5G Electronics: bridging the measurements challenges

M. Olszewska-Placha, M. Celuch

QWED Sp. z o.o., Poland

Outline

- ❑ Modelling-based resonant material characterisation techniques for 5G and other emerging technologies.
- ❑ Broadband mm-wave characterisation of materials.
- ❑ iNEMI Project Tasks
- ❑ Advances in resonator-based characterisation techniques – application to project tasks.
- ❑ Conclusions & outlook.

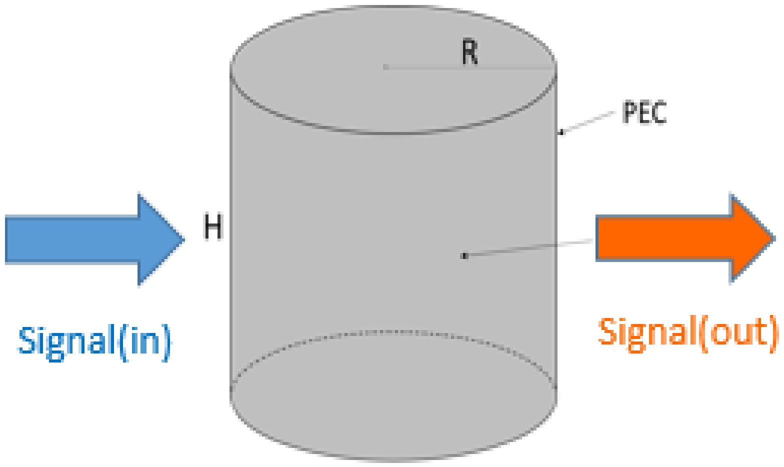
Modelling – based characterisation of materials for emerging technologies

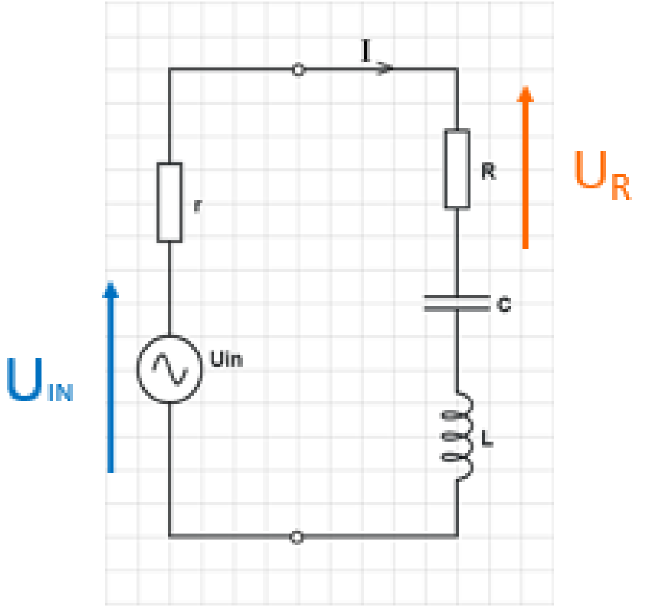
Focus on resonant methods:

- ❑ proven ultra-high acccuracy in GHz range
- ❑ dedicated to low-loss & low-resitivity materials (both, bulk and thin sheets)
- ❑ ease-of-use
- ❑ available on the market
- ❑ repeatability & reproducibility for 5G under iNEMI project studies

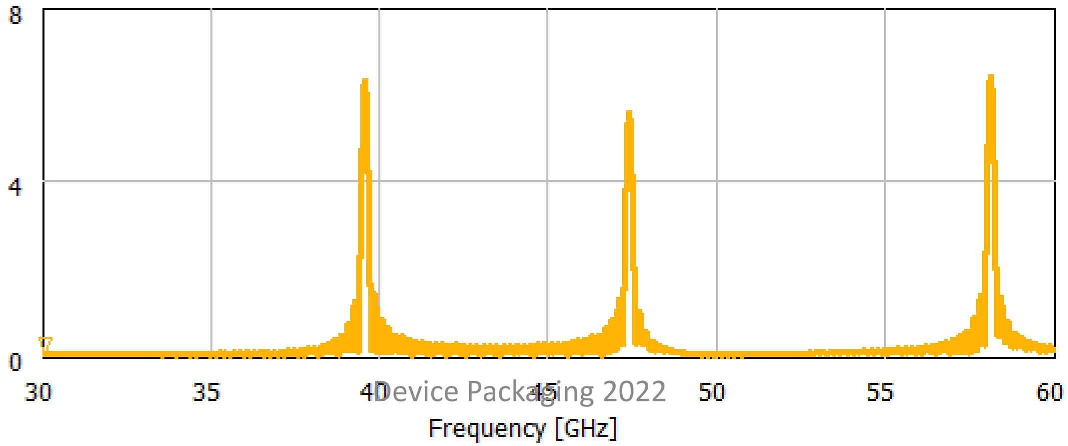
Resonator methods – motivation and background (1)

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



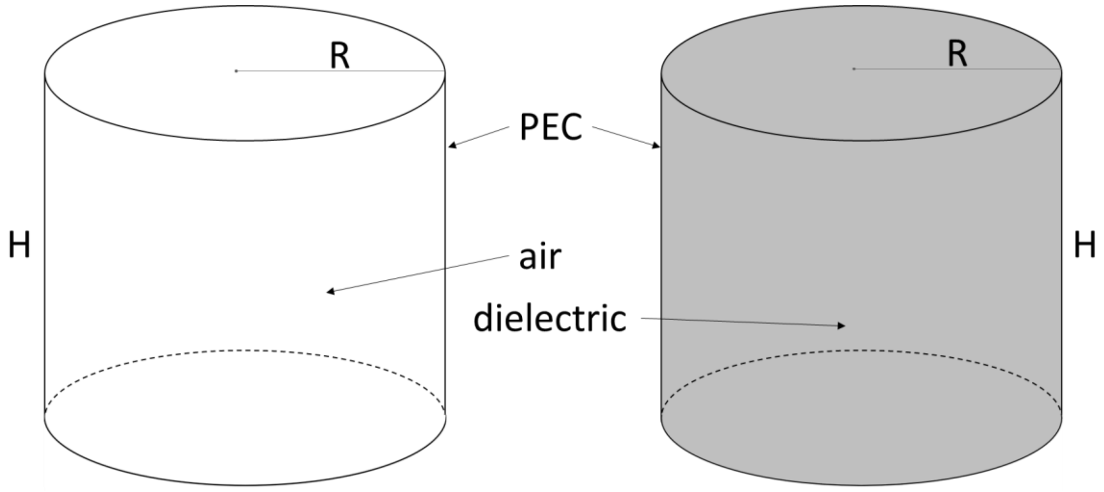


δ(t)



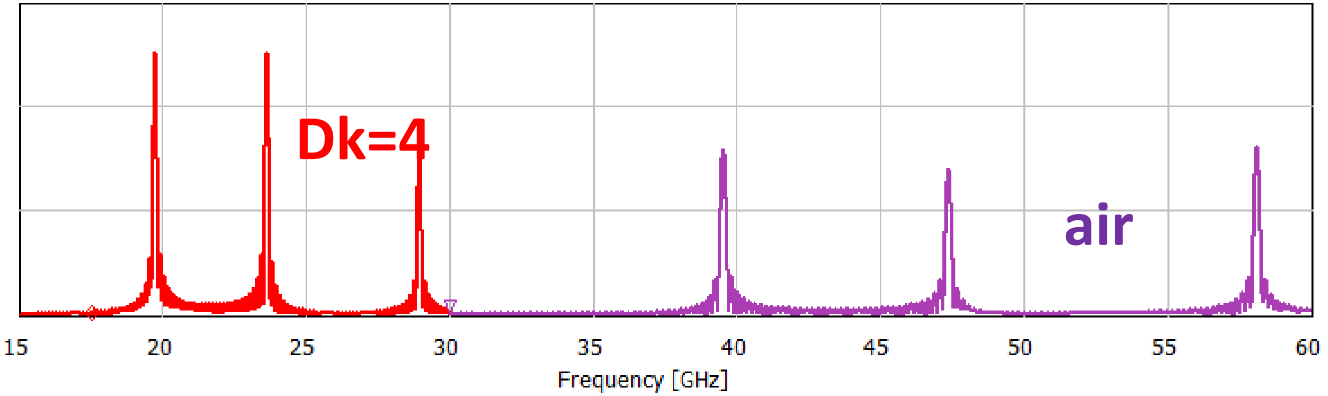
Resonator methods – motivation and background (2)

Resonance in theory: non-zero electromagnetic fields (modes) exist in isolated structures (no excitation).
Field properties are well-defined and linked to material properties.
E.g. for cylindrical cavities:

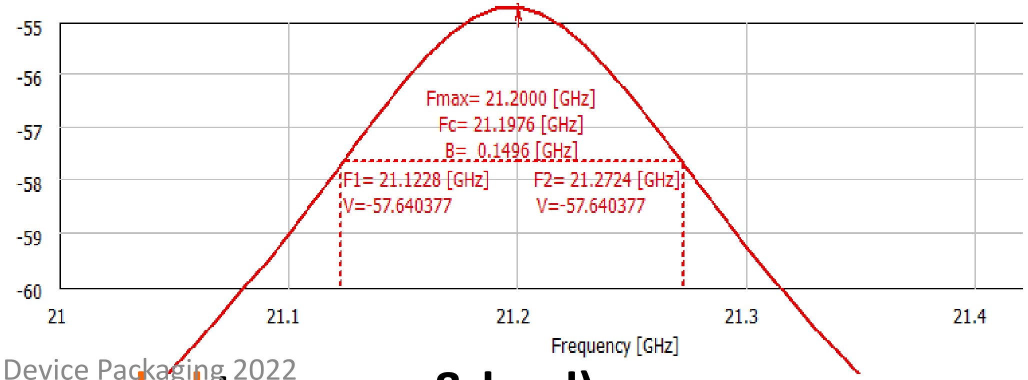


$$f_{r,mnp} = \frac{c}{\sqrt{Dk}}\sqrt{\left(\frac{\kappa_{mn}^{(,)}}{\pi R}\right)^2 + \left(\frac{p}{H}\right)^2}$$

in non-magnetic low-loss dielectrics



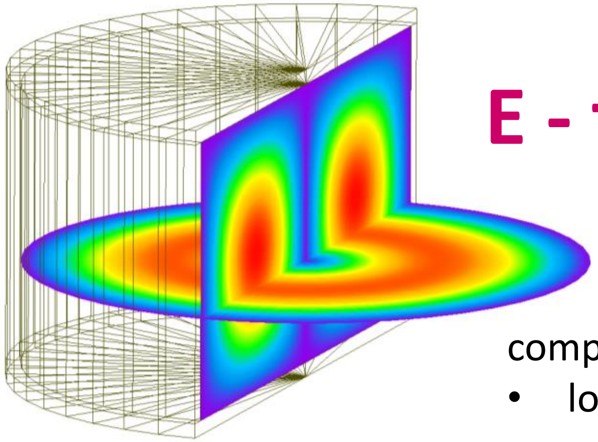
$$Q = 2\pi \frac{\iiint_V \varepsilon \vec{E}\cdot\vec{E}^* dv}{T\iiint_V \sigma \vec{E}\cdot\vec{E}^* dv} = \frac{\omega\varepsilon}{\sigma} = \frac{1}{Df} \approx \frac{fres}{\Delta f}$$



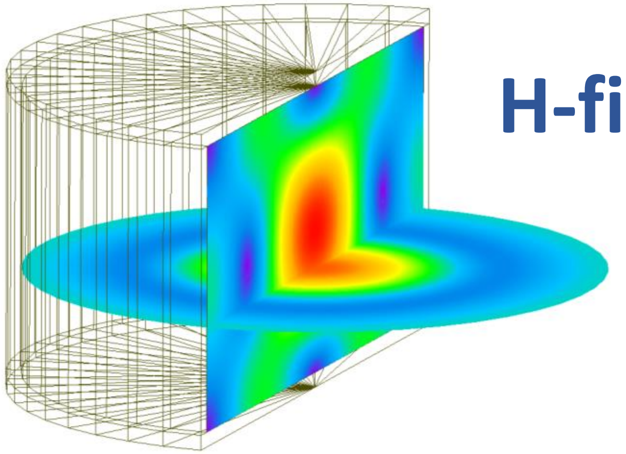
Analytical solutions are for eigenvalue problems.
Measurement problems are deterministic (cavity is coupled to source & load).

Cylindrical resonator: single-mode versus multi-mode operation

TE011 mode



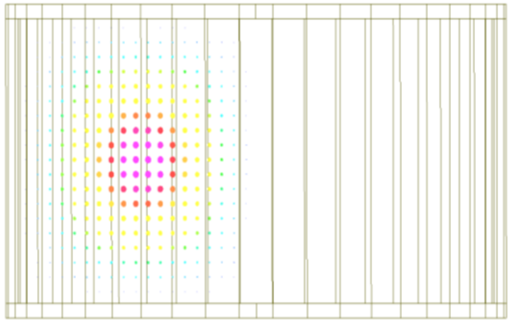
E - field

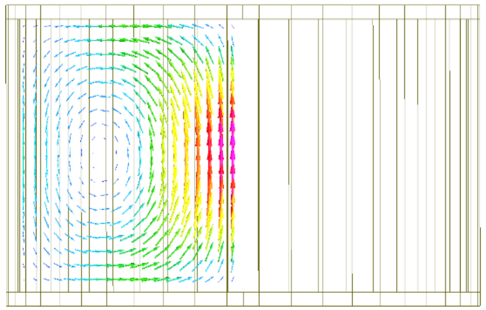


H-field

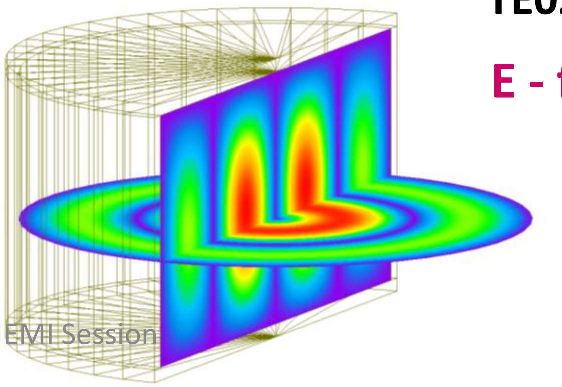
compared to rectangular (cuboidal) cavities, typically:

- lower contribution of wall losses
- easier standard manufacturing





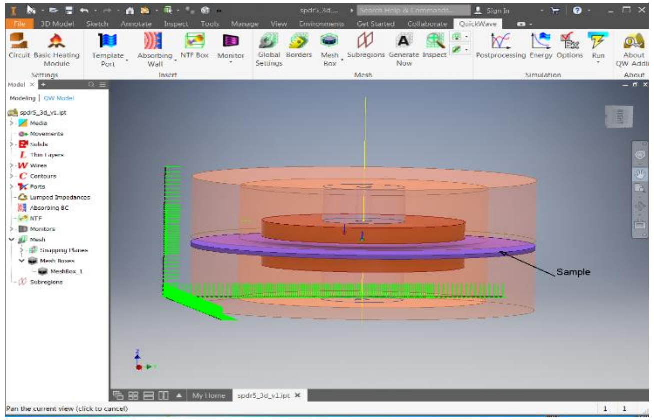
TE021 mode

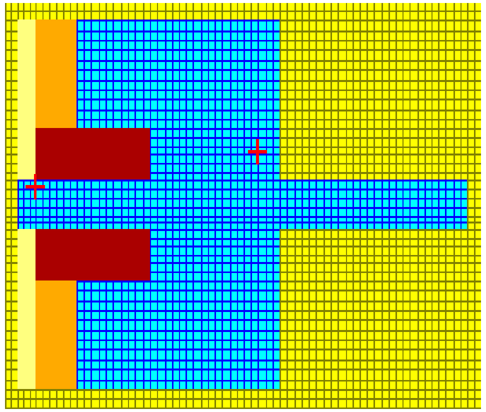


E - field

- ❑ Resonators are multimode devices hence formally, material measurement can be performed at many frequencies in the same resonator.
- ❑ Some modes provide highest accuracy of material characterization. Some are difficult to excite.
- ❑ Software provided with the resonator in compatible only with modes pre-selected by the vendor.
- ❑ Single-mode resonators: SPDR, SCR
- ❑ Multi-mode resonators: BCDR and FPOR.

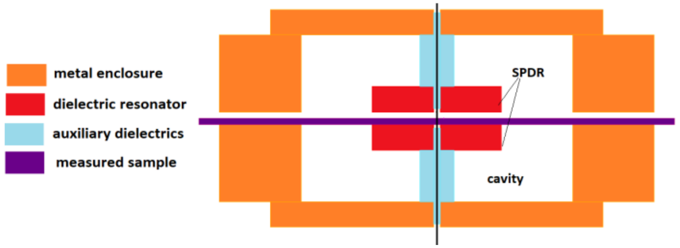
Split-Post Dielectric Resonator (SPDR) - basics





Full 3D model of 10GHz SPDR in QW-AddIn for Autodesk® Inventor® Software
(common environment for modelling & manufacturing)

Axisymmetrical 2D BOR model full EM information
economies in computer effort : 10^3 or more

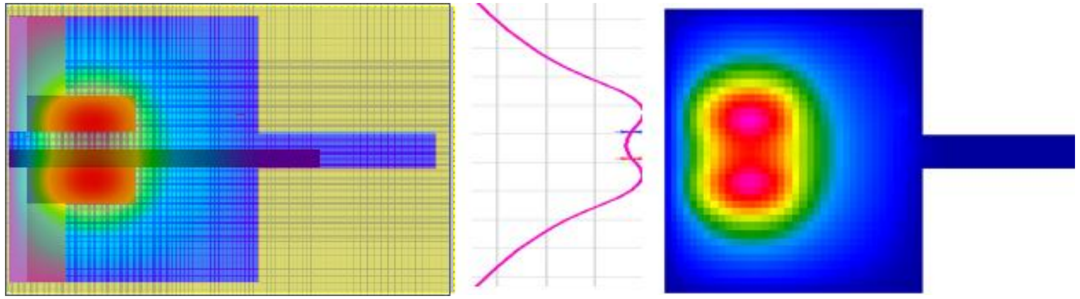


For laminar dielectrics and high-resistivity semiconductors

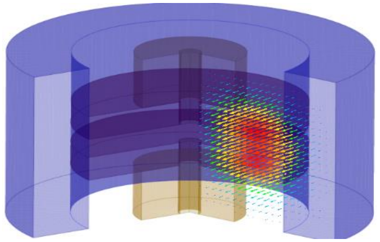
- resonant mode with EM fields mostly confined in and between those ceramic posts
- Field patterns remain practically unchanged but resonant frequencies and Q-factors change, providing information about SUT material parameters

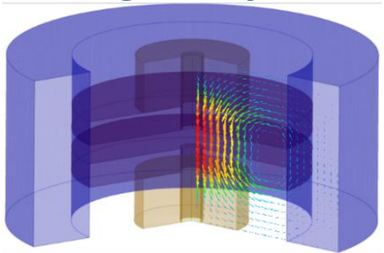
SUT of $\varepsilon_s = \varepsilon_s' - j\,\varepsilon_s''$ is inserted into DR: resonant frequency changes from f_e to f_s and Q-factor changes from Q_e to Q_s.

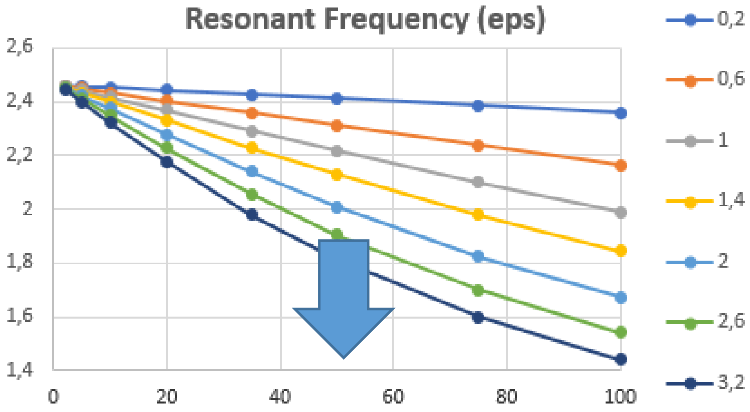
Sample in strong E-field nearly constant between the two posts



Electric field ***Magnetic field***





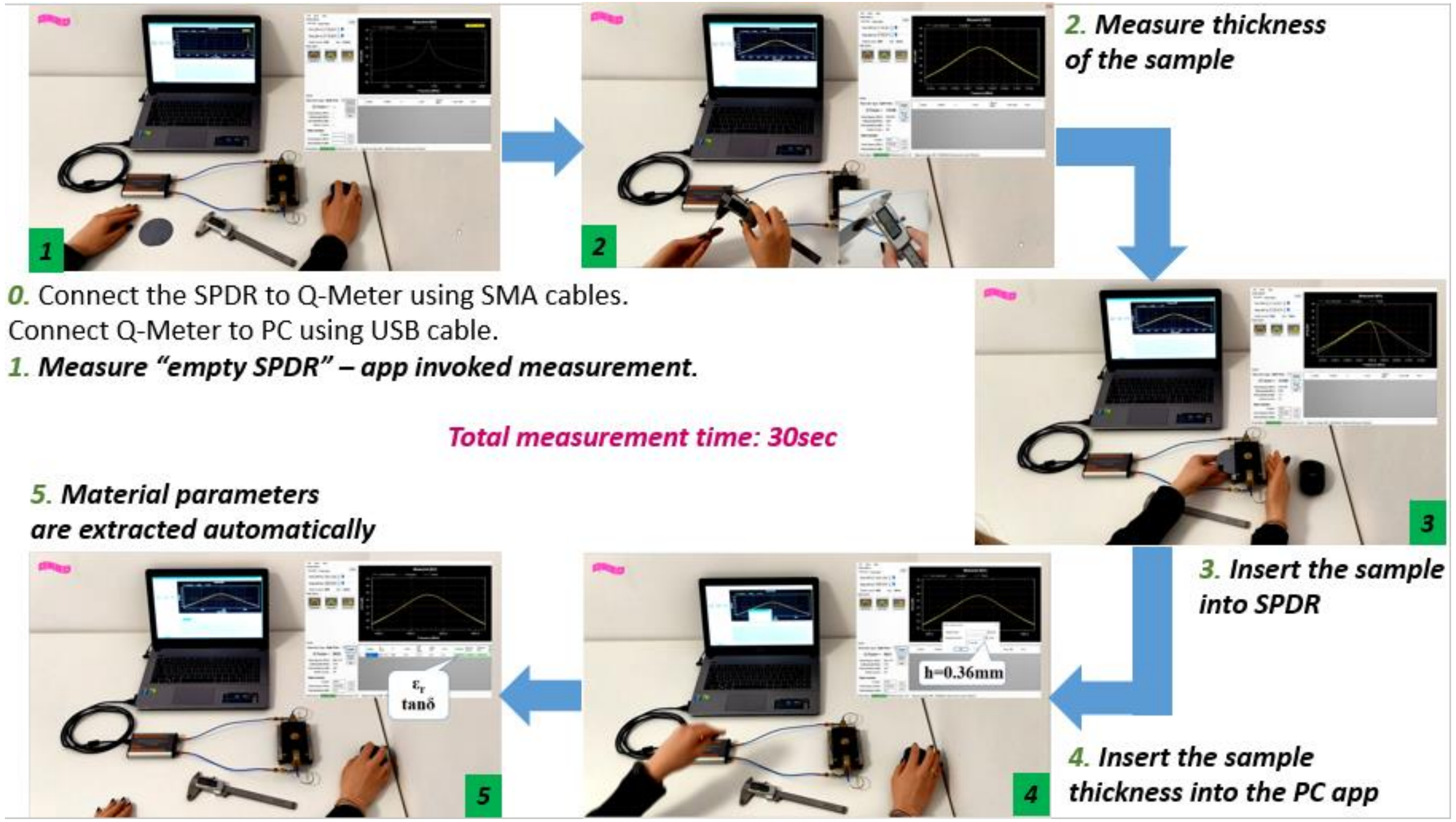


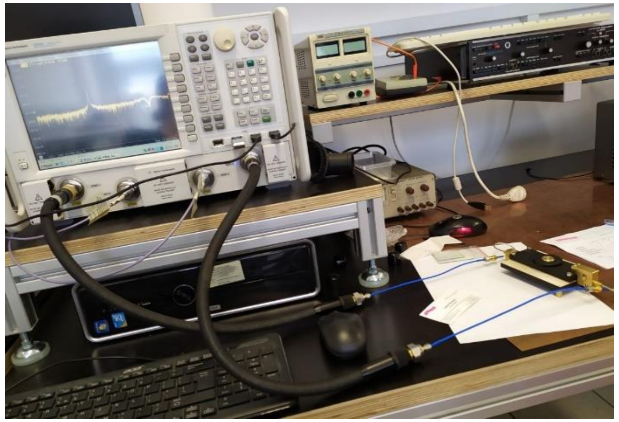
QuickWave simulations of 2.5GHz SPDR performed in automatic Parameter Sweep for varying sample thickness (colours) and dielectric constant (eps)

Data for dedicated software for material parameters extraction

Split-Post Dielectric Resonator (SPDR) – operation

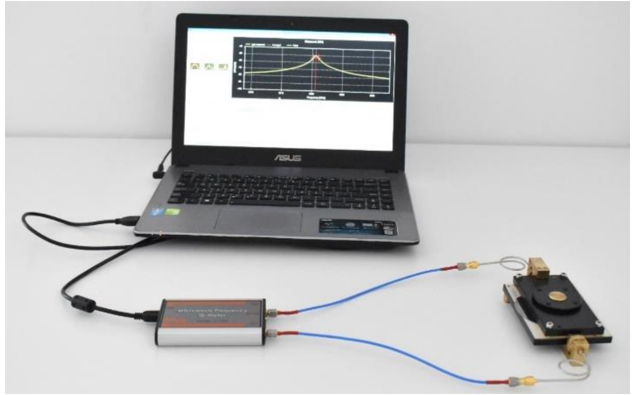
Operation workflow – with the use of Q-Meter





SPDR use in labs...

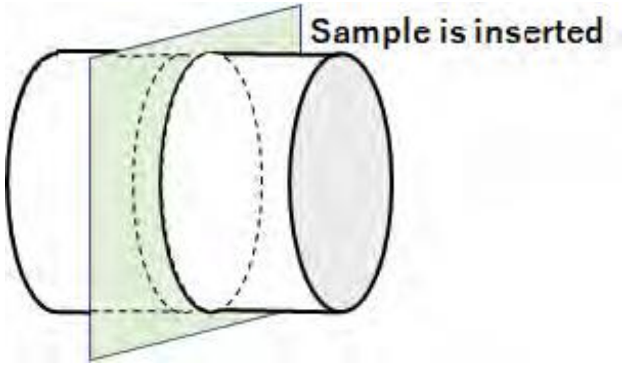
...and at home

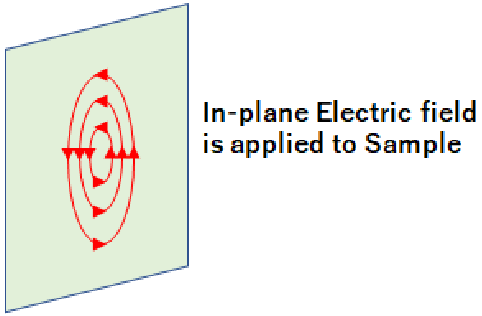


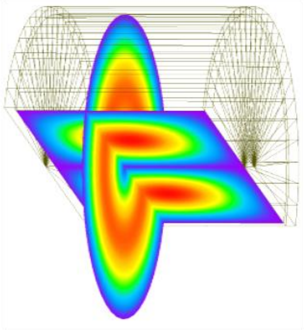
For many practical materials, measuring only abs (S21) provides appropriate accuracy.

Keysight Option N1500A uses S21 (amplitude & phase) which helps enhance accuracy (*under study in iNEMI project*).

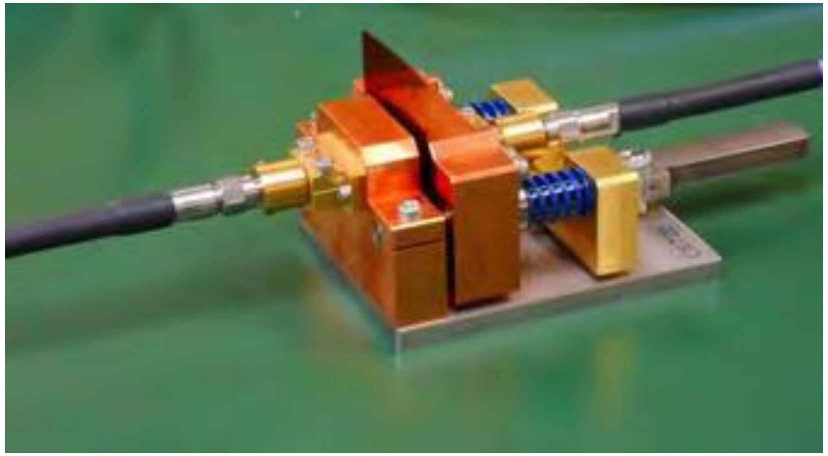
Split Cylinder Resonator (SCR) – basics & operation



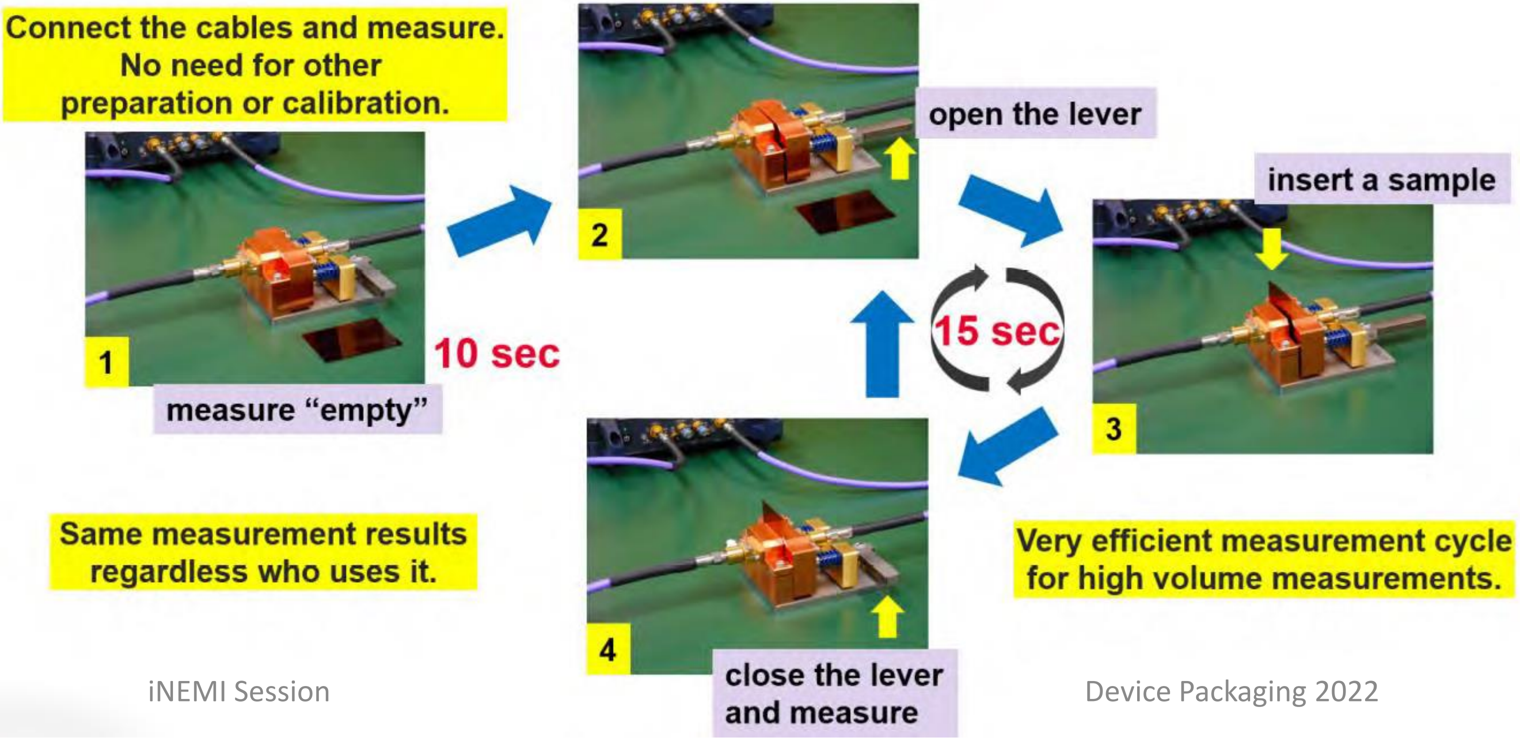




TE011 mode



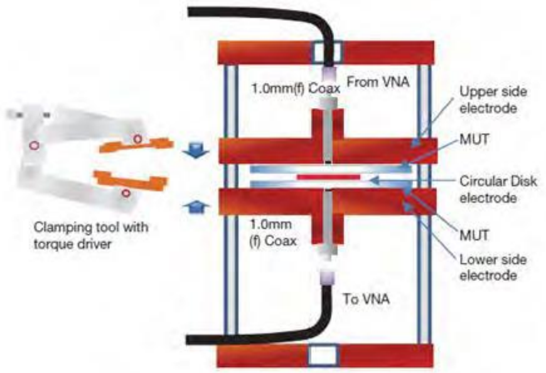
Operation workflow

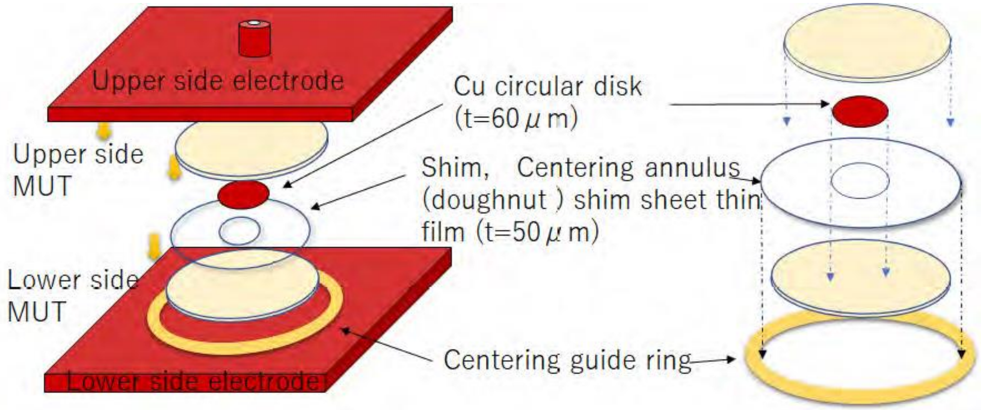


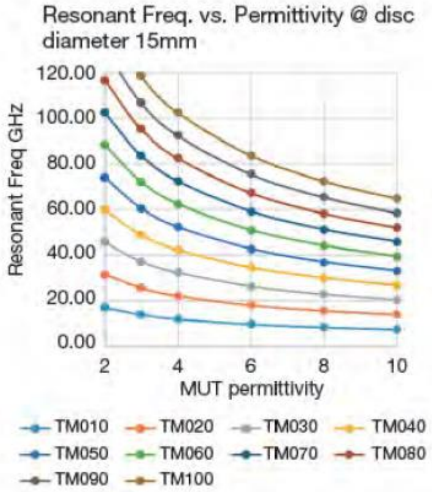
Discrete frequency points from 10 GHz up to 80 GHz

- 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

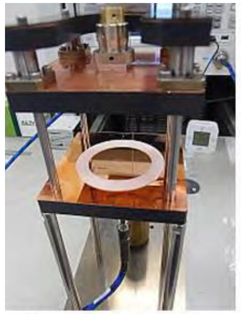
Balanced-type circular disk resonator (BCDR) – basics & operation

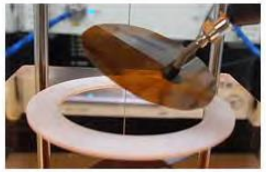


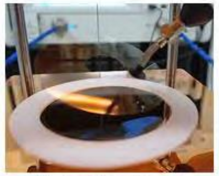


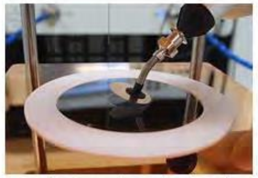


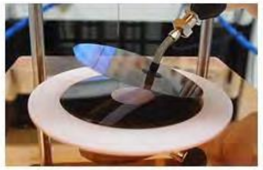
Operation workflow

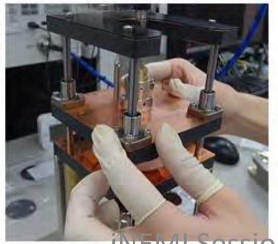

Open the resonator


Set lower side sample


Set shim sheet


Set center electrode


Set upper side sample


Close the resonator

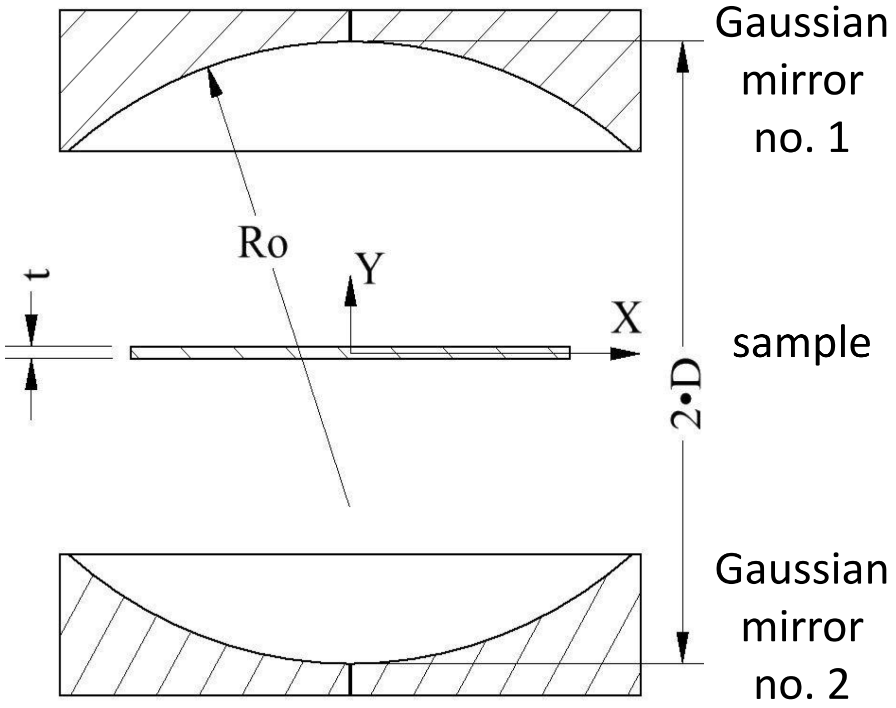

Clamp and measure

Multiple discrete frequency points from 10 GHz up to 120 GHz	• High measurement precision • Requires full 2-port calibration (mechanical to 110 GHz or electrical to 67 GHz) • Typically out-of-plane component of permittivity • Typical sample thicknesses less than 1 mm • IEC 63185 • https://www.keysight.com/us/en/assets/7120-1214/flyers/N1501AE11-67-Balanced-Type-Circular-Disk-Resonator-BCDR.pdf

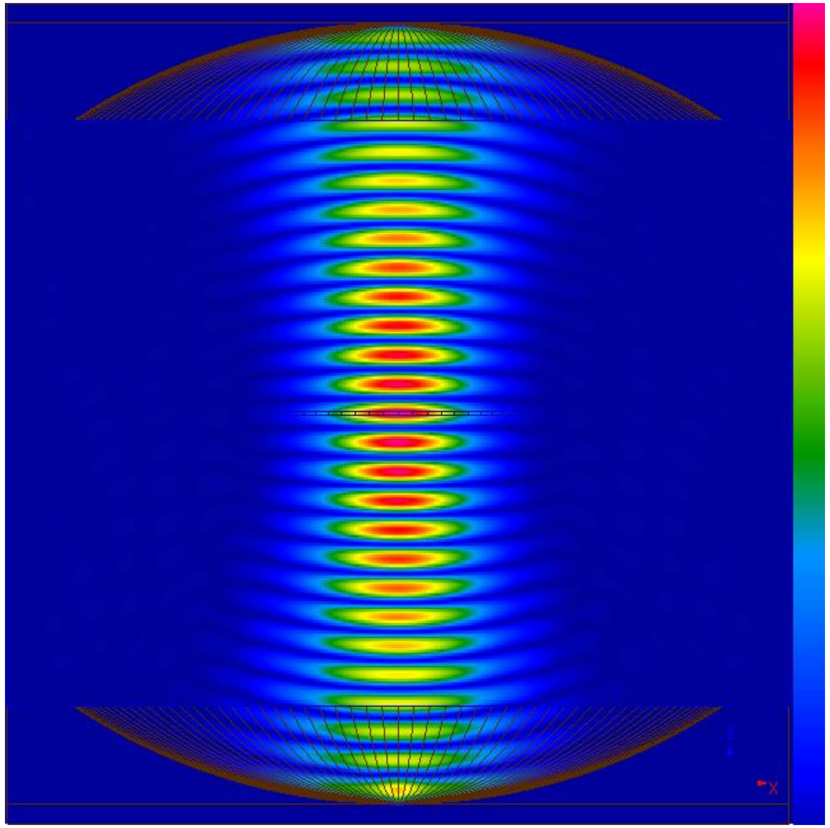
Millimetre-wave characterisation of dielectric materials

Fabry-Perot Open resonator

Bridging the gap between classical resonant methods and free space methods



*Gaussian **TEM00q** modes*



Electric field distribution - simulation model in QuickWave software

- Single device
- Spectrum: 20-110 GHz
- Frequency resolution: ca. 1.5 GHz
- Dk accuracy: $\Delta\varepsilon/\varepsilon < 0.5$ %
- Df range: $10^{-5} < \tan\delta < 10^{-2}$
- Sample diameter: > 3 inches
- Sample thickness: < 2 mm
- Fully automated measurement: (ca. 10 minutes in 20-50GHz)

Fabry-Perot Open Resonator (FPOR) – measurement concept

Measurement:

Resonant frequency and Q factor

Electromagnetic model simulation

Dielectric constant and loss tangent

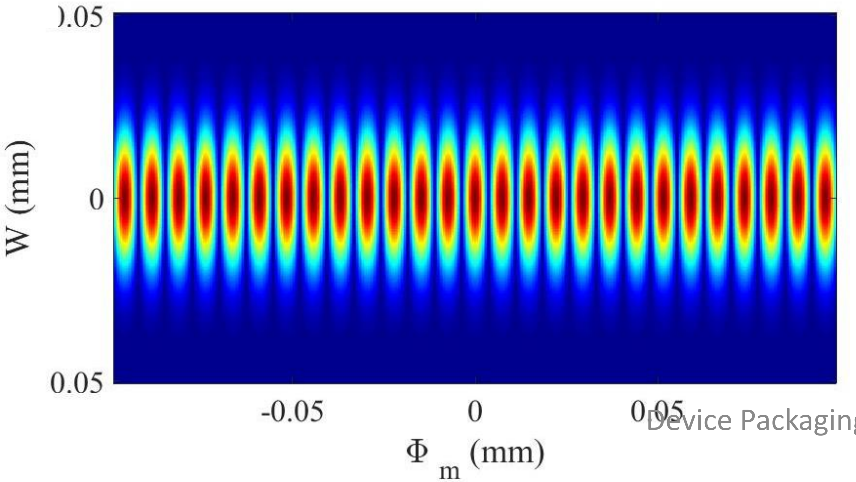
@ multiple frequencies

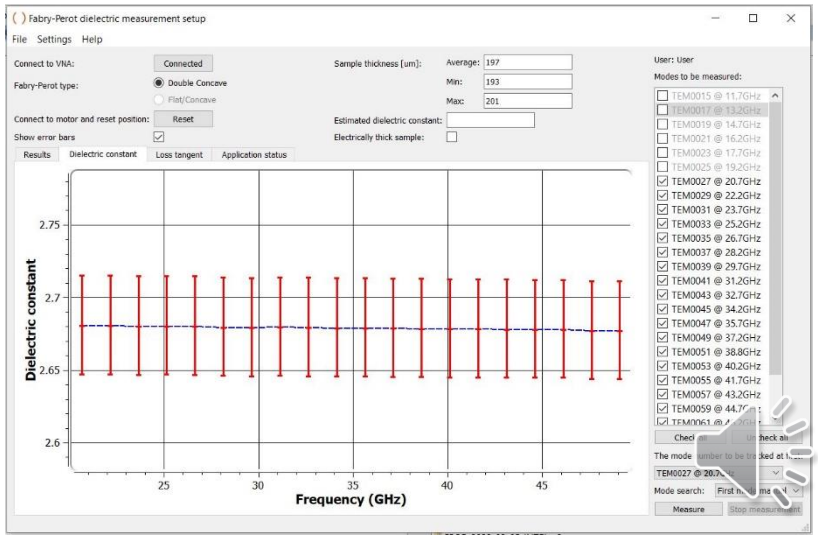
Challenges for user

- mode identification
- mode tracking among plenty of other modes occurring in the FPOR

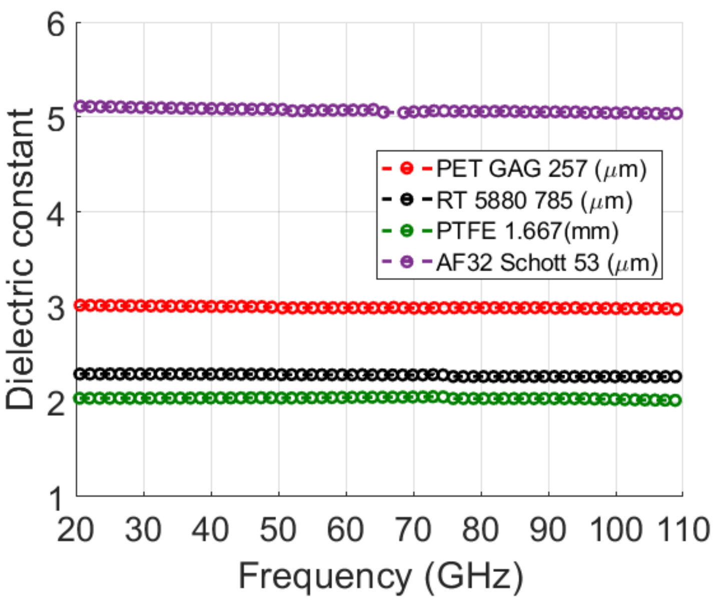
Solution

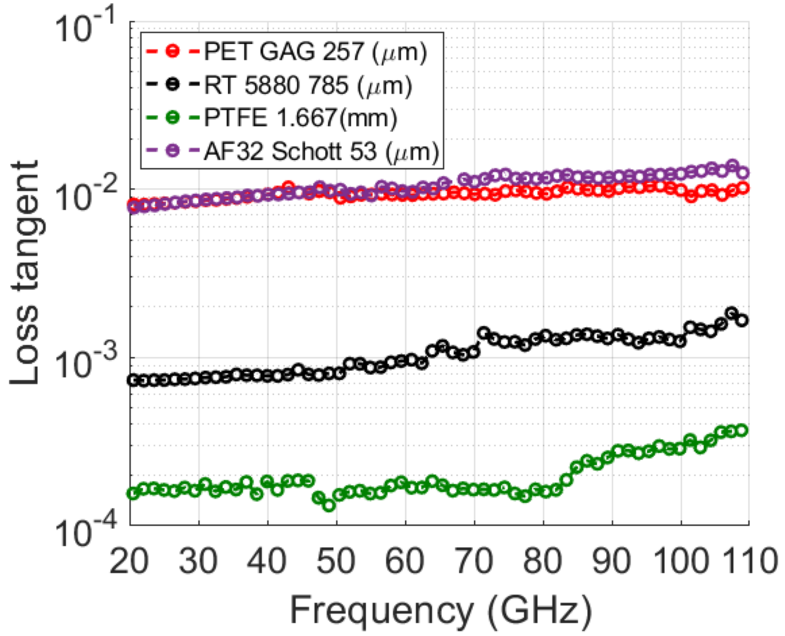
- Dedicated control software
- Automatic adaptive mode tracking algorithm
- No user intervention needed

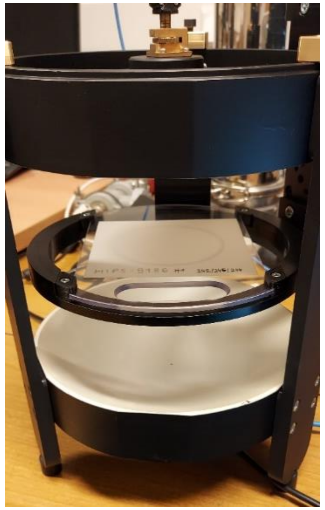




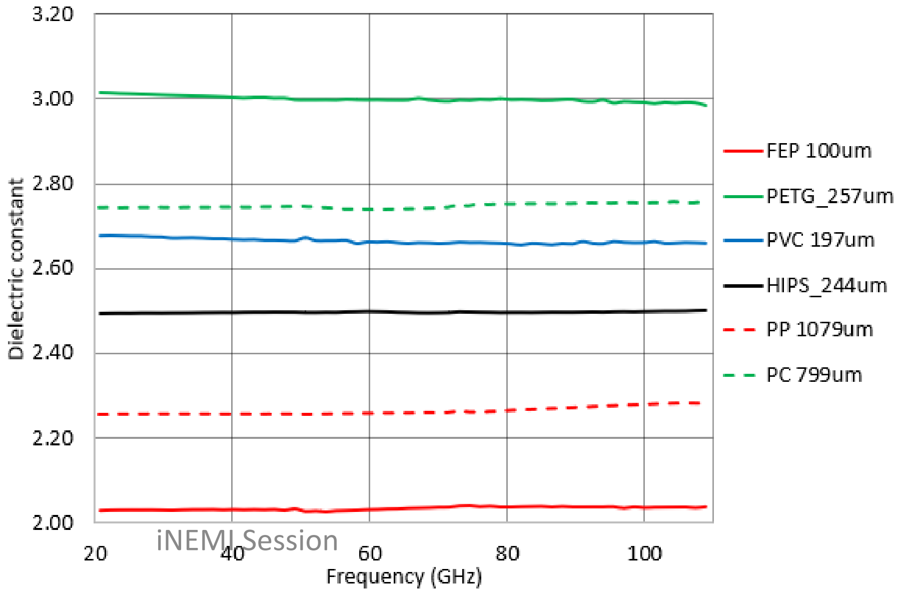
Fabry-Perot Open Resonator (FPOR) – results

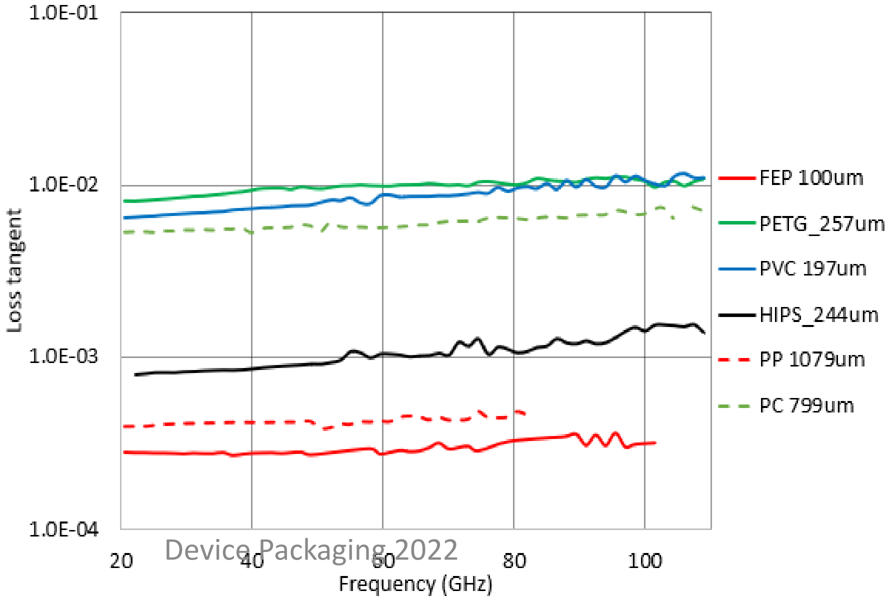


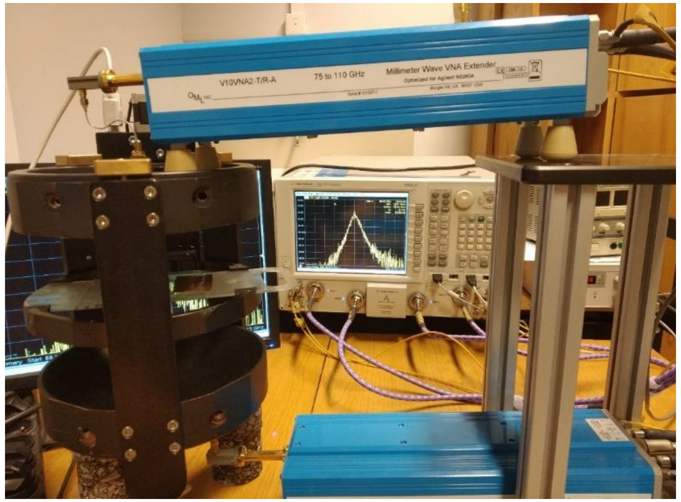




FPOR with a polystyrene (HIPS) sample placed on a sample holder





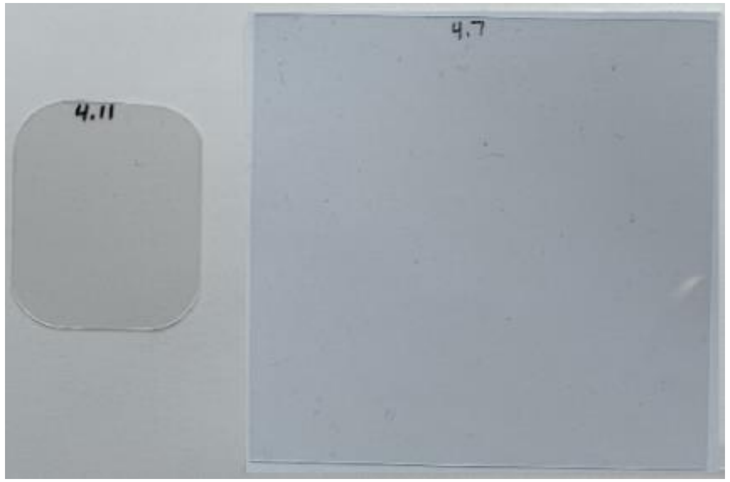


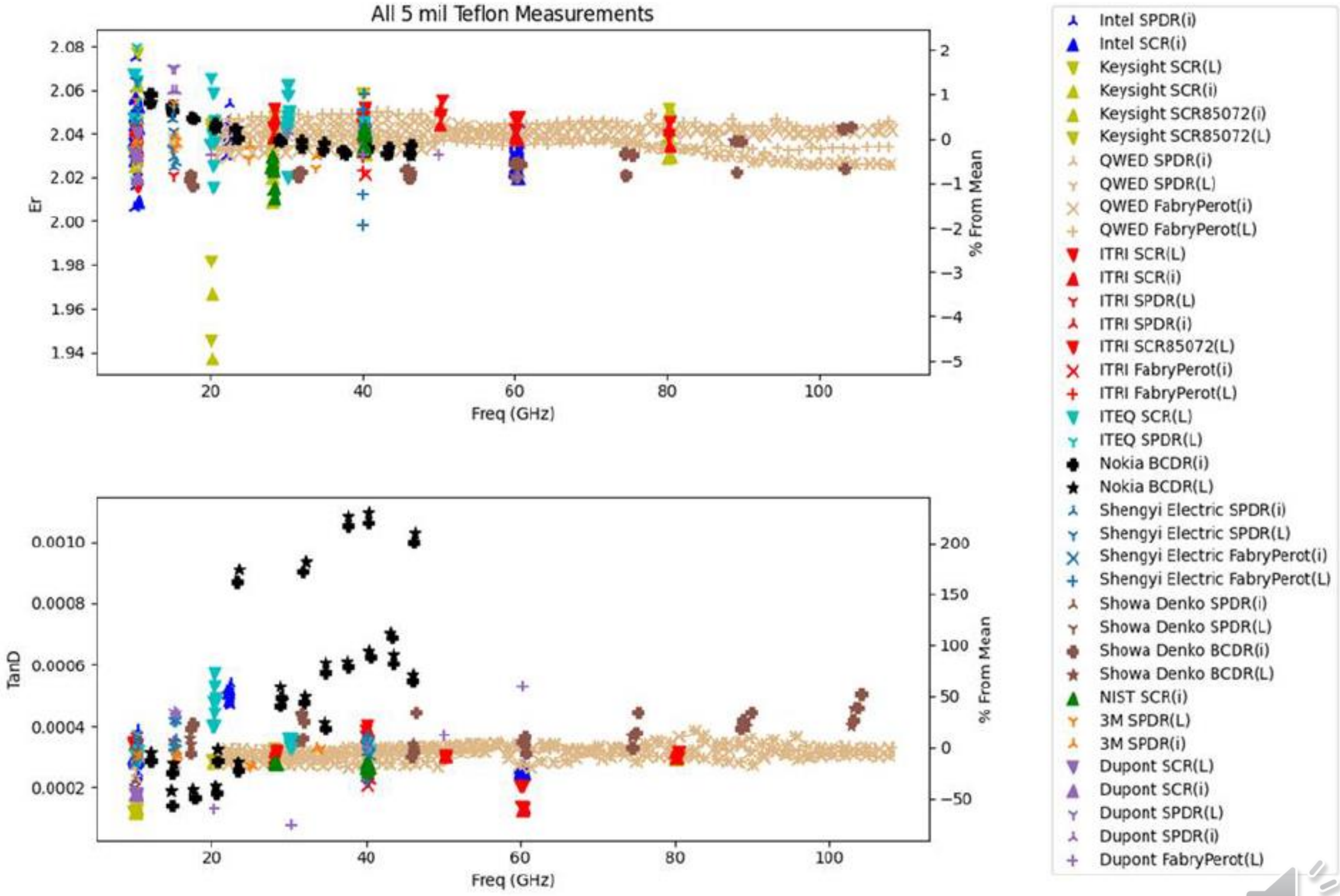
FPOR with OML frequency extenders operating in 75-110 GHz range.

5G/mmWave Materials Assessment and Characterization

Project Task3

- Benchmarking popular measurement techniques on known material samples
- 3 material types
- 12 samples (6 in each of two sizes: 35x45mm, 90x90mm)
- 10 samples kits
- 11 labs

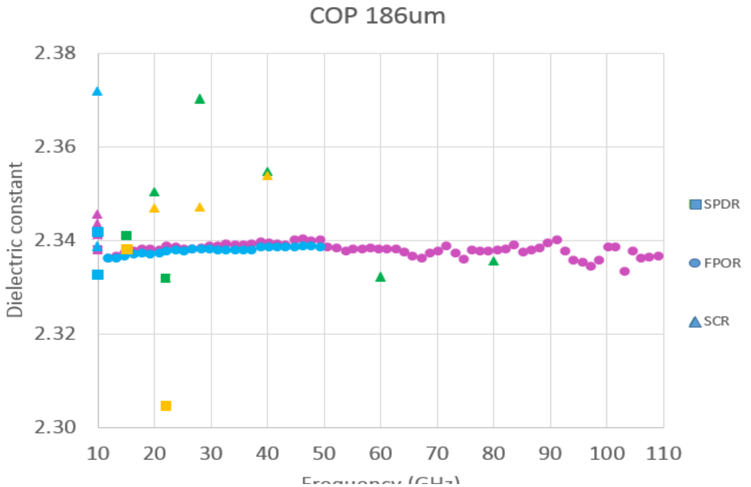


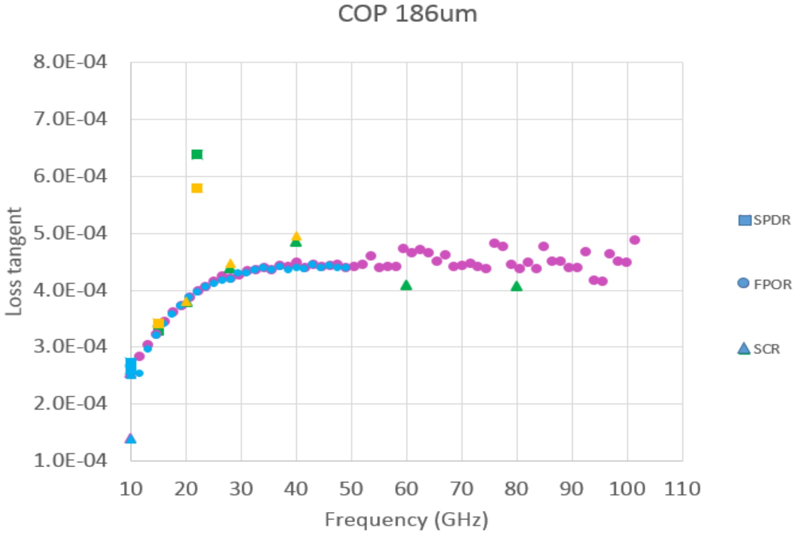


5G/mmWave Materials Assessment and Characterization

Project Task3

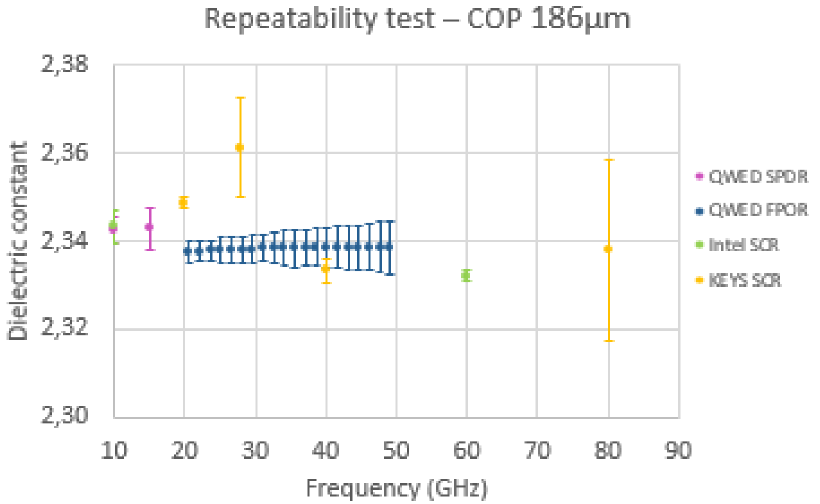
Measurements & *Repeatability and reproducibility studies*

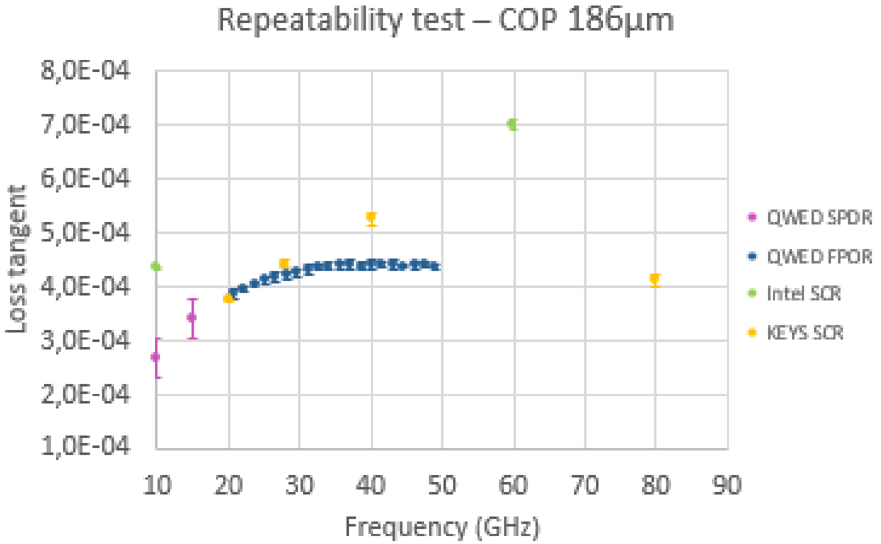




Task 3 Report

Task 4





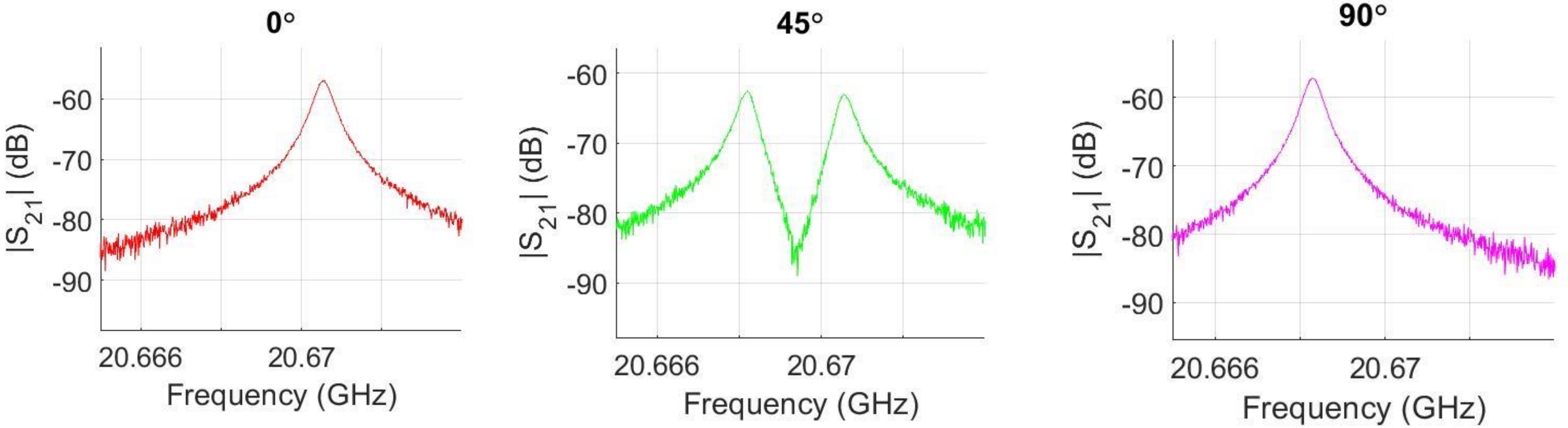
**M. Celuch et al. "Bridging the materials' permittivity traceability gap for 5G applications", IEEE Antennas & Propagation Symposium, 2021.*

Project Task4

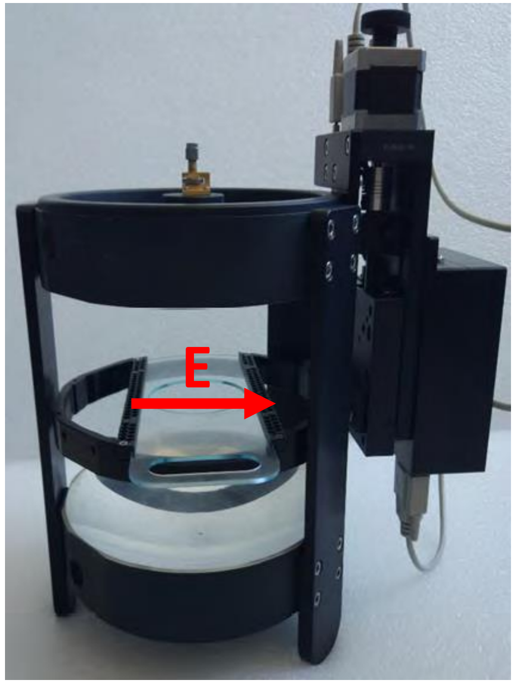
- ❑ Industry samples provided by the members of Project Consortium
- ❑ 2 types of material samples: electronic and automotive
- ❑ Challenges in handling thin samples (e.g. fused silica)
- ❑ Challenges in measuring thick automotive samples
- ❑ Over 50 samples in total
- ❑ 5 labs
- ❑ 4 measurement techniques
- ❑ In the middle of the task completion

Fabry-Perot Open Resonator (FPOR) – in-plane anisotropy

With appropriately designed feeding loops, FPOR is capable of linear E-field polarization and hence detecting in-plane anisotropy:

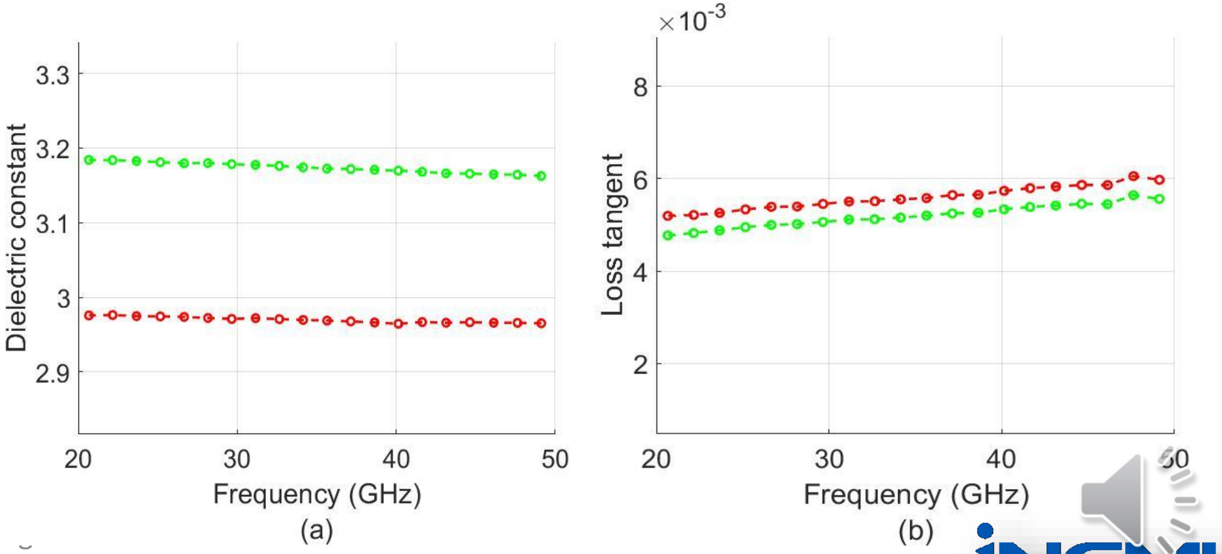


Resonances detected for BoPET sample (t = 0.100 mm), turned in xy plane.



BoPET (biaxially-oriented PET) involves thermal drawing in two in-plane directions with substantially different draw ratios, followed by crystallization. Hence, it is in-plane anisotropic.

For PETG (non-crystalline copolyesters, isotropic), resonant frequency does not depend on angular position of the sample.



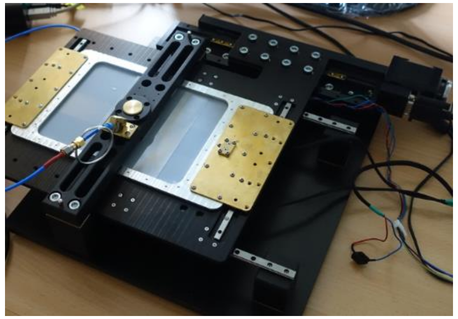
T.Karpisz et al, " Measurement of in-plane anisotropy of dielectric materials with a Fabry-Perot open resonator", Proc. MIKON 2020

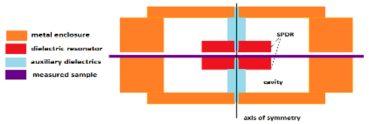
Task 4 additional activity: 2D imaging of material parameters

- 2D maps of electrical parameters: *relative permittivity* (Dk), *loss tangent* (Df), *resistivity*, or *surface resistance*
- Material homogeneity testing
- For qualitative and quantitative material testing
- Laminar dielectrics – packaging in 5G systems
- Semiconductors industry – high density packaging at a single wafer
- Battery cells materials – uniformity of electrical parameters of anodes

2D imaging of material parameters – laminar dielectrics (1)

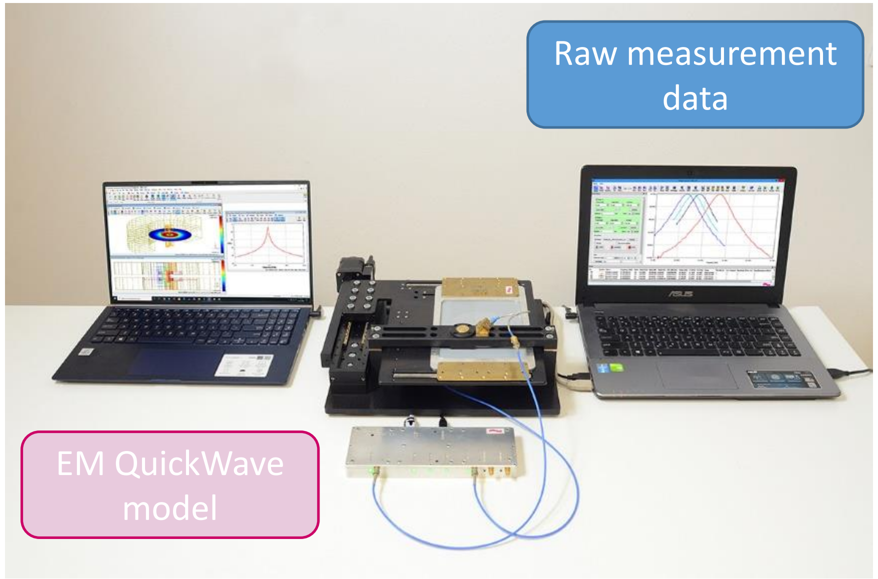
For low-loss dielectrics and high-resistivity semiconductors





- ❑ SPDR technique based 2D scanner
- ❑ Simulation model accounting for mechanical constraints, e.g. dielectric membrane serving as sample holder
- ❑ 10GHz for higher spatial resolution

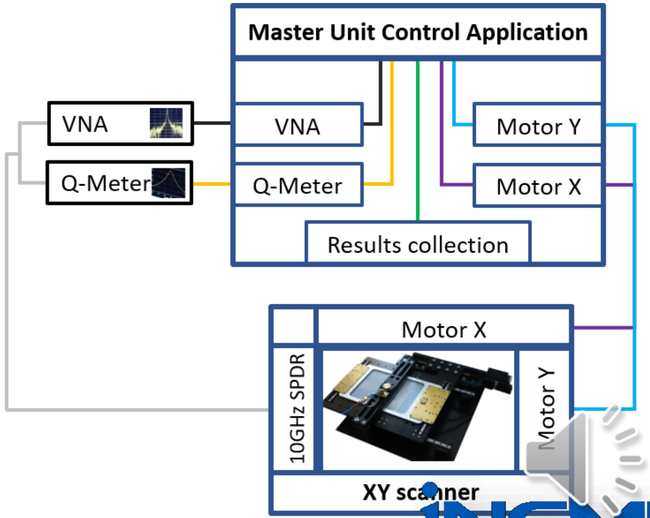
A joint product of QWED and Keysight, developed in the H2020 MMAMA project, has been acknowledged as
Innovation Radar
of the European research.



|S21| curves are for several scanning positions:

- curve max indicates resonant freq. (Dk)
- curve 3dB width indicates losses (Df)

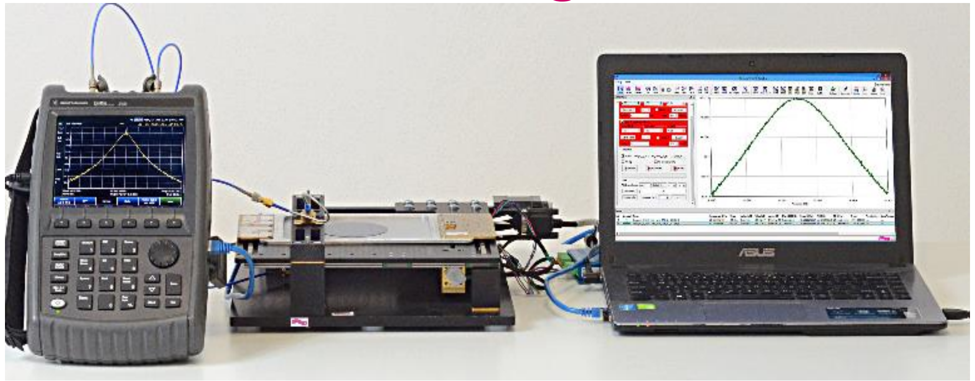
Fully automated measurement procedure through control application

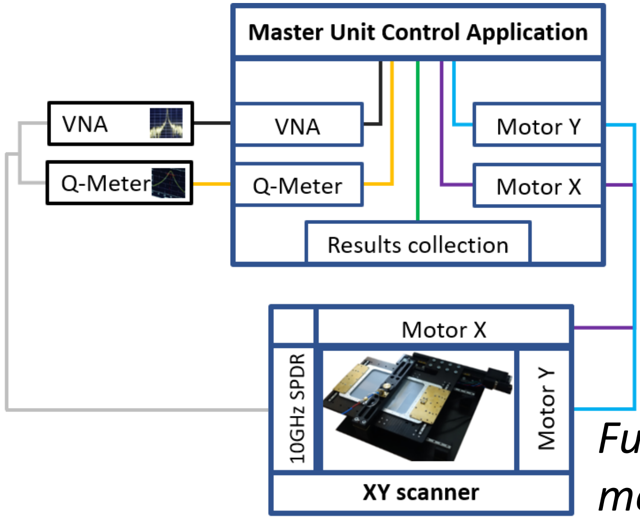


2D imaging of material parameters – laminar dielectrics (2)

For low-loss dielectrics and high-resistivity semiconductors

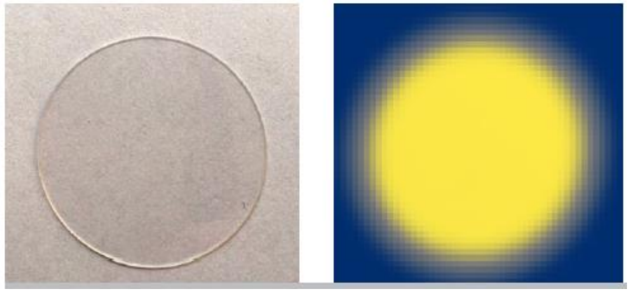
2D SPDR scanner @ 10GHz



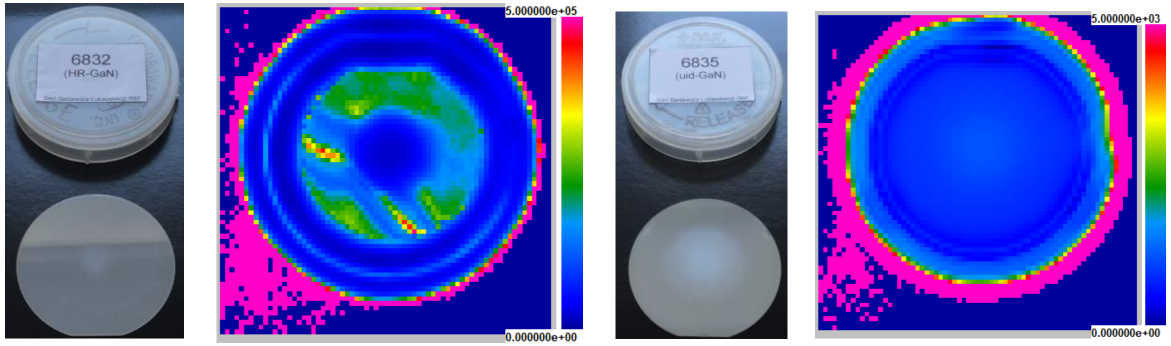


Fully automated measurement procedure

2D surface map of dielectric constant of quartz



2D surface map of resistivity of semiconductor wafers

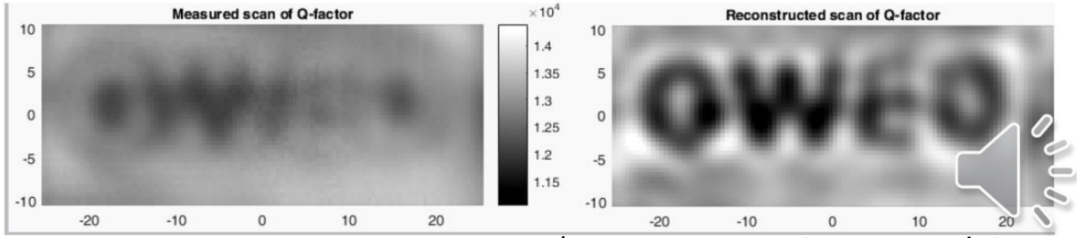


**courtesy L-IMP, Poland*

2D surface map of measured Q-factor of „QWED" pattern made of organic semiconductor deposited on quartz

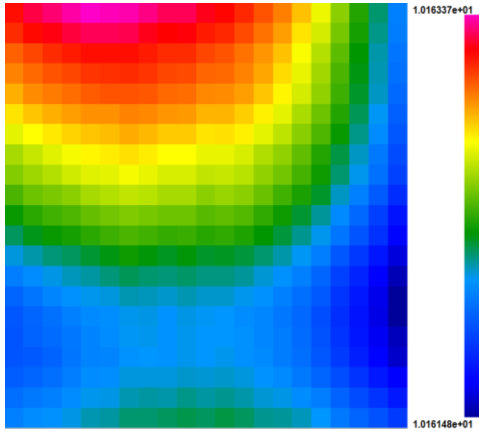
Raw data image

Data post-processed using field pattern simulated in QuickWave



**courtesy MateriaNova, Belgium*

2D imaging of material parameters – conducting materials

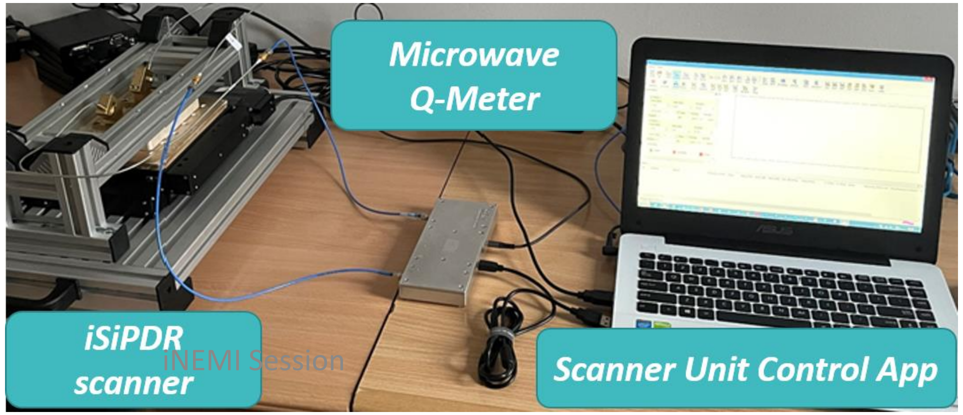


2D map of resonant frequency (in GHz) of 2D SiPDR scanner

Motorised 2D surface scanner based on SiPDR

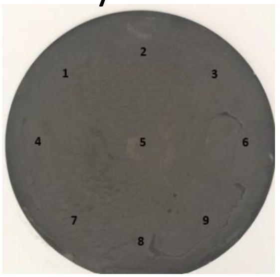
VNA
*courtesy Keysight Technologies, Austria

Scanner Unit Control App



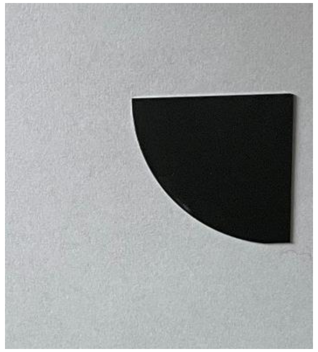
Nano Bat

Graphene –based battery anode



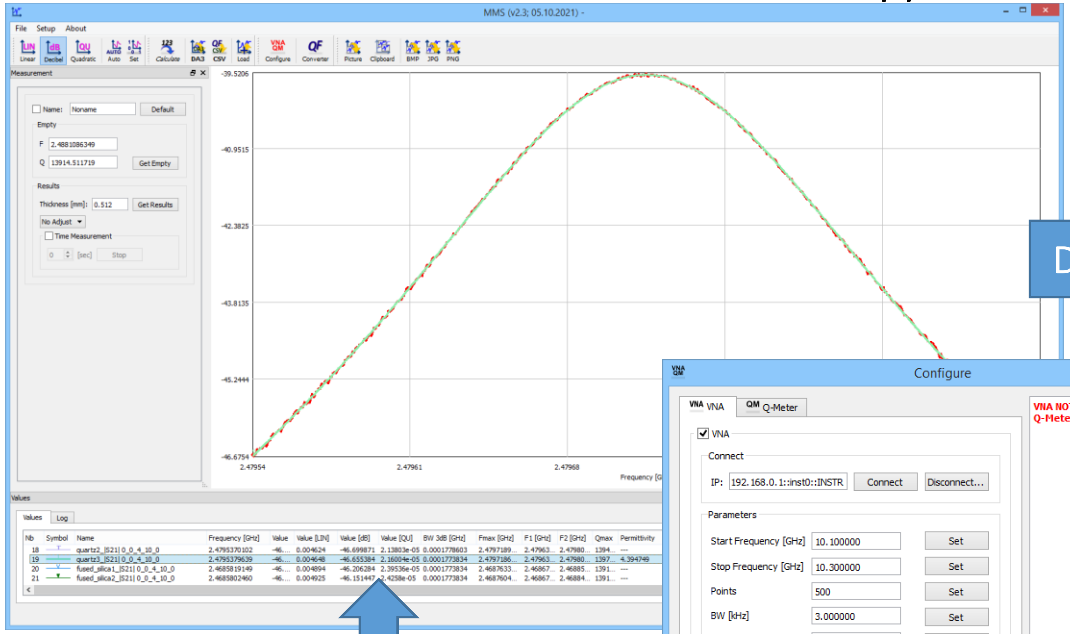
*courtesy PLEIONE Energy, Greece

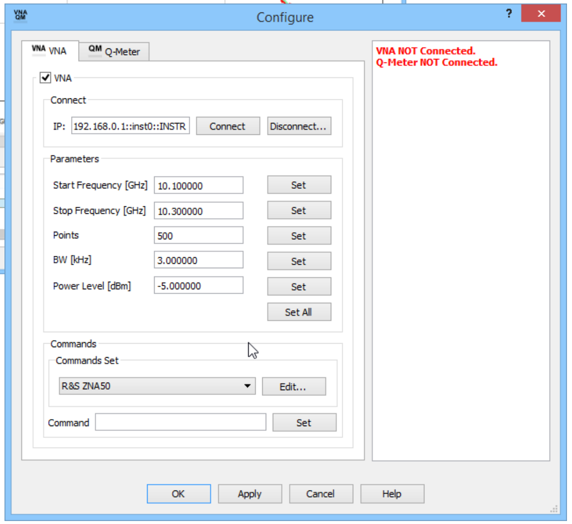
Semiconductor sample and its 2D resistivity map

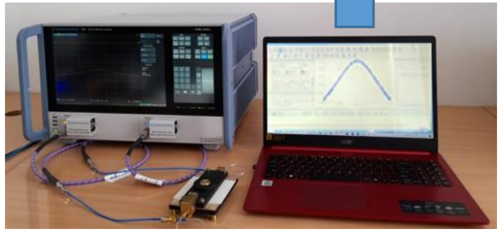


Dedicated measurement control software

SPDR & SiPDR measurement control app

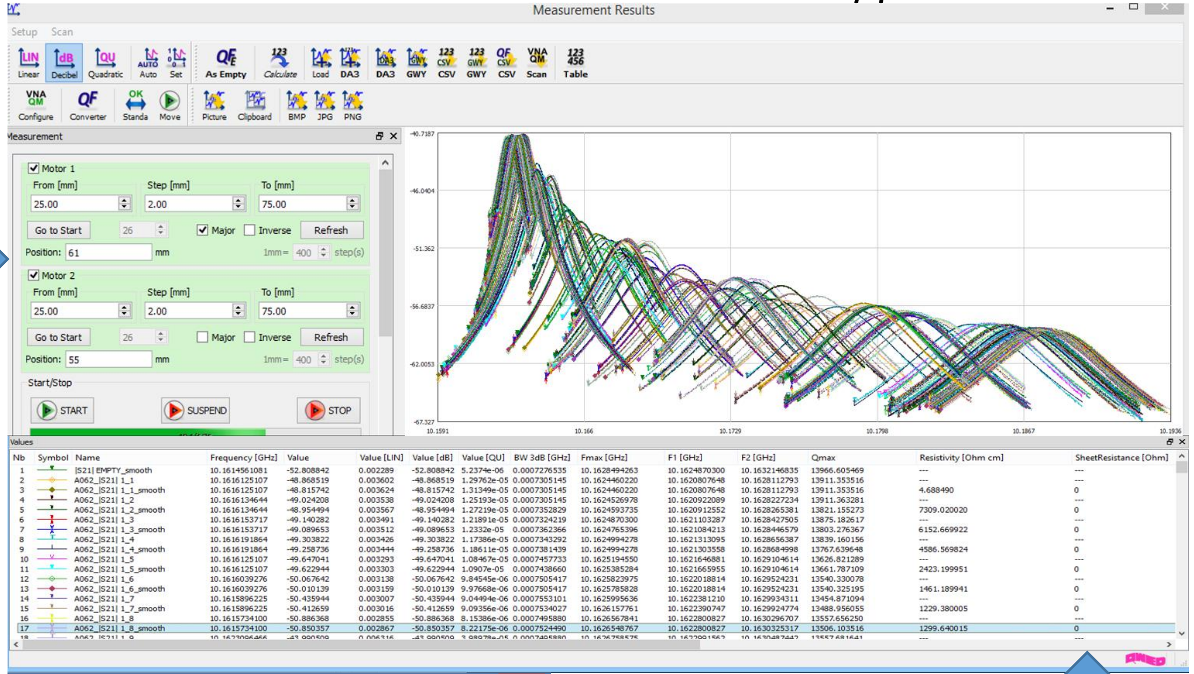


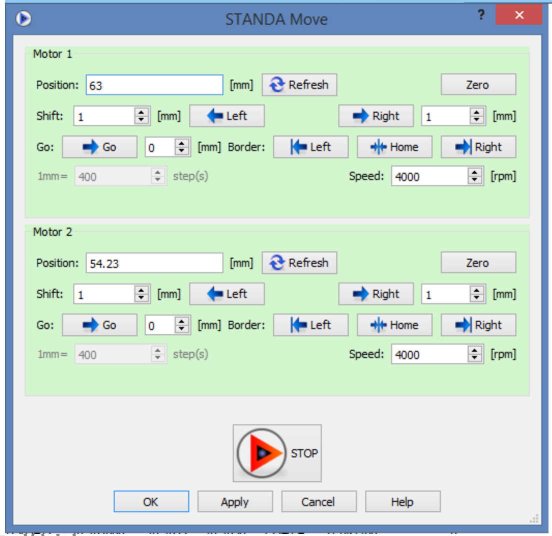




Development

Scanner Unit Control app





- ✓ Fully automated measurement procedure
- ✓ VNA/Q-Meter configuration, communication & control
- ✓ Built-in procedure for enhanced accuracy of Q-factor extraction
- ✓ Material parameters extraction
- ✓ Visualisation of measured material parameters values
- ✓ Import/export options

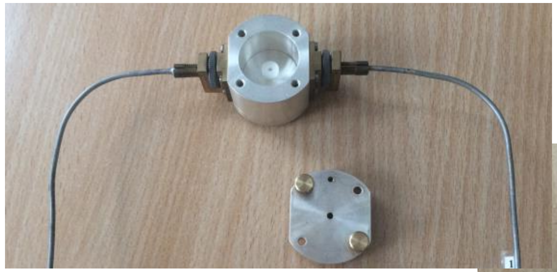
- ✓ Configuration and control of the motors and XY- translation table
- ✓ Export of scan results to *.csv and industrial *.gwy formats

Ultra-Low Temperature Co-fired Ceramics for 6th Generation Electronic Packaging

ULTCC6G_EPac« M-ERA-NET Joint Project Ref CEA : X40955

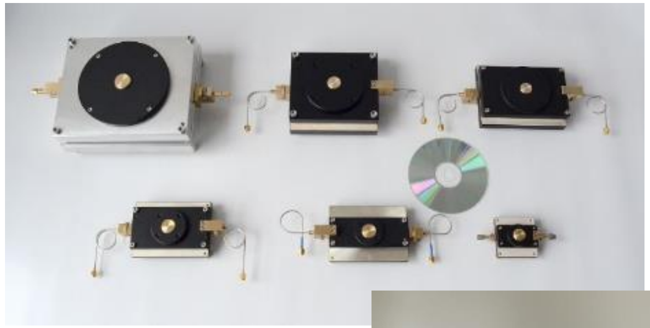
M-ERA.NET Fraunhofer IKTS leti ceatech TECHNOLOGY RESEARCH INSTITUTE inoveos HYPERFREQUENCES EN PUISSANCE QWED Łukasiewicz IMiF

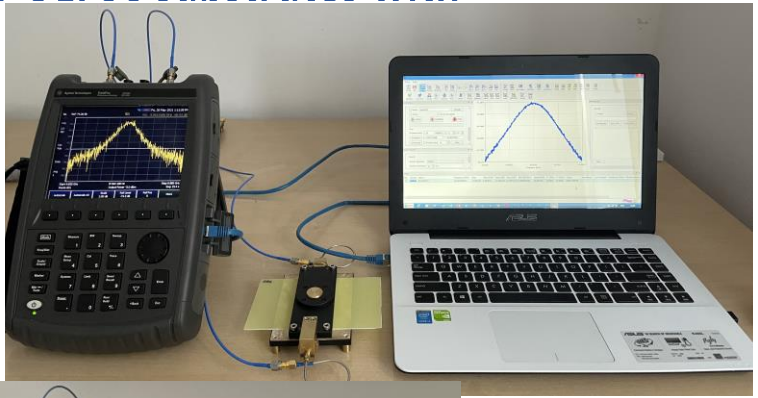
Measurements of bulk ULTCC composites

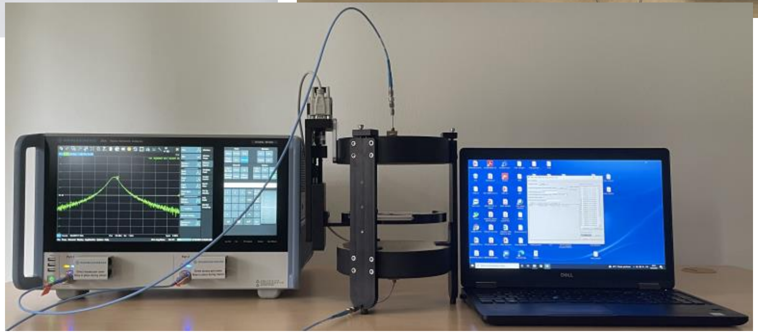


TE01delta cavity with a sample

Measurements of multilayer ULTCC substrates with SPDR and FPOR techniques







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NCBR

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(website: www.nanobat.eu)

Simulations conducted with QuickWave EM software, developed & commercialised by QWED.

The original designs of QWED resonators for material measurements from Prof. Jerzy Krupka, e.g.:

J. Krupka, A. P. Gregory, O. C. Rochard, R. N. Clarke, B. Riddle, and J. Baker-Jarvis, "Uncertainty of complex permittivity measurements by split-post dielectric resonator technique", *J. Eur. Ceramic Soc.*, vol. 21, pp. 2673-2676, 2001.

J. Krupka and J. Mazierska, "Contactless measurements of resistivity of semiconductor wafers employing single-post and split-post dielectric-resonator techniques," *IEEE Trans. Instr. Meas.*, vol. 56, no. 5, pp. 1839-1844, Oct. 2007.

THANK YOU!