MTT-S Webinars

Modelling-Based Measurements of Materials for Application in 5G and Energy Sectors

mceluch@qwed.eu

Dr. Malgorzata Celuch

President, Senior Scientist, Co-Founder

QWED Sp. z o.o Warsaw, Poland

www.qwed.eu

IEEE Poland Section Women in Engineering AG
Vice-Chair

www.ieee.pl/wie

IEEE MTT-1

https://mtt.org/technical-committees/mtt-1-field-theory-and-computational-em-committee/

European Materials Modelling Council
Co-Chair Model Development

www.emmc.eu

CEN Workshop on Materials Characterisation

www.cen.eu/news/workshops/Pages/WS-2020-010.aspx

EU H2020 NanoBat project

www.nanobat.eu

other projects & associations:

…

Technical Content:

1. The science of electromagnetic (EM) modelling as the origin of QWED company.
2. QWED Pillar #1: computer EM simulations including EM wave interactions with materials.
3. QWED Pillar#2: modelling-based design of test-fixtures for materials' characterisation.
4. Extension of Pillar#1 to multiphysics simulations: modelling-based design of applicators for materials' processing.
5. Remarks on FAIR data and Open Science for modelling and characterisation (as in European projects).

Examples: joint application of computer modelling and material measurements in emerging technologies and green energy sectors.

Thoughts while preparing the talk:

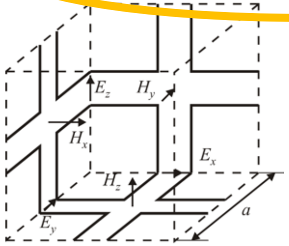
1. Do I need to choose between science and business for my career?
2. Laboratory experiment versus computer simulations: a never-ending competition or a synergy to be exploited?
3. The principles of FAIR data and Open Science – are they realistic?
4. Being a woman in STEM: does it matter?
5. Education for the future?...
6. ..?

My background:

Life – work balance never existed for me!

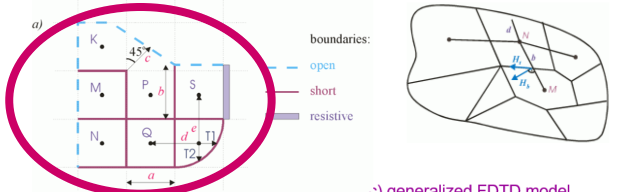
YEAR	ACADEMIA	COMMERCIAL	PRIVATE
1981-1983	**scholarship at the United World College of the Atlantic**		
1989-1996	on a maternity leave for most of the time but running classes at WUT and Franco-Polish School of New Information and Communication Technologies; later lecturing at Chalmers	technical translator English teacher in kindergarden	struggling to combine child-raising, Ph.D. research, making a living, and pro-publico-bono activities
1996	Ph.D. at the Warsaw University of Technology : *A generalised approach to the FDTD and TLM algorithms for microwave circuit modelling*	Ph.D. results amalgamated in **QuickWave** software: beta-version of QuickWave tested at Chalmers,Kent, and Helsinki universities	
1997	employed as assistant professor at WUT	**QWED company founded** **first sales of QuickWave** to Saab Ericsson Space, NASA-related las (NRAO, JPL), and a leading MW oven producer	my son enters a primary school
1997-2017	full-time at WUT 20+ courses, tutorials, lectures in academia &industry reviewer of Ph.D. thesis in Canada & Finland	QWED VP – full time	full-time mother (at least until 2008)
2017->	QWED-WUT collaborations industrial co-supervisor of Ph.D. theses expert for the European Commission	QWED President & Senior Scientist	a happy period of marriages and grandchildren

FDTD versus TLM
Theorem of Formal Equivalence



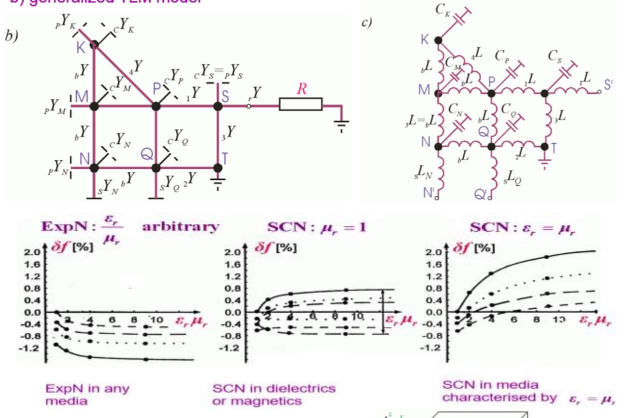
nodes: FDTD discretisation of Maxwell eqs.
connecting lines & stubs: TLM discretisation of Huygens principle

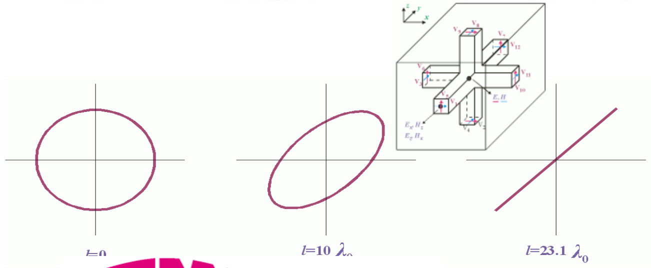
a) generalized gridding of a microwave structure



b) generalized TLM model

c) generalized FDTD model

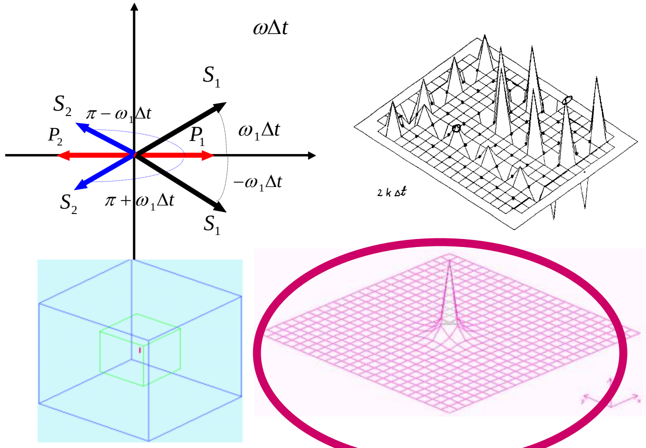




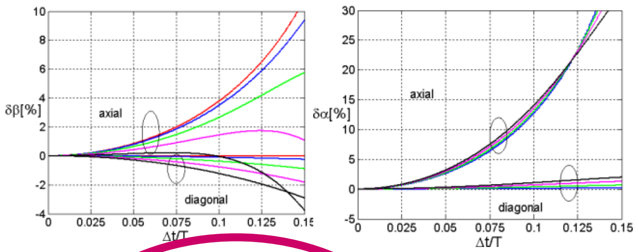
Generalised dispersion relations
Theory of P- and S-eigenmodes

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

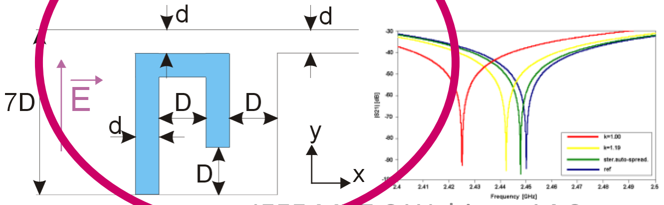
$$\omega_{ph}^2[-\omega_{ph}^2\mu\varepsilon + \beta_{xph}^2 + \beta_{yph}^2 + \beta_{zph}^2]^2 = 0$$



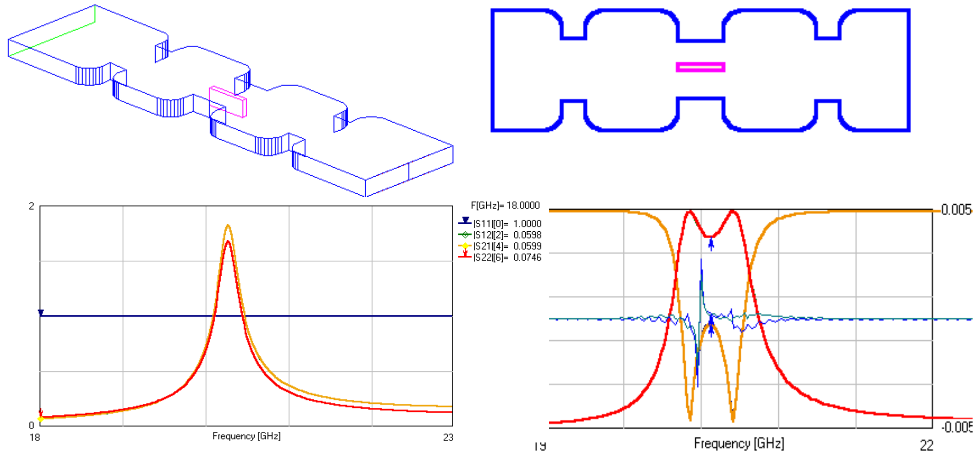
Dispersion in lossy media



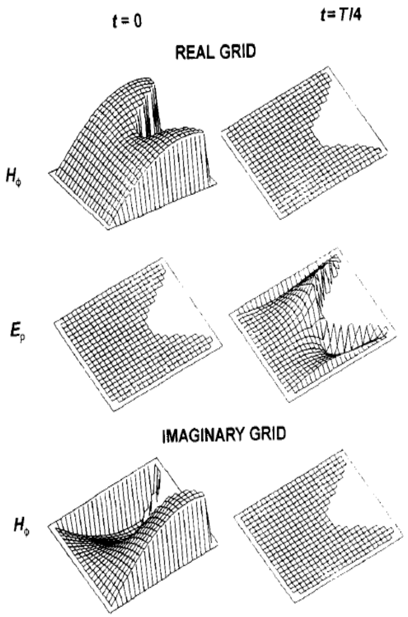
Field singularities



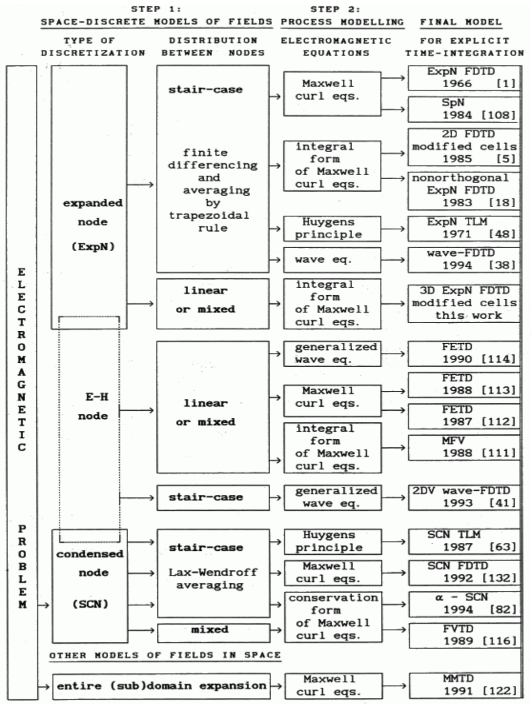
Generalised extraction of S-parameters in multi-modal transmission lines (incl. evanescent modes)



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



Classification of time-domain methods



QuickWave software & QWED company:

challenge to prove our points on the open market ← Barriers to attending international conferences (from behind ”the iron curtain”) & delayed publishing of research results

- Polish high-tech SME.
- Over 24 years on the global market.
- Established in 1997 by four academics from the Warsaw University of Technology, under the leadership of Prof. Wojciech Gwarek, IEEE Fellow & recipient of IEEE MTT Pioneer Award, with the mission to supervise the commercial development of their research results.
- Founders awarded with several prestigious awards for scientific and technical achievements (e.g. European Information Technology Prize, Prime Minister of Poland awards).
- Two leading branches of research and business:

  - QuickWave software for electromagnetic design and simulation (incl. consulting and commercial design works) – since 1997,

  - Resonator test-fixtures for precise measurements of material properties of materials in GHz range - since 2001.

- Synergies between the two branches:

  - are explored in R&D and industrial projects,

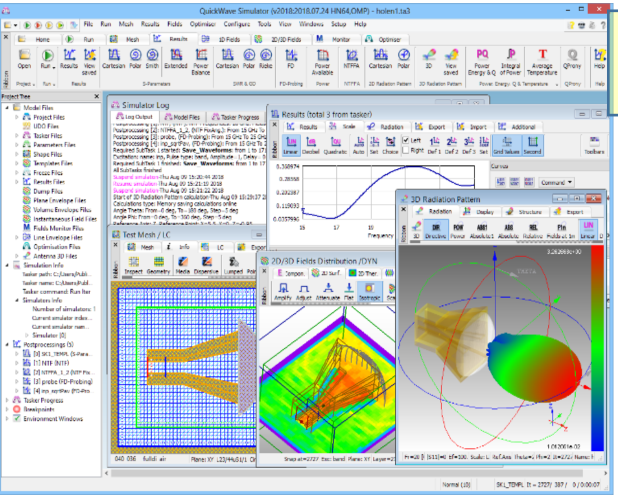
  - lead to successful market products and contributions to Open Innovation.

QuickWave Electromagnetic Design

-> company name is due to bureaucratic barriers…

Polish high-tech SME - 24 years on the world's market

Business branches *presented annually at IEEE IMS Show*

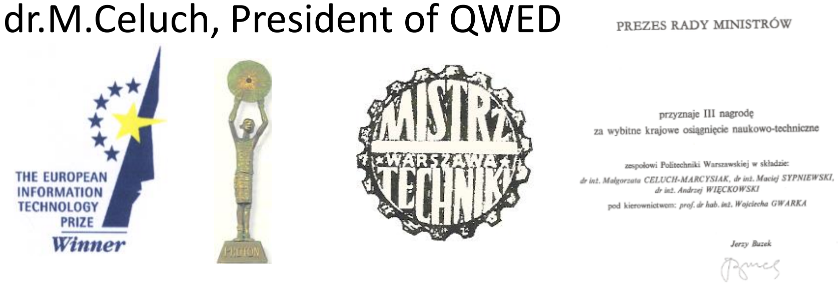


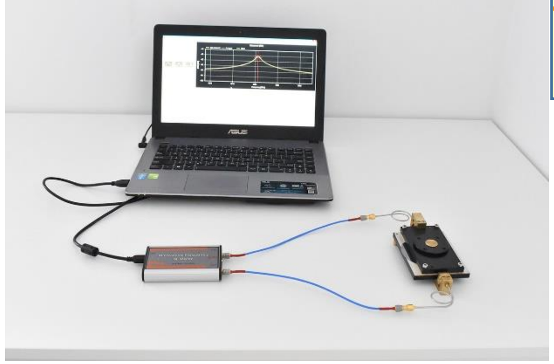
Electromagnetic simulation & design software, 3D & BOR 2D tools

based on 300+ publications by:

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

dr.M.Celuch, President of QWED

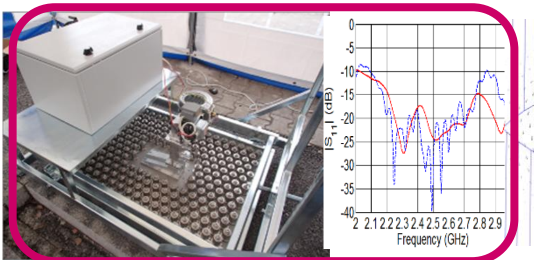


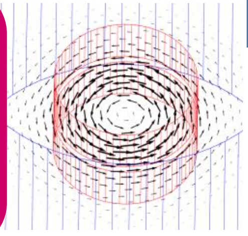


Test-fixtures for precise material measurements

based on 300+ publications

by prof.J.Krupka, IEEE Fellow



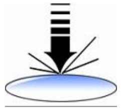


Consultancy & design services based on EM expertise & tools

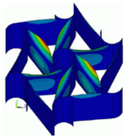
team of 10+engineers, 4 PhDs, 2 Profs

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) – accelerating the development of high efficiency solar cells through application and enhancement of material measurement techniques

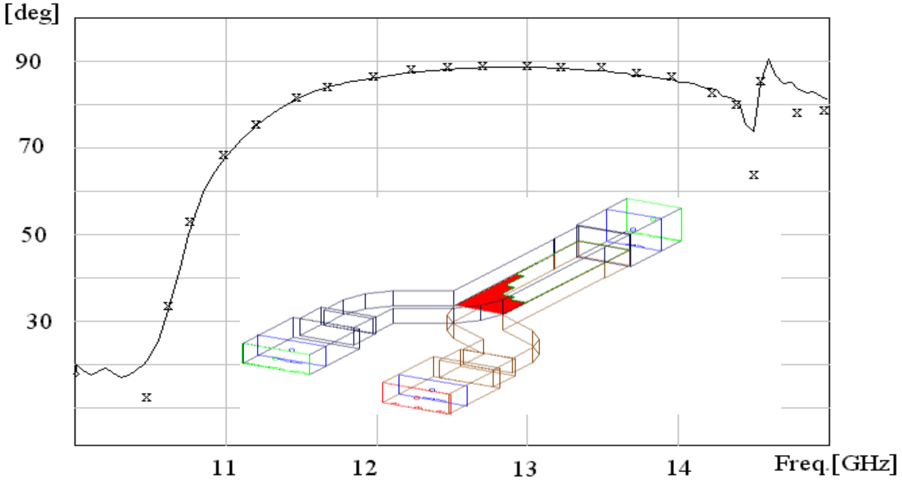
NanoBat - developing a novel nanotechnology toolbox for quality testing of Li-ion and beyond Lithium batteries with the potential to redefine battery production in Europe and worldwide.

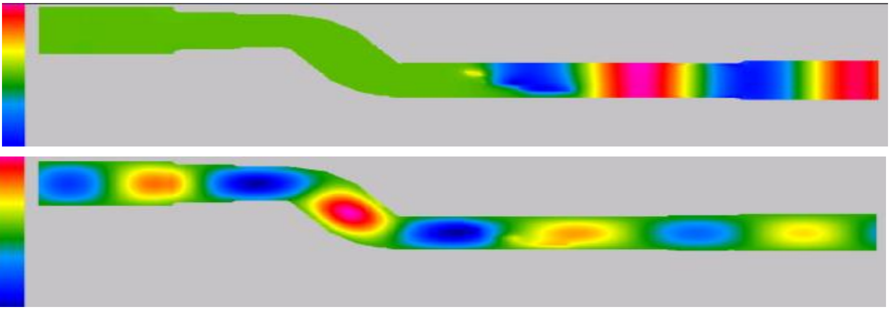
QuickWave original applications in cosmic reseach & satellite telecommunication

Septum polariser by SES

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

below: differential phase-shift



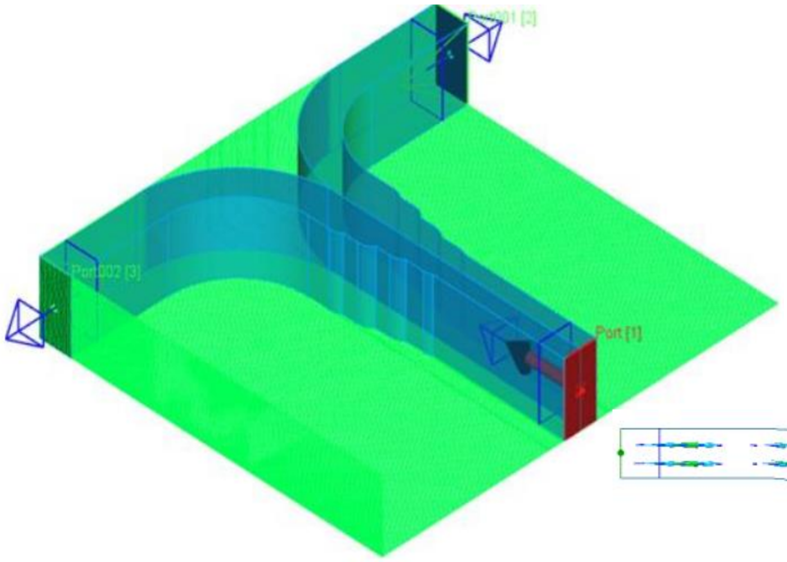


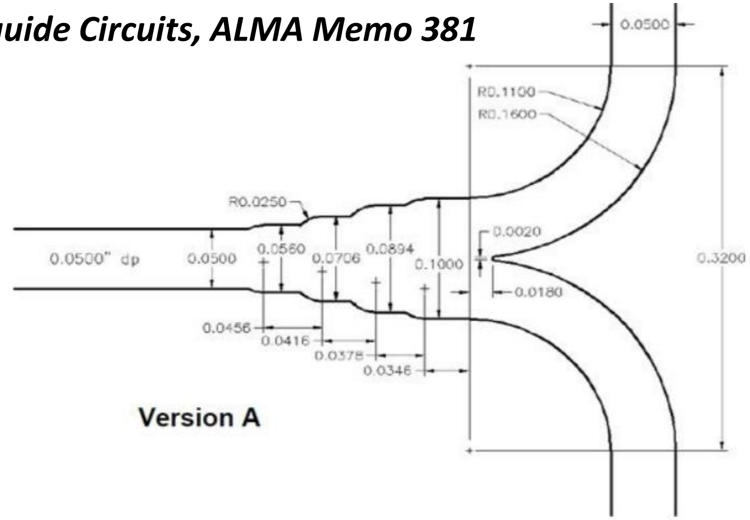
propagation of two polarisations

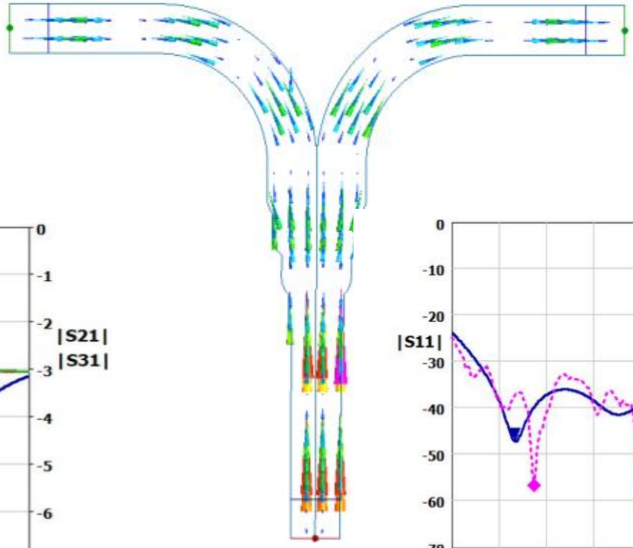
at centre frequency

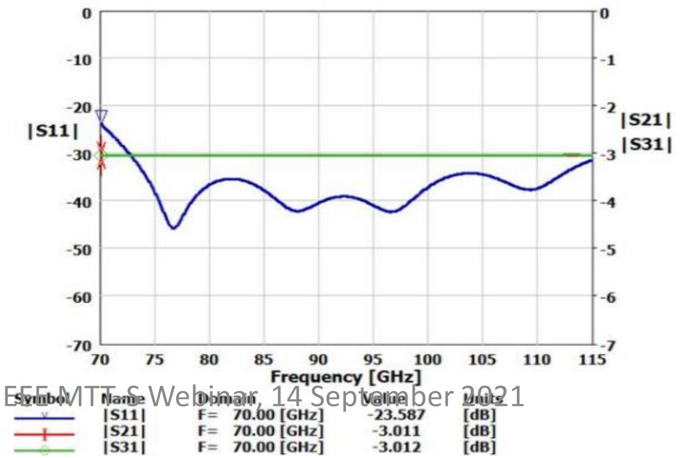
E-plane Y-junction by NRAO

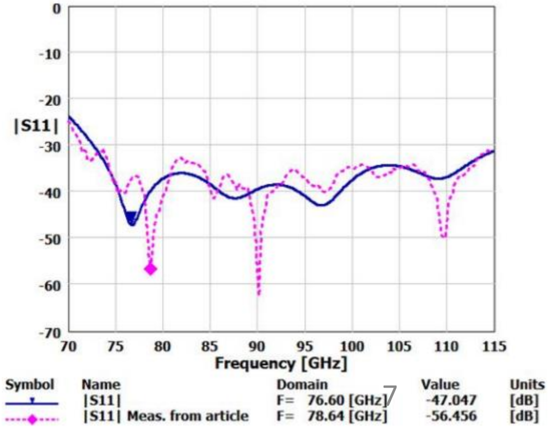
after A. R. Kerr, Elements for E-Plane Split-Block Waveguide Circuits, ALMA Memo 381





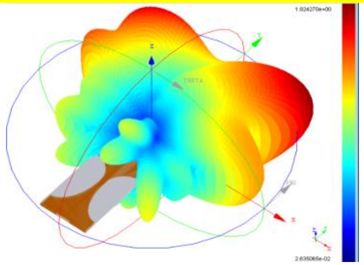




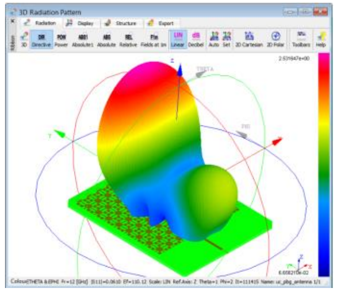


QuickWave further applications to the design of antennas & feeds

general 3D FDTD

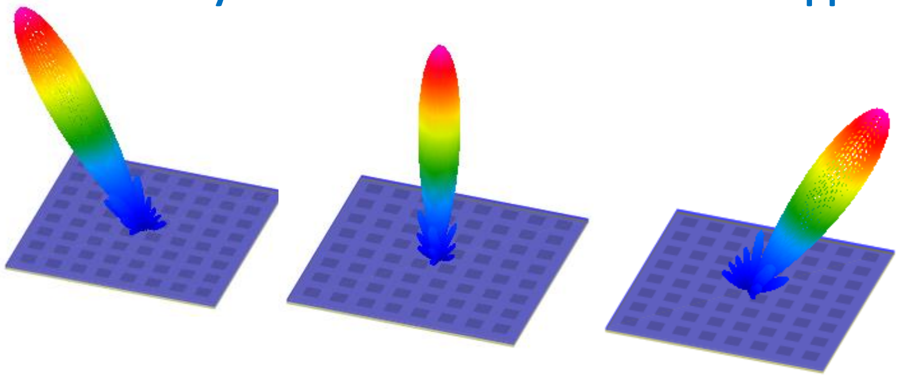


Balanced antipodal Vivaldi antenna & 3D radiation pattern at 10 GHz.



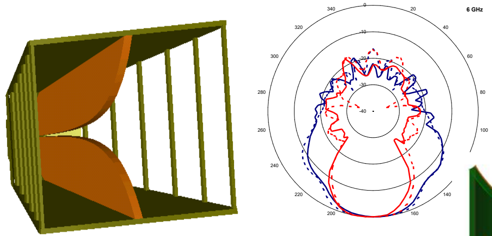
Aperture-coupled patch antenna on uniplanar photonic bandgap substrate & its radiation pattern at 12 GHz.

Antenna arrays for 5G and automotive radar application

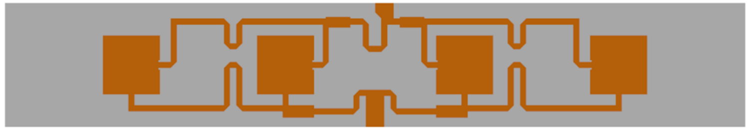


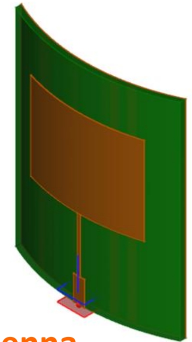
Designing and verifying tracking capabilities

Pyramidal horn antenna for military surveillance measured (prof.B.Stec Warsaw Military Academy of Technology) & simulated patterns

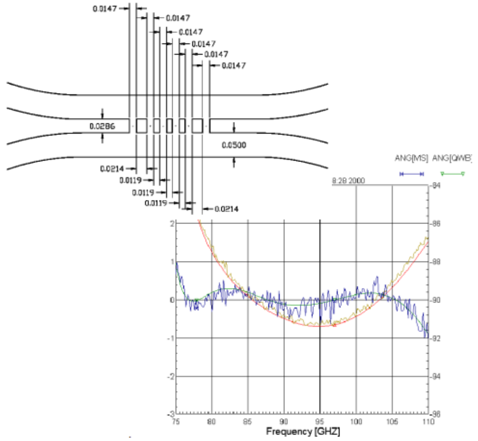


Planar antennas for smart bio-sensors



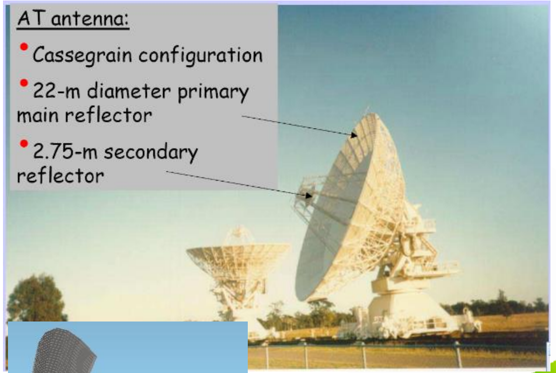


Antenna feed systems designed by NRAO



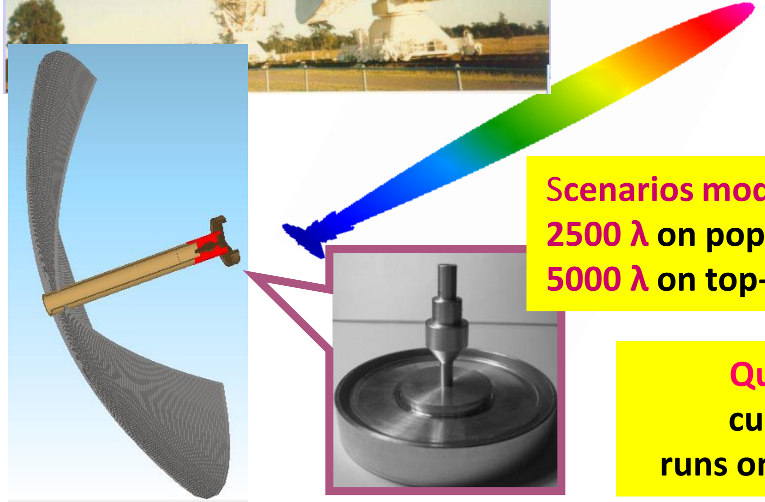
QuickWave 3D results at NRAO, see: ALMA Memos 381, 343, 325, 278.

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



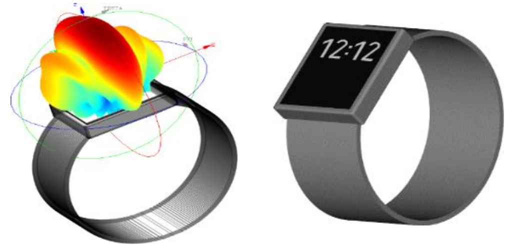
BOR FDTD

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

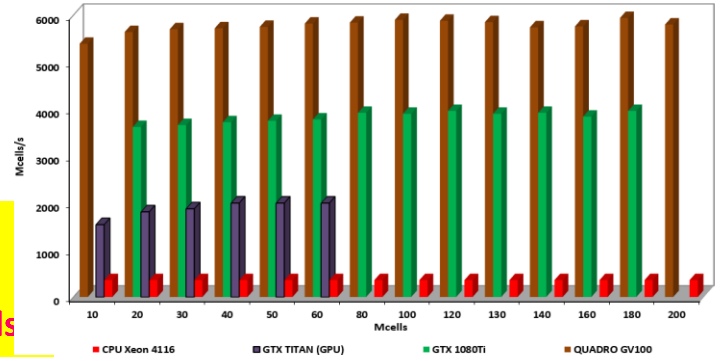


Scenarios modelled full-wave by QW-BoR:
2500 λ on popular PC (64 GB)
5000 λ on top-shelf PC

Smartwatch with embedded patch antenna



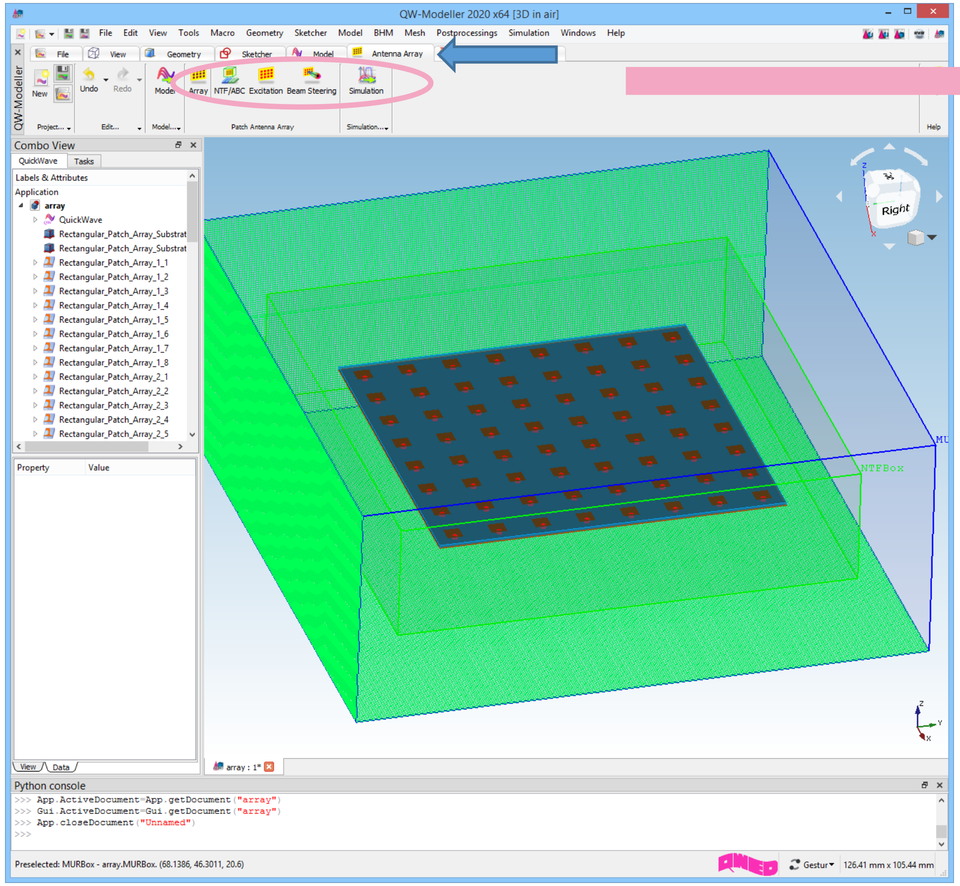
QuickWave is optimised for speed currently upm to 6000 Mcells/sec, runs on professional & low-cost video cards

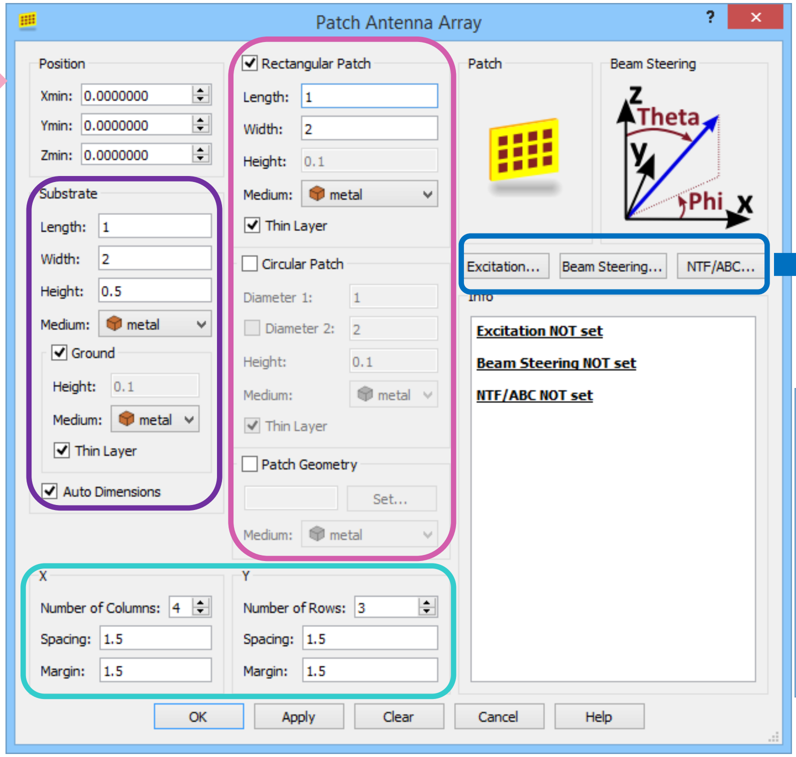


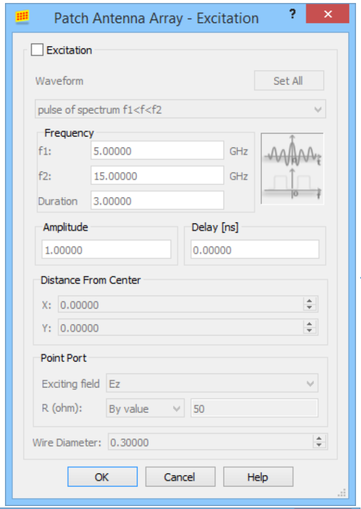
QWED

QuickWave for antenna design: dedicated wizards for 5G patch antenna array project creation

QW-Modeller

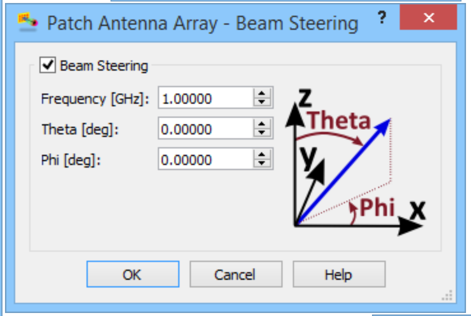




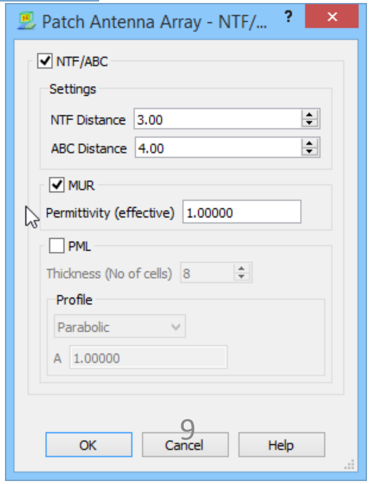


Feed parameters @ each patch

Automatic phase-shift adjustment between patches



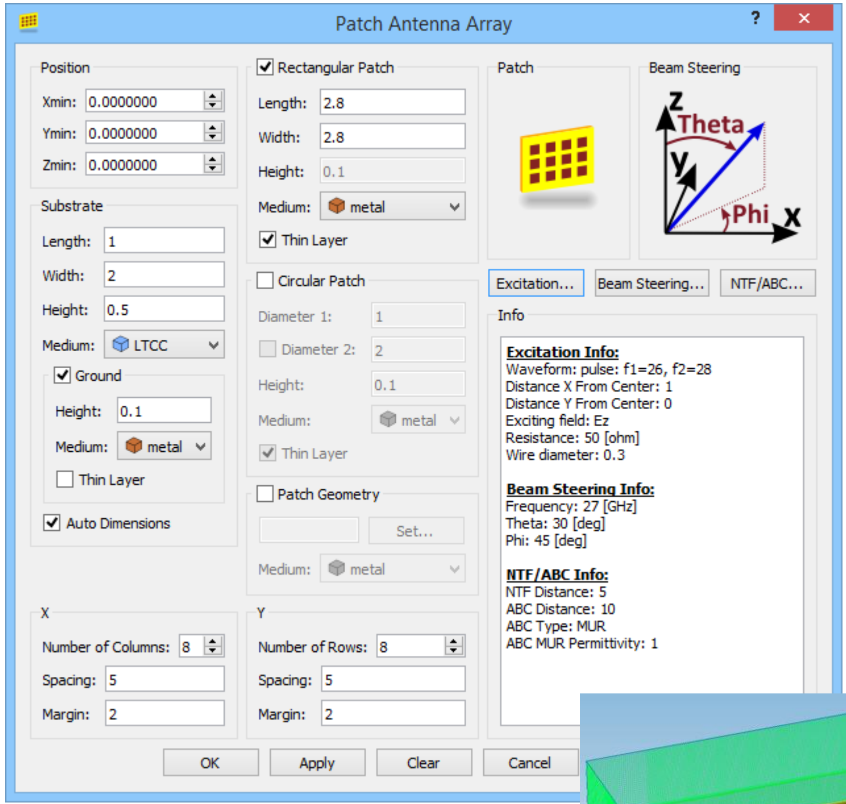
User defined main beam angle

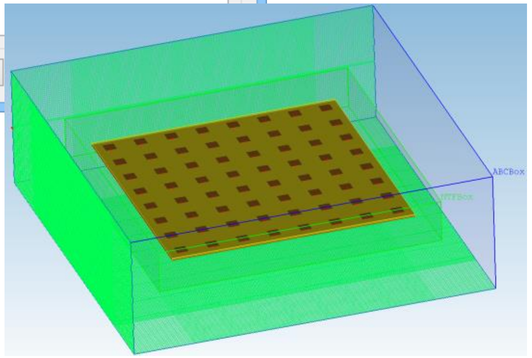


Choice of suitable absorbing BC

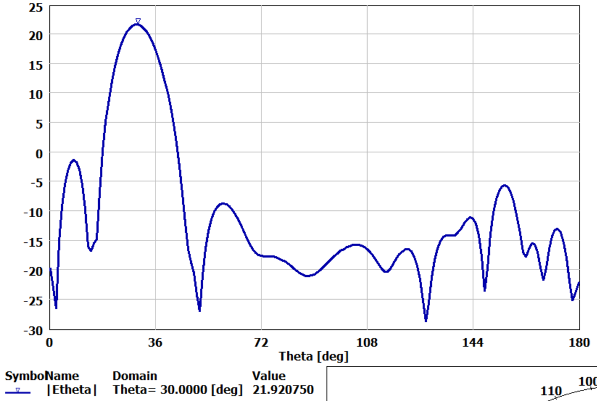
- ✓ Various patch shapes, incl. user-defined geometries
- ✓ Automatic substrate/ground inclusion, incl. dimensions auto-scaling
- ✓ Automatic matrix arrangement

QuickWave for antenna design: 5G-dedicated simulation regimes & display

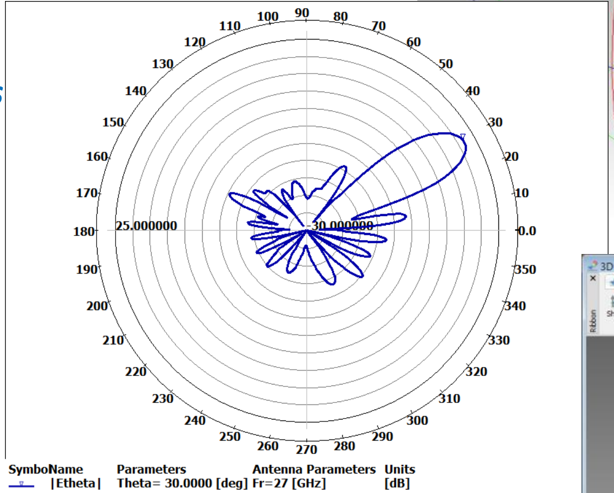


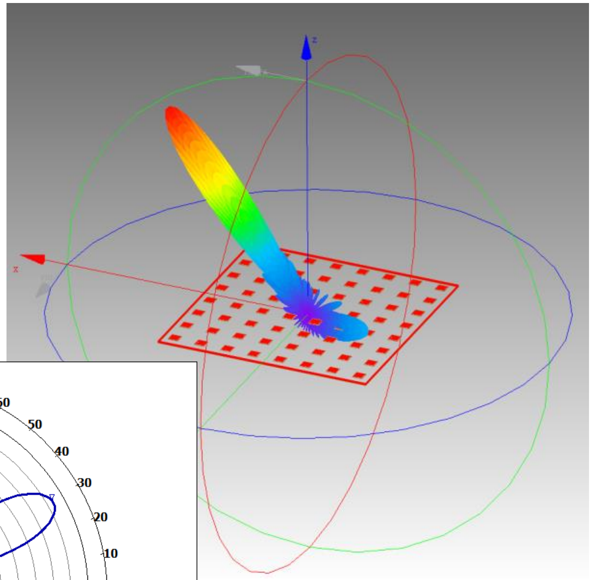


LTCC-based 8x8 patch array



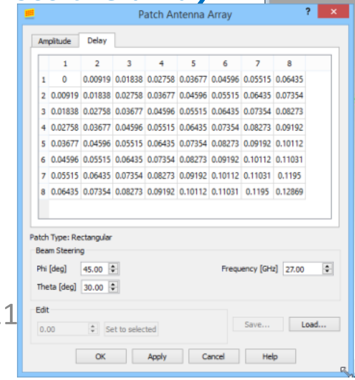
2D radiation patterns

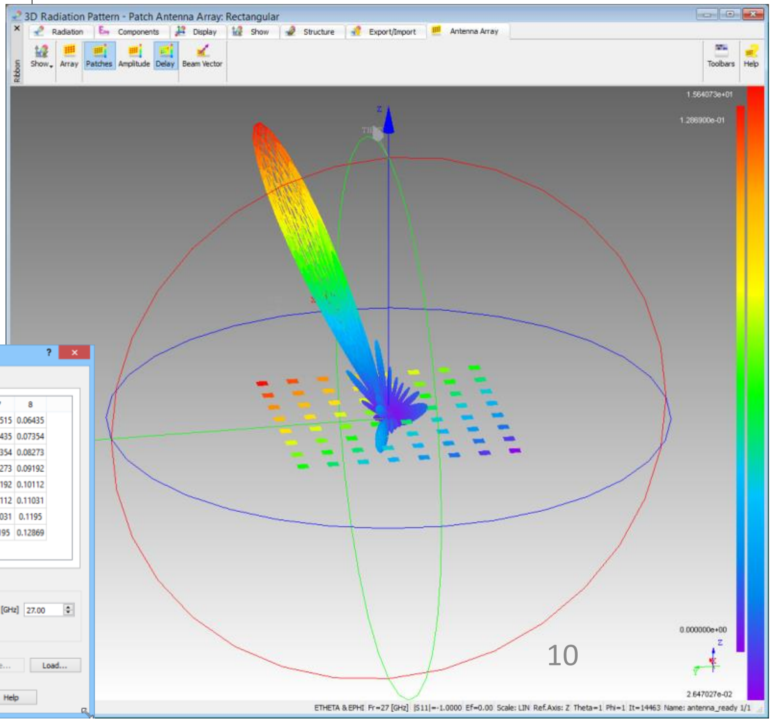




3D radiation pattern

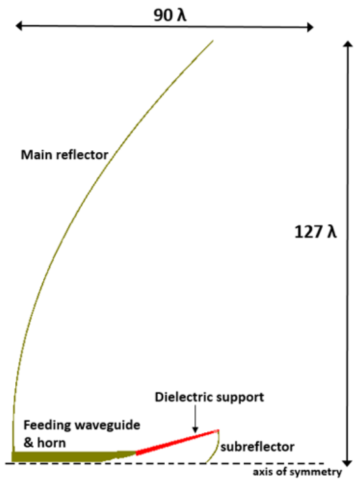
Distribution of source phase shifts across the array



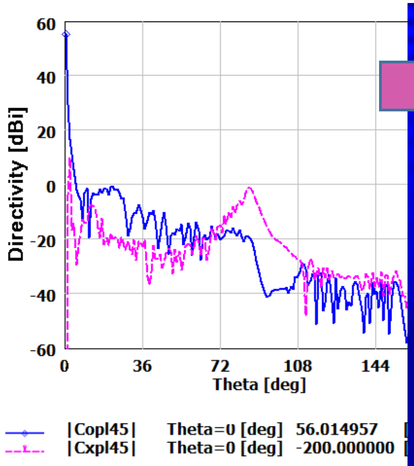


Near-field FDTD workflow - insight into device performance

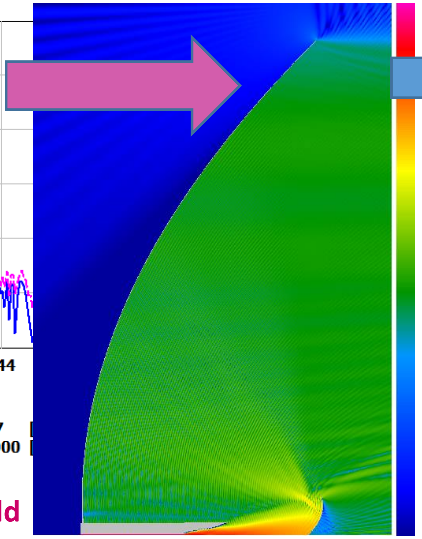
Dynamic field displays can be invoked at any time, anywhere in the computational domain.

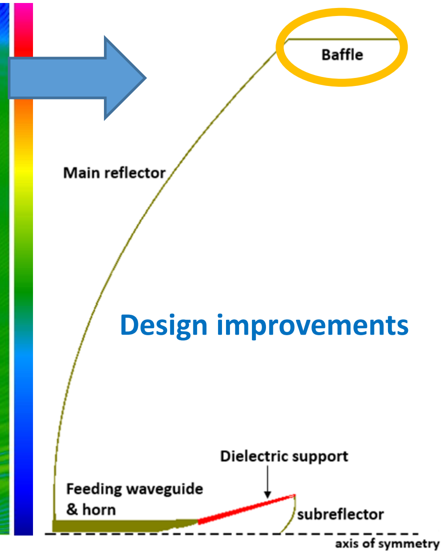


Dual -reflector antenna

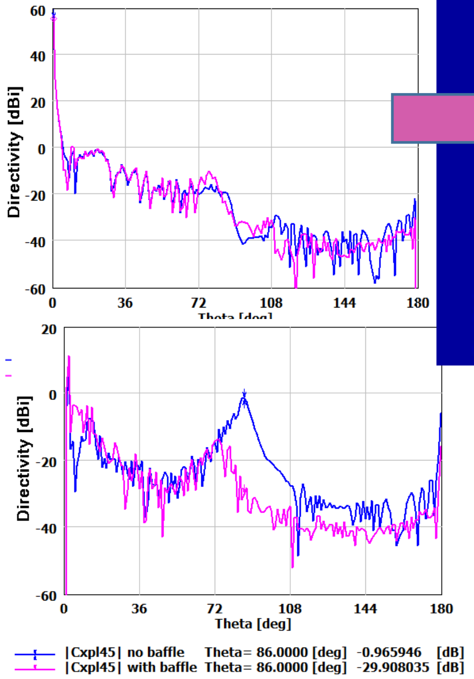


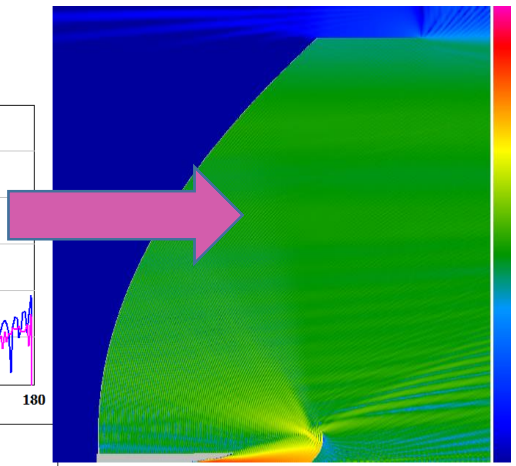
Insight into EM near-field





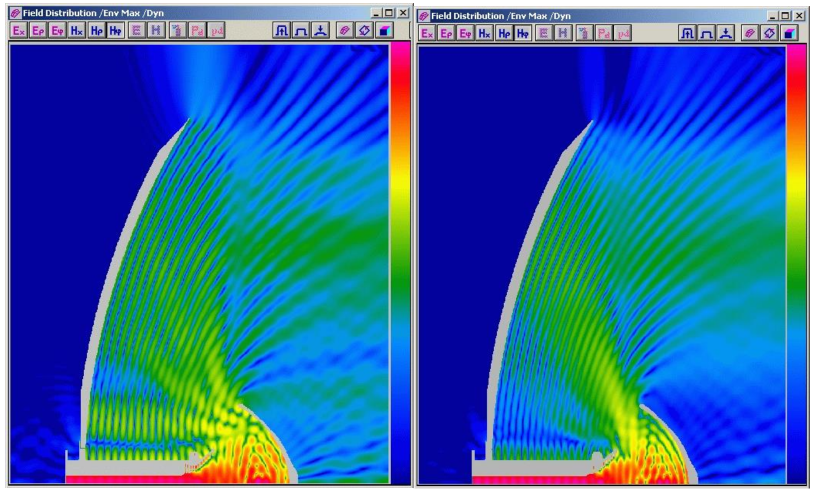
Design improvements

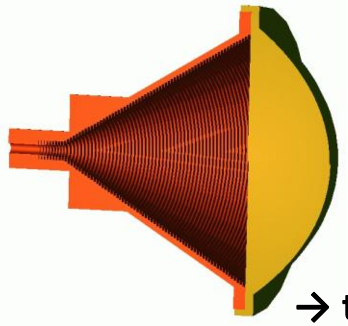




9m – diameter main reflector
Meshing: λ/40
Time to solution: 8 min
Radiation pattern @24 freq.,
Δθ=1deg : 5 s

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 %





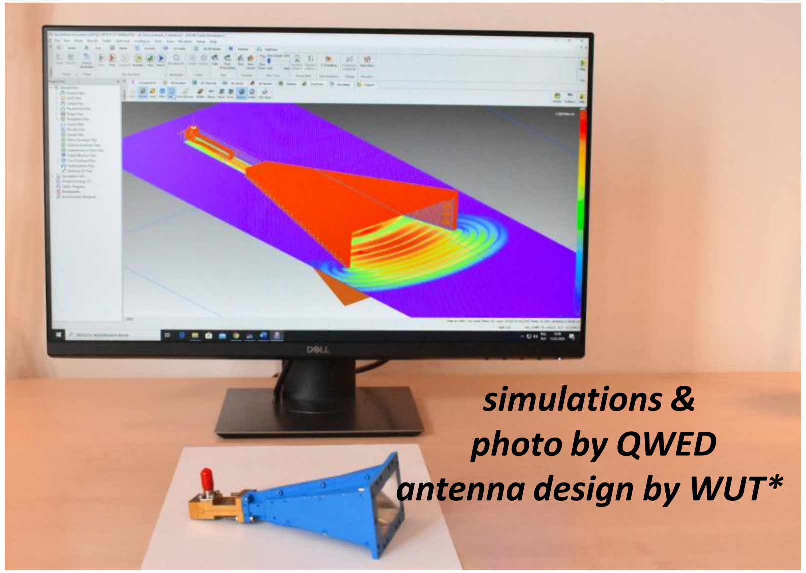
Gaussian beam formation for quasi-free-space material measurements

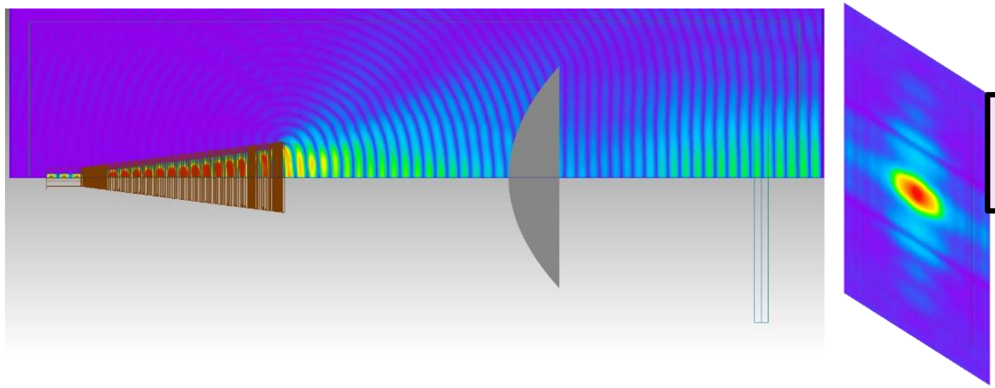
→ this concept further used for QWED's new Fabry Perot Open Resonator

Modelling-based design for quasi-free-space material measurements

Modelling of pyramidal horn antenna for material measurements in 18-40 GHz band

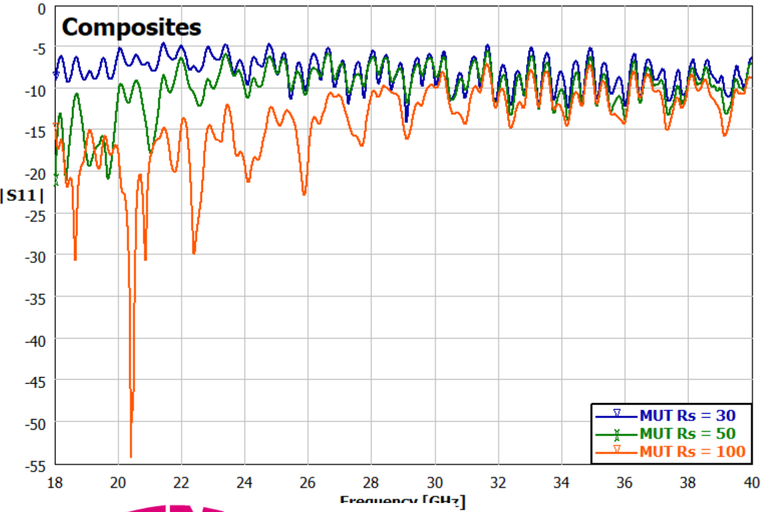
QWED collaborations with the Warsaw Univ. of Technology

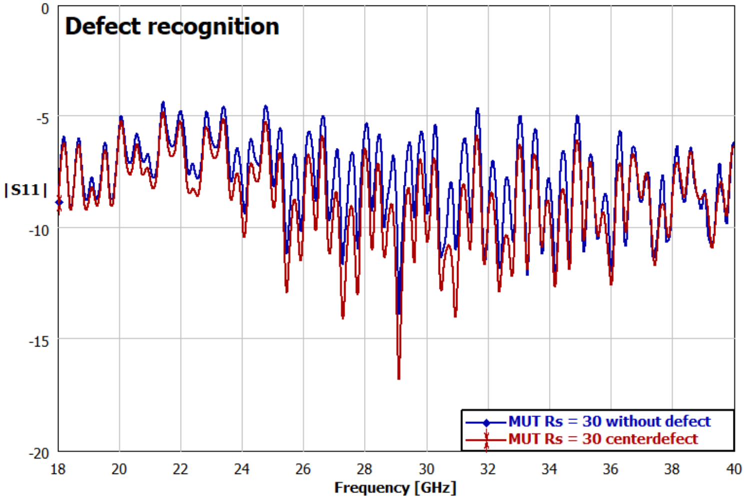


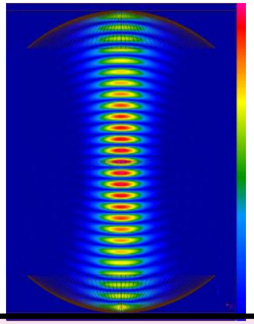


J.Cuper, B.Salski, P.Kopyt, A.Pacewicz, A.Raniszewski, "*Double-ridged horn antenna operating in 18-40 GHz range*", Proc. Microwave & rfadar Week, MIKON-2018.

Example use in H2020 MMAMA project for feasibility study of quality control of novel composites for aeronautic applications







T.Karpisz, B. Salski, P. Kopyt, and J. Krupka, "*Measurement of Dielectrics From 20 to 50 GHz With a Fabry–Pérot Open Resonator*" IEEE Trans. MTT, vol. 67, no. 5, pp. 1901–1908, May 2019, doi: 10.1109/TMTT.2019.2905549

From corrugated horn for Gaussian beam generation to new Fabry-Perot Open Resonator with Gaussian mirrors

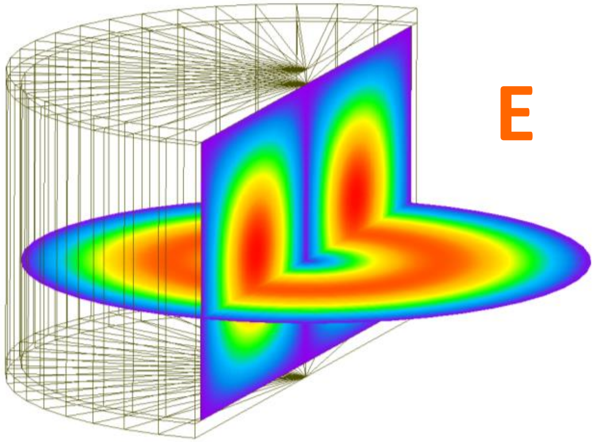
see further slides for round-robin evalution in iNEMI 5G project

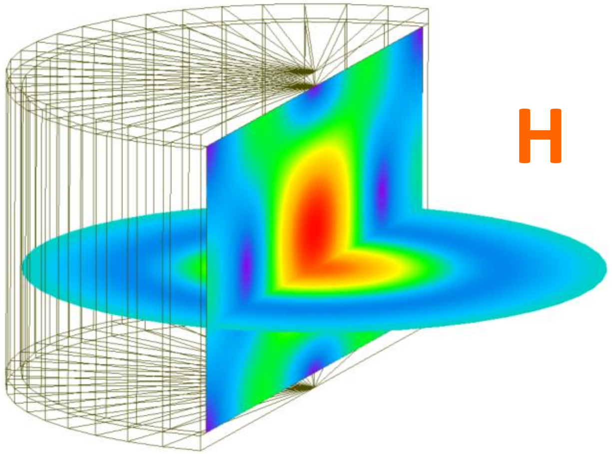
Application of the RESONANCE in material measurements (*for newcomers to the field*)

Eigenvalue problem in theoretical electromagnetics:

- Non-zero electromagnetic fields (non-zero energy) exist in a region without any energy exchange with the outside (no "feeding").
- This is mathematically possible at specific frequencies (eigenfrequencies). The corresponding spatial field patterns are called modes (eigenmodes).
- In a lossless region, the fields exists ("ring") *ad infinitum* (sinusoidal oscillations).
- If there are (not-too-high) losses in the region, the fields are gradually damped (damped sinusoidal oscillations) with damping characterised by quality factor (Q-factor) and frequency little alterated (compared to the same materials with losses neglected).

Example: TE011 mode in cylindrical cavity



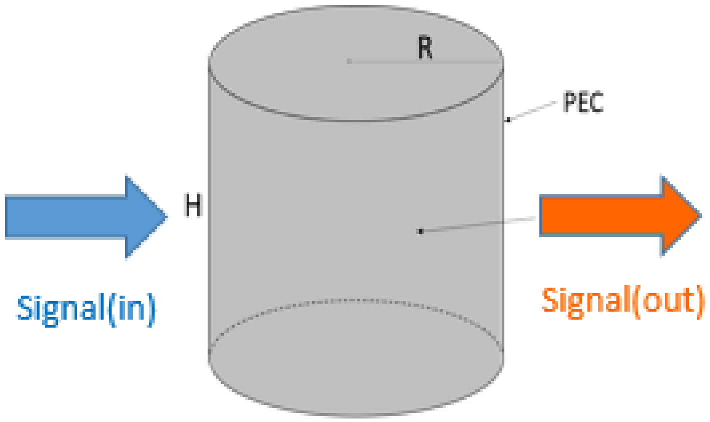


Resonance problem in applied electromagnetics:

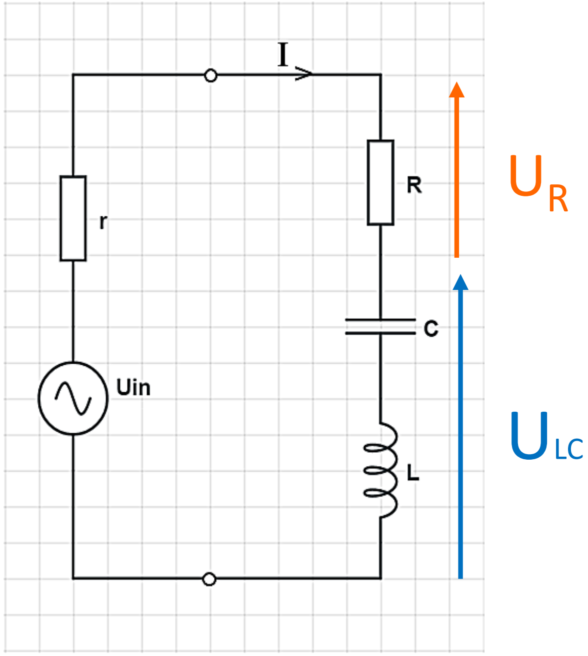
- There is feeding from the outside, but the coupling is non-too-strong.
- The corresponding resonant frequencies are close to eigenfrequencies of the corresponding isolated problem.
- Energy loss in a lossy resonating region is compensated with energy supplied by the feed. Energy is also lost on internal losses (resistance) of the feed.

Circuit-theory interpretation (*for newcomers to the field*)

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



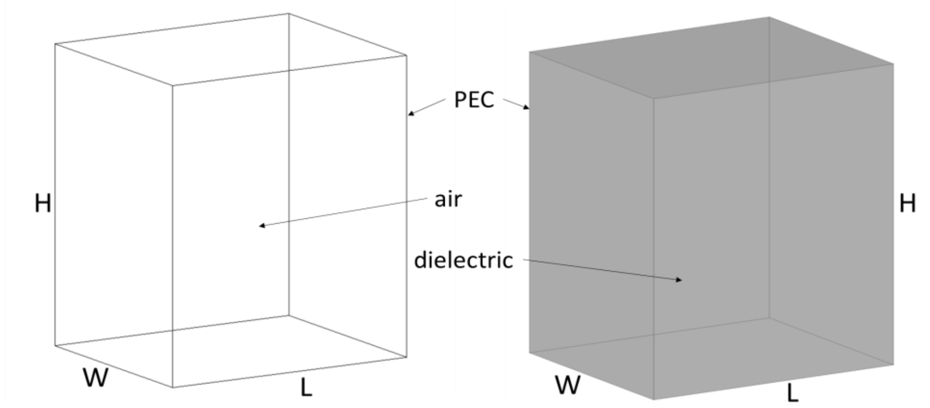
given fixed strength of Signal(in),
at resonance Signal (out) is strongest



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

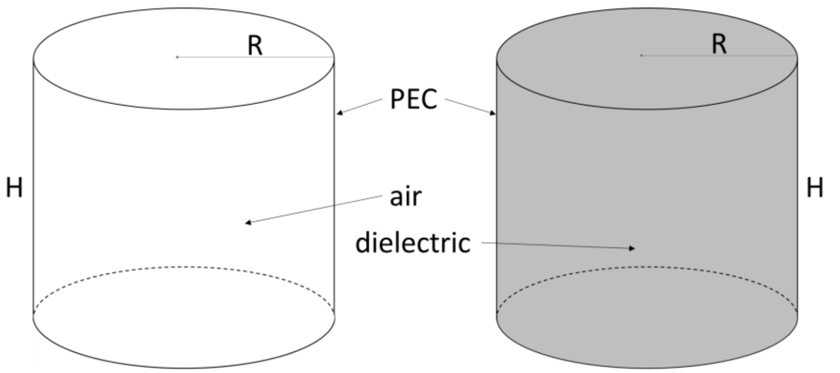
Canonical examples of resonators (*for newcomers to the field*)

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



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

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

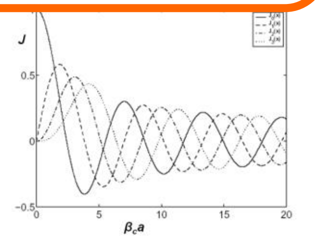


$$f_{r,mnp} = \frac{v}{2}\sqrt{\left(\frac{m}{W}\right)^2 + \left(\frac{n}{L}\right)^2 + \left(\frac{p}{H}\right)^2}$$

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

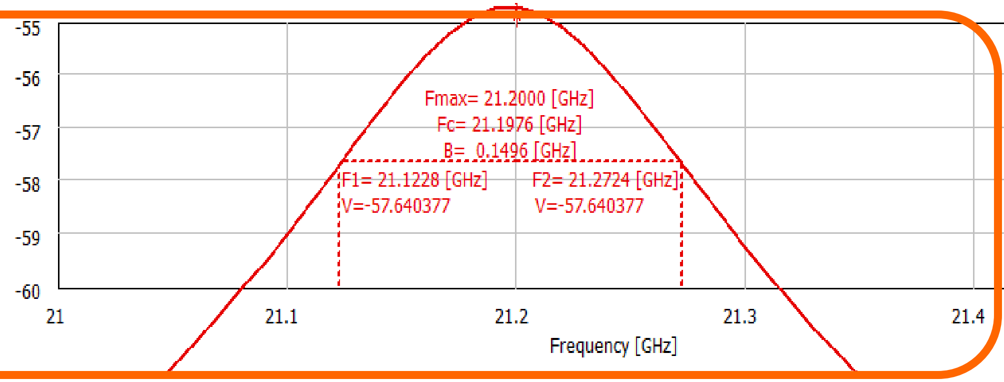
$$f_{r,mnp} = \frac{v}{2}\sqrt{\left(\frac{\kappa_{mn}^{(')}}{\pi R}\right)^2 + \left(\frac{p}{H}\right)^2}$$

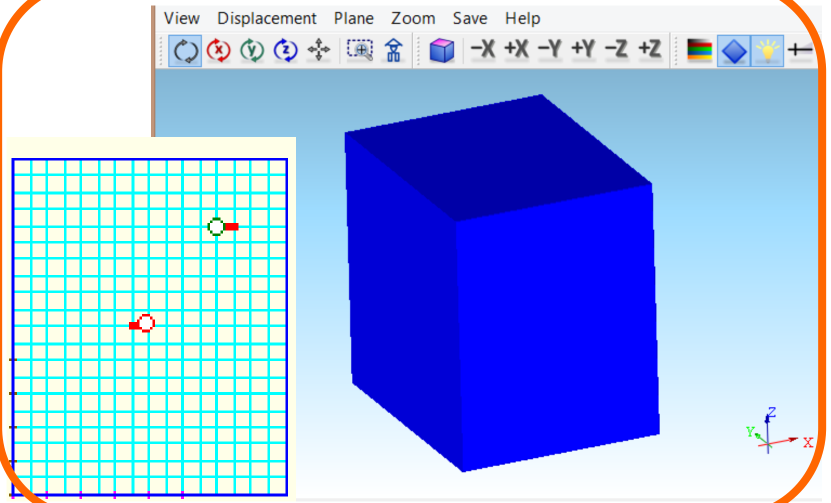
→ application of cavities to Dk measurements appears straightforward!
(but cavity losses should be minimised & 100% filling factor is difficult to achieve)

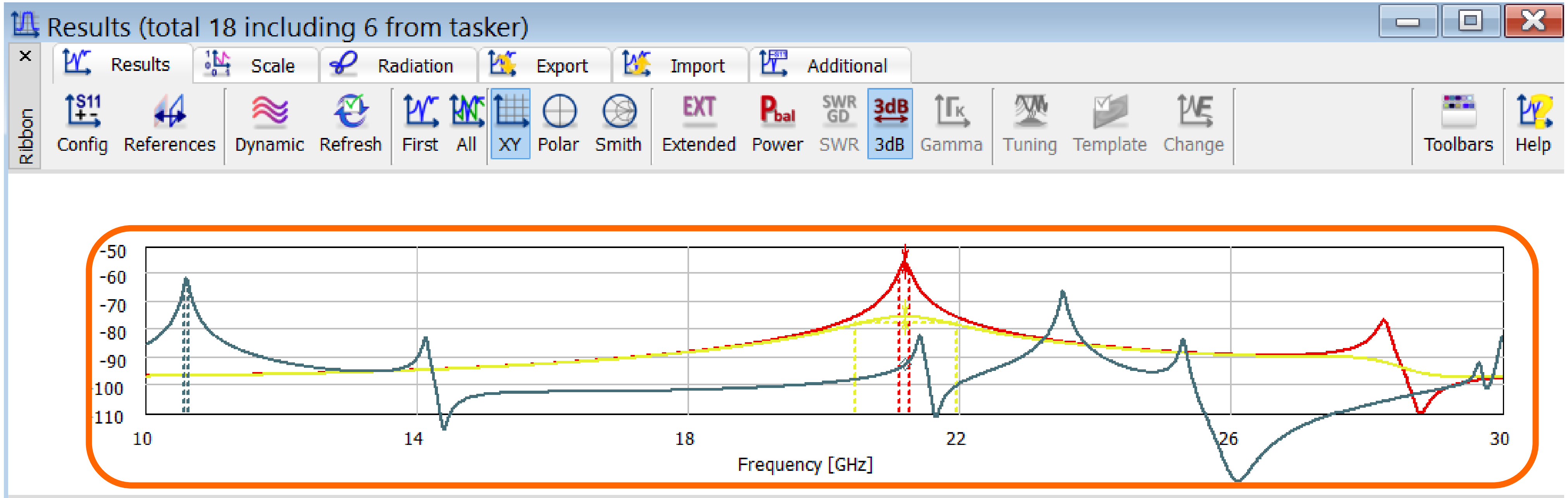


QuickWave model of a cuboidal cavity

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







ε_r=1 σ=0.00833 S/m @21.2GHz:

tanδ=0.071

Q_{SUT}= 1 / 0.0071 = 141

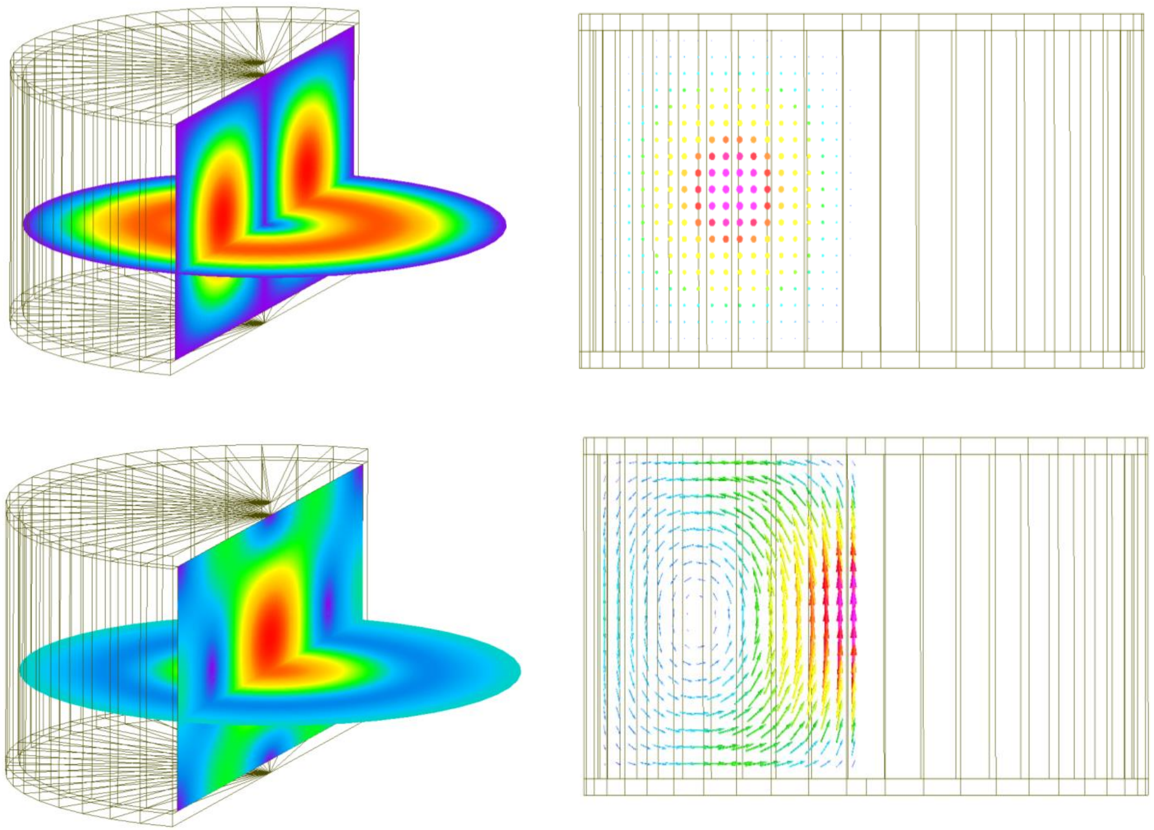
Q_{S21}=21.2/0/1496= 141

ε_r=1 σ=0.0833 S/m

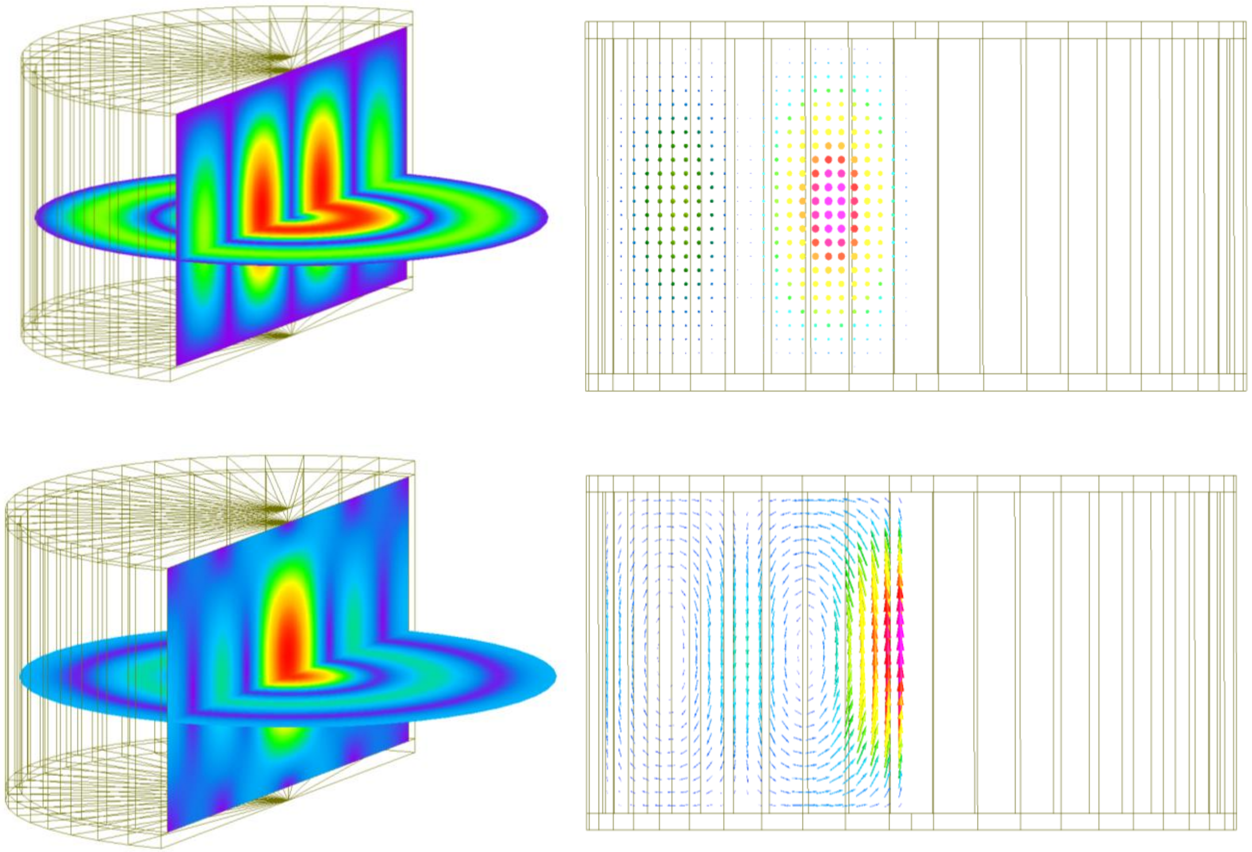
ε_r=4 σ=0.0166 S/m

QuickWave model of a cylindrical cavity

TM011 mode



TM021 mode

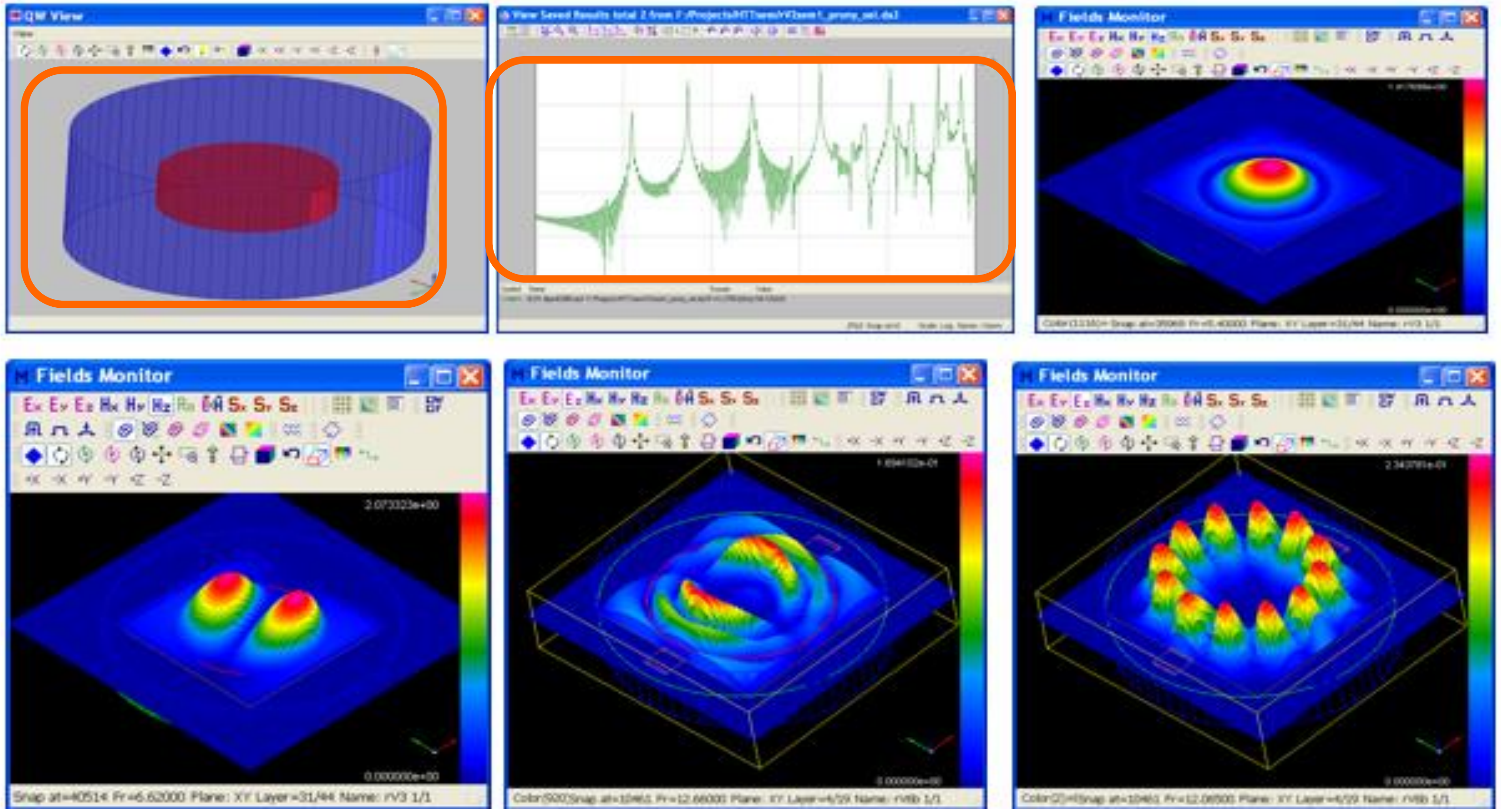


compared to rectangular (cuboidal) cavities, typically:

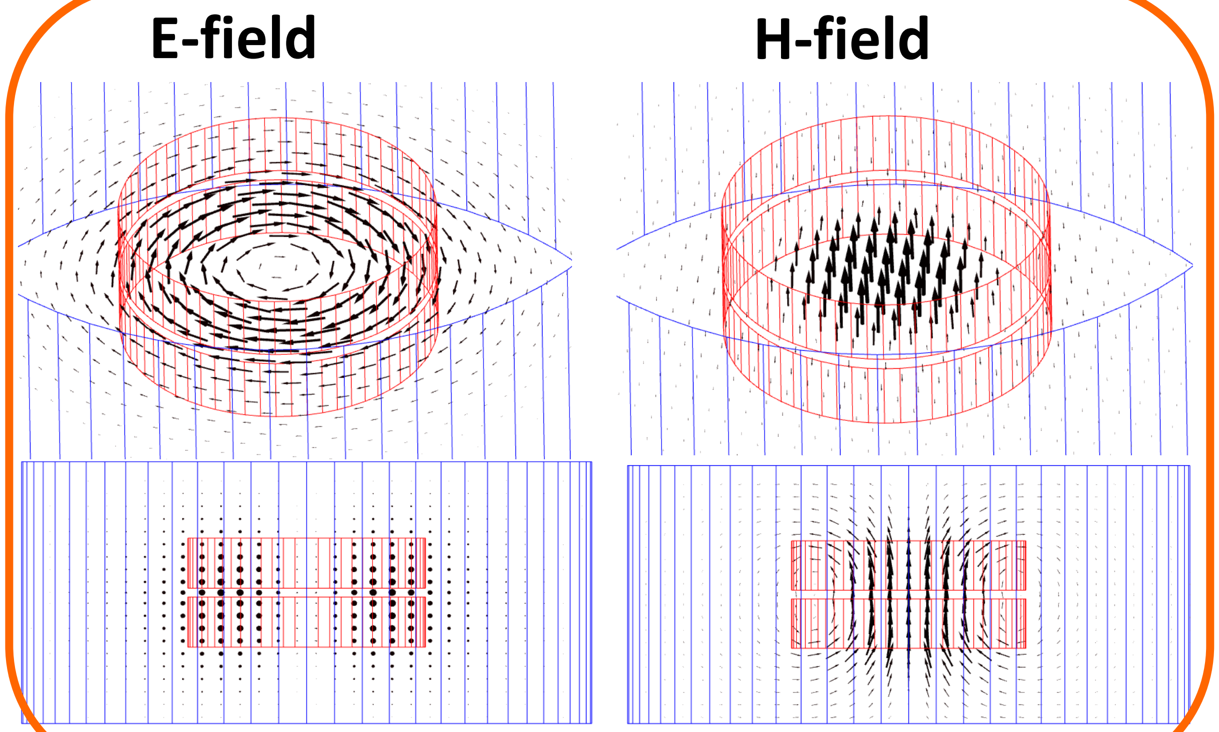
- lower contribution of wall losses
- easier standard manufacturing

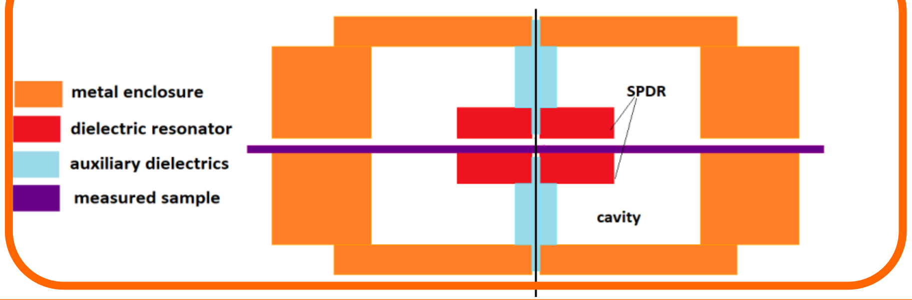
How do dielectric resonators work (*with QuickWave illustration*)

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



Split-Post Dielectric Resonator method – as implemented by QWED





- resonant mode with EM fields mostly confined in and between those ceramic posts → minimial losses in metal enclosure
- H-field is only vertical at the side wall of the enclosure → only circumferential currents in side wall → no radiation through slot
- E-field tangential to SUT → air slots between SUT and posts have negligible effect
- **easy SUT insertion through slot, no dismatling, NDT method**
- all EM energy injected through the coupling loops in contained within in the SPDR "head" (inside the enclosure)
- an estimated 95% of energy confined in and between the ceramic posts
- **once-in-a-lifetime calibration suficient for general materials (NOTE: new calibration services dedicated to 5G coming soon!)**

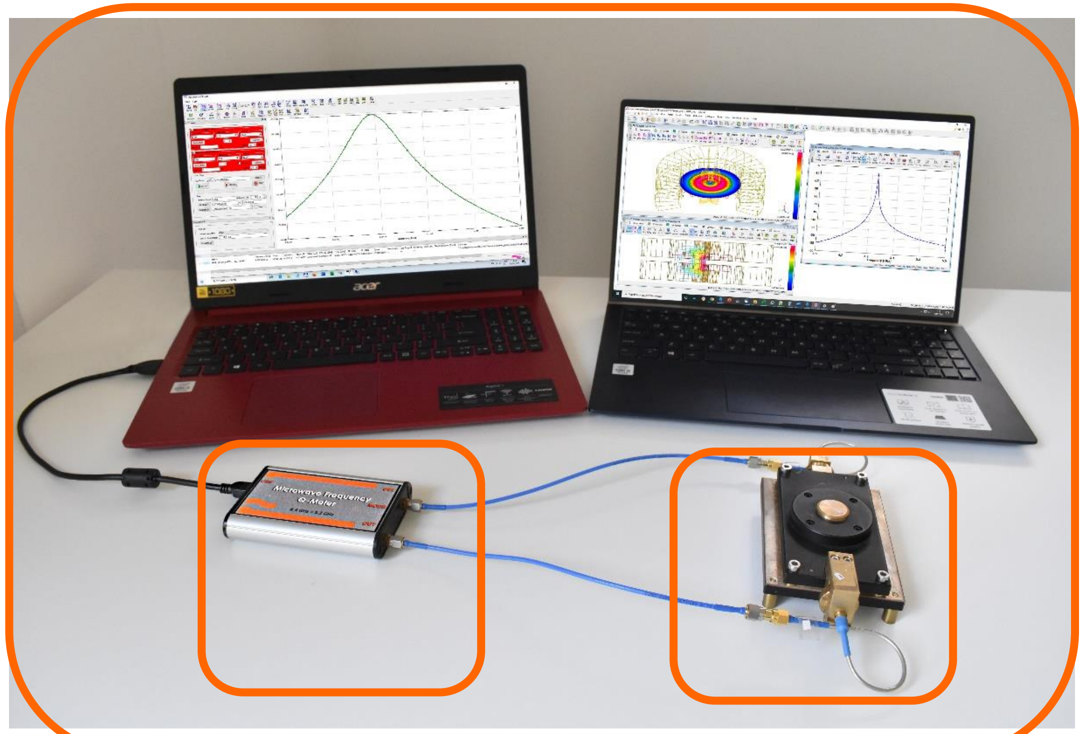
Split-Post Dielectric Resonator method – as implemented by QWED

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

$$\frac{f_e - f_s}{f_e} \approx \frac{h}{2C} \iint_S \left[\varepsilon_s'(x,y) - 1 \right] \left| E(x,y) \right|^2 dS$$

$$\frac{1}{Q_s} - \frac{1}{Q_e} \approx \frac{h}{C} \iint_S \varepsilon_s''(x,y) E^2(x,y)\, dS$$

$$C = \iiint_V \left| E(x,y) \right|^2 dV$$



field assumed invariant in *z*-direction
S is called the DR's *head*
sign ≈ reflects field patern changes caused by SUT

field variation in *z*
field changes due to SUT
manufacturing tolerances

calibration (based on modelling)
minimises efects of:

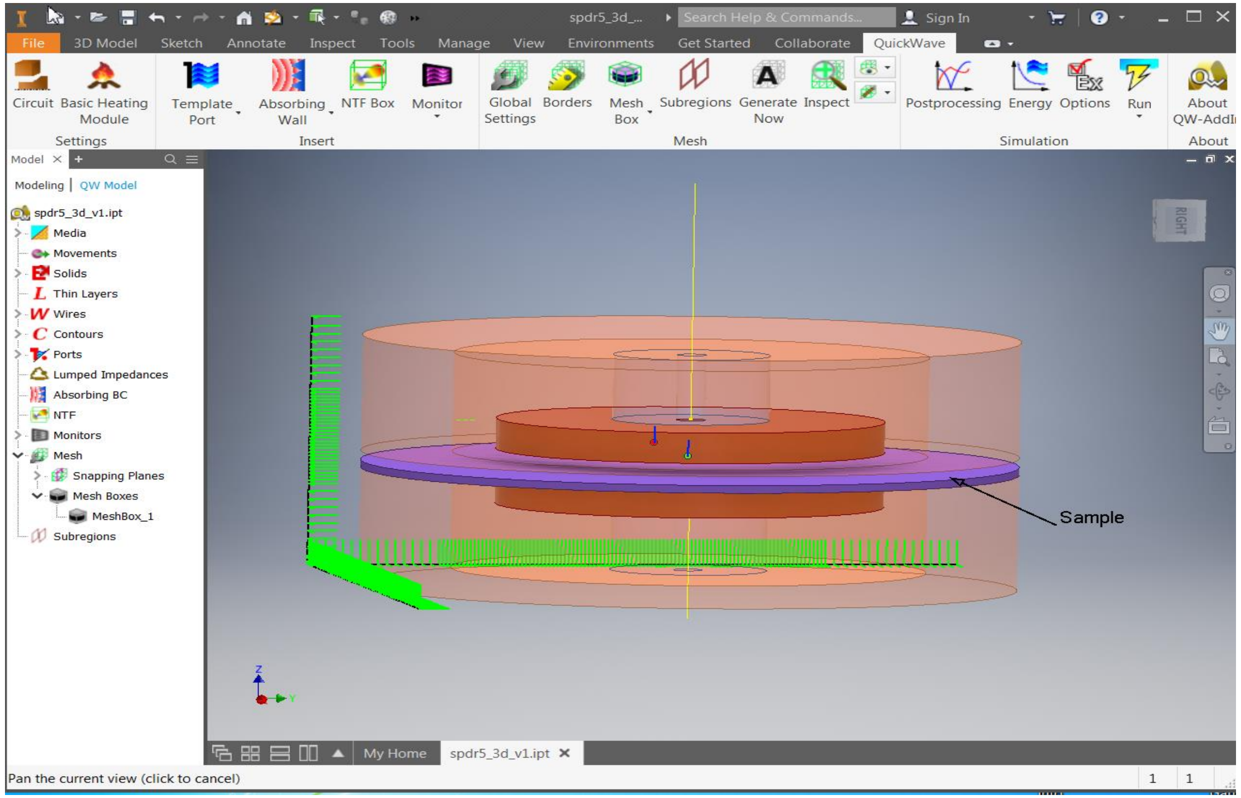
Advantages of QWED's SPDRs for 5G applications

- proven ultra-high acccuracy in GHz range (0.3% for Dk, IEC 61189-2-721:2015)
- dedicated to low-loss materials & thin material sheets
- ease-of-use
- available on the market
- repeatability & reproducibility for 5G confirmed by independent studies

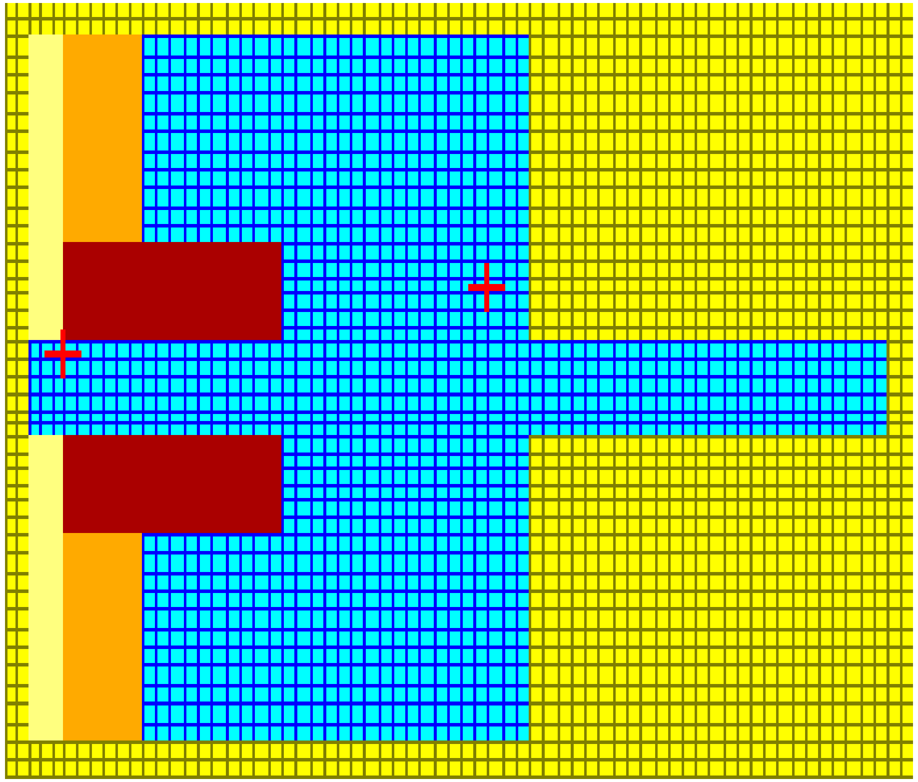
iNEMI International Electronics Manufacturing Initiative

https://www.inemi.org/5g-mat-assessment

QuickWave modelling of SPDR

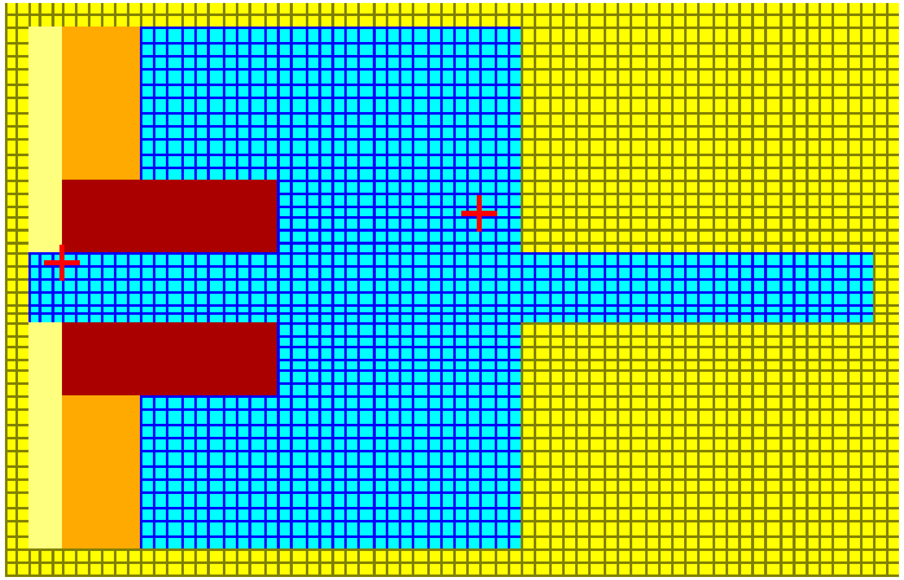


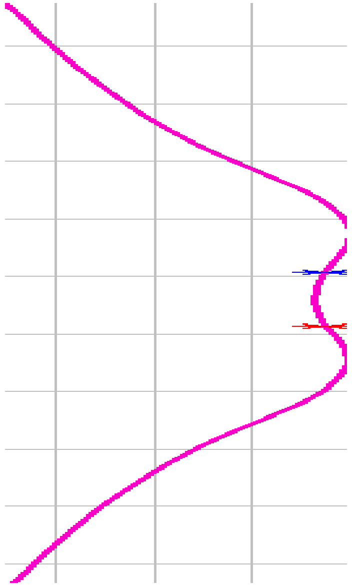
Full 3D model of 10GHz SPDR
in QW-AddIn for Autodesk® Inventor® Software
(common environment for modelling & manufacturing)

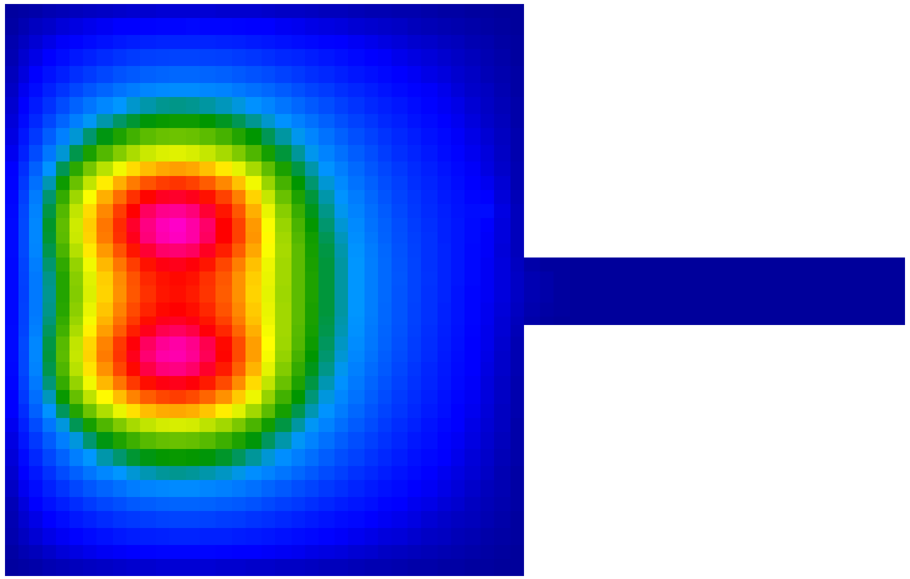


Axisymmetrical 2D BOR model
full EM information
economies in computer effort : 10^3 or more

QuickWave model of SPDR field distribution

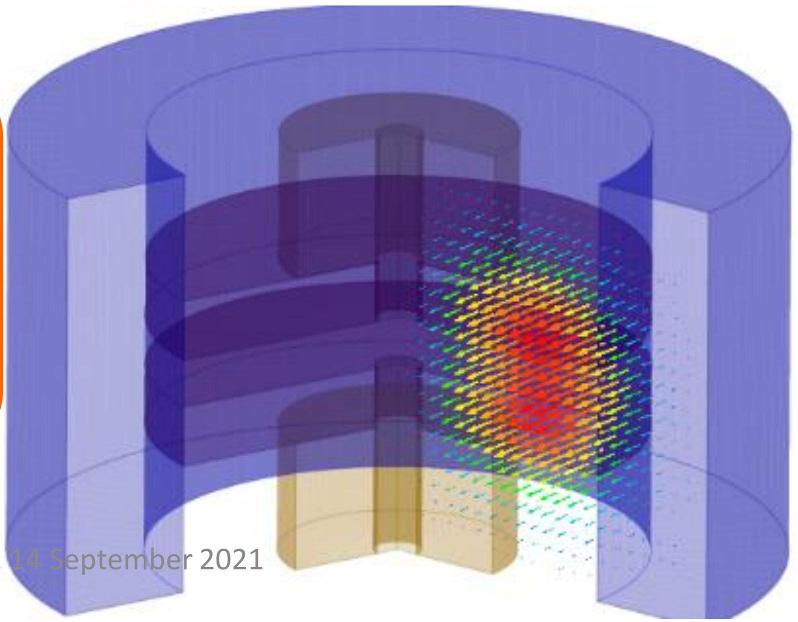




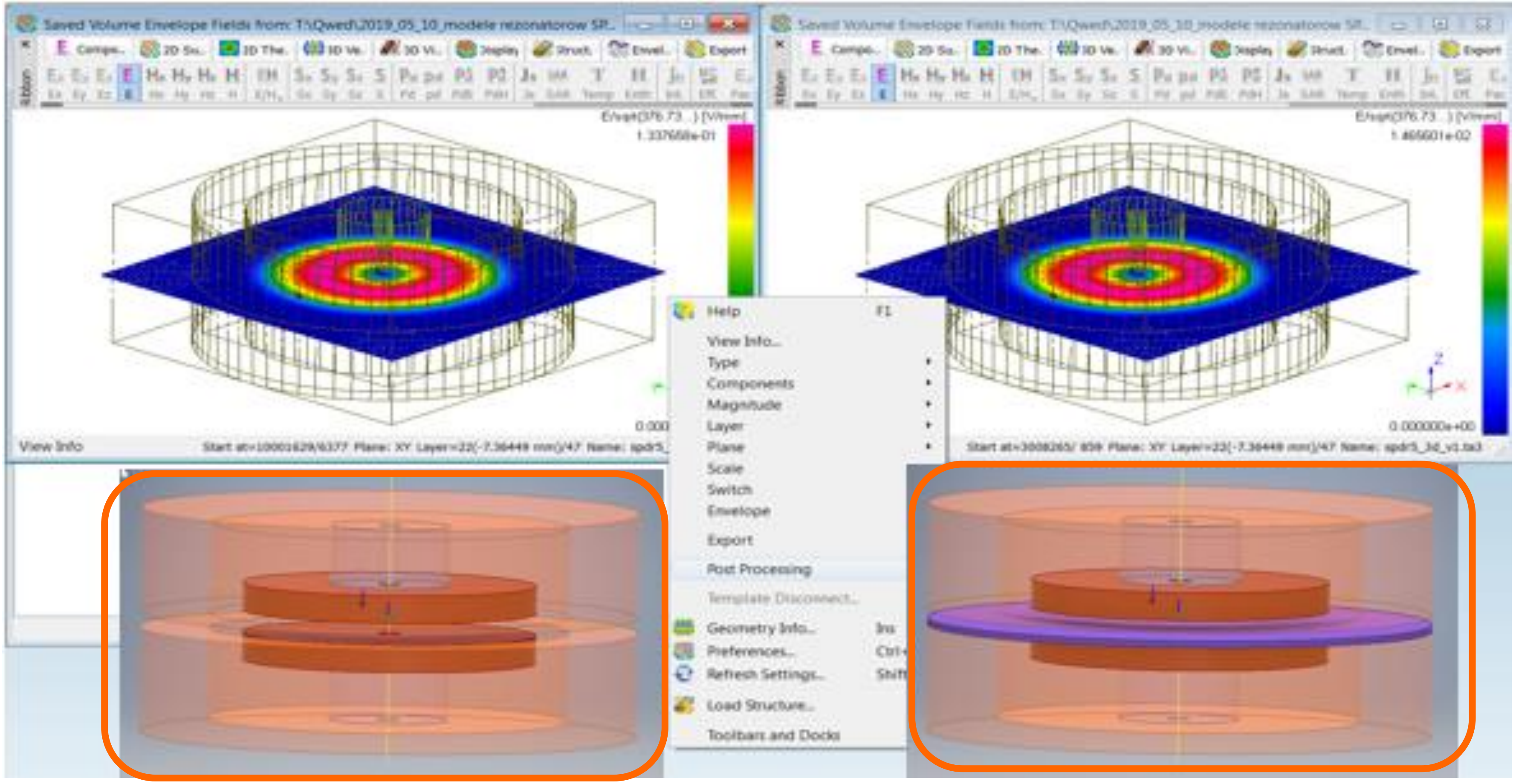


Sample in strong E-field nearly constant between the two posts

- **applicable to thin sheets**
- **low sensitivity to sample positioning along the height of the slot**



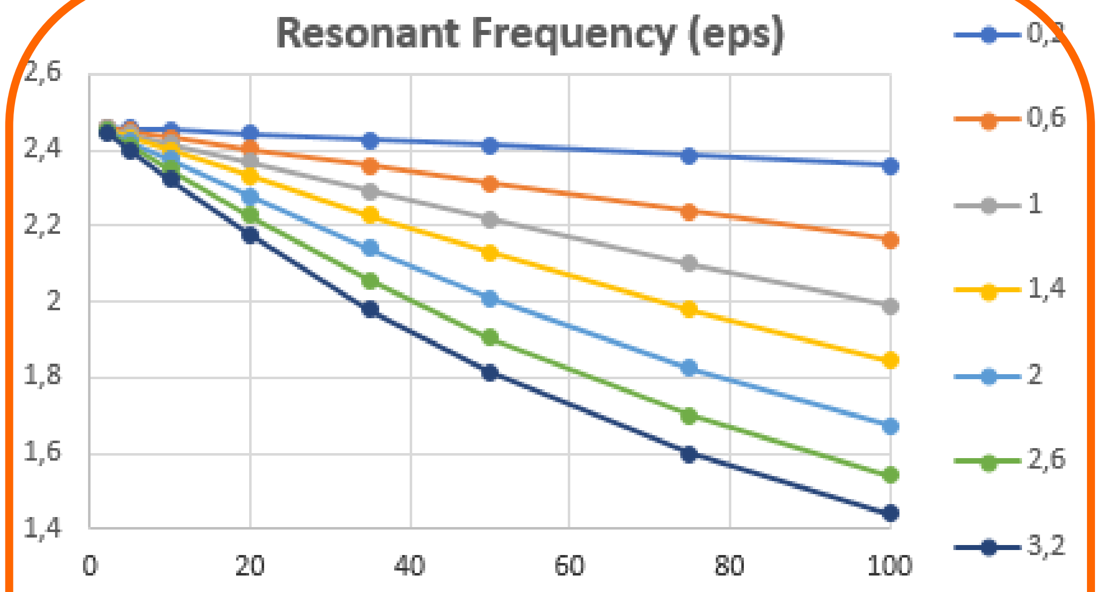
QuickWave model for SPDR loaded with sample



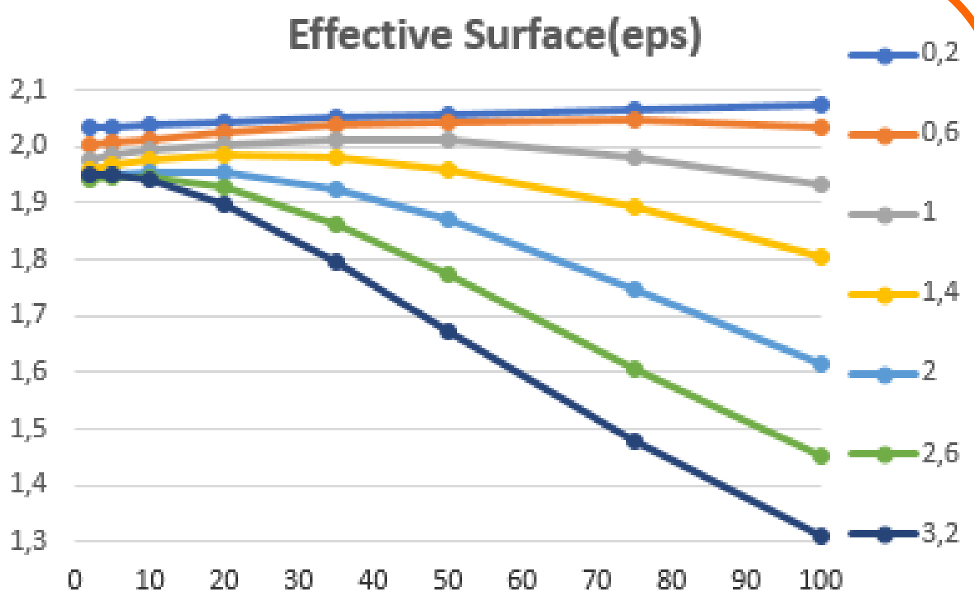
Field patterns remain practically unchanged
by resonant frequencies and Q-factors change,
providing information about SUT material parameters

QuickWave model for SPDR loaded with sample

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

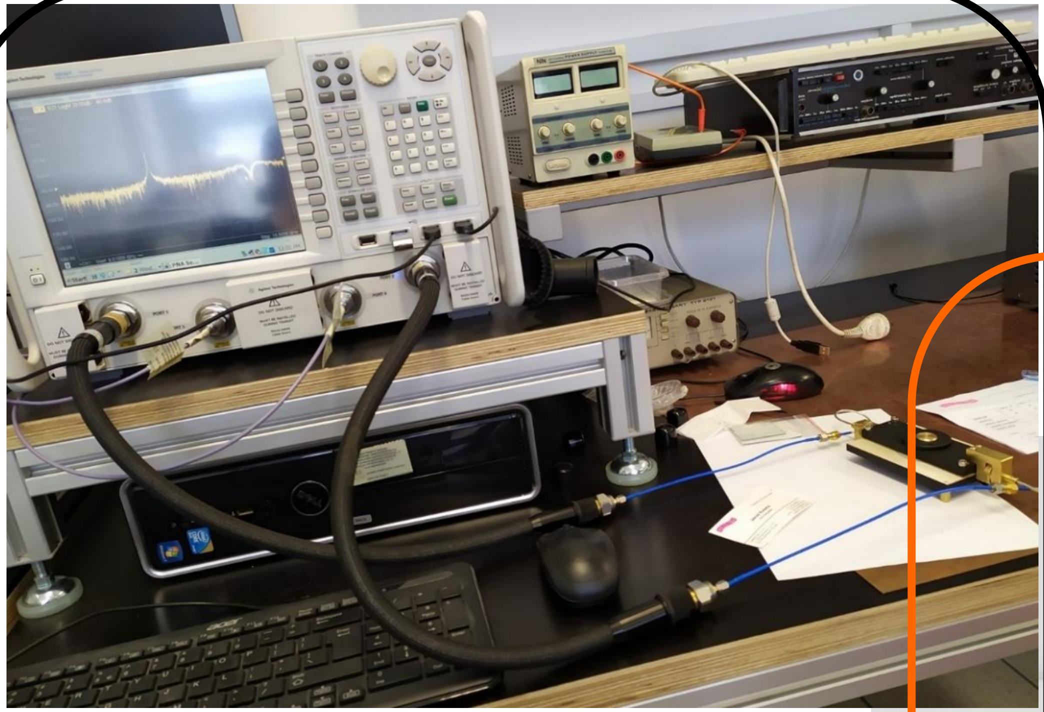


resonant freq. changes are nonlinear
(simple perturbation eqs. are not accurate enough)



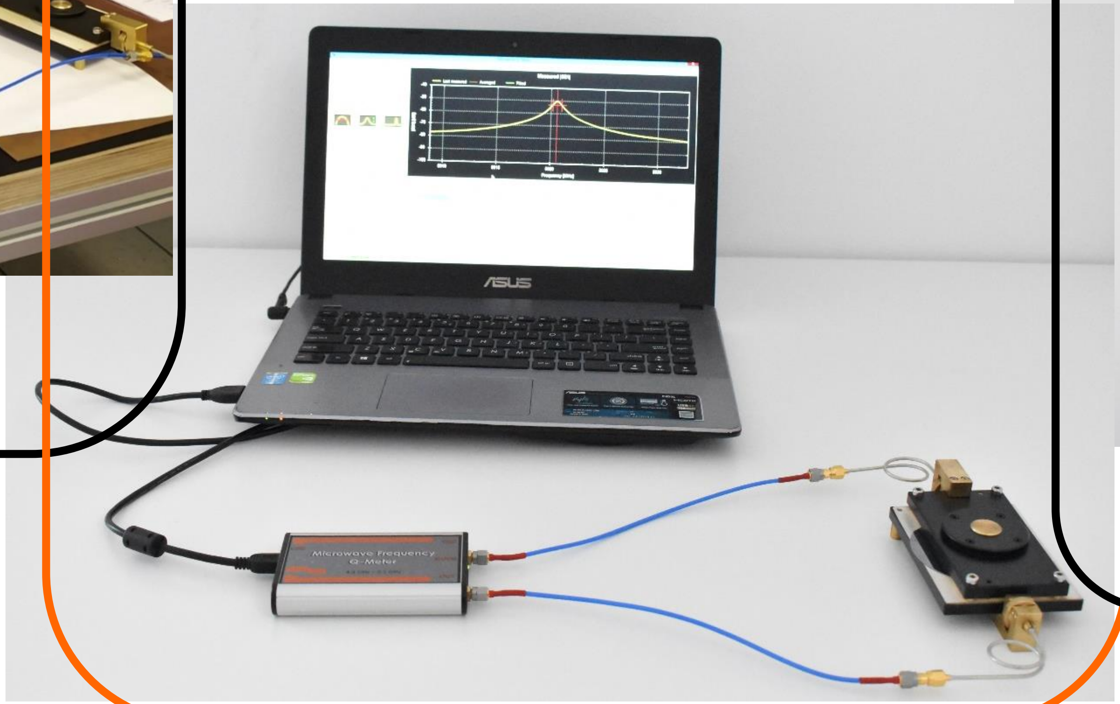
intermediate parameter is defined
leading to slowly-varying functions
tuned in calibration

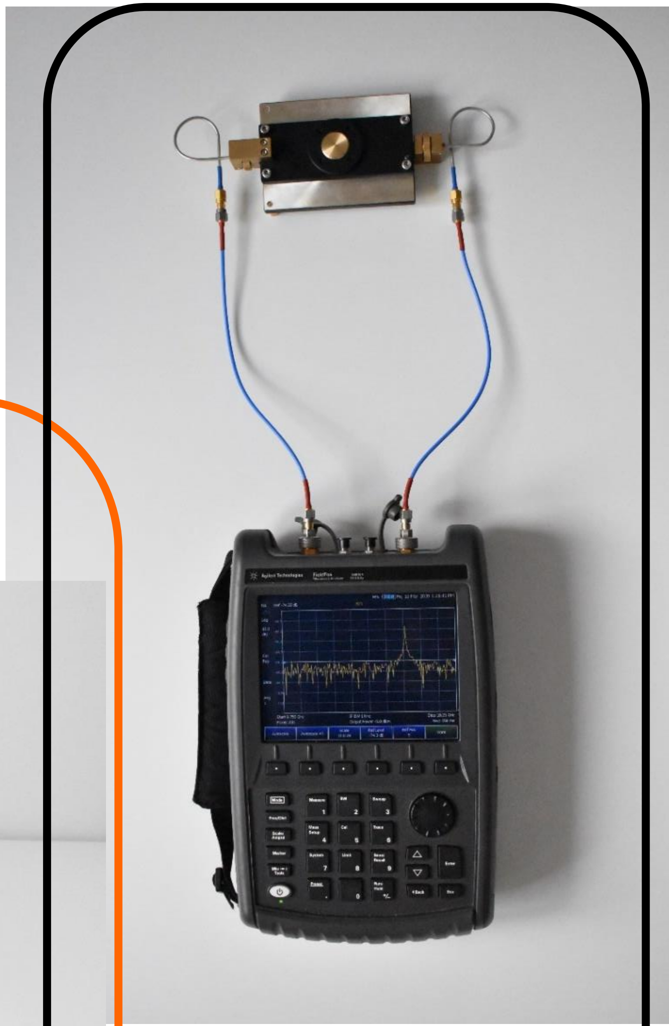
QWED material test-fixtures use in big & small labs...



professional setup
(with laboratory VNA)

low-cost home-office setup
(with QWED's Q-Meter)





portable setup
(with Keysight's FieldFox)

2D SPDR scanner for surface imagining of high-resistivity materials

The first version of QWED's 2D SPDR Scanner for the Imaging of 5G and energy materials
was developed with contributions from KEYSIGHT TECHNOLOGIES within the H2020 MMAMA project,

run in the period 2017-2020 under grant agreement MMAMA No. 761036
of the European Union's Horizon 2020 research and innovation programme (*H2020-NMBP-07-2017*).

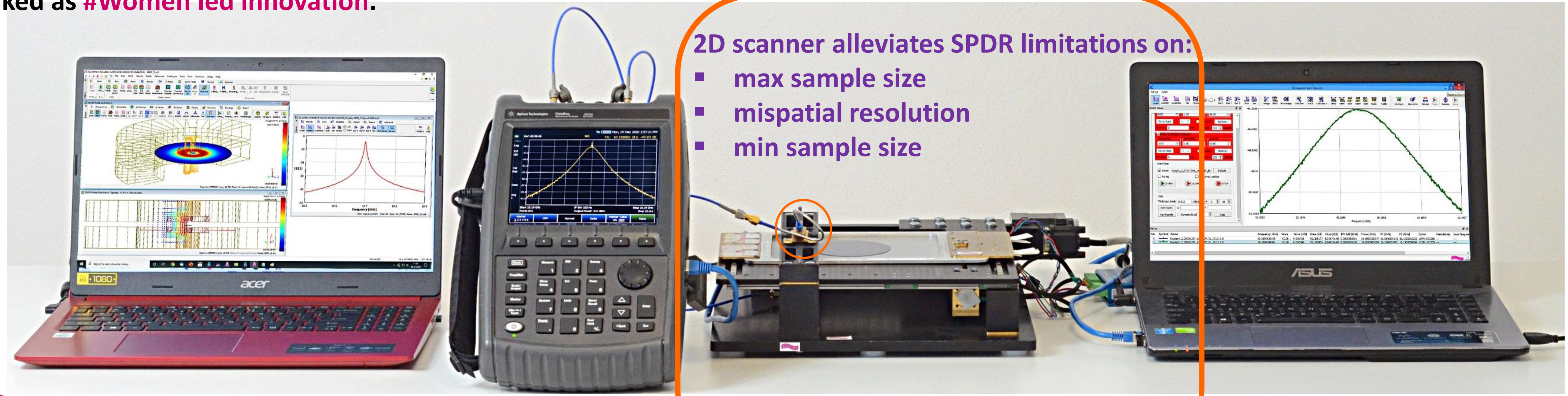
The 2D SPDR scanner - MMAMA version (*see photo below*)
was acknowledged under the European Commission > Horizon 2020> Innovation Radar under the name:

Automatic portable microwave dielectric resonator kit for millimetre scale permittivity evaluation on large samples, comprising QWED SPDR and KEYSIGHT FieldFox.

and marked as #Women led innovation.

CLICK PHOTO to RUN MOVIE

quartz substrate used by MATERIA NOVA
& its measured permittivity map



2D scanner alleviates SPDR limitations on:

- max sample size
- mispatial resolution
- min sample size

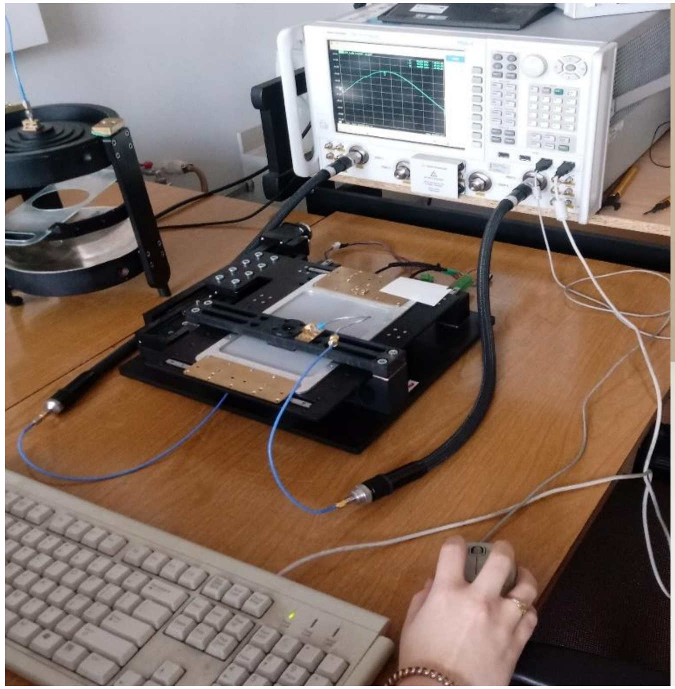
QWED's QuickWave simulation – modelling of the SPDR head which interacts with the sample

active microwave unit hand-held VNA –KEYSIGHT FieldFox

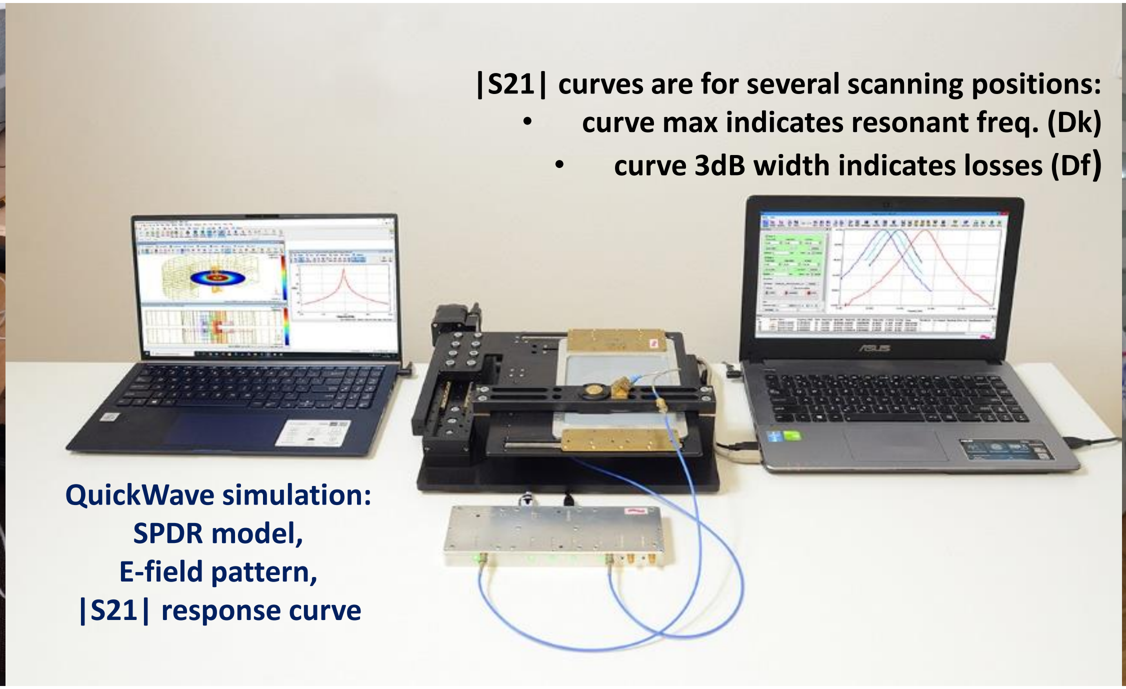
QWED's 2D scanner incorporating 10GHz SPDR head

QWED's Master Unit Control application – steering the scanner and the VNA, and importing modelling data from QuickWave

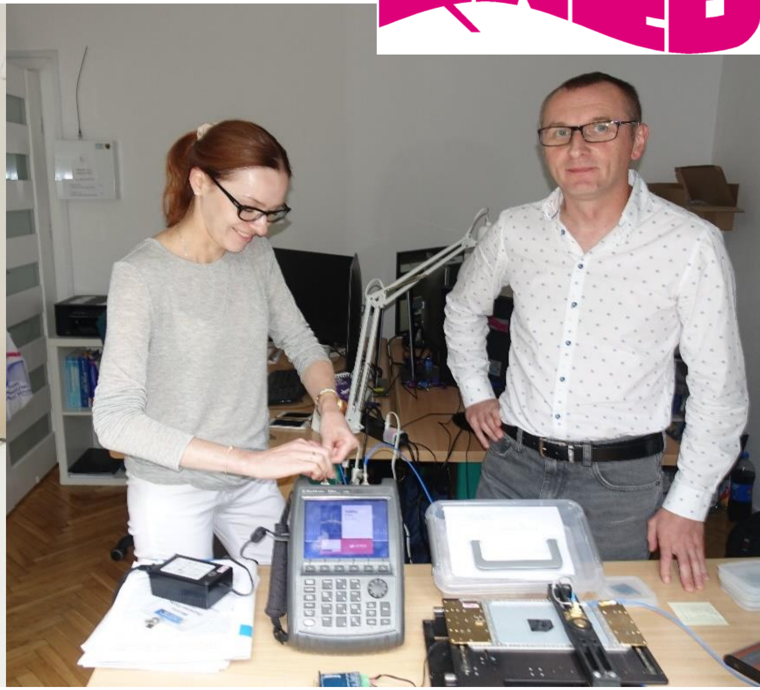
2D SPDR scanner: suitable and affordable for any laboratory



2D SPDR scanner professional setup
(used with a fully-fledged VNA)
in the professional Microwave Laboratory
of the Warsaw University of Technology



2D SPDR scanner MMAMA / NanoBat setup
(used with QWED's Q-Meter)
photo in Home Office



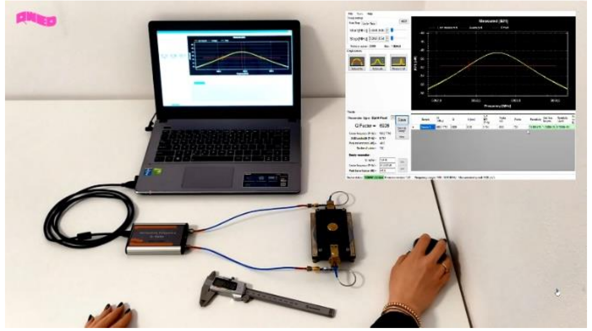
2D SPDR scanner MMAMA setup
(used with FieldFox)
photo in QWED R&D labs

FEATURE	setup with professional VNA	setup with Q-Meter	setup with FieldFox
ACCURACY	**EQUIVALENT** (note: results subject to the user's competences, next row)		
required user competences	PROFESSIONAL	UNDERGRADUATE	GRADUATE
PORTABILITY	NO	YES	YES
COST ca.	200 kEUR	8 kEUR	40 kEUR
UNIQUE ADVANTAGE	-	COMPLETE & CALIBRATED SETUP PURCHASED from a SINGLE VENDOR DIRECT USER SUPPORT by MICROWAVE ENGINEERS & MATERIAL SCIENTISTS	-

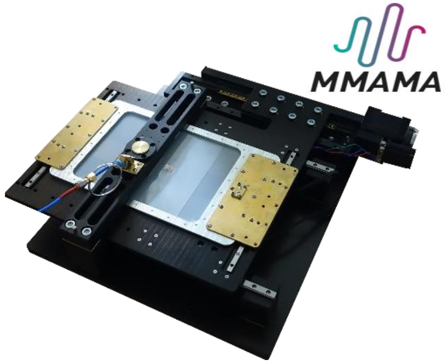
Challenges of characterisation of organic semicomductors for solar cells' applications and QWED response within H2020 MMAMA

QWED test-fixtures applied:

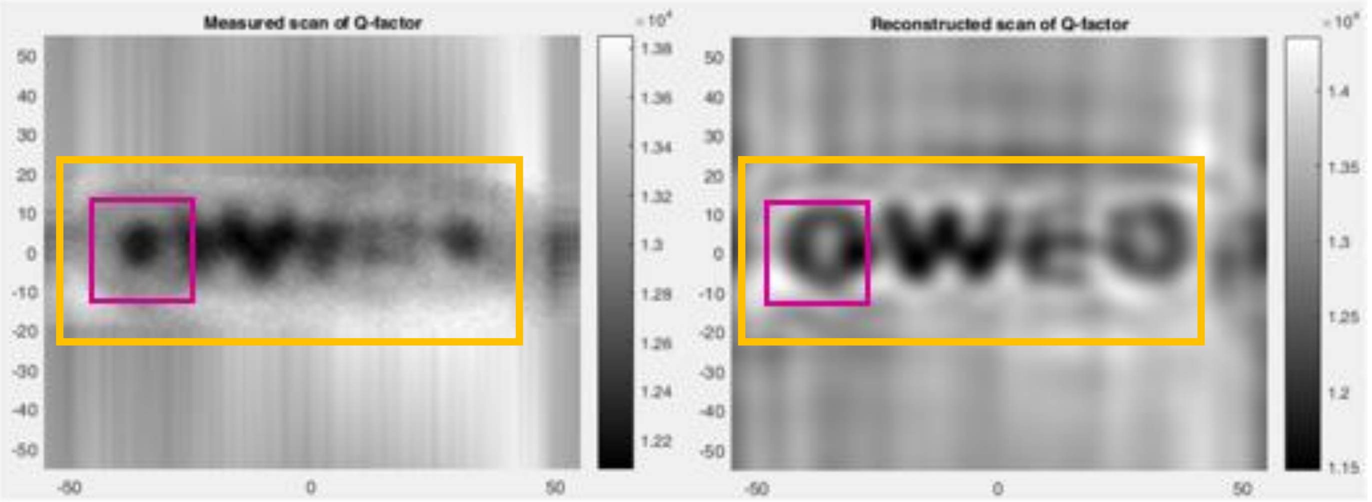
QWED SPDR with Q-Meter



2D SPDR scanner

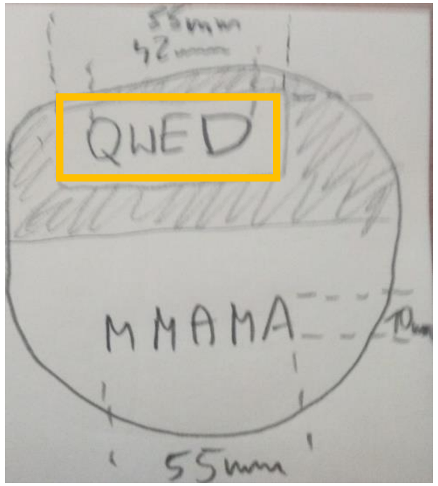


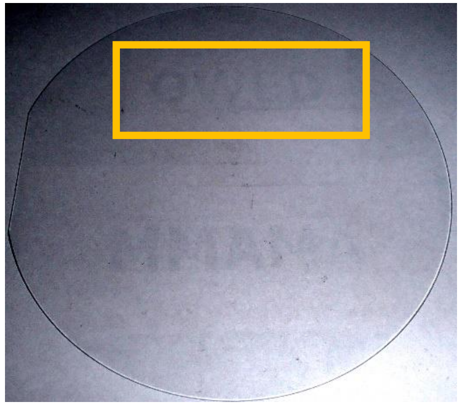
Materials studied in the MMAMA project and QWED results:

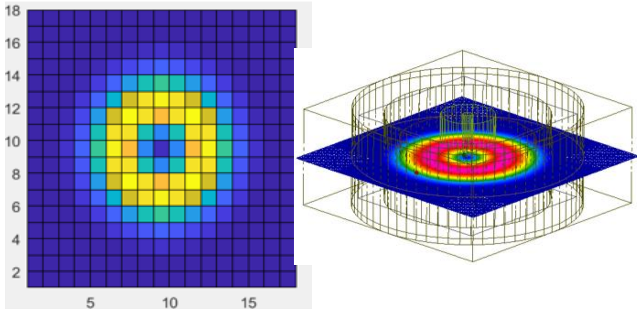


raw image of sample resistivity (measured Q-Factor)

image further post-processed using SPDR field pattern pre-simulated in QuickWave







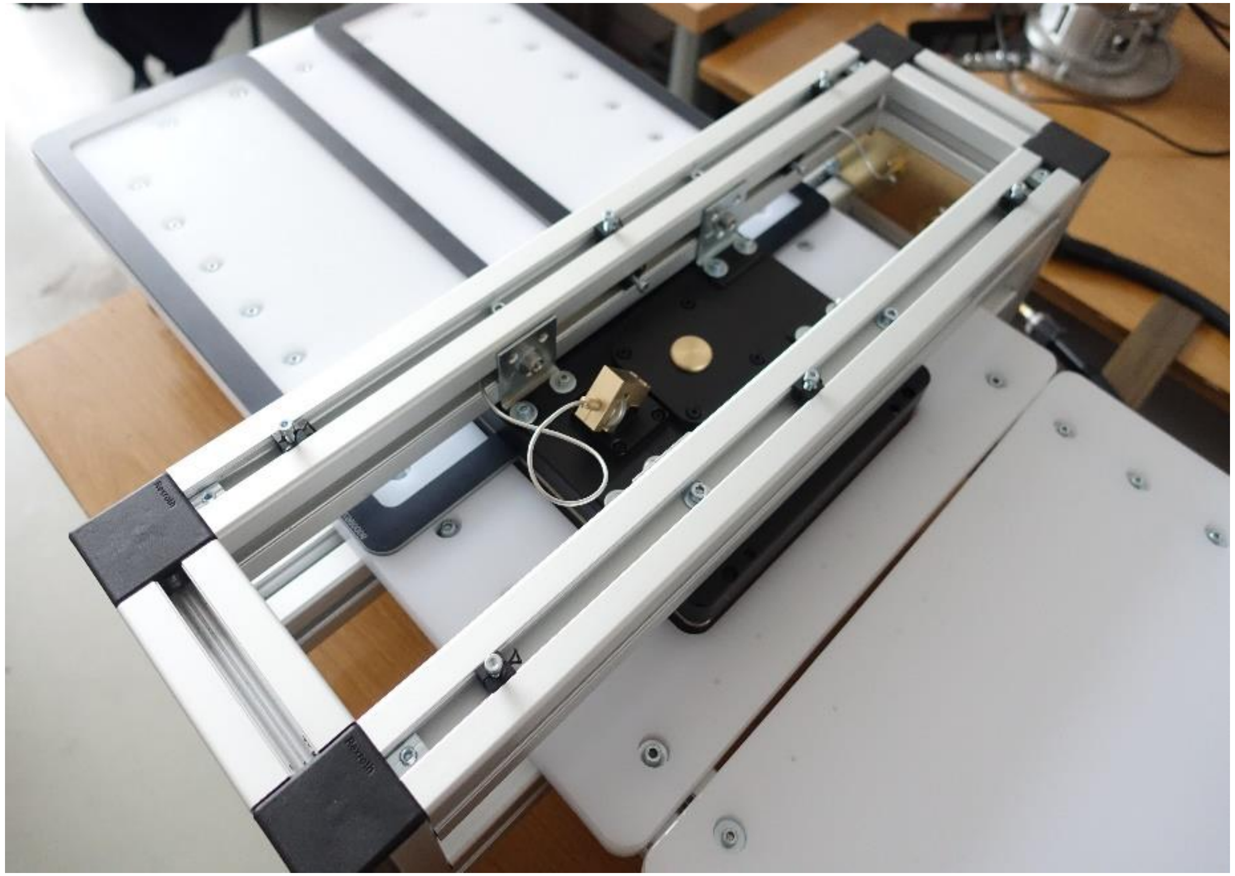
Patterned PEDOT:PSS sample courtesy MateriaNova, Belgium

Extension of 2D SPDR scanner to ultra-large surfaces

The work was performed for a leading producer of household appliances, whose question was inspired by the 2D SDPR scanner - MMAMA setup.

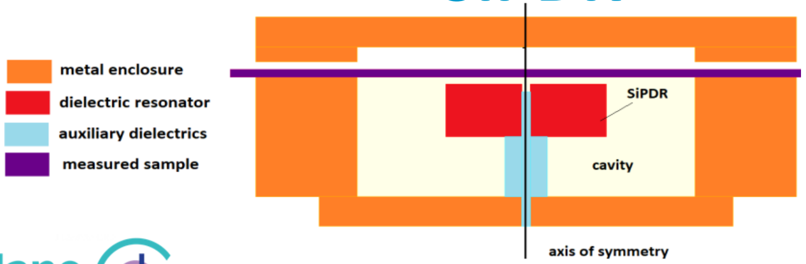
The photo shows a 2D SPDR scanner setup for Larger Surfaces loaded with 2 panes of microwave oven window glass.

The characterisation is needed to ensure that customer safety measures against EM radiation are ensured by the oven design.

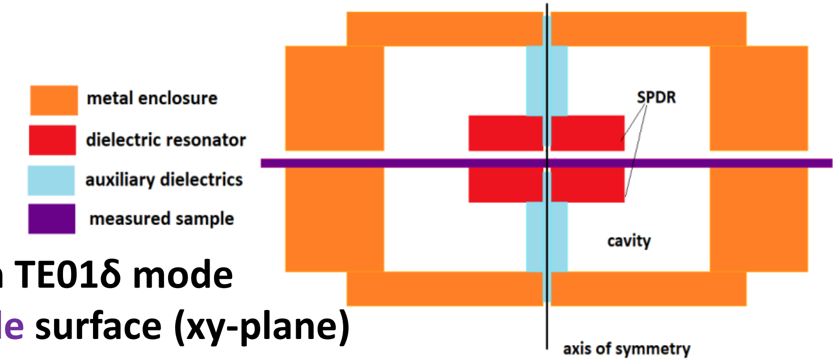


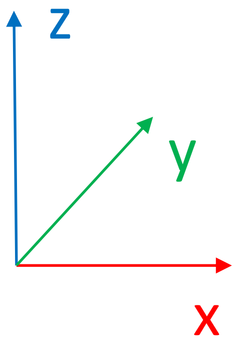
Single-Post Dielectric Resonator method for thin conductive films

SiPDR

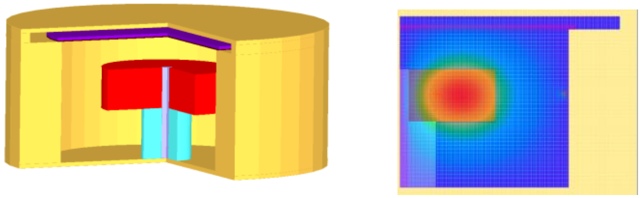


SPDR

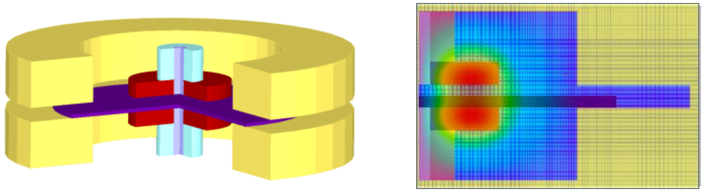




two configurations used with TE01δ mode
E-field tangential (parallel) to sample surface (xy-plane)



E-field distribution in the half cross-section



E-field distribution in the half cross-section

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

weak E-field in sample plane
note: tangential E-field is zero at ground plane;
it increases linearly in –z direction towards sample plane

measurement of very lossy samples possible
but measurement sensitive to sample position in z-direction

measures **resistivity or sheet resistance**
(effects of dielectric constact are negligible)

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

strong E-field at sample plane
note: field nearly constant along the height of the slot

measurement insensitive to sample position in z-direction
but measurement of very lossy samples impossible

measures mainly dielectric constant
(and resistivity or sheet resistance, if sufficiently high)

2D SiPDR scanner for conductive films

Compared to the MMAMA exploitable result, in NanoBat the SPDR unit is replaced by a modified SiPDR, which allows for the imaging of conductive sheets. Mechanical design and scanner control application are modified accordingly.

Mechanical design of 2D SiPDR scanner

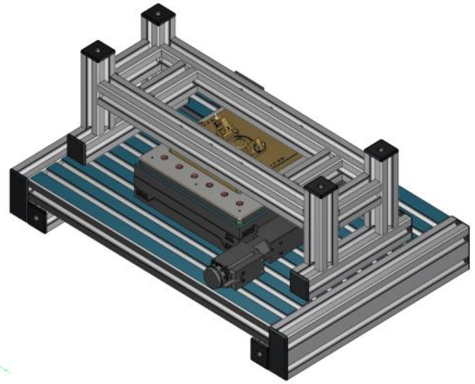
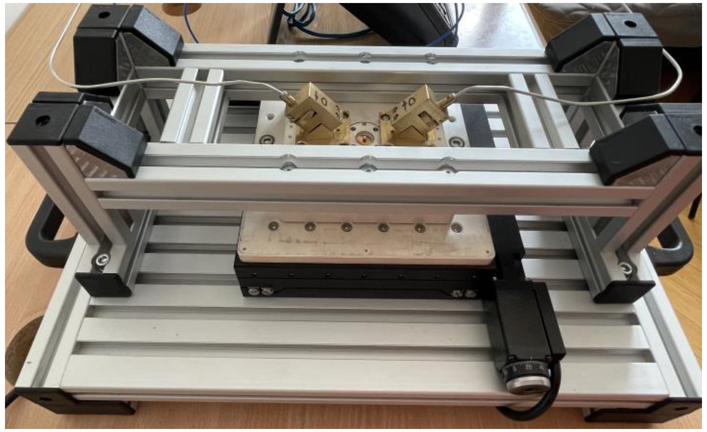


Photo of 2D SiPDR scanner

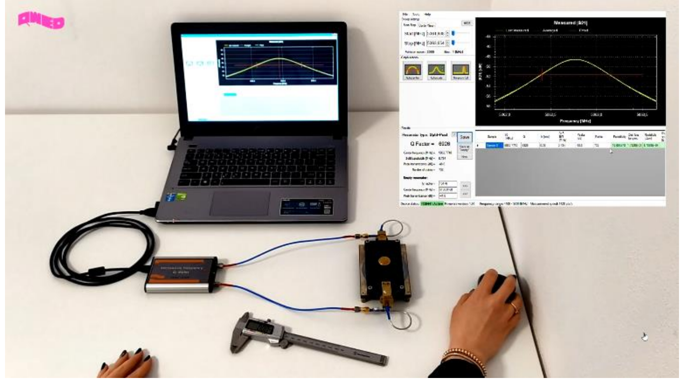


2D SiPDR scanner – NanoBat setup (with KEYSIGHT FieldFox)

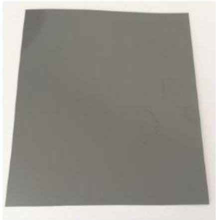
QWED's 2D SiPDR scanner *Keysight's FieldFox* *QWED's Scanner Unit Control application*

Application of SPDR and SiPDR for energy materials

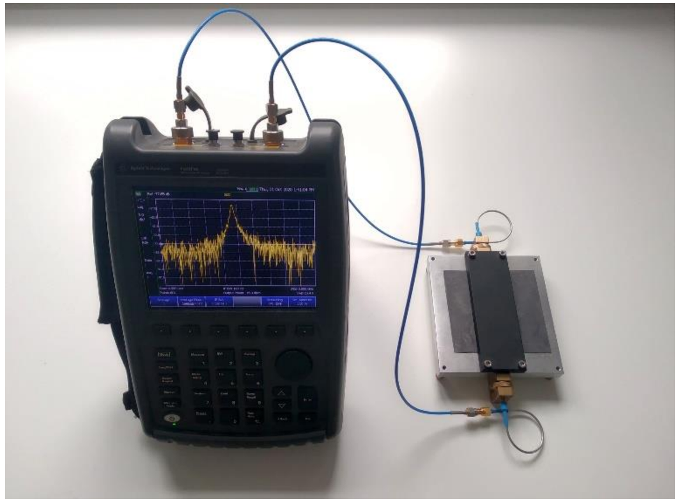
Application of stand-alone SPDR & SiPDR to graphene anodes & substrates from Pleione (Greece) – characterisation @ 2.45, 5, 10GHz; material used in batteries



Dielectric substrates
(*PLEIONE, Greece*)



Sample	2.45 GHz		10 GHz	
	Dielectric constant	Loss tangent	Dielectric constant	Loss tangent
Quartz	4.42	0.000202	4.41	0.000164
Polymer	4.90	0.27403	5.49	0.091955



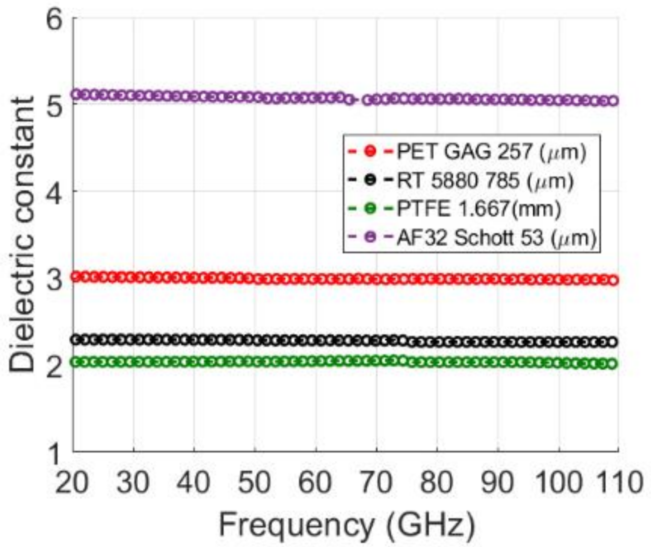
Graphene anodes
(*PLEIONE, Greece*)

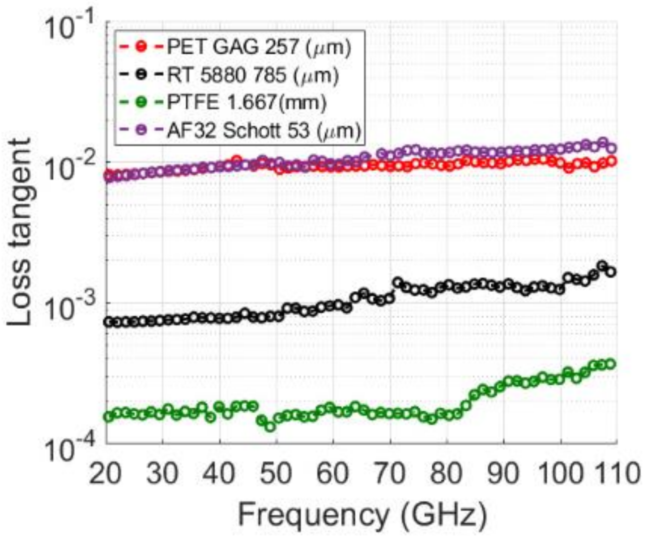
Sample		Surface resistance [Ω/□]
GNP on quartz	Edge	21.485
	Centre	21.020
GNP on polymer	Edge	90.167
	Centre	25.557

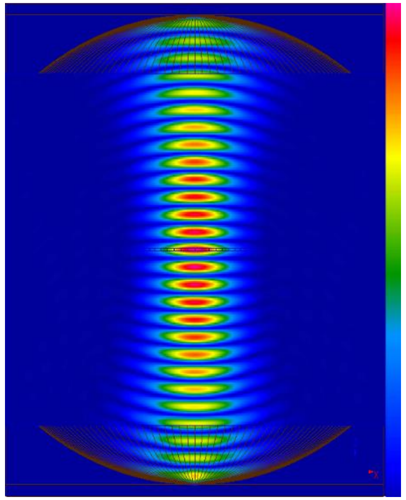
QuickWave design of mm-Wave resonators

- Standard SPDRs are provided for 1.1GHz – 15 GHz
- Custom designs feasible for 20 GHz, further limitation due to wavelength, manufacturing tolerances & losses
- Other resonator solutions (**FPOR, BCDR**) designed & recommended >15GHz

Fabry-Perot Open Resonator for 20-110 GHz







Fully automated wide-band multi-mode measurement: (10-15 min)

- Spectrum: 20-110 GHz
- Dk accuracy: $\Delta\varepsilon/\varepsilon < 0.5$ %
- Df range: $10^{-5} < \tan\delta < 10^{-2}$
- Sample diameter: > 3 inches
- Sample thickness: < 2 mm

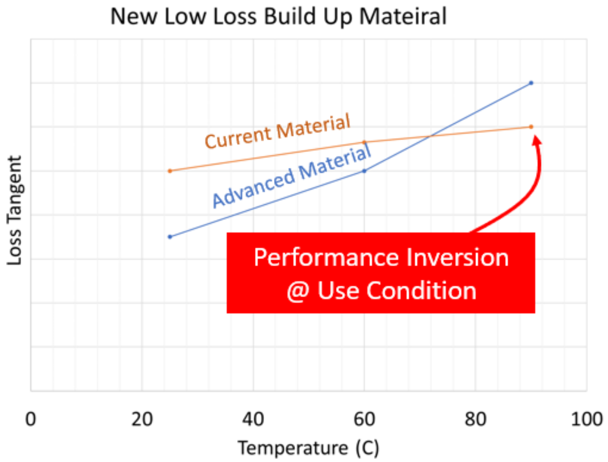
Challenges of materials' characterisation for 5G and QWED positioning on the arena

Motivation & Industry Needs

- Development of new materials requires the ability to evaluate the performance of those materials at use condition
- Errors can be very costly

Cost to switch: ~$2 per CPU substrate

x 20M units = $40M

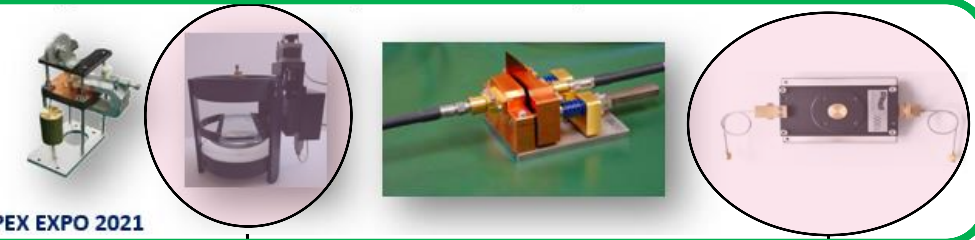


Errors in characterization can cost many $10's of millions for a single program, or worse, induce unexpected product failures

Acknowledgement:
This slide is composed of fragments of the IPC APEX EXPO 2021 presentation by M.Hill (Intel Corp.) and M.Celuch (QWED)

Increasing frequency

- Severe limitations on sample thicknesses
- Non-uniform requirements between measurement systems
- Incompatible sample dimension requirements
- Higher sensitivity to operator techniques

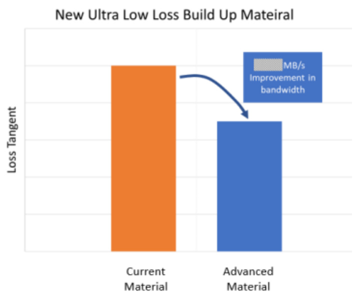


QWED new FPOR for material measurements in 5G / mm-Wave range

QWED classical SPDR, core building block of 2D SPDR scanner

AGC-Nelco
AT&S
Centro Ricerche FIAT-FCA
EMD Performance Materials (Ormet Circuits)
Flex
Georgia Tech
ShowaDenko Materials
IBIDEN Co Ltd
IBM
Intel
Isola
ITEQ
ITRI
Keysight
MacDermid-Alpha
Mosaic Microsystems
NIST
Nokia
Penn State
QWED
Shengyi Technology Company
Sheldahl
Unimicron Technology Corp
Wistron
Zestron

IPC APEX EXPO 2021

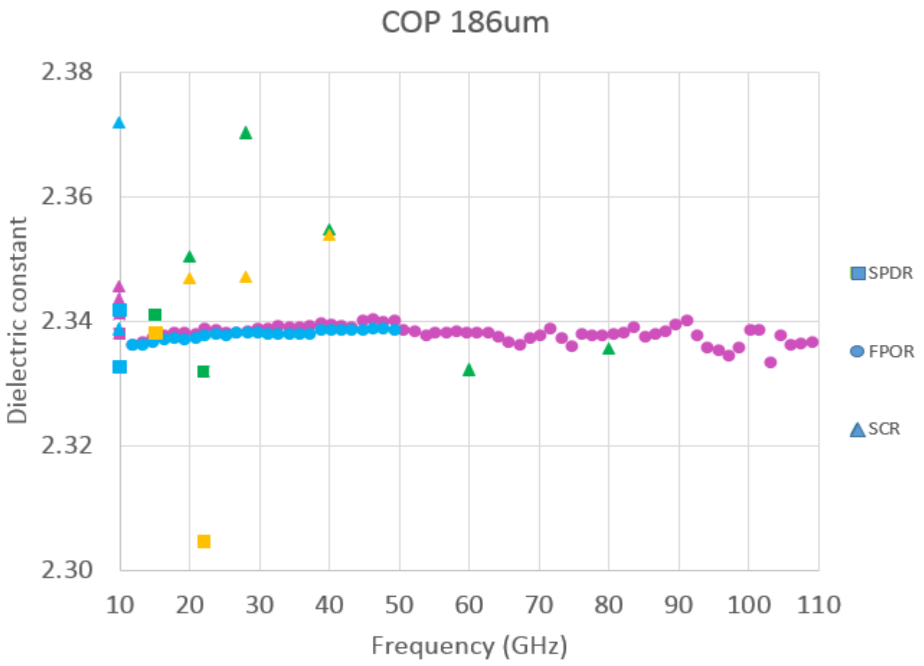


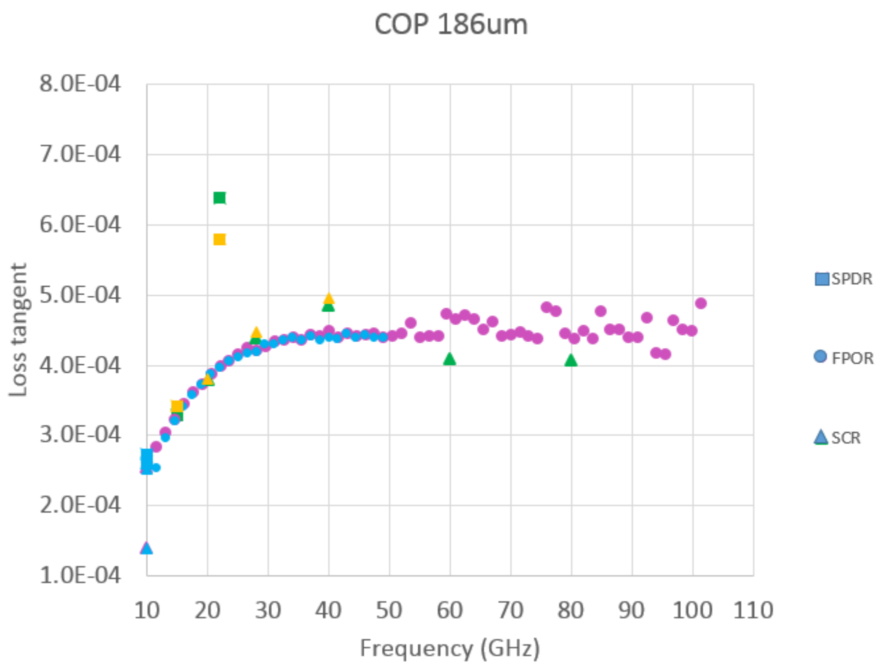
QWED provides 2 out of ONLY 4 resonant test-fixtures considered relevant for 5G materials' measurements by the international industrial iNEMI consortium;
2D SPDR scanner will be applied in Task 4 for the imaging of real-life materials provided by e.g. automotive industry.

Examples of iNEMI round-robin results for 5G materials' characterisation

Cyclo Olefin Polymer coupon (COP; from Zeon) of nominal thickness 186 µm cut into 40 samples and circulated between 10 labs; over 1500 measurements

Included here: 112 representative results for 4 samples (diferent colour) in 3 types of GHz resonators (see legend)





Excellent consitency.

- **Dk** spread, after removing three outliers, is **below 1%** (below **3%** including outliers, traced back to non-standard SPDR unit for 20GHz),
- **repeatability**, defined as three time standard deviation to average ratio for 16 consecutive measurements, did not exceed **0.5%**,
- at mm-Waves Dk fluctuations below 0.1% ; **Df** is 2x higher that at 10 GHz

after: M. Celuch, M.J. Hill, T. Karpisz, M. Olszewska-Placha, S. Phommakesone, U. Ray, B. Salski, "*Bridging the materials' permittivity traceability gap for 5G applications*", IEEE AP-S 2021, Dec.2021 - accepted version.

QuickWave modelling EM field interaction with tissues (for 5G safety studies)

Recent research on 5G safety
June 2020

Absorption of 5G Radiation in Brain Tissue as a Function of Frequency, Power and Time

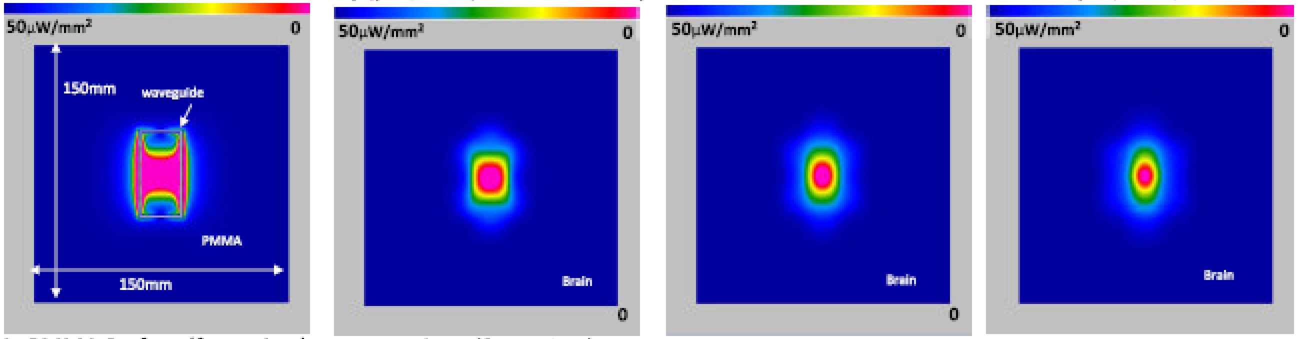
IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

DAVID H. GULTEKIN[1,2] AND PETER H. SIEGEL[2,3,4], (Life Fellow, IEEE)
[1]Zuckerman Mind Brain Behavior Institute, Columbia University, New York City, NY 10027, USA
[2]THz Global, La Cañada Flintridge, CA 91011, USA
[3]Jet Propulsion Laboratory, National Aeronautics and Space Administration, Pasadena, CA 91109, USA
[4]Department of Electrical Engineering, California Institute of Technology, Pasadena, CA 91125, USA

QuickWave modelling applied to interpret laboratory experiments with bovine tissue irradiation

4 GHz

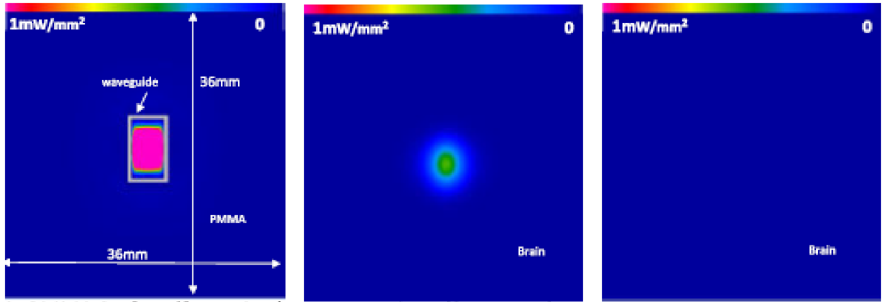
Simulated Surface Power Density (μW/mm²) at **4 GHz** vs. Depth in Brain Tissue. LINEAR SCALE: Pink=50μW/mm²; Blue=0



At PMMA Surface (front view) | 1mm deep (front view) | 6mm deep (front view) | 11mm deep (front view)

39 GHz

Simulated Surface Power Density (μW/mm²) at **39 GHz** vs. Depth in Brain Tissue. LINEAR SCALE: Pink=1mW/mm²; Blue=0

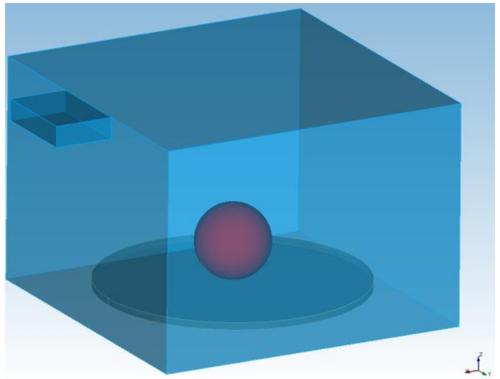


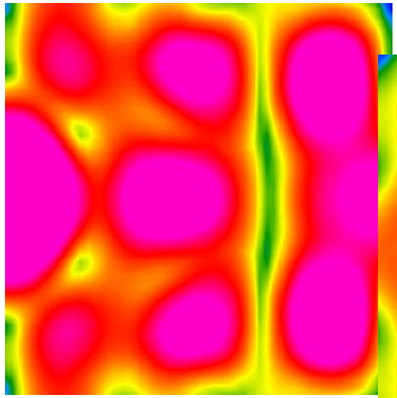
At PMMA Surface (front view) | 1mm deep (front view) | 6mm deep (front view)

Using 1W of incident power,
an average power density of 138, 613 and 16 578 W/m2 (at 1.9, 4, 39GHz, respectively)
is derived at the tissue surface.

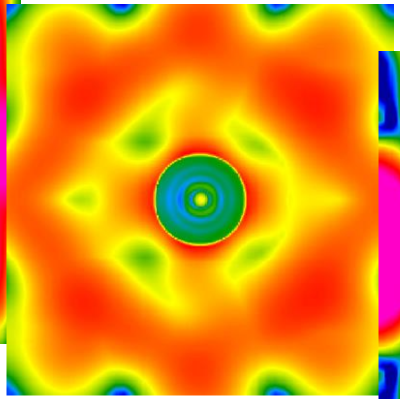
QuickWave modelling EM field interaction with tissues (for food processing & medical applicators)

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

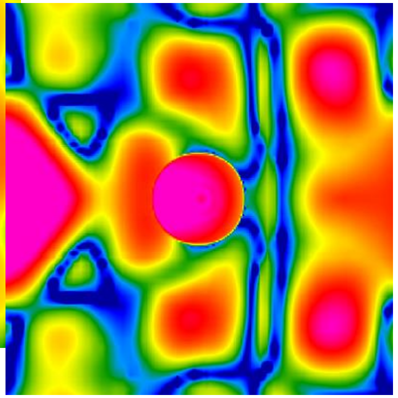




E-field in an empty cavity

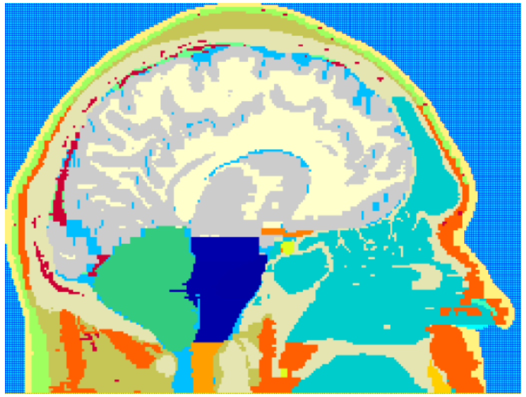


E-field in a loaded cavity

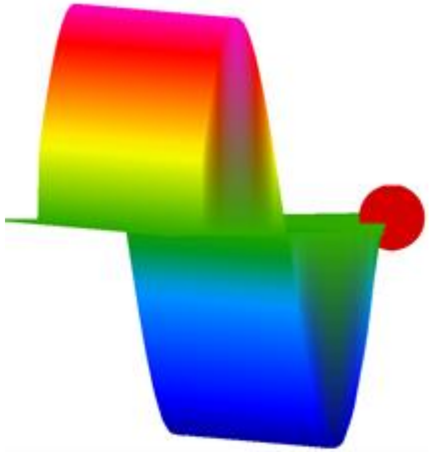


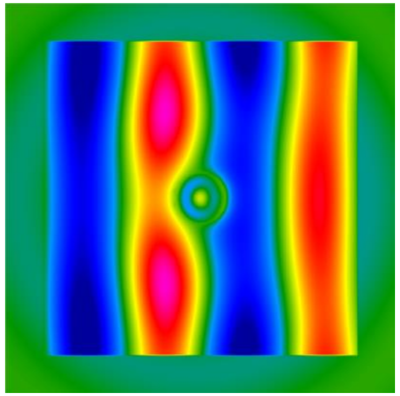
Scattered near-filed in cavity

Detection of inhomogenities in tissues

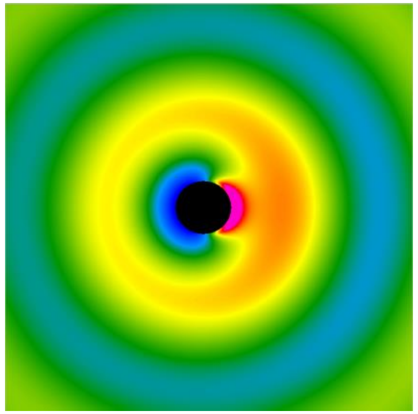


AustinMan model* converted to **QuickWave EM** software for Mälardalen University, Sweden

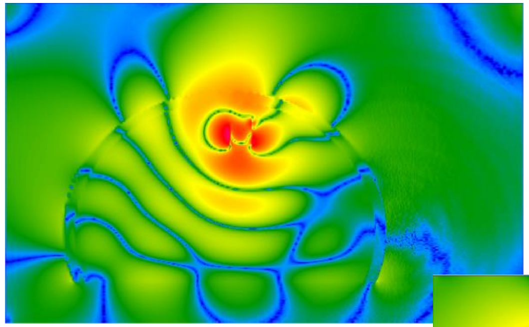


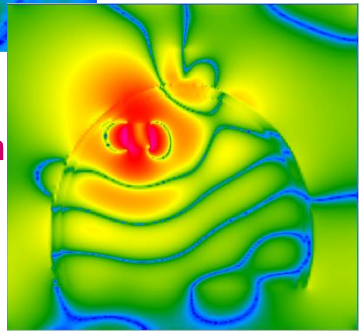


Total field
Focusing by the load
„exploding egg effect”



Diffracted field reveals cause of focusing: circumferential resonance





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

QWED

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

QuickWave Multiphysics Regimes

QW-BHM regimes initiated in 2000 (AMPERE 2000, Springer 2006)

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
Fluid Flow

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

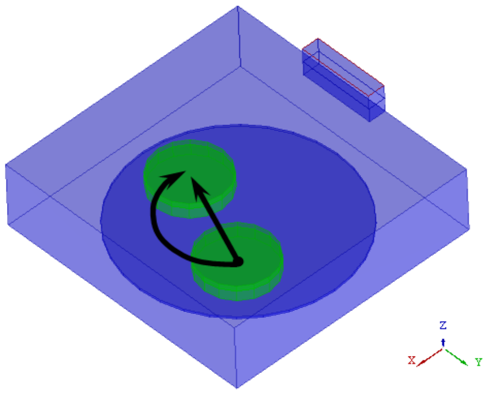
Material and ***thermal parameters*** update in 3D domain $\varepsilon(x,y,z) = \varepsilon[T(x,y,z)]$
$\sigma(x,y,z) = \sigma[T(x,y,z)]$
from *.pmo file

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

material parameters from text files (QWED libraries or user's proprietary data)

```
#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
```

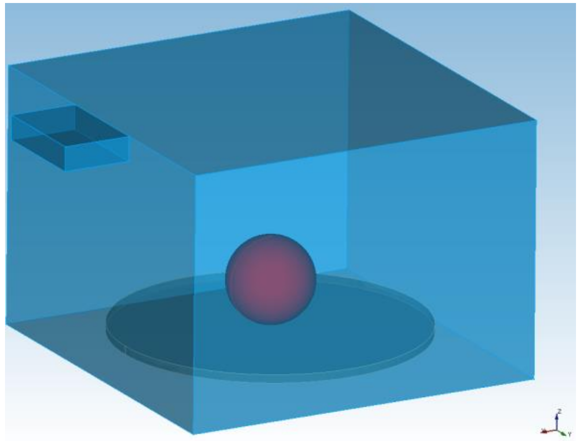
!Temperature # Data deg C	Enthalpy J/cm3	EPa	SIGa S/m	SpecHeat	Density	Ka
-20	0	4.9	0.064	2.21	1.06	0.0069
-15	14.0	5.5	0.093	2.21	1.06	0.0069
-10	34.4	6.1	0.153	2.21	1.06	0.0069
-5	71.4	12.3	0.573	2.21	1.06	0.0069
-3	110.4	22.0	1.118	2.21	1.06	0.0069
-2.2	144.4	30	1.636	2.21	1.06	0.0069
-1.6	192.4	42	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



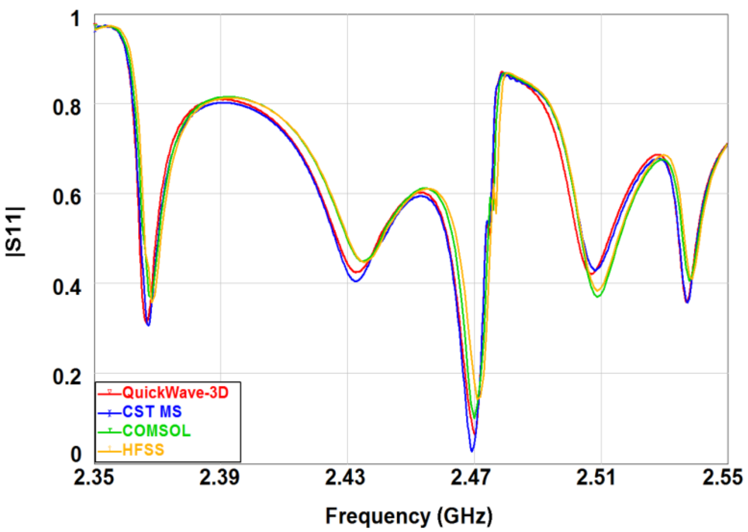
methodology for suppressing spurious modes that may arise from approximating the non-linear problem by a parametric one presented at IEEE IMS 2004

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

Simple microwave heating benchmarks & microwave heating phenomena studies*



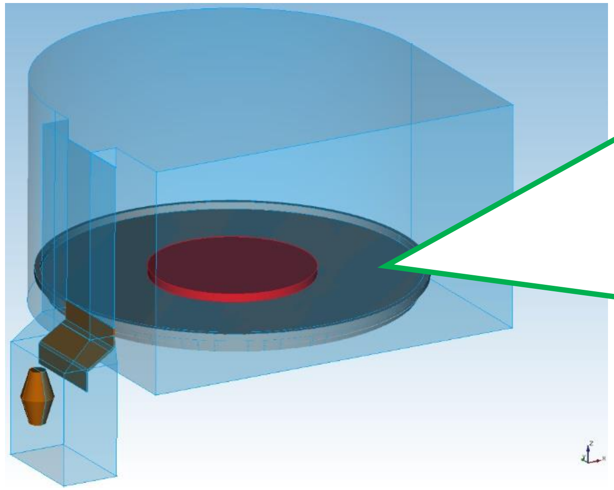
- heat transfer & load dynamics
- Load rotation & arbitrary movement during heating
- Source parameters tuning – regime for solid state sources
- Temperature dependence of material parameters



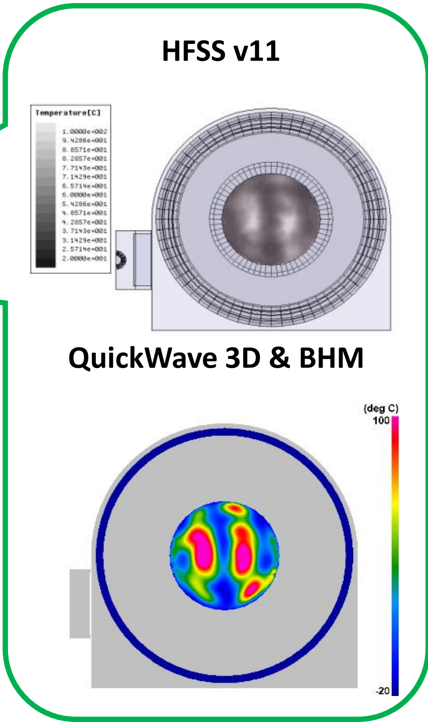
Freezing to file the state of the simulation

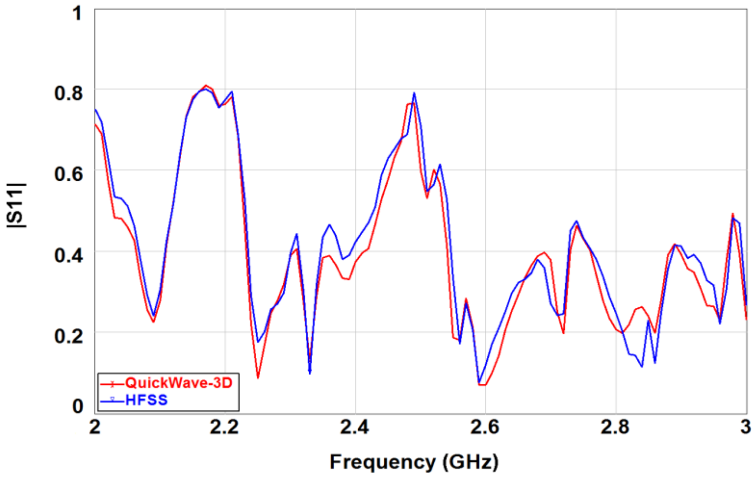
De-freezing on arbitrary computer & at convenient time

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



Courtesy of Whirlpool Inc. – Whirlpool MAX oven



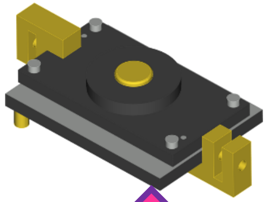


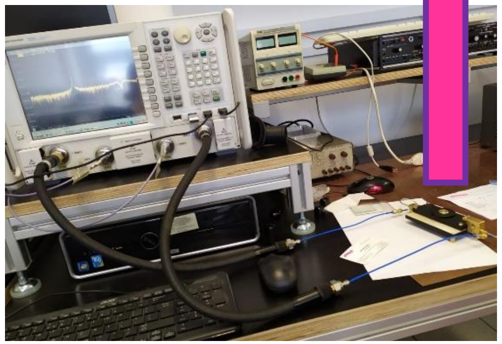
With QuickWave EM computation as fast as 1 min 18s on a low-cost video card – supporting all graphic cards with OpenCL

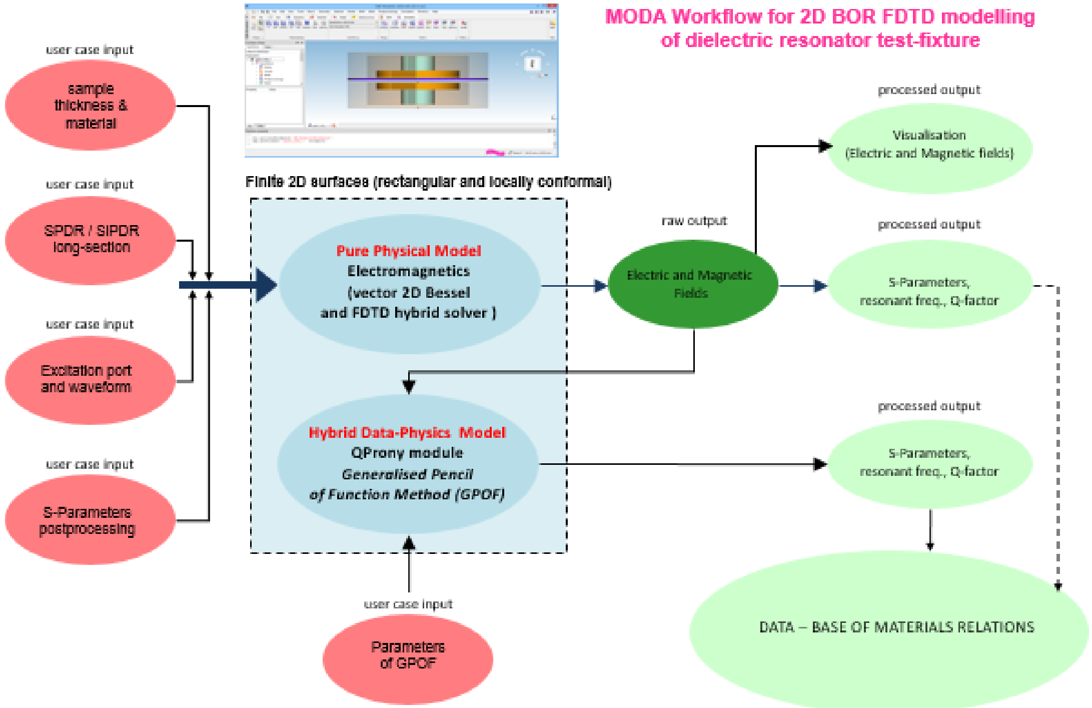
* M.Celuch, P.Kopyt & M. Olszewska-Placha in eds. M. Lorence, P. S. Pesheck, U. Erle, *Development of packaging and products for use in microwave ovens*, 2nd Ed. Elsevier 2020.

EU action: FAIR data & data documentation

MODA

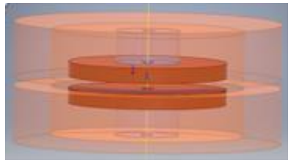




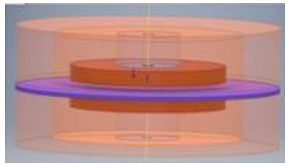


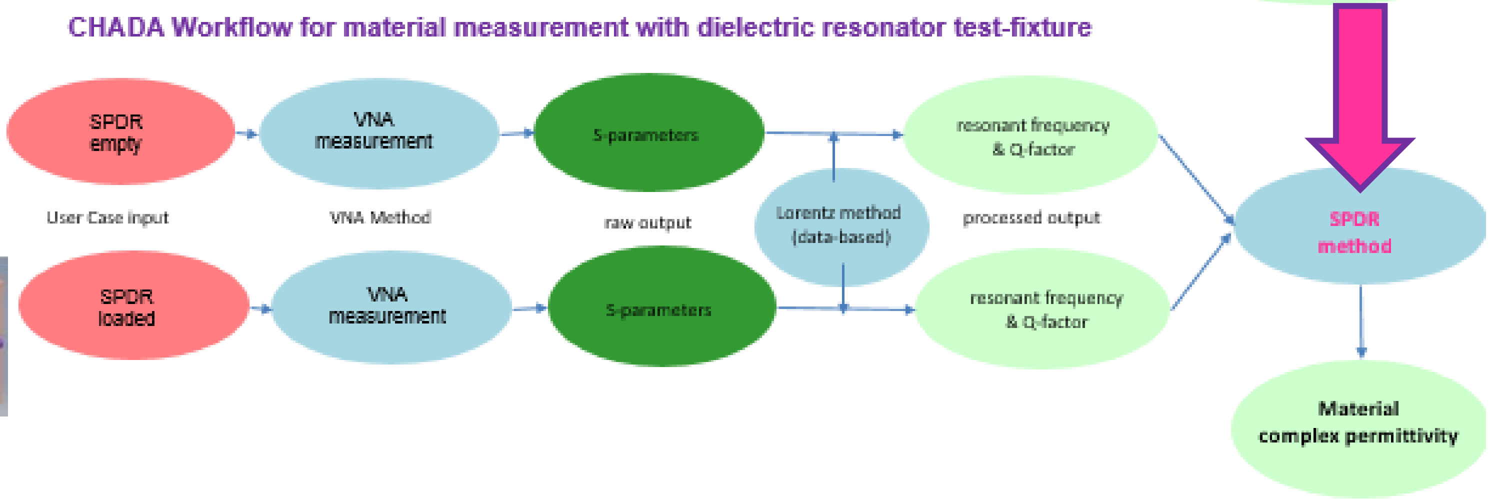
...also provides more physics insight...

input from MODA is ESSENTIAL to complete CHADA!



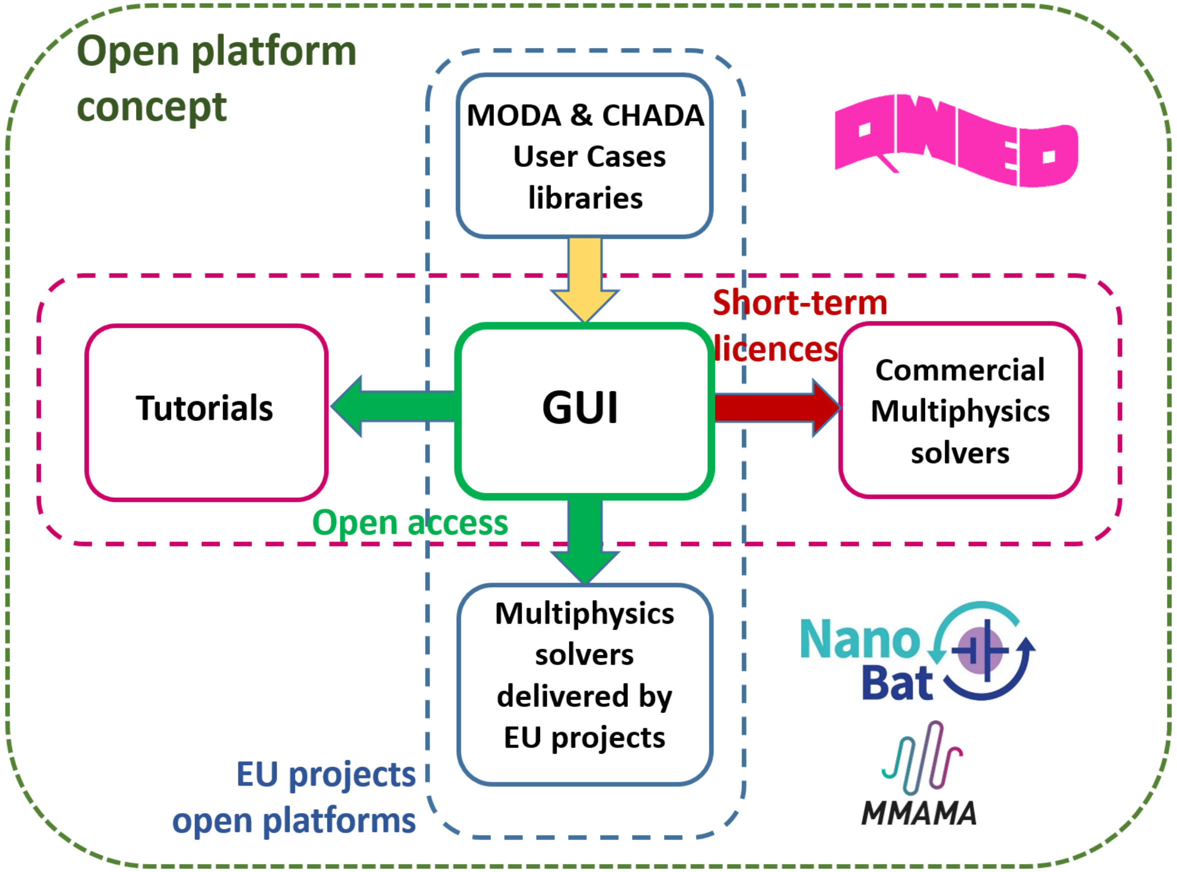
CHADA





QWED Example: twinned MODA + CHADA for SPDR method

EU action: Open Science



- ✓ **Interoperable, licence-free, time-unrestricted CAD-based GUI**
- ✓ **Tutorials** – teaching and project's results dissemination
- ✓ **Library of modelling examples** – documented in MODA format, incl. related CHADAs
- ✓ **Physics-based solvers** - solvers coming from EU projects or other initiatives, willing to provide their tools as open-access.
- ✓ **Data repositories –** linked through reading and processing the data in text files exported by GUI.

EMMC Task Group proposal

Version 2, February 2021

by Marzena Olszewska-Placha and Malgorzata Celuch (QWED)

Focus Area: ***Model Development (also Software)***

Linking and Coupling Computational Chemistry to Electromagnetics

QWED example: Open Platform with MODA & CHADA libraries

Acknowledgements (professional)

QWED's developments of materials' modelling and characterisation technologies

are currently receiving funding from the

European Union's Horizon 2020

research and innovation programme

under grant agreement

NanoBat No 861962.

(website: www.nanobat.eu)

Simulations conducted with QuickWave EM software by QWED.

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

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

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

Scenarios of microwave medical applicators from Per O. Risman, Microtrans AB & Malardalen University, Sweden.

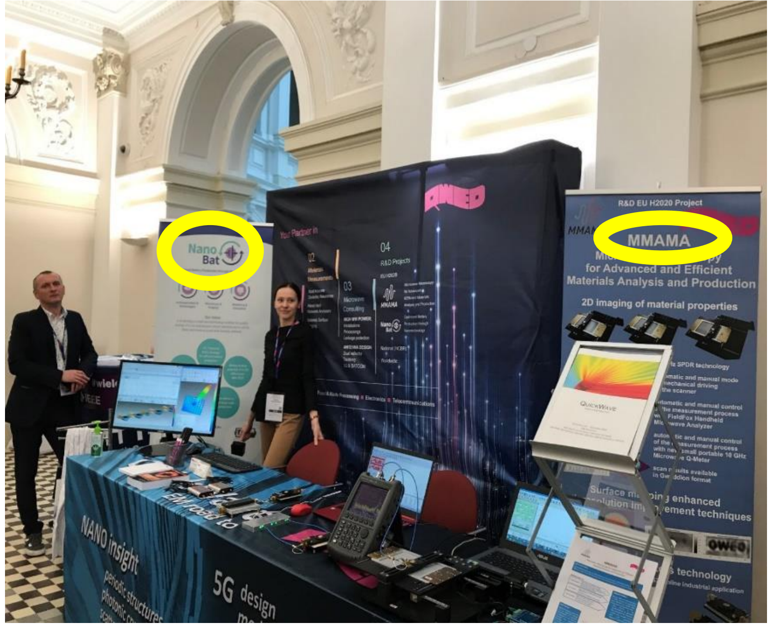
Acknowledgement (educational)

Notwithstanding the importance of university studies, the Speaker's interests in international projects, collaborations, and mere understanding are due to her 2 years at the United World College of the Atlantic (1981-1983), which adheres to the UWC mission *"to make education a force to unite people, nations and cultures for peace and a sustainable future"*, and to always be ready to respond to contemporary needs worldwide.

"How can there be peace without people understanding each other, and how can this be if they don't know each other?"
– Lester B. Pearson, Nobel Peace Prize Lecture 1957

First-ever Women in Microwaves session at MRW

QWED sponsoring the event



Photos from our only physical exhibition since the pandemics started: Microwave & Radar Week held at the Warsaw University of Technology in October 2020.

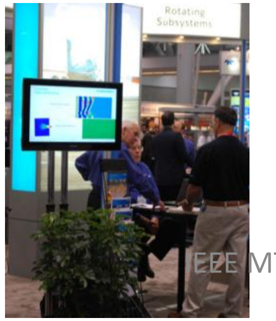
THANK YOU FOR YOUR INVITATION & ATTENTION!

...and hoping to get a chance again to give a live presentation at future (hopefully live) IEEE IMS (QWED IMS booth since 1998)

Philadelpia, 2003

San Francisco, 2006
Agilent promoting QWED's SPDRs

Boston, 2009
QuickWave promoted as Cobham CONCERTO



Tampa, 2014
an experimental solid-state-fed MW oven (with QuickWave) in NXP booth

Philadelphia, 2018