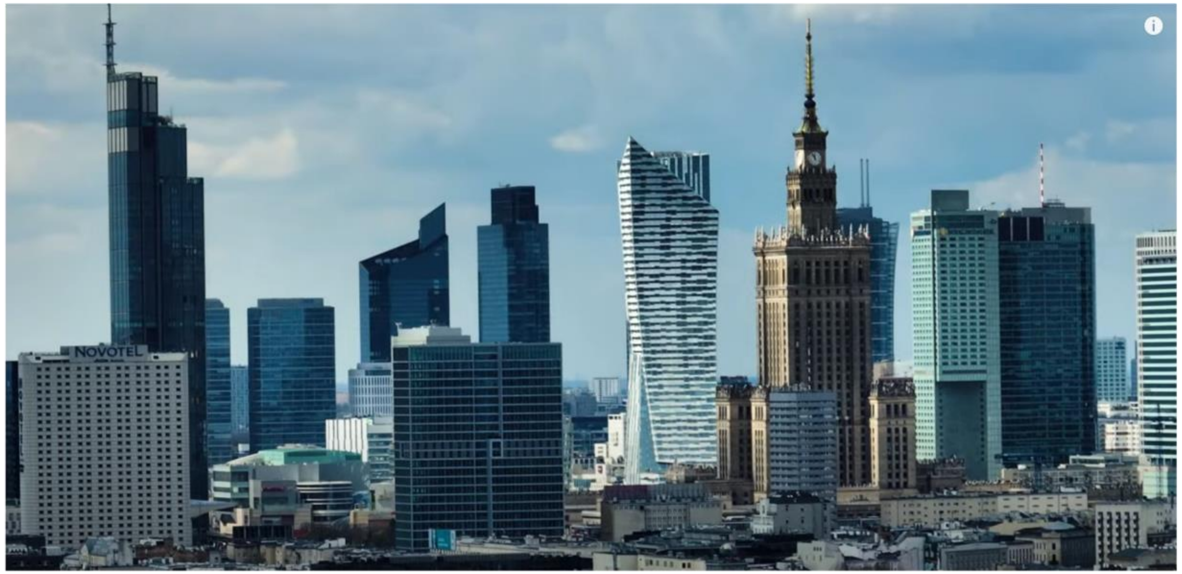
Neutron-irradiation-resistant high-temperature graphene Hall effect sensor for advanced magnetic diagnostics

Tymoteusz Ciuk, PhD

Łukasiewicz Research Network



Institute of Microelectronics and Photonics, Warsaw, Poland

I4Bags

G-Flake

I4BAGS Webinar **January 10, 2023**

Neutron-irradiation-resistant high-temperature graphene Hall effect sensor for advanced magnetic diagnostics

Thermal stability of transport properties

Two-dimensional character **Why graphene?** Relatively high charge carriers mobility

Well-defined charge carriers concentration

Neutron-irradiation-resistant high-temperature graphene Hall effect sensor for advanced magnetic diagnostics

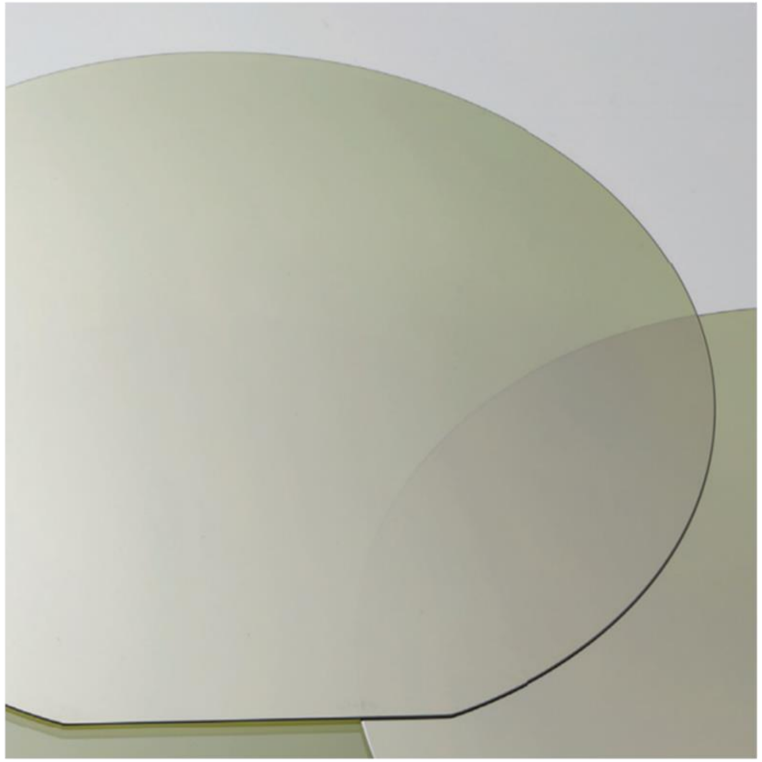
Epitaxy: Chemical Vapor Deposition (CVD)

Carbon source: methane or propane

Substrate: 4H-SiC(0001) or 6H-SiC(0001)

Type: semi-insulating on-axis

Dimensions: 20 mm x 20 mm



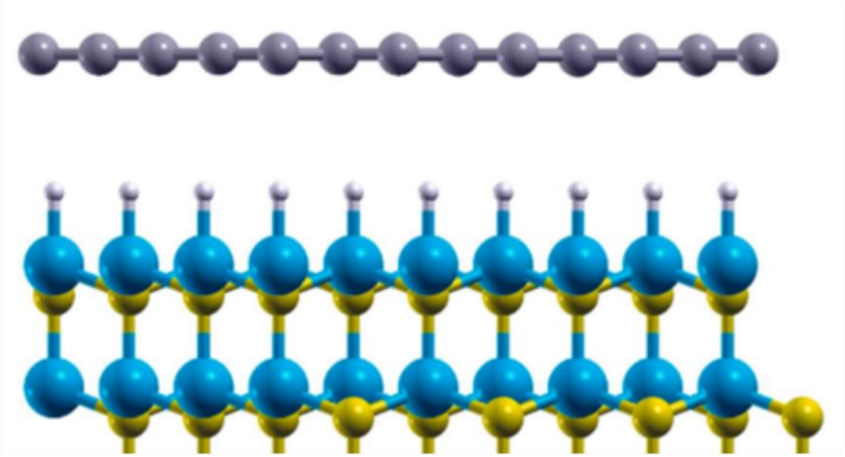
dx.doi.org/10.1016/j.carbon.2015.06.032 dx.doi.org/10.1016/j.carbon.2016.01.093

Neutron-irradiation-resistant high-temperature graphene Hall effect sensor for advanced magnetic diagnostics

Hydrogen intercalation: quasi-free-standing graphene

On 4H-SiC(0001): $p = 1.2$ E13 cm^{-2}

On 6H-SiC(0001): $p = 7.5$ E12 cm^{-2}



doi.org/10.1016/j.apsusc.2020.148668

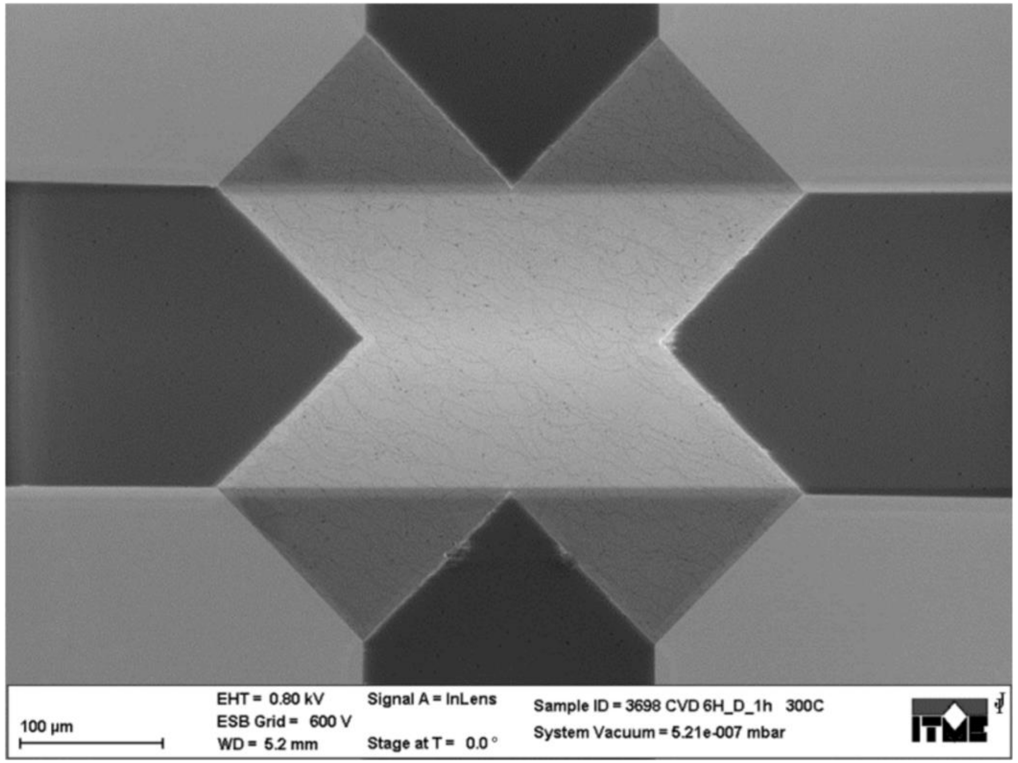
Neutron-irradiation-resistant high-temperature graphene Hall effect sensor for advanced magnetic diagnostics

Principle of operation: classical Hall effect

Configuration: van der Pauw

Active area: equal-arm cross 100 µm x 300 µm

Total dimensions: 1.4 mm x 1.4 mm



doi.org/10.1016/j.carbon.2018.07.049

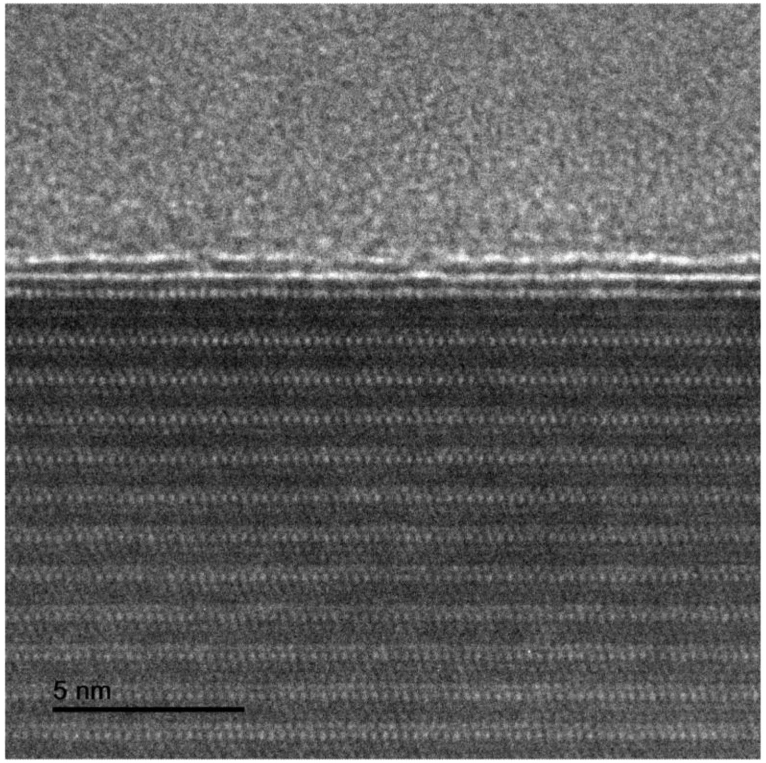
Neutron-irradiation-resistant high-temperature graphene Hall effect sensor for advanced magnetic diagnostics

Passivation: aluminum oxide

Process: atomic layer deposition

Precursors: TMA and DI

Purpose: environmental protection



doi.org/10.1016/j.physe.2022.115264

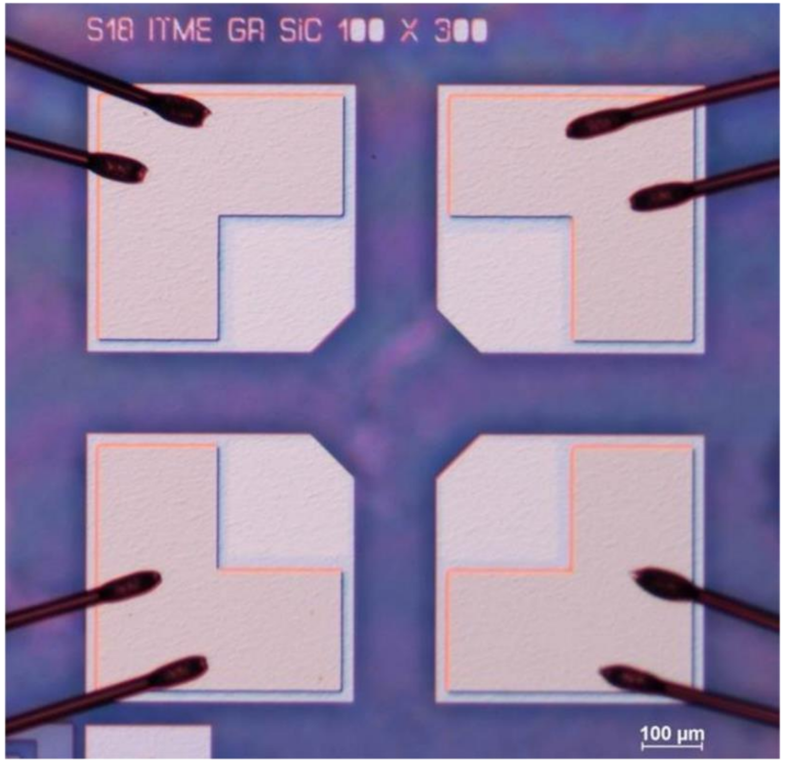
Neutron-irradiation-resistant high-temperature graphene Hall effect sensor for advanced magnetic diagnostics

Mounting: custom holders or ceramic packages

Feed current: < 10 mA

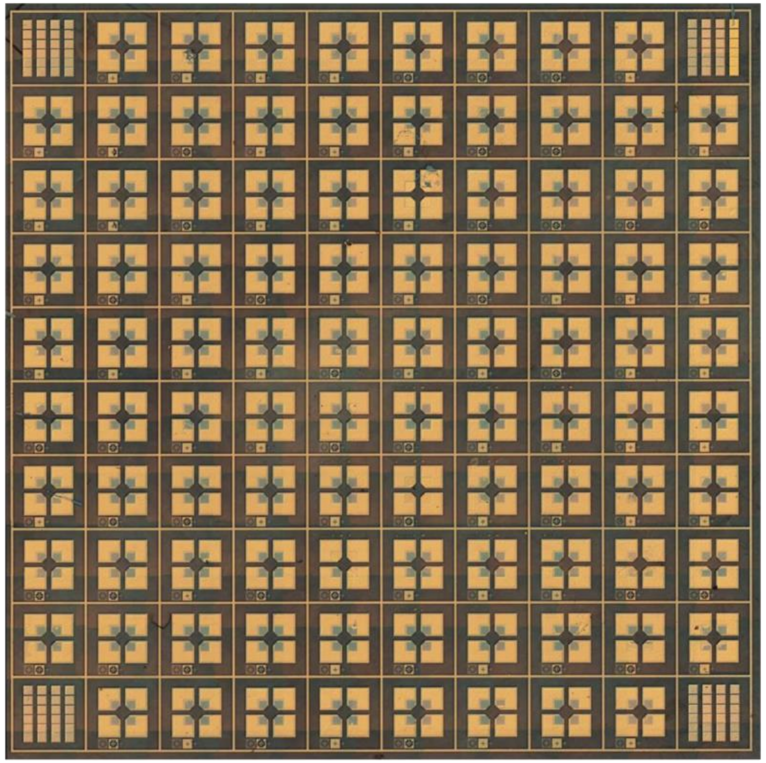
Magnetic induction: 0.55 T

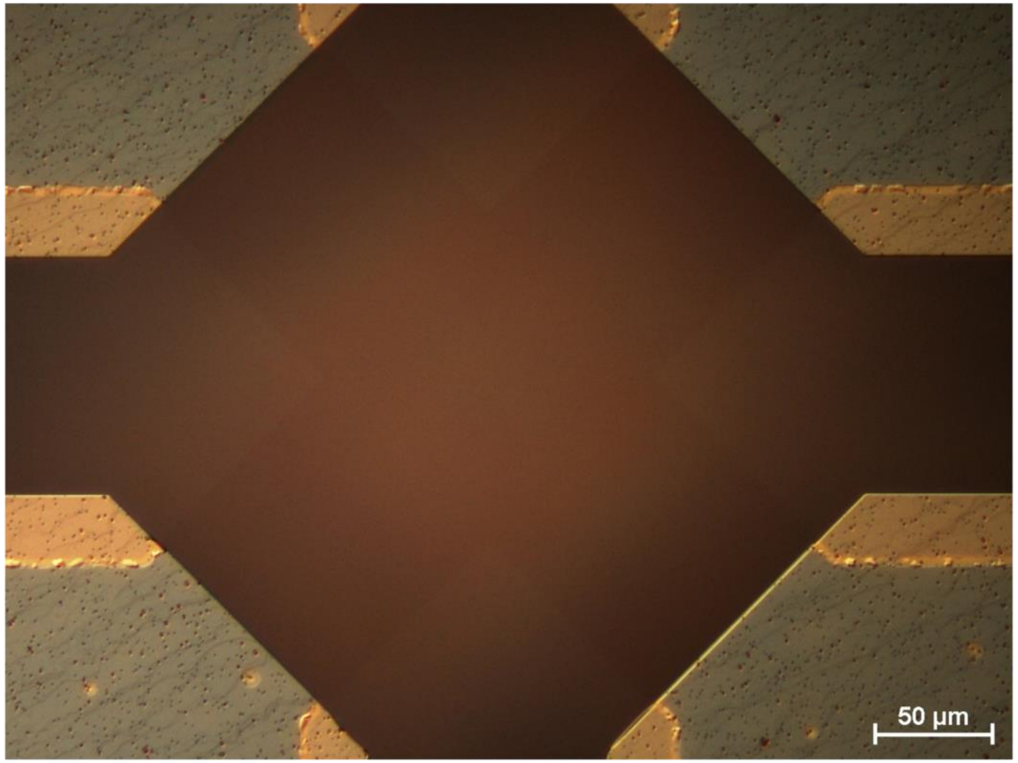
Temperatures: from liquid nitrogen to 500 °C



10.1109/TED.2019.2915632

Neutron-irradiation-resistant high-temperature graphene Hall effect sensor for advanced magnetic diagnostics





doi.org/10.1016/j.physe.2021.114853

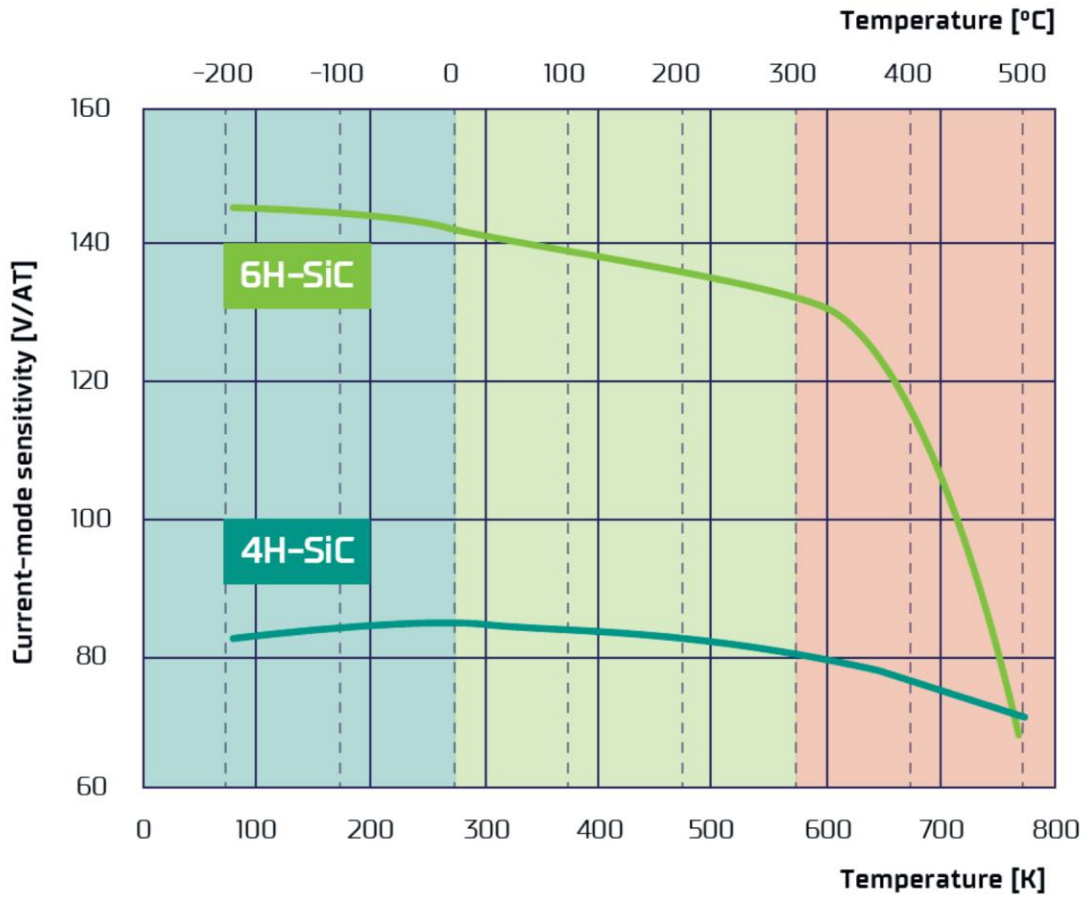
Neutron-irradiation-resistant high-temperature graphene Hall effect sensor for advanced magnetic diagnostics

Two platforms: 6H-SiC and 4H-SiC

Two levels of sensitivity: 140 V/AT, 80 V/AT

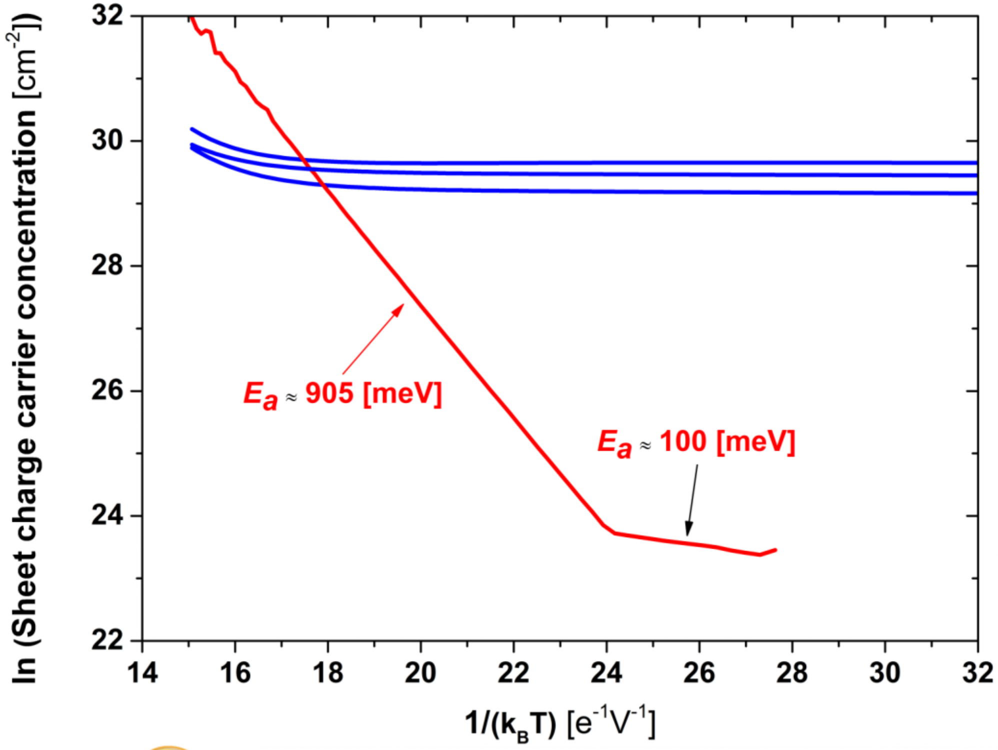
Start temperature: liquid nitrogen

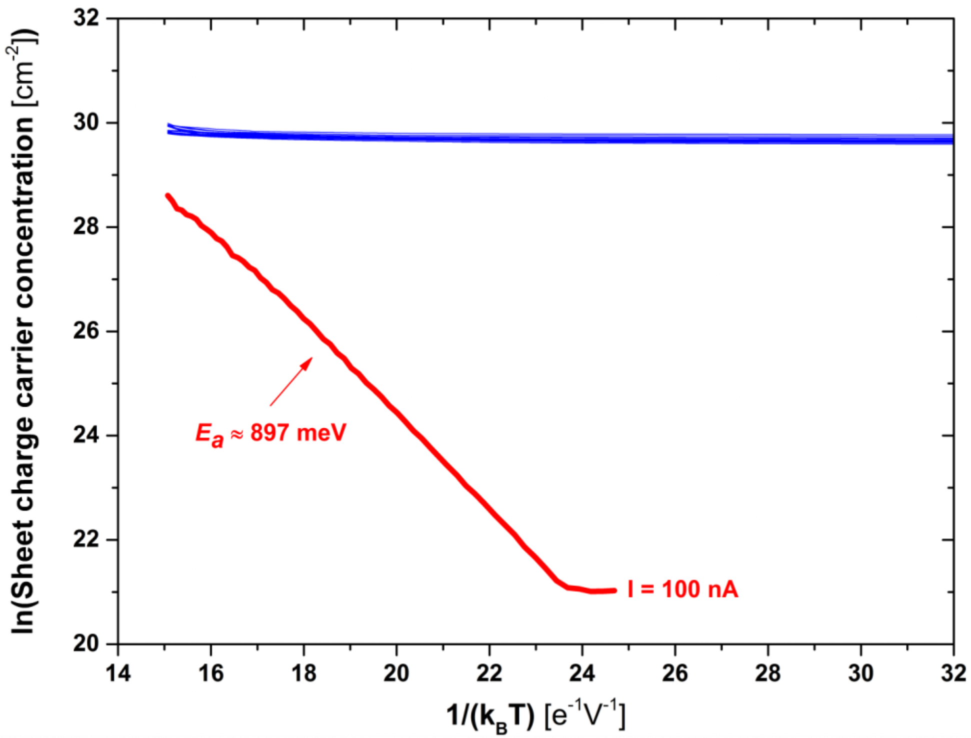
End temperature: 500 °C



Neutron-irradiation-resistant high-temperature graphene Hall effect sensor for advanced magnetic diagnostics

Double-carrier transport: holes in QFS graphene and thermally-activated electrons emitted in the bulk of the semi-insulating 6H-SiC(0001) and 4H-SiC(0001)





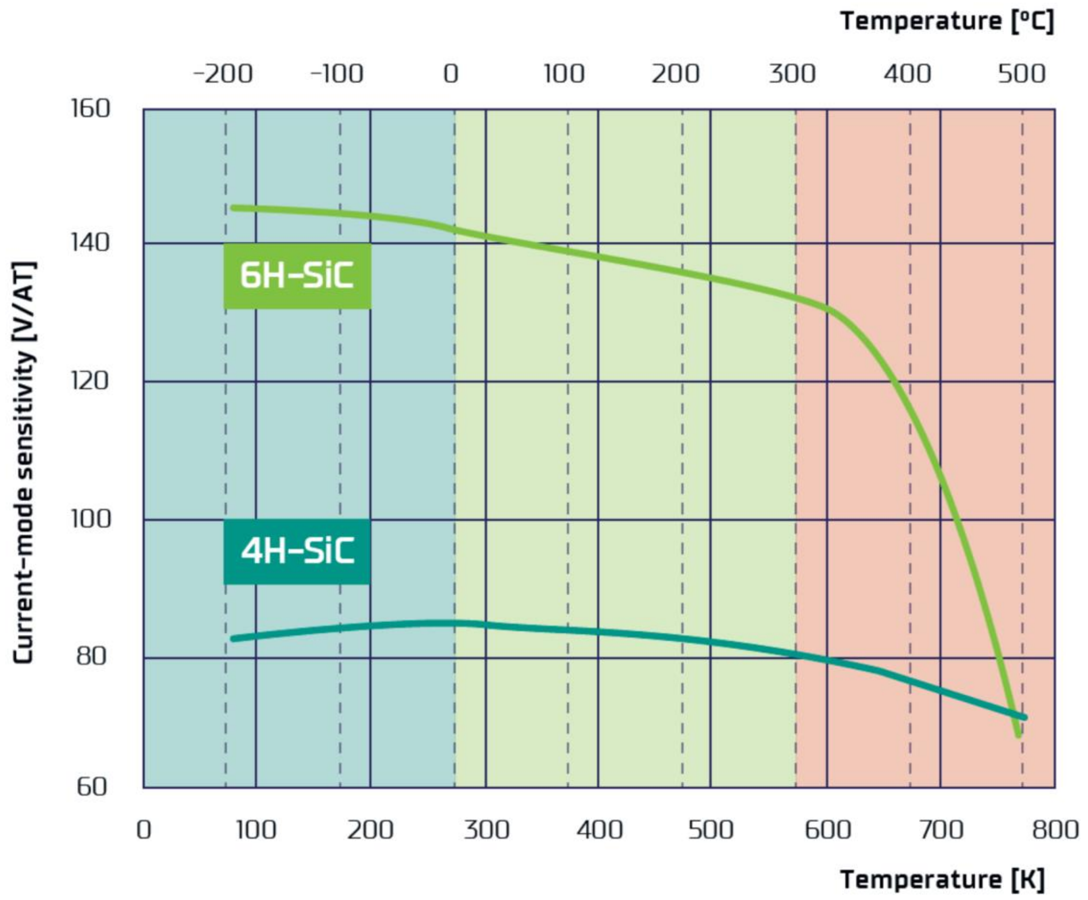
Neutron-irradiation-resistant high-temperature graphene Hall effect sensor for advanced magnetic diagnostics

Two platforms: 6H-SiC and 4H-SiC

Two levels of sensitivity: 140 V/AT, 80 V/AT

Start temperature: liquid nitrogen

End temperature: 500 °C



Neutron-irradiation-resistant high-temperature graphene Hall effect sensor for advanced magnetic diagnostics

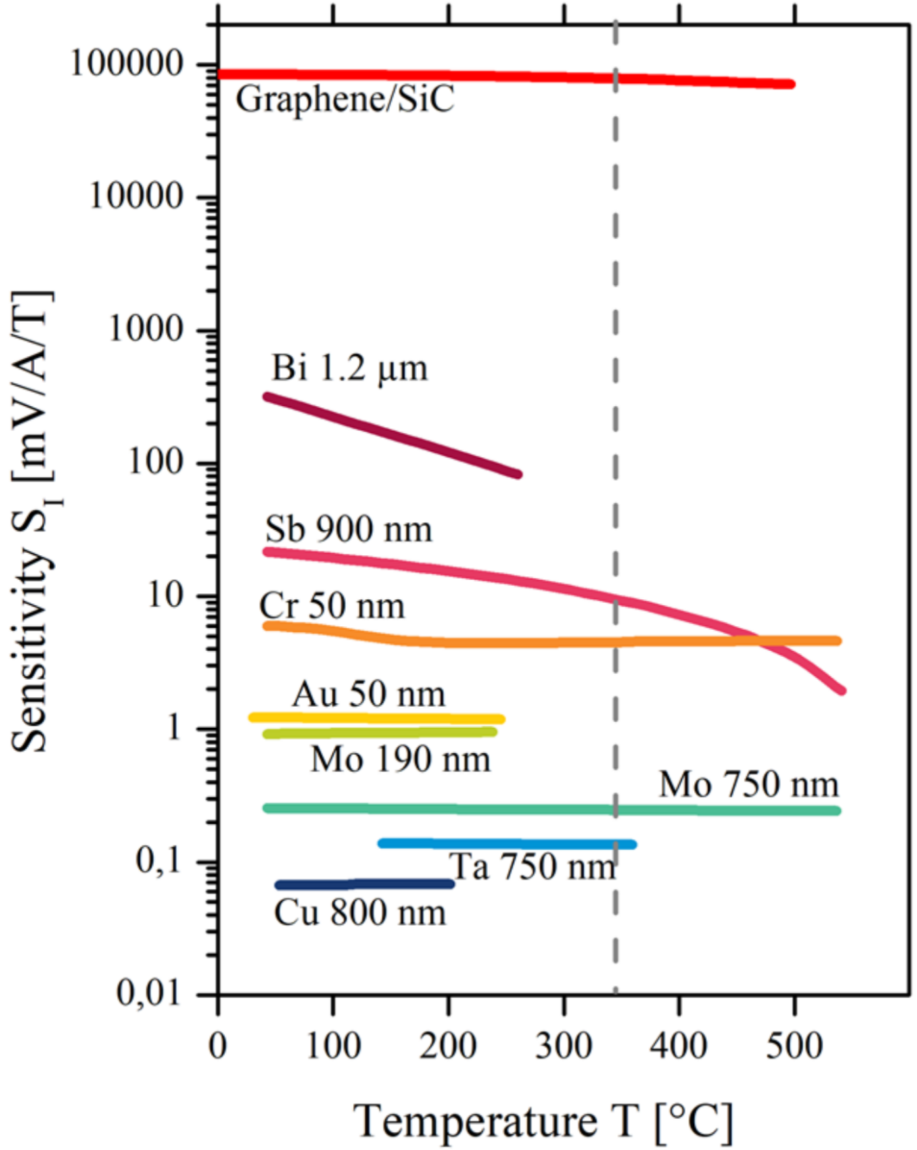
Alternative platforms: Bi, Sb, Cr, Au, Mo, Ta, Cu

Sensitivities: 0.1 mV/AT - 100 mV/AT

Start temperature: 50 °C

End temperature: 500 °C

Source: Entler S., et al., Sensors 2021, 21, 721.



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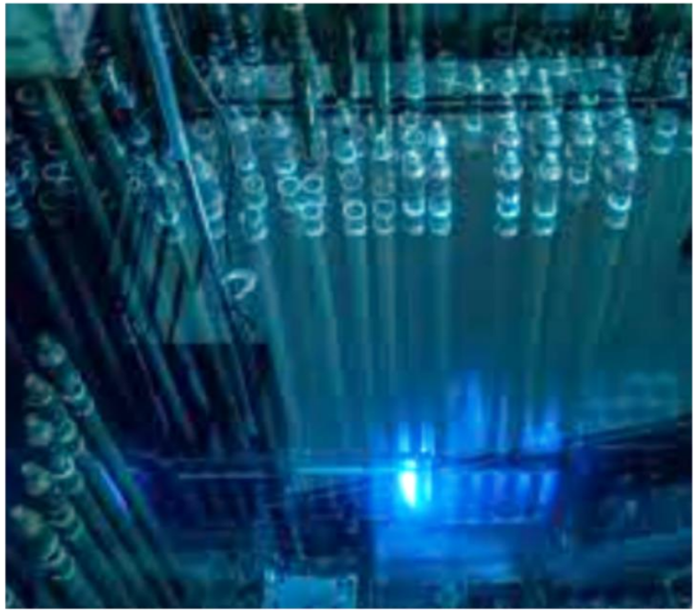
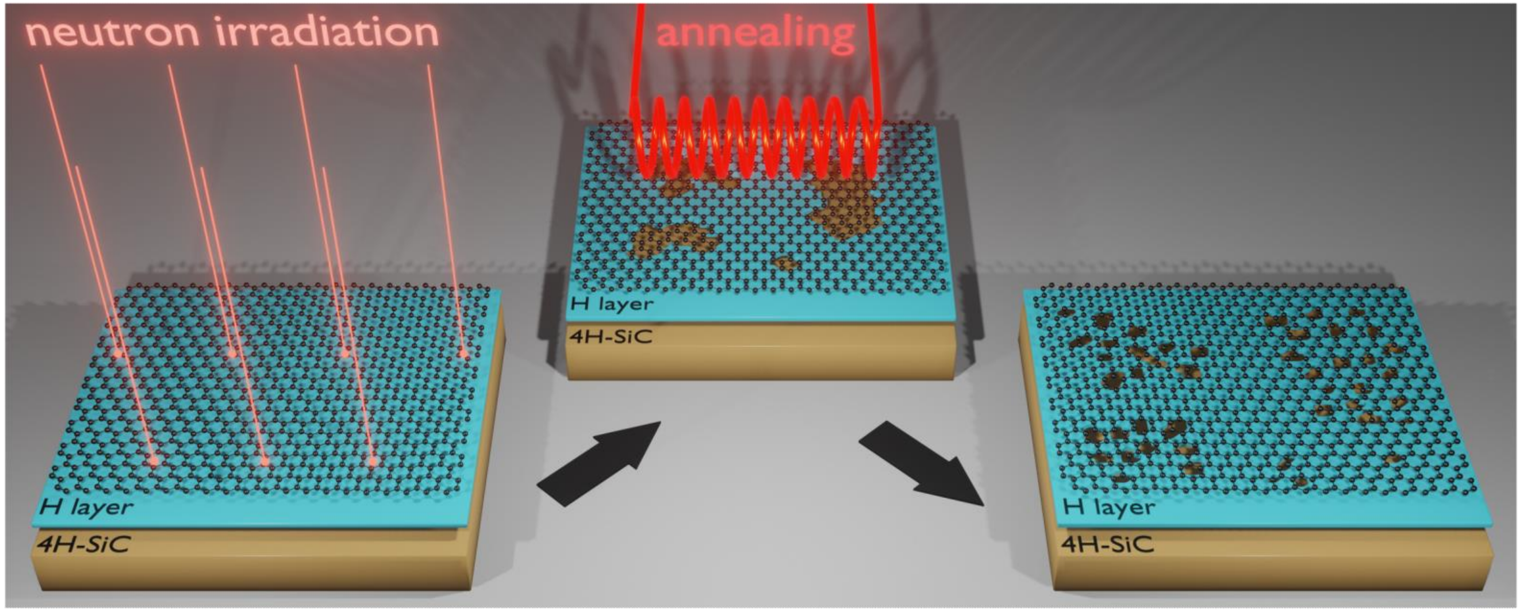
Neutron-irradiation-resistant high-temperature graphene Hall effect sensor for advanced magnetic diagnostics

Completed experiment in MARIA reactor: neutron fluence of 6.7 10E17 cm^{-2}

Estimated defect density: 4 E10 cm^{-2} (low cross-section)





doi.org/10.1016/j.apsusc.2022.152992 doi.org/10.3390/s22145258

Neutron-irradiation-resistant high-temperature graphene Hall effect sensor for advanced magnetic diagnostics

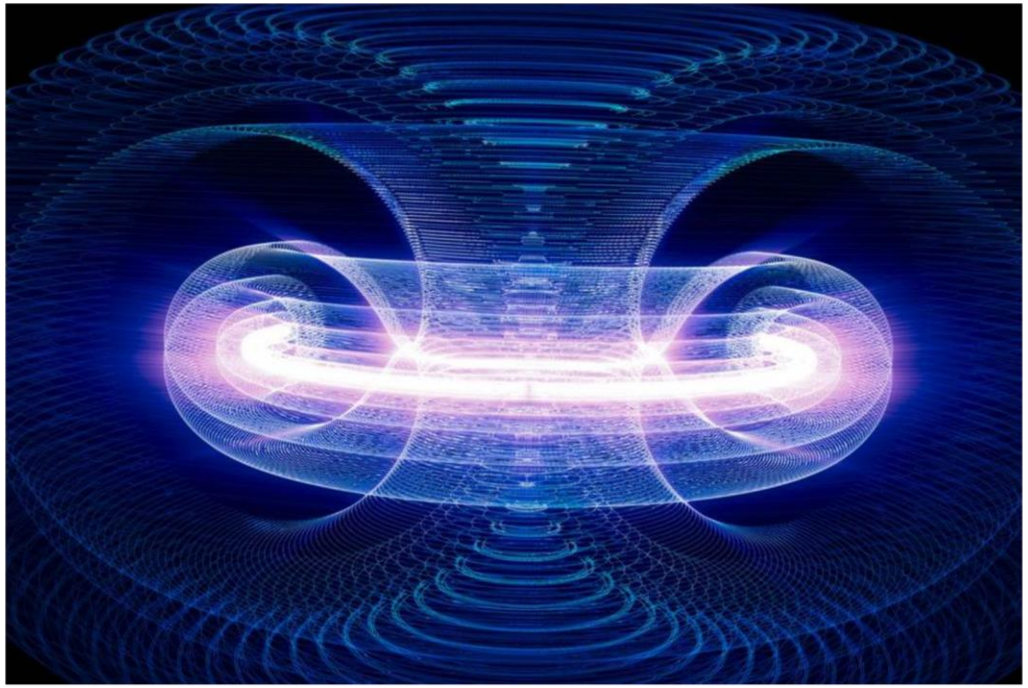
Summary: Al_2O_3/QFS-graphene/SiC(0001)

Competitive advantages:

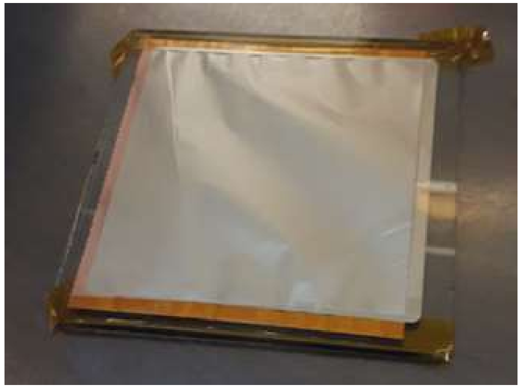
- operates at elevated temperatures
- largely resistant to neutron irradiation

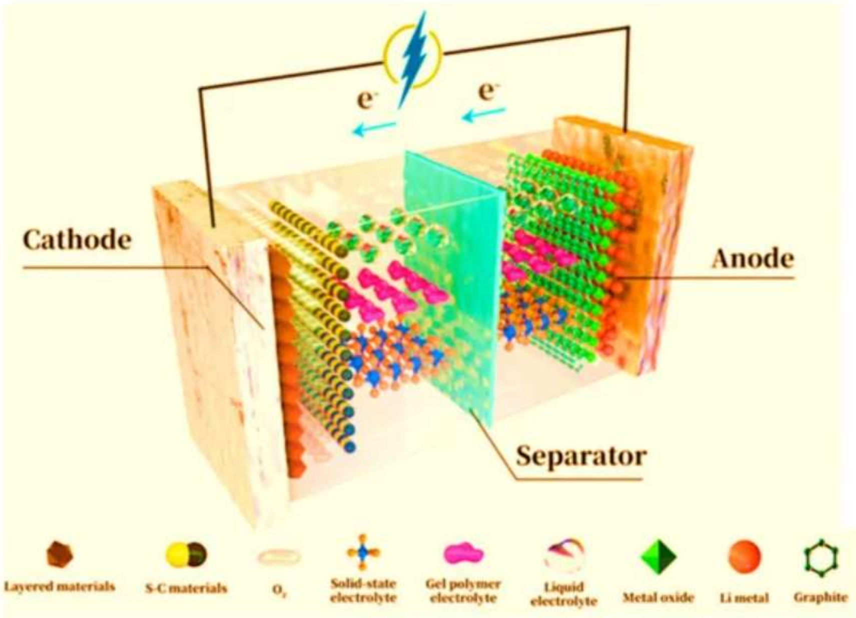
Potential application:

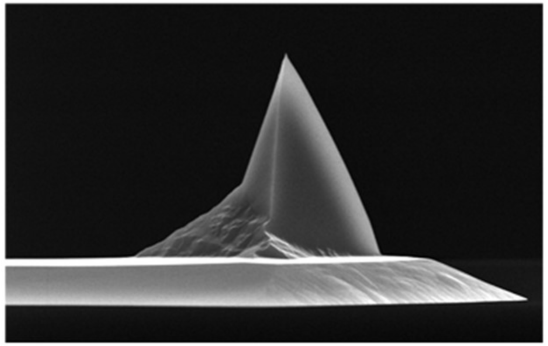
- magnetic diagnostics in fusion reactors



I4BAGS – Technical kick off meeting January 10th 2023







Ion implantation for monitoring material properties in thin film solid state battery

Outline

- Presentation of Materia Nova
- Battery development
- Action Plans
- Equipment
- Collaborative activities

Presentation of Materia Nova

20 years

Turn over: 8 Million €

80 Experts
(with UMONS -285 Experts)

MATERIA NOVA Materials R&D Center

THE TECHNOLOGICAL ACCELERATOR OF RESPONSIBLE INNOVATIONS IN MATERIALS AND PROCESSES

Equipments
(> 300 analytical measurements)

International network

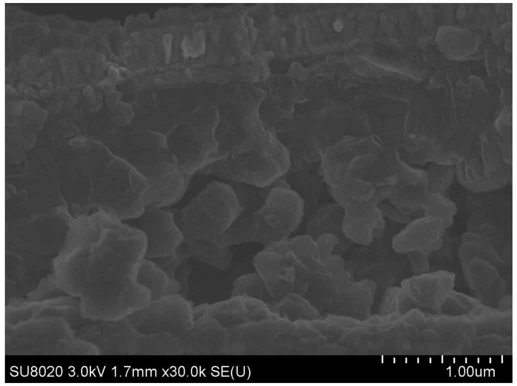
Projects
Services
Patents

Battery developments at Materia Nova

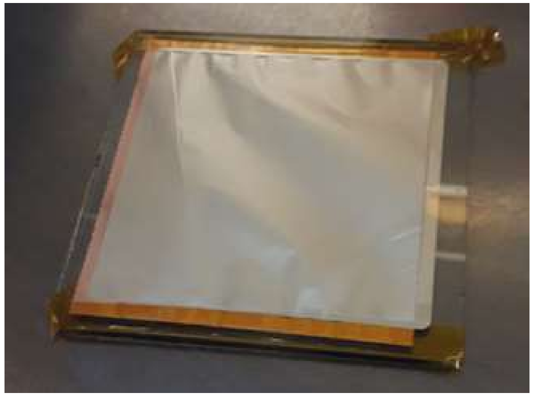
Materia Nova : validator off innovative material and processing solution in thin film battery

Background and current activities:

- Li layer (up to 10 µm) deposited by PVD
- Deposition of thin film anode by PVD for low weight solid state batteries
- Characterization of materials thin films towards (semi-)battery systems

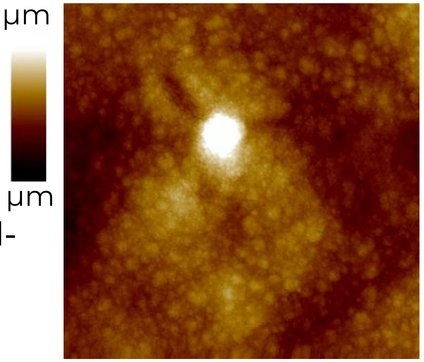


Cross-sectional topography of Li thin film by SEM



Li film on 5x5 cm² glass (left) and 10x10 cm² Cu substrates

15x15 µm² TM-AFM of Li film



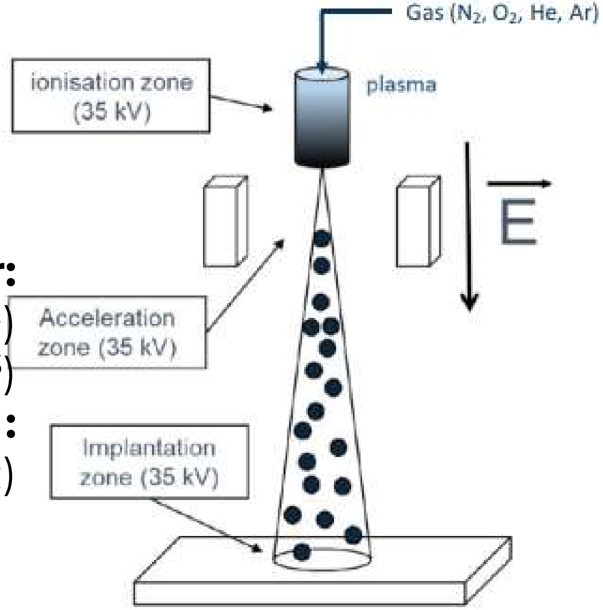
Impedance spectroscopy of solid-state devices

Equipment for thin film deposition and ion implantation

Deposition methods

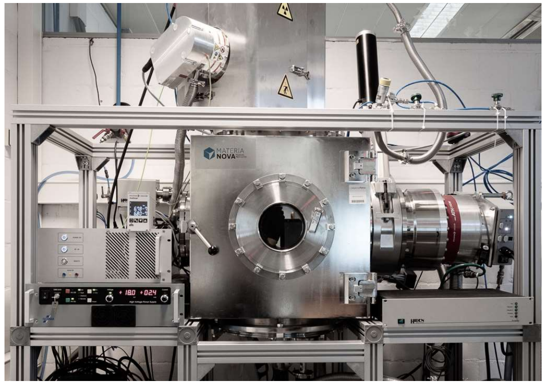
Spectros™150 from K. J. Lesker
Connected to a Glovebox Jacomex conditioned in inert atmosphere (Ar)

Ion Implantation



3 lab-scale ion implanter for:
Flat samples (up to 40x40cm²)
Small 3d shape and powder (up to 100cm³)
2 semi-industrial ion implanter (Ionics) for :
large dimensions (1.6x1.6 m²; R2R)

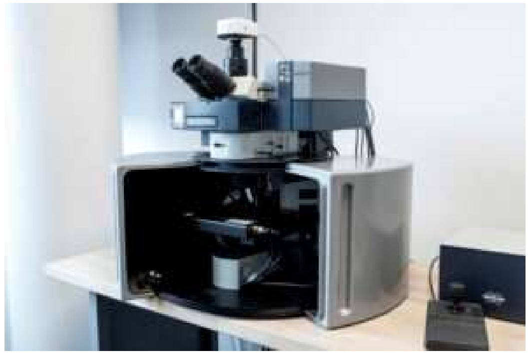
Magnetron sputtering and PECVD chambers
To be equipped with ion gun for direct implantation



Equipment for characterization of materials and devices

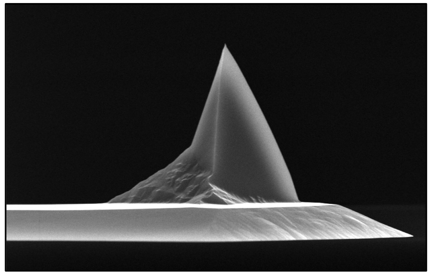
Chemical analysis

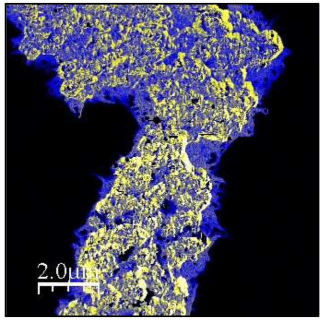
XPS
(Omicron)



Raman spectrometer
(Bruker Senterra)

Topographical and electrical analysis





Atomic Force Microscope with electric modules
Low T to RT Hall effect characterization platform

Device conditionning

MSK-115 Vacuum Sealing Machine
Conditioned in inert atmosphere (Ar)

PEC Corp multichannel cell tester
PEC ACT0505 Table Top
Cell Tester. 10 Ch. 5A, 5V Incl LifeTest

Low energy and low coast ion implantation activities at Materia Nova and Ionics

R&D activities

Implanted species: all kind of gaseous atomic or molecular compound
Operating environment: high vacuum (~10^{-5} Torr)
Energy range: 10 keV to 40 keV
Dose (fluence): 10^{14} cm^{-2} to 10^{18} cm^{-2}
Near surface implantation: up to 500 nm

Simple process ➔ Industrialization

- Any solid materials: metals - polymers - glasses…
- Any shapes: flat - powders - small 3D objects, wire…
- No adherence issues

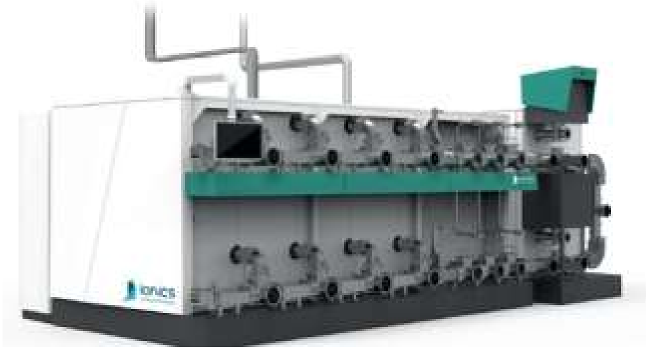
Monitoring mechanical properties

- Surface hardening
- Improved corrosion and HT oxidation resistance
- Wettability modification
- Adhesion improvement at interfaces
- Enhancing barrier properties (polymers)
- Doping and allowing (oxides, nitride…)

ionics surface technologies

Spin off from Materia Nova

Design, conception and fabrication of ion implanter
Large dimension implantation equipment
Versatile application: automotive, health…



Action plan at Materia Nova

2023

Graphite electrodes:

- Purchasing of graphite thick electrode
- Carbon thin film (50 nm) deposited by magnetron sputtering

Ion implantation

- Non-reactive implantation: Ne, Ar for monitoring vacancies in graphite
- Reactive implantation: N for doping

Morphological, chemical and electrical characterization

Solid state electrolytes:

Materials and fabrication methods: Li-PEO (Wet X) and LIPON (PVD)

Non-reactive ion implantation for monitoring ionic transport: Species: Ar, N, He, Ne

Electrical characterization with impedance spectroscopy (Biologic, Modulab)

2024

Li electrode:

Deposition of Li layer (µm) and additional interfacial thin film (LiF, MoS_2)

Transfer issue to be solved to prevent contamination (C, N, and O)

Ion implantation for monitoring stability upon cycling

Non-reactive implantation of multilayer vs. Reactive implantation (H_2S, CF_4) of Li layer

Characterization of layers in half cells: capacity & energy, (de)charging time, stability in cycling

Collaborative actions

From Materia Nova to QWED:

- Fabrication on low loss substrate (quartz, borosilicate glass) of reference (thin) films (graphite, solid electrolyte, Li) ion implanted upon selected protocols to be sent to QWED
- Electrical characterization (determination of permittivity) of reference samples with microwave dielectric resonator
- Model supply to describe electrical properties and transport (electrons, ions) behavior

First samples to be sent: ion implanted carbon and graphite thin films on quartz samples
What are the maximum dimensions of the sample to be sent?

From L-IMIF to Materia Nova

- Determination of ion implantation protocol for SiC/graphene reference structures and devices (sensors)
- Reference graphene/SiC reference structures to be sent to Materia Nova for ion implantation, then to be returned for comparative testing

What are the dimensions of the reference samples to be received

Bridging the gaps between microwave modelling and materials measurements *and between women and engineering*

Malgorzata Celuch
QWED Sp. z o.o., Poland

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

with an appeal for a stronger response
to Russia's invasion of Ukraine
to prevent Siberia happening to my children

Outline

1. From research on Electromagnetic Modelling to its exploitation by QWED

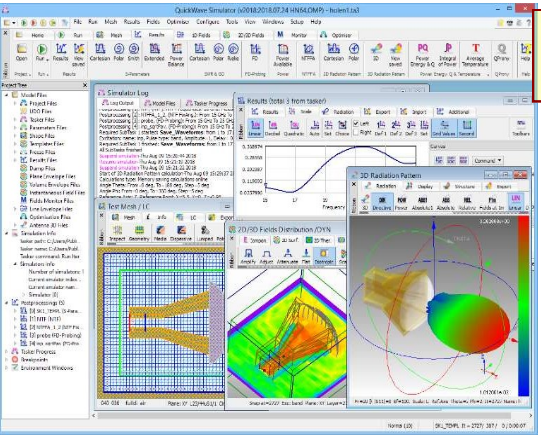
2. QWED expanding into Material Measurements

3. Exploring the synergies between EM Modelling and Material Measurements

4. Validation of resonators in 5G/mmWave iNEMI project

25 years in a Nutshell

presented annually at IEEE IMS Show

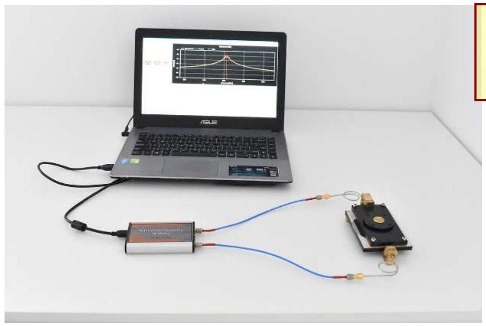


Electromagnetic simulation & design software, 3D & BOR 2D tools

based on 300+ publications by:

prof.W.Gwarek, IEEE Fellow, DML, Pioneer Award

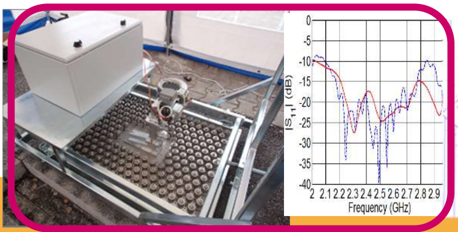
dr.M.Celuch, President of QWED

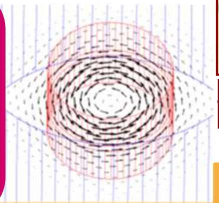


Instruments for precise material measurements

based on 300+ publications

by prof.J.Krupka, IEEE Fellow



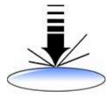


Consultancy & design services based on EM expertise & tools

team of 10+engineers, 4 PhDs, 2 Profs

key areas: MW power appliances, customised resonators, antennas &feeds

R&D projects



FP6 SOCOT – development and validation of an optimal methodology for overlay control in semiconductor industry, for the 32 nm technology node and beyond.

FP6 CHISMACOMB – development, modelling, and applications of chiral materials → EM validation of mixing rules

Eureka E! 2602 MICRODEFROST MODEL – innovative software-based product development tool for simulating and optimising heating and defrosting processes in microwave ovens

FP7 HIRF SE (High Intensity Radiated Field Synthetic Environment) - numerical modelling framework for aeronautic industry

Eureka FOODWASTE – developing new microwave treatment system for high water content waste

ERA-NET MNT NACOPAN – applications and modelling of nano-conductive polymer composites

NGAM2 – designing an industrial device for thermal bonding of bituminous surfaces with the aid of microwave heating

MMAMA (Microwave Microscopy for Advanced and Efficient Materials Analysis and Production) – EM modelling & characterisation for the development of high efficiency solar cells

NanoBat - developing a novel nanotechnology toolbox for quality testing of Li-ion and beyond Lithium batteries with the potential to redefine battery production in Europe and worldwide.

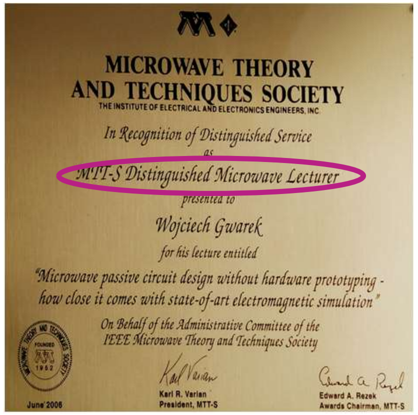
M-ERA.NET

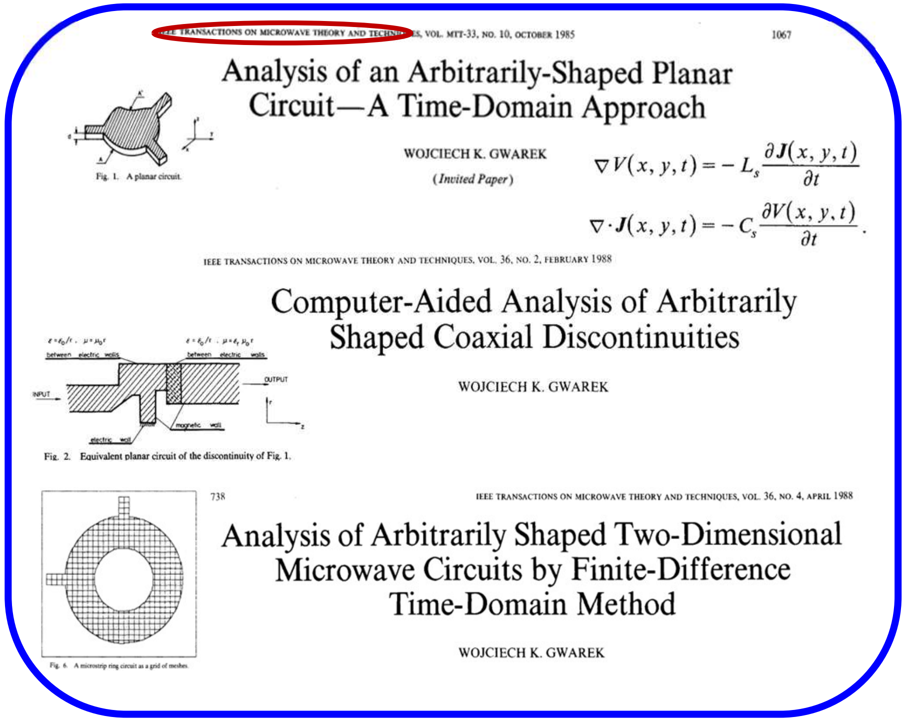
ULTCC6G_EPac – development & application of novel ceramics for 5G & beyond

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

Origins of QWED Computer Modelling

since 1980s…
IEEE- awarded research of Prof. Wojciech Gwarek
on 2D FDTD modelling (with novel conformal meshing)
Fellow, Pioneeer Award, DML

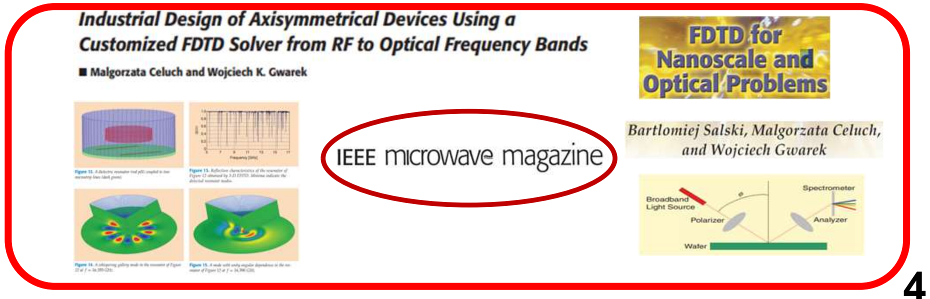




$$\nabla V(x,y,t) = -L_s \frac{\partial J(x,y,t)}{\partial t}$$

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

… by early 2000s:
QWED commercialises & continues the development
licences for QuickWave-3D by QWED used worldwide
industrial applications from RF to optical bands



QWED started 1997

celebrating 25 years

Founders: A.Wieckowski, M.Sypniewski, M.Celuch, W.Gwarek

Prof. Jerzy Buzek awarding QWED team in 1998
Prime Minister of Poland 1997-2002
President of the European Parliament 2009-2012

Dr. Malgorzata Celuch
President since 2017, VP 1997-2017
- 35 y experience in mathematical, 25 y in management
- Awards for excellence from e.g. Prime Minister of Poland, Rector of WarsawUnivTech

Janusz Rudnicki, MS,
VP for IT
- 22 years of experience in simulation software development

Dr. Marzena Olszewska-Placha,
VP for R&D
- 15 y of experience in simulation-based MHz to THZ design and consultancy
- 4 y experience in research management

Dr. Andrzej Więckowski
Senior in CAD
- 48 years of experience in computer-aided electronic engineering and engineering software development

Prof. Wojciech Gwarek,
President 1997-2017
- 22 years of experience in simulation software development

Dr. Maciej Sypniewski
Senior in CAE
- 35 years of experience in engineering software development and GHz measurements

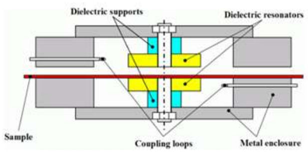
10
people employed

7
consultants cooperating

50%
female

Origins of QWED Material Measurements

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

Agilent Both
IEEE IMS 2006, San Francisco, CA

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

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

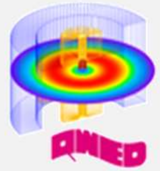
Current Work: Bridging Computer Modelling with Material Measurements

Commercial since 1997
QuickWave Simulation Software
~1000 licences implemented

THE EUROPEAN ICT PRIZE WINNER

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

INNOVATION

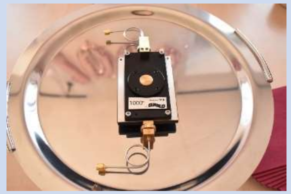


Applicator design & model for parameter extraction

Material measurements

Commercial resonator test-fixtures since 2001

1000th unit sold in 2020



Accurate material parameters (constitutive relations)

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

Open Platform Examples & Tools

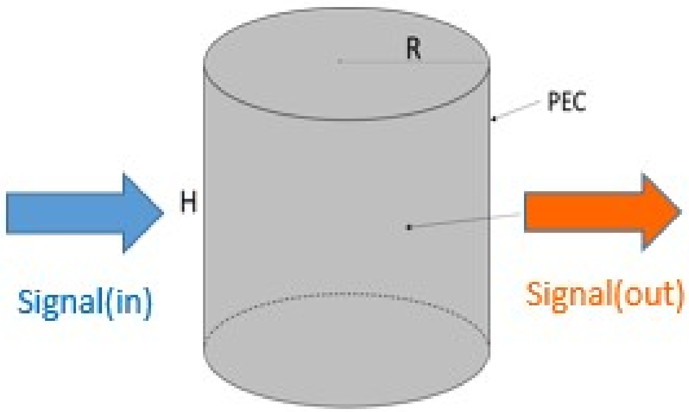
QW-Modeller for QuickWave
Free general purpose 3D CAD modeller for QuickWave.

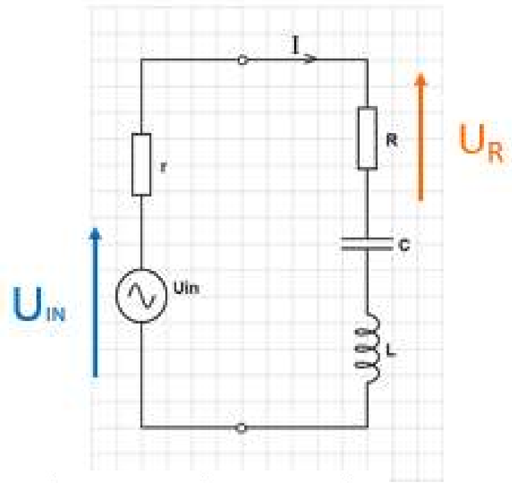
Open Platform Examples:

SMM tip presented at Numerical Electromagnetic

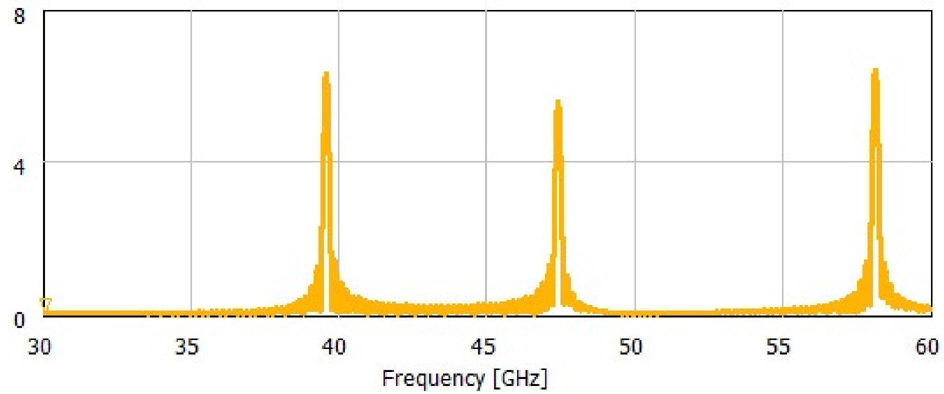
Resonator methods – motivation and background (1)

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





δ(t)

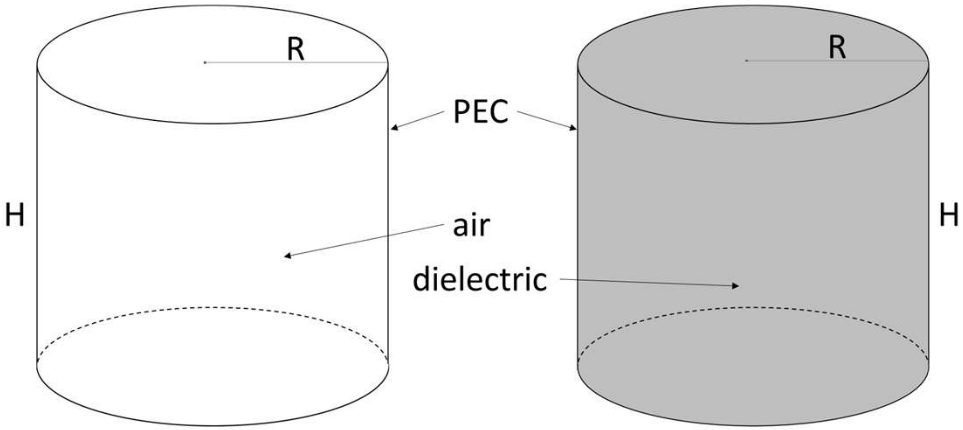


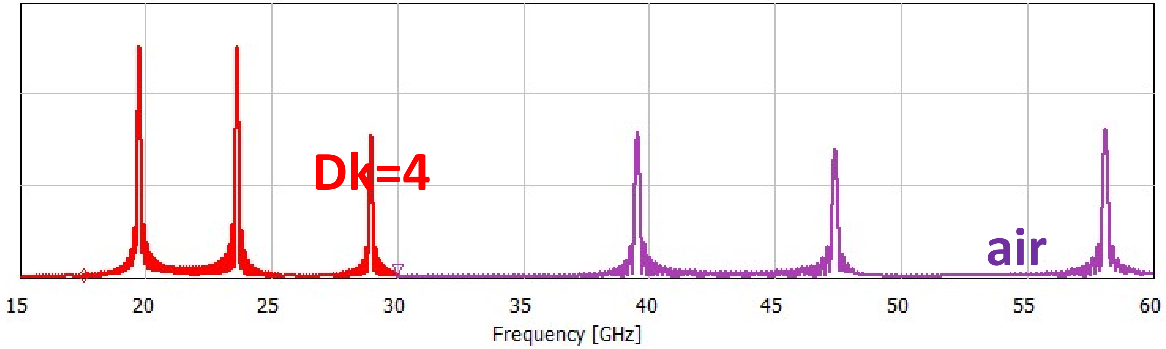
Resonator methods – motivation and background (2)

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

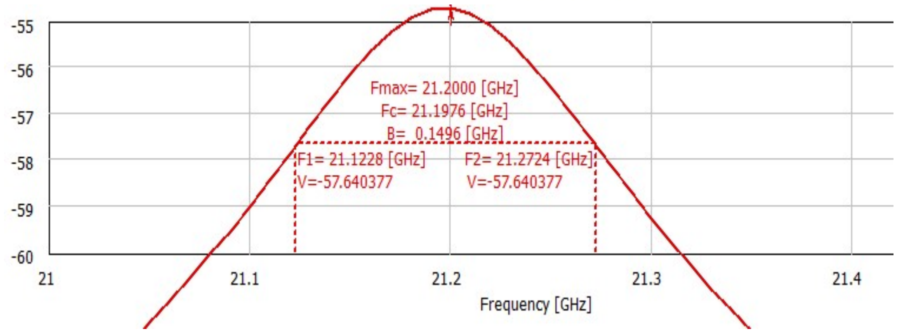
$$f_{r,mnp} = \frac{c}{\sqrt{Dk}} \sqrt{\left(\frac{\kappa_{mn}^{(,)}}{\pi R}\right)^2 + \left(\frac{p}{H}\right)^2}$$

in non-magnetic low-loss dielectrics

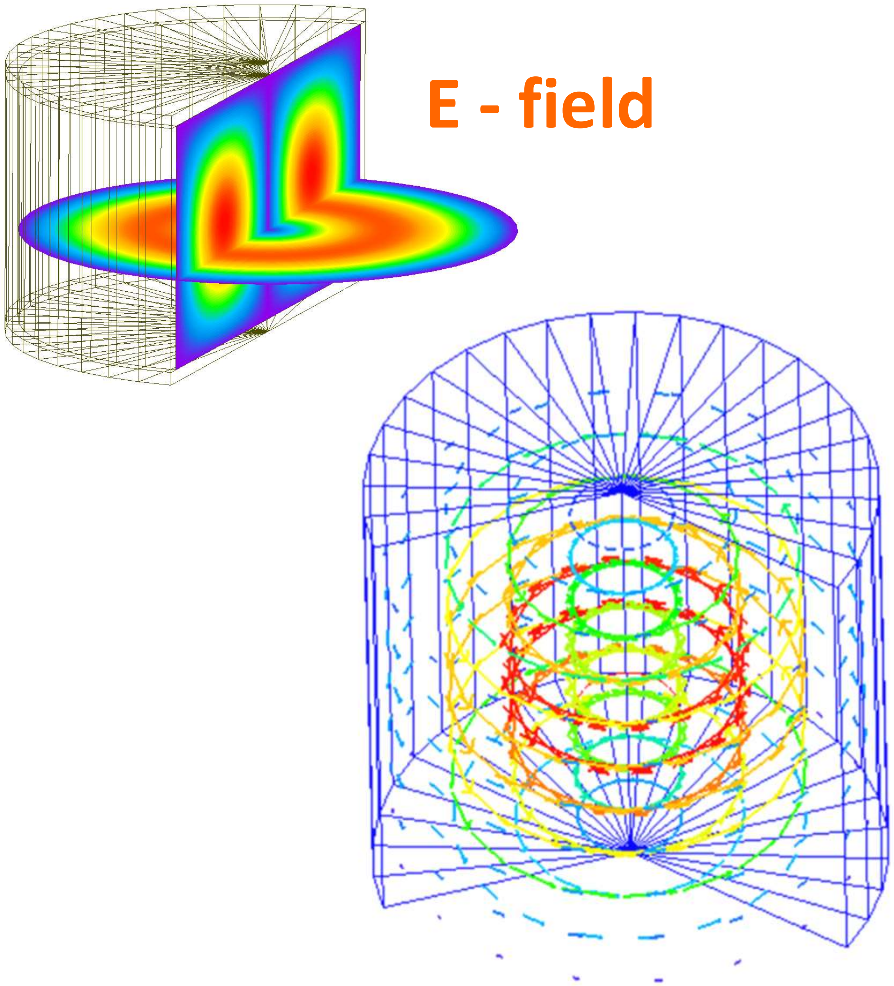


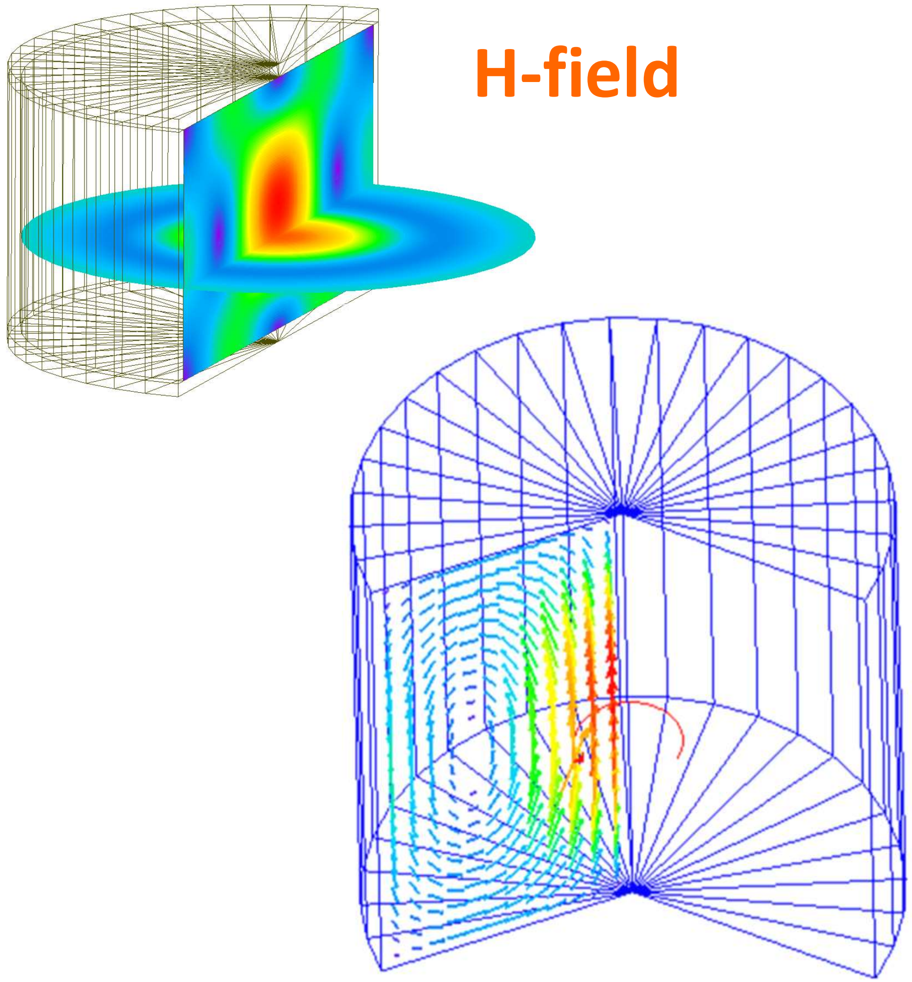


$$Q = 2\pi \frac{\iiint_V \varepsilon \vec{E} \cdot \vec{E}^* dv}{T \iiint_V \sigma \vec{E} \cdot \vec{E}^* dv} = \frac{\omega\varepsilon}{\sigma} = \frac{1}{Df} \approx \frac{fres}{\Delta f}$$

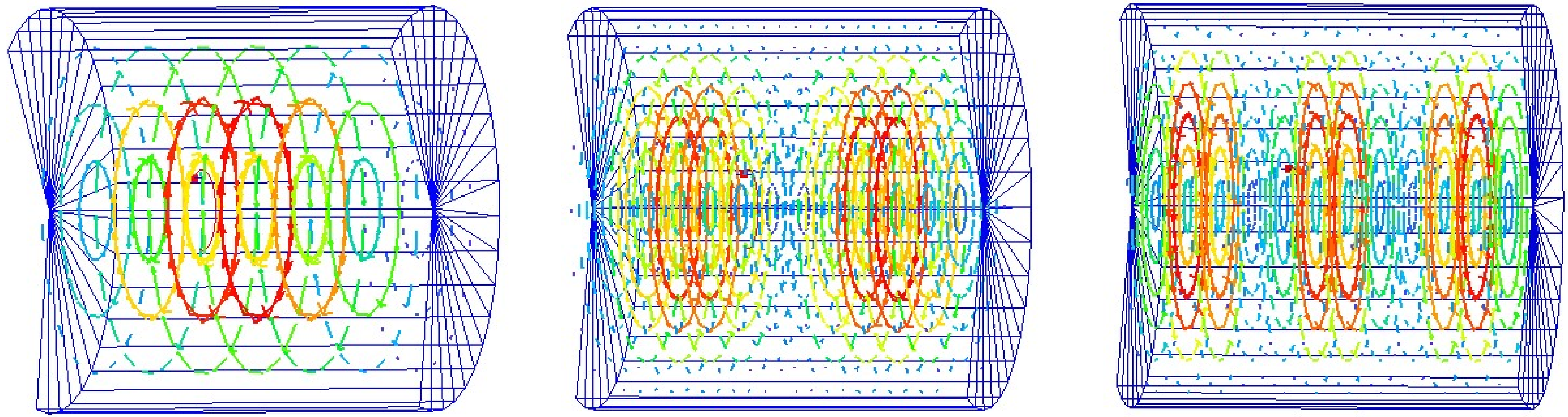


Cylindrical resonator: TE011 mode





Cylindrical resonator: single-mode versus multi-mode operation



TE01**1** **@ 29.43 GHz** | **TE012 @ 47.25 GHz** | **TE013 @ 57.95 GHz**

Resonators are multimode devices.

Hence formally, material measurement can be performed at many frequencies in the same resonator.

However, some modes provide highest accuracy of material characterization. Some are difficult to excite.

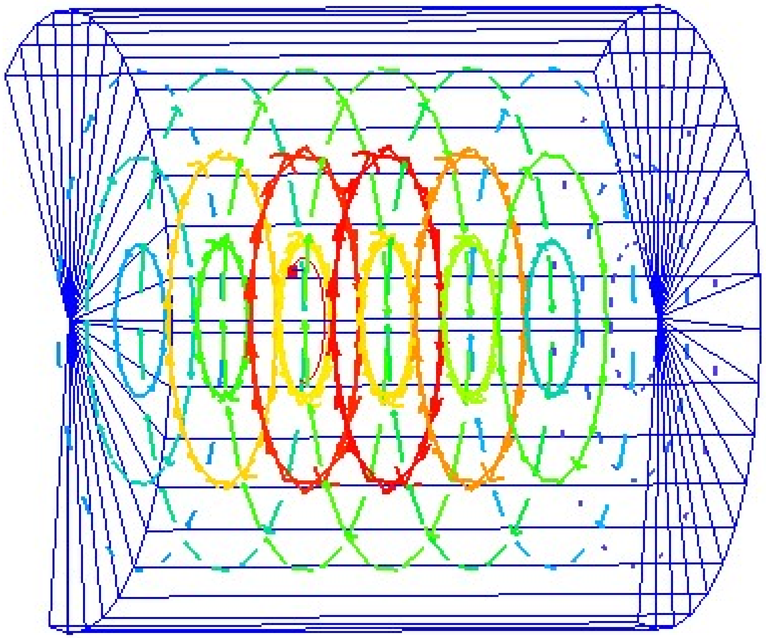
Software provided with the resonator in compatible only with modes pre-selected by the vendor.

Software provided with the resonator in compatible only with modes pre-selected by the vendor.

Among the popularly available resonators, BCDR and FPOR work as multi-modal.

Resonator methods – motivation and background (3)

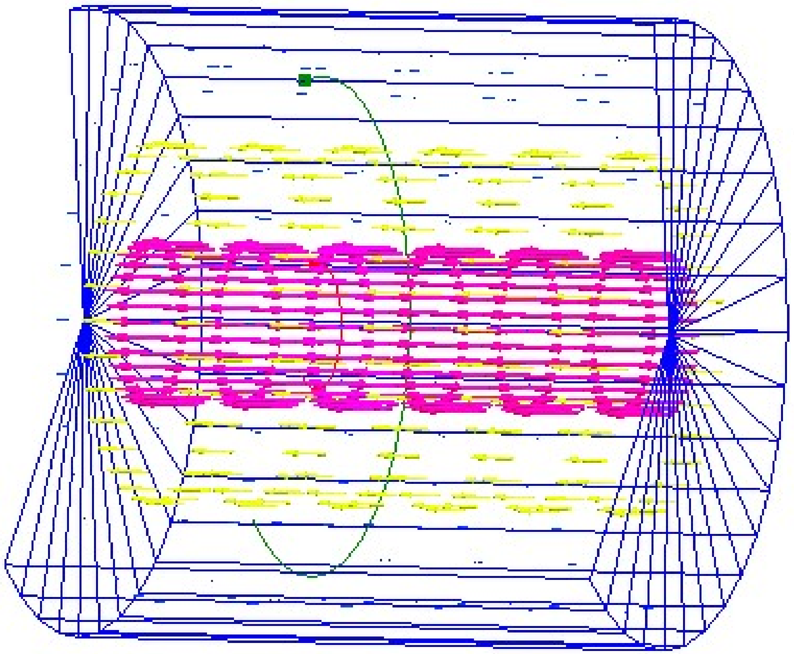
TE010



TE modes to measure
in-plane component of Dk, Df

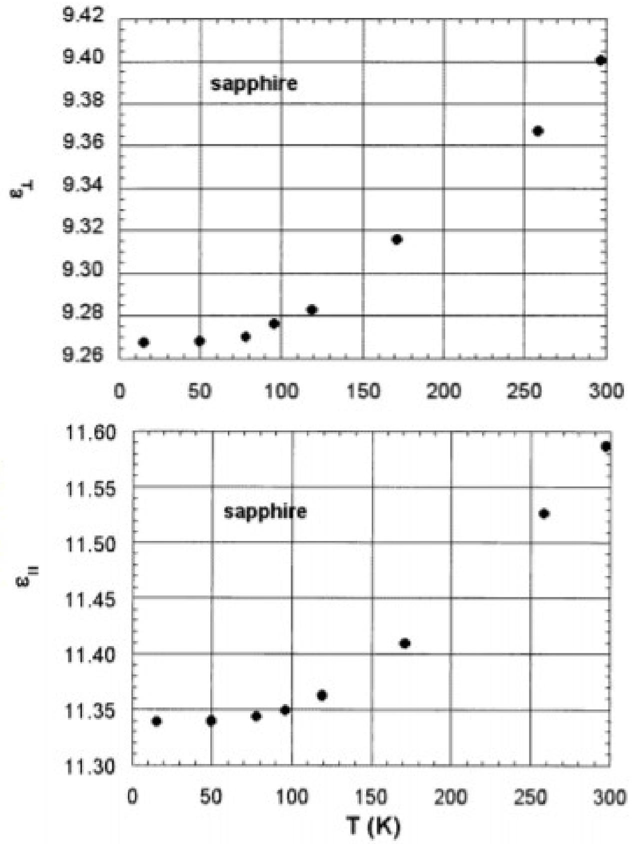
SCR, SPDR, FPOR

TM010



TM modes to measure
out-of-plane component of Dk, Df

BCDR

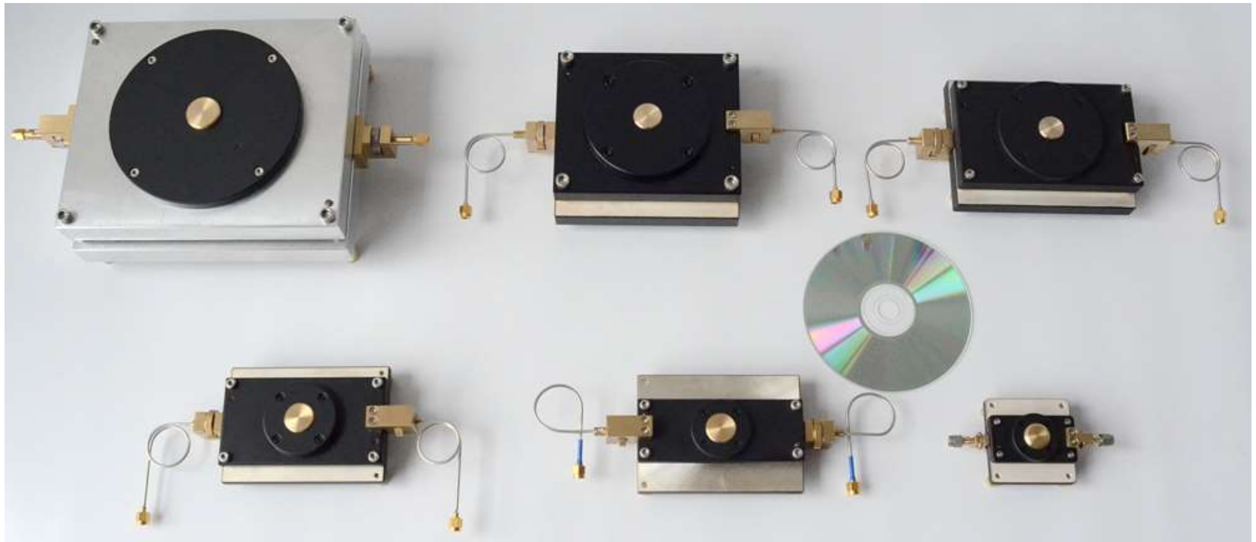


J.Krupka et al., "Complex permittivity of some ultralow loss dielectric crystals..", Meas. Sci. Technol. 10 (1999).

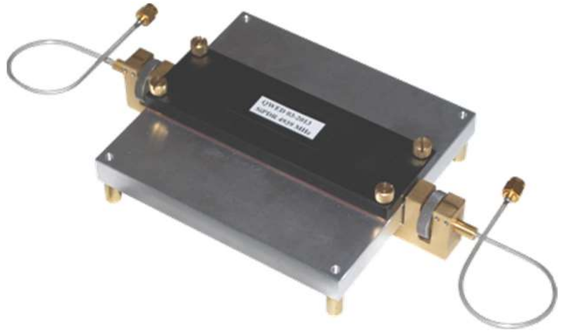
Full characterisation of anisotropic materials (like crystals) requires both measurements.

Popular Dielectric Resonators by QWED

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

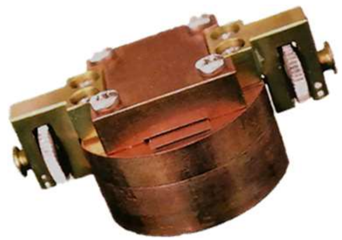


5 GHz SiPDR for resistive sheets

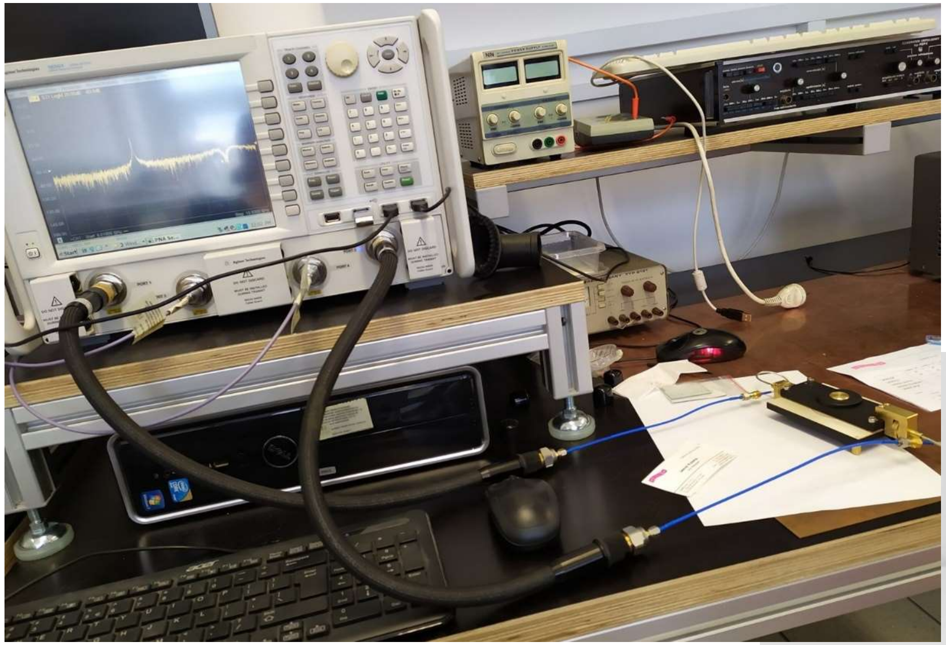


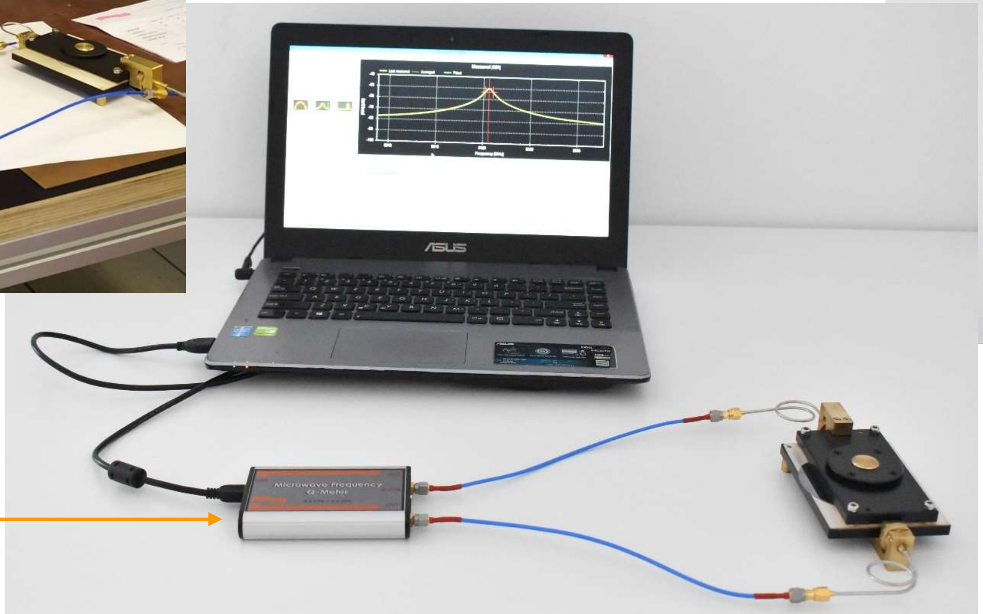
TE01δ cavities, typically 1 – 10 GHz
for bulk low-loss dielectrics

modified SiPDR for graphene



Resonators Operating in Different Setups

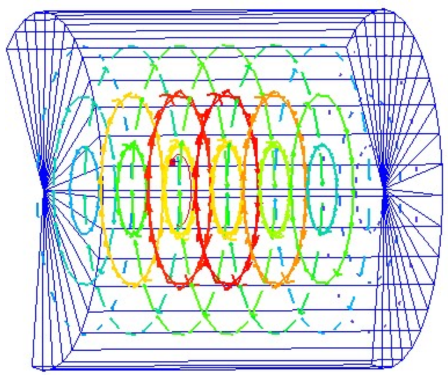


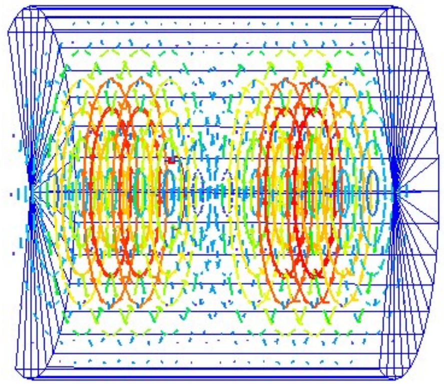


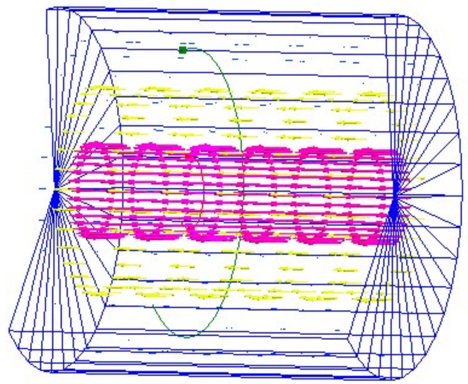
also for home-office!

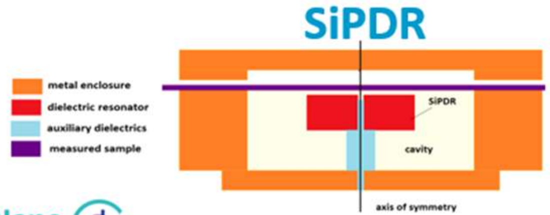
QWED Microwave Frequency Q-Meter units for 5 GHz and 10 GHz

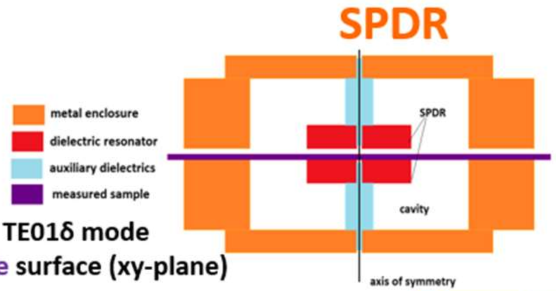
QuickWave Modelling for Enhanced Design & Calibration of Resonators

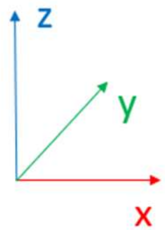






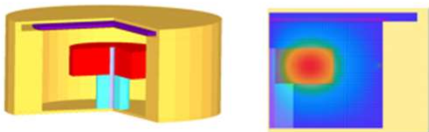






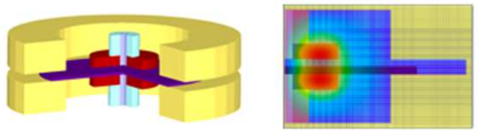
Tutorial examples on
NanoBat Open Platform
https://qwed.eu/nanobat.html

two configurations used with TE01δ mode
E-field tangential (parallel) to sample surface (xy-plane)



E-field distribution
in the half cross-section

sample between the **single post dielectric** and the **ground plane**



E-field distribution
in the half cross-sectior

sample half-way between the **two dielectric posts** (in the "split" of the "post")

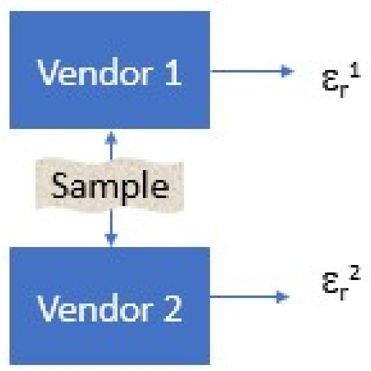
Resonator methods considered in iNEMI 5G project

Presentation will be illustrated with full-wave electromagnetic modeling with QuickWave™ software by

Why we use resonant methods

How these resonant methods work

Why these different methods may produce different results

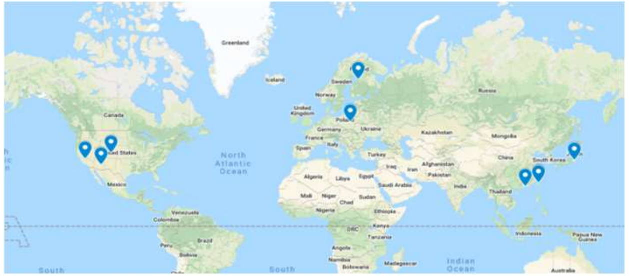


what is vendor-specific,
what is method-specific,
and what other criteria may come into play

iNEMI 5G Round Robin Overview

Our project: iNEMI

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



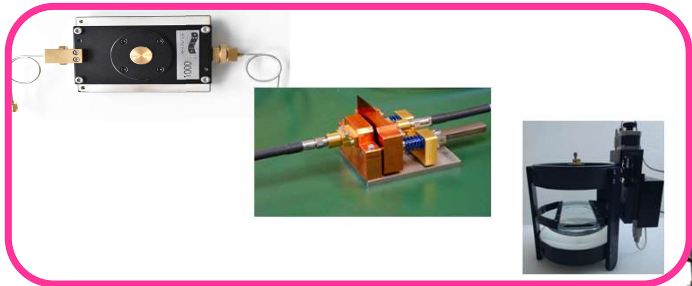
Sample Material Requirements
- Stable, Low loss
- Low moisture absorption / temperature dependency
- Isotropic
- Good mechanical & handling properties

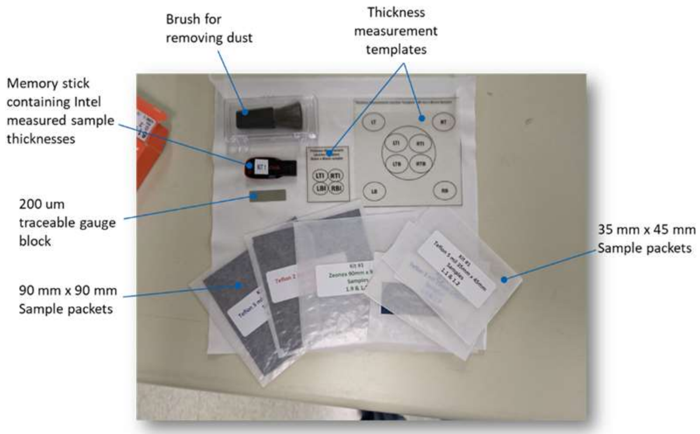
1st Project Stage
- Precision Teflon
- Cyclo Olefin Polymer

2nd Project Stage
- Rexolite
- Fused Silica

Industrial
- Automotive

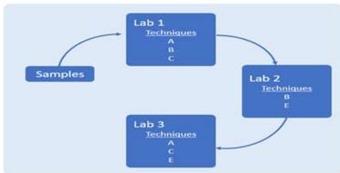
Techniques Included
- Split Post Dielectric Resonator
- Split Cavity Resonator
- Fabry-Perot
- Balanced Circular Disk Resonator





→ Frequency Span : 10GHz – 100GHz with overlaps

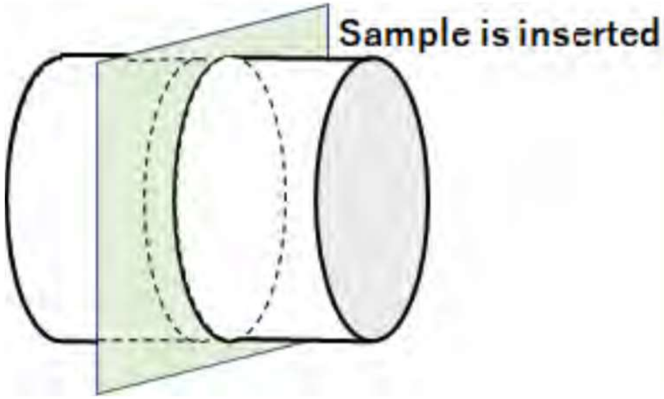
10 Laboratory Round Robin

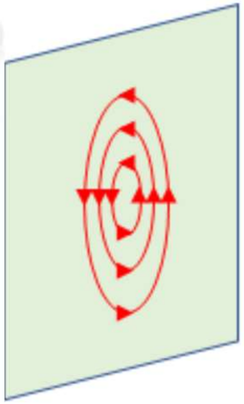


10 Sample Kits Created
- Sample sizes 35 mm x 45 mm, 90 mm x 90 mm
- circulated between 10 labs

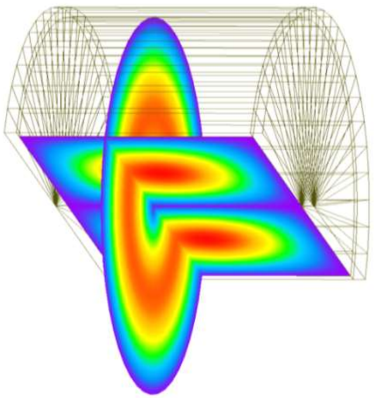
QWED

Split Cylinder Resonator (SCR) - basics

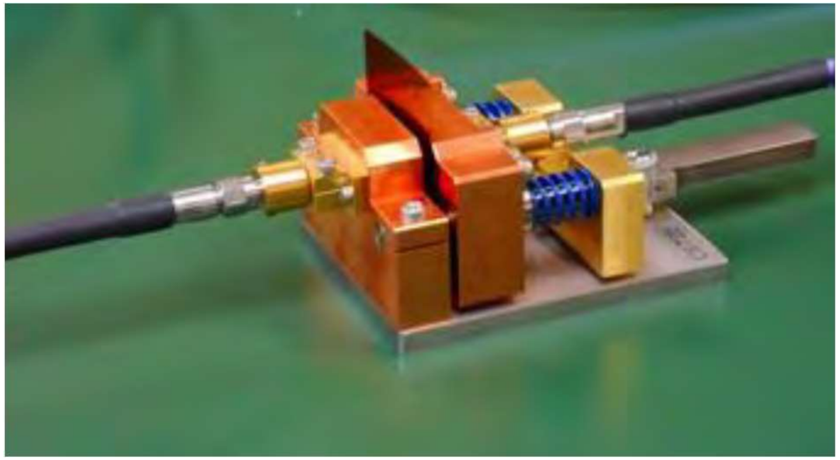




In-plane Electric field
is applied to Sample

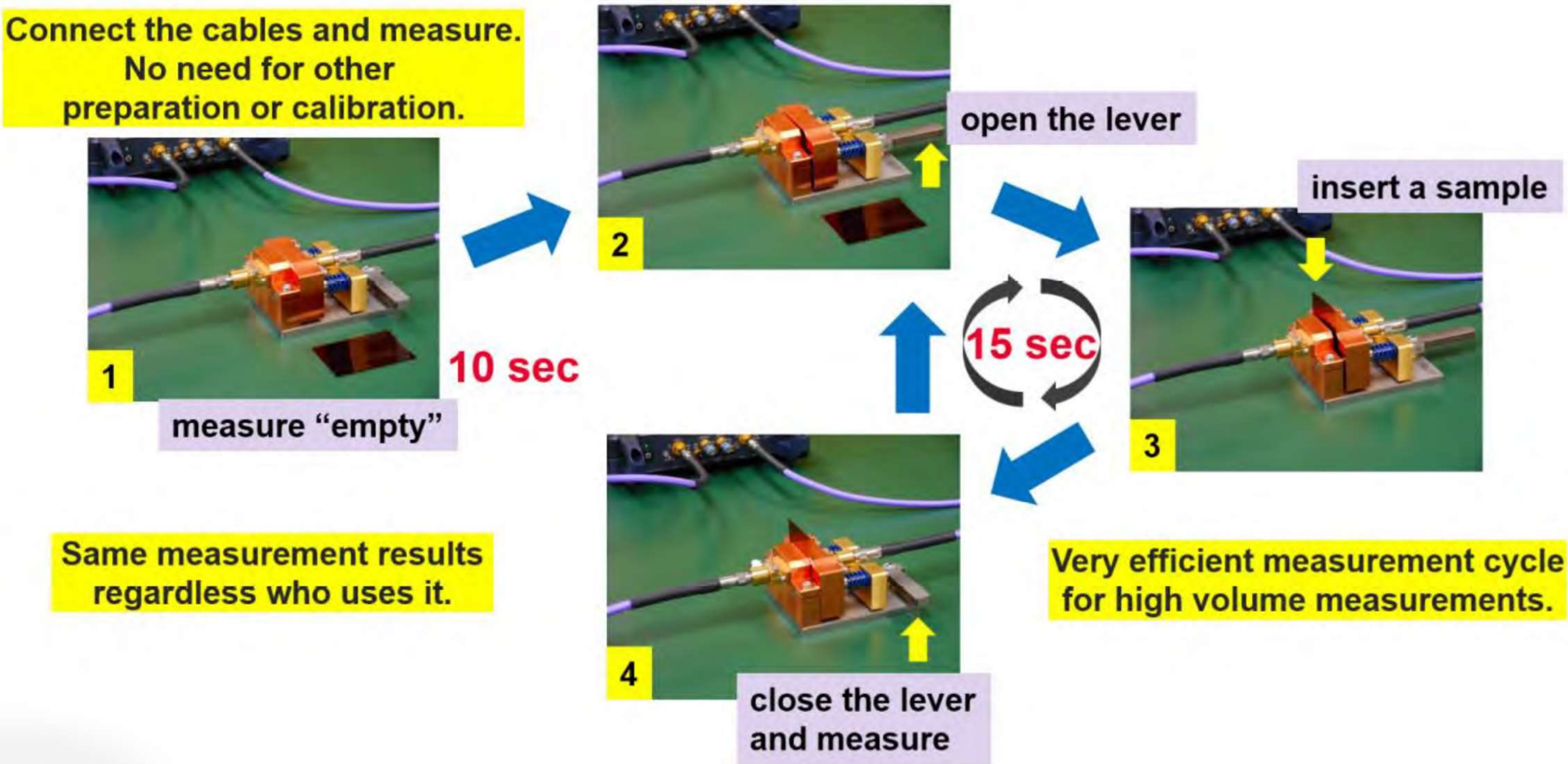


TE011 mode

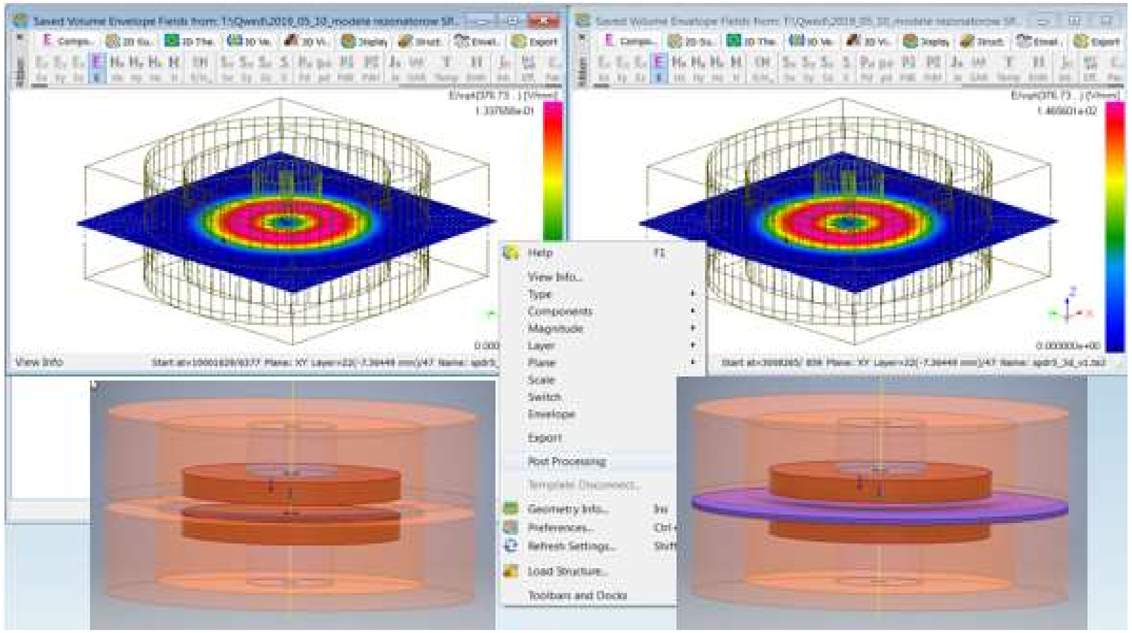


Split cylinder resonator (SCR)	Discrete frequency points from 10 GHz up to 80 GHz	• High measurement precision • Can be sensitive to many user errors • Typically interpolated to 5G mmWaves • Typically in-plane component of permittivity • Typical sample thicknesses around 100 um • Support temperature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

Split Cylinder Resonator (SCR) - operation



Split-Post Dielectric Resonator (SPDR) - basics



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

→ minimial losses in metal enclosure

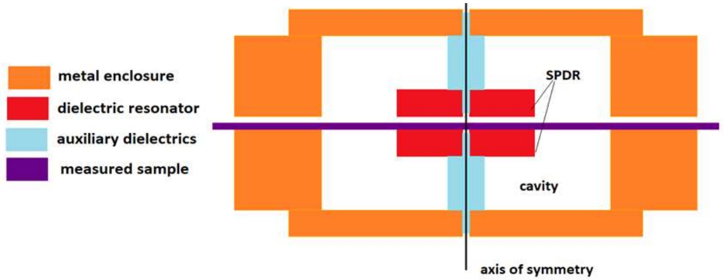
- H-field is only vertical at the side wall of the enclosure → circumferential currents

→ no radiation through slot

- E-field tangential to SUT

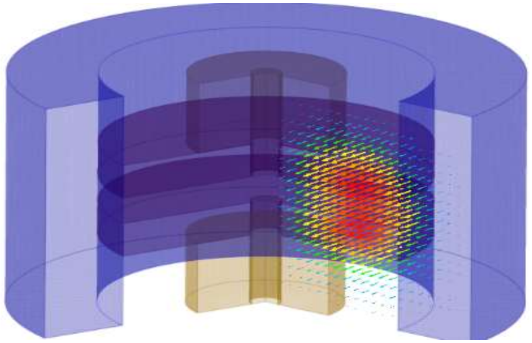
→ air slots between SUT and posts have negligible effect

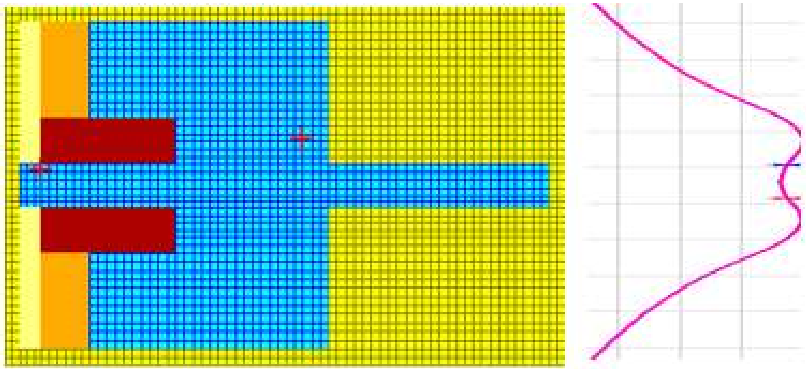
- **easy SUT insertion through slot, no dismatling**

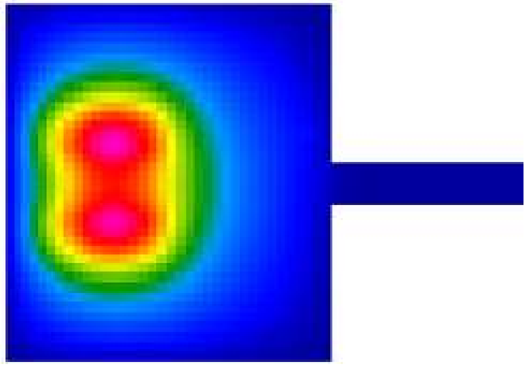


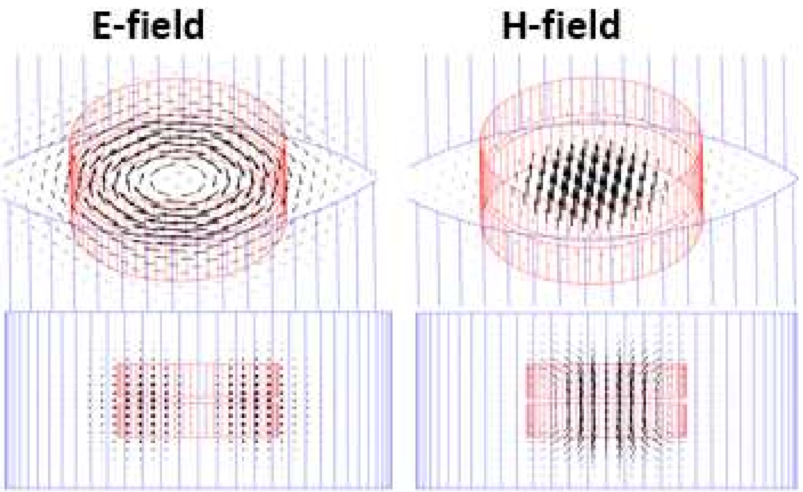
Split-post dielectric resonator (SPDR)	Discrete frequency points from 1 GHz up to 15 GHz	• High measurement precision • Easy to use • Insensitive to many user errors • Typically in-plane component of permittivity • Typically extrapolated to 5G mmWaves • Typical sample thicknesses less than 1 mm • IEC 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

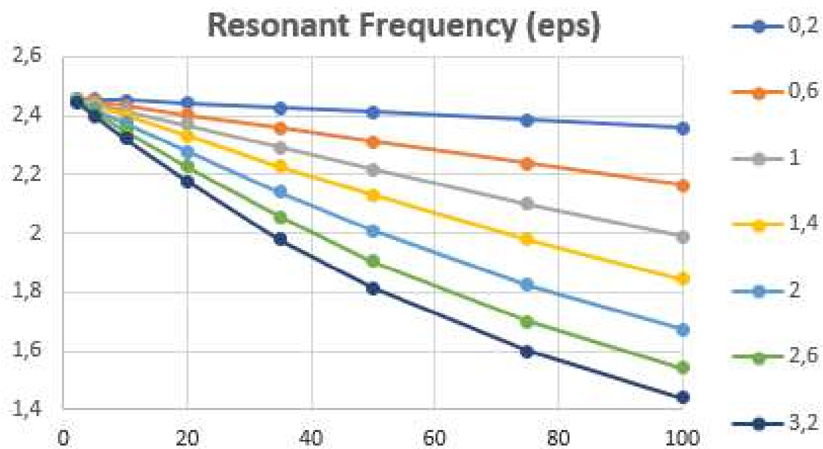
Split-Post Dielectric Resonator (SPDR) – modelling results



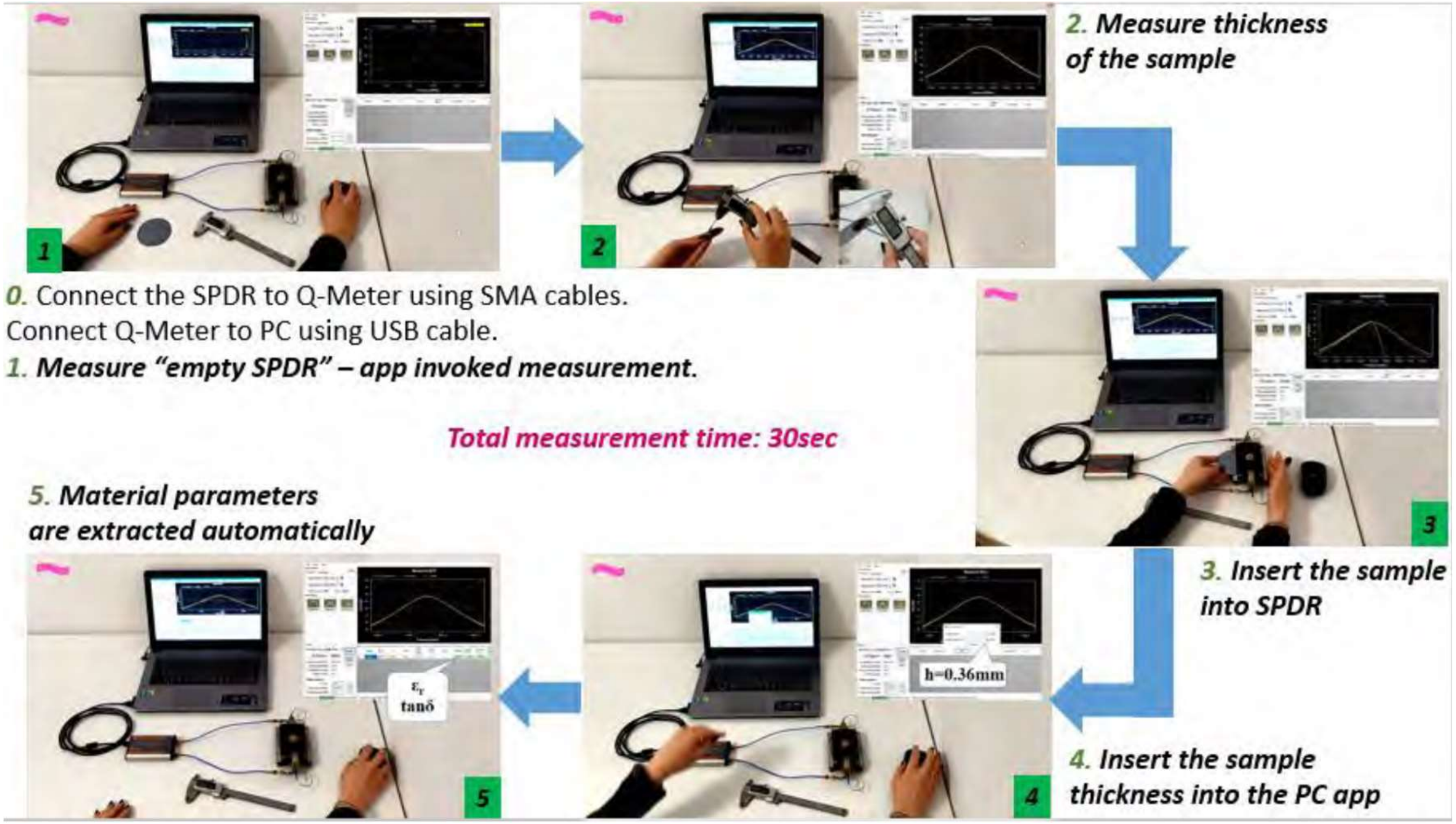




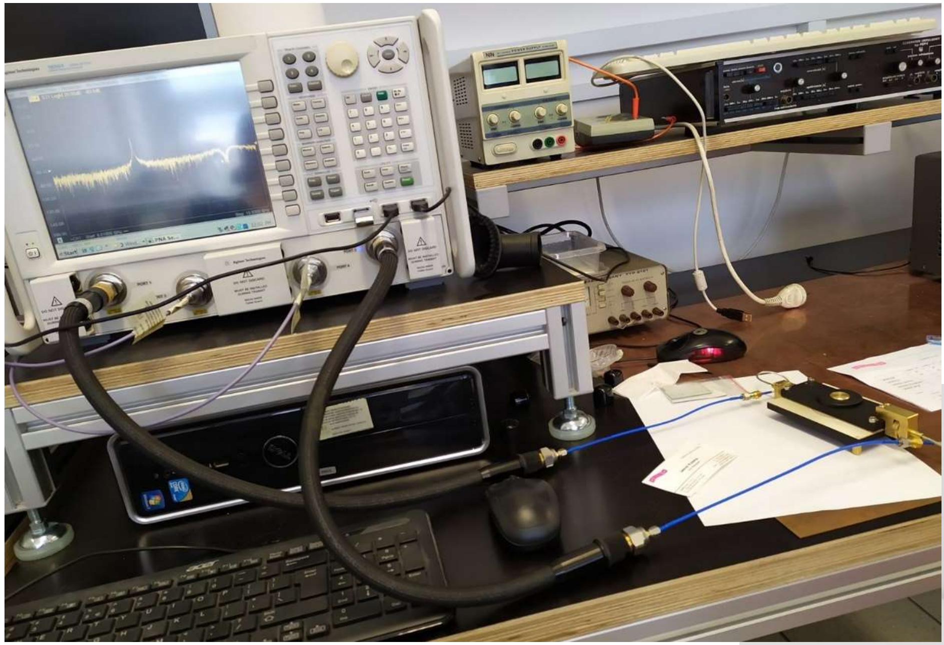




Split-Post Dielectric Resonator (SPDR) – operation (1)



Split-Post Dielectric Resonator (SPDR) – operation (2)

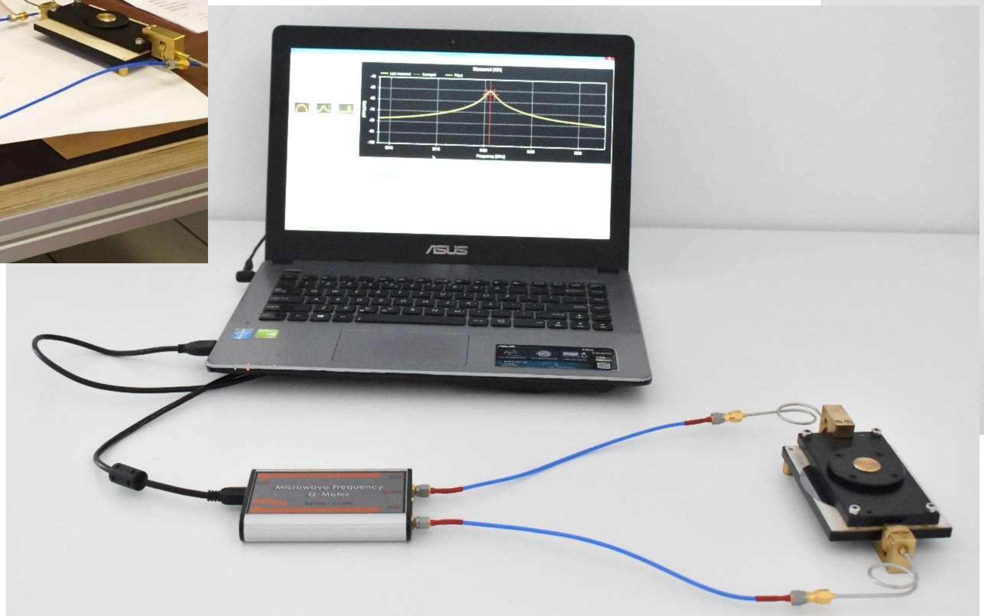


SPDR use in labs...

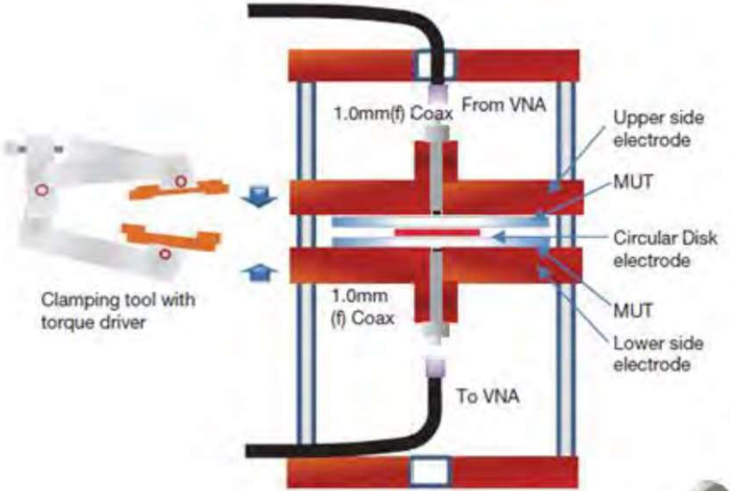
...and at home

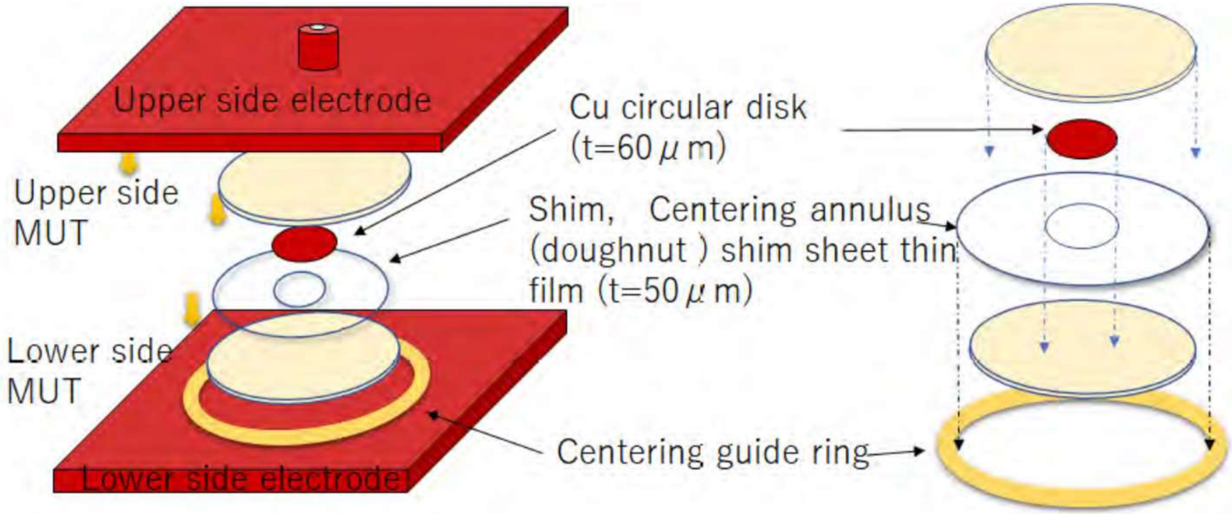
For many practical materials, measuring only abs (S21) provides appropriate accuracy.

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



Balanced-type circular disk resonator (BCDR) - basics

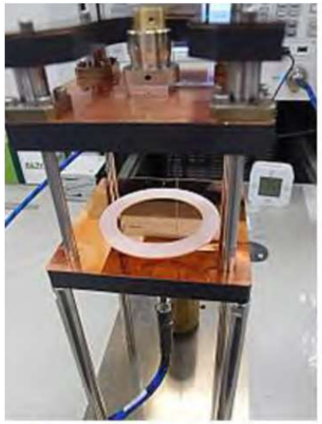




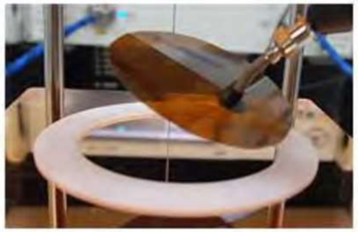
Balanced-type circular disk resonator (BCDR)	Multiple discrete frequency points from 10 GHz up to 120 GHz	• High measurement precision • Requires full 2-port calibration (mechanical to 110 GHz or electrical to 67 GHz) • Typically out-of-plane component of permittivity • Typical sample thicknesses less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

Balanced-type circular disk resonator (BCDR) - operation

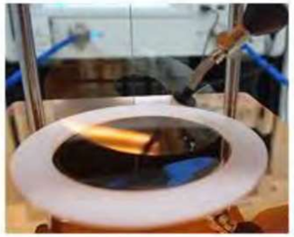
concentricity must be preserved



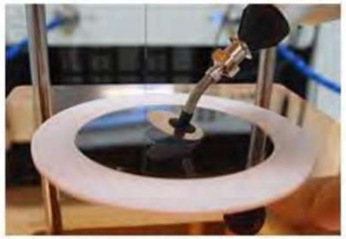
Open the resonator



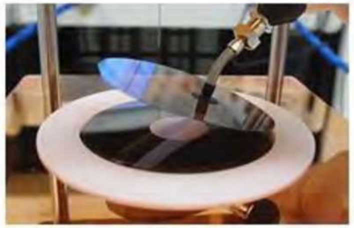
Set lower side sample



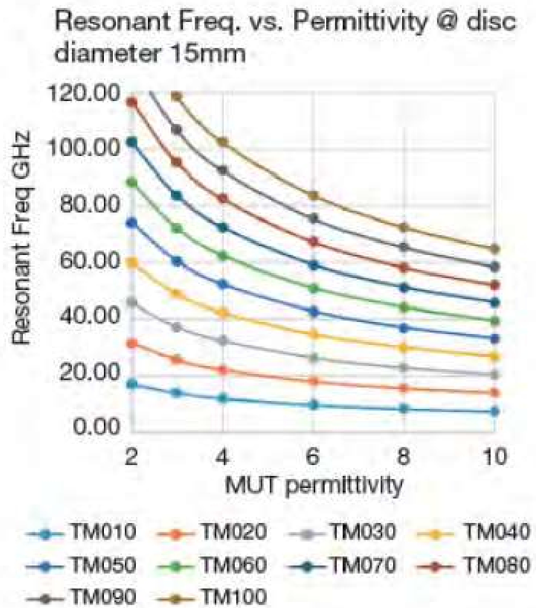
Set shim sheet

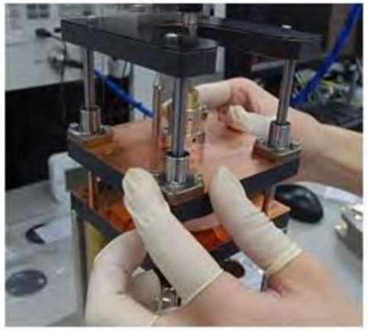


Set center electrode



Set upper side sample

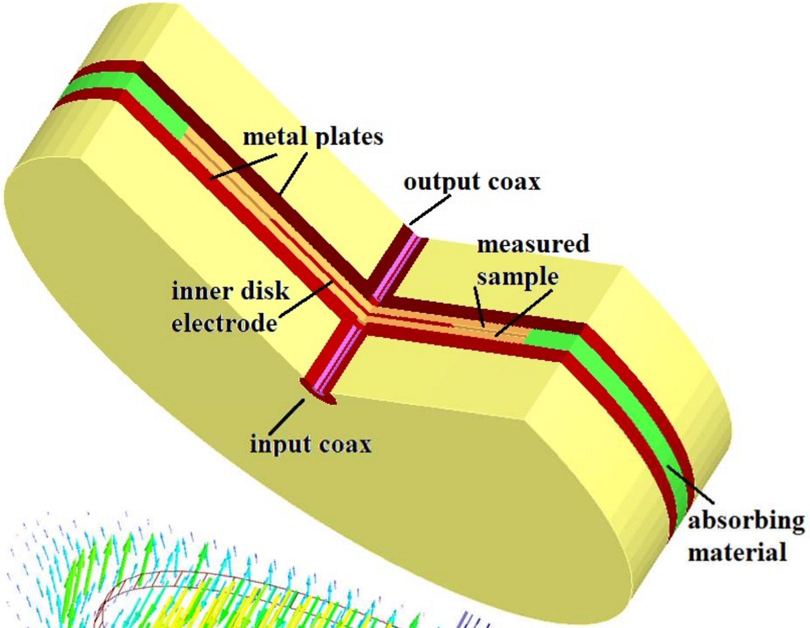


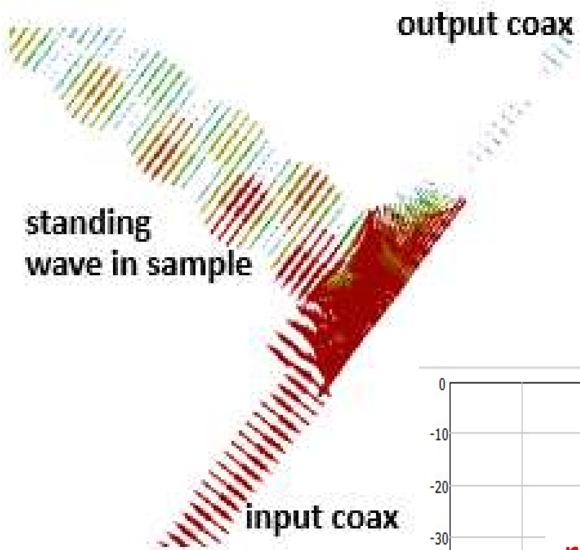


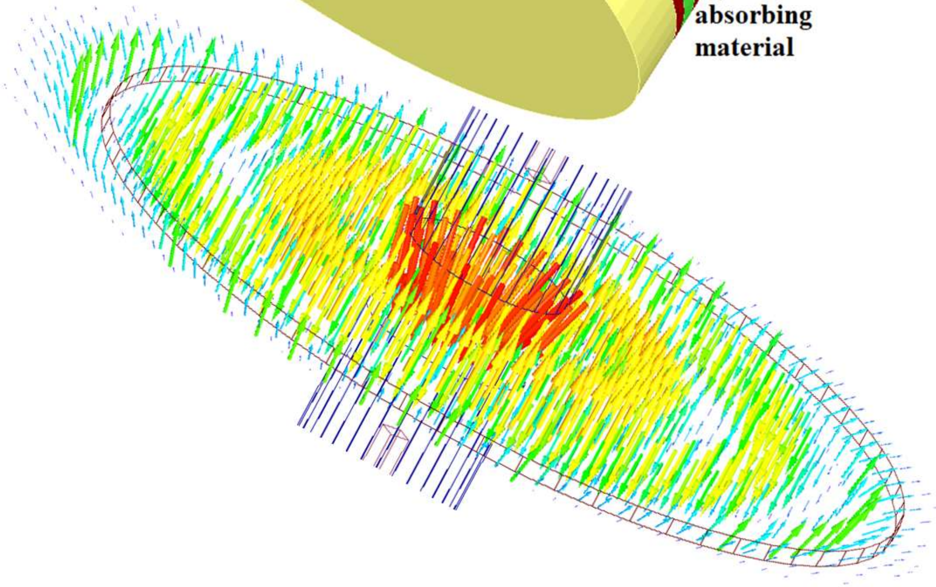
Close the resonator

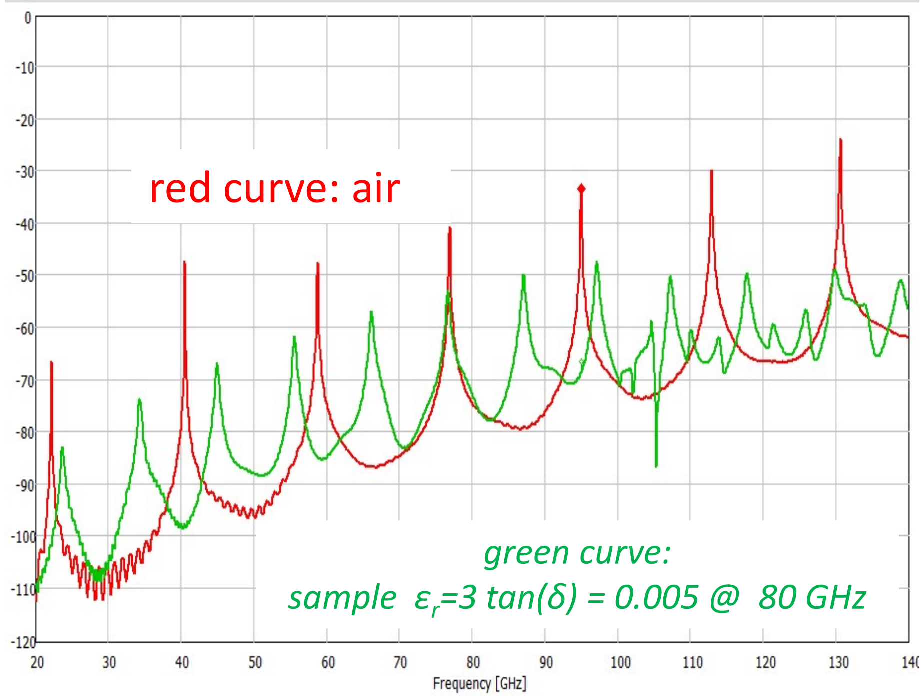
Clamp and measure

Balanced-type circular disk resonator (BCDR) – modelling

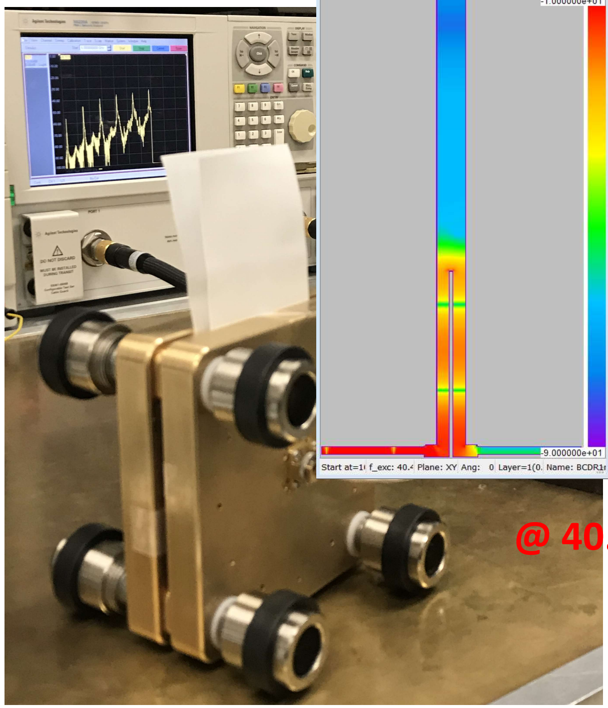


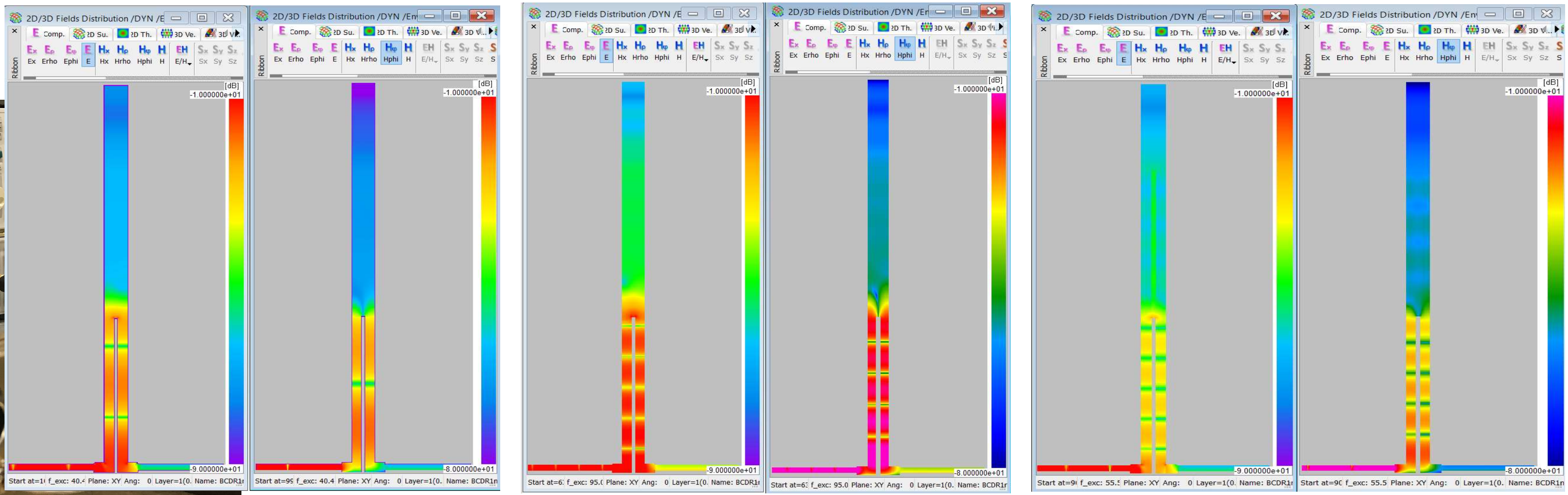






Balanced-type circular disk resonator (BCDR) – modelling





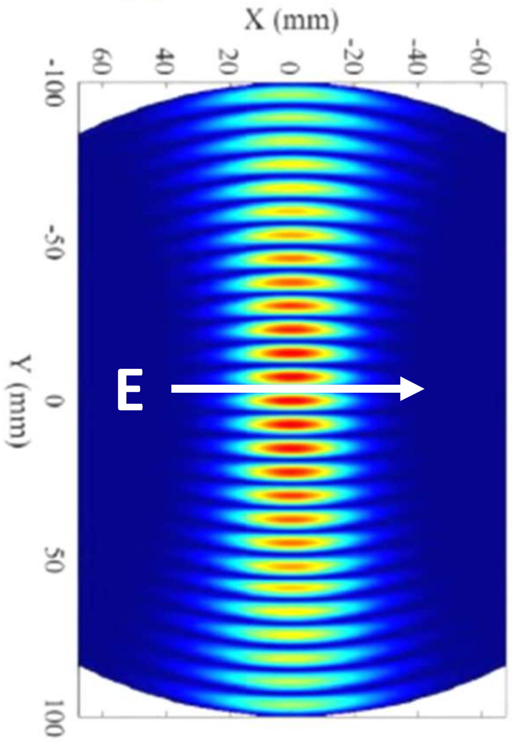
@ 40.49 GHz, air

@ 95.06 GHz, air

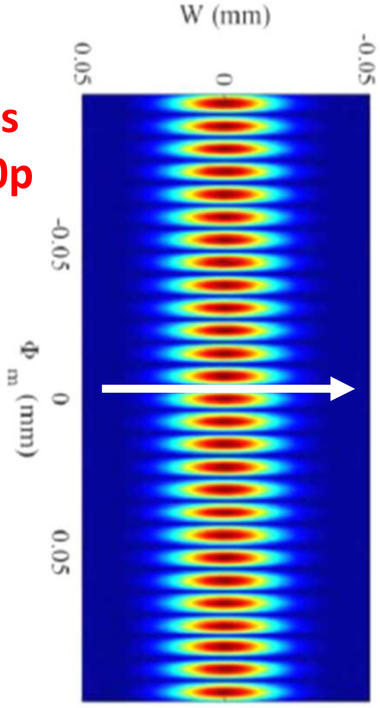
@ 55.57 GHz, sample

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

Fabry-Perot Open Resonator (FPOR) – basics..



modes
TEM00p

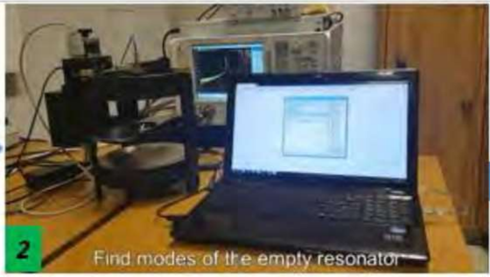


Fabry-Perot open resonator (FPOR, also called open-cavity)	Discrete frequencies between 20 GHz up to 110 GHz	• High measurement precision • Can be sensitive to many user errors • Uncertainty increases with increasing frequency • Typically in-plane component of permittivity • JIS R1660-2 • https://www.qwed.com.pl/resonators.html#ResonatorFPOR • https://www.keysight.com/main/editorial.jspx?cc=US&lc=eng&ckey=2276755&nid=null&id=2276755

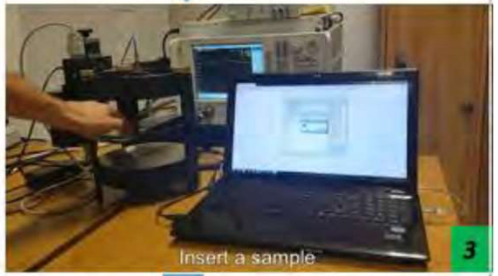
..and modeling

Fabry-Perot Open Resonator (FPOR) - operation

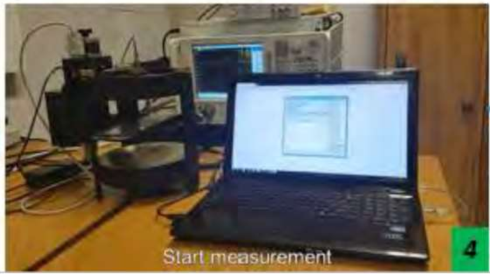
1. Connect the FPOR to VNA and PC with control app.



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



3. Insert the sample into FPOR

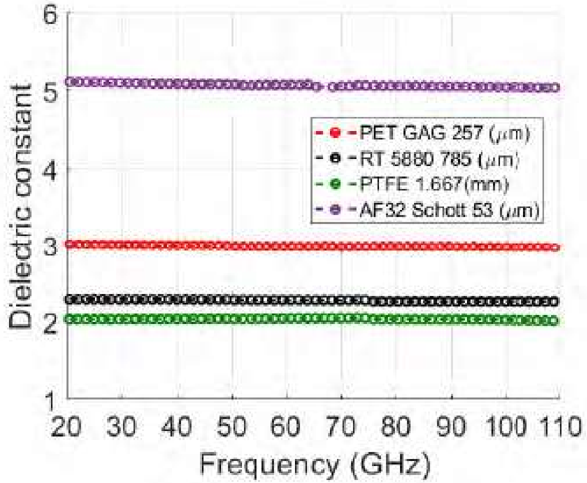


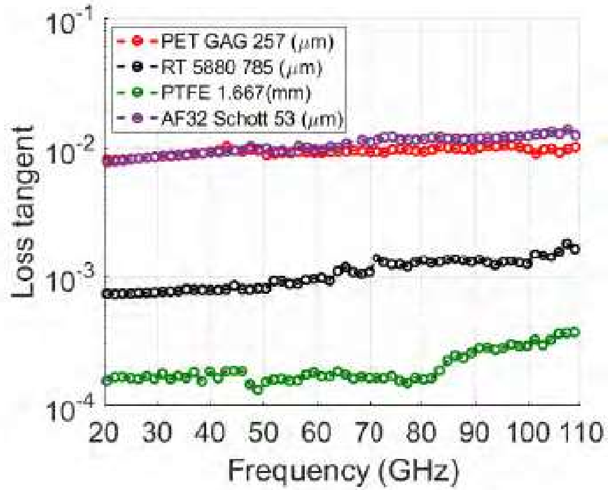
4. Automatic procedure finds M..N modes of sample-loaded FPOR

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

PC app invoked and controlled measurement – fully automatic

Total measurement time: 10min





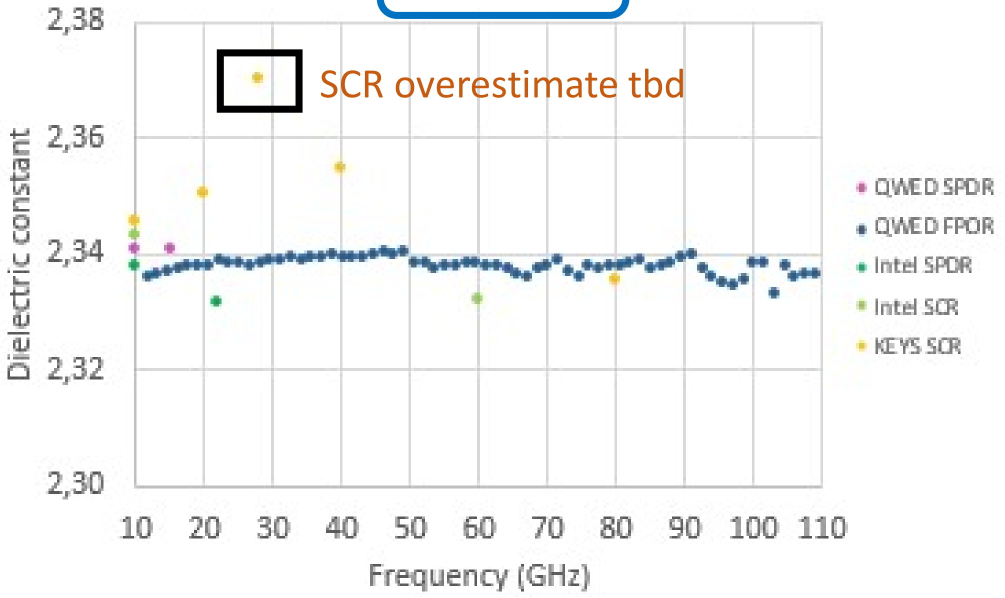
Characterisation Results - Consistency

3 labs, 3 techniques, 14 laboratory setups

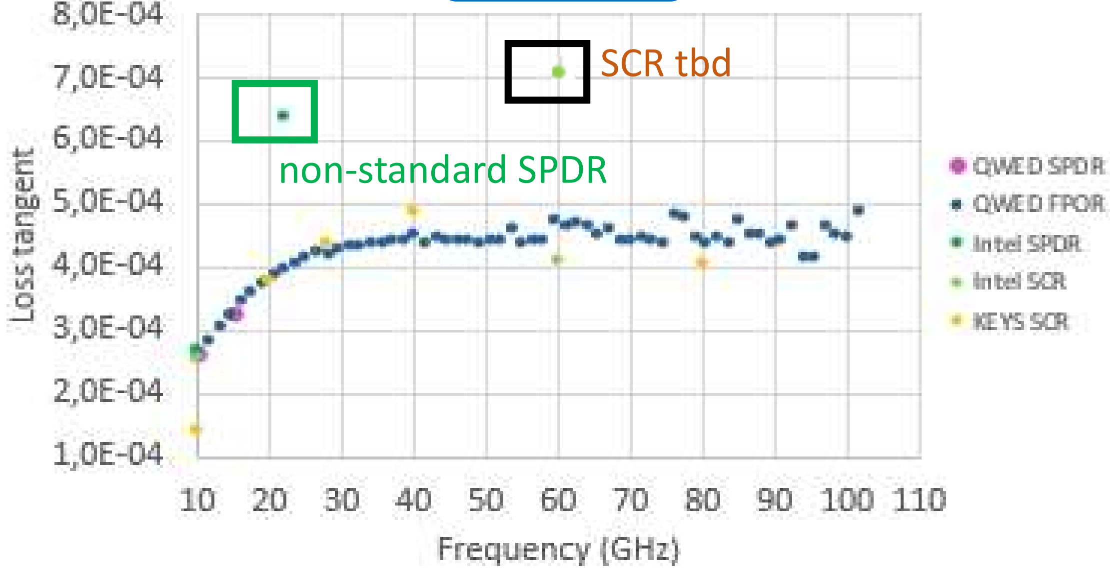
Intel - SCR at 10 / 60 GHz and SPDR at 10/ 20 GHz,
Keysight - SCR at 10 / 20 / 28 / 40 / 80 GHz
QWED - SPDR at 10/ 15 GHz and FPOR over 10-110GHz.

COP 186µm

dot colours denote testing sites



COP 186µm



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

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

Techniques selected for Task 3 if iNEMI 5G project (FPOR)

	Preferred techniques with sample dimensions			Optional
Technique	Split cylinder resonator (SCR)	Balanced-type circular disk resonator (BCDR)	Fabry-Perot open resonator (also called open cavity)	Split-post dielectric resonator (SPDR)
Sample dimensions	20 um ~ 300 um (best for 100 um), 34 mm x 45 mm > 20G	0.1 mm ~ 1 mm, Best for 0.2~0.5 mm, 50 mmΦ x 2 each	0.050 – 3 mm, min. diameter: 75 mm max diameter: 150 mm	max 0.6 mm, min. 15 mm x 15 mm max 40 mm x 40 mm @15G

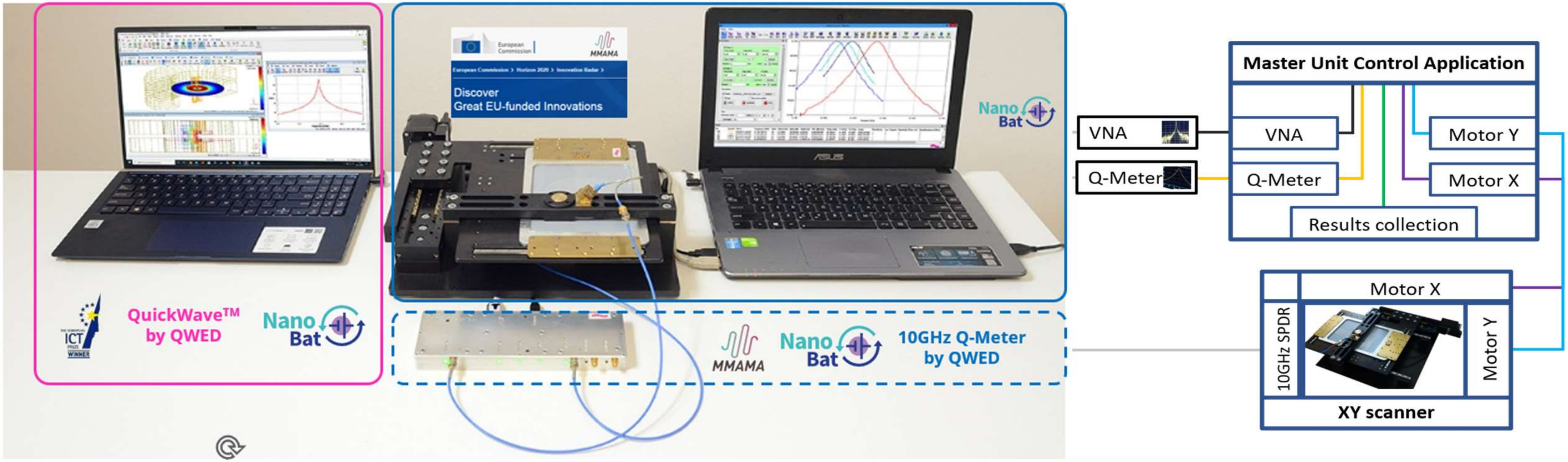
Samples under test in Task 3:

35 mm x 45 mm thickness: 50, 125, 188 µm

90 mm x 90 mm

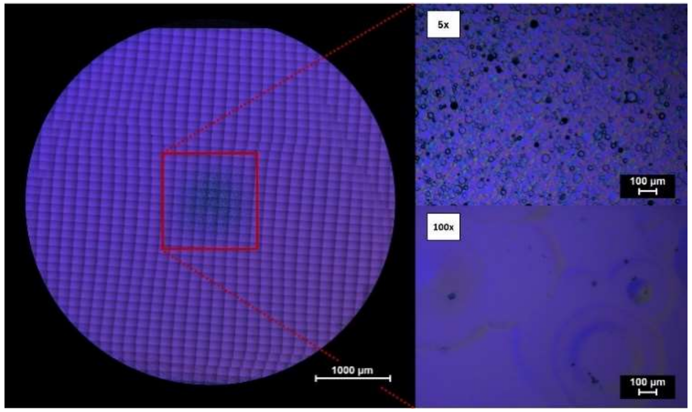
2D Imaging of Low-Loss Dielectric Materials

2D scanner designed with a modified 10 GHz SPDR



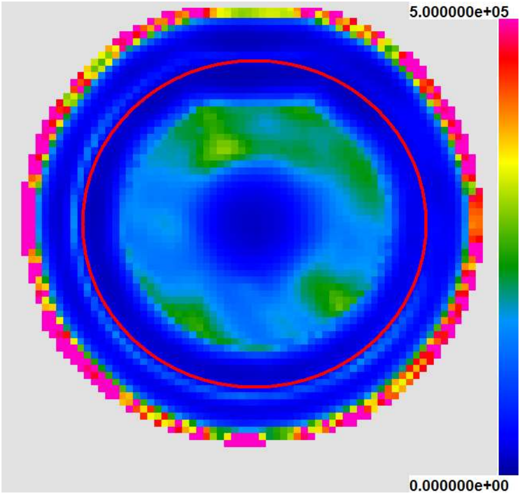
Finalist of the European Innovation Radar Prize 2021

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



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

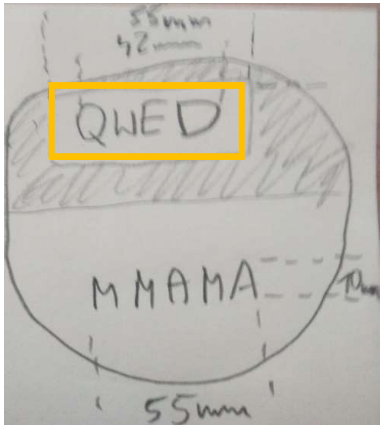
- in qualitative terms only,
- attributed to non-uniformity of the growth,
- only the central part appears unuseful for making devices.

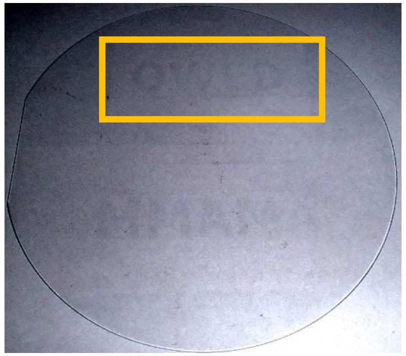


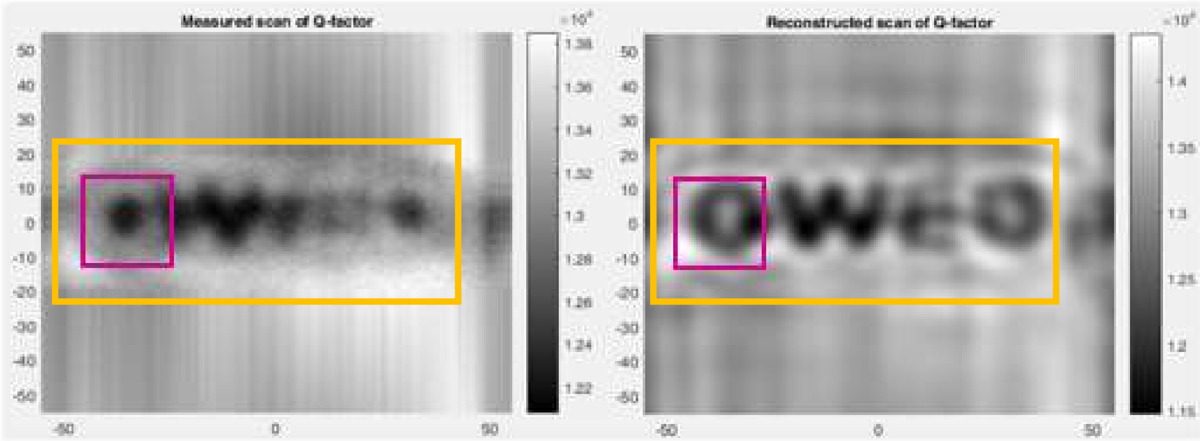
SPDR image:

- shows this whole GaN template unuseful,
- quantitative evaluation:
  - edge ring inherent to so-called edge effect,
  - ca. $2\cdot10^4$ Ωcm in the centre (dark blue),
  - ca. $5\cdot10^4$ Ωcm along the inner ring (light blue),
  - up to $1.2 – 3 \cdot10^5$ Ωcm across outer SUT's area (blue-green),
  - edge effect along the circumference.

Modelling-Based Resolution Enhancement of Surface Images





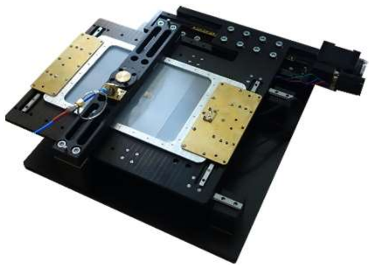


raw image of sample resistivity
(measured Q-Factor)

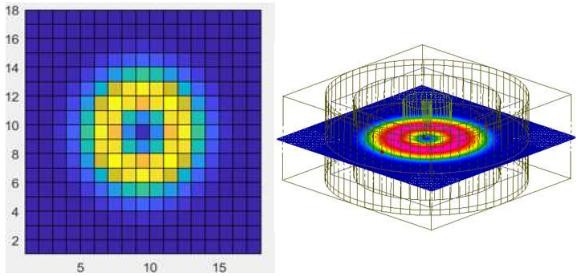
image further deconvolved
using SPDR field pattern
pre-simulated in QuickWave

MMAMA MATERIA NOVA M-ERA.NET

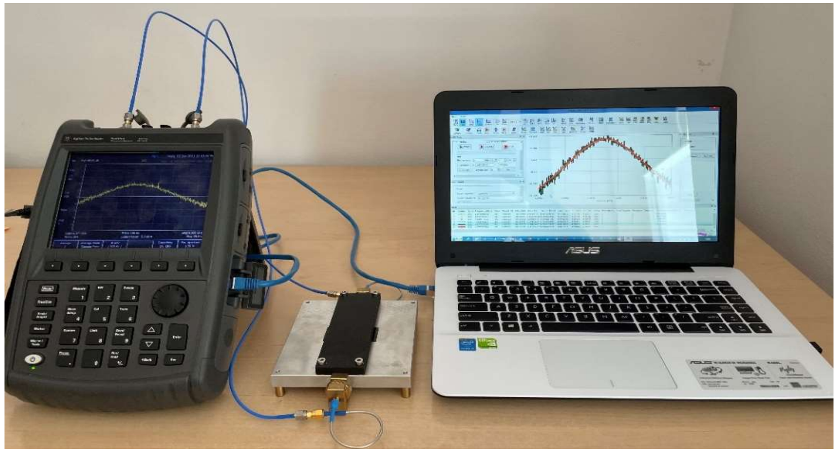
Patterned PEDOT:PSS sample
courtesy MateriaNova, Belgium

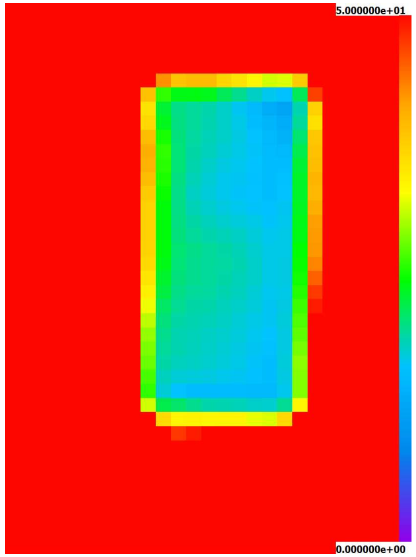


2D SPDR scanner



2D Imaging of Conductive Films – Application to Graphene Anodes

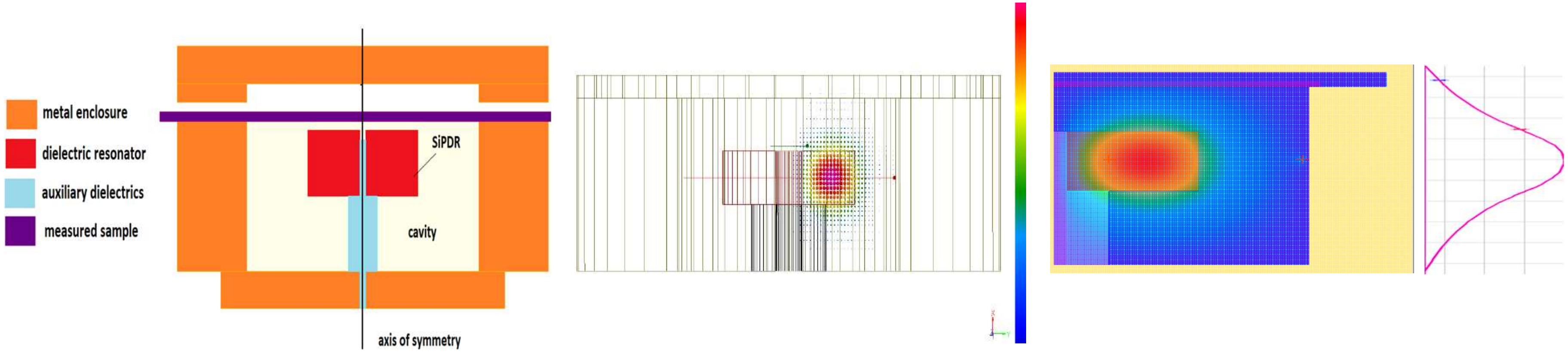




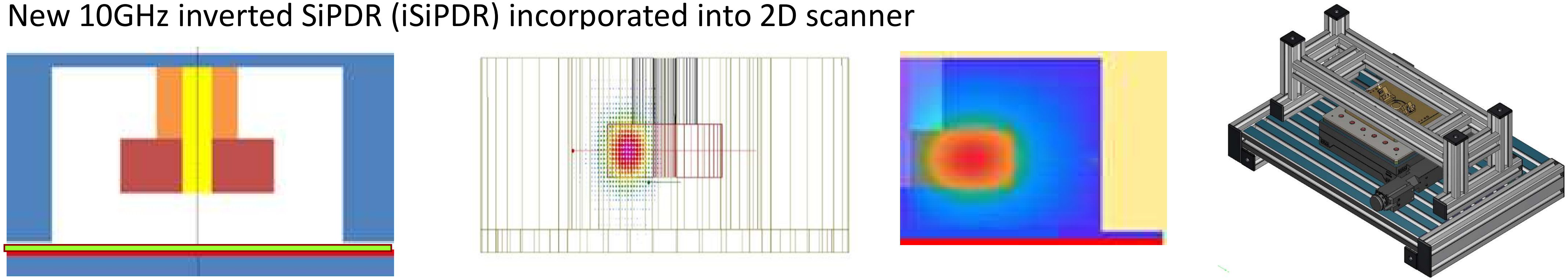
- Scanning area: 50 mm x 75 mm (25 mm margin around SUT)
- Uniform scanning step: 2 mm
- 1014 measurement points
- Avr thickness of the deposited graphene anode layer: 0.130 mm $\pm$ 0.02 mm
- Non-uniformities in R_s map due to sample thickness variation
- R_s extracted for average thickness value
- An absolute value of R_s can vary within uncertainty of $\pm$15%
- Avr R_s of 19.3 Ω/sq. in exact agreement with point-wise 5GHz SiPDR device.

2D Imaging of Conductive Films – iSiPDR Scanner Design

Commercial 5GHz Single-Post Dielectric Resonator (SiPDR): schematics and E-field distribution



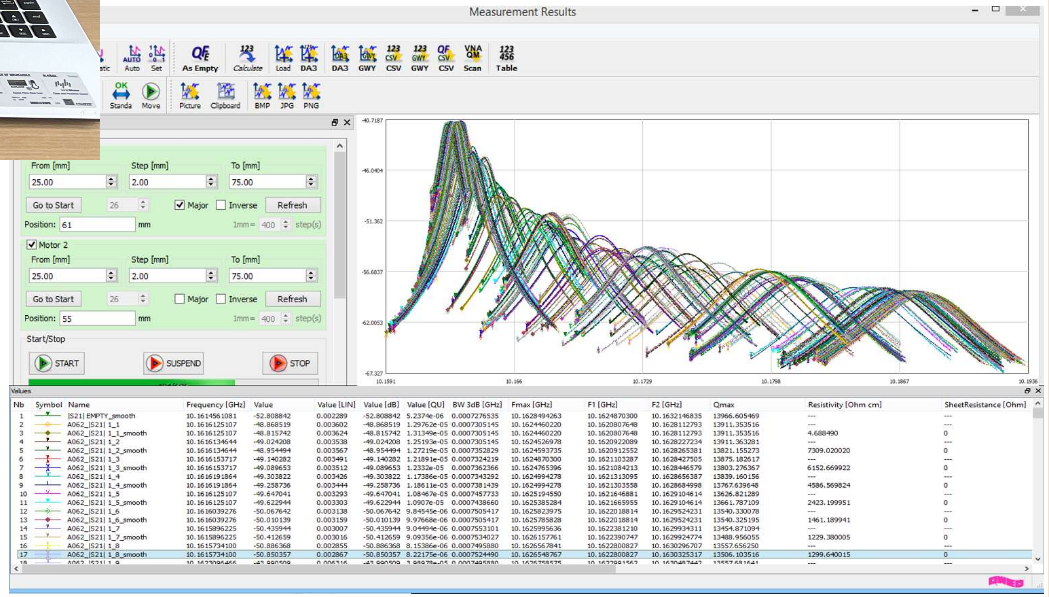
New 10GHz inverted SiPDR (iSiPDR) incorporated into 2D scanner



more sophistocated design & calibration:
active sheet facing the **DR head** → distance depends on the thickness of sample **substrate**

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

a family of |S21| curves obtained in one scan



2D SiPDR scanner

Keysight FieldFox

Control App

Concluding remarks

In the on-going iNEMI project, the four resonator methods (SCR, SPDR, BCDR, FPOR) are studied in terms of accuracy, repeatability, and reproducibility.

Each method has specific features, which can make it preferable for a particular application (e.g., different sample Dk / Df, thickness, expected anisotropy; frequency & temperature range of use).

Attention:

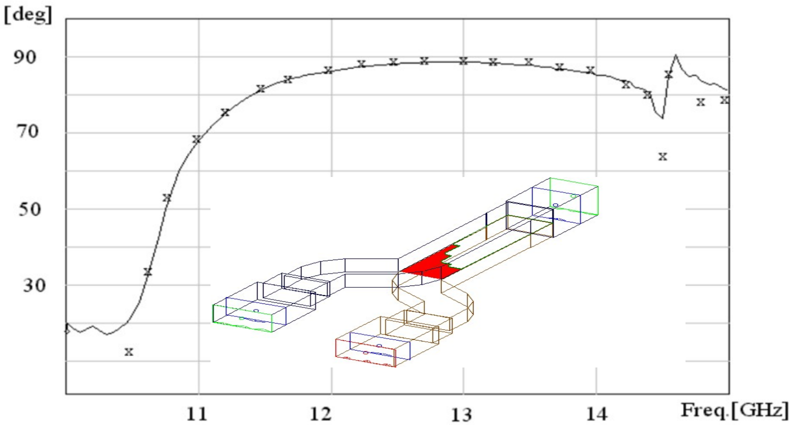
Each resonator is just a passive test-fixture.
All resonators must be used with VNA (*in some cases, scalar analyser is sufficient*).
Using the same resonator used with different network analysers (and signal processing software) may lead different results.

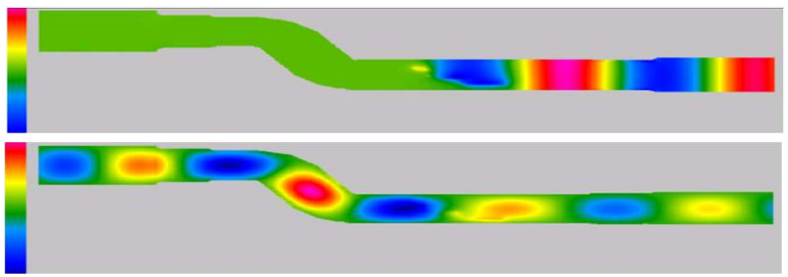
QuickWave original applications in cosmic reseach & satellite telecommunication

Septum polariser by SES

design & measurements: Saab Ericsson Space
modelling: QWED, 1997

below: differential phase-shift



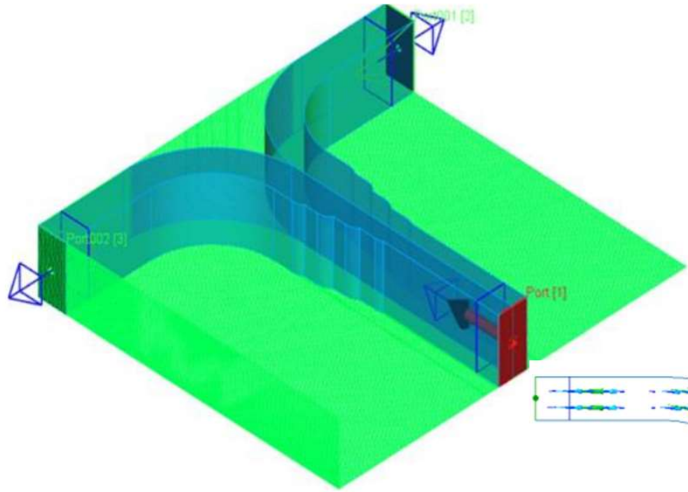


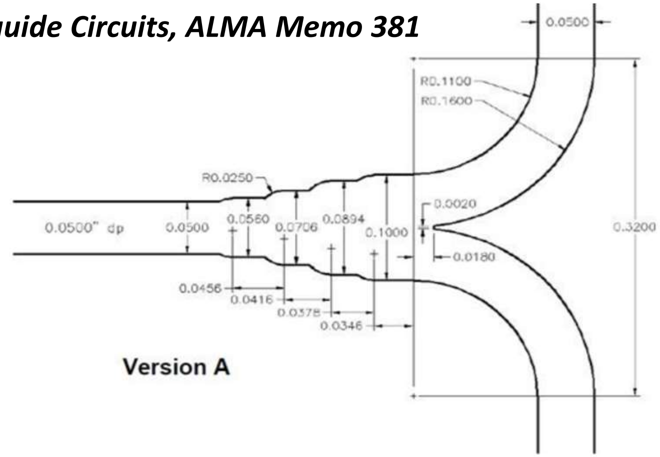
propagation of two polarisations

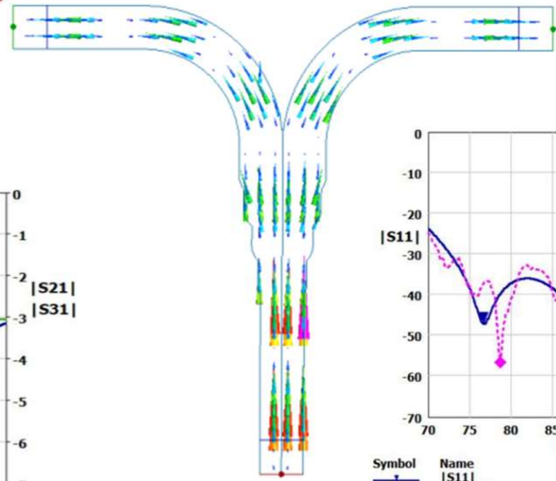
at centre frequency

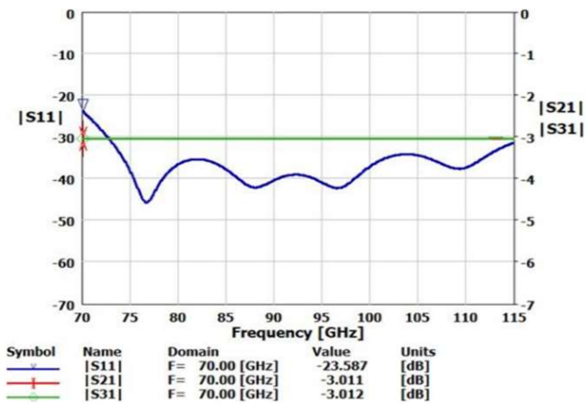
E-plane Y-junction by NRAO

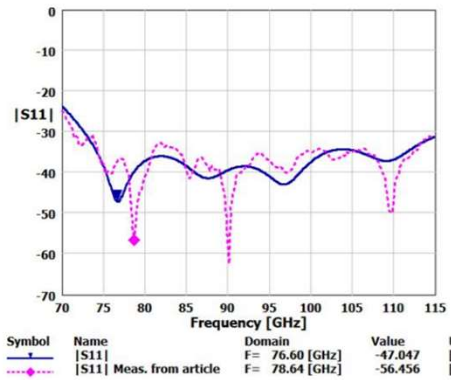
after A. R. Kerr, Elements for E-Plane Split-Block Waveguide Circuits, ALMA Memo 381





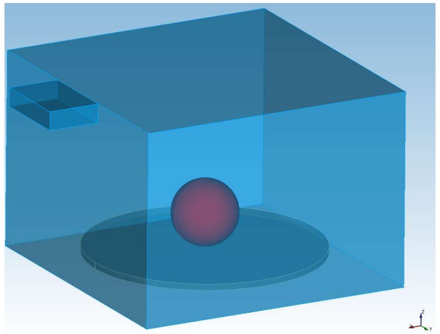


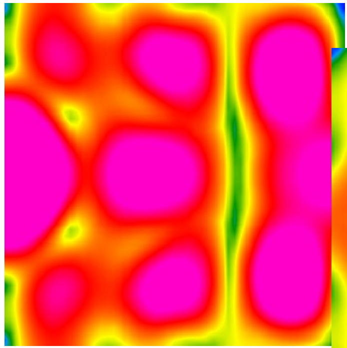




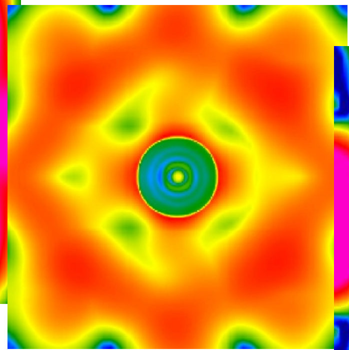
QuickWave modelling EM field interaction with tissues (for food processing & medical applicators)

Separation of incident and diffracted fields (*option implemented per request of P.O.Risman, Malardalen Univesity*)

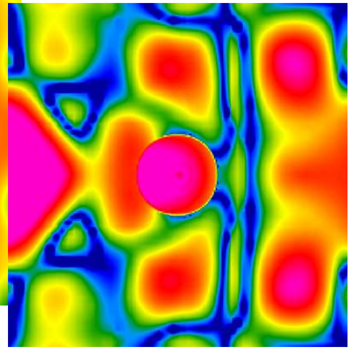




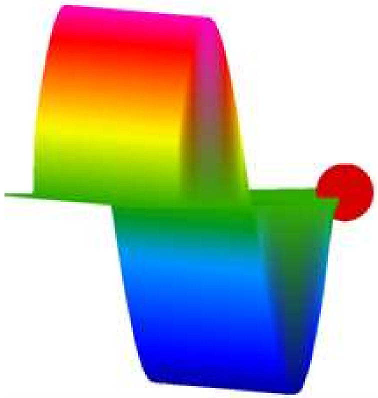
E-field in an empty cavity

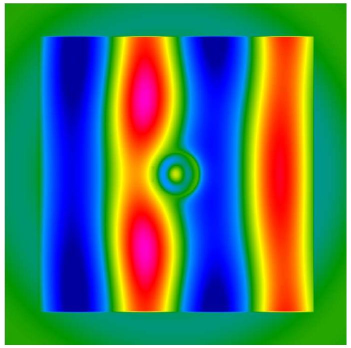


E-field in a loaded cavity

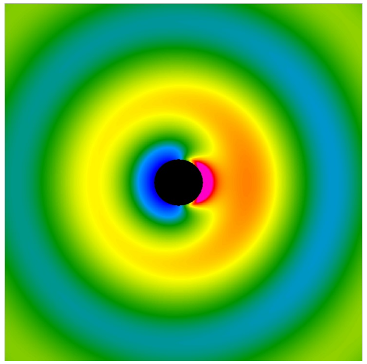


Scattered near-fied in cavity



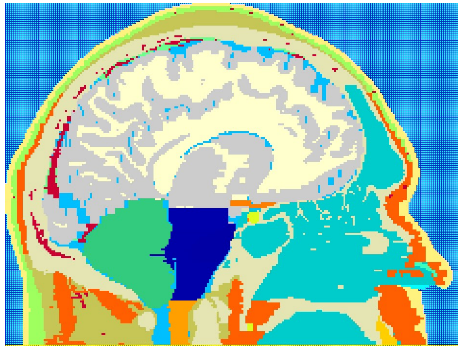


Total field
Focusing by the load
„exploding egg effect"

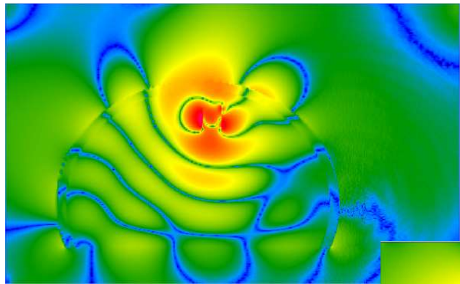


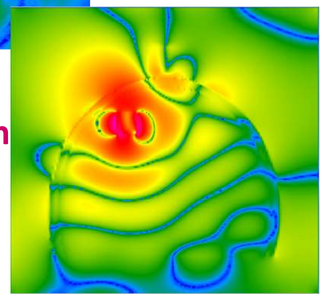
Diffracted field reveals cause of focusing: circumferential resonance

Detection of inhomogenities in tissues



AustinMan model* converted to **QuickWave EM** software for Mälardalen University, Sweden



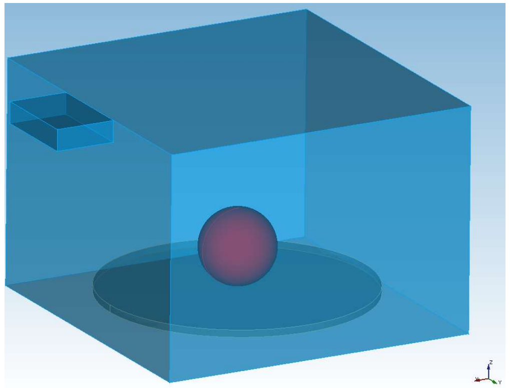


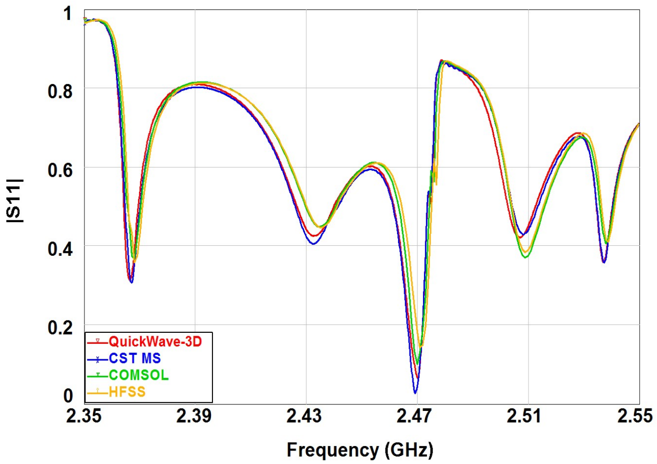
- ✓ Tumours & haemorrhages detection
- ✓ Optimisation of multiantenna tomographic systems

* https://sites.utexas.edu/austinmanaustinwomanmodels/

Ilustration & cross-verification of QuickWave Multiphysics Regimes in Elsevier Book

Simple microwave heating benchmarks & microwave heating phenomena studies*



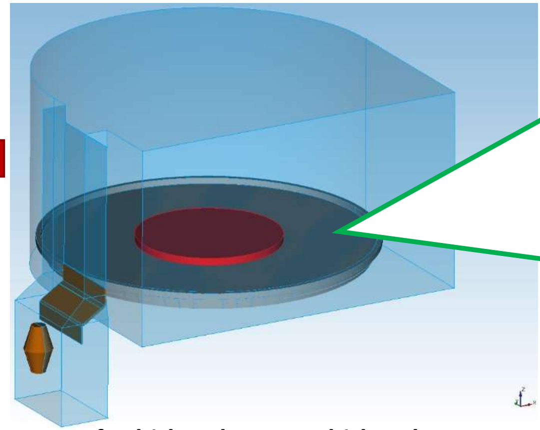


- heat transfer & load dynamics
- Load rotation & arbitrary movement during heating
- Source parameters tuning – regime for solid state sources
- Temperature dependence of material parameters

Freezing to file the state of the simulation

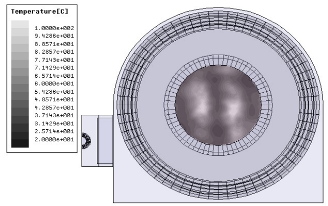
De-freezing on arbitrary computer & at convenient time

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

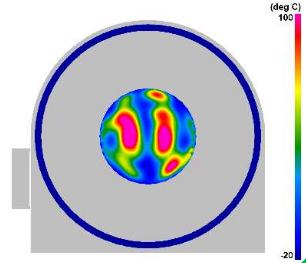


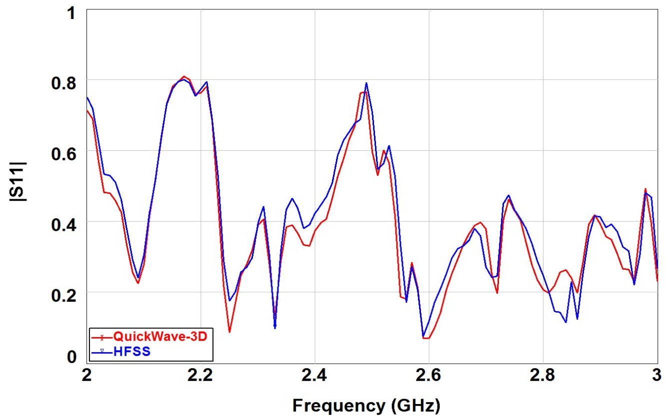
Courtesy of Whirlpool Inc. – Whirlpool MAX oven

HFSS v11



QuickWave 3D & BHM



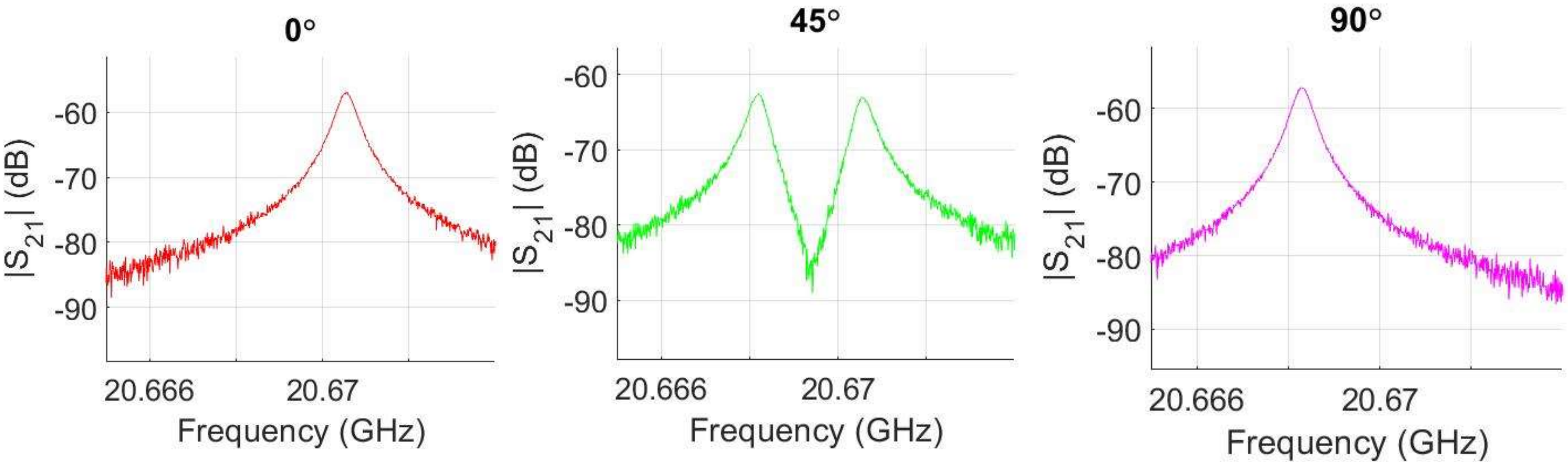


With QuickWave EM computation as fast as 1 min 18s on a low-cost video card – supporting all graphic cards with OpenCL

* 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.

Fabry-Perot Open Resonator (FPOR) - operation

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