Modelling-Based Characterisation of Materials from Micro- to Millimetre-Waves

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

M-ERA.NET
The National Centre for Research and Development
I4Bags
ULTCC6G_EPac
Nano Bat
iNEMI International Electronics Manufacturing Initiative

IEEE Radio & Wireless Week, Women in Microwaves Event
Las Vegas, Nevada, 22 January 2023

IEEE Women in Engineering WIE
IEEE Advancing Technology for Humanity
MTT-S MHz to THz Community

IEEE RADIO & WIRELESS WEEK 2023

RWW 2023 Women in Microwaves Event: Distinguished Women in Microwaves

Jasmin Grosinger

"Modeling-Based Characterization of Materials From Microwaves to Millimeter Waves"

Talk Outline

1. What is DISTINCTIVE my caree path:
   - what it combines,
   - how it has come about.

2. Two IEEE MTT-S Fellowships merged & transformed into a successful business:
   - Electromagnetic MODELLING at the Warsaw University of Technology, giving rise to QWED,
   - Materials' CHARACTERISATION at the Warsaw University of Technology, helping expand QWED.

3. Examples of microwave design & multiphysics modelling with QuickWave™ software by QWED.

4. Modelling-based development of resonator techniques
   - recent industrial benchmarking for 5G,
   - recent extensions to surface imaging & novel materials.

5. My contributions:
   - to academic research at WUT,
   - to research & innovation at QWED,
   - to QWED management,
   - to European initiatives & policy making,
   - to Women in Microwaves / Engineering / Science.

6. Summary & acknowledgements.

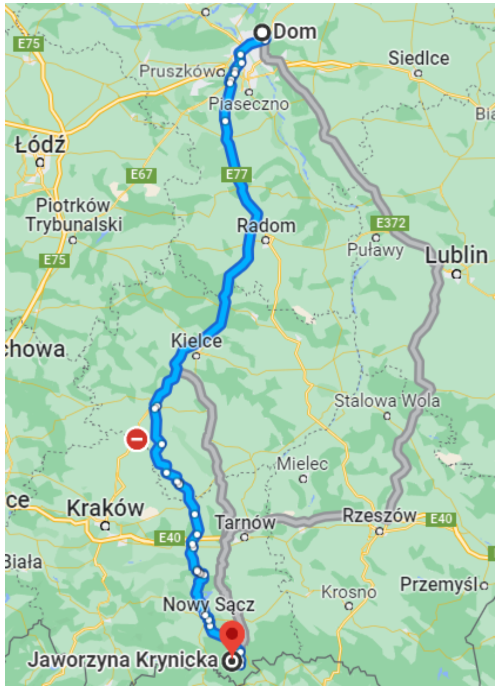
My Professional Paradox

I never wanted to become an engineer.

Many engineering tools are my enemies…

hardware ↓

software →



And even today, I don’t consider myself a *real* engineer.

although some are good friends:

↑
software

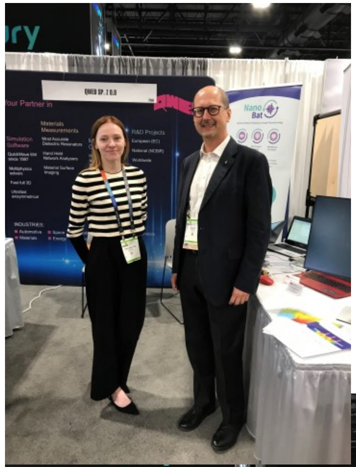
In partnership with UWC

← hardware

And There are Great Friends in the Society!

Anaheim, CA, 1999

San Francisco, CA, 2006



Denver, 2022

An Unbelievable Opportunity: My Scholarship to UWCA 1981-1983

MALGORZATA CELUCH

Polish (100/) — 10/5/64
Maths, Further Maths, Geography, Physics, English, Polish, Russian.
EMU EMC
Spanish, Volleyball, Weaving, Bandy, Badminton . . . AHMAS(?) . . .

Quiet, quiet, quiet . . . and soon proved to be a chief Maths tutor, a real revolutionary (. . . "but Deon . . . Poland has got a desert!) . . . and . . . a master of ceremonies at midnight parties.
"The only true law is that which leads to freedom. There is no other."
Scientific exploration of the Bristol Channel followed by the exploration of humanity: apart from the change to Extra-Mural this included more of the intellectual conversations in Mendellsohn House.
Polish hospitality helped keep dorm 12 a home.
From depression to the highest happiness. . . . No, Gosia was not lacking her own problems, but she used them as a backing for understanding the others.
Don't believe your eyes-all they show is limitation.

. . . Look with your heart.

It was like winning a lottery – except that I never bought a ticket!

United World College of the Atlantic in South Wales,

the most FANTASTIC school on Earth,

where the main objective was INTERNATIONAL UNDERSTANDING

(rather than science or engineering)

I wanted to work with people, nature, and diversity

-> considered geography with economics and a focus on marine science.

But I felt it my duty to return to Poland after IB

-> where studying the above did not make sense (and it was still martial law).

In a guide to Polish universities I read that:

"Telecommunication includes exploring the interior of Earth with radiowaves".

Thus I ended up as a student of Electronic Engineering

(while remaining a mathematician and globetrotter by passion)

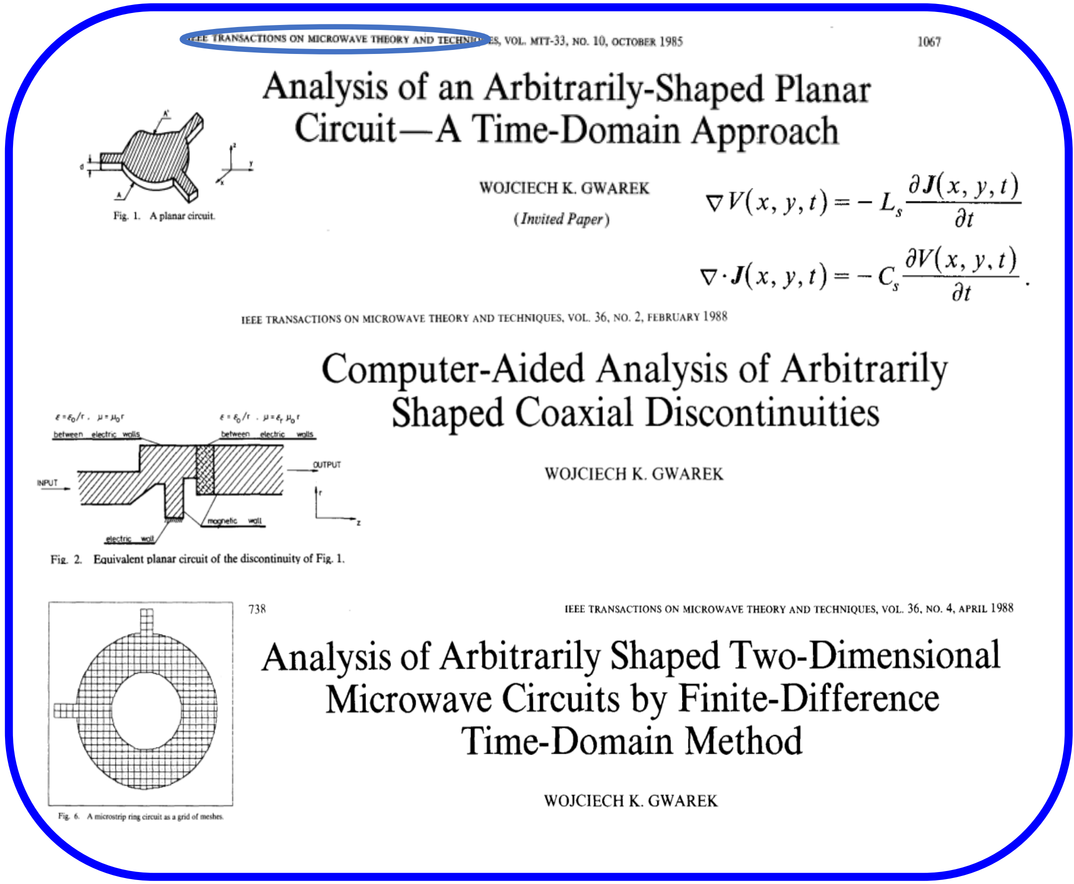
In my 1st year, Maths and Circuit Theory were OK (99-100%)

but all the engineering courses were not making any sense to me. I was feeling out of place.

In my 2nd year, Electromagnetics started. And later Numerical Methods. This is how I did not quit.

EM Modelling: from WUT to QWED

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


IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. MTT-33, NO. 10, OCTOBER 1985 1067

Analysis of an Arbitrarily-Shaped Planar Circuit—A Time-Domain Approach

WOJCIECH K. GWAREK
(*Invited Paper*)

Fig. 1. A planar circuit.

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

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

IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 36, NO. 2, FEBRUARY 1988

Computer-Aided Analysis of Arbitrarily Shaped Coaxial Discontinuities

WOJCIECH K. GWAREK

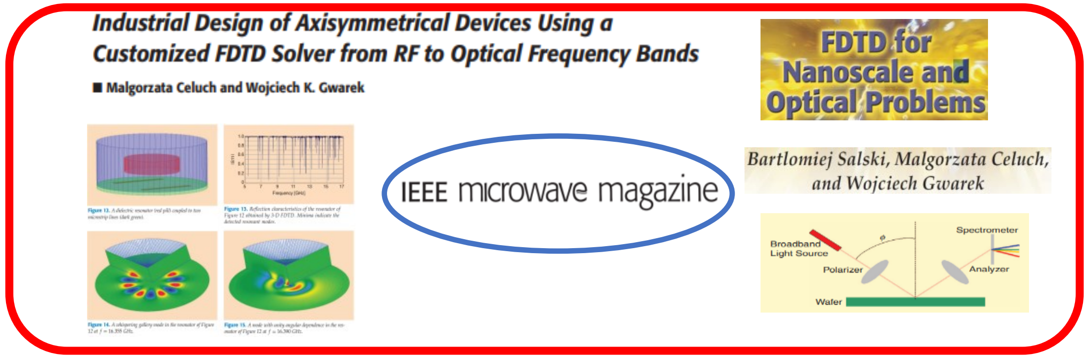
Fig. 2. Equivalent planar circuit of the discontinuity of Fig. 1.

738 IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 36, NO. 4, APRIL 1988

Analysis of Arbitrarily Shaped Two-Dimensional Microwave Circuits by Finite-Difference Time-Domain Method

WOJCIECH K. GWAREK

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


Industrial Design of Axisymmetrical Devices Using a Customized FDTD Solver from RF to Optical Frequency Bands

Malgorzata Celuch and Wojciech K. Gwarek

IEEE microwave magazine

FDTD for Nanoscale and Optical Problems

Bartlomiej Salski, Malgorzata Celuch, and Wojciech Gwarek

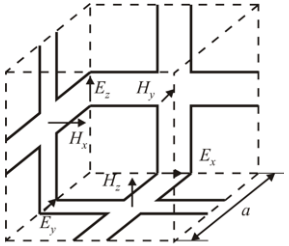
A European COPERNICUS project in 1994-1996 helped our team initiate a commercial version of QuickWave™ software.

First licence sales in 1997
(to SES, NRAO, JPL, and a leading MW oven producer).

By today: ~ 1000 licences implemented worldwide.

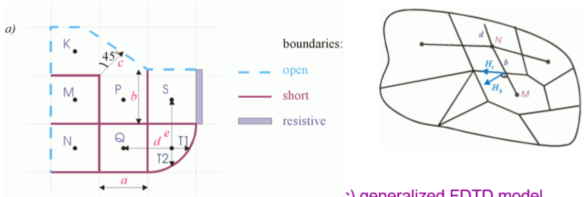
My Contributions 1990s

FDTD versus TLM
Theorem of Formal Equivalence



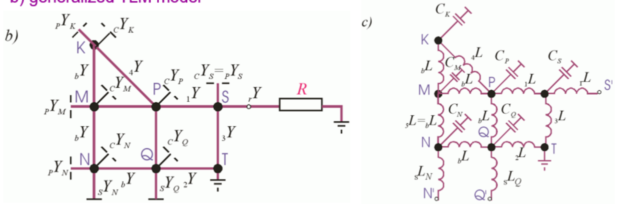
nodes: FDTD discretisation of Maxwell eqs.
connecting lines & stubs: TLM discretisation of Huygens principle

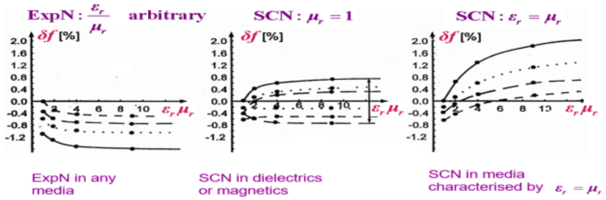
a) generalized gridding of a microwave structure

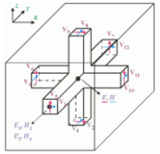


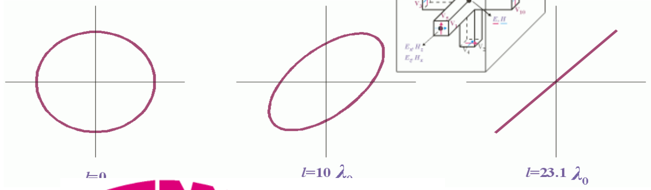
b) generalized TLM model

c) generalized FDTD model





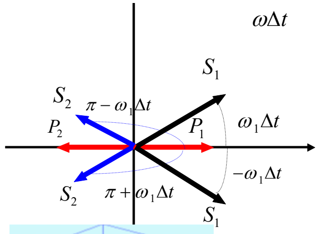


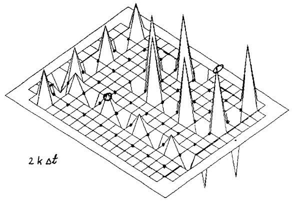


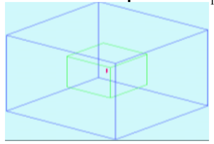
Generalised dispersion relations
Theory of P- and S-eigenmodes

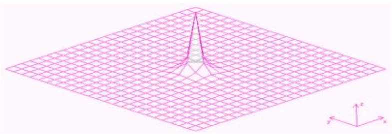
$$P(\omega\Delta t)\ S(\omega\Delta t, \beta_x a, \beta_y a, \beta_z a) = 0$$

$$\omega_{ph}^2[-\omega_{ph}^2\mu\varepsilon + \beta_{xph}^2 + \beta_{yph}^2 + \beta_{zph}^2]^2 = 0$$

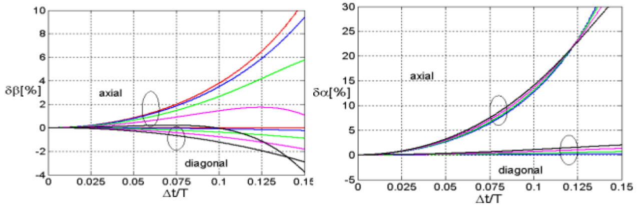




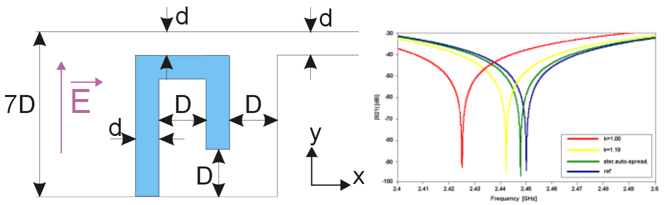




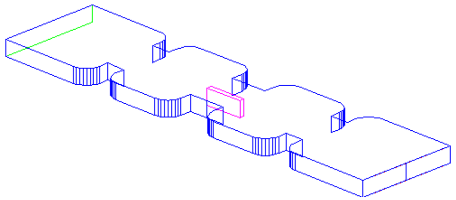
Dispersion in lossy media

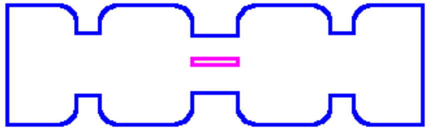


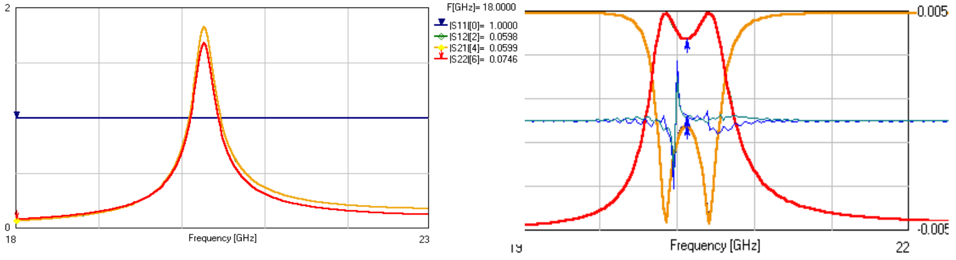
Field singularities



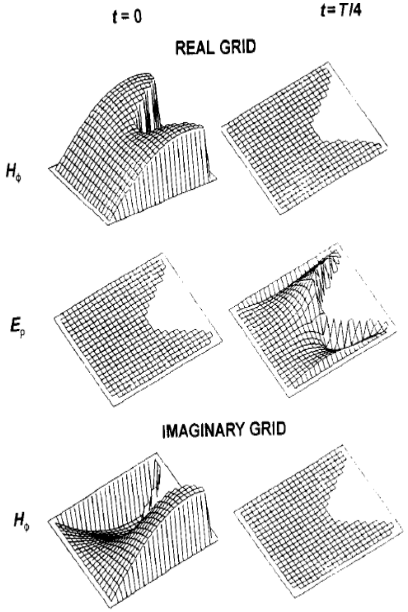
Generalised extraction of S-parameters in multi-modal transmission lines (incl. evanescent modes)



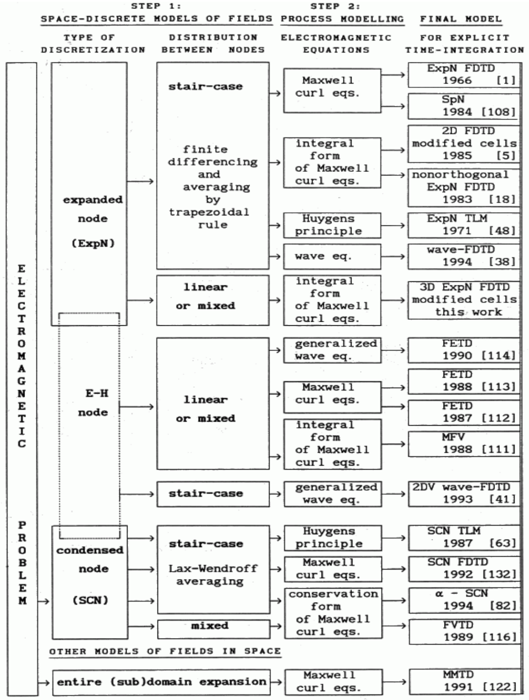




Periodic & vector 2D FDTD and TLM in real & complex form

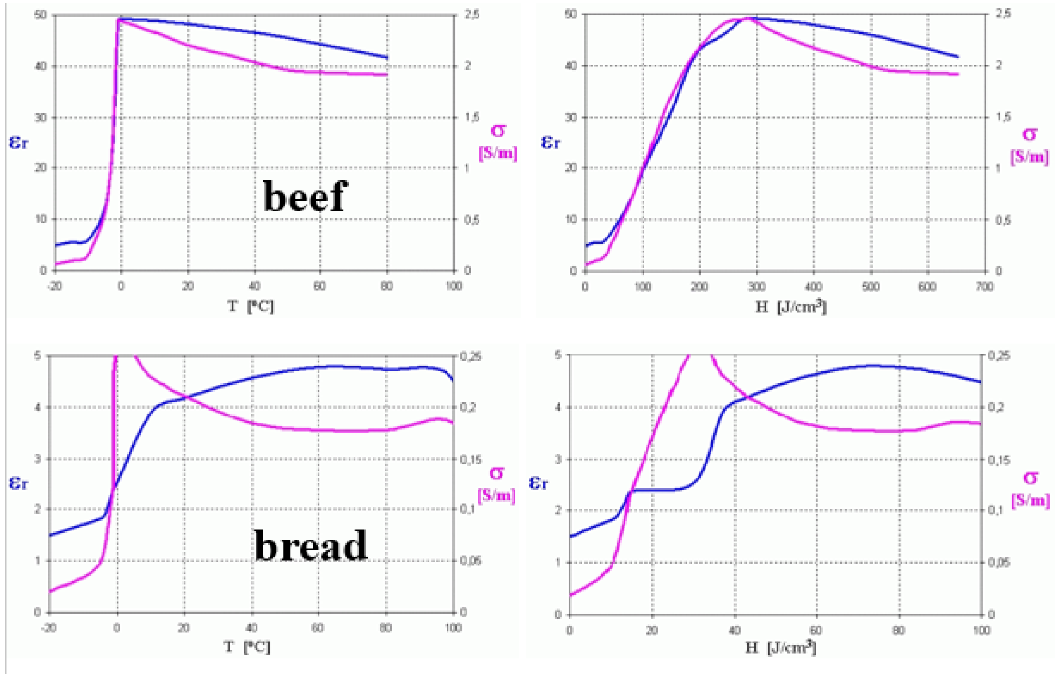


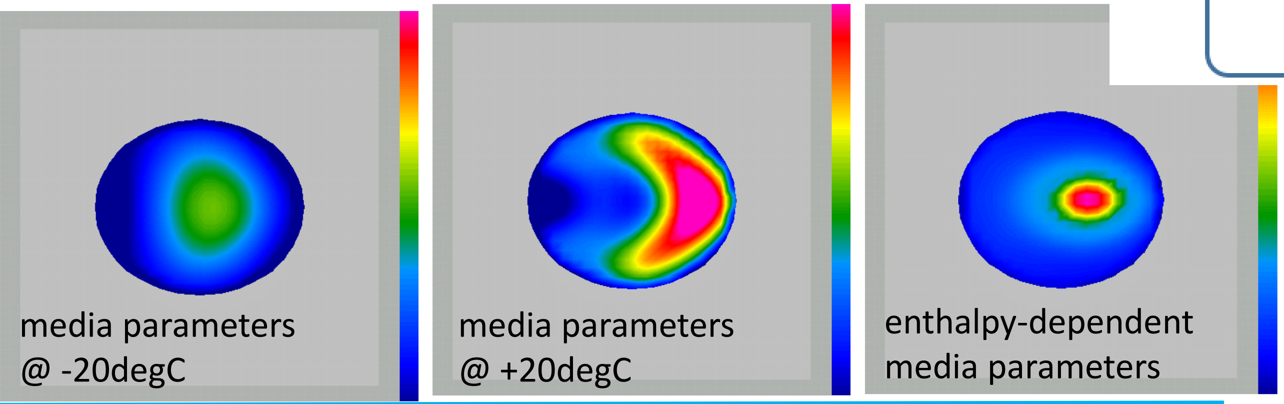
Classification of time-domain methods



Multiphysics Modelling for MW Heating Applications

QW-BHM 2000





FDTD analysis with sinusoidal excitation at ***f=f0***

Calculation of 3D pattern of ***dissipated power*** ***$P_{avg}(x,y,z)$***

Enthalpy update in 3D domain

$$H^{n+1}(x,y,z) = H^{n}(x,y,z) + \frac{P^{n}_{avg}(x,y,z)\Delta\tau^{n}}{\Delta V(x,y,z)}$$

Temperature update in 3D domain
$T(x,y,z) = T[H(x,y,z)]$
from *.pmo file

Load movement/rotation
Translation of the object and thermal quantities along user-defined trajectory

Calculation of heat transfer
Enthalpy and ***temperature*** update in 3D domain

Material and ***thermal parameters*** update in 3D domain $\varepsilon(x,y,z) = \varepsilon[T(x,y,z)]$
$\sigma(x,y,z) = \sigma[T(x,y,z)]$
from *.pmo file

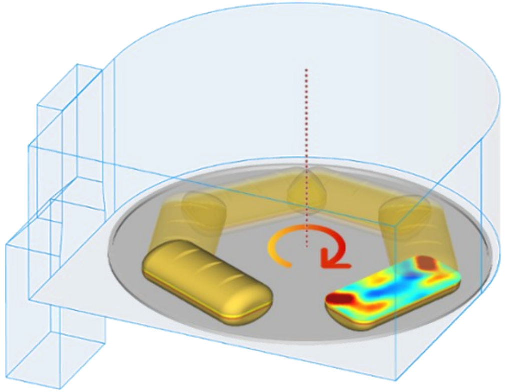
Source tuning to ***f=f1***
Changing operating frequency: automatically to the deepest resonance or manually upon user's criterion

QW-BHM module of QuickWave:

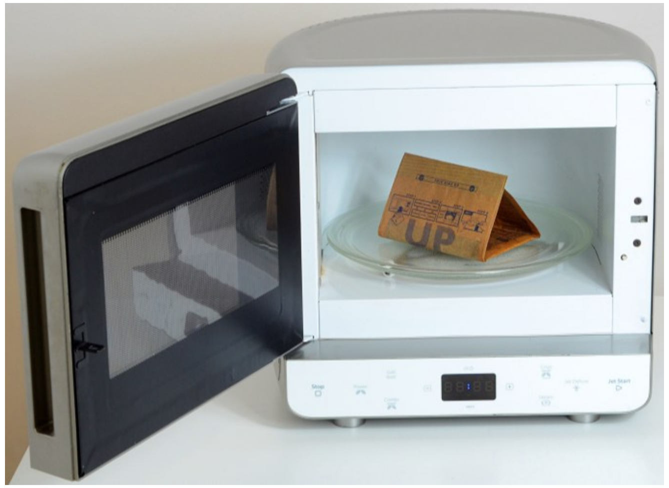
- automatic system
- each cell heated individually
- no need to define 1000s of "media"
- bilateral coupling EM - thermal

Conferences and Exhibitions Related to MW Power

EMB-1998, Linkoping, Sweden (complex geometries of ovens & feeds, enthalpy-dependent material paremeters, load rotation, microwave popcorn)



Whirlpool – MAX domestic oven



IEEE IMS 2014, Tampa, FL
(NXP experimental oven designed in ENIAC-HEECS project: solid-state MW sources, controlled field polarisation)

IMPI Congress 2022

QWED started in 1997

celebrating 25 years

Purpose: to supervise the commercial development of QuickWave software for Electromagnetic Design.
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
- 25 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
- 50 years of experience in computer-aided electronic engineering and engineering software development

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

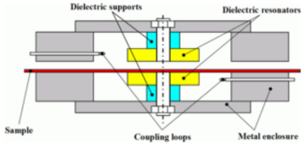
Dr. Maciej Sypniewski
Senior in CAE
- 35 years of experience in engineering software development and GHz measurements

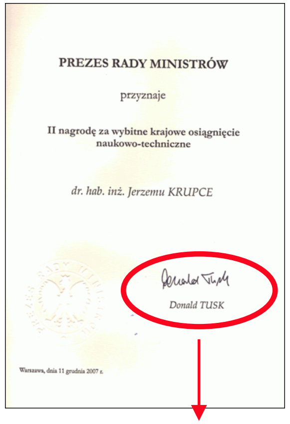
10
people employed

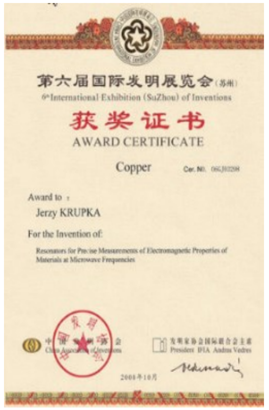
50%
female

Material Measurements: from WUT to QWED

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





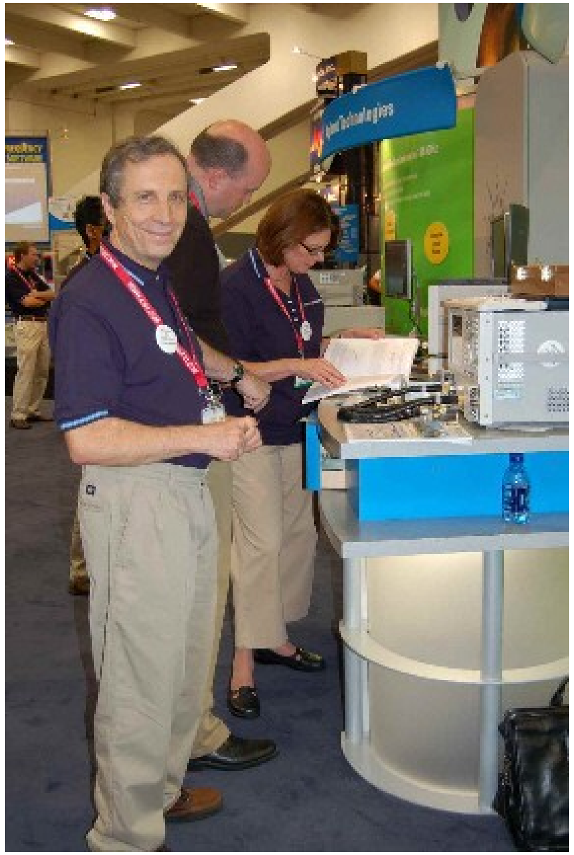


by Donald Tusk
Prime Minister of Poland 2007-2014
President of the European Council 2014-2019

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

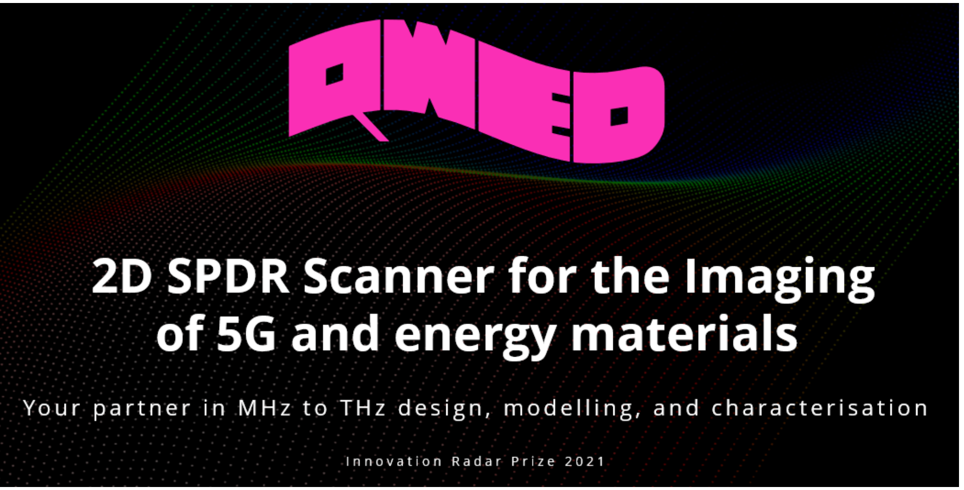
1000th unit sold in 2020.

Today ~120 units/year.



Agilent Both
IEEE IMS 2006, San Francisco, CA

MMA-2010, Warsaw PL
co-organised by QWED & WUT



Market Study

for the Finals of the European Innovation Radar Prize, 2021

Disclaimer: it was not me doing the study!

Strong opportunities from 2 fast-growing markets

- Global EM simulation market estimated at **500 MEUR** (2020)
- Estimated to grow at a ***CAGR of 9%*** during the forecast period (2020-2025)

- Global market of EM testing of materials estimated at **2,3 Bn EUR** (2016)
- Estimated to grow at a ***CAGR of 5%*** during the period (2017-2023)

An innovation solution present on both market

Our innovative solution coupling EM / multiphysics simulation with material measurements is expected to:

- increase QWED share in both above markets individually,
- and create new markets by dissemination, training, and synergy effects.

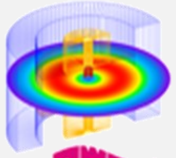
The emerging technologies (5G and Green Energy) form a new market for our solution, estimated at 5 MEUR and rapidly growing.

www.qwed.eu

Current Work: Bridging Computer Modelling with Material Measurements

Commercial since 1997
QuickWave Simulation Software
~1000 licences implemented

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



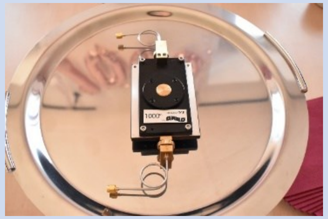
Applicator design
& model for
parameter extraction

INNOVATION

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

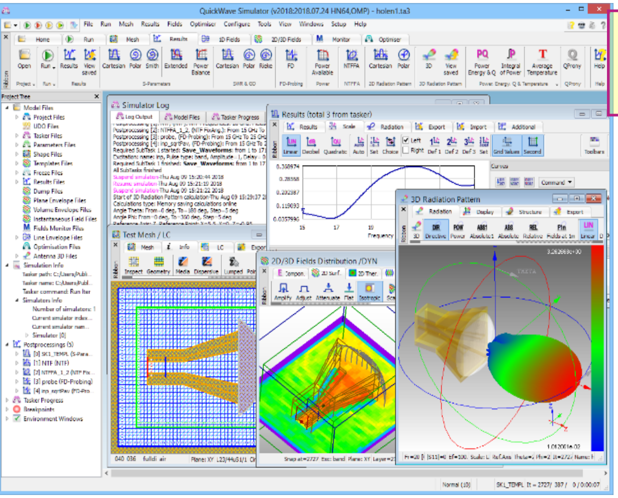
Open Platform Examples & Tools

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

Open Platform Examples:

SMM tip presented at Numerical Electromagnetic nt @ IEEE RWW, Las Vegas

25 years in a Nutshell

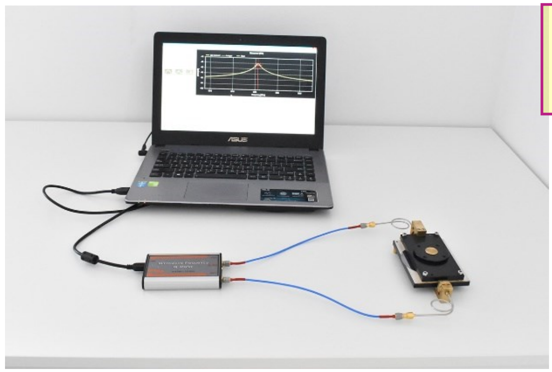


Electromagnetic simulation & design software, 3D & BOR 2D tools

based on 300+ publications by:

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

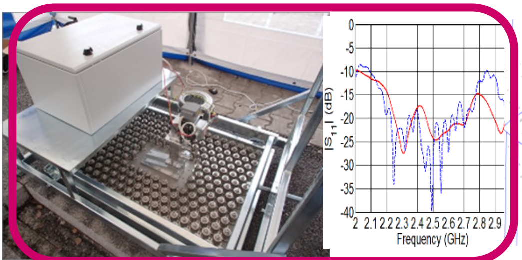
dr.M.Celuch, President of QWED

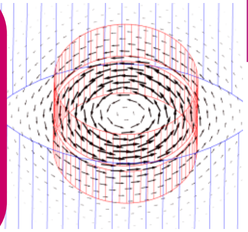


Instruments for precise material measurements

based on 300+ publications

by prof.J.Krupka, IEEE Fellow



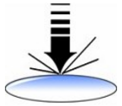


Consultancy & design services based on EM expertise & tools

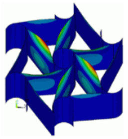
team of 10+engineers, 4 PhDs, 2 Profs

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

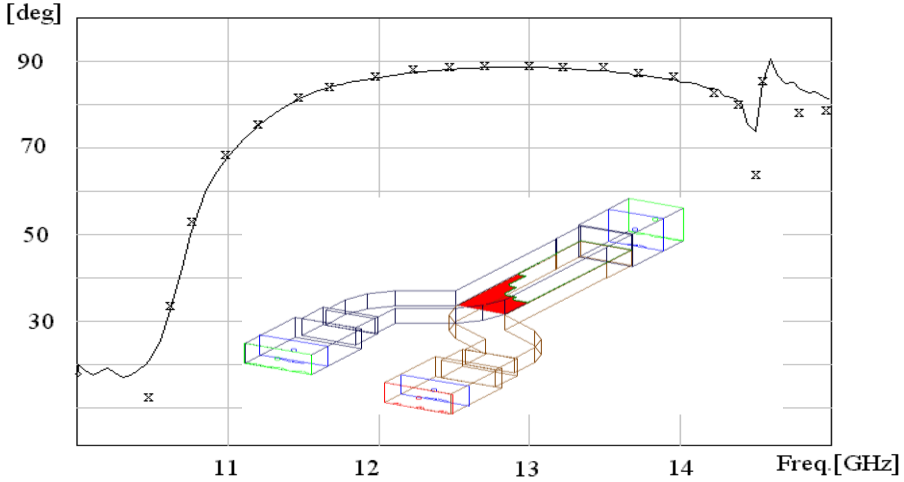
I4BAGS – modelling & characterisation of ion-implanted battery & graphene-enabled devices

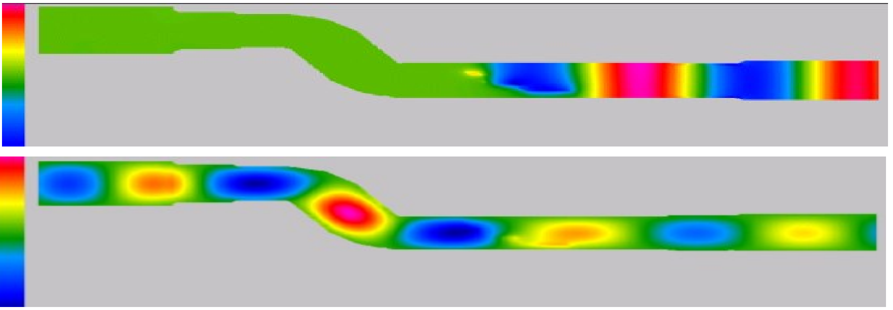
QuickWave^{TM} original applications in space reseach & SATCOM

Septum polariser by SES

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

below: differential phase-shift



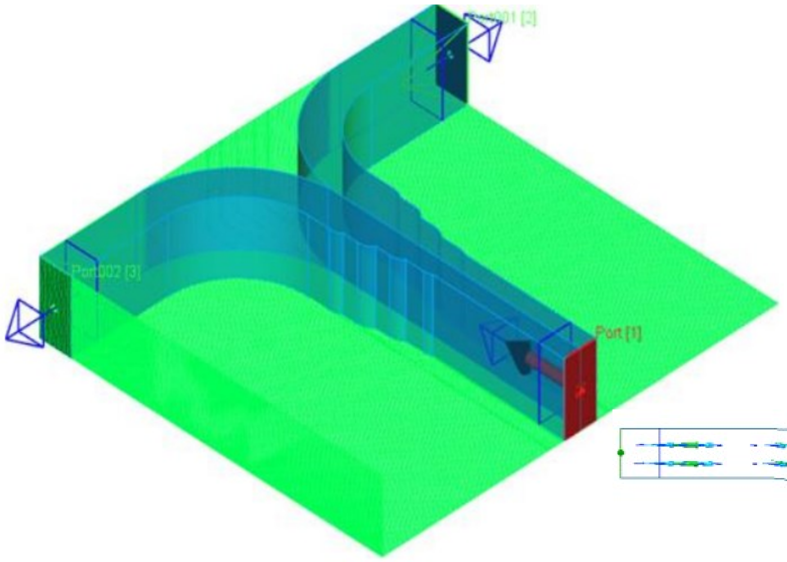


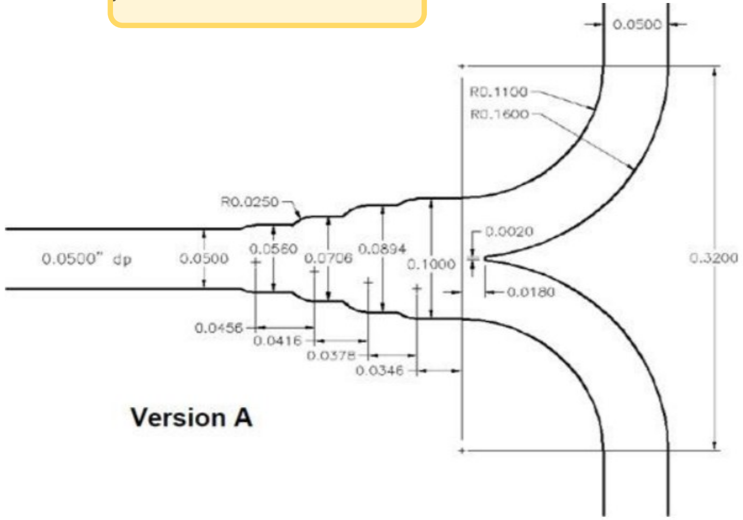
propagation of two polarisations

at centre frequency

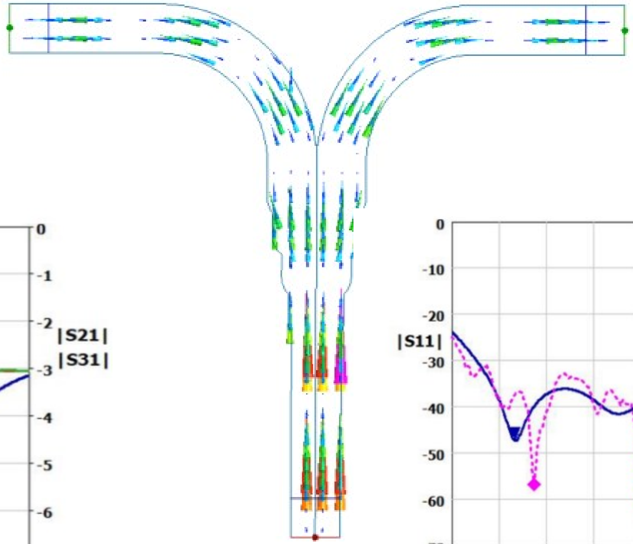
E-plane Y-junction by National Radio Astronomy Observatory, Charlottesvile, VA

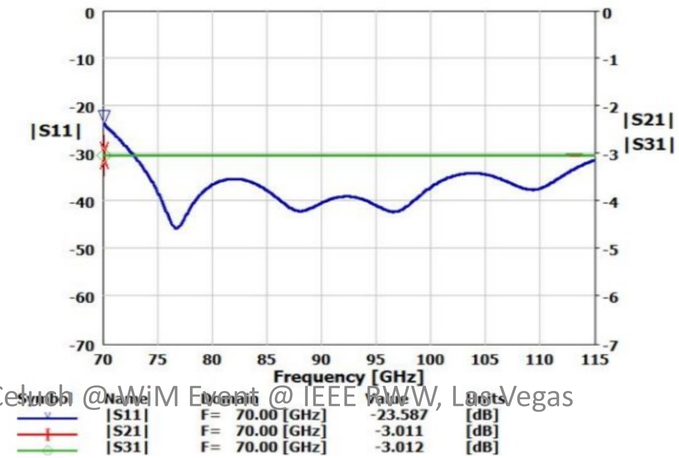
after A. R. Kerr, Elements for E-Plane Split-Block Waveguide Circuits, ALMA Memo 381

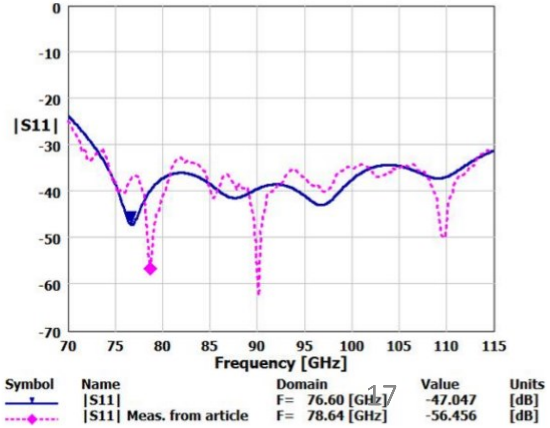




Version A

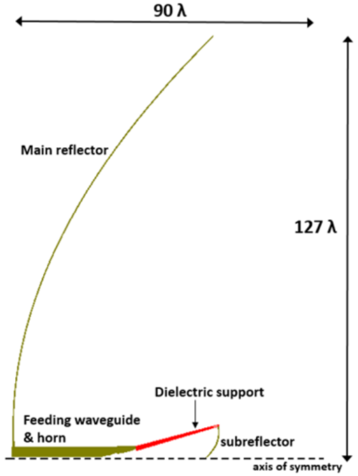


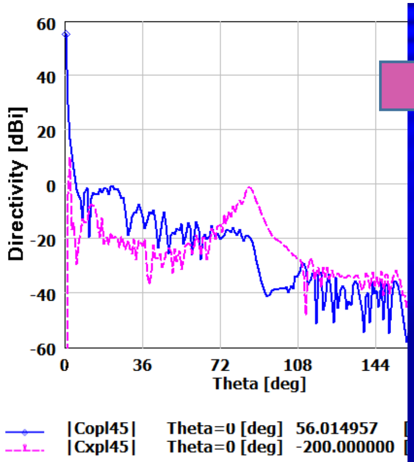


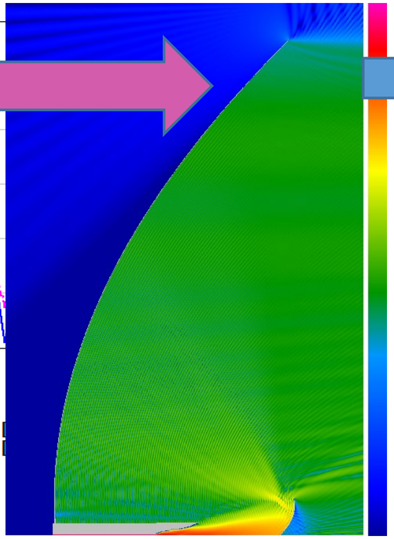


QW-V2D: Unique Ultra-Fast Hybrid EM-Bessel for Bodies of Revolution

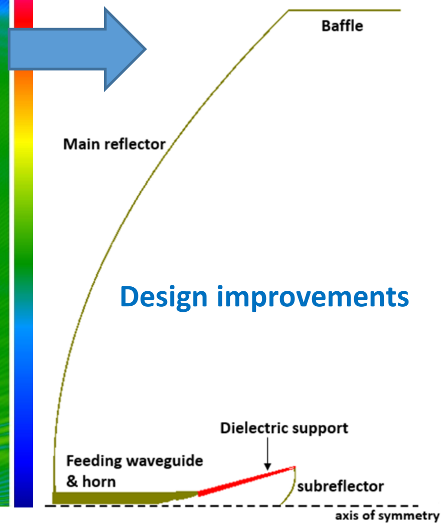
Unique, ultra-fast vector 2D Bessel & FDTD hybrid solver for design & analysis of devices with axial symmetry

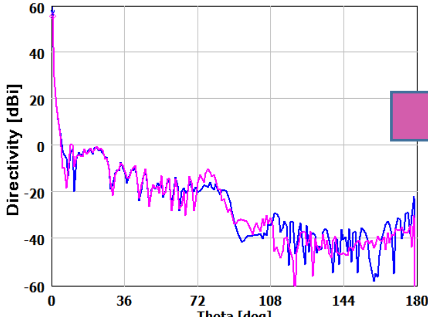


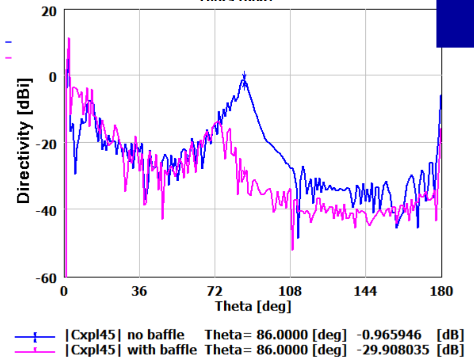


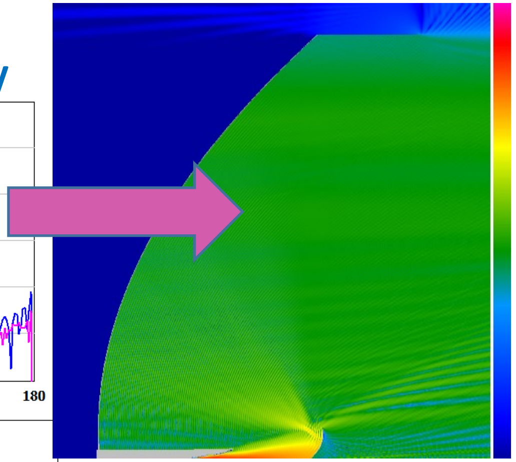


Dual -reflector antenna **Insight into EM near-field**



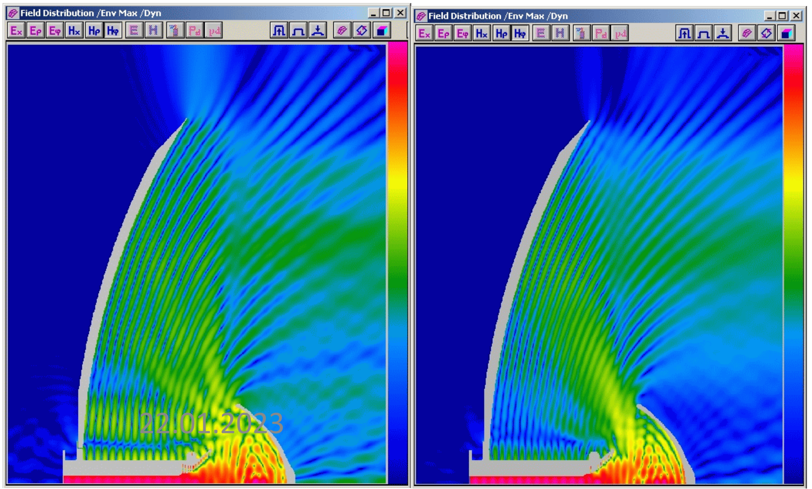






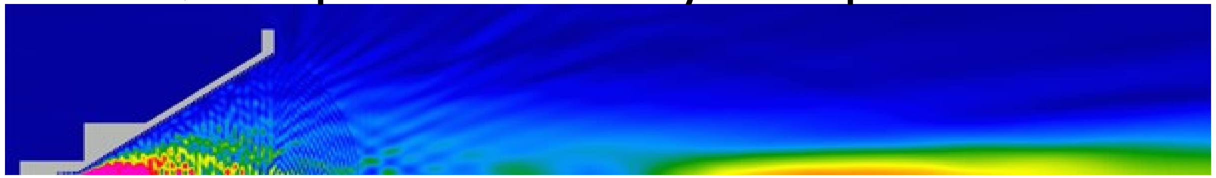
9m – diameter main reflector
Meshing: **λ/40**
Time to solution: **8 min**
Radiation pattern **@24 freq.**,
Δθ=1deg : **5 s**

A different cause of spillover from a bi-reflector antenna:
Hϕ amplitude in logarithmic scale shows FPOR at feed
from max (purple) down to -60 dB (blue) at two freqs. within 3 %



BOR FDTD

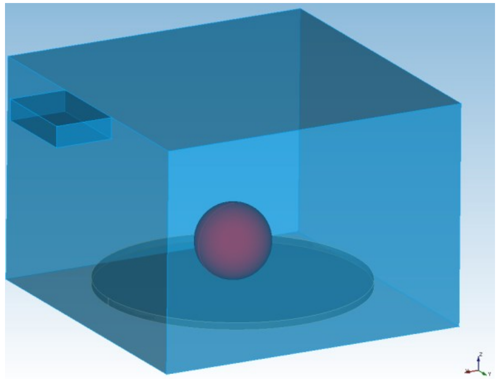
Gaussian beam formation for quasi-free-space material measurements
→ concept used for new Fabry Perot Open Resonator

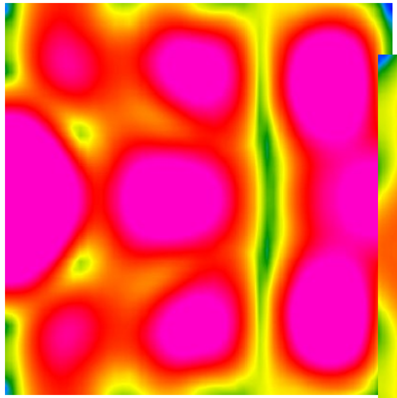


Scenarios modelled full-wave: **250 λ** (in each dir.) modelled on average laptop
2500 λ on popular PC
5000 λ on top-shelf PC

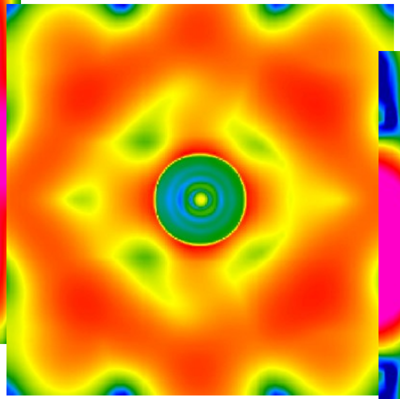
QuickWave Applications for EM Field Interaction with Tissues and Foods

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

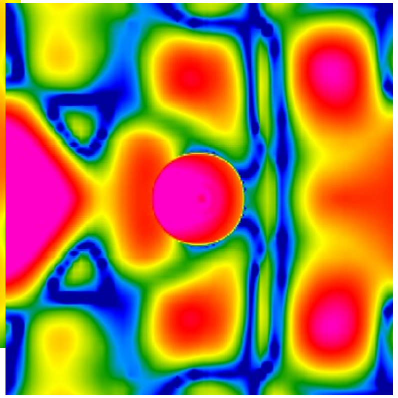




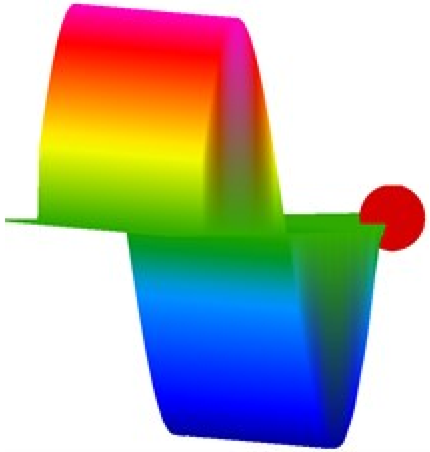
E-field in an empty cavity

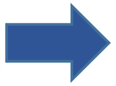


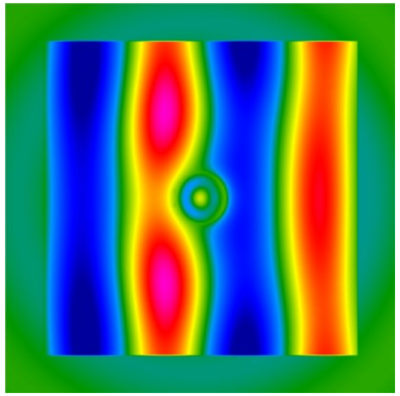
E-field in a loaded cavity



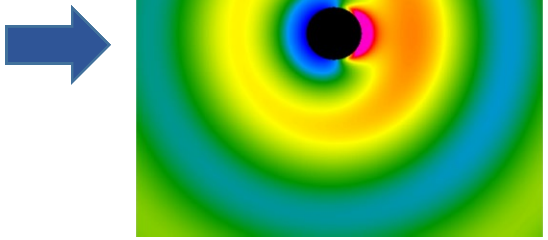
Scattered near-fied in cavity





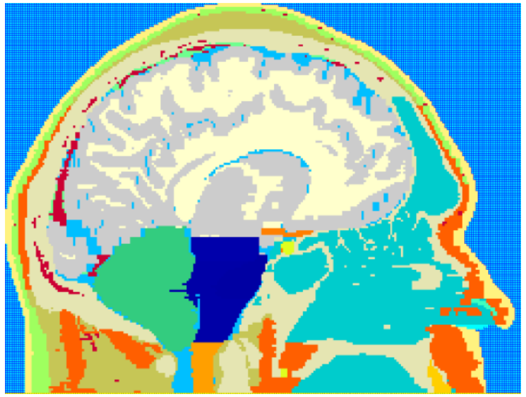


Total field
Focusing by the load
„exploding egg effect"

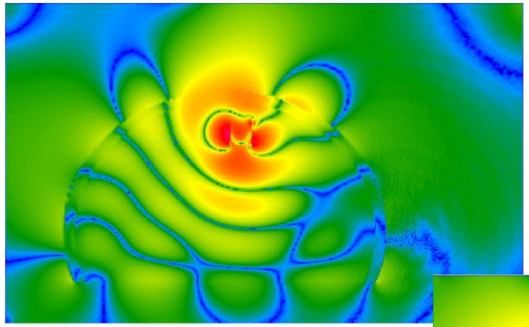


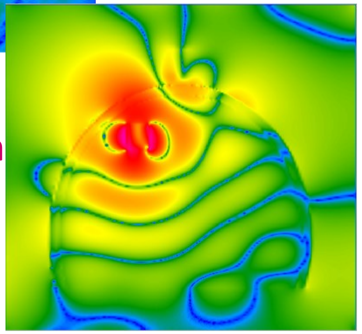
Diffracted field reveals cause of focusing: circumferential resonance

Detection of inhomogenities in tissues



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





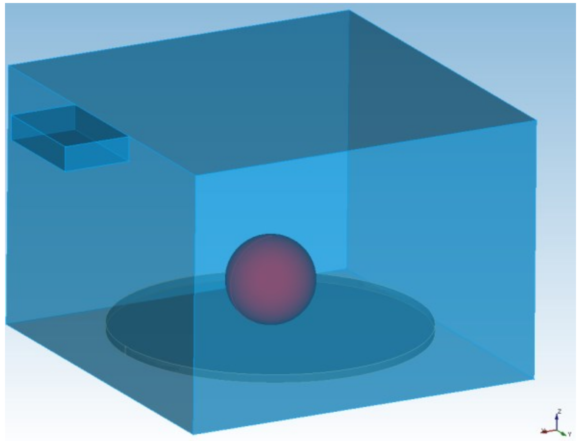
- ✓ **Tumours & haemorrhages detection**
- ✓ **Optimisation of multiantenna tomographic systems**

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

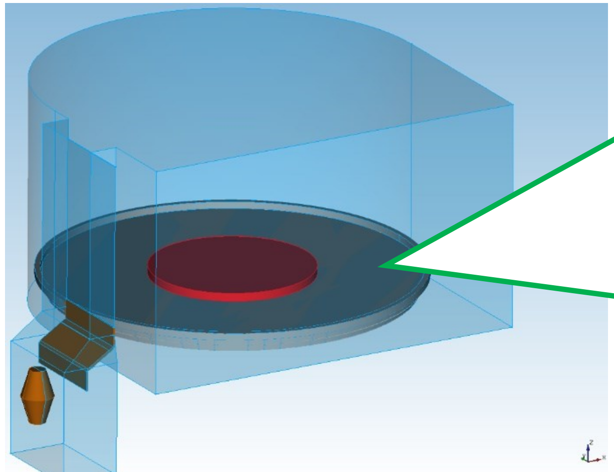
Ilustration & Benchmarking of QuickWave Multiphysics Regimes in Elsevier Book

Simple microwave heating benchmarks & microwave heating phenomena studies*

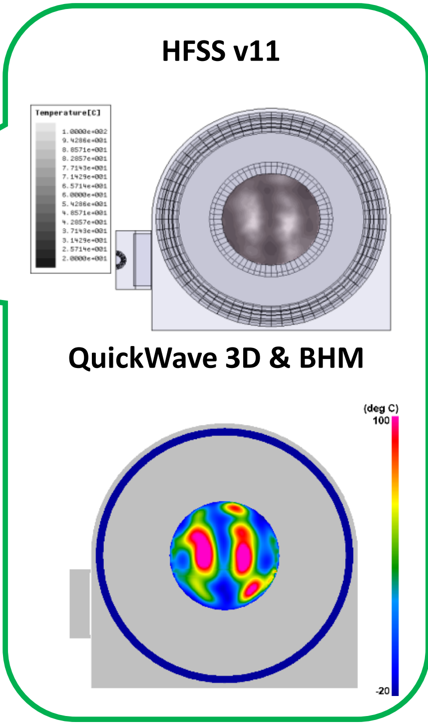
Design & analysis of real-life microwave oven cavities, incl. complicated cavity shapes and advanced feeding system*



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

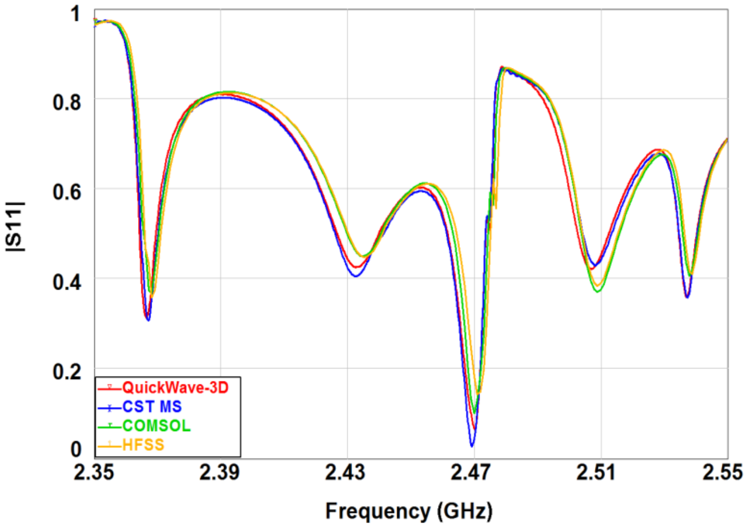


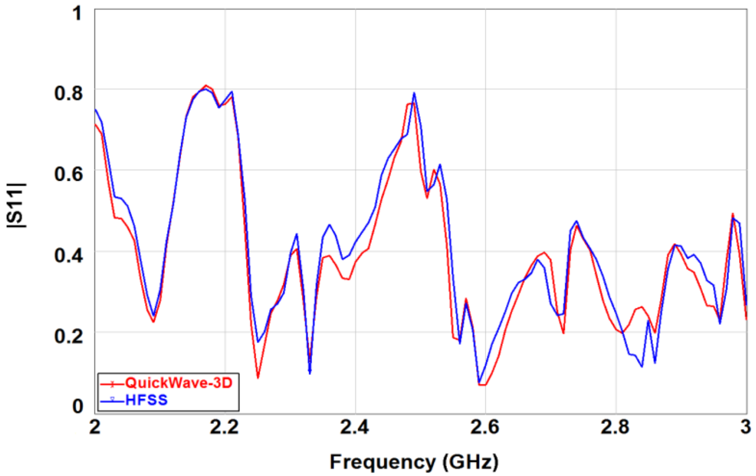
Courtesy of Whirlpool Inc. – Whirlpool MAX oven



Freezing to file the state of the simulation

De-freezing on arbitrary computer & at convenient time

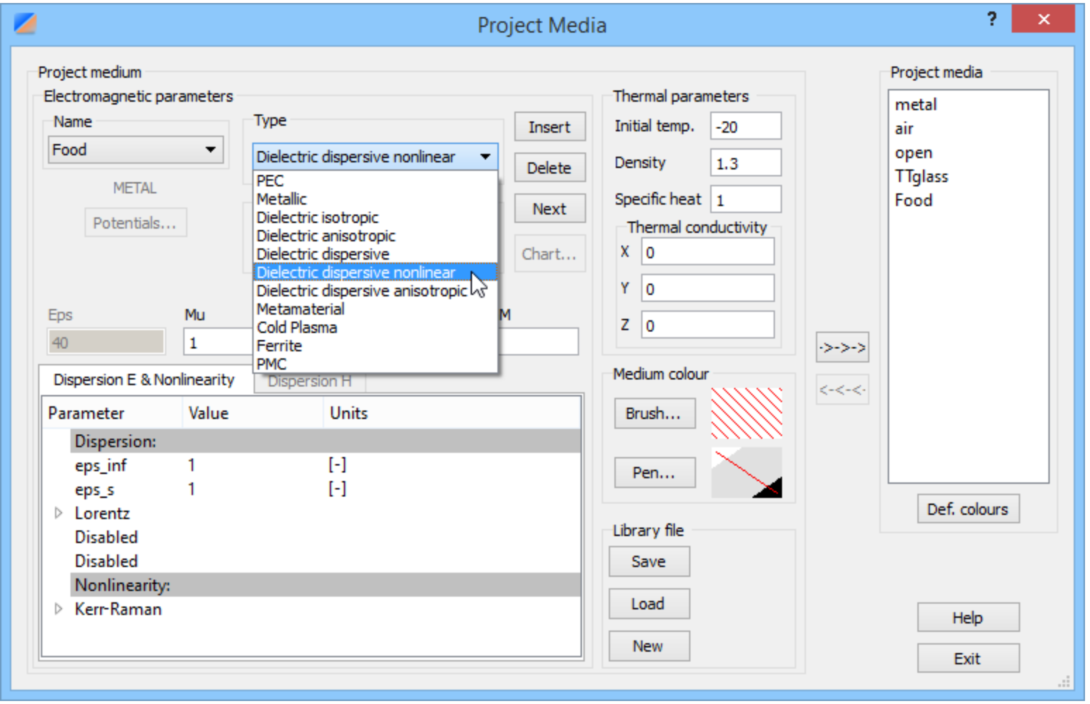




With QuickWave EM computation as fast as **1 min 18s** on a **low-cost video card** – supporting **all** graphic cards **with OpenCL**

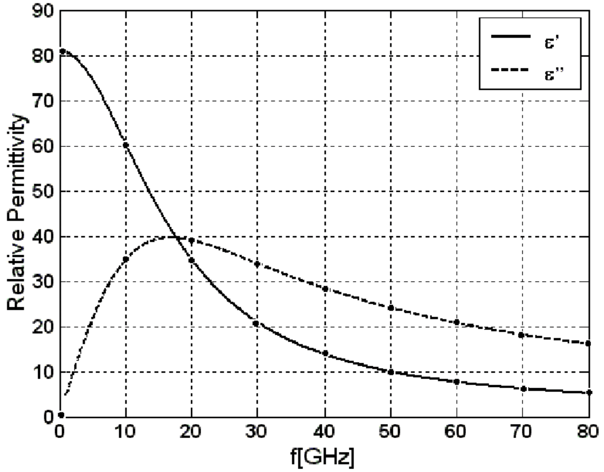
* M.Celuch, P.Kopyt & M. Olszewska-Placha in eds. M. Lorence, P. S. Pesheck, U. Erle, *Development of packaging and products for use in microwave ovens*, 2nd Ed. Elsevier 2020.

Models of Materials in Simulation Software



material models given by physics-based equations

Debye model for water



$$\textit{Drude:}\quad \varepsilon_r(\omega) = \varepsilon_\infty + \frac{(2\pi f_p)^2}{(j\omega 2\pi \nu_c - \omega^2)}$$

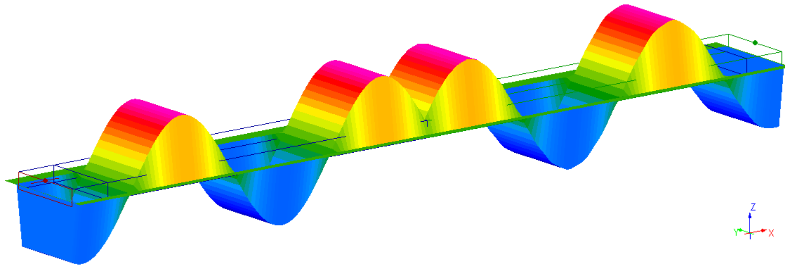
$$\textit{Debye:}\quad \varepsilon_r(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{(1 + j\omega\tau)}$$

$$\textit{Lorentz:}\quad \varepsilon_r(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty (2\pi f_p)^2}{((2\pi f_p)^2 + j\omega 2\pi \nu_c - \omega^2)}$$

material models given by data sets

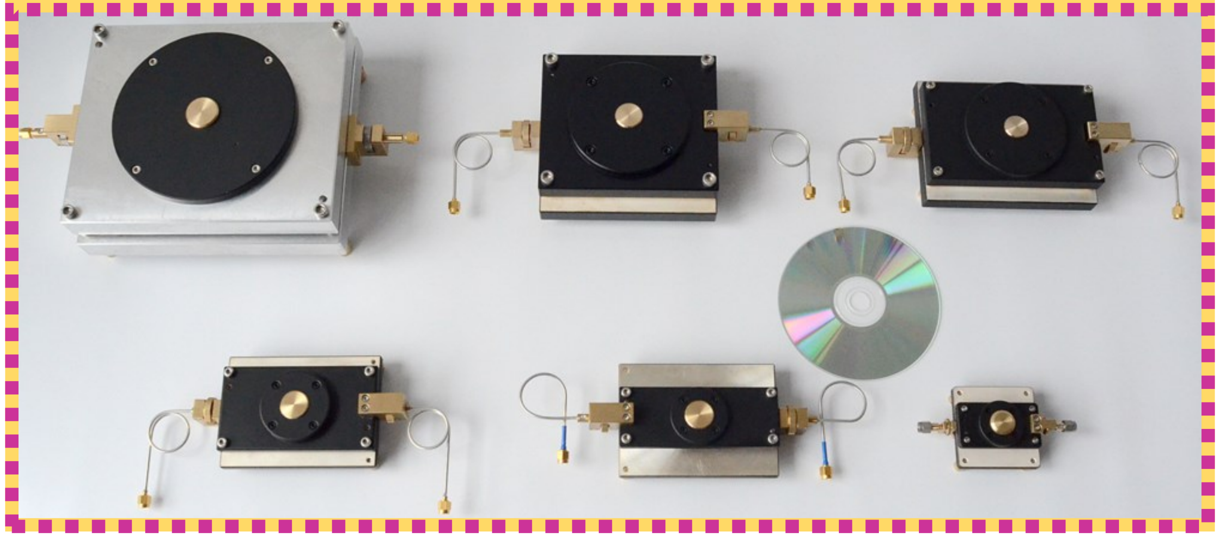
#Raw beef draft media file for QW-BHM module (00-09-06 POR)
#Measurements & refinements by Per O Risman, Microtrans AB, Sweden
#Modified by QWED, Poland
DATA FROM -20 C to +80 C, dH/dV in J/cm3 reversedEnth/Temp column

!Temperature # Data deg C	Enthalpy J/cm3	EPa	SIGa S/m	SpecHeat	Density	Ka
-20	0	4.9	0.064	2.21	1.06	0.0069
-15	14.0	5.5	0.093	2.21	1.06	0.0069
-10	34.4	6.1	0.153	2.21	1.06	0.0069
-5	71.4	12.3	0.573	2.21	1.06	0.0069
-3	110.4	22.0	1.118	2.21	1.06	0.0069
-2.2	144.4	30	1.636	2.21	1.06	0.0069
-1.6	192.4	42	2.113	2.21	1.06	0.0069
-1.3	240.4	46	2.385	2.21	1.06	0.0069
-1.1	274.4	48.9	2.426	2.21	1.06	0.0069
-1.0	288.4	49.2	2.440	2.21	1.06	0.0069
10	327.9	48.9	2.317	2.21	1.06	0.0069
20	382.9	48.2	2.194	2.21	1.06	0.0069
35	450.4	46.9	2.072	2.21	1.06	0.0069
50	517.9	45.5	1.949	2.21	1.06	0.0069
65	585.4	43.6	1.922	2.21	1.06	0.0069
80	652.9	41.7	1.908	2.21	1.06	0.0069



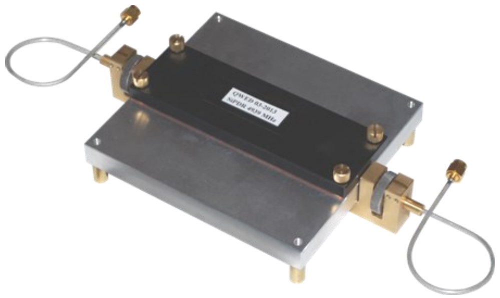
QWED's Popular Dielectric Resonators and more recent FPOR

Split-Post Dielectric Resonator, typical units for 1.1 GHz -15 GHz
for laminar low-loss dielectric materials

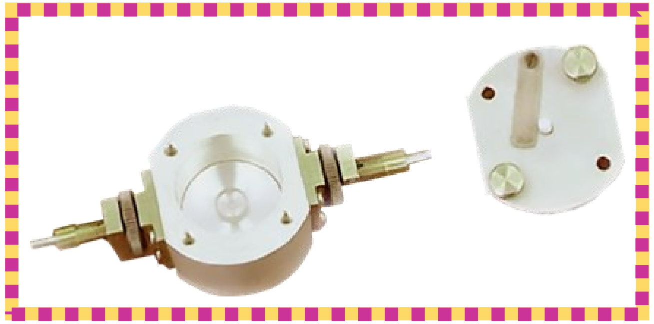


Fabry-Perot Open Resonator
automatic span, quasi-continuous 20 .. 120 GHz

5 GHz SiPDR
for resistive sheets



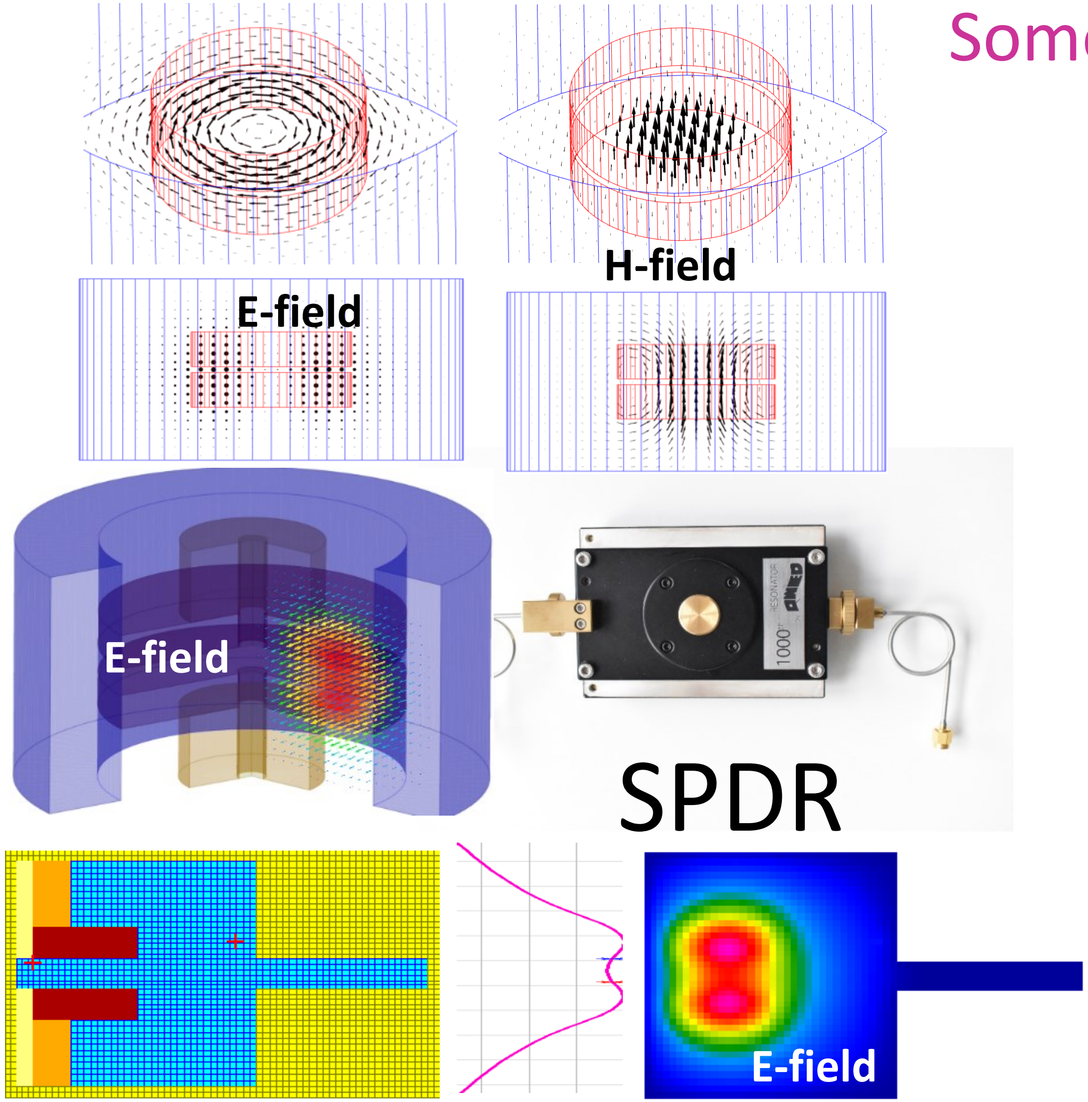
TE01δ cavities, typically 1 GHz – 10 GHz
for bulk low-loss dielectrics



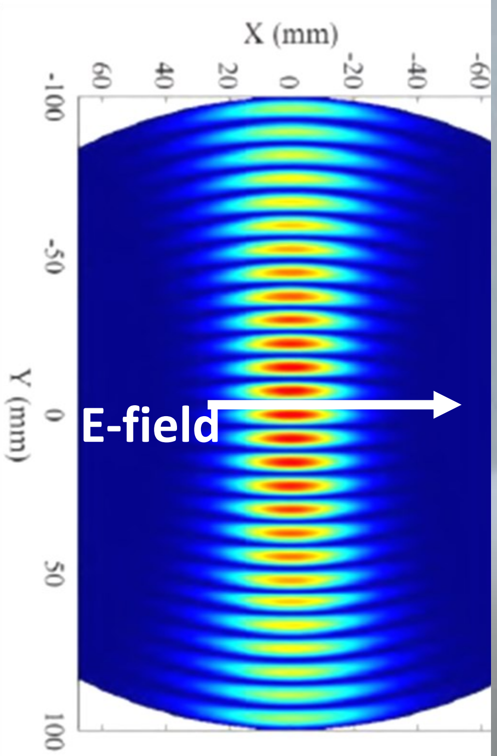
RECENTLY APPLIED TO CERAMICS FOR 5G & 6G

APPLIED IN TEMPERATURE-VARYING CONDITIONS

Some Physics behind our Resonators



FPOR

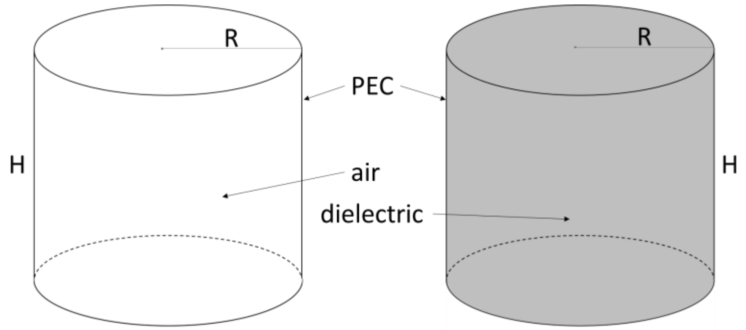


Field distributions obtained from full-wave EM simulations (QuickWave^{TM} software by QWED).
Accurate design & calibration of resonator test-fixtures facilitated by accurate EM modelling!

Why Resonators: Well Controlled Sensitivity to Material Properties

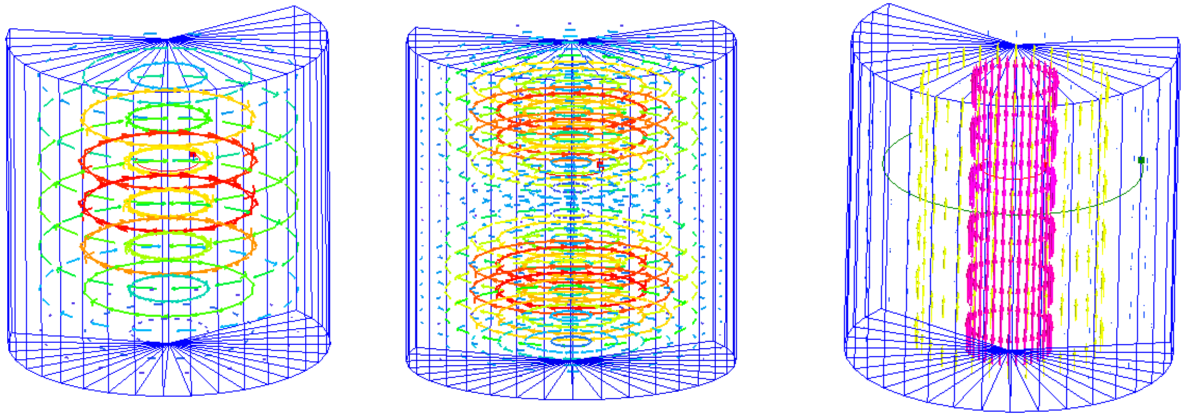
Resonance in theory: non-zero electromagnetic fields exist in isolated structures (no excitation). Field properties are well-defined and **linked to material properties.**

E.g. for cylindrical cavities:

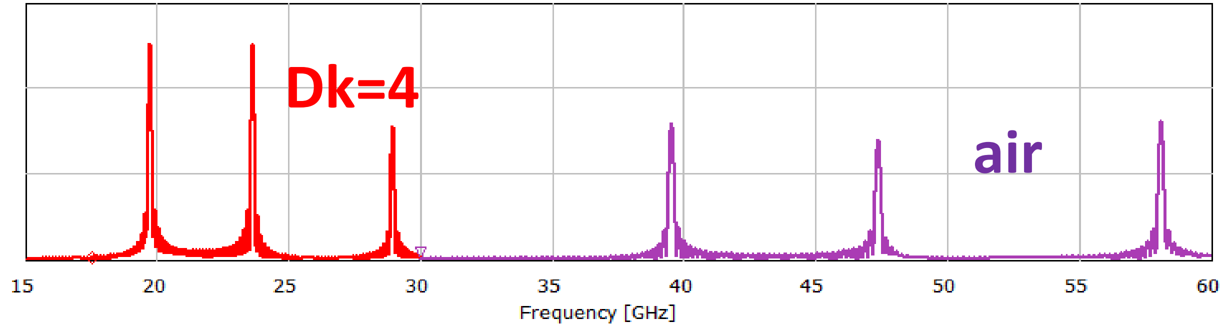


$$f_{r,mnp} = \frac{c}{\sqrt{Dk}} \sqrt{\left(\frac{\kappa_{mn}^{(,)}}{\pi R}\right)^2 + \left(\frac{p}{H}\right)^2}$$

in non-magnetic low-loss dielectrics



TE011 TE012 TM010



For filled cavities of any shape:

$$f_{r,mnp} = \frac{c}{\sqrt{Dk}} K(\text{modal\_index, cavity dimensions})$$

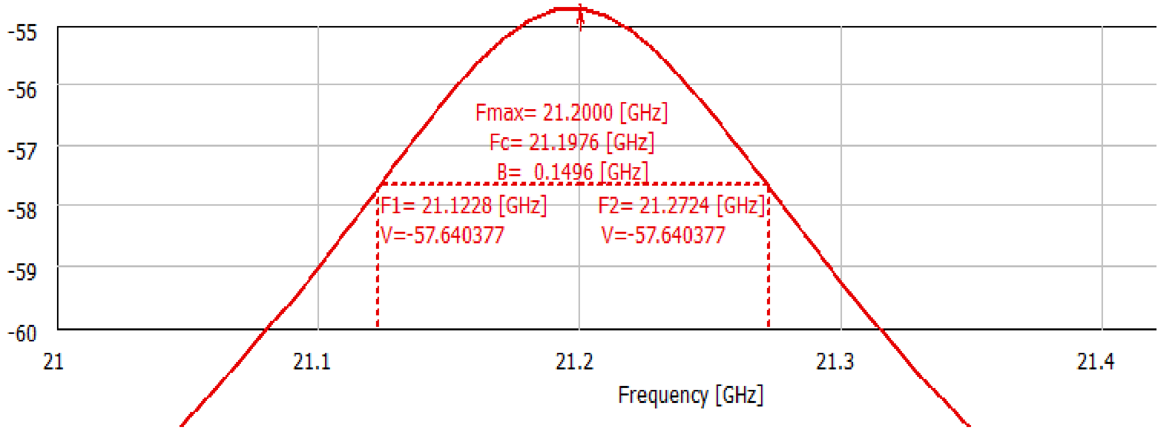
Why Resonators: High Sensitivity to Material Losses

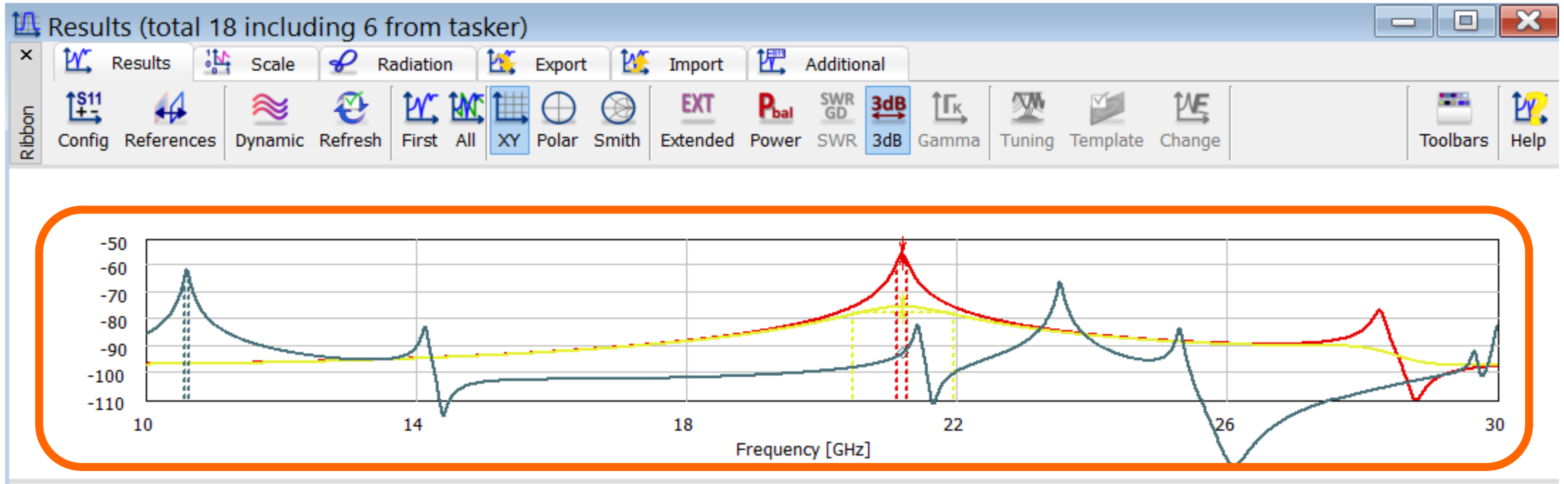
in non-magnetic
low-loss dielectrics

2* electric_energy_stored

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

electric_dissipated_power





ε_r=1 σ=0.00833 S/m
@21.2GHz:
tanδ=0.071
Q_{SUT}= 1 / 0.0071 = 141
Q_{S21}=21.2/0/1496= 141

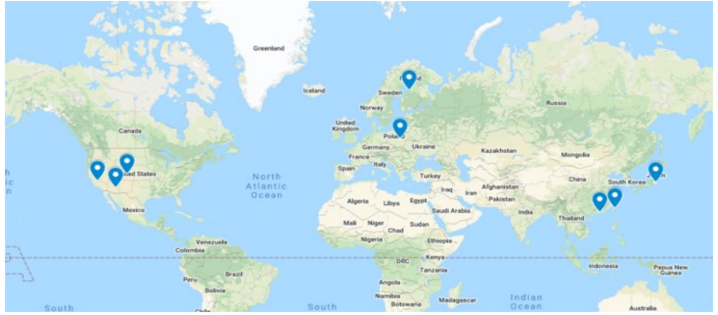
ε_r=1 σ=0.0833 S/m

ε_r=4 σ=0.0166 S/m

Recent Industrial Benchmarking: 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



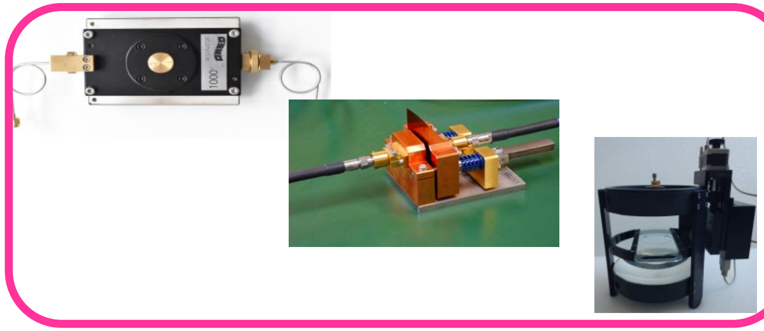
Sample Material Requirements
- Stable, Low loss
- Low moisture absorption / temperature dependency
- Isotropic
- Good mechanical & handling properties

1st Project Stage
- Precision Teflon
- Cyclo Olefin Polymer

2nd Project Stage
- Rexolite
- Fused Silica

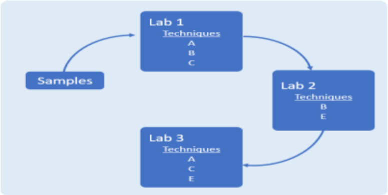
Industrial
- Automotive

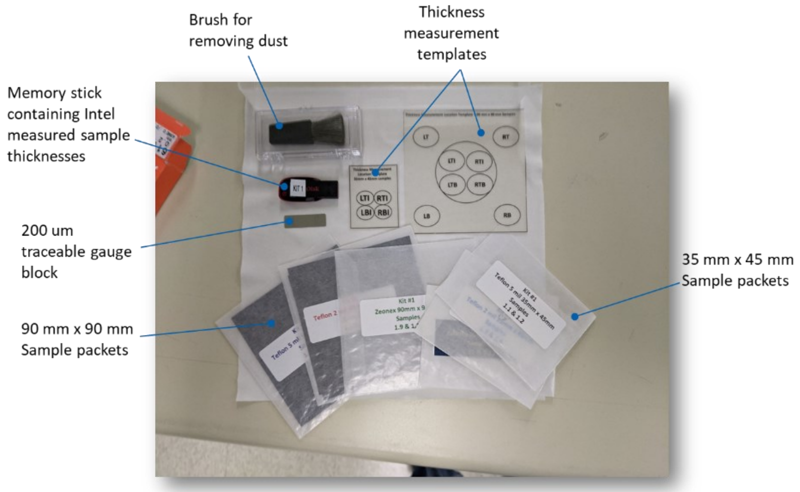
Techniques Included
- Split Post Dielectric Resonator
- Split Cavity Resonator
- Fabry-Perot
- Balanced Circular Disk Resonator



→ Frequency Span : 10GHz – 100GHz with overlaps

10 Laboratory Round Robin





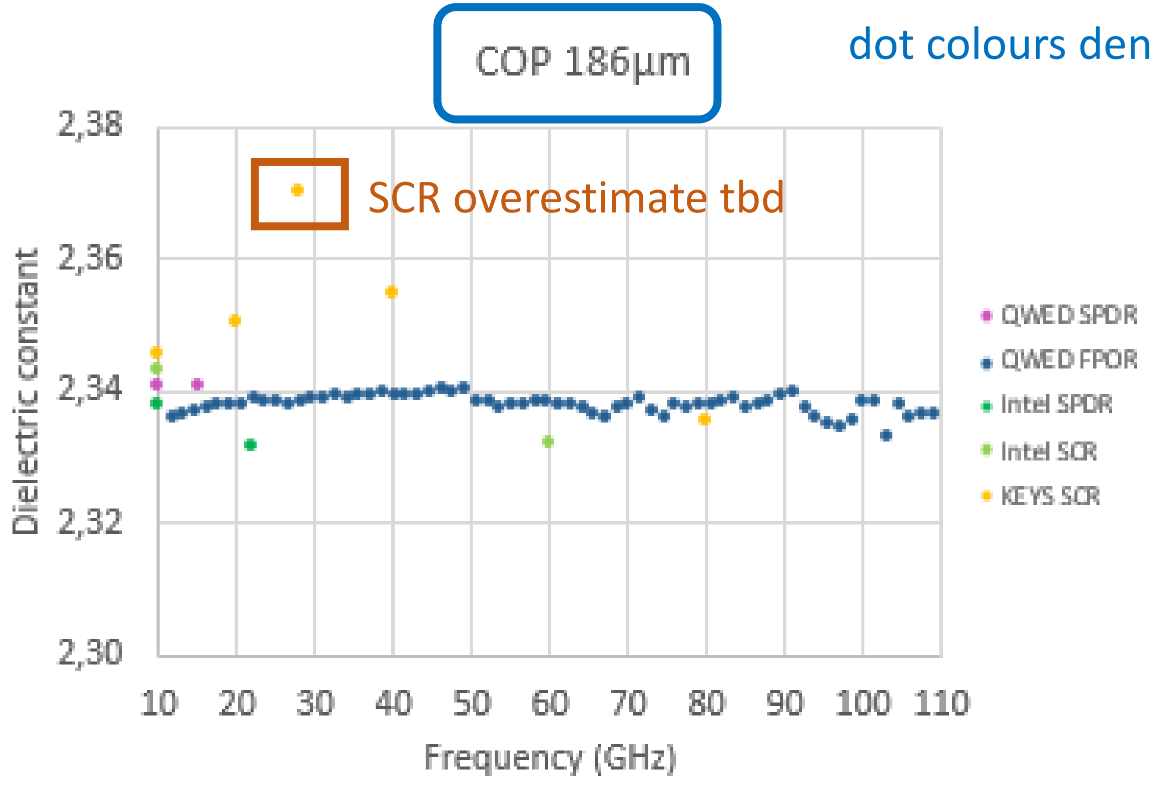
10 Sample Kits Created
- Sample sizes 35 mm x 45 mm, 90 mm x 90 mm
- circulated between 10 labs

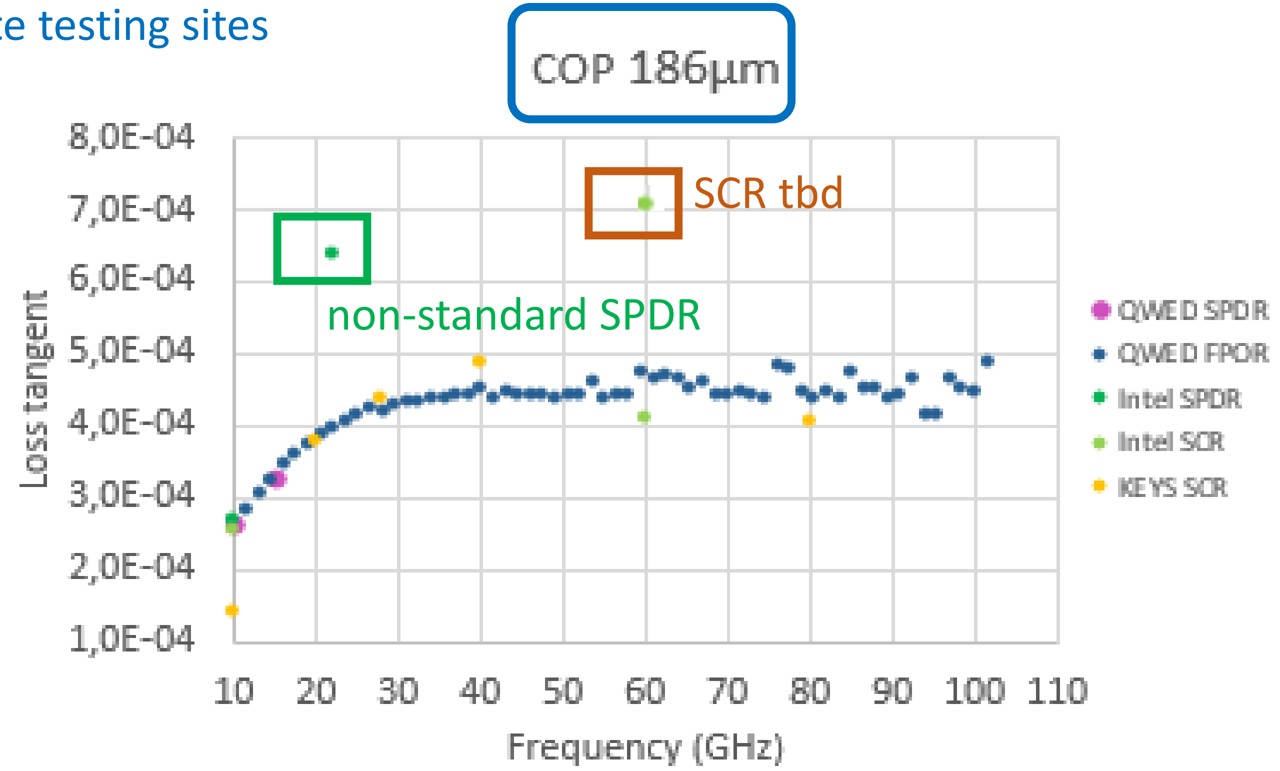
iNEMI 5G Round Robin: Example Results

3 labs, 3 techniques, 14 laboratory setups

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

dot colours denote testing sites





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

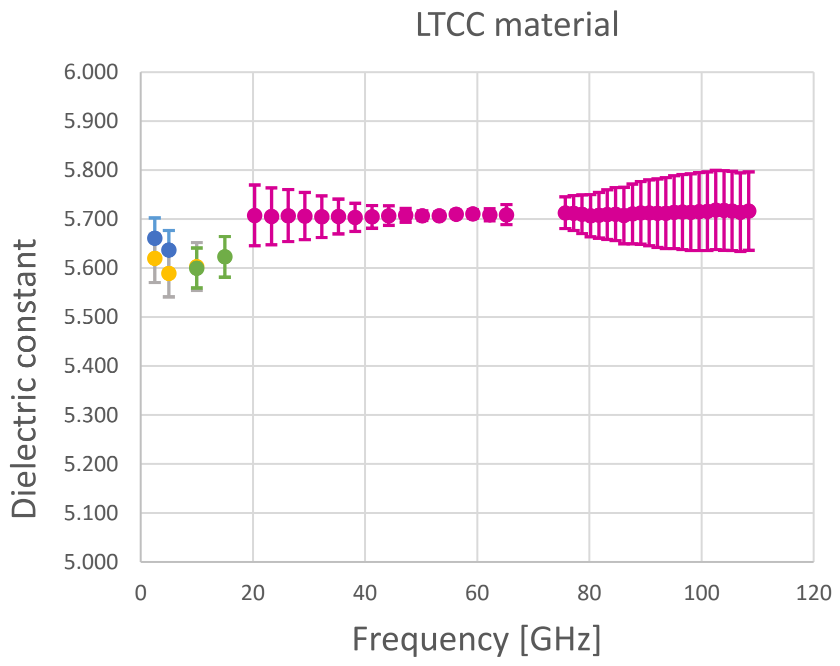
> 40GHz 2x increase in Df compared to 10GHz

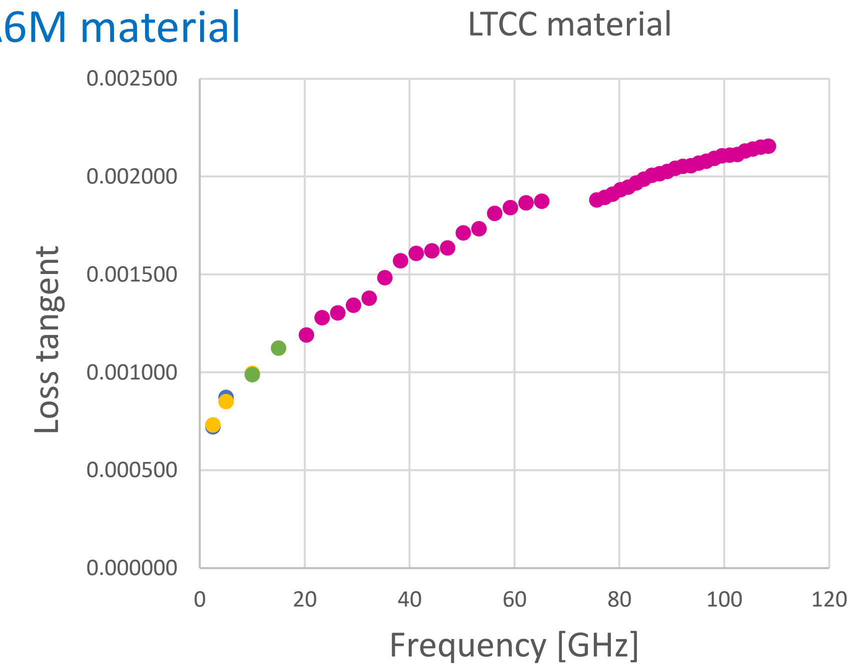
Recent Applications to ULTCC Materials: test of commercial A6M ceramic

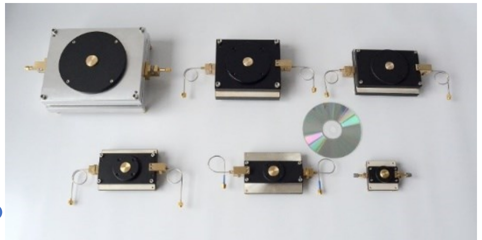
Ultra-Low Temperature Co-fired Ceramics for 6th Generation Electronic Packaging **(ULTCC6G_EPac under M-ERA.NET 2)**

ULTCC6G_EPac project is co-financed by the National Centre for Research and Development under M-ERA.NET2/2020/1/2021 contract.

Commercial A6M material



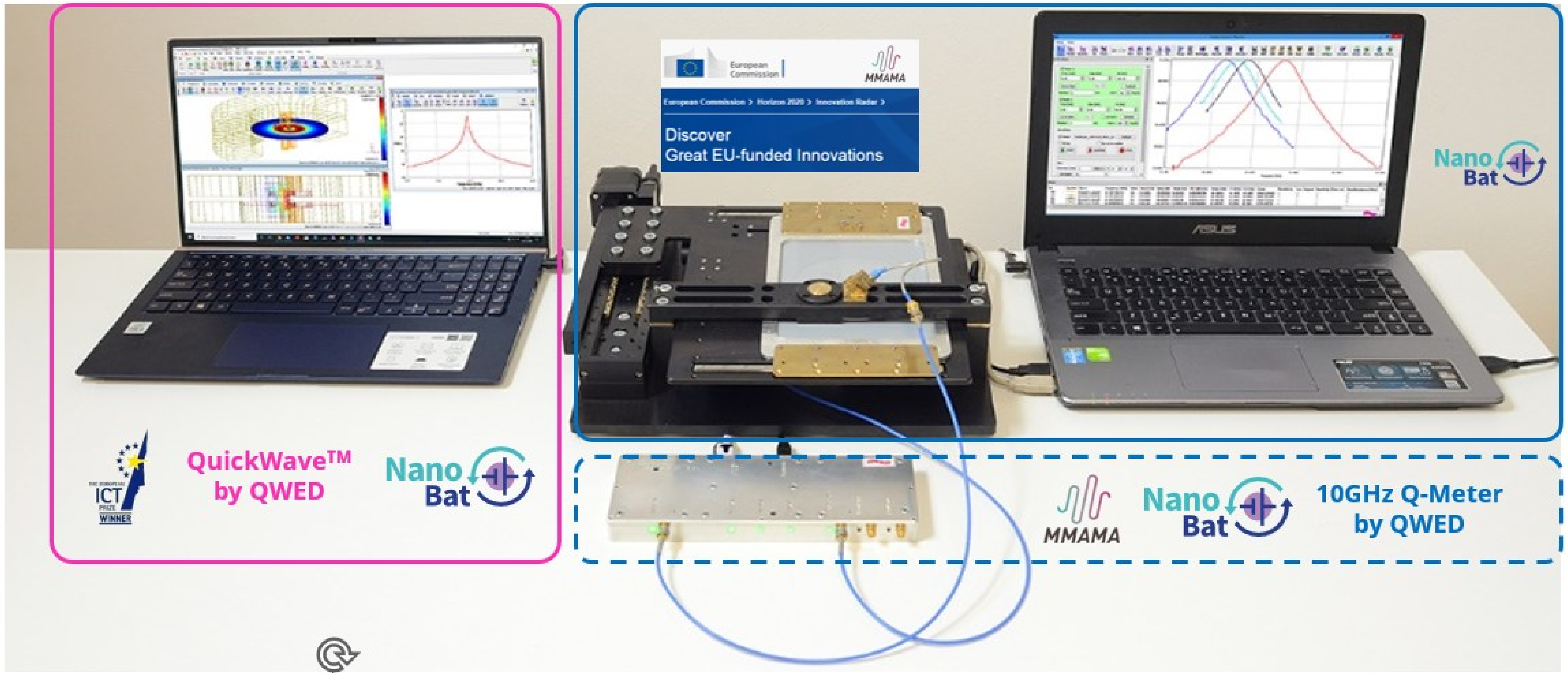


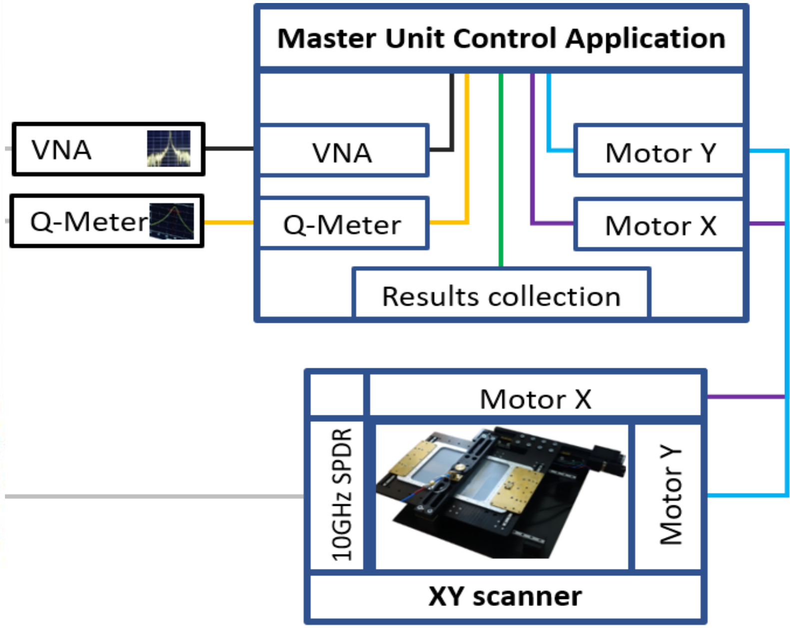


SPDRs and FPOR results consistent within uncertainty bounds – related to thickness variation

Extension of the SPDR Method to 2D Imaging of Planar Samples

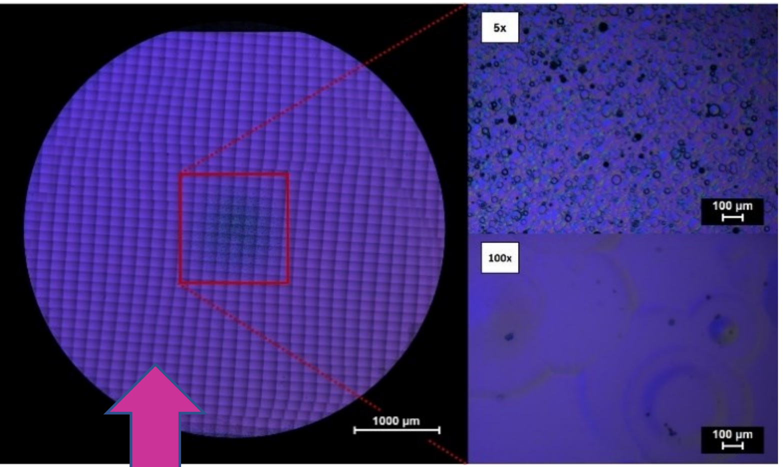
2D scanner designed with a modified 10 GHz SPDR





Finalist of the European Innovation Radar Prize 2021

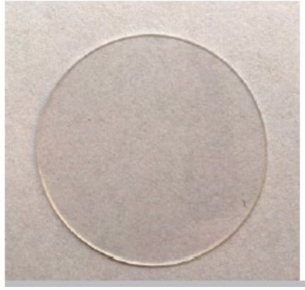
2D SPDR Imaging of HR- GaN for Light & Power Electronics Devices

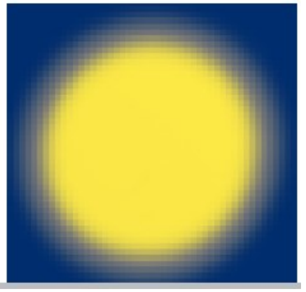


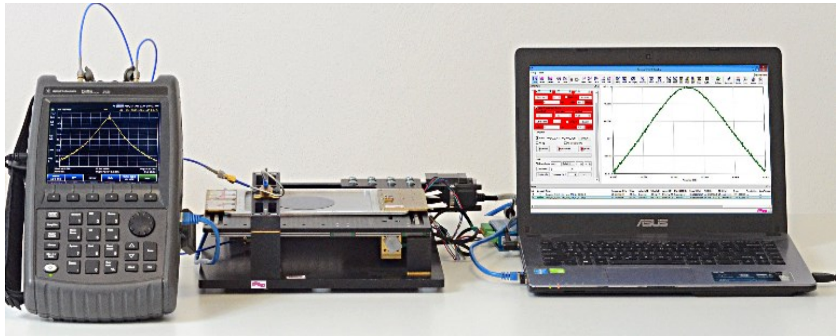
Optical microscopy image at L-IMiF
reveals morphology inhomogeneity
in the central area:

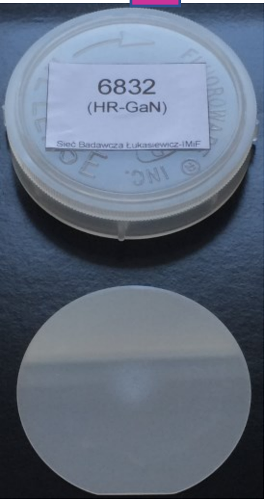
- in qualitative terms only,
- attributed to the growtch non-uniformity,
- only the central part appears unuseful for making devices.

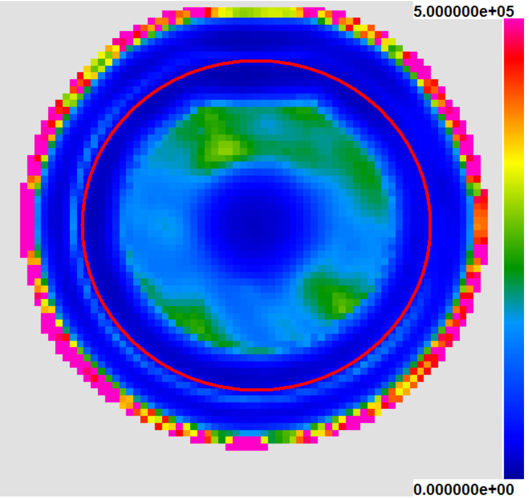
2D map of quartz wafer











SPDR image:

- shows this whole GaN template unuseful,
- quantitative evaluation:
  - 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),
  - edge effect along the circumference.

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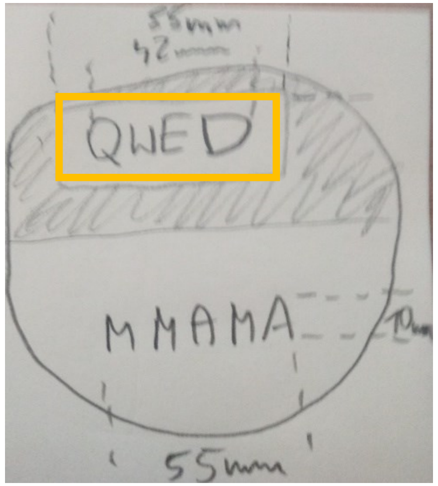
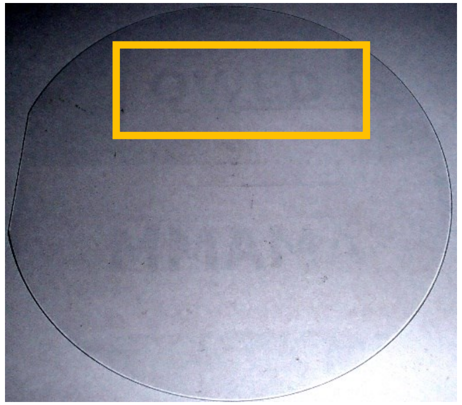
Łukasiewicz IMiF

2D Imaging of Organic Semiconductors for Solar Cells

Modelling-Based Resolution Enhancement of Surface Images

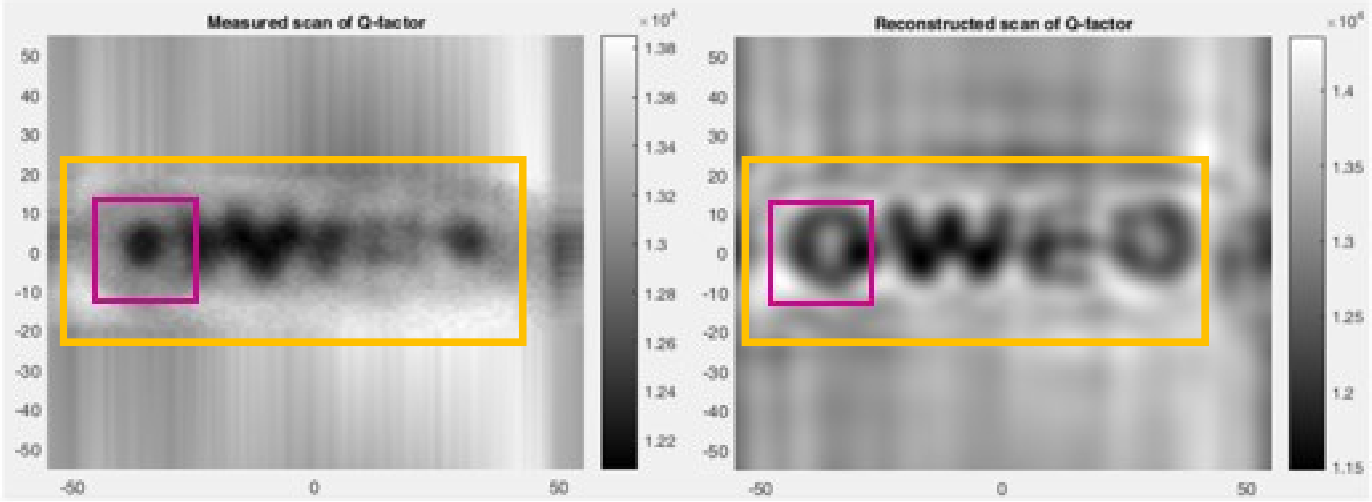




Patterned PEDOT:PSS sample
courtesy MateriaNova, Belgium

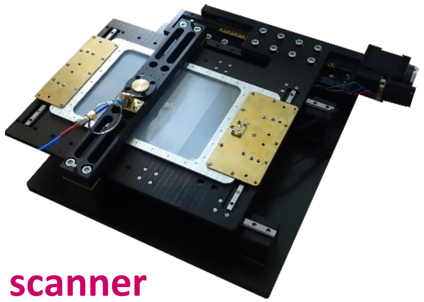
MMAMA

MATERIA NOVA

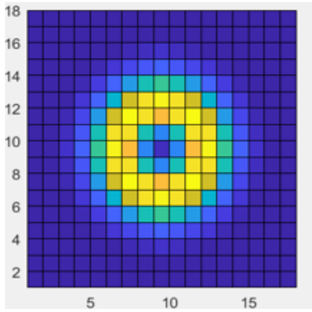


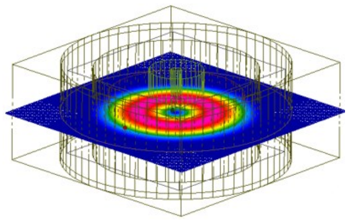
raw image of sample resistivity
(measured Q-Factor)

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



2D SPDR scanner





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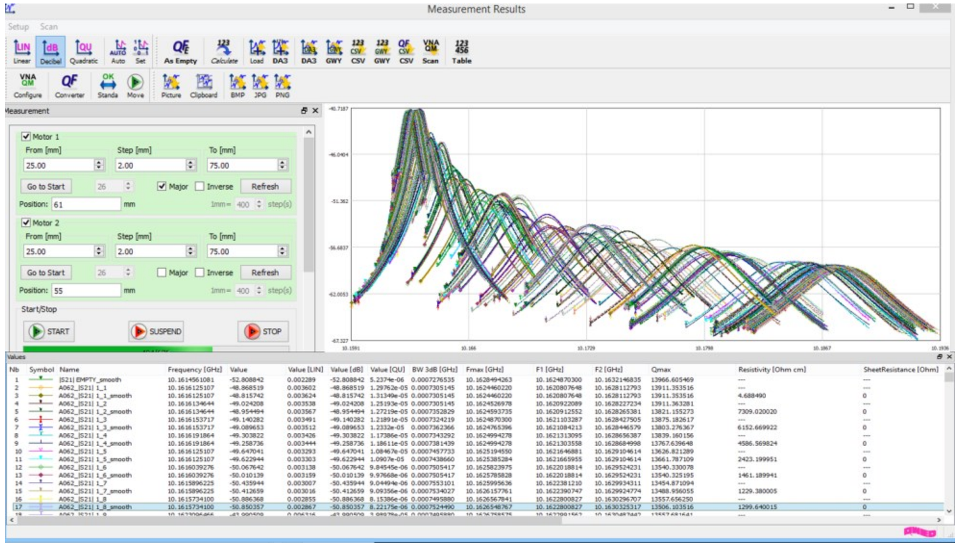
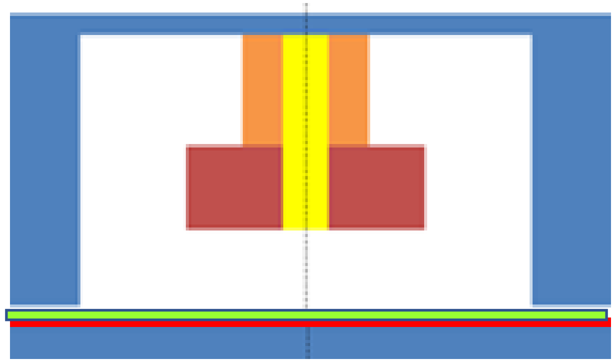
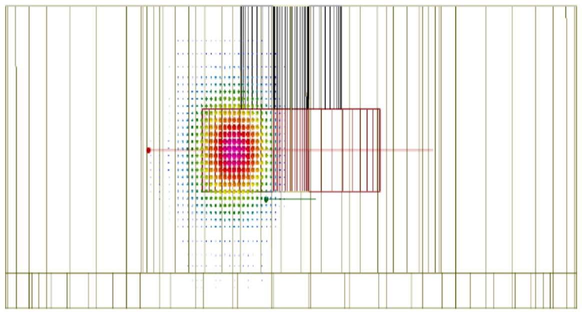
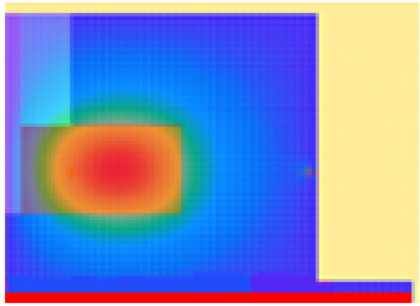
2D Imaging of Conductive Films – 10 GHz iSiPDR Scanning Setup

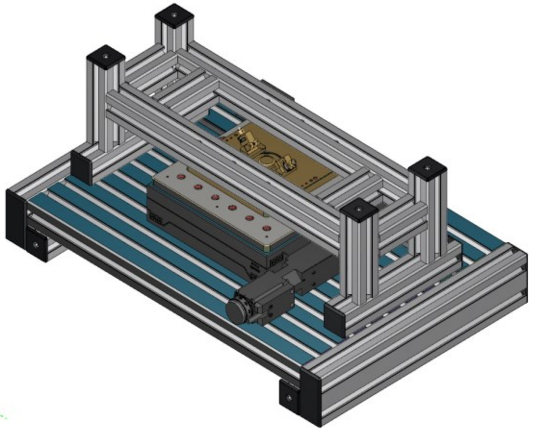


2D SiPDR scanner Keysight FieldFox Control App





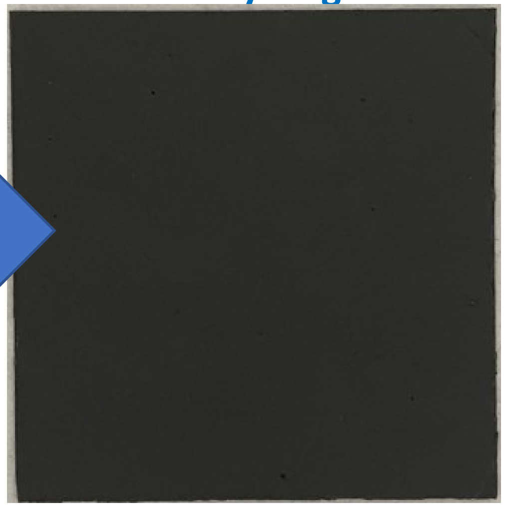




2D Imaging of Conductive Films – Graphene Anodes Before & After Cycling

Copper electrode

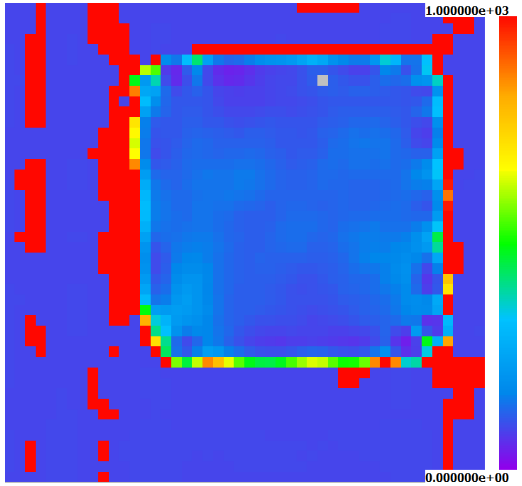
Graphene –based battery anode before cycling



Scanning range: 80 x 80 mm,
scanning step: 2mm
Measurement points: 1681
Scanning time: ca. 2h

2D map of Rs [Ω/sq.]

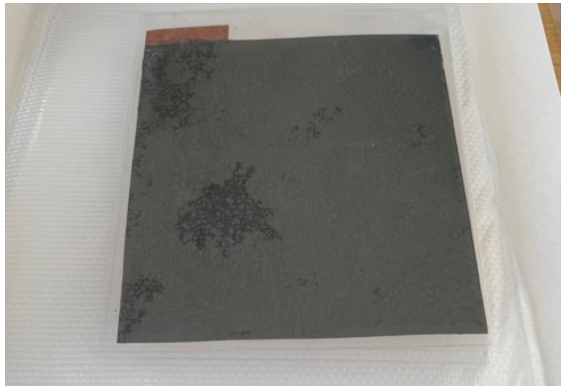
values of Rs [Ω/sq.]



85 – 160 [Ω/sq.]

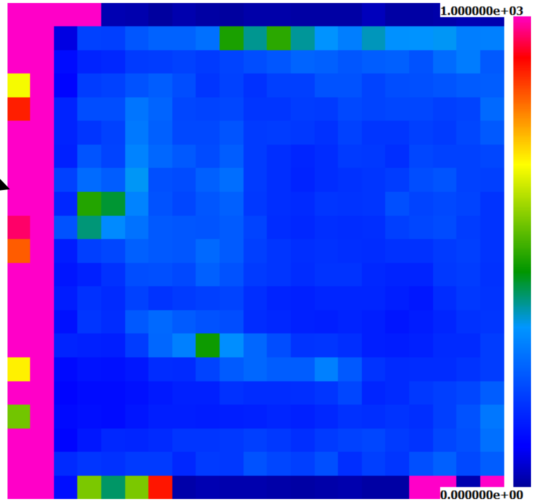
**courtesy PLEIONE Energy, Greece*

PLEIONE ENERGY re-think energy!



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

Sample edge (protecting foil)



110 – 340 [Ω/sq.]

increase indicates SEI formation

NanoBat

Contributions to European Initiatives and Policy Making

2008 Paris, France

Consolidating Research and Innovation for European SMEs Conference
Paris, France
September 15-16, 2008

Dr. M. Celuch was an invited speaker in the high level Conference jointly organised by the European Commission and OSEO ***"Consolidating Research and Innovation for European SMEs: How to do more and better"***, which took place at the French Ministry for Economy, Industry and Employment, place on September 15-16, on the occasion of the French Presidency of the European Union. Video recordings of the Conference are available at **http://www.ue-recherche-et-pme.oseo.fr/**. Dr. Celuch participated in Debate: ***How to adapt support for SMEs within an enhanced networking approach***.

The European Commission also organised, in parallel with and in complement to the main conference, a ***dedicated EC press programme*** for journalists present at the Conference. QWED was proud to be ***one of fifteen European research success stories*** selected for presentation.

N. Adamovic[1], G. Goldbeck[2], M. Celuch[3]

1] TU-Wien, Vienna, Austria. H2020 OntoCommons, OntoTrans
2] Goldbeck Consulting Ltd, Cambridge, UK. H2020: OYSTER, NanoMECommons
3] QWED. Poland. H2020 NanoBat

nanoMECommons Co-Creation Workshop
13 December 2021

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June 8, 2021 — Report — Open Access

Report on Advanced materials modelling and characterisation: strategies for integration and interoperability

Adamovic, Nadja; Boskovic, Bojan; Celuch, Małgorzata; Charitidis, Costas; Friis, Jesper; Goldbeck, Gerhard; Hashibon, Adham; Hurtós, Esther; Sebastiani, Marco; Simperler, Alexandra

Materials are Key Enablers for Green & Digital Transition

IndTech 2022

Contributions to European Initiatives and Policy Making

Model Development

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Vienna, 26-28 April 2023

digitalisation critical for more agile and sustainable product development.

IDENTIFY MAIN OBSTACLES

SUPPORT SUSTAINABILITY

FACILITATE INTEGRATED

COORDINATE & SUPPORT

SUPPORT THE SOFTWARE INDUSTRY

INCREASE AWARENESS & ADOPTION

Leading Team

Chair: Kersti Hermansson *(Uppsala University, Sweden)*

Co-chairs: Malrgorzata Celuch (*QWED, Poland*), Maria Alfredsson (*University of Kent, UK*)

MY OBJECTIVE:

TO COMBINE THE WORLDS OF MATERIAL SCIENCE

& MICROWAVE ENGINEERING

Focus Areas

Model Development

Everything that has to do with the capabilities and qualities of the materials models and the modelling workflows: development, validation and application.

Read more

Digitalisation & Interoperability

Topics include the semantic foundation (from terminology to ontology), standardised documentation and cross-domain interoperability platforms.

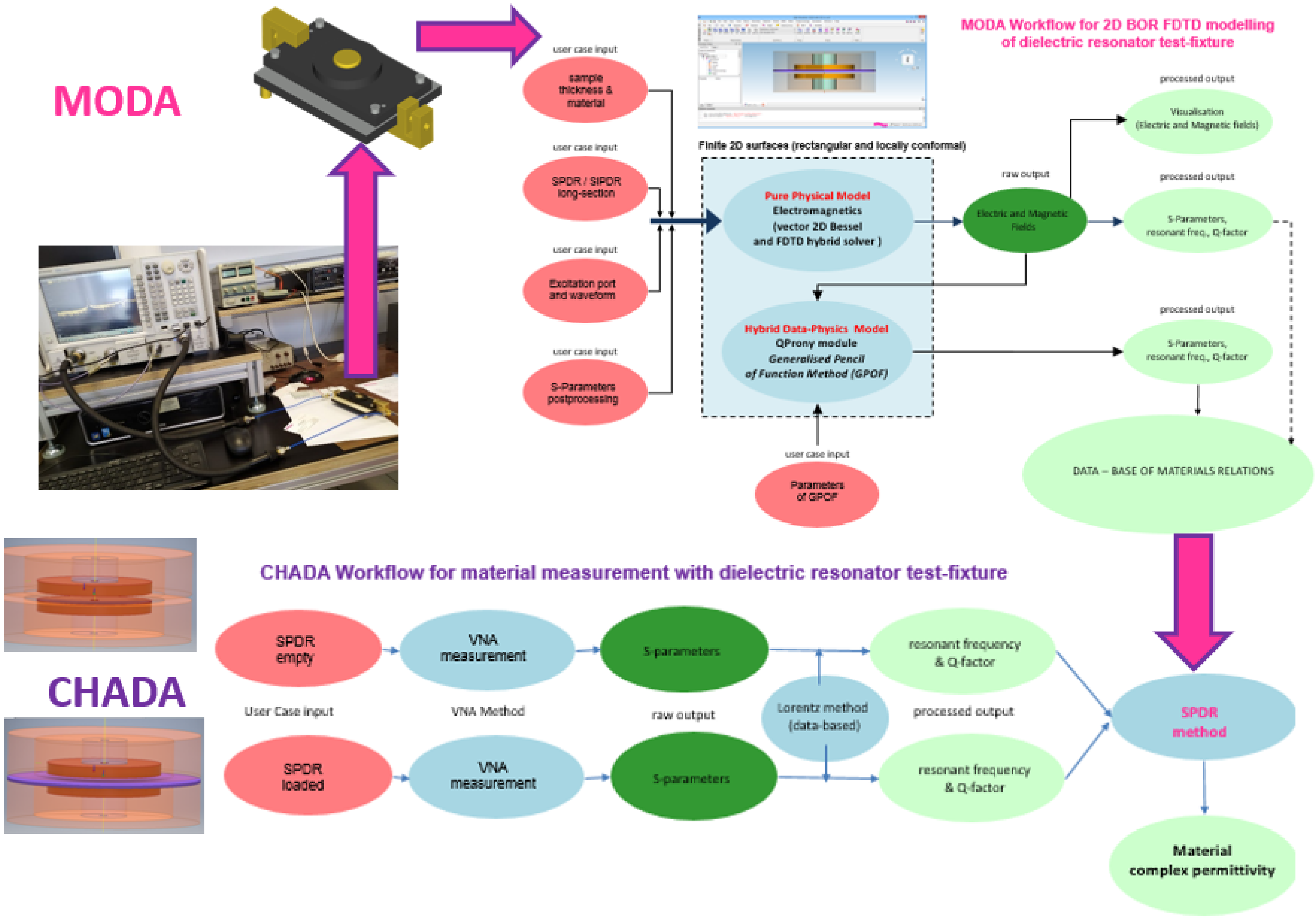
Read more

Software

Successful materials modelling software uses the best algorithms, it is numerically robust, carefully validated, well documented, easy to use, and continuously maintained during decades.

Read more

Twinned MODA + CHADA Concept (Pioneered by QWED / me)



Behind each measure
is a model of the physical
processes assumed to be taking place
in the material.

The measurement
serves to identify those model parameters.

Hence, a reliable simulation
of the measured scenario
is needed to
validate the constructed model
under various conditions.

WiM / WiE / WiSE Events

Women in Microwaves
MRW 2020 Microwave and Radar Week
Warsaw, Poland

Featured in IEEE Microwave Magazine
by M.Celuch, July 2021

2022-April – Warsaw

IEEE Region 8

Women in Science and Engineering
MRW 2022 Microwave and Radar Week
Gdansk, Poland

Featured in IEEE Microwave Magazine
by R. Henderson, December 2022

IEEE Women in Engineering WIE
IEEE Advancing Technology for Humanity
IEEE Ukrainian Microwave Week
Women in Engineering Meeting

Session WIE, Thursday, 17 November 2023, 15:00-17:00 Kyiv Time (14:00-16:00 CET)

40th Anniversary of KARTA Historical Memory Foundation, Warsaw, May 2022

QWED

What I consider distinctive in my professional career:

It combines scientific & engineering work
with business implementation.

I never wanted to be an engineer.

I never thought of becoming a businesswoman.

But my career has so evolved!

Following my Father's Footsteps

to my Father,
MSc in engineering with PhD in economics,
working in foreign trade (aeronautics technology),
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

Acknowledgements

The work of my research team at QWED is currently co-funded by:

the *European Union's Horizon 2020* research and innovation programme under grant agreement *NanoBat No 861962*.

the *Polish National Centre for Research and Development* under contracts *M-ERA.NET2/2020/1/2021* and *M-ERA.NET3/2021/83/I4BAGS/2022*.

M-ERA.NET 3 has received funding from *the European Union's Horizon 2020* research and innovation programme under grant agreements *No 958174*.

ULTCC6G_EPac

I4Bags

We kindly acknowledge the collaborations with our partners in the above European projects.

We acknowledge the iNEMI "5G" partnerships for round-robin experiments and discussions.

Special thanks to all our industrial clients and partners for driving our developments and their kind permission to publish selected industrially-representative results.

Thank you for your attention!

mceluch@qwed.eu

www.qwed.eu

2022: our 25 years

1997: QWED founded
1998: Prime Minister Award

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

2020: sale of our 1000th resonator