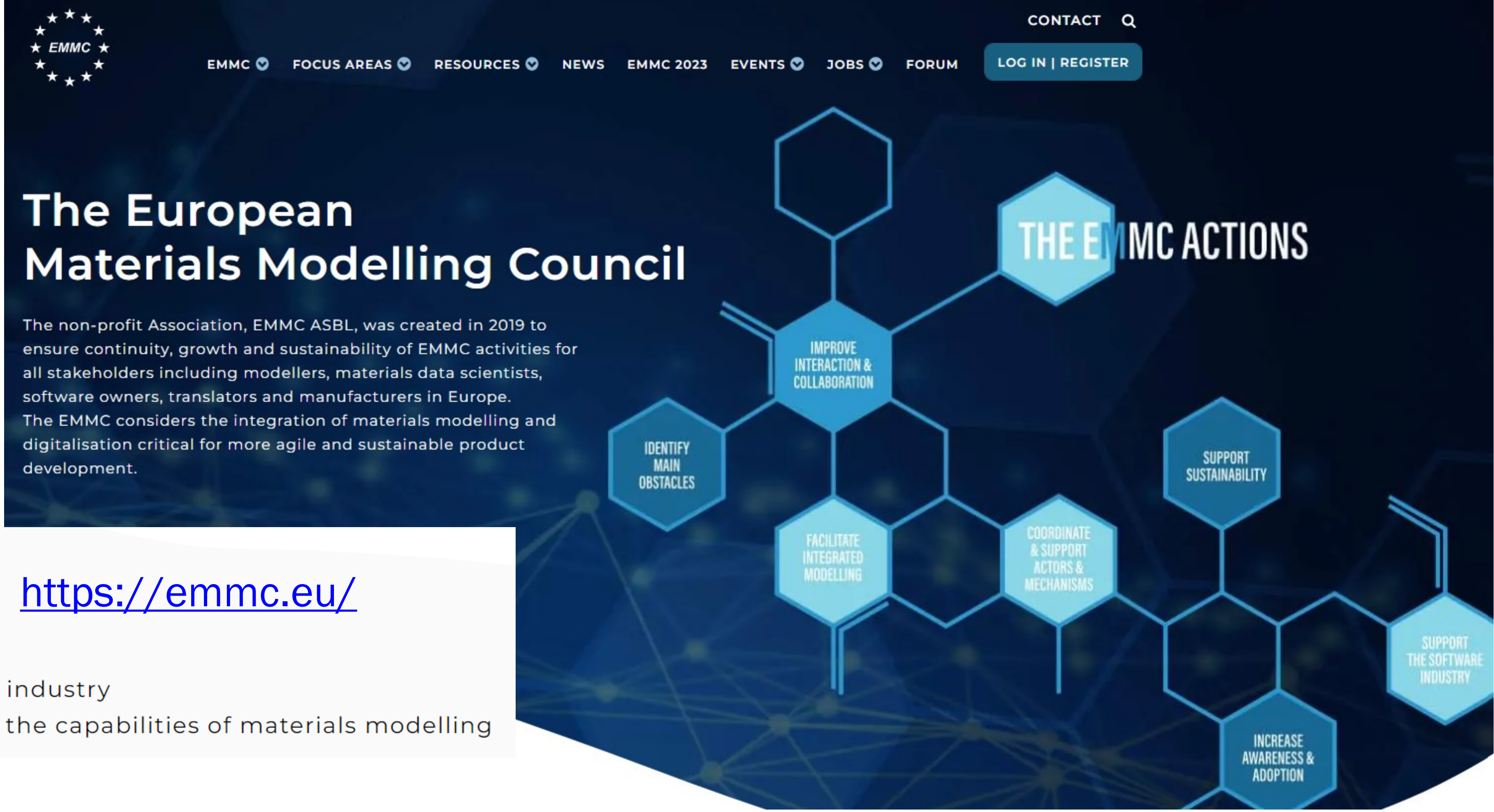
Model Development

Home | Focus Areas | Model Development

Objectives

- Promote the use of materials modelling in industry
- Promote actions and activities to enhance the capabilities of materials modelling



https://emmc.eu/

EMMC considers the integration of materials modelling & digitalisation critical for more agile and sustainable materials & product development.

New and improved materials and the use of existing materials in new applications are a key factor for the success and sustainability of European industry and society in general.

to my Father,
MSc in engineering with PhD in economics,
Sybirak - survivor of Soviet deportation to Siberia

1^0 because it is his birthday

2^0 because I find myself more & more following his footsteps

3^0 with an appeal for a sustained response
to Russia's invasion of Ukraine
to prevent Siberia happening to my grandchildren

Acknowledgements

iNEMI
International Electronics Manufacturing Initiative

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NMIs: Nate Orloff and Lucas Enright (NIST), Chiawen Lee and Chang-Sheng Chen (ITRI)

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