WMH-4

Emerging applications of microwave resonators to energy- and biobased-materials under extended temperature and humidity ranges

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Emerging applications of microwave resonators

Emerging applications

- Materials testing for 5G and beyond
  - Dielectric substrates
  - Conductor foils and pastes
- Light and power electronics
- Electronic and food liquids
- Energy materials

5G materials testing – where to start?

- New material for mmWave 5G applications - careful consideration to determine best measurement methodology, fixture, sample fabrication and test instrument
- Dozens of different methodologies - which to choose is often not obvious.

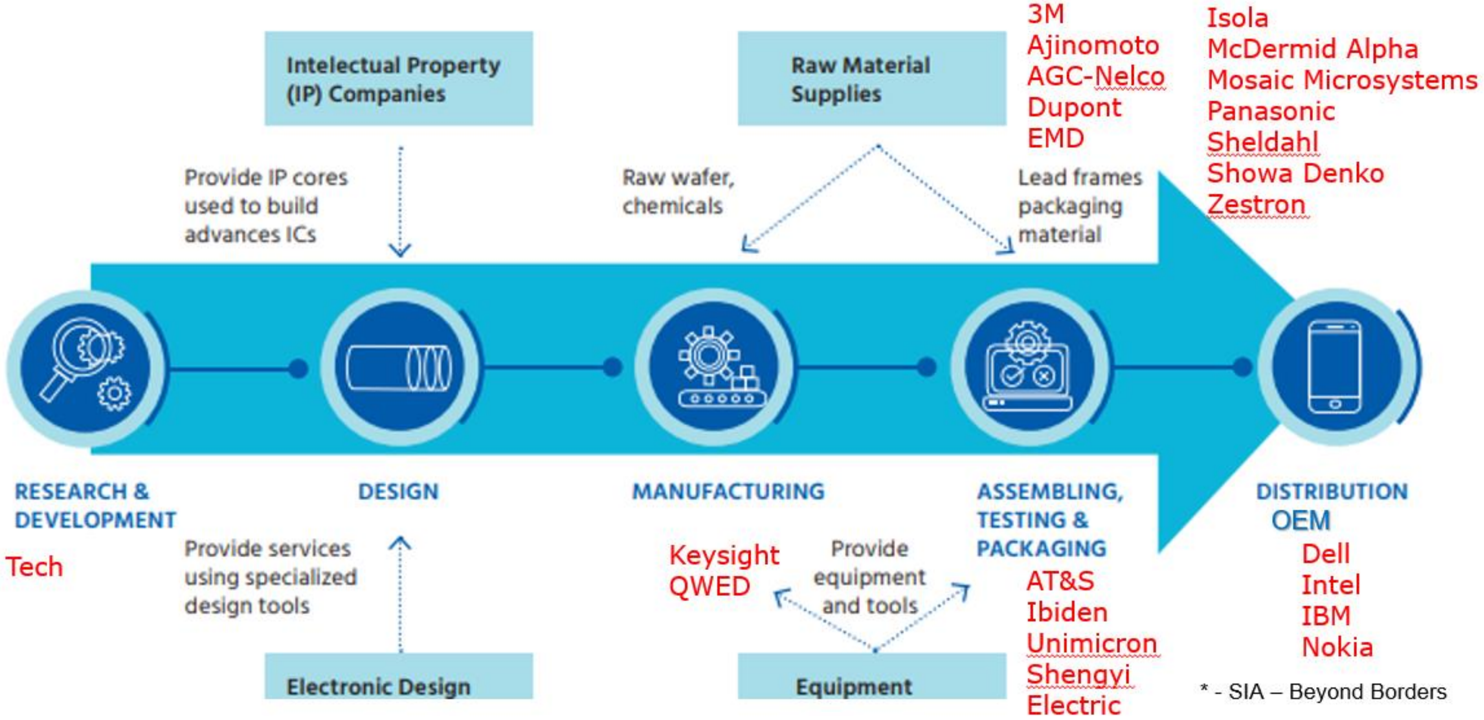
- International initiatives e.g. *International Electronics Manufacturing Initiative (iNEMI)*
- Associating standardization institutes, electronic industry, equipment vendors, materials producers, etc.
- Benchmarking existing materials characterisation methods
- Applicability for emerging 5G and 6G technologies
- Investigation of repeatability and reproducibility
- Known and industrial materials

iNEMI 5G Project Members

Project Team

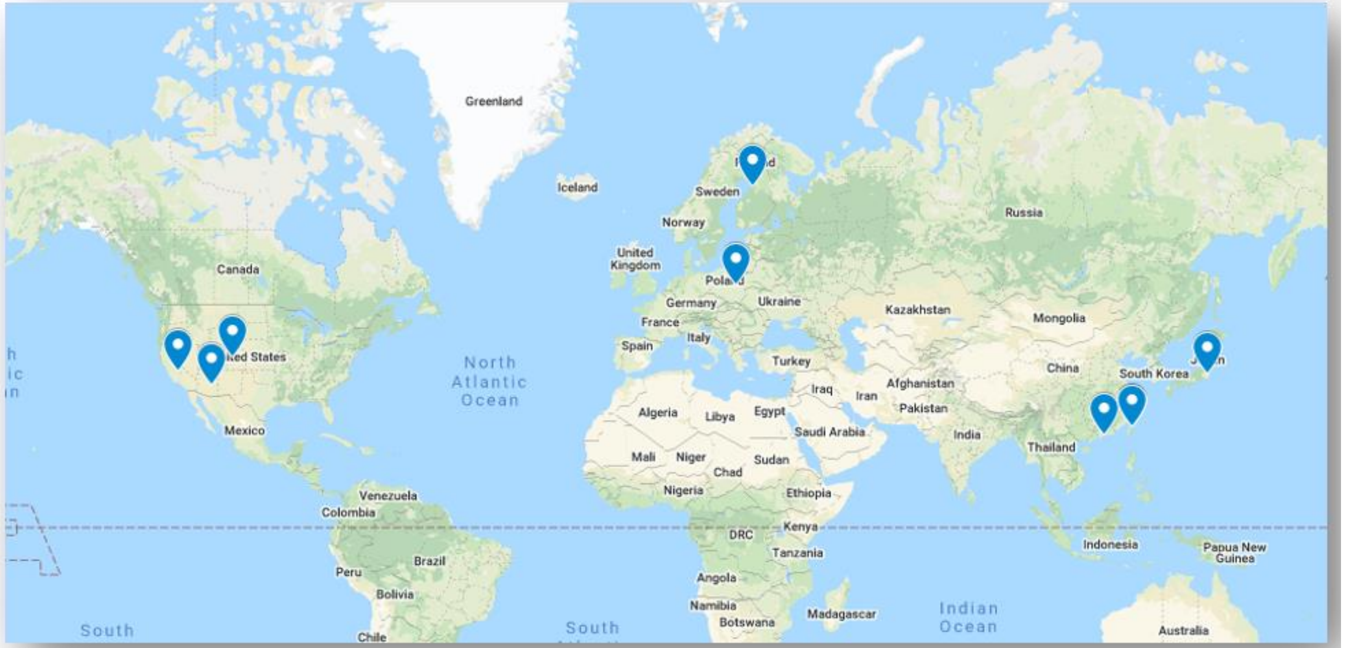
- 3M
- AGC-Nelco
- Ajinomoto USA
- AT&S
- Centro Ricerche FIAT-FCA
- Dell
- Dupont
- EMD Electronics (Co-Chair)
- Flex
- Georgia Tech
- Showa Denko Materials
- IBIDEN Co Ltd
- IBM
- Intel
- Isola
- ITRI (Co-Chair)
- Keysight (Co-Chair)
- MacDermid-Alpha
- Mosaic Microsystems
- NIST
- Nokia
- Panasonic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

iNEMI 5G Project Team –
Spanning across Supply Chain



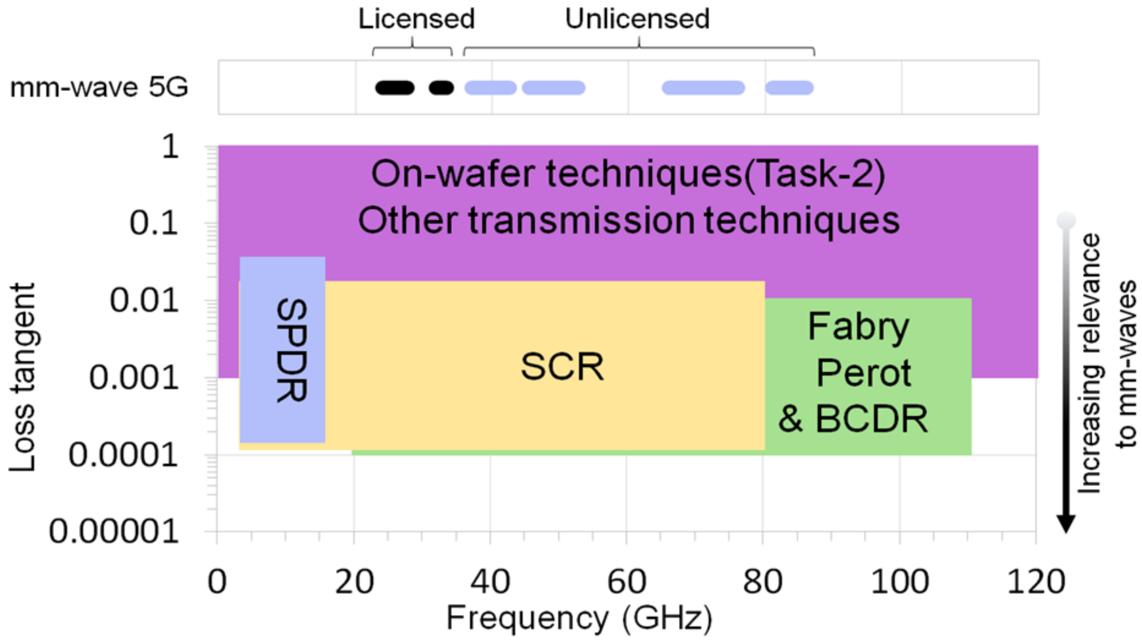
* - SIA – Beyond Borders

iNEMI 5G Project Working Group



3M, USA	**Keysight,** USA
Dupont, USA	**Nokia,** Finland
Intel, USA	**NIS,**: USA
ITEQ, Taiwan	**Showa-Denko,** Japan
ITRI, Taiwan	**Shengyi Electric,** China
QWED, Poland	

Map of available techniques vs Frequency

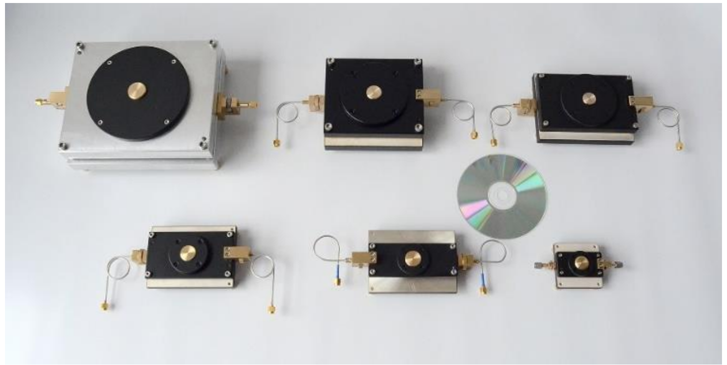


Benchmarking activities

INEMI *5G/mmWave Materials Assessment and Characterization* project results

- Four resonant methods:
  - SPDR, SCR, BCDR, FPOR
- 3 material types
- 12 samples (6 in each of two sizes)
-
- 10 samples kits
- 11 labs
- Following common thickness acquisition procedure

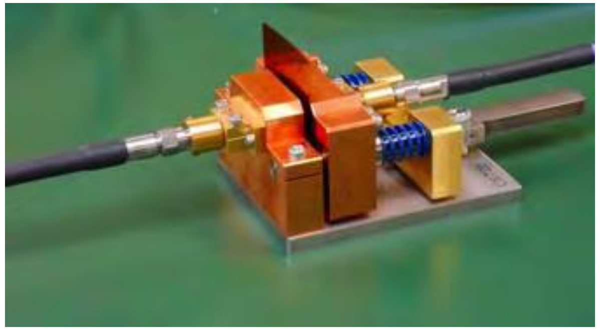
SPDRs



FPOR

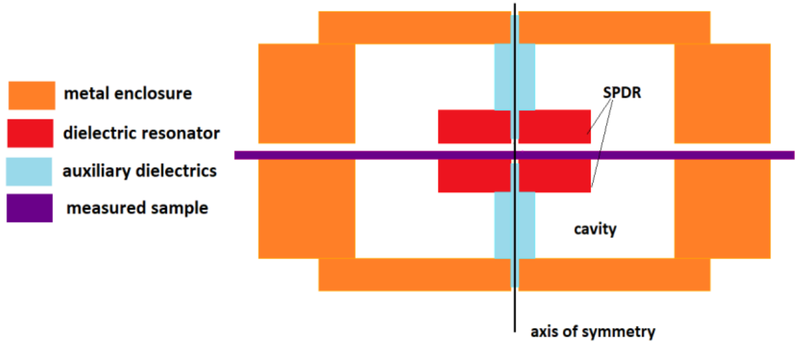
BCDR

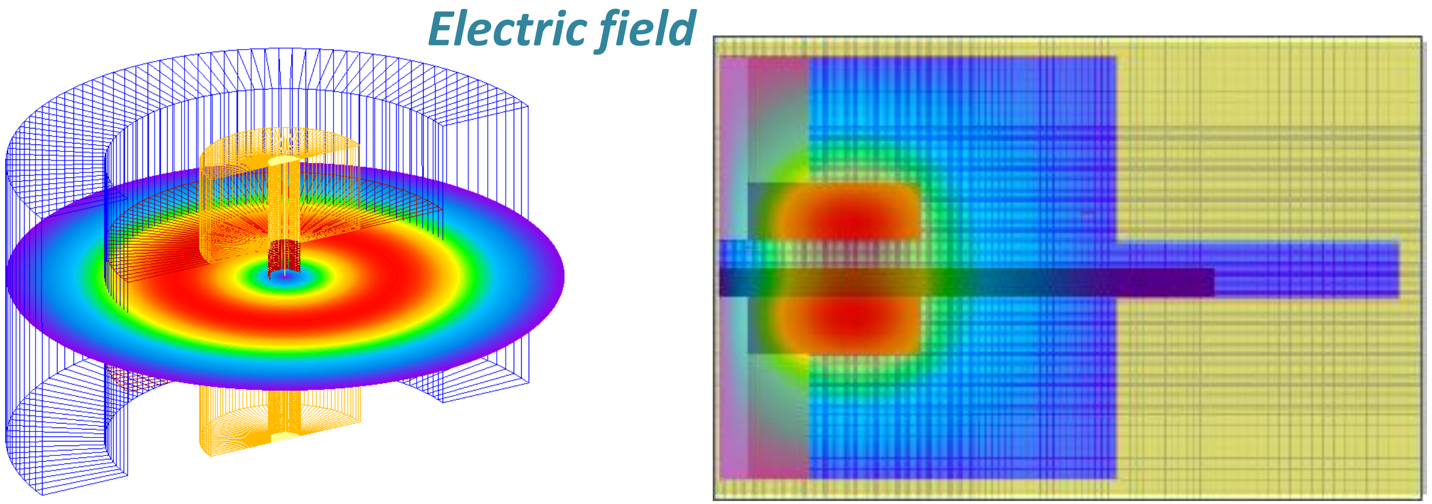
SCR

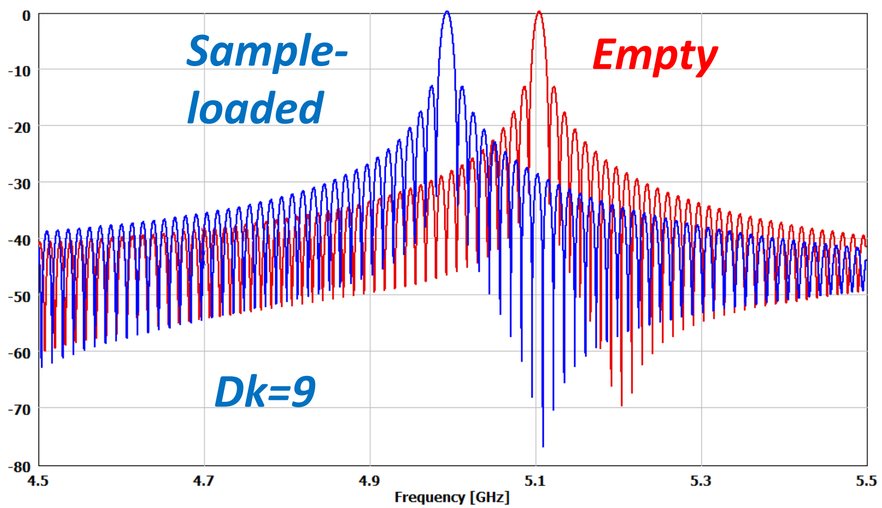


Split-Post Dielectric Resonators

- Two dielectric posts
- Resonant mode with EM fields confined in and between posts
- E-field circumferential and tangential to SUT
- H-field is only vertical at the side wall of the enclosure
- Average of in-plane components of complex permittivity tensor







Field patterns remain practically unchanged but resonant frequencies and Q-factors change.

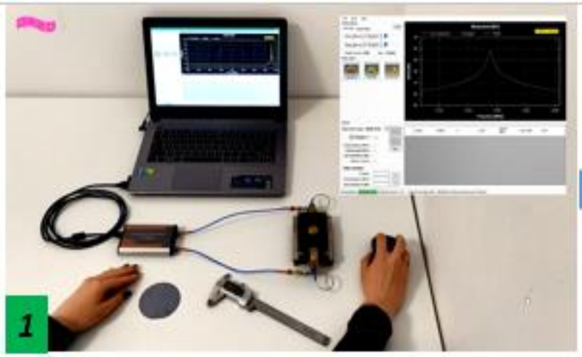
SUT of $\varepsilon_s = \varepsilon_s' - j\,\varepsilon_s''$ is inserted into DR:
resonant frequency changes from f_e to f_s and Q-factor changes from Q_e to Q_s.

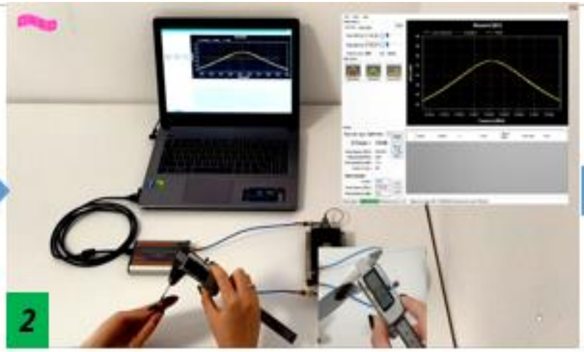
Measurement procedure - SPDR

IMS — Connecting Minds. Exchanging Ideas.

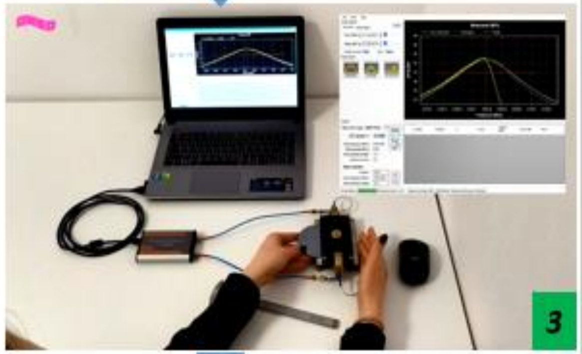
The Coolest Ideas Under the Sun — SAN DIEGO 2023

Operation workflow – with the use of Q-Meter





2. Measure thickness of the sample

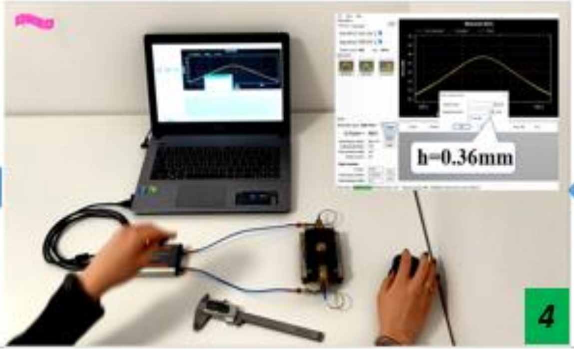


0. Connect the SPDR to Q-Meter using SMA cables.
Connect Q-Meter to PC using USB cable.

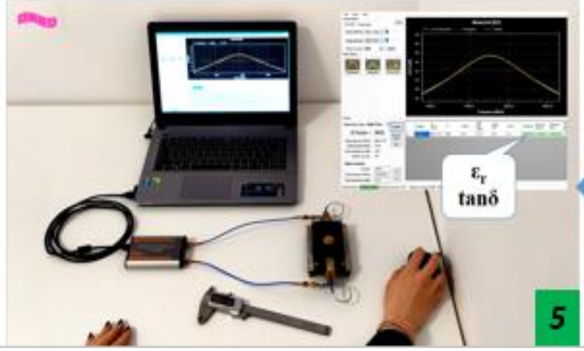
1. Measure "empty SPDR" – app invoked measurement.

Total measurement time: 30sec

3. Insert the sample into SPDR



4. Insert the sample thickness into the PC app



5. Material parameters are extracted automatically

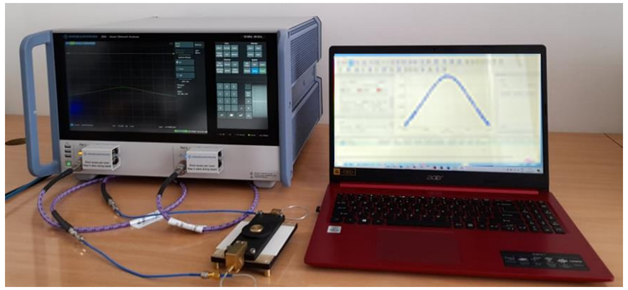
General measurement scheme is common for most of resonant methods

Split-Post Dielectric Resonators (2)

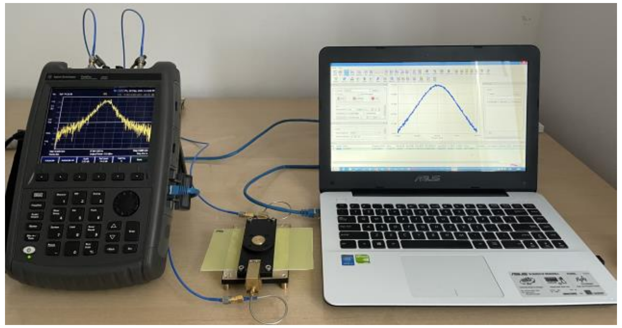
Major properties of the SPDR method:

- **dielectric constant**: Dk = 1 - 100 (accuracy: δDk < 0.15%)
- **loss tangent**: Df > 2 10^{-5} (maximum achievable accuracy: δDf < 2%)
- **sample dimensions** depend on the operating frequency
- **temperature dependent** measurements (standard up to 110 C deg)
- average of **in-plane** Dk and Df components

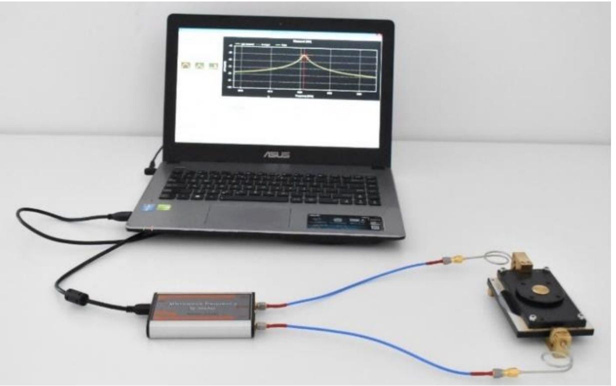
Measurement setups



Laboratory-scale VNA



Hand-held VNA



Portable Microwave Q-Meter

SPDR-compatible samples dimensions depending on the operating frequency

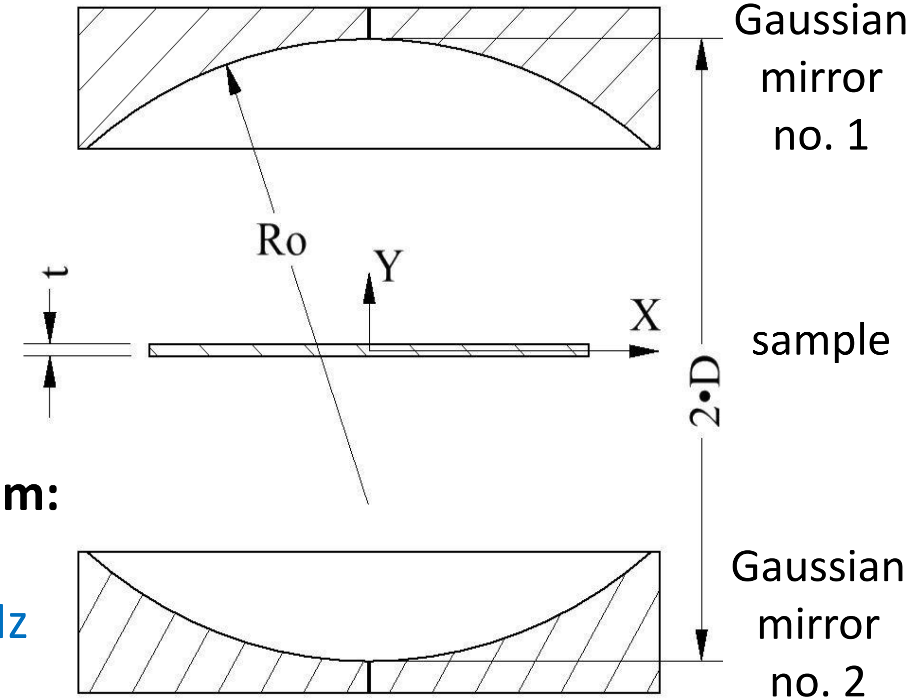
Nominal frequency [GHz]	Minimum sizes/diameter of sample (*dmin*) [mm]	Maximum width of sample (*dmax*) [mm]*^	Recommended sizes of sample (*drec*) [mm]**	Maximum thickness of sample [mm]
1.1	120x120 / 120	165	165	6.0
2.45 / 2.5	55x55 / 55	100	85	3.1
5 / 5.1	30x30 / 30	90	65	1.95
10	22x22 / 22	90	45	0.95
15	14x14 / 14	40	35	0.6

* Limitation for diameter of circular samples. For rectangular samples, limitation relates only to one sample dimension (the other dimension may be larger).
** For easy sample handling, diameter ***d*** of circular sample is recommended to be ***drec<d<dmax***. For rectangular samples of size ***a x b***, the recommendation is ***a>drec*** while ***dmin<b<dmax***.
^ For non-standard sample sizes contact QWED team.

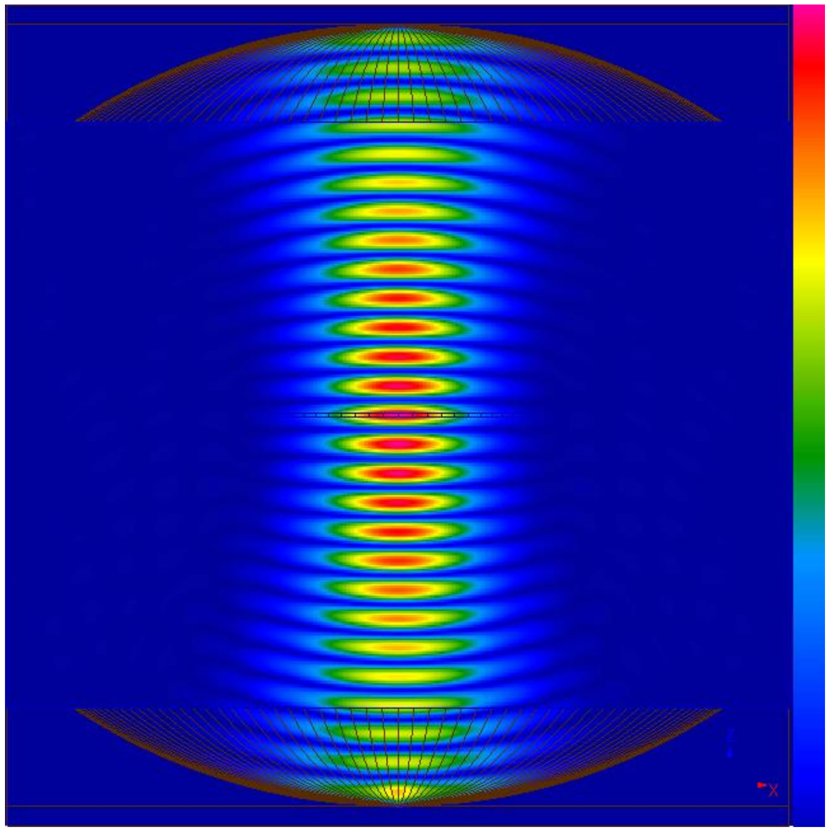
Fabry-Perot Open Resonator

Fabry-Perot Open resonator

Bridging the gap between classical resonant methods and free space methods



Gaussian ***TEM00q*** *modes*



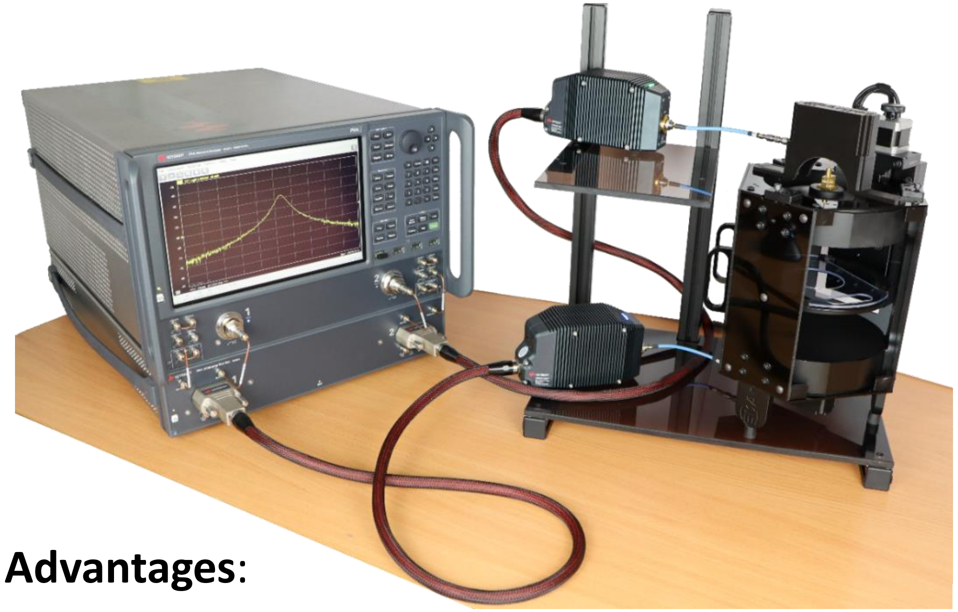
Electric field distribution - simulation model in QuickWave software

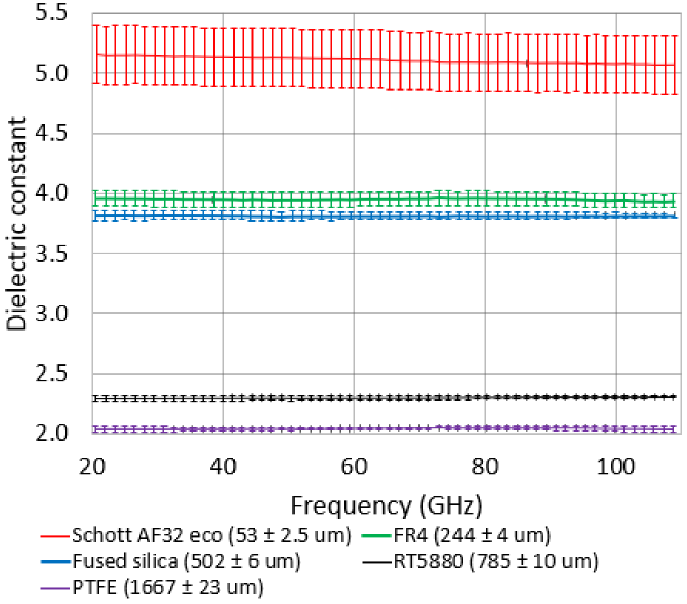
Major properties of the FPOR system:

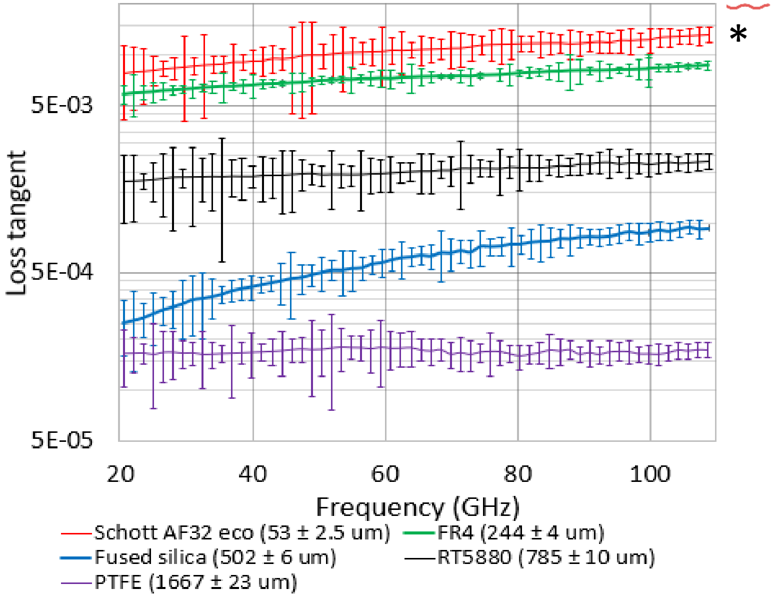
- Single device for: 20-130 GHz
- Frequency resolution: ca. 1.5 GHz
- Dk accuracy: $\Delta\varepsilon/\varepsilon < 0.5\ \%$
- Df range: $10^{-5} < \tan\delta < 10^{-2}$
- Sample diameter: > 3 inches
- Sample thickness: < 2 mm
- Fully automated measurement: typically 3 minutes in 20-130GHz

Fabry-Perot Open Resonator (2)

FPOR measurement setup



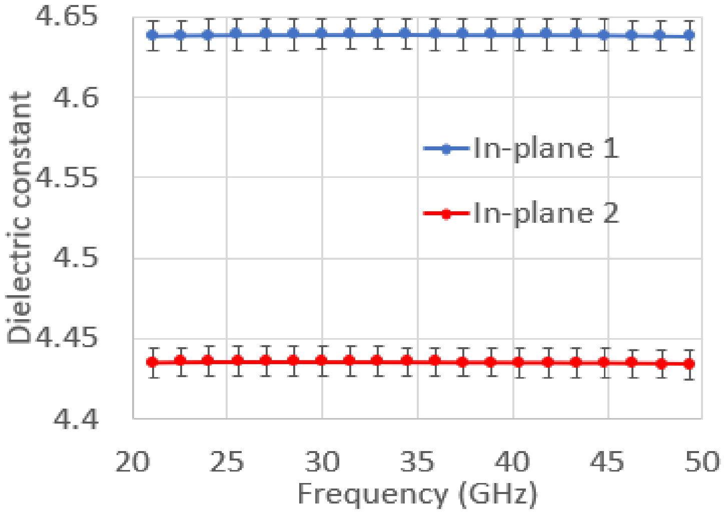


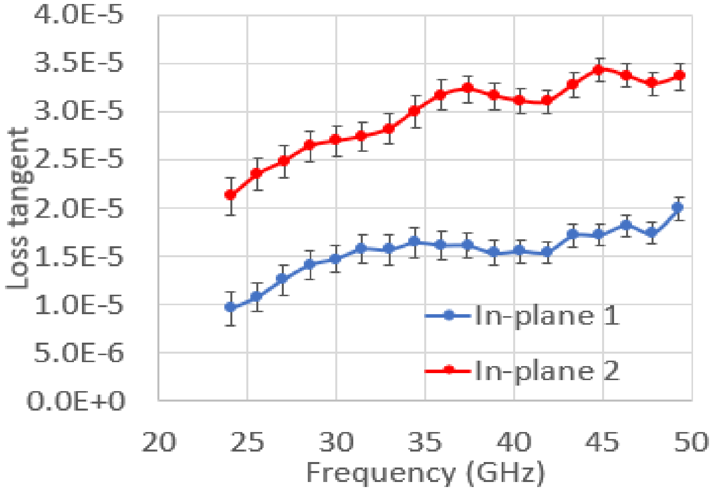


Advantages:

- broadband and accurate characterization of dielectric sheets in a single fixture
- high repeatability
- software-controlled and fully automated
- easy insertion of the sample
- non-destructive measurement

Anisotropic dielectric materials: X-cut quartz; th=492 ± 1μm



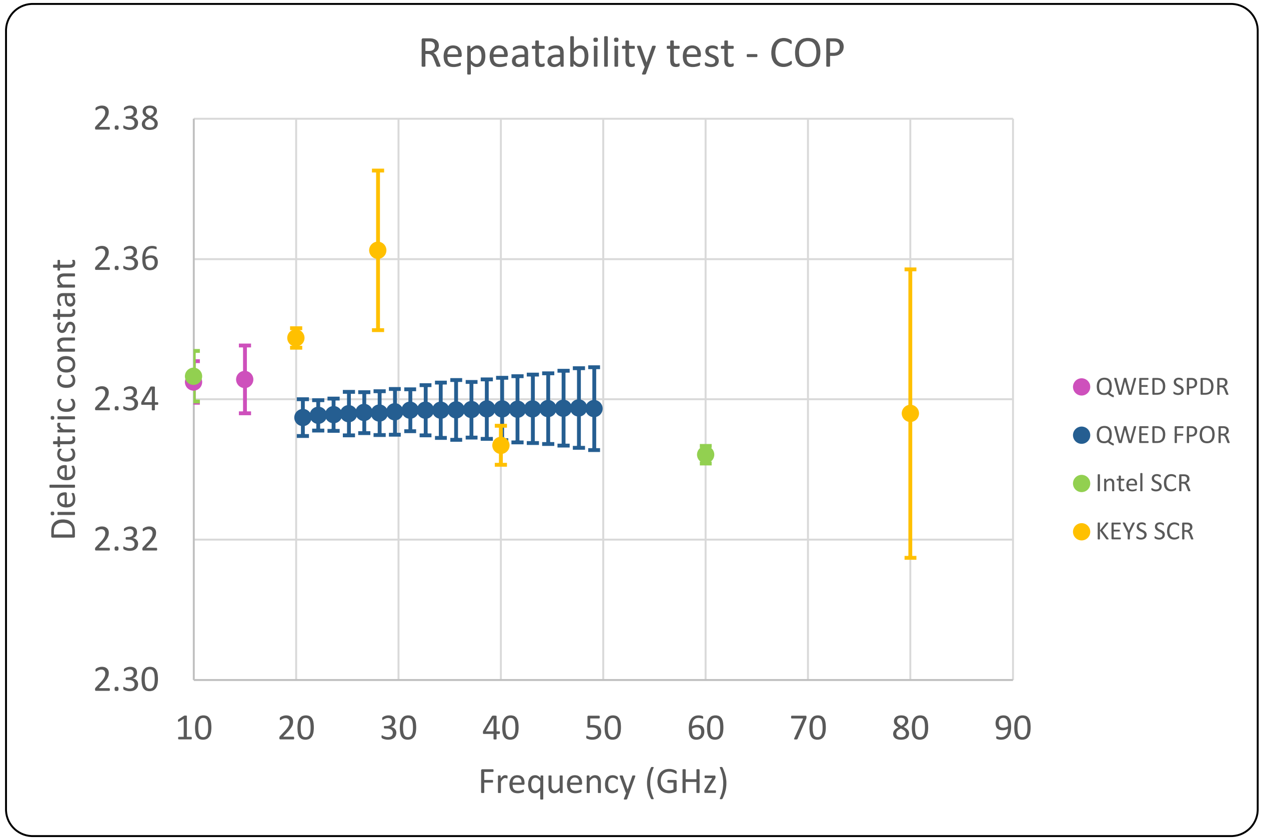


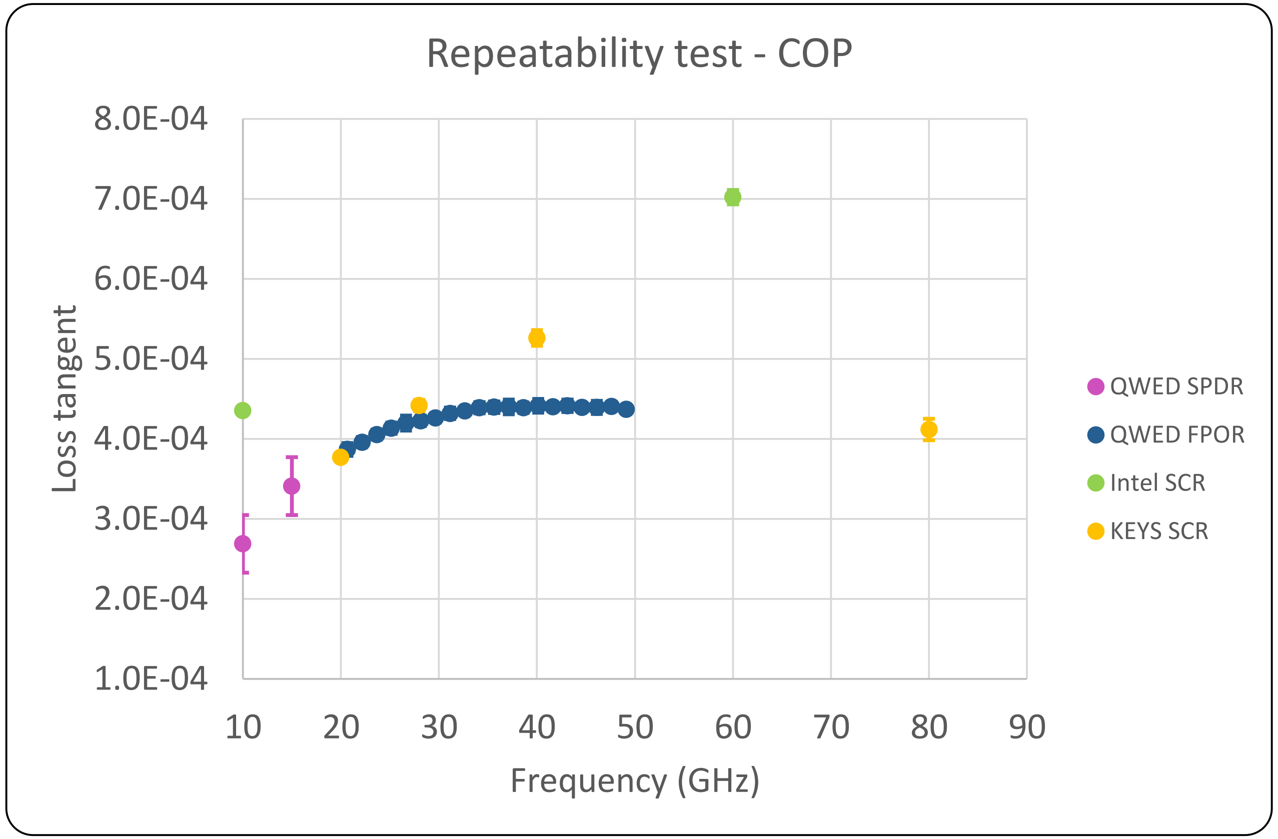
*for more details, see: https://www.qwed.eu/resonators_fpor.html

Benchmarking results

INEMI *5G/mmWave Materials Assessment and Characterization* project results

Repeatability studies





Each measurement repeated 16 times

Repeatability bounds: ±3σ

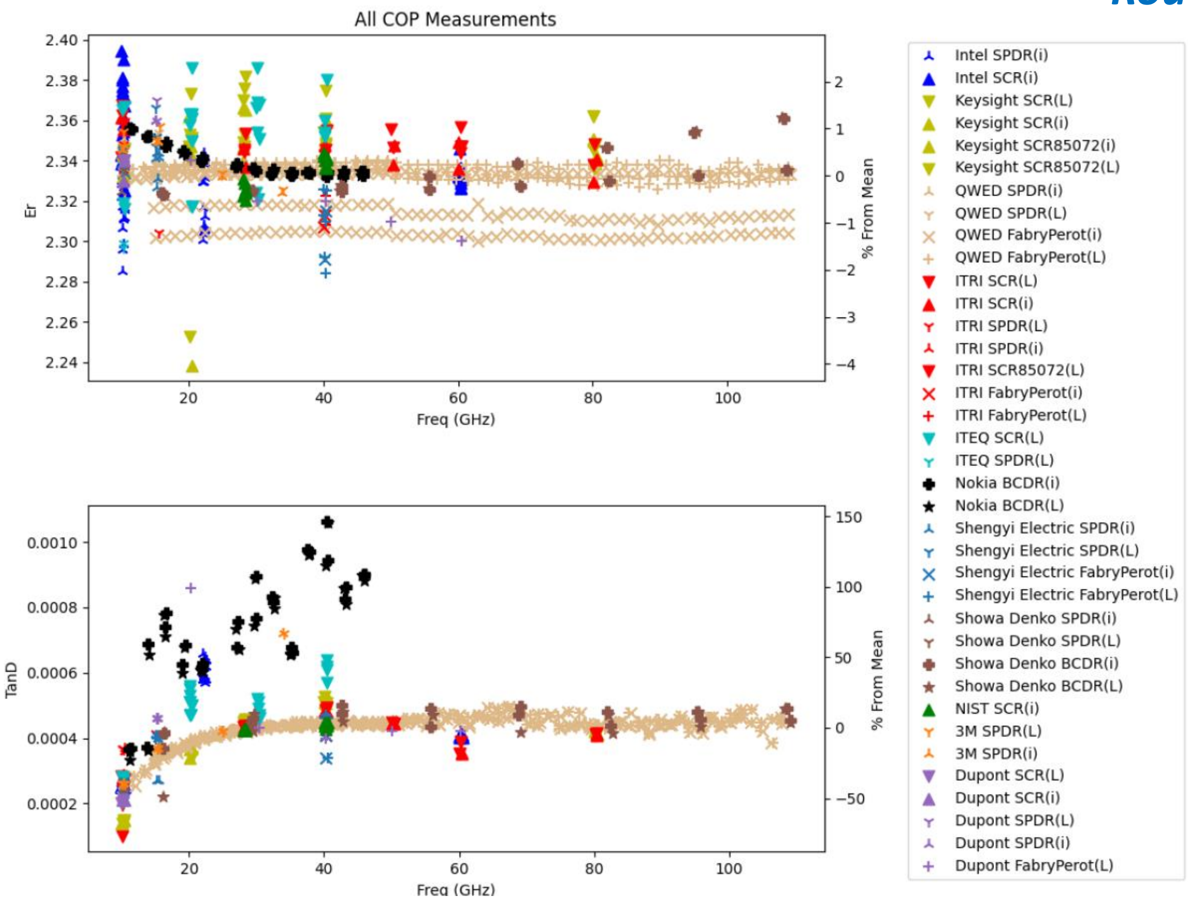
M. Celuch, M.J. Hill, T. Karpisz, M. Olszewska-Placha, S. Phommakesone, U. Ray, B. Salski, "Benchmarking of GHz resonator techniques for the characterisation of 5G/mmWave materials", 51st European Microwave Conference April 2021, pp. 568-571.

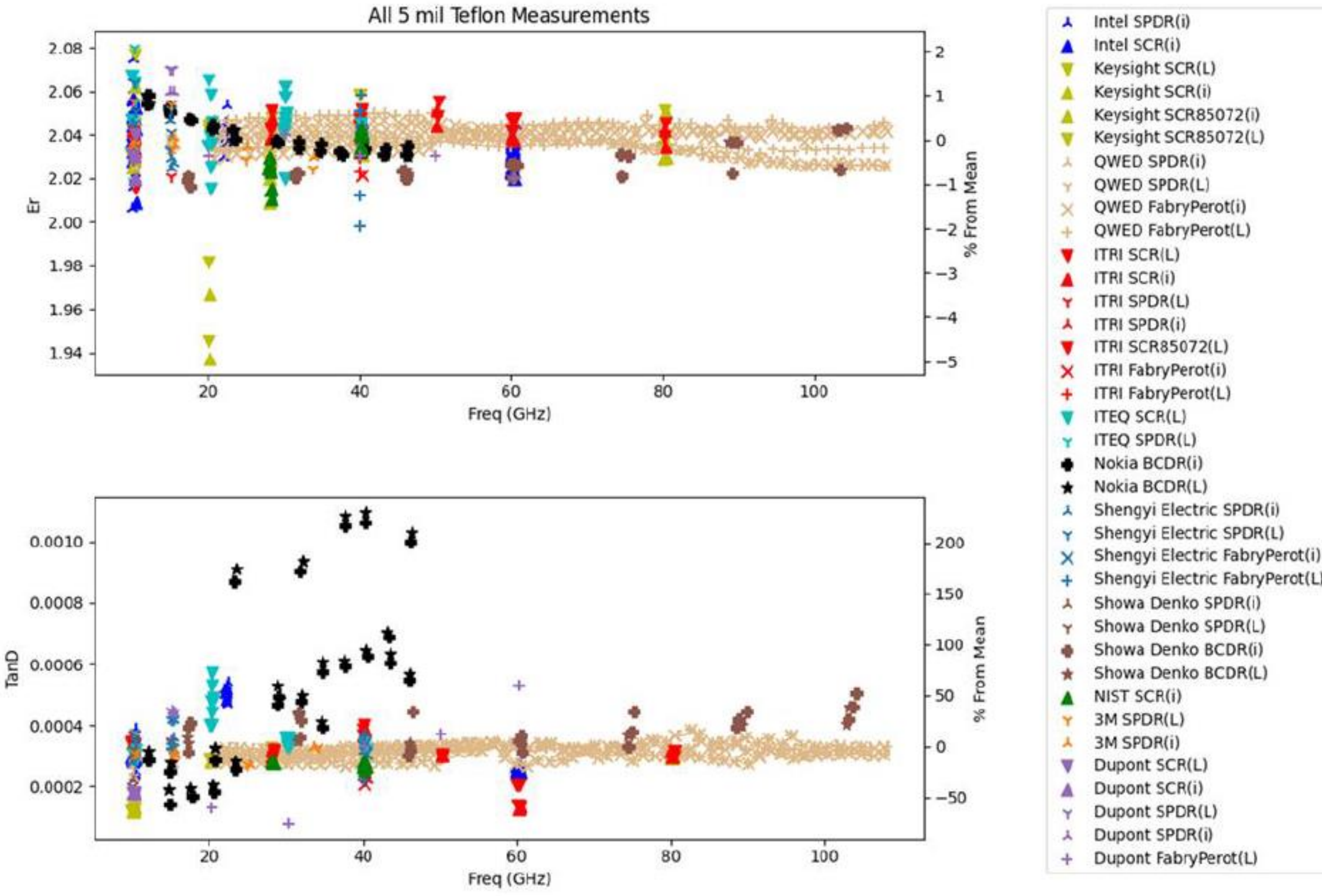
Benchmarking results

INEMI *5G/mmWave Materials Assessment and Characterization* project results

Over 1000 measurement points in total

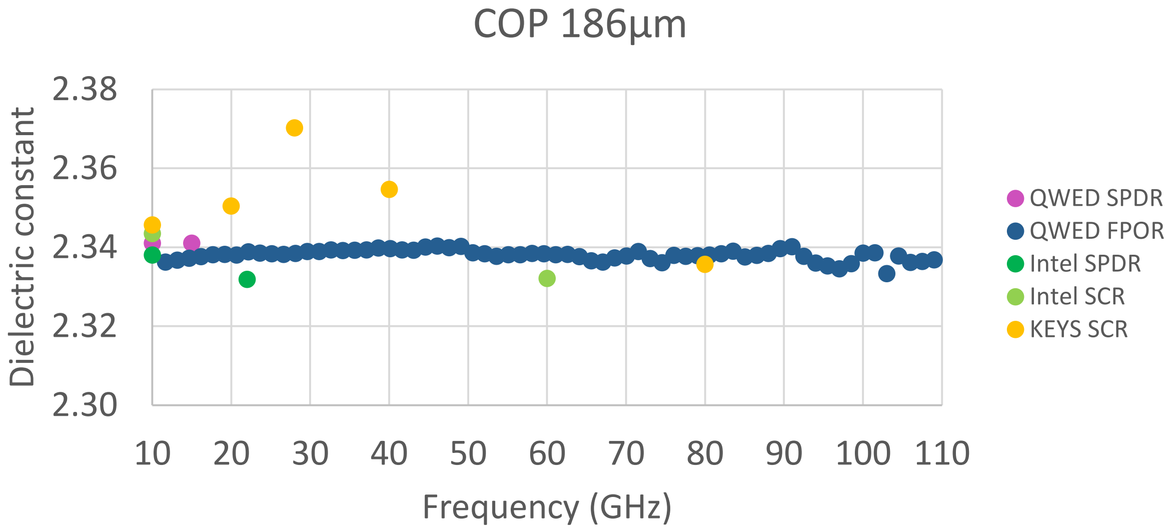
Round 1

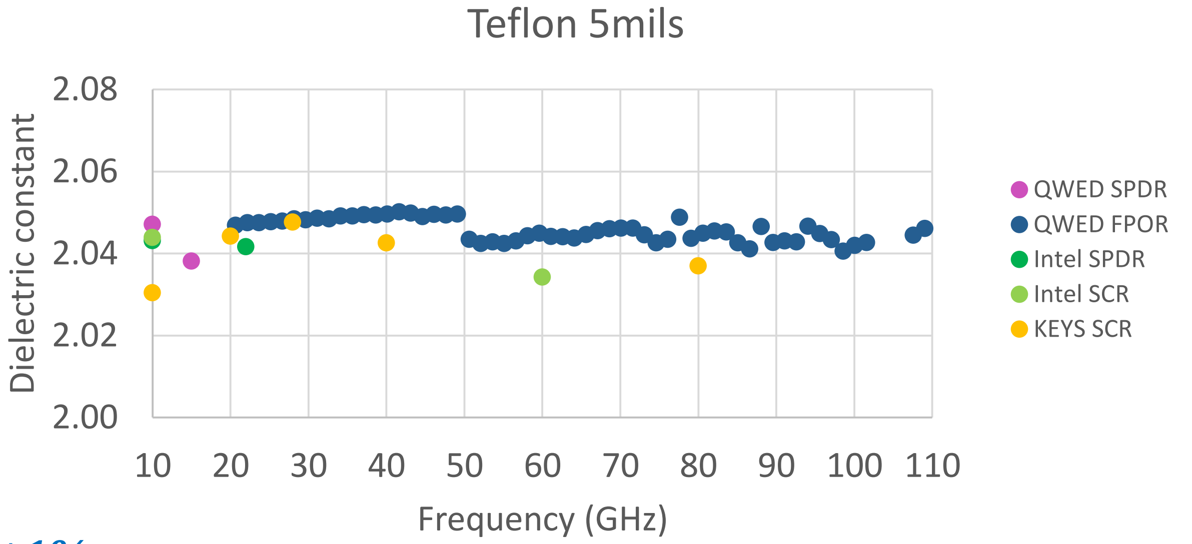




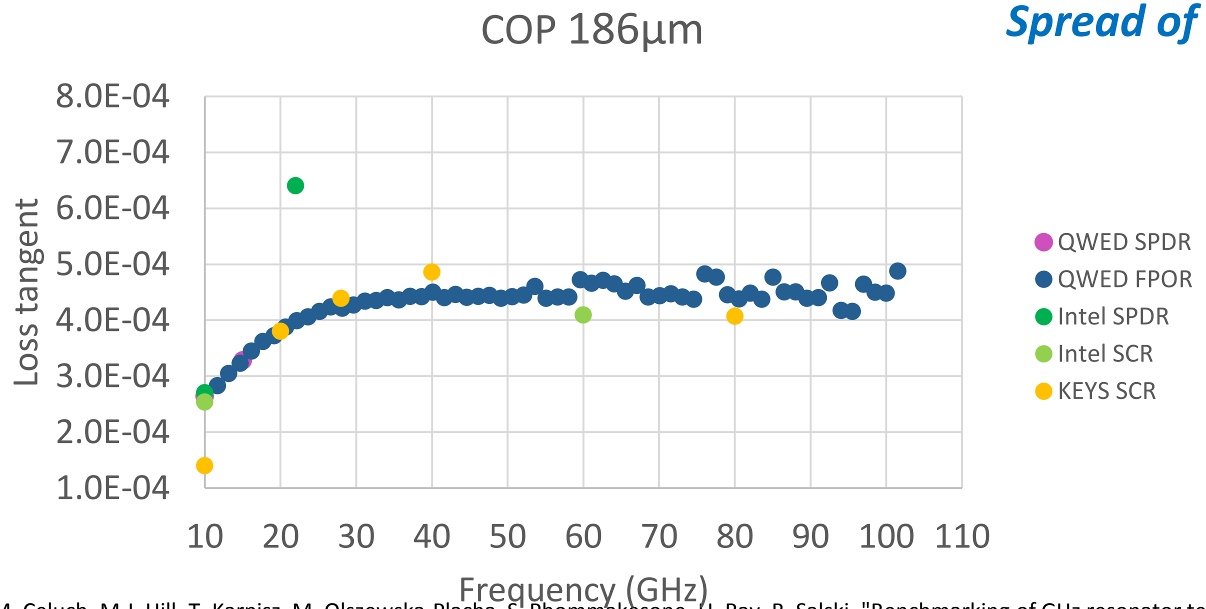
Spread of Dk: ±2%

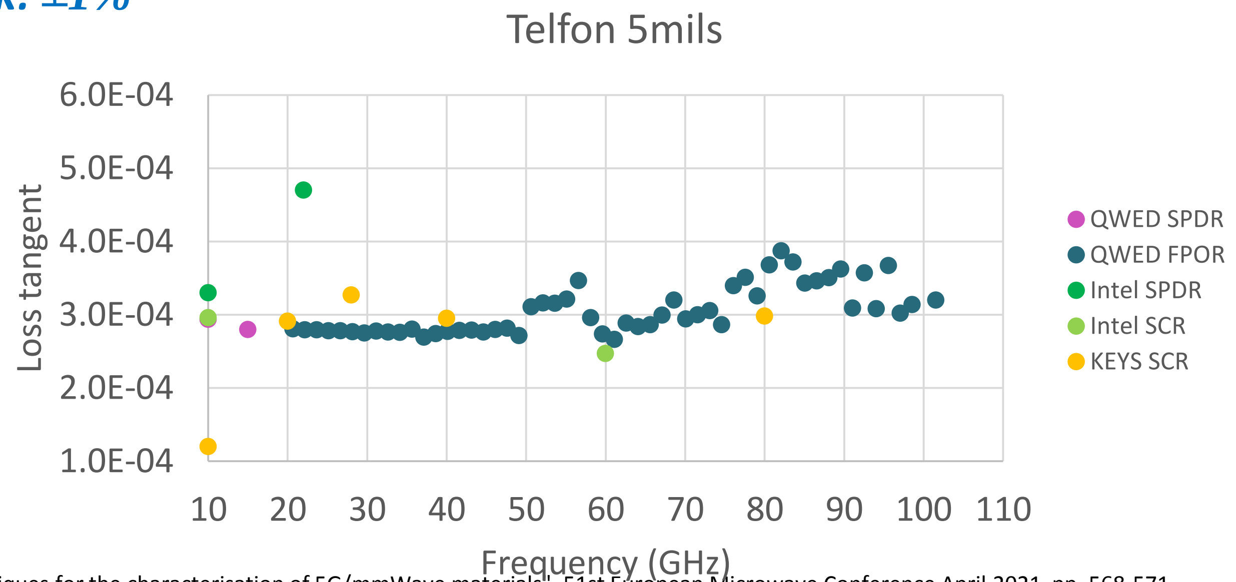
Benchmarking results





Spread of Dk: ±1%





M. Celuch, M.J. Hill, T. Karpisz, M. Olszewska-Placha, S. Phommakesone, U. Ray, B. Salski, "Benchmarking of GHz resonator techniques for the characterisation of 5G/mmWave materials", 51st European Microwave Conference April 2021, pp. 568-571.

Observations and conclusions

- Two sample size sufficient to cover all considered test methods
- Accurate thickness evaluation is of high importance
- Thickness variation and sample flatness determine uncertainty of Dk extraction
- Results variation across the labs of ±2%

- *Standard reference materials are of high interest*
- Traceable standard – dielectric parameters certified by NIST
- Calibration of 5G & 6G material characterization fixtures
- Targeting 0.2% uncertainty in SRM in round robin results

New activities

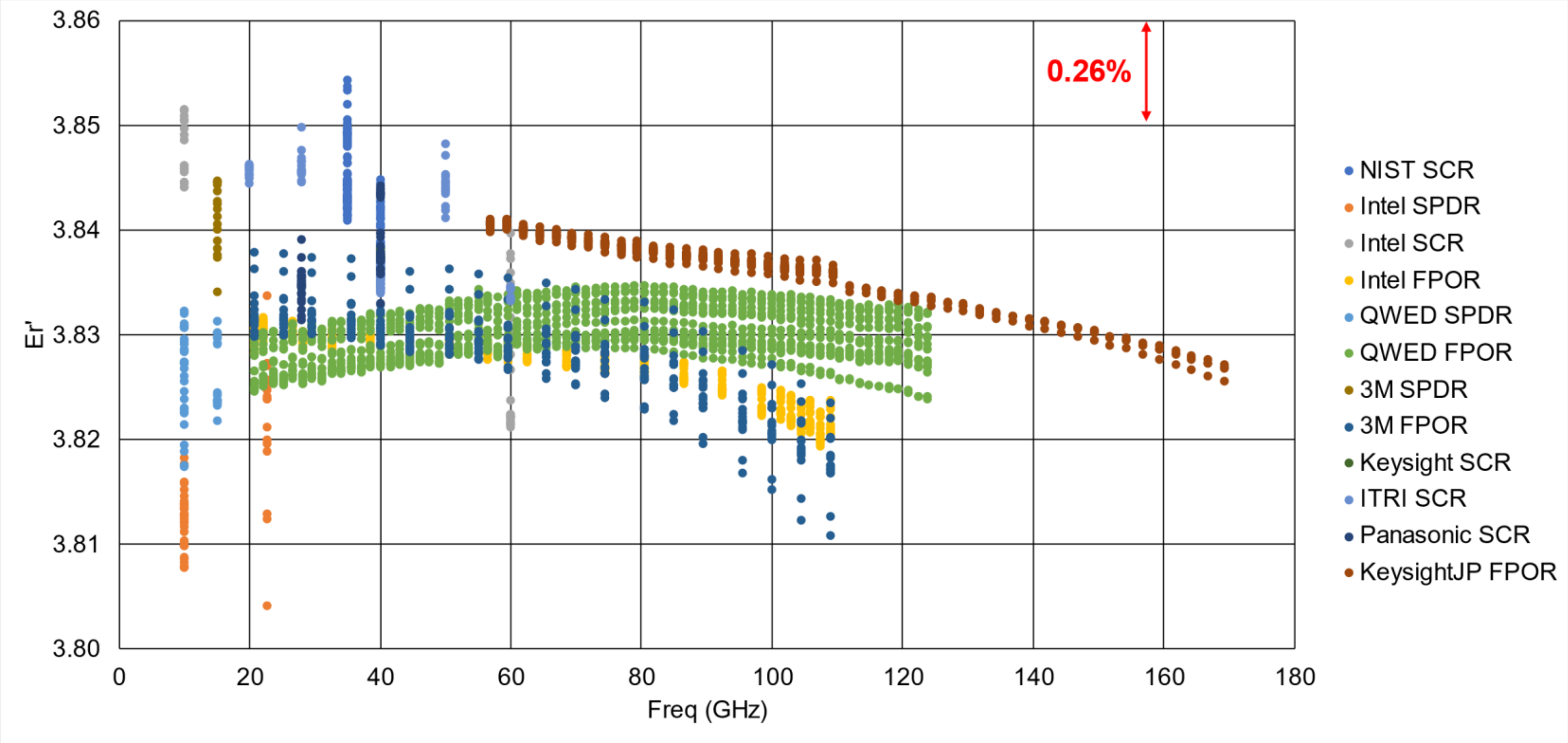
- *mmWave Permittivity Reference Material Development* project
- Developing traceability path for material characterisation methods (NIST)
- Certification of SRMs (NIST)
- Support with Round Robin testing of SRM candidates (8 labs)

- *5G/6G mmWave Materials and Electrical Test Technology Roadmap (5G/6G MAESTRO)* project

SRM candidate testing

INEMI *mmWave Permittivity Reference Material Development* project

In-plane measurements of RR1



Agreement within 1.6%

Industry Workshop IWWE6

mmWave Permittivity Standard Reference Material Development

Wednesday 1:30 pm

Location: 29D

New materials for 5G technologies

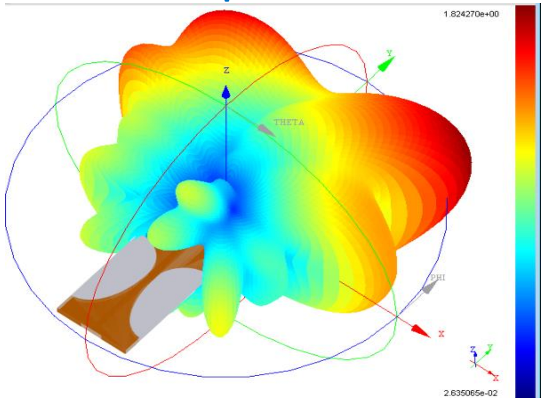
Materials for 5G and beyond

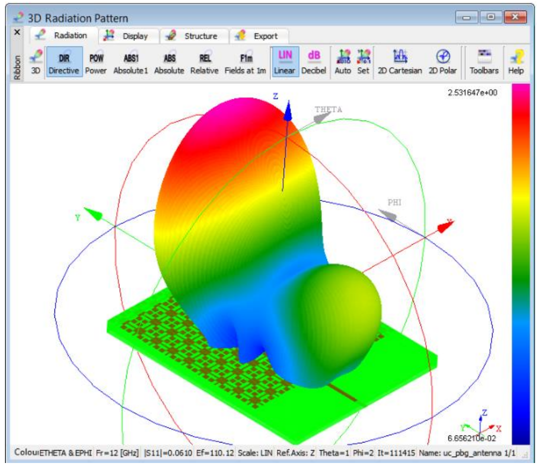
- LTCC and ULTCC materials for electronic substrates
  - LTCC – sintering temperature: ca. 800 - 900°C
  - ULTCC – sintering temperature: ca. 400-700°C
- Lower energy consumption
- Precise characterisation needed
- Point-wise & surface-wise (important for high density packaging at single substrate)

- Direct conductor testing – evaluation and optimization on the signal loss in final devices

Antenna & feed systems designs

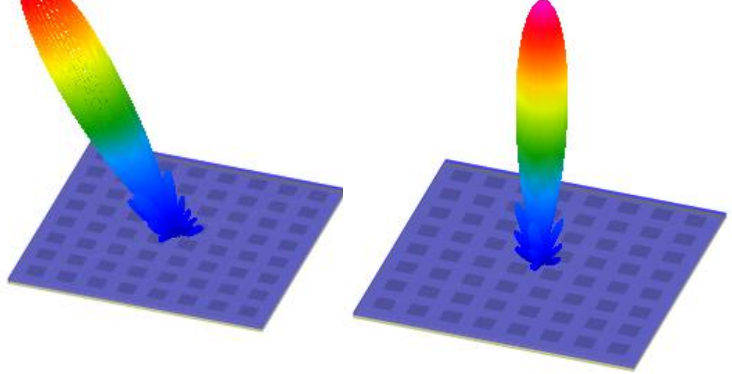
Balanced antipodal Vivaldi antenna & 3D radiation pattern at 10 GHz.

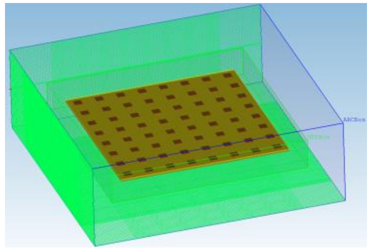


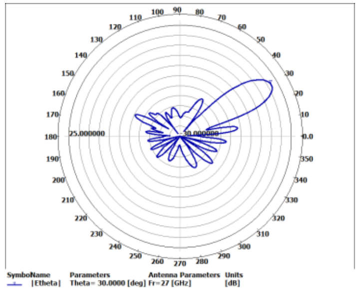


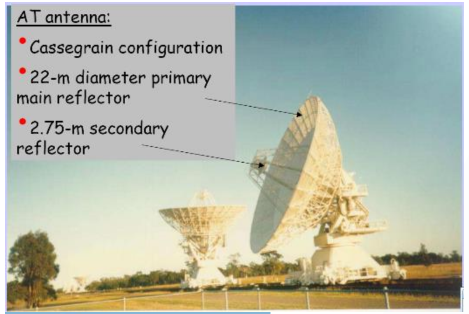
Aperture-coupled patch antenna on uniplanar photonic bandgap substrate & its radiation pattern at 12 GHz.

Antenna arrays for 5G and automotive radar application

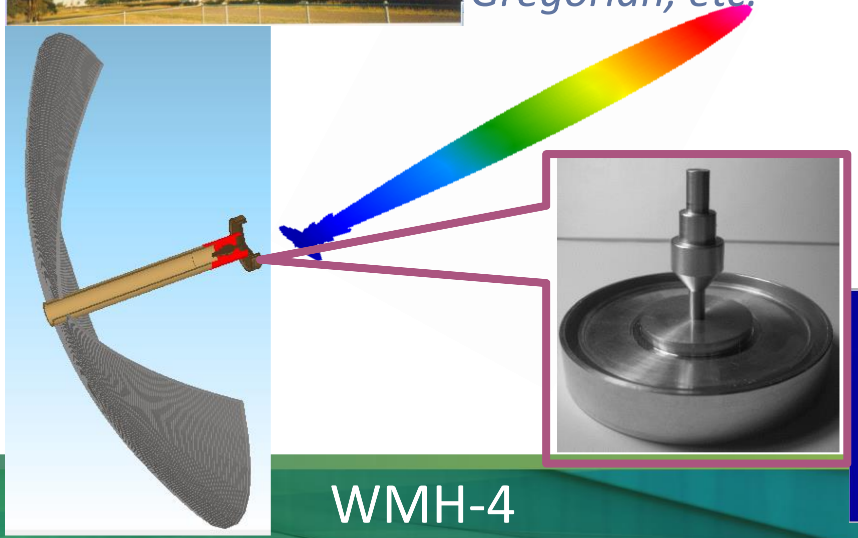




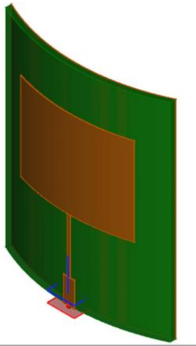


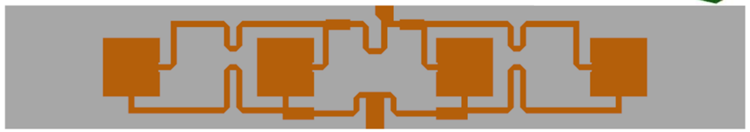


Large dual reflector antennas: *Cassegrain, Gregorian, etc.*

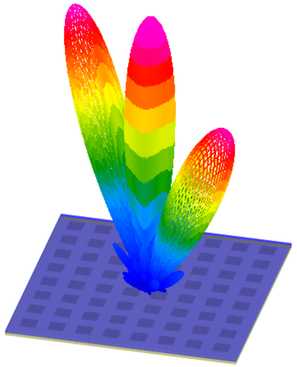


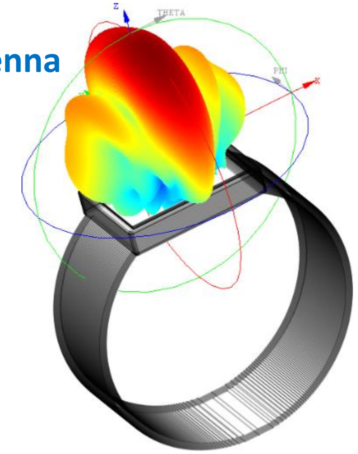
Planar antennas for smart bio-sensors



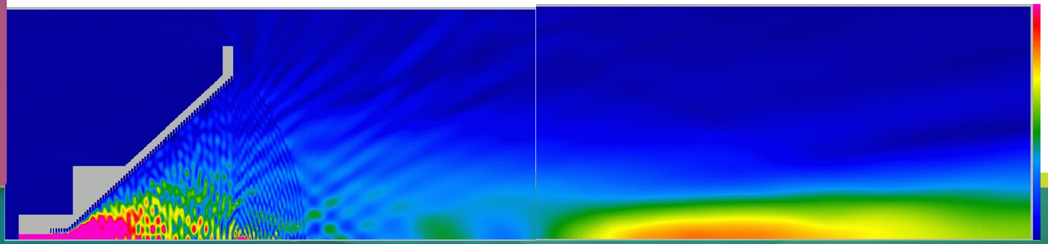


Smartwatch with embedded patch antenna



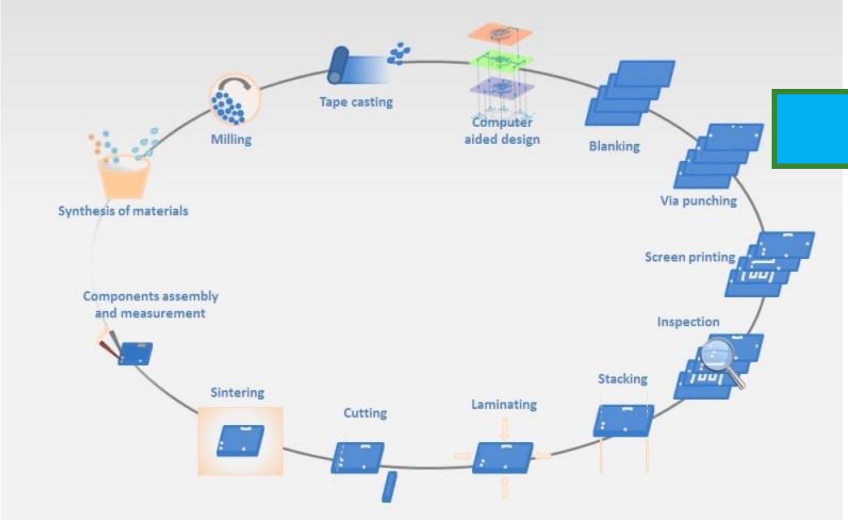


Corrugated horn antenna for material measurements

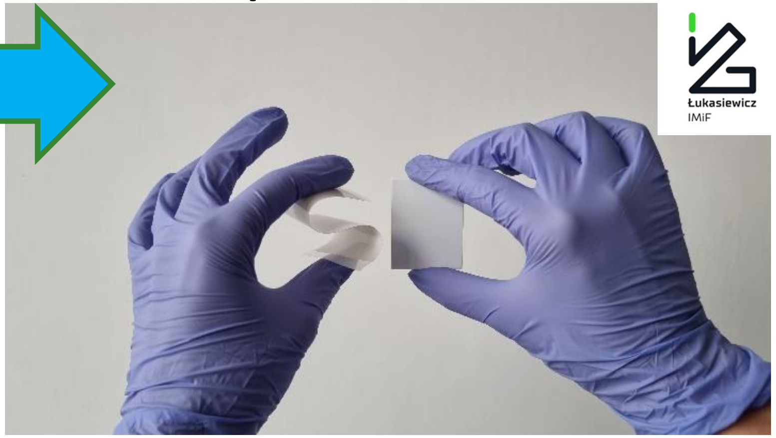


LTCC/ULTCC fabrication scheme

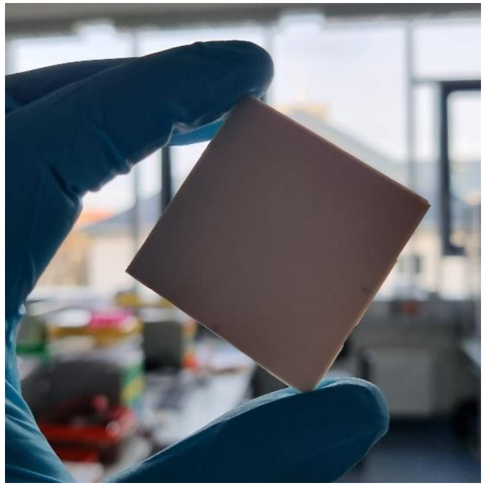
LTCC/ULTCC substrate fabrication scheme



Flexible tape to substrate



Composites characterisation before substrate fabrication

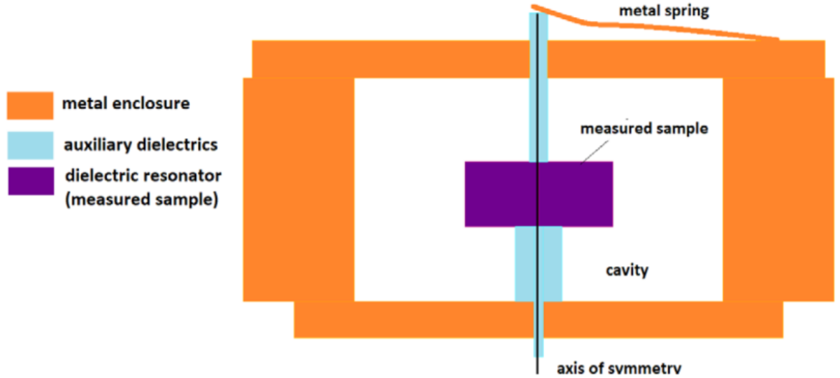


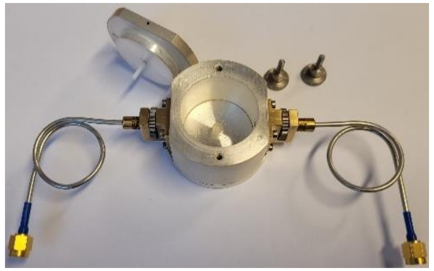
Fraunhofer
IKTS

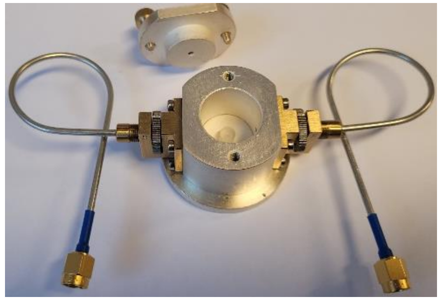
ULTCC bulk composites (1)

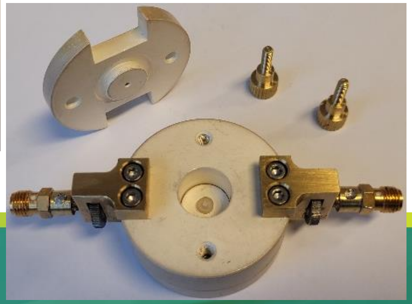
- Sample under test serves as dielectric resonator
- Df as low as $5\ 10^{-7}$
- Accuracy:
  $\Delta\varepsilon/\varepsilon = T*\Delta h/h + (2-T)*\Delta d/d$, for $0 < T < 2$
  $\Delta\tan\delta = \pm 2*10^{-6}$ or $\pm 0.03*\tan\delta$
- **Precisely machined samples**
- Sample: 0.25 - 0.6 of the cavity size
- Family of TE01δ cavities:
  D= 12mm (ca. 38GHz),
  D= 18mm (ca. 23GHz),
  D= 24mm (ca. 19GHz),
  D= 32mm (ca. 15GHz),
  D= 60 mm (ca. 7.5GHz)
- Temperature coefficient of resonant frequency (TCF)

TE01δ cavity









ULTCC bulk composites (2)

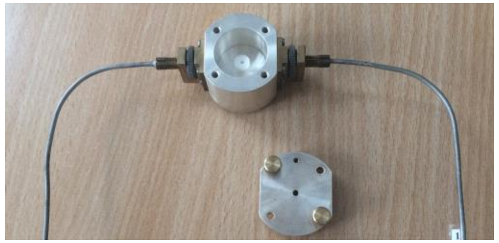
TCF of ULTCC with TE01δ cavity

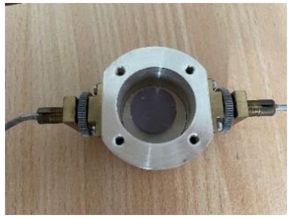
Measurement setup

PC with control app

VNA

Climatic chamber with 32mm TE01δ cavity





TE01δ cavity with SUTs

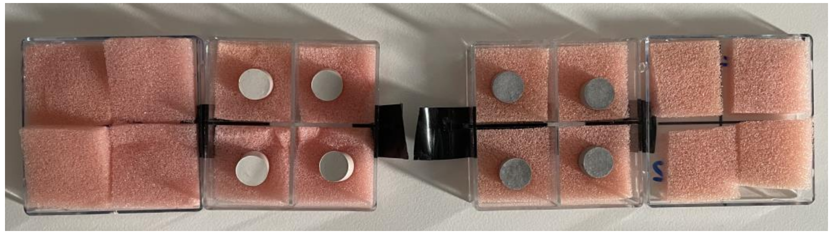
ULTCC bulk composite samples

D$\approx$ 8mm, H $\approx$ 4mm

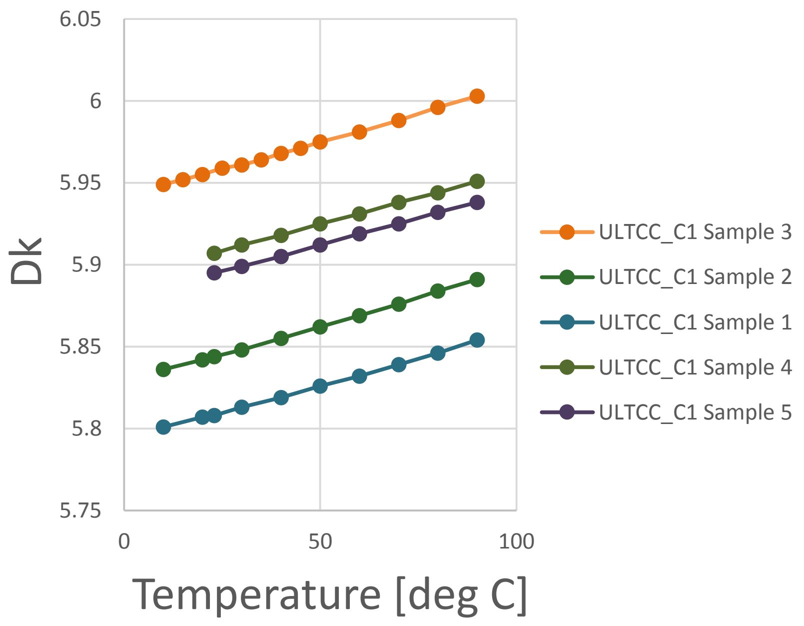
ULTCC bulk composites (3)

Temperature and humidity dependent measurements

ULTCC6G_EPac **project activities**



ULTCC_C3 ULTCC_C2

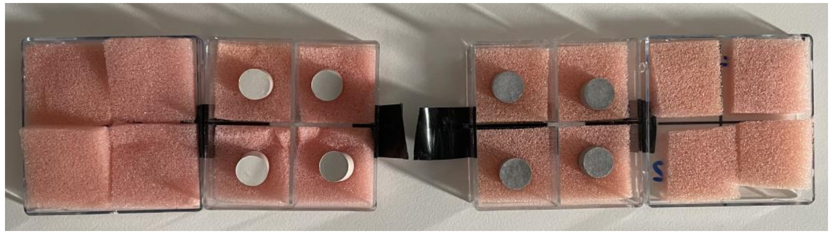


Sample	*Dk*	*Df*	*Humidity [%]*	*TC Dk [ppm] (25→85°C)*	*TCF [ppm] (25→85°C)*
ULTCC_C1 Sample 1	5.80	0.000288	35	*114*	*-58.6*
ULTCC_C1 Sample 2	5.84	0.000296	35	*120*	*-61.2*
ULTCC_C1 Sample 3	5.959	0.000359	35	*114*	*-58.6*
ULTCC_C1 Sample 3	5.96	0.000592	65		
ULTCC_C2 Sample 1	4.05	0.004945	35	*213*	*-106*
ULTCC_C2 Sample 2	3.96	0.005534	35	*210*	*-104*
ULTCC_C3 Sample 1	13.91	0.002227	35	*64.7*	*-34.6*
ULTCC_C3 Sample 2	14.08	0.002201	35	*63.9*	*-34.3*

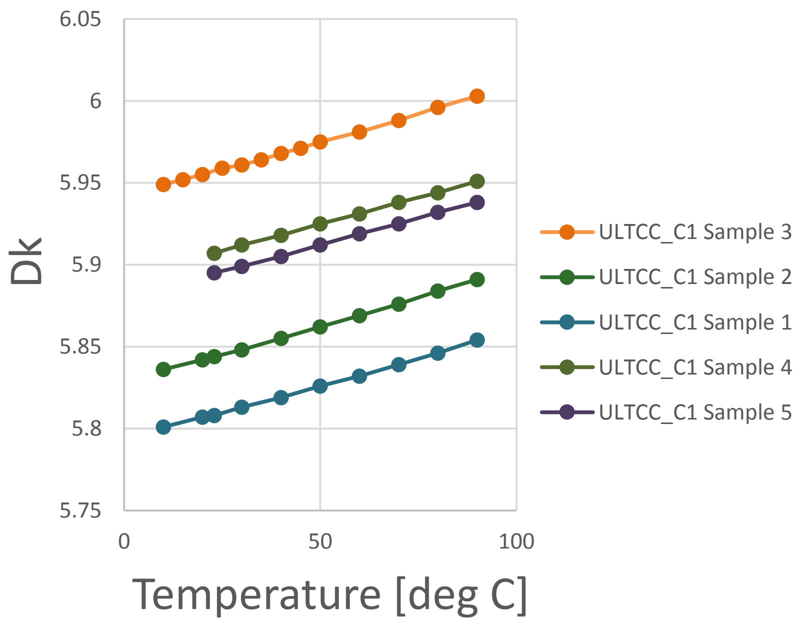
ULTCC bulk composites (3)

Temperature and humidity dependent measurements

ULTCC6G_EPac **project activities**



ULTCC_C3 ULTCC_C2

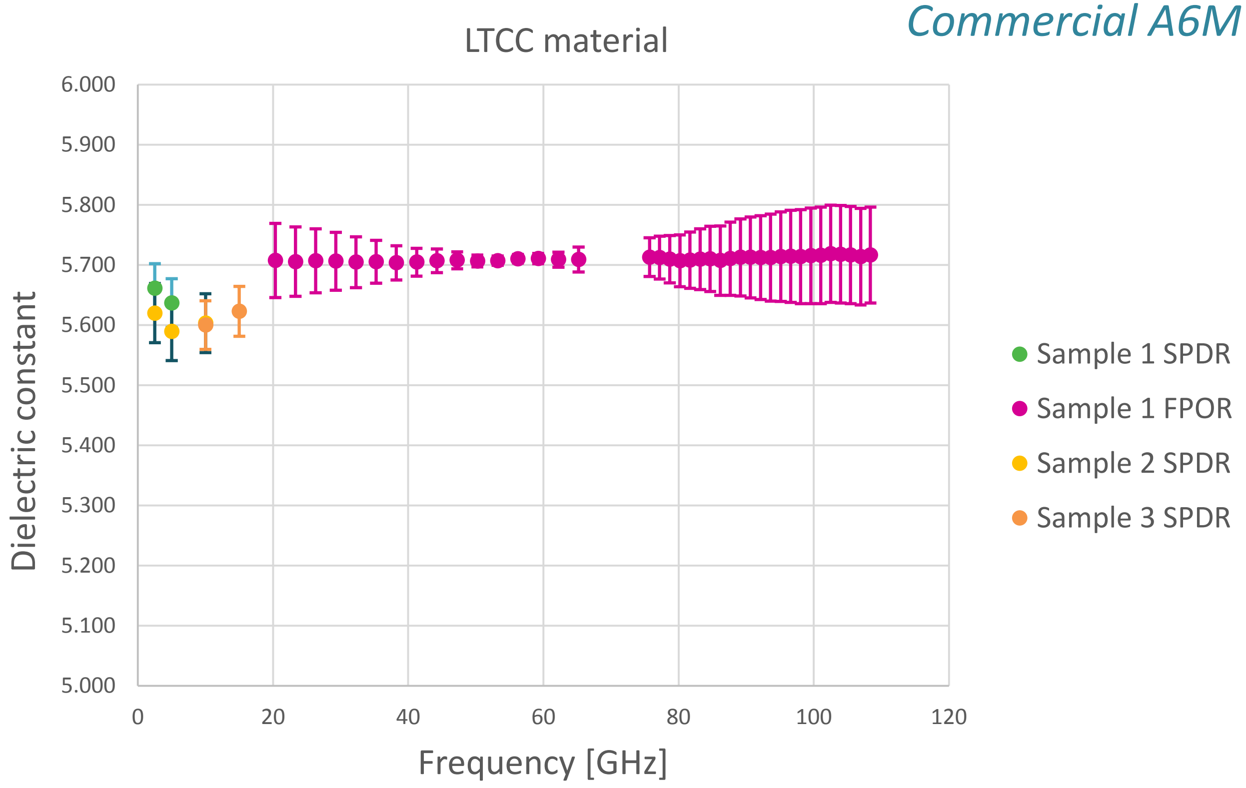


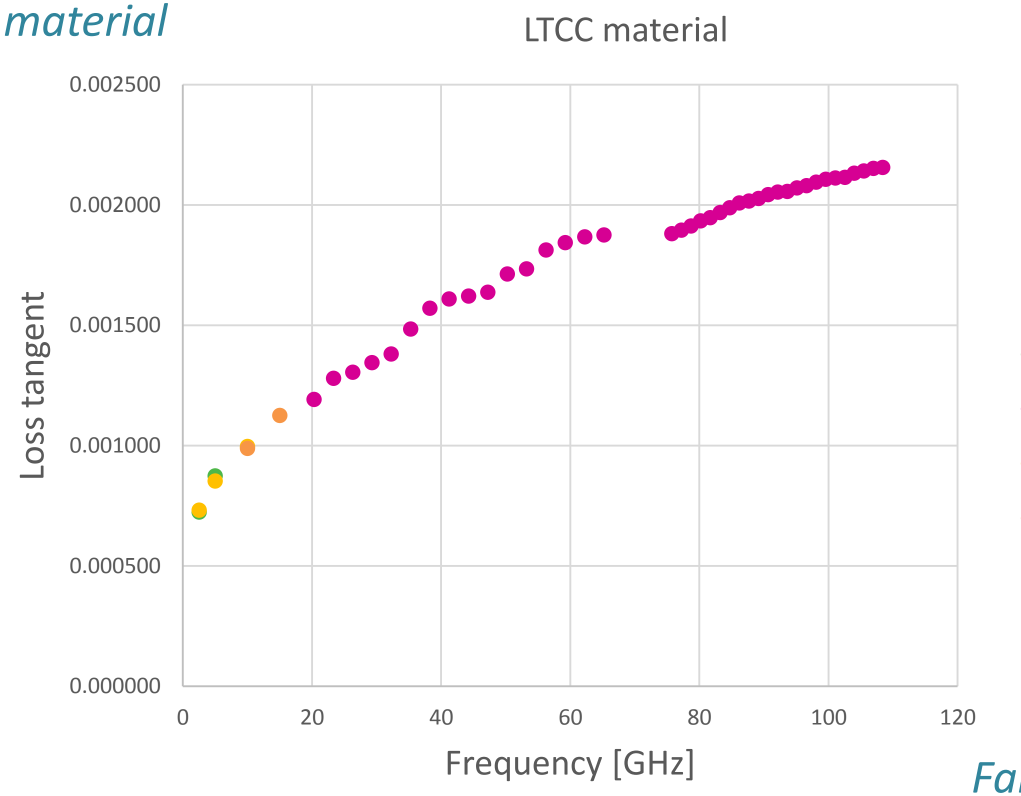
Sample	*Dk*	*Df*	*Humidity [%]*	*TC Dk [ppm] (25→85°C)*	*TCF [ppm] (25→85°C)*
ULTCC_C1 Sample 1	5.80	0.000288	35	***114***	***-58.6***
ULTCC_C1 Sample 2	5.84	0.000296	35	***120***	***-61.2***
ULTCC_C1 Sample 3	5.959	0.000359	35	***114***	***-58.6***
ULTCC_C1 Sample 3	5.96	0.000592	65		
ULTCC_C2 Sample 1	4.05	0.004945	35	***213***	***-106***
ULTCC_C2 Sample 2	3.96	0.005534	35	***210***	***-104***
ULTCC_C3 Sample 1	13.91	0.002227	35	***64.7***	***-34.6***
ULTCC_C3 Sample 2	14.08	0.002201	35	***63.9***	***-34.3***

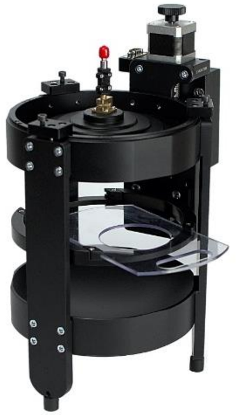
LTCC and ULTCC substrates (1)

***Ultra-Low Temperature Co-fired Ceramics for 6th Generation Electronic Packaging* (ULTCC6G_EPac) project**

Commercial A6M material

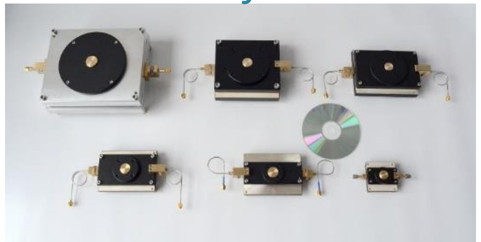






Consistent within uncertainty bounds – related to thickness variation

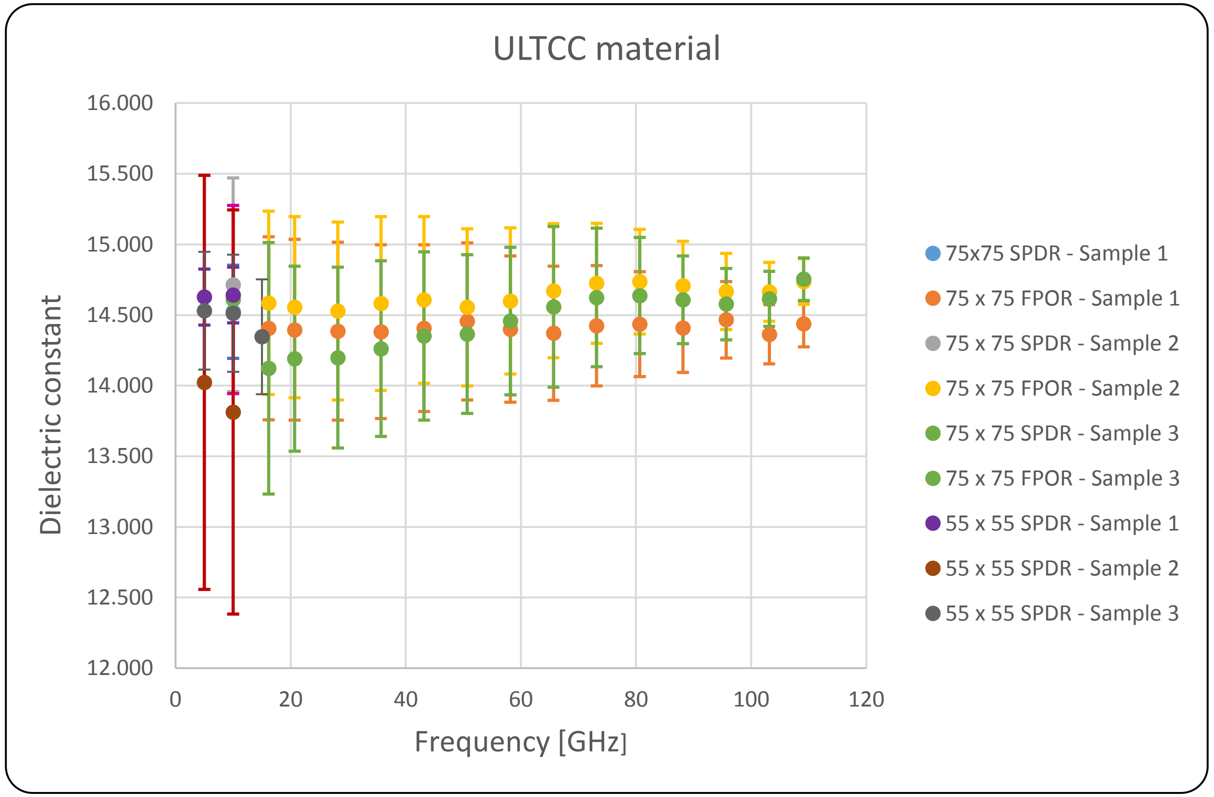
Family of SPDR fixtures

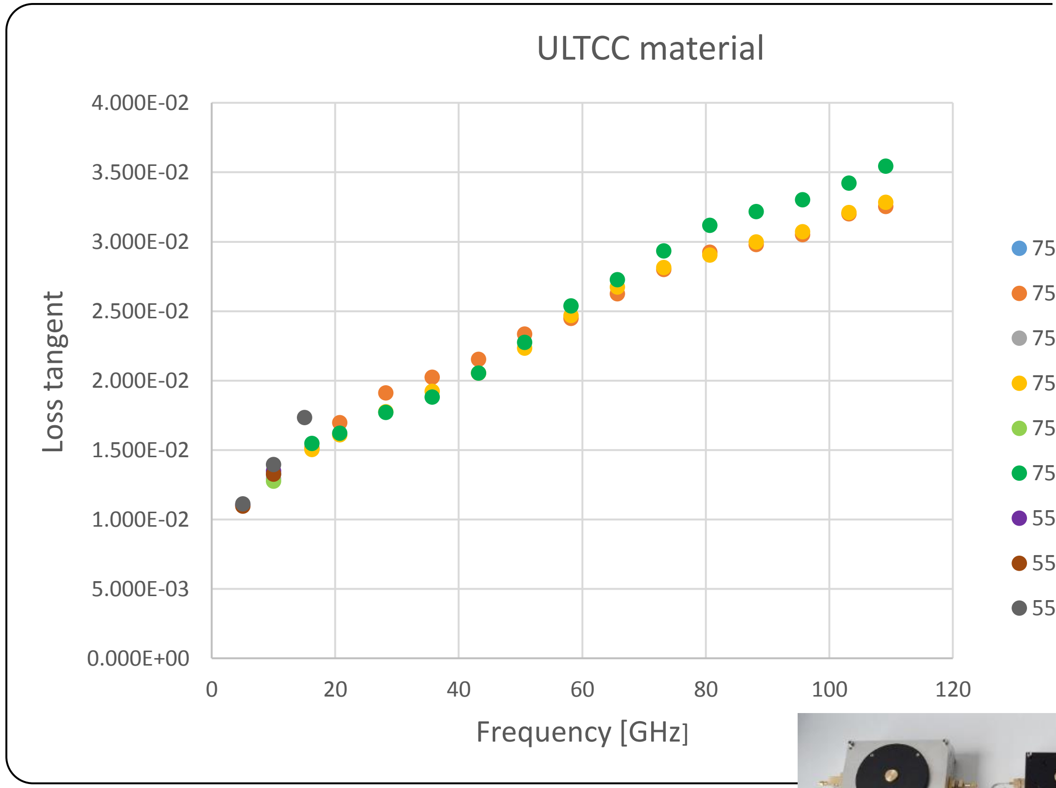


LTCC and ULTCC substrates (2)

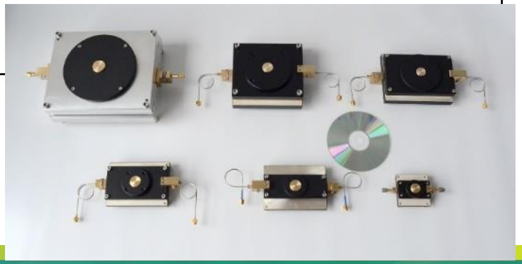
Ultra-Low Temperature Co-fired Ceramics for 6th Generation Electronic Packaging **(ULTCC6G_EPac) project**

ULTCC material developed in ULTCC6G_EPac Fraunhofer IKTS





Thickness variation – major issue for Dk uncertainty



Family of SPDR fixtures

LTCC and ULTCC substrates (2)

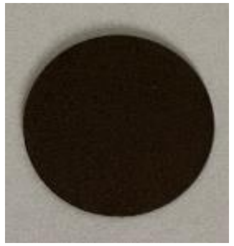
ULTCC6G_EPac **project activities**

Expected by chemical composition:

Dk= 4-6.5

Df= 0.0005-0.005

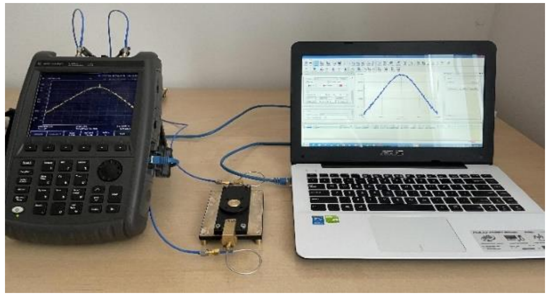
Li_2WO_4+4% $CuBi_2O_4$



Li_2WO_4+4%$AlF_3CaB_4O_7$

$LiBO_2$+4% $CuBi_2O_4$

$LiBO_2$+4%$AlF_3CaB_4O_7$



SPDR 10GHz measurement setup

PARAMETERS OF ULTCC MATERIALS MEASURED WITH 10 GHZ SPDR

Sample name	***Thickness [mm]***	***Dielectric constant***	***Loss tangent***
Li_2WO_4 with 4 wt.% $CuBi_2O_4$	0.485 ± 0.015	5.40 ± 2.5%	0.00200 ± 3%
Li_2WO_4 with 4 wt.% $AlF_3CaB_4O_7$	0.64 ± 0.030	6.52 ± 4%	0.00233 ± 3%
$LiBO_2$ with 4 wt.% $CuBi_2O_4$	0.6 ± 0.030	5.12 ± 4%	0.00195 ± 3%
$LiBO_2$ with 4 wt.% AlF_3-CaB_4O_7	0.55 ± 0.020	4.48 ± 3%	0.00328 ± 3%

M. Olszewska-Placha, D. Szwagierczak, B. Synkiewicz-Musialska, J. Rudnicki, J. Kulawik, "GHz Characterisation of dielectric properties of ultra-low temperature co-fired ceramic materials for 6G systems application", 24th International Microwave and Radar Conference, 12-14 Septemeber 2022, Gdansk, Poland.

Temperature dependent measurements

TC for relative permittivity of LTCC and ULTCC with SPDRs

Control PC with MMS app *Handheld VNA* *Climatic chamber with 10GHz SPDR*

Up to 110 deg C in standard SPDRs configuration

Temperature dependent measurements with FPOR under development

Temperature dependent measurements

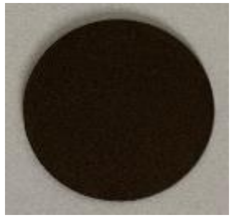
Temperature and humidity dependent measurements

ULTCC6G_EPac **project activities**

LTCC Sample 1

ULTCC Sample 1

ULTCC_c Sample 1



Sample	*Method*	*Dk*	*Df*	*Humidity [%]*	*Temperature coefficient Dk [ppm] (25→85°C)*
LTCC Sample 1	SPDR 10GHz	5.61	0.000995	35	***120***
LTCC Sample 2	SPDR 10GHz	5.62	0.000110	35	***91***
ULTCC Sample 1	SPDR 10GHz	10.02	0.02673	35	***711***
ULTCC Sample 1	SPDR 15GHz	9.88	0.03038	35	***515***
ULTCC Sample 2	SPDR 15GHz	9.91	0.02136	35	***494***
ULTCC_c Sample 1	SPDR 15GHz	5.43	0.00160	35	***170***
ULTCC_c Sample 1	SPDR 15GHz	5.32	0.00155	5	***300***

Temperature dependent measurements

Temperature and humidity dependent measurements

ULTCC6G_EPac **project activities**

Sample	*Method*	*Dk*	*Df*	*Humidity [%]*	*Temperature coefficient Dk [ppm] (25→85°C)*
LTCC Sample 1	SPDR 10GHz	5.61	0.000995	35	***120***
LTCC Sample 2	SPDR 10GHz	5.62	0.000110	35	***91***
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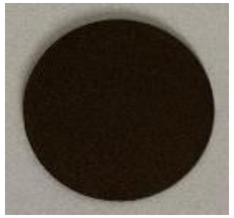
ULTCC Sample 1	SPDR 15GHz	9.88	0.03038	35	***515***
ULTCC Sample 2	SPDR 15GHz	9.91	0.02136	35	***494***
ULTCC_c Sample 1	SPDR 15GHz	5.43	0.00160	35	***170***
ULTCC_c Sample 1	SPDR 15GHz	5.32	0.00155	5	***300***

LTCC Sample 1

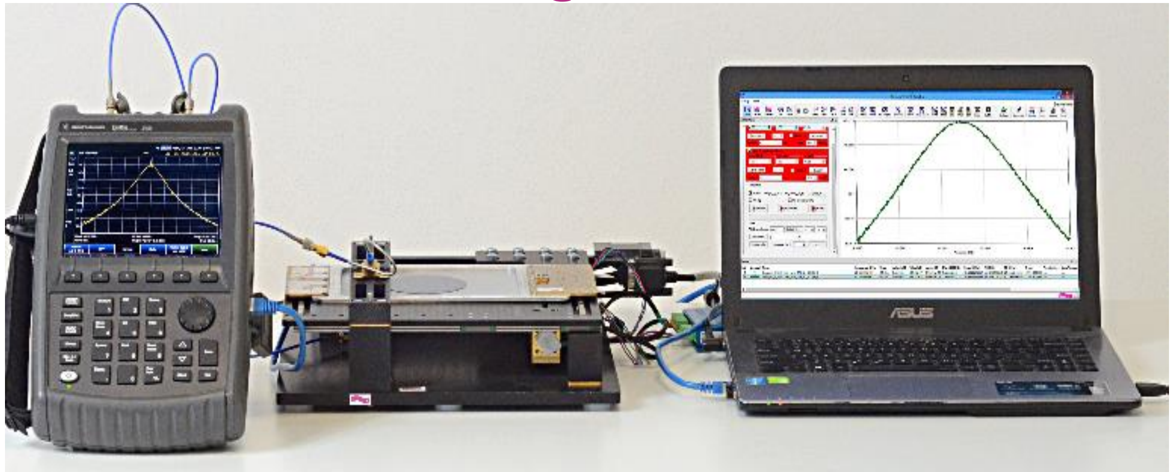
ULTCC Sample 1

ULTCC_c Sample 1

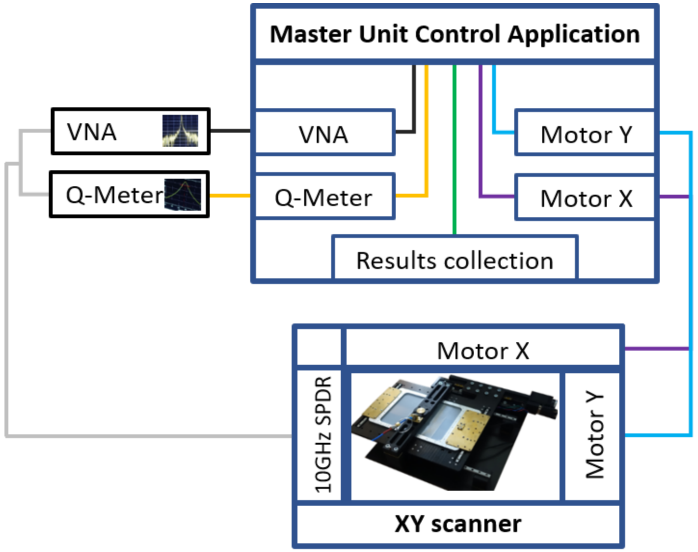


2D imaging of material parameters (1)

2D SPDR scanner @ 10GHz

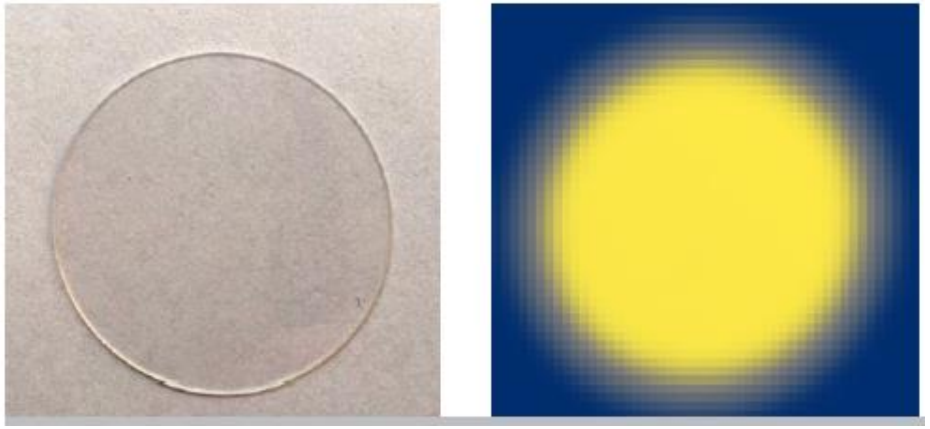


- 2D SPDR-based scanner
- 10GHz for higher spatial resolution
- For low-loss dielectrics and high-resistivity semiconductors
- Maximum sample size: 80 x 120 mm
- 2D maps of Dk, Df, and resistivity



Fully automated measurement procedure

2D surface map of dielectric constant of quartz

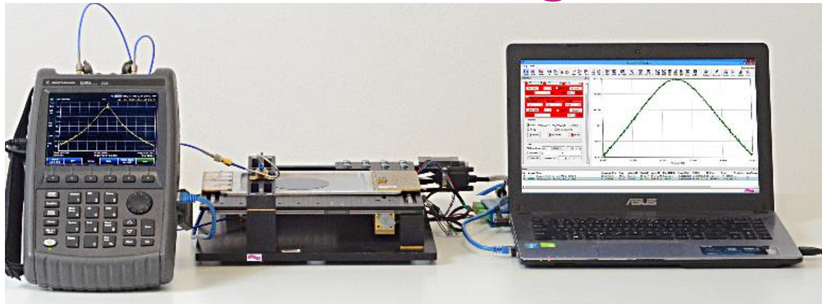


2D imaging of material parameters (2)

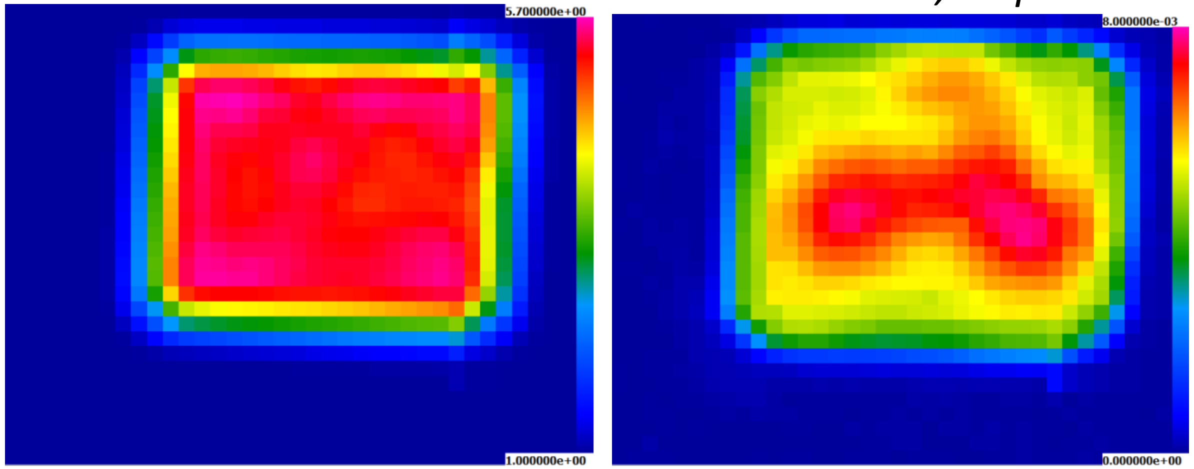
Surface-wise measurements of LTCC and ULTCC materials

ULTCC6G_EPac **project**

2D SPDR scanner @ 10GHz

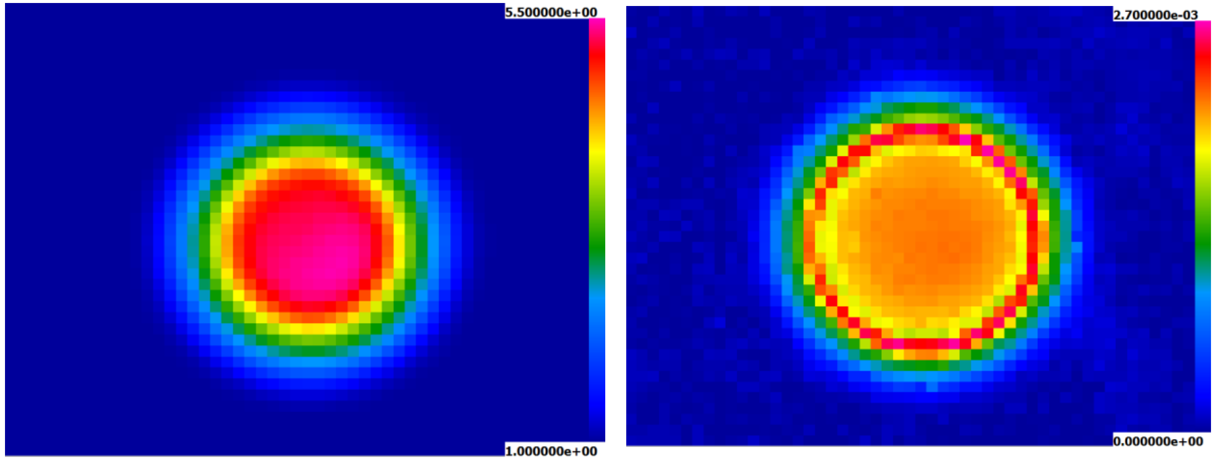


LTCC - 60 x 70 mm, step: 2mm



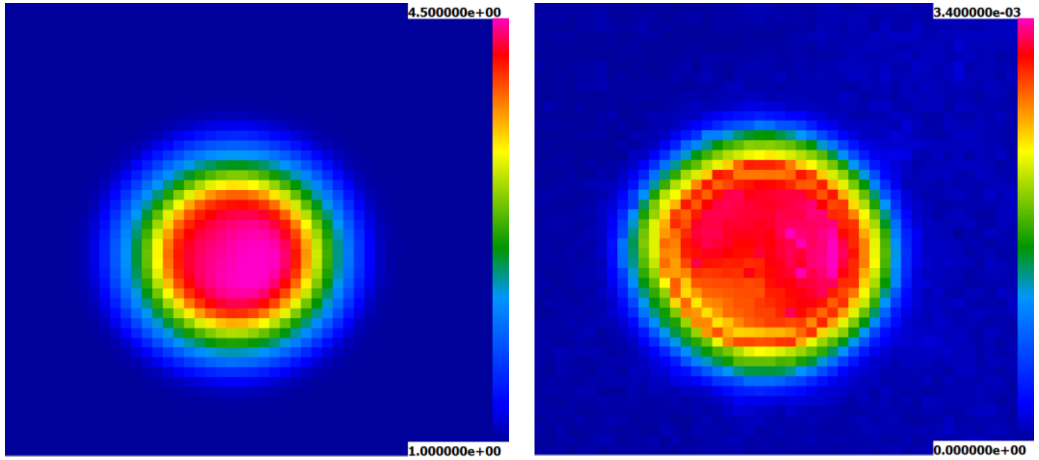
Dk nonuniformities related to thickness variation

ULTCC - Li_2WO_4 with 4 wt.% $CuBi_2O_4$



40 x 50 mm, step: 1mm

ULTCC - $LiBO_2$ with 4 wt.% AlF_3-CaB_4O_7

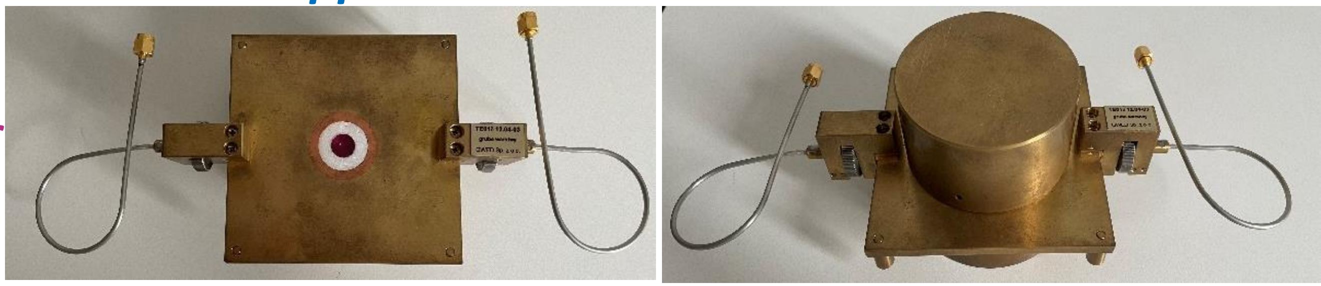


40 x 45 mm, step: 1mm

Conductor testing

- ❑ Industry need for testing and standards
- ❑ iNEMI *Reliability & Loss Properties of Copper Foils for 5G Applications* project
- ❑ Investigation of surface roughness
- ❑ Surface resistance and effective conductivity
- ❑ Sapphire Dielectric Resonators (SaDR)
- ❑ SaDR – dual mode device (e.g. 13.5 GHz and 20 GHz)
- ❑ Fabry-Perot Open Resonator – prototype within 20 – 50 GHz
- ❑ Accuracy ± 2%
- ❑ Testing methods in iNEMI project

Sapphire Dielectric Resonator



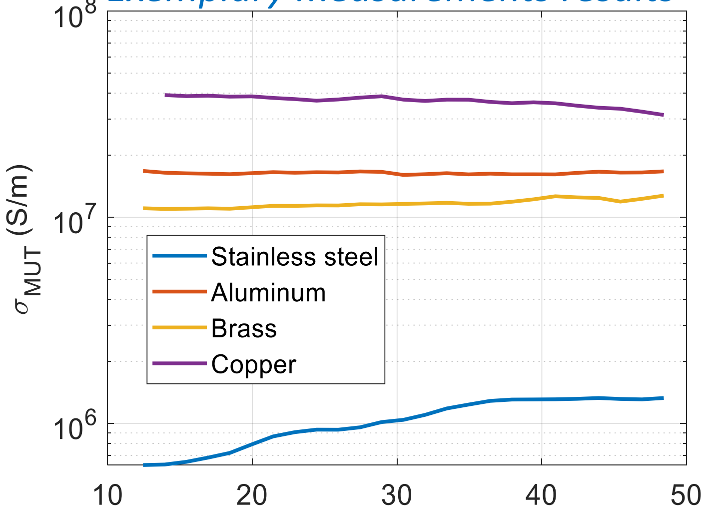
200 um copper foil @ 13.5 GHz: $\sigma=5.45 \cdot 10^7$ S/m

9 um copper foil @ 13.5 GHz: $\sigma=4.64 \cdot 10^7$ S/m

Fabry-Perot Open Resonator

*

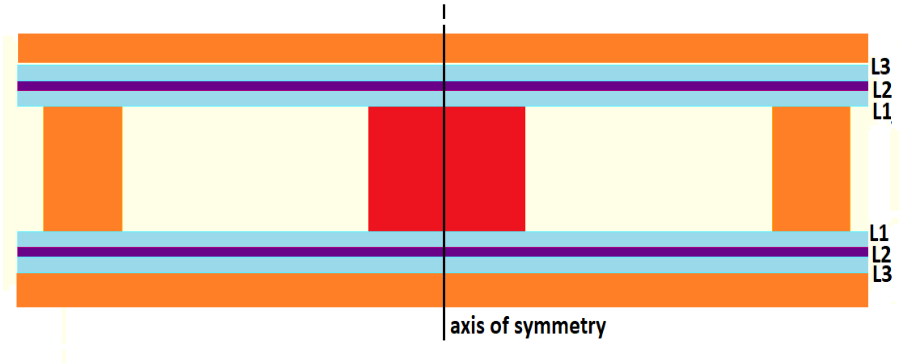
Exemplary measurements results



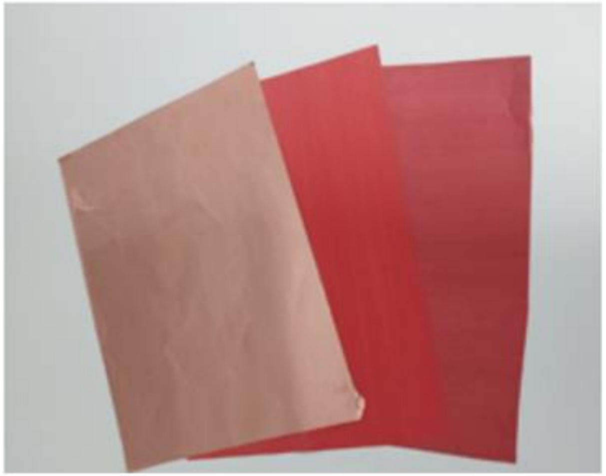
**based on the setup proposed for solid metals in the IMS 2020 paper by J.Cuper et al.: doi: 10.1109/IMS30576.2020.9224069 validated but under development for metal foils*

Conductor testing (2)

Conceptual scheme of SaDR



Copper foil samples



SaDR testing results of copper foils

Foil name	***Expected Surface roughness -rank***	***Rs at 13.8GHz***	***Rs at 20.4GHz***	***Rank at 13.8GHz***	***Rank at 20.4GHz***
Foil 1 – base foil	4	32,108	41,515	4	3
Foil 2	7	34,677	46,407	7	7
Foil 3	3	32,131	41,925	5	5
Foil 4	*3*	32,247	41,946	5	5
Foil 5	8	46,979	67,165	8	8
Foil 6	*2*	31,949	41,494	2	2
Foil 7	5	32,013	41,832	3	4
Foil 8	*1*	31,683	41,186	1	1

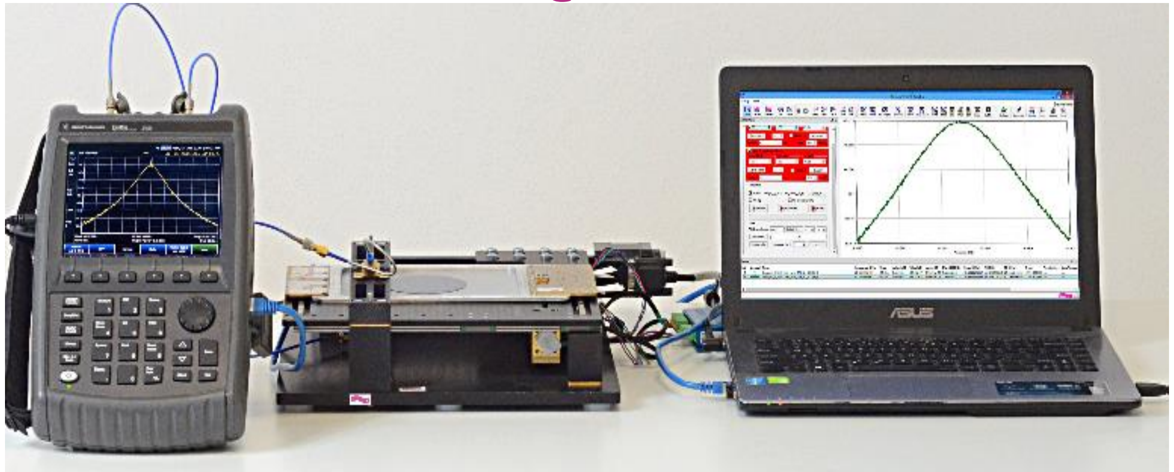
$$\delta Rs = 1.5\% + \delta Q \rightarrow$$

- VNA settings
- vibrations

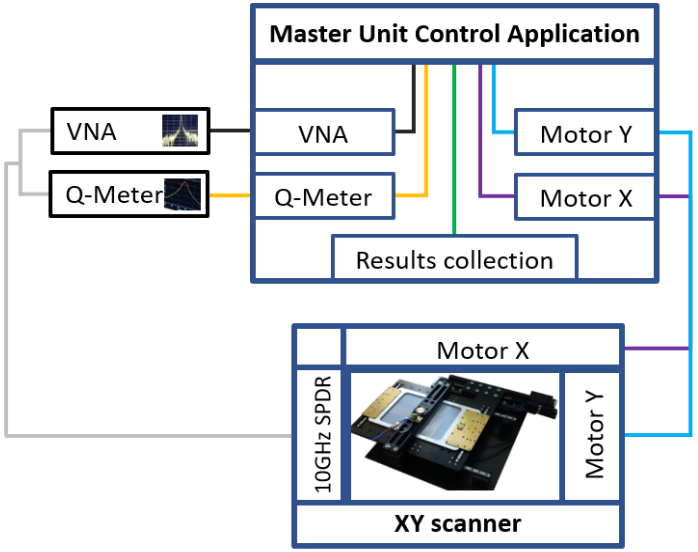
Light and power electronics

2D imaging of material parameters (1)

2D SPDR scanner @ 10GHz



- 2D SPDR-based scanner
- 10GHz for higher spatial resolution
- For low-loss dielectrics and high-resistivity semiconductors
- Maximum sample size: 80 x 120 mm
- 2D maps of Dk, Df, and resistivity



Fully automated measurement procedure

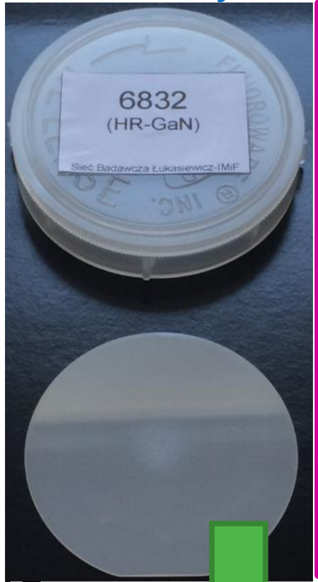
- High densification of semiconductor devices over a single wafer
- Surface-wise measurements of material parameters
  - Substrate
  - Final semiconductor structure/device
  - Repeatability of device parameters (e.g. LED diode)

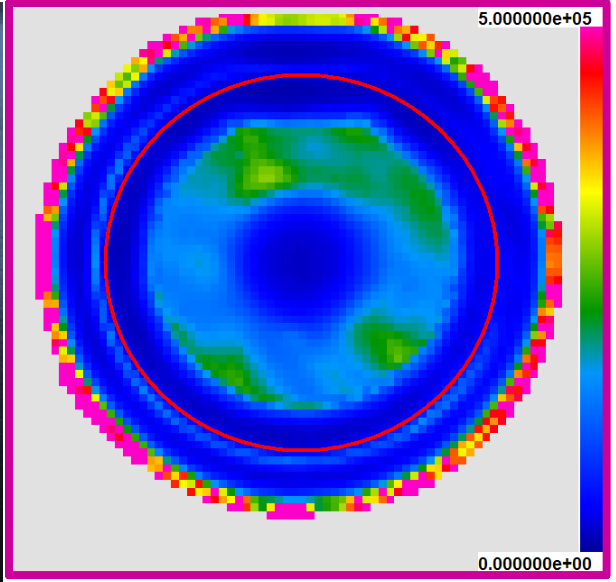
Light and power electronics

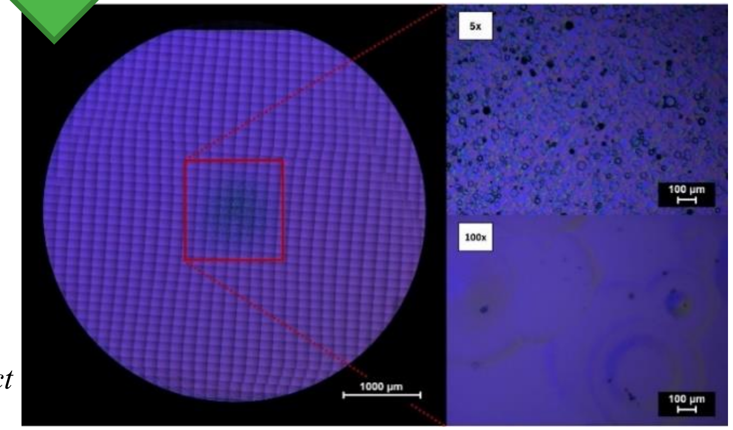
- Quantitative and qualitative measures → usability of material
- Scanning area: 70 mm x 70 mm
- Uniform scanning step: 1 mm
- 5112 measurement points
- HR-GaN template:
  - edge ring inherent to so-called edge effect
  - ca. $2 \cdot 10^4$ Ωcm in the centre (dark blue),
  - ca. $5 \cdot 10^4$ Ωcm along the inner ring (light blue)
  - up to $1.2 - 3 \cdot 10^5$ Ωcm across outer SUT's area (blue-green).

Higher range for resistivity is needed
Device needs to be enhanced towards that requirement

2D surface map of resistivity of semiconductor wafers [Ohm cm]







M-ERA.NET3 I4BAGS project
**samples by L-IMP, Poland*

Electronic and food liquids

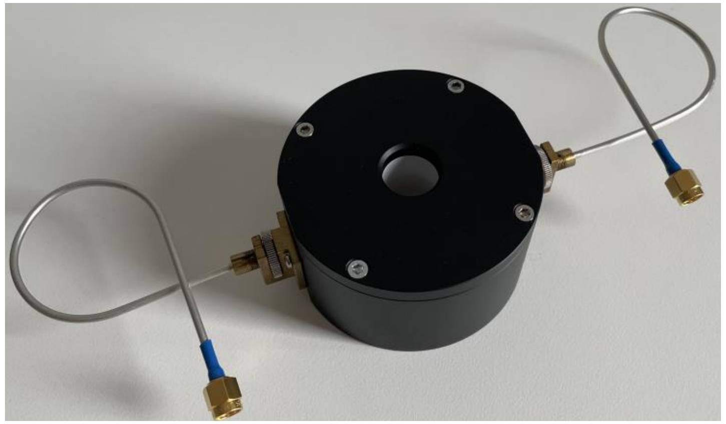
Measurements of liquids (1)

- Dielectric characterization of “loose” materials
  - Liquids
  - Powders
- Electronic coolants
- Food industry
- Raw materials producers
- Characterization with resonant methods
  - Cavity devices
  - Fabry-Perot Open Resonator

Measurements of liquids (2)

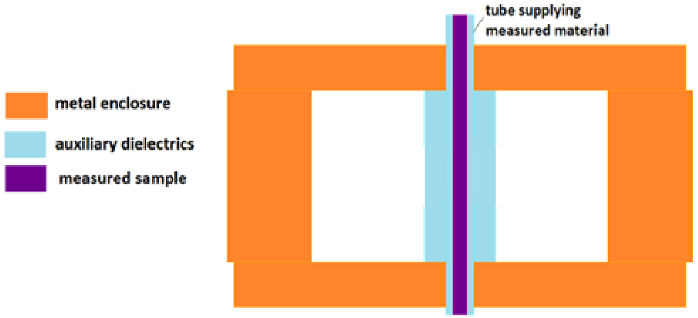
Resonant methods are proven to be the most accurate among microwave material characterisation methods

Low frequency dielectric resonator cavities



Dielectric resonator cavity at 1 GHz

Higher frequency cavity resonators



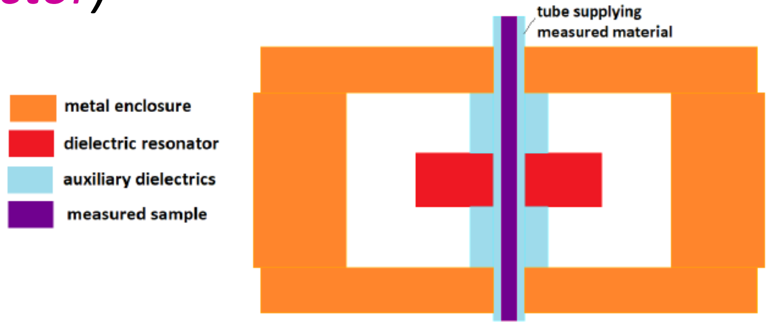
24-GHz Cavity resonator
(with fused silica tube, rubber tube and syringe)

Fabry-Perot Open Resonator

Single solution for 20-50GHz

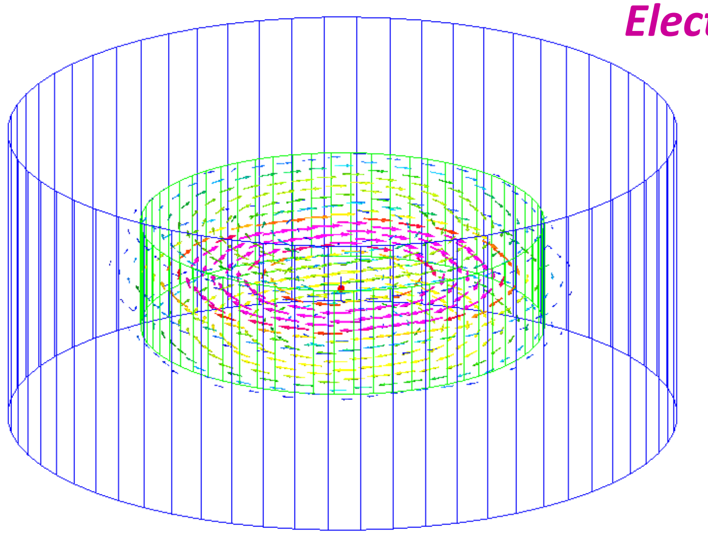
Measurement methods

- $TE_{01\delta}$ resonance mode *(described with resonant frequency and Q-factor)*
- Electric field mostly confined within the dielectric pill
- Circumferential electric field
  → no issues with galvanic connection of the lid
- Zero electric field at $\rho=0$
  → no risk of supressing resonance if lossy sample is inserted

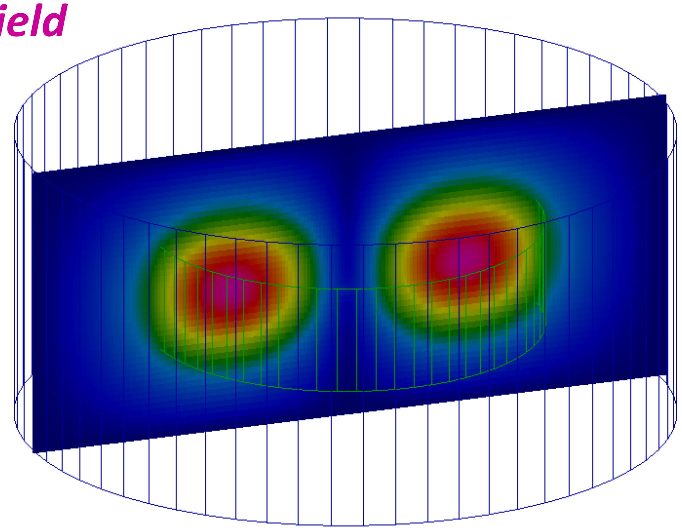


Resonance mode within dielectric resonator cavity *

Electric field

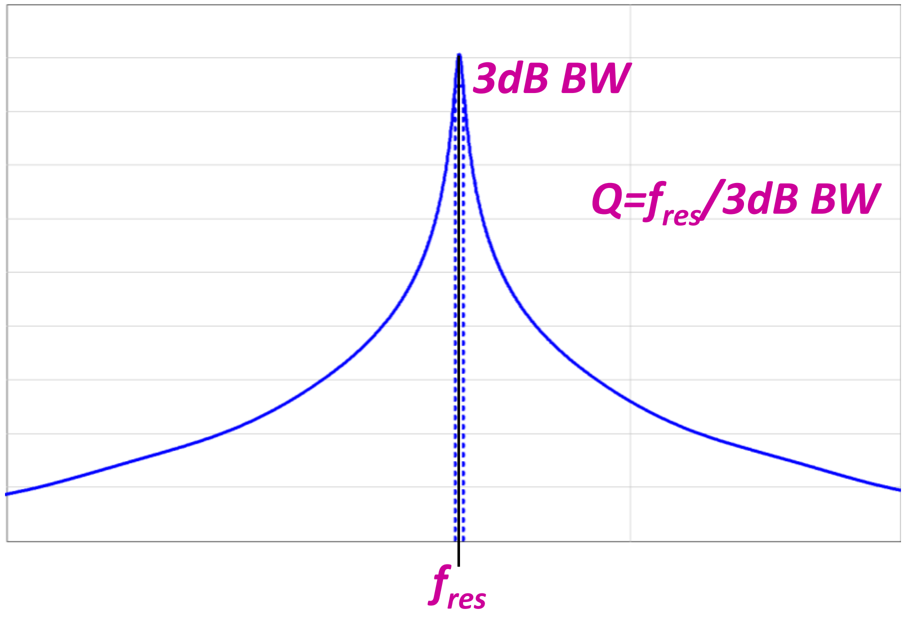


Vector view



Amplitude view (cross section)

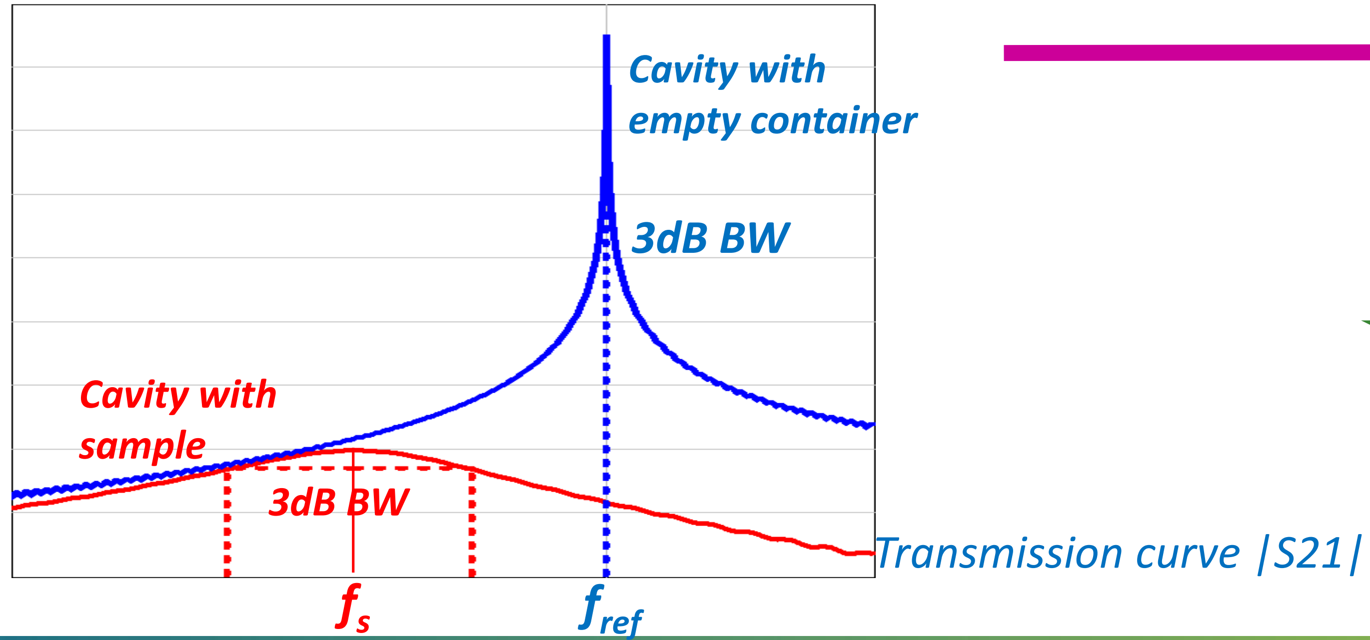
Transmission curve |S21|

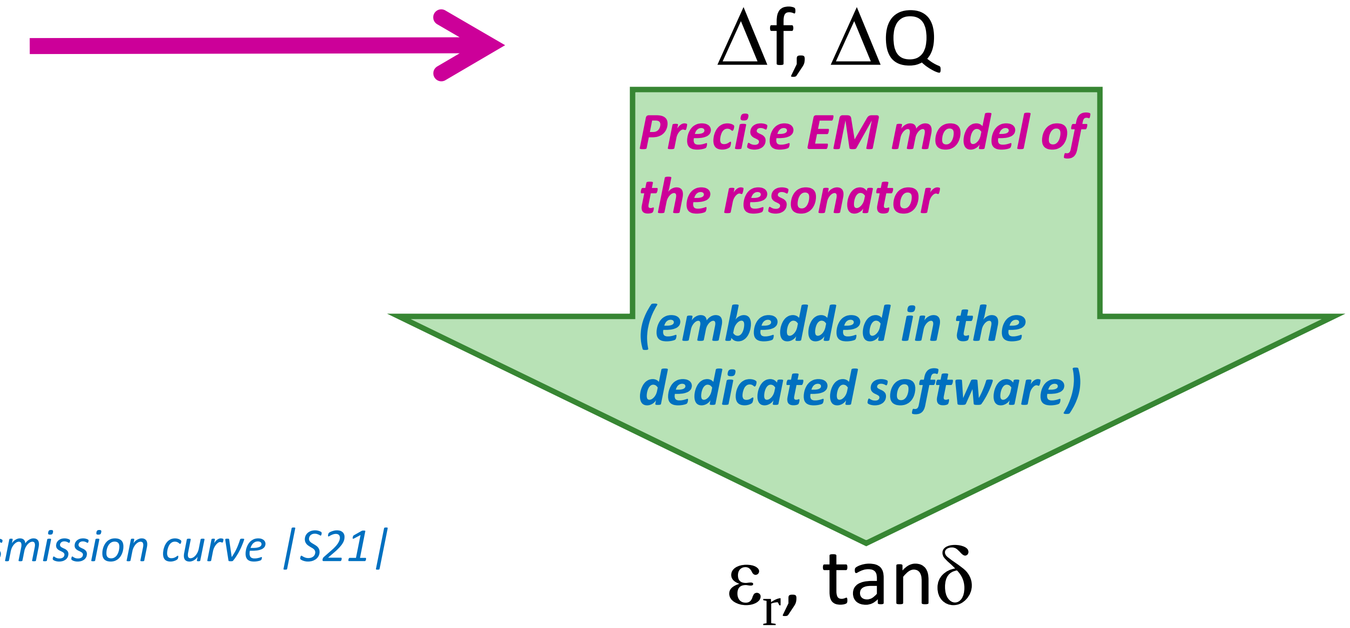


**** Obtained with QuickWave 3D software***

Measurement methods (2)

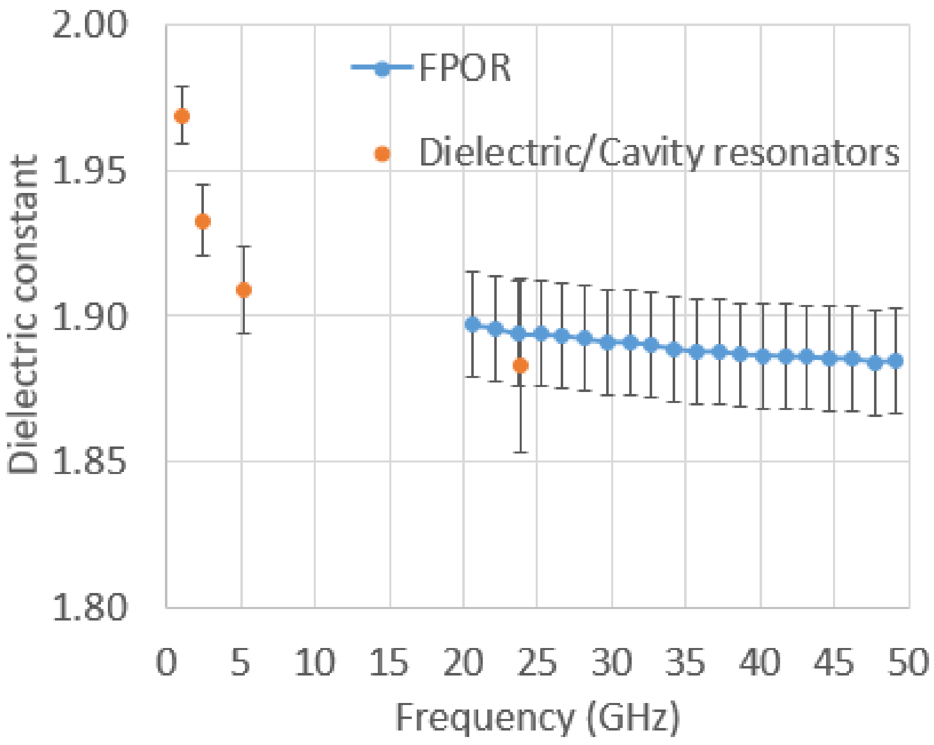
- Two/three stage measurement
- Reference measurement – cavity with empty container (f_{ref} and Q_{ref})
  → the inner diameter of the container needs to be precisely calibrated
- Measurement of sample-loaded cavity (f_s and Q_s)
- Scalar measurement of transmission curve (|S21|) is typically sufficient





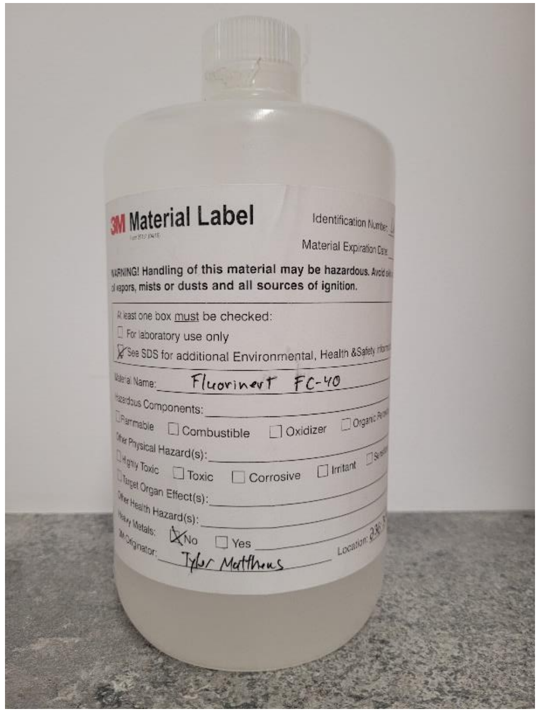
Measurements of liquids (3)

Measurement results for a well-known electronics coolant liquid obtained with all resonant methods

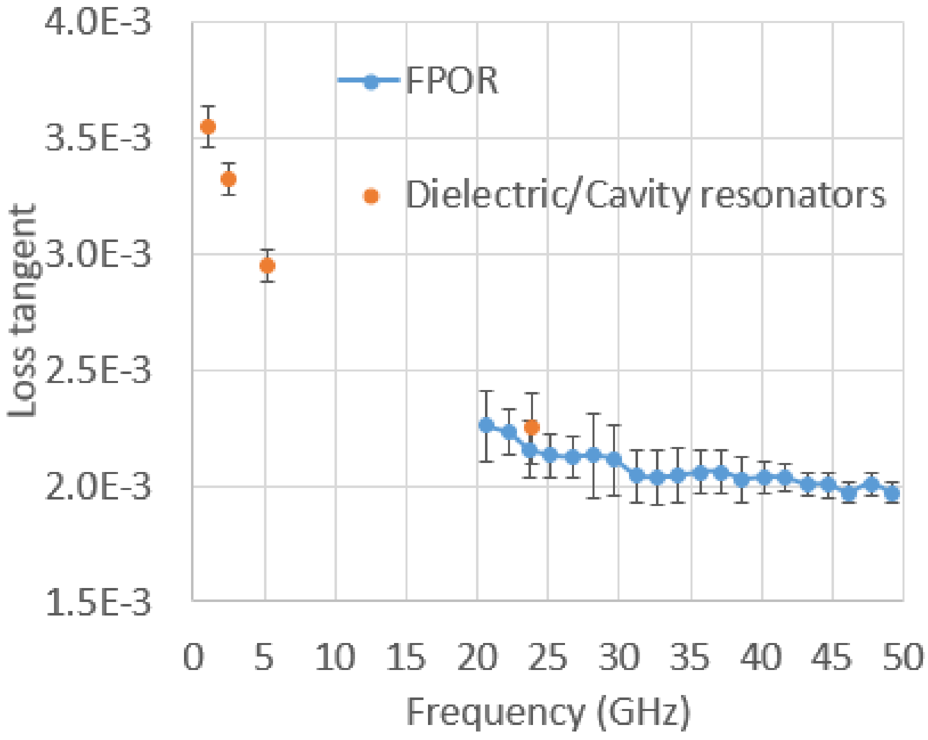


Dielectric constant

Uncertainty of Dk <1%



Fluorinert
(3M FC-40)



Loss tangent

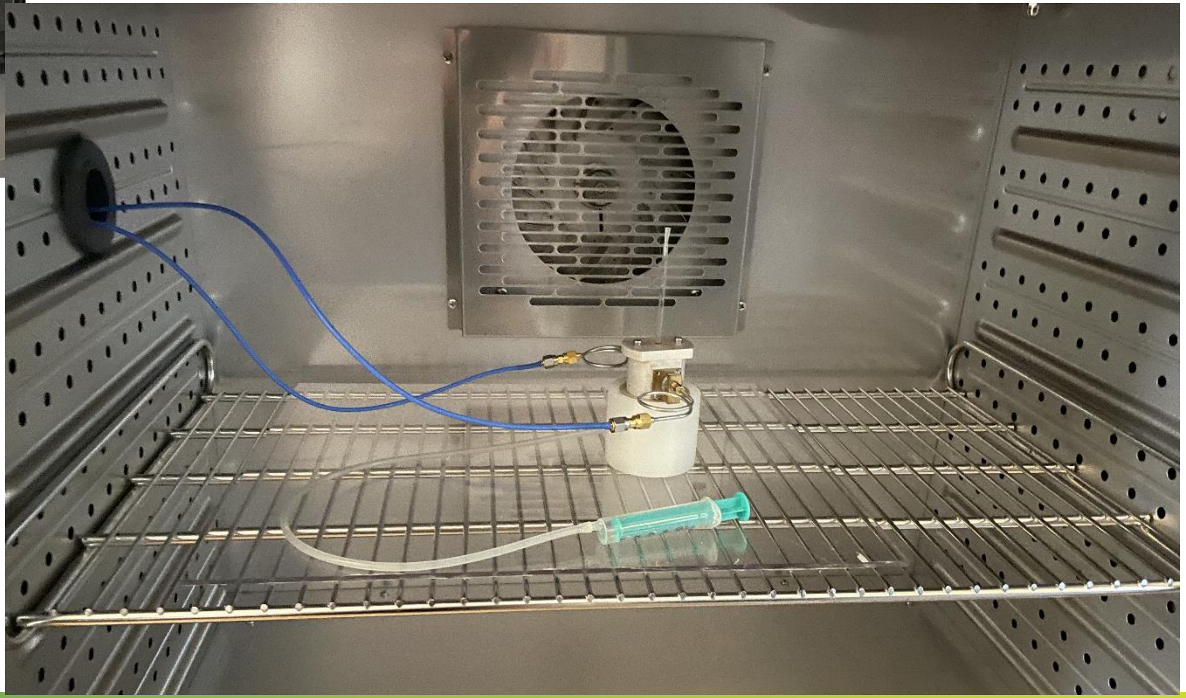
Measurements versus temperature

Dielectric characterization versus temperature

PC with control app

VNA

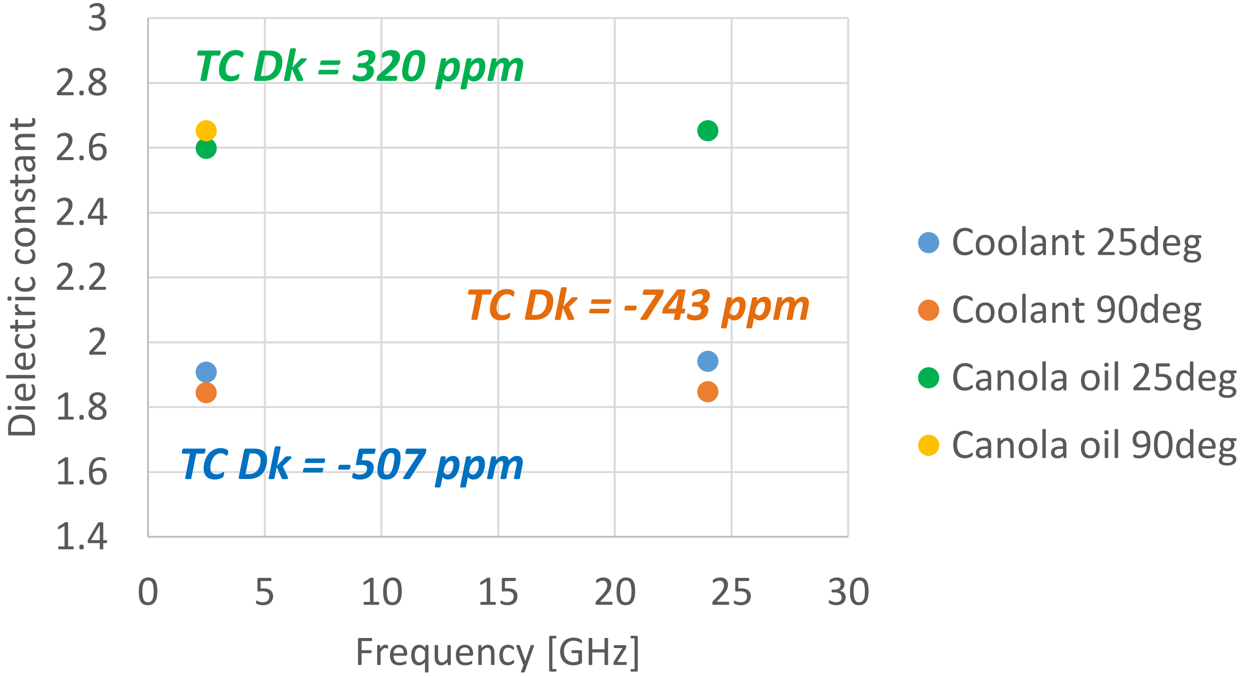
Climatic chamber with cavity resonator @24GHz

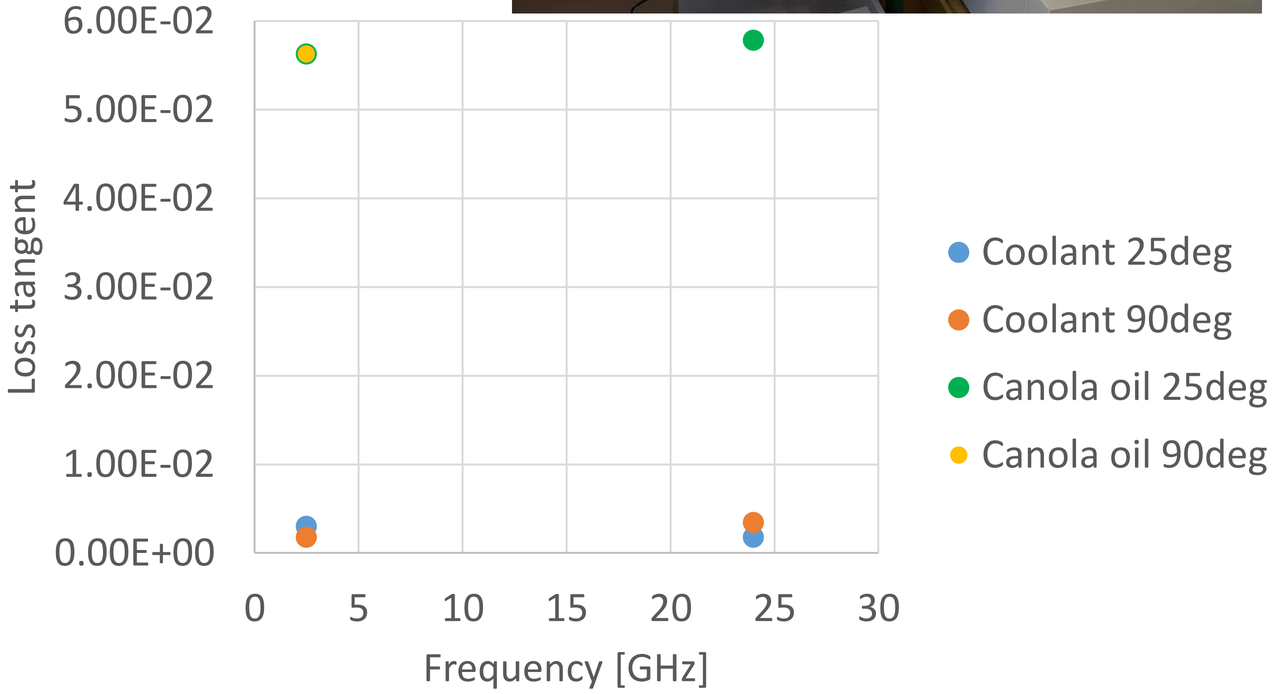


Measurements versus temperature (2)

Dielectric characterization versus temperature

coolant liquid and canola oil





Uncertainty of Dk due to variation of diameter of quartz tube

@2.5 GHz – 0.1% *@24GHz – 0.7%*

Energy materials

Energy materials

- Efficient energy systems
- Well-controllable energy devices and systems
- Electrical characterization

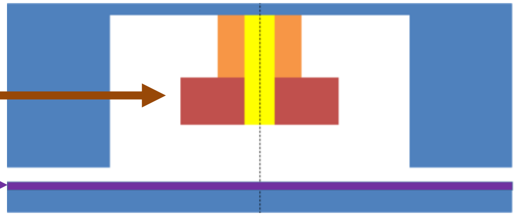
- Semiconductor materials for photovoltaic cells (SPDR scanner)
- Battery testing – anodes for battery cells

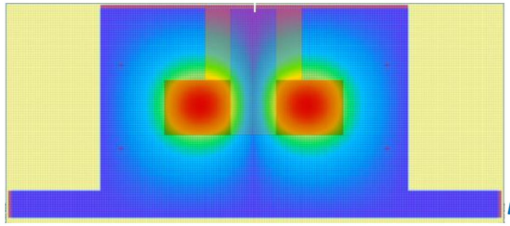
- 2D imaging for qualitative and quantitative measures of parameters uniformity

2D imaging of energy & power materials

Dielectric resonator

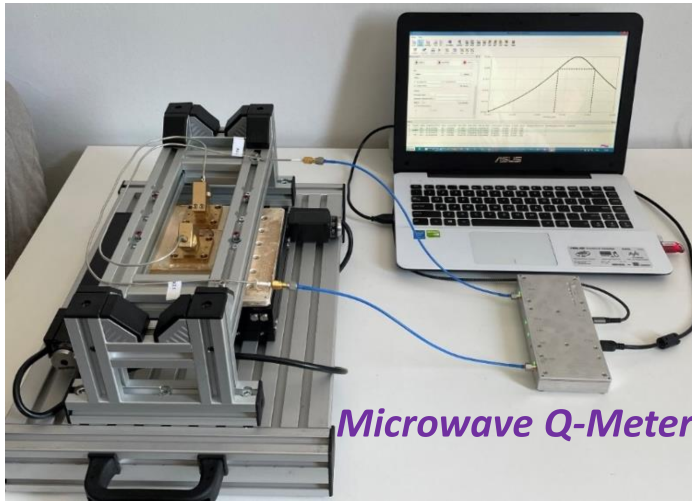
Sample





E field distribution

- ❑ 2D Single Post Dielectric Resonator-based scanner
- ❑ 10GHz for higher spatial resolution
- ❑ For low-resistivity materials, e.g. semiconductors
- ❑ Resistivity and sheet resistance measurements
- ❑ Accuracy ±2%



Microwave Q-Meter

Measurement setup with 2D 10 GHz SiPDR scanner

Nano Bat

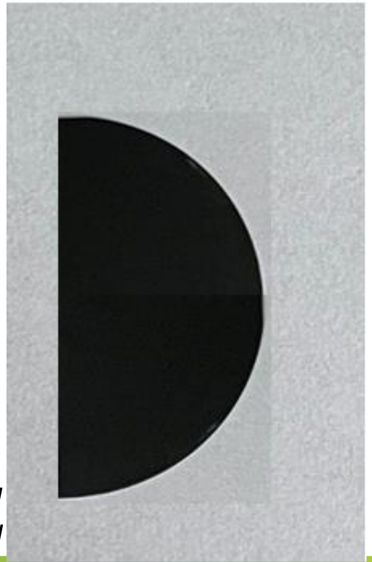
*

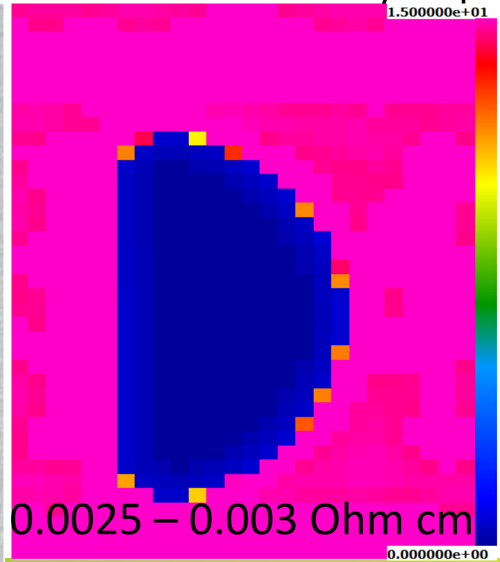
Motorised 2D surface scanner

**courtesy Keysight Technologies, Austria*

Scanner Unit Control App

Semiconductor sample and its 2D resistivity map





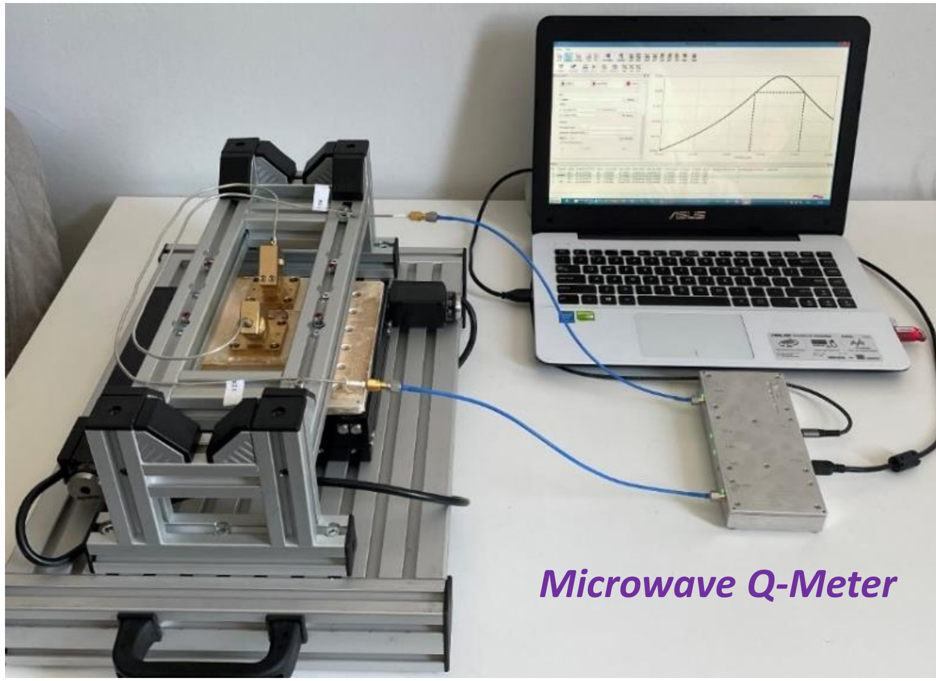
**courtesy SEEN Semiconductors, Poland*

2D imaging of energy materials

- Designed and developed for anode materials on semi-insulating substrates

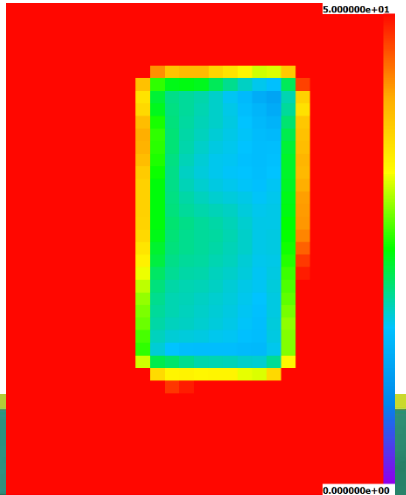
- Adopted to actual anode samples – anode on copper
  - Pre-cycling testing – straightforward
  - Post-cycling testing – battery disassembly needed, protection required

- High control of fabrication process needed to get meaningful results for SEI presence

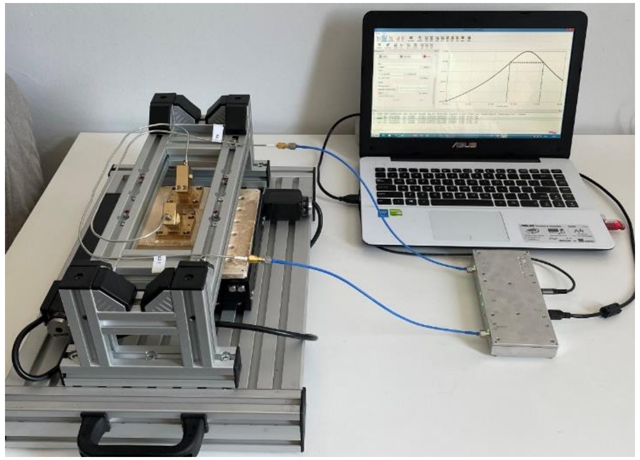


Substrate glass material and sample under test

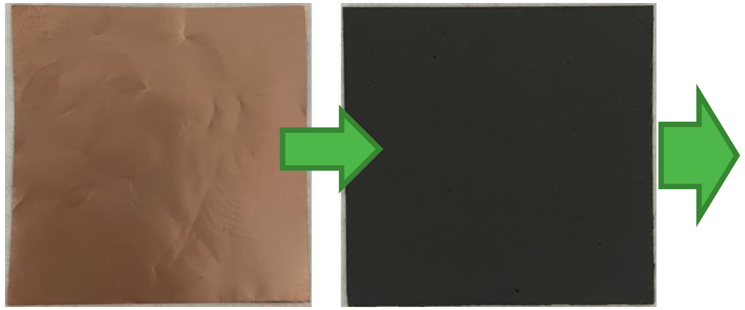
2D map of Rs [Ω/sq.]



2D imaging of battery anodes

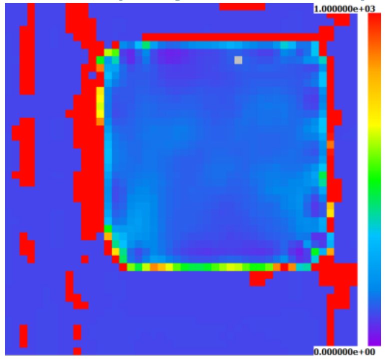


Graphene–based battery anode before cycling



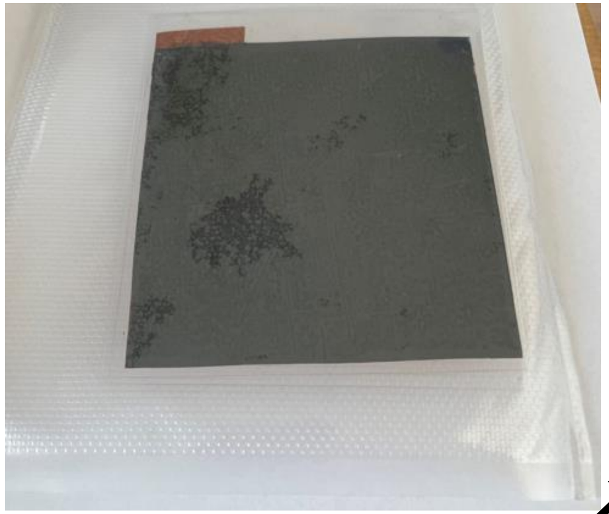
samples courtesy PLEIONE Energy, Greece

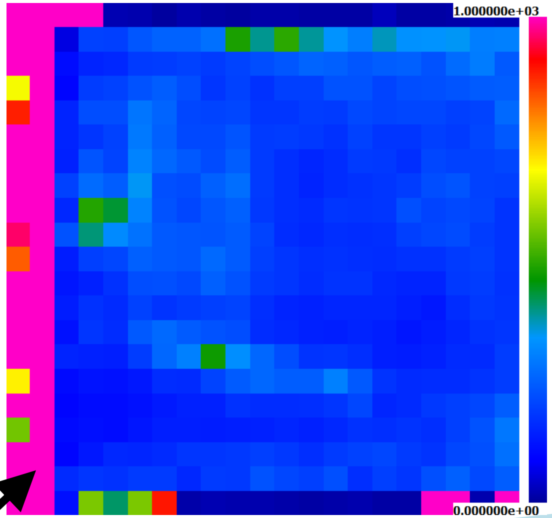
2D map of Rs [Ω/sq.]



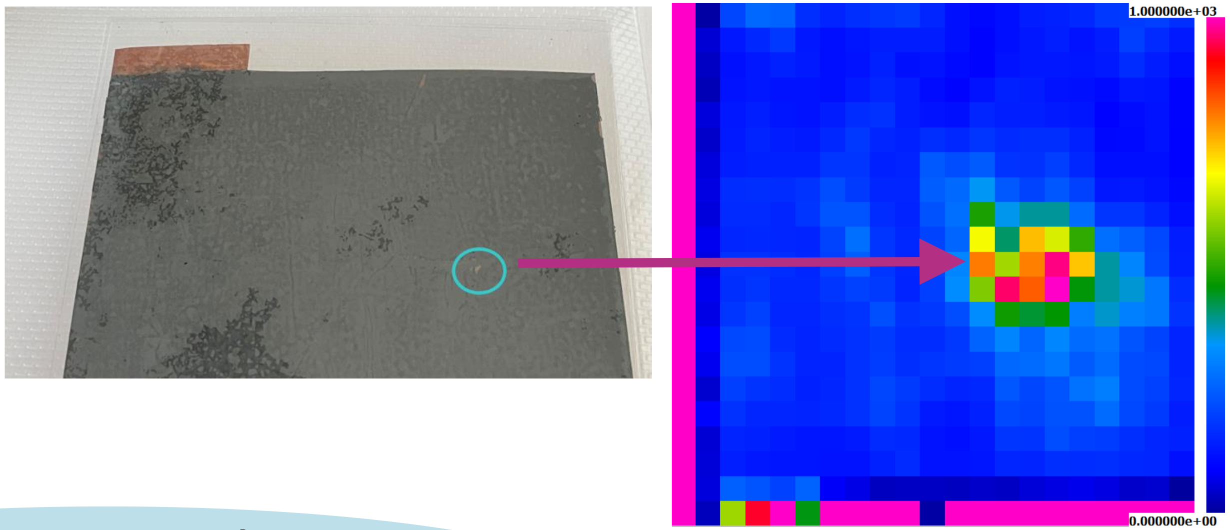
- Rs=85 – 160 [Ω/sq.]
- Scanning range: 80 x 80 mm,
- scanning step: 2mm
- Measurement points: 1681
- Scanning time: ca. 2h

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





Sample edge (protecting foil)



Rs = 110 – 340 [Ω/sq.] –
higher than before cycling → **SEI formation**

Scanning range: 100 x 100 mm
scanning step: 5mm
Measurement points: 441
Scanning time: ca. 30 min

Summary

- Resonant methods have wide spectrum of applications
- Existing methods are applied to new materials
- Enhancements are needed to extend material parameters range
- New dedicated resonant methods are developed depending on material type

- Specific challenges appear for each material type

Acknowledgement

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*under **M-ERA.NET3/2021/83/I4BAGS/2022** contract*

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

Ion Implantation for Innovative Interface modifications in BAttery and Graphene-enabled Systems

QWED, Fraunhofer IKTS, Łukasiewicz IMiF, leti ceatech, Technology Research Institute, inoveos Hyperfrequences en puissance

QWED, Łukasiewicz IMiF, MATERIA NOVA, ionics surface technologies

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

[1] 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.

[2] 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.

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NanoBat

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Thank you for the attention