QWED presentation for iNEMI:

EM modelling ↔ materials characterisation

Dr. Malgorzata Celuch,
President & Senior Scientist
Dr. Marzena Olszewska-Placha,
Senior Engineer & Customer Relations

Outline:

1. QWED at a glance
2. QWED concept & synergies
3. QuickWave simulation software by QWED
4. QWED resonators – types & applications
5. QuickWave demo

23 July 2020

QWED *short story* of 23 years +

Microwave reasearch teams at the Warsaw Univ. Tech. in 1980s:
- Wojciech Gwarek (State Prof, IEEE Fellow, recipient of IEEE Microwave Pioneer Award) – microwave design, EM simulations (QuickWave 3D commercialised by ArguMens GmbH)
- Jerzy Krupka (State Prof, IEEE Fellow) – microwave measurments of materials, dielectric resonators (Marie Curie US-Poland projects, collaboratons with NIST)

QWED started operation on 10 May 1997:
- **to bring our scientific results to the market (first focus on EM simulations)**
- **owned & managed by 4 academics from Warsaw Univ. Tech. – MW engineers with complementary perspectives**

First sales for QuickWave EM software licences already in 1997:
- **cosmic research: Saab Ericsson Space (SE), National Radio Astronomy Observatory (VA, US),**
- **domestic microwave ovens (confidential customer),**
- **all triggered by our winning in benchmarks (septum polariser, waveguide, vaccum window, MW heating) to which worlds-leading software participated.**

QuickWave sold as VF Concerto 1998-2008 by Vector Fields – Cobham.

First sales of dielectric resonators in 2000s:
- **SPDRs manufactured and calibrated based on the original designs of J.Krupka,**
- **new designs: custmised for industry and in public co-funded projects,**
- **1000th resonator sold in March 2020.**

QWED has grown autonomously. No external capital. Human capital - our former students. Self-managed.

QWED attributes

EU recognition

THE EUROPEAN INFORMATION TECHNOLOGY PRIZE

Winner


DIPLOMA

BRUSSELS Eureka!

THE BELGIAN AND INTERNATIONAL TRADE FAIR FOR TECHNOLOGICAL INNOVATION

to

Jerzy KRUPKA

Politechnika Warszawska – Wydział Elektroniki i Technik Informacyjnych (Warsaw University of Technology – Faculty of Electronics and Information Technology)

for the innovation

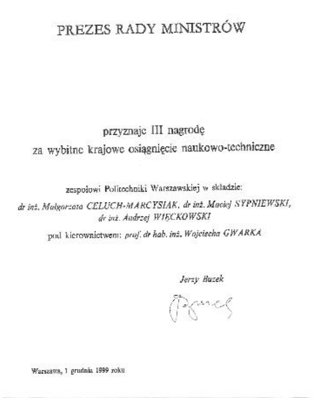
Résonateurs pour des mesures précises des propriétés électromagnétiques de matériaux à bande de fréquence micro-ondes.

Médaille d'or

THE PRESIDENT OF THE INTERNATIONAL JURY

THE PRESIDENT

National recognition


PREZES RADY MINISTRÓW

przyznaje III nagrodę
za wybitne krajowe osiągnięcie naukowo-techniczne

zespołowi Politechniki Warszawskiej w składzie:
dr inż. Małgorzata CELUCH-MARCYSIAK, dr inż. Maciej SYPNIEWSKI, dr inż. Andrzej WIĘCKOWSKI
pod kierownictwem: *prof. dr hab. inż. Wojciecha GWARKA*

Jerzy Buzek

Warszawa, 1 grudnia 1999 roku


PREZES RADY MINISTRÓW

przyznaje

II nagrodę za wybitne krajowe osiągnięcie naukowo-techniczne

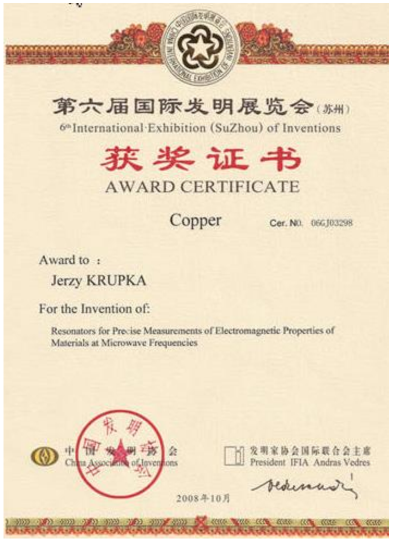
dr. hab. inż. Jerzemu KRUPCE

Donald TUSK

Warszawa, dnia 11 grudnia 2007 r.

Technical excellence

MISTRZ TECHNIKI WARSZAWA


第六届国际发明展览会（苏州）

6th International·Exhibition (SuZhou) of Inventions

获奖证书

AWARD CERTIFICATE

Copper Cer. N0. 06GJ03298

Award to :

Jerzy KRUPKA

For the Invention of:

Resonators for Precise Measurements of Electromagnetic Properties of Materials at Microwave Frequencies

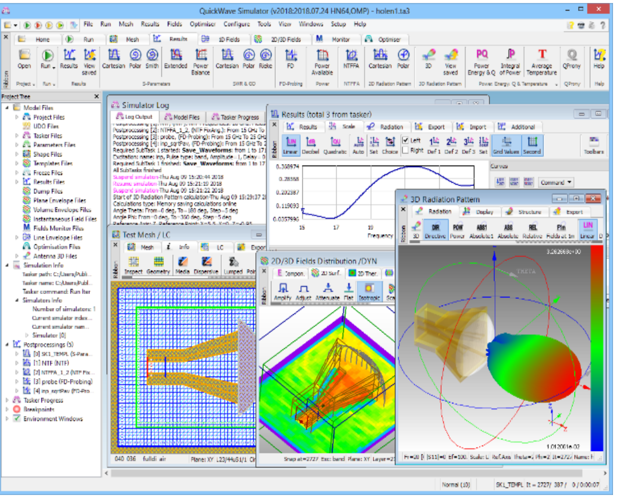
中国发明协会 China Association of Inventions

发明家协会国际联合会主席 President IFIA Andras Vedres

2008年10月

QWED at a glance: Polish high-tech SME 23 years on the market

Business branches *nnually at IEEE IMS Show*

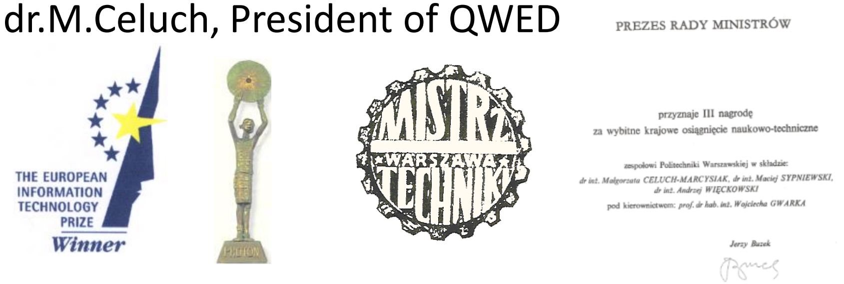


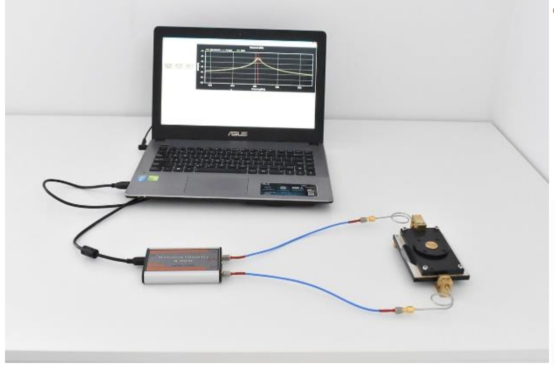
Electromagnetic simulation & design software, 3D & BOR 2D tools

based on 300+ publications by:

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

dr.M.Celuch, President of QWED

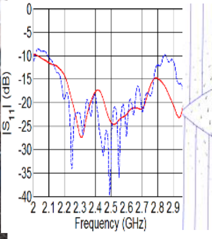


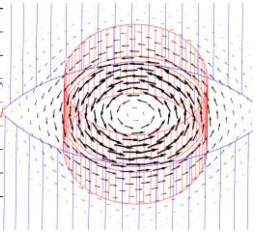


Test-fixtures for precise material measurements

based on 300+ publications

by prof.J.Krupka, IEEE Fellow



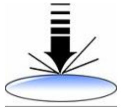


Consultancy & design services based on EM expertise & tools

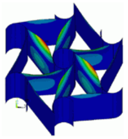
team of 10+engineers, 4 PhDs, 2 Profs

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.

concept & synergies

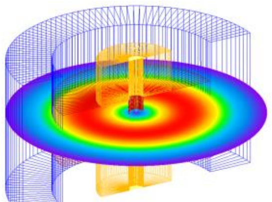
Modelling & measurements are not two separate worlds.
Exploring **synergies** is where QWED sees the future.
This is also where QWED is **unique**.

QWED's conformal FDTD offers outstanding modelling flexibility & computational efficiency

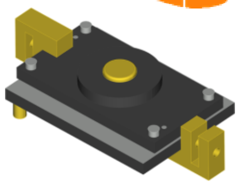
Modelling

(EM, MW, multiphysics,...)

- **waves in free space is "easy" Maxwellian**
- **wave interaction with matter is "complicated"...**



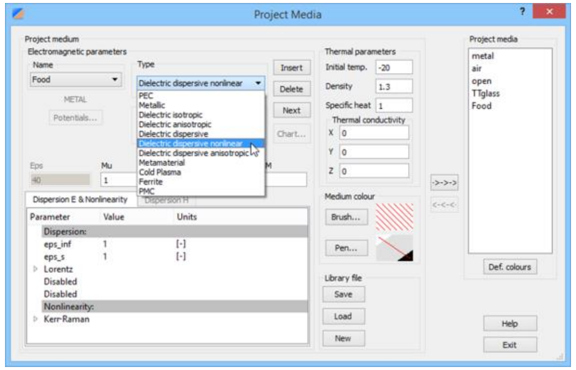
applicator design & model for parameter extraction



Material measurements

QWED's SPDRs offer outstanding accuracy for low-loss dielectrics

accurate material parameters (constitutive relations)

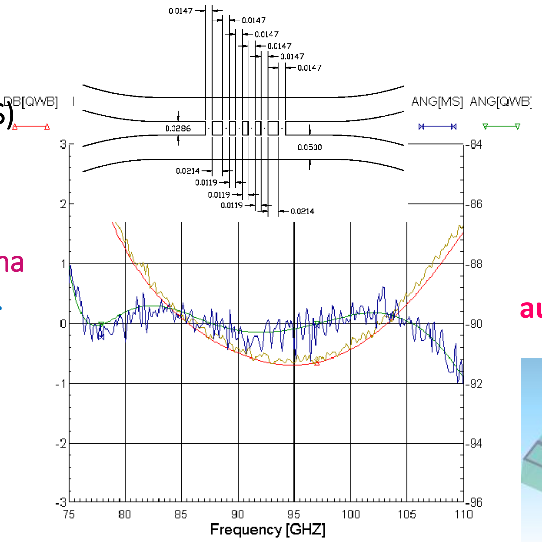


Electromagnetic modelling and design

QuickWave-3D:
world's recognised 3D EM simulation tool

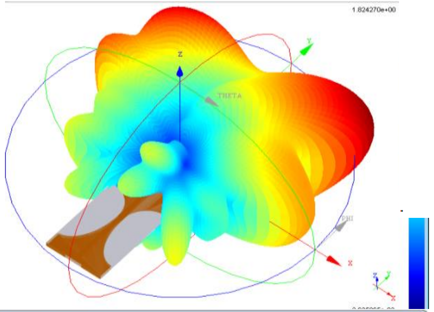
Space research:
NASA related laboratories:
National Radio Astronomy Observatory (VA US),
Jet Propulsion Laboratory (CA US)
Universities:
CALTECH (US), Chalmers (S), etc.

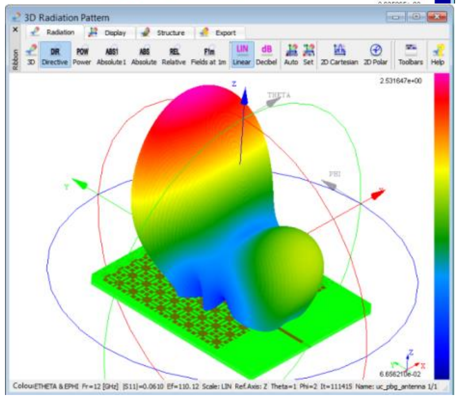
Antenna feed systems designed by NRAO



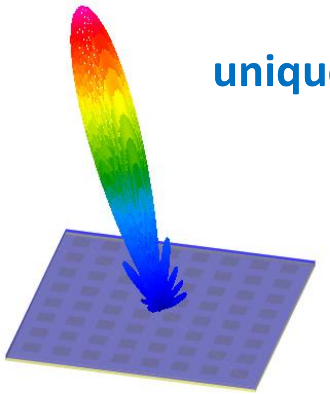
QuickWave 3D results at NRAO, see:
ALMA Memos 381, 343, 325, 278.

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

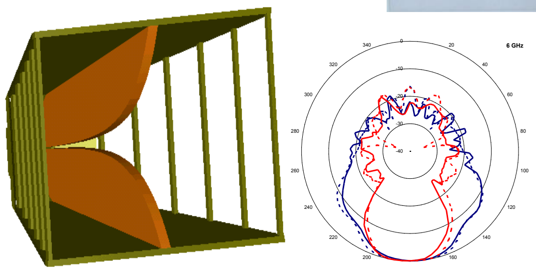




Aperture-coupled patch antenna
on uniplanar photonic bandgap substrate
& its radiation pattern at 12 GHz.

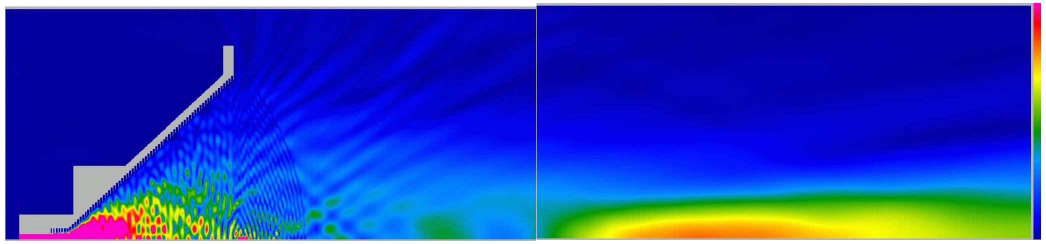


Antenna arrays for 5G and
automotive radar application

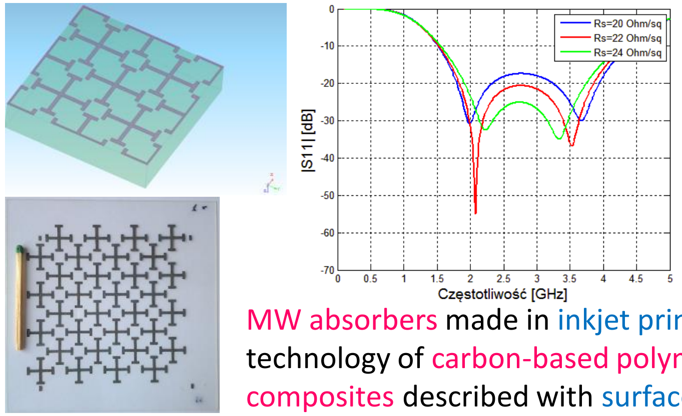


Pyramidal horn antenna for military surveillance
measured (courtesy prof.B.Stec)
& simulated patterns

QuickWave BOR:
unique on the market & ultrafast tool for axisymmetrical structures

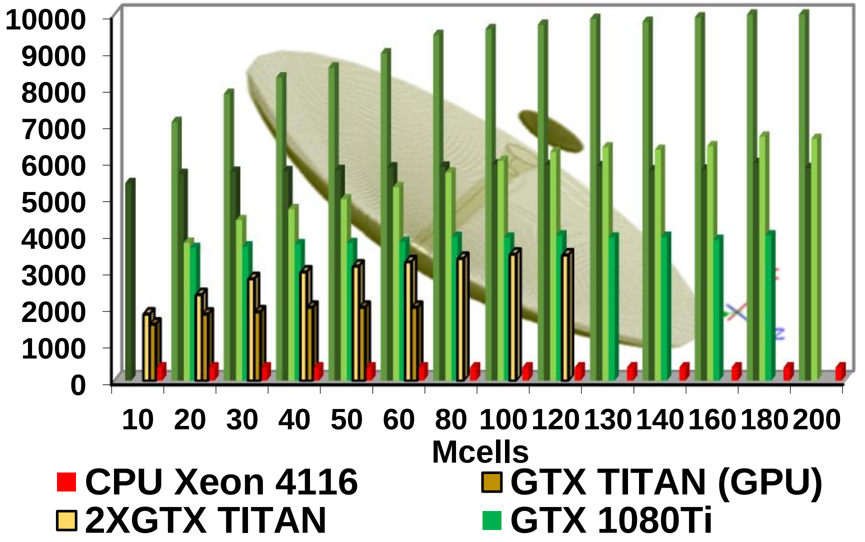


Antennas as large as 2600 λ in diametre on moderate PC



MW absorbers made in inkjet printing technology of carbon-based polymer composites described with surface resistance in [Ω/□]

QuickWave is optimised for speed plotted in (Mcells/sec),
runs on professional & low-cost video cards

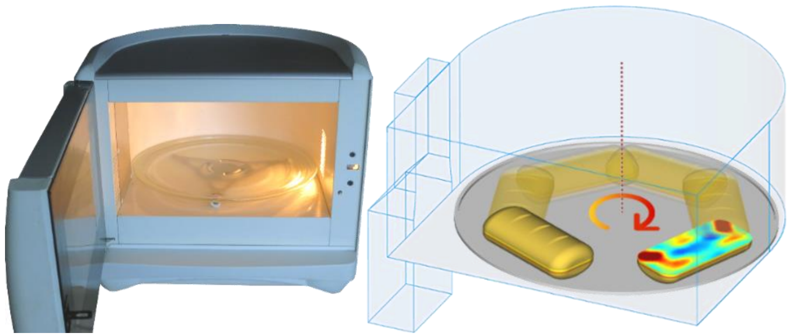


Pioneering background:
W.Gwarek, *IEEE Trans. MTT*: vol.33 Oct.1985; vol.36 Feb.& Apr. 1988.
Key developments:
M.Celuch & W.Gwarek, *IEEE Trans. MTT*, vol.43 Sep.1995, vol.41 May1993, vol.45 May1997, vol.51 Aug.2003; *EuMC* 1991-1997; *IEEE IMS* 2001-2004.
Reviews: *IEEE Microwave Mag.*, Dec.2008 & Apr.2010; *IJMPEE* vol.41 2007.

Electromagnetic modelling & design – high MW power applications

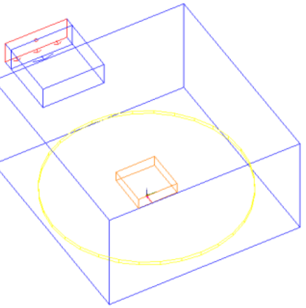
Modelling of MW heating effects in domestic oven

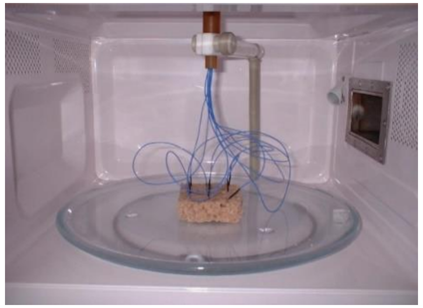
Full-wave EM simulation & heat transfer & load dynamics
Load rotation & arbitrary movement during heating
Source frequency tuning regime for solid state sources
Temperature dependence of material parameters

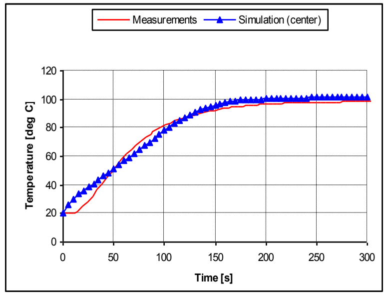


Whirlpool Max oven considered by M.Celuch et al.,
in *Development of packaging and products for use in microwave ovens*,
1st edition Woodhouse CRC Press 2009, 2nd Ed. Elsevier 2020.

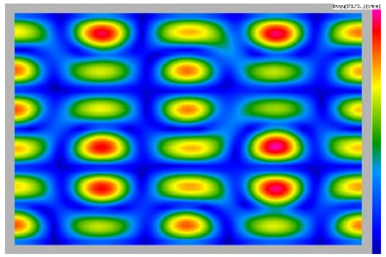
QuickWave modelling of heating confirmed by real-life experiments – joint work of QWED and WUT in Eureka E!2602 project



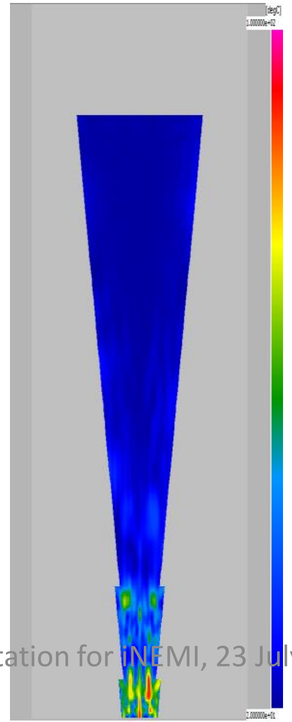




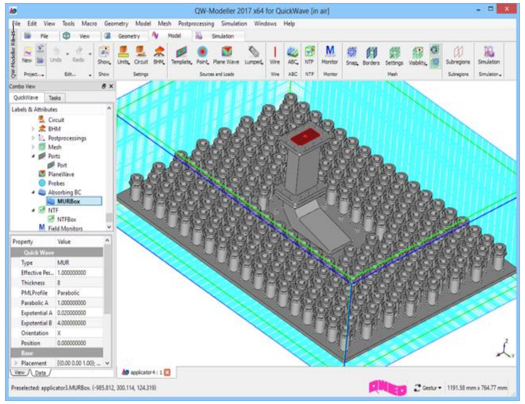
Free-fall waste processing on ships (Eureka FOODWASTE)



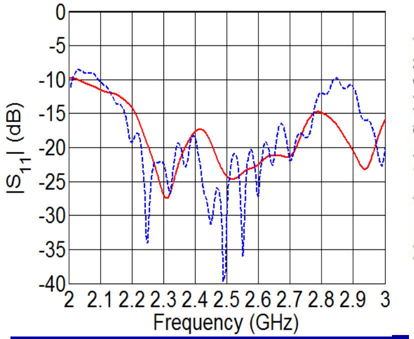
E-field in horizontal & vertical cut

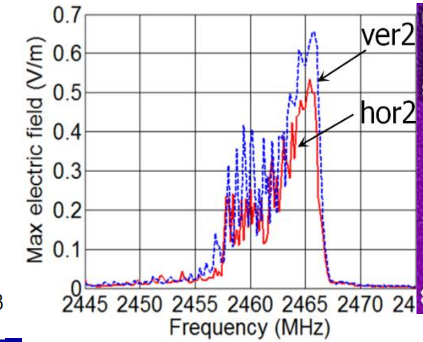


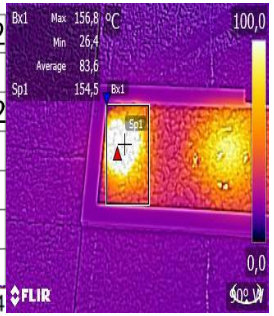
High power applicator for MW treatment of bituminous surfaces (road repair, NGAM project)

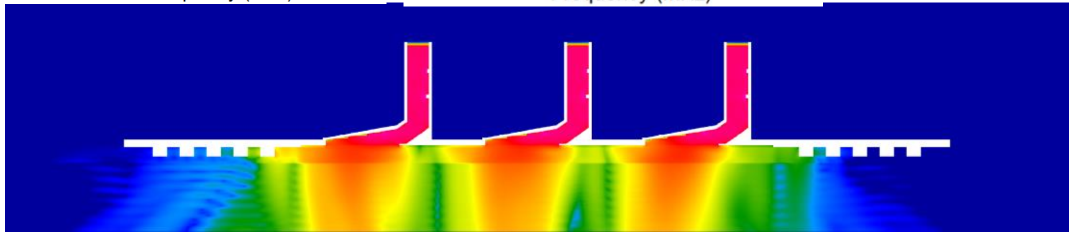


convenient CAD input









System of three MW power applicators with feeding system and leakage preventing chokes: designed, manufactured, tested

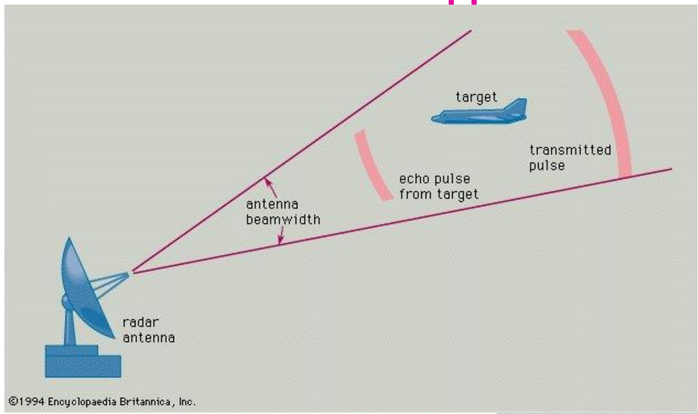
B.Salski et al., *IEEE MTT Trans.*, vol.65, Sep.2017.

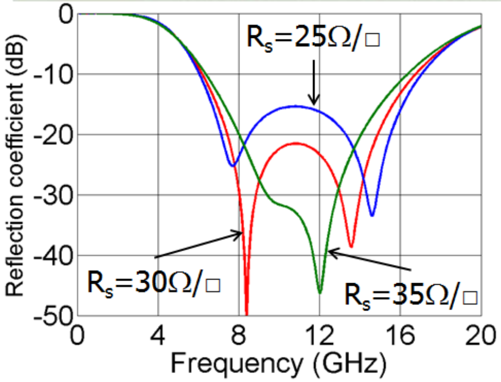
Material parameters are needed for MW design & thus for EM simulations

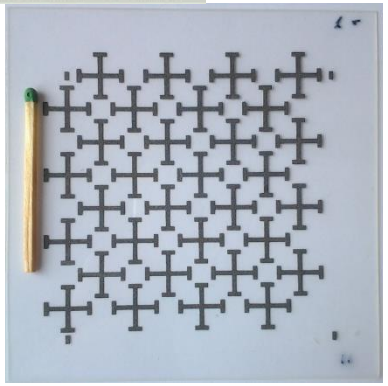
Electromagnetic characterisation of materials with QWED test-fixtures:

- Complex permittivity (relative permittivity and loss tangent)
- Resistivity
- Surface resistance

Radar and EMC applications







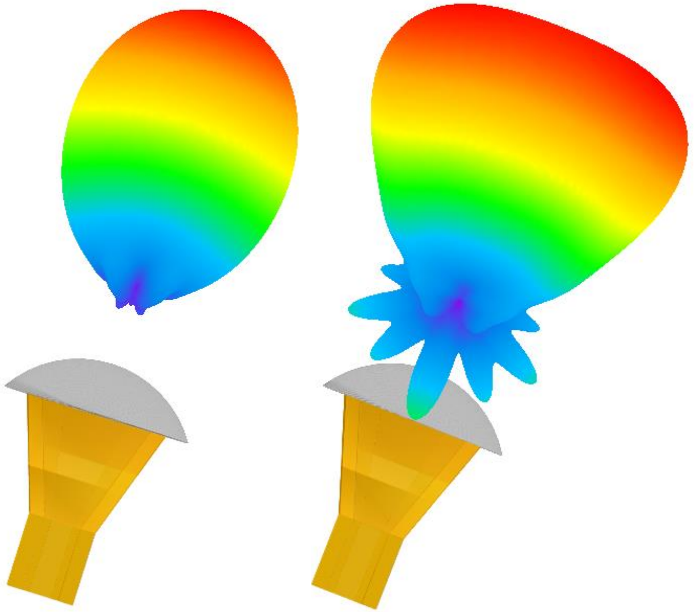
EM absorber characteristic – dependence on surface resistance of resistive sheet

Crucial for e.g.

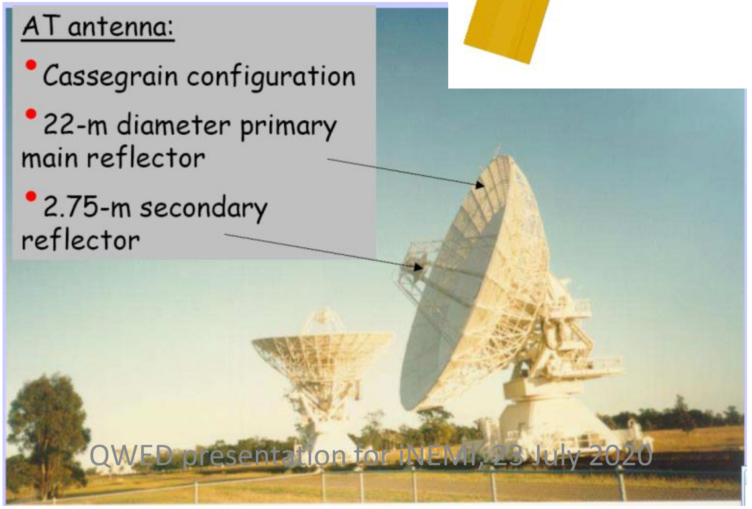
- The ability of receiving/transmitting required information signal
- Influence on the antenna coverage range

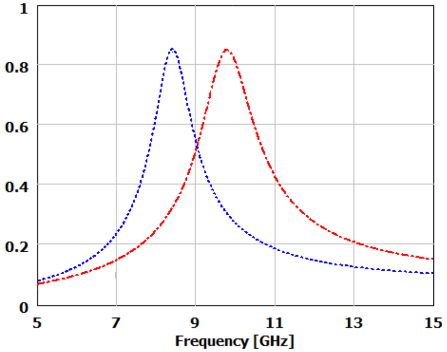
Communication quality

Antenna applications



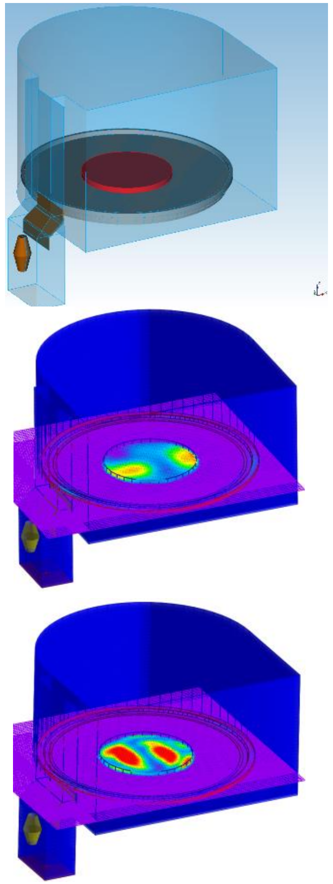
Antenna characteristic – dependence on the lens material





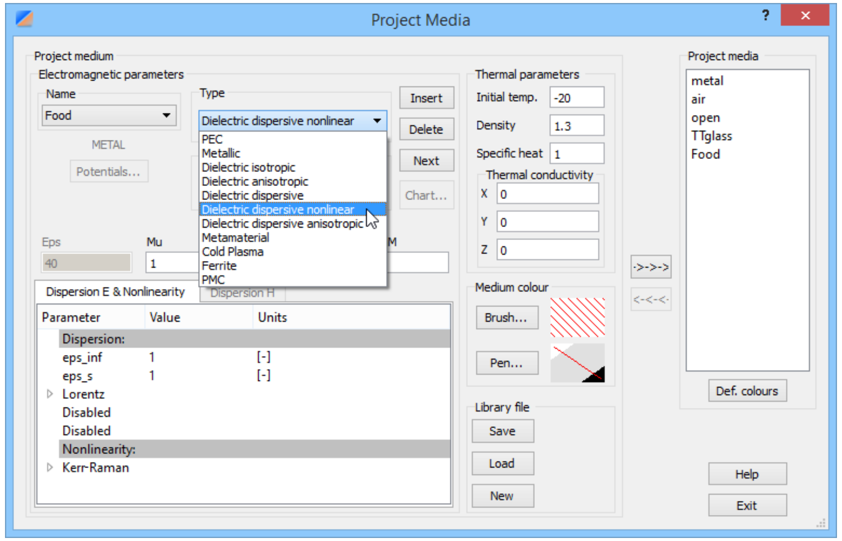
Filter characteristic – dependence on substrate permittivity

Microwave power applications

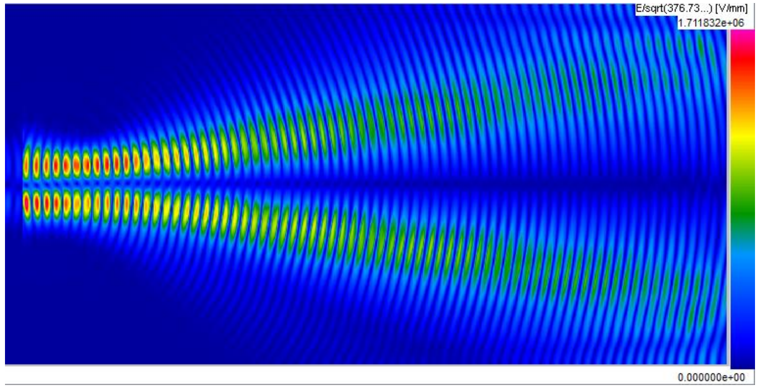


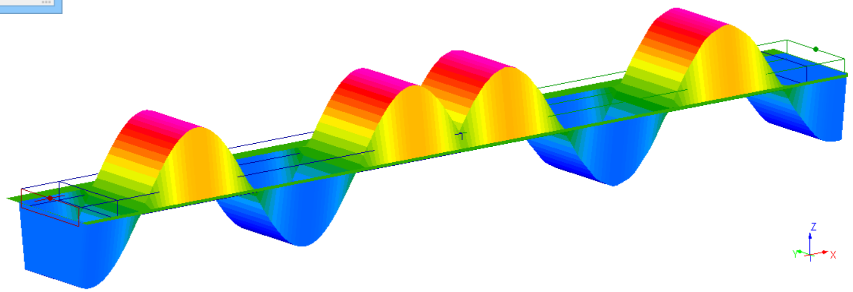
Courtesy of Whirlpool Inc. – Whirlpool MAX oven

Materials in electromagnetic & multiphysics modelling softwa



Modelling of material nonlinearities at THz frequencies



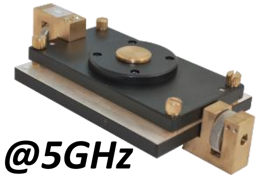


Drude: $\varepsilon_r(\omega) = \varepsilon_\infty + \frac{(2\pi f_p)^2}{(j\omega 2\pi \nu_c - \omega^2)}$

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

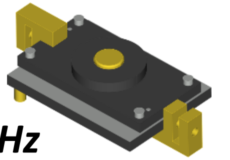
Lorentz: $\varepsilon_r(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty (2\pi f_p)^2}{((2\pi f_p)^2 + j\omega 2\pi \nu_c - \omega^2)}$

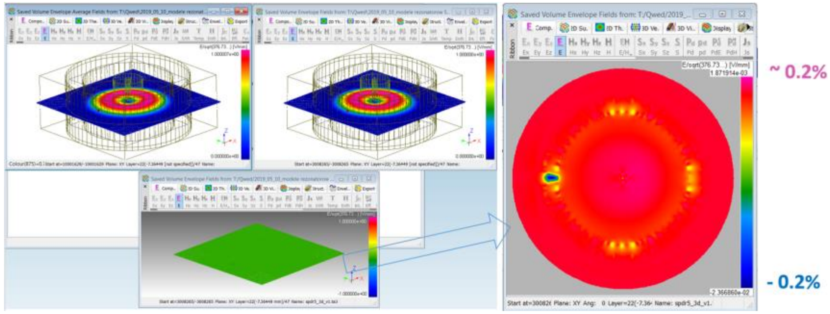
Modelling bases for material measurements



SPDR @5GHz

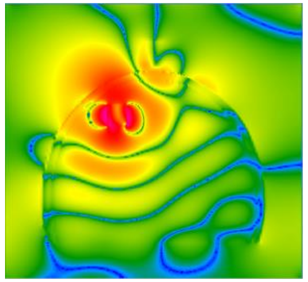
CAD model of SPDR @5GHz

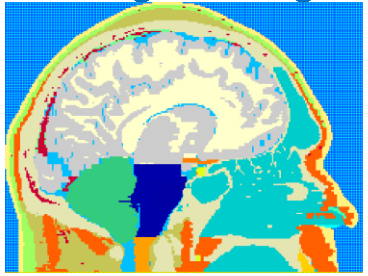


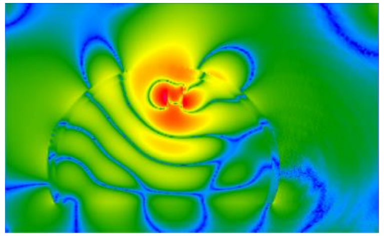


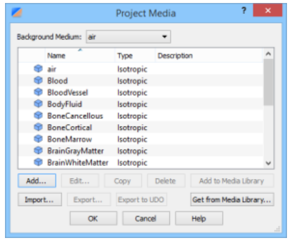
EM simulation of SPDR without and with SUT

Macroscopic modelling of biological problems



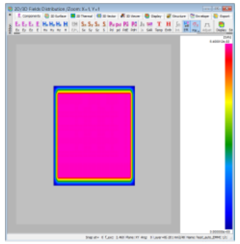




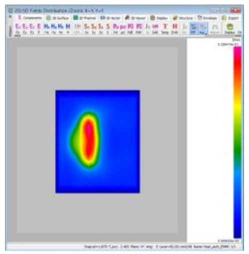


Detection of inhomogeneities, e.g. tumours

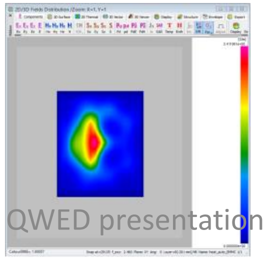
Material parameter dependent on process driving force



Initial loss values distribution in the object



Losses after 30sec of MW heating



Losses after 90sec of MW heating

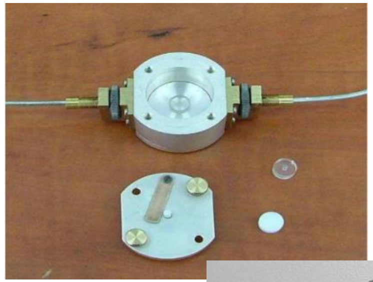
Polish high-tech SME - 23 years on the world's market

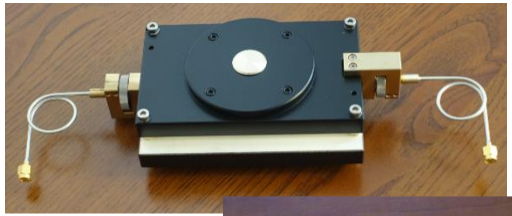
- Quality of QWED measurement devices has been recognised by:
  - industrial practitioners (including biggest dielectric laminates manufacturers),
  - leading researchers (international laboratories e.g. ESA labs, etc.),
  - industrial standard creators (e.g. International Electrotechnical Commission (Switzerland), resulting in e.g. IEC 61189-2-721 standard dedicated to SPDRs.

- QWED's test-fixtures for material measurements are widely used for materials quality control and characterisation in a variety of science and industrial domains:
  - electronics (e.g. printed electronics, semiconductor materials and structures, etc.),
  - radioelectronics (e.g. antennas, filters, diplexers, etc.),
  - space technology,
  - automotive technology,
  - energy saving technology (e.g. elements of photovoltaics systems),
  - biology,
  - biomedicine,
  - chemistry, etc.

Polish high-tech SME - 23 years on the world's market

- Hardware products offer consists of several types of devices for GHz range:
  - Split-Post Dielectric Resonators (SPDRs),
  - Single-Post Dielectric Resonators (SiPDRs),
  - TE10δ cavities,
  - Fabry-Perot Open Resonator (FPOR),
  - etc.,





designated for characterisation of wide spectrum of materials, from dielectric laminates, through semiconductor wafers, thin resistive and conductive films (e.g. polymer composites reinforced with metal or carbon inclusions) and metals, to powders and liquids.

- A well-established position on the global market of microwave devices for electromagnetic characterisation of materials.

- A decade average amounts to 100 test fixtures with the accompanying software that are sold per year.

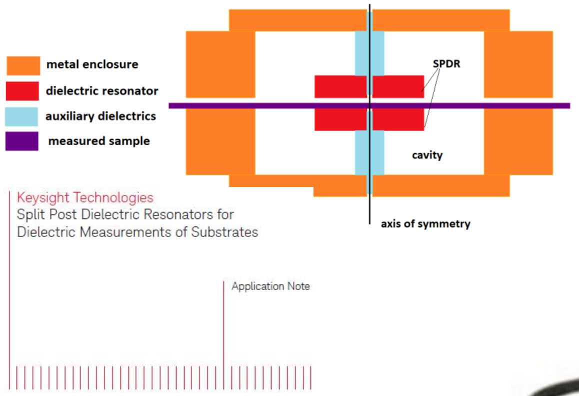
- **1000th** sold in March 2020.

1000th SPDR

Test-fixtures for precise material measurements

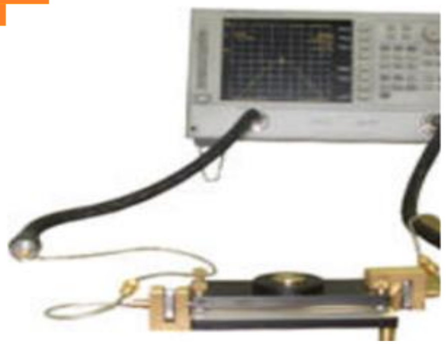
Low-loss laminar dielectrics (including 5G): SPDR & FPOR

Split-post dielectric resonators subject of European Standard IEC 61189-2-721:2015 distributed also by Keysight Technologies Option 003 N1500A

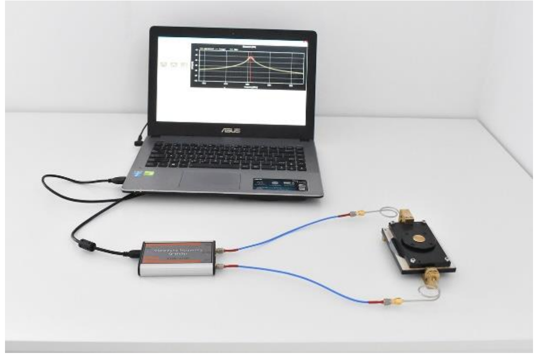


Robust, easy-to-use with:

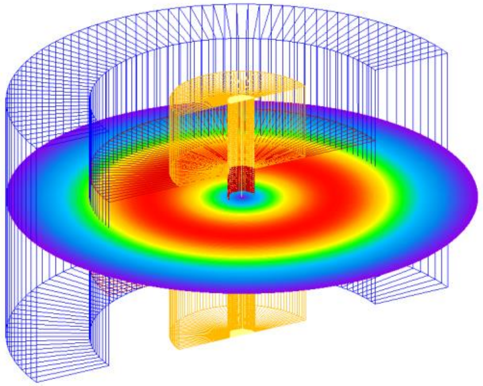
standard VNA



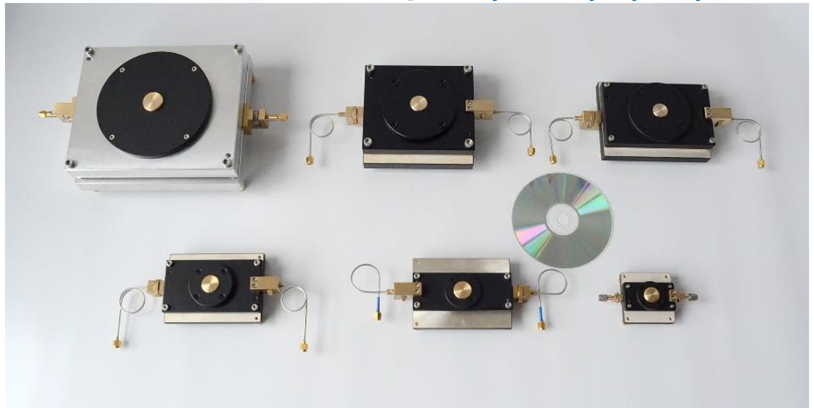
QWED portable
low-cost Q-Meter



Simulated E-field

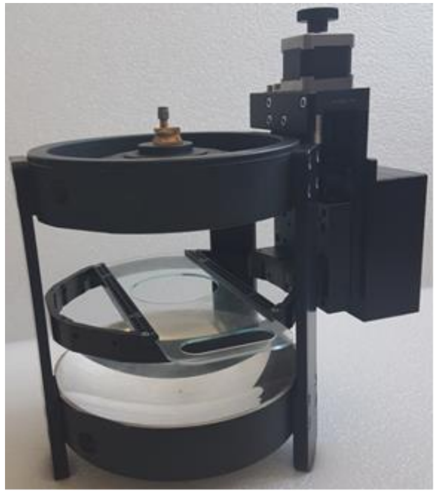


QWED standard SPDRs @ *1.1, 2.45, 5, 10, 15 GHz*

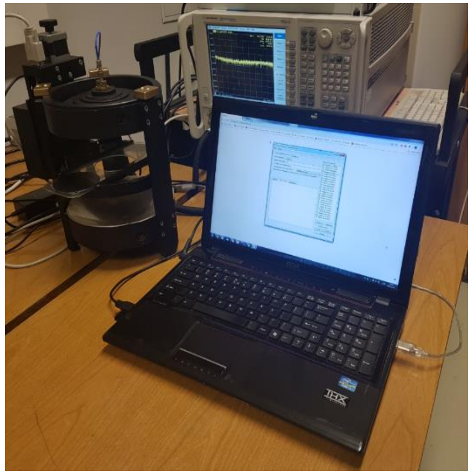


Fabry-Perot Open Resonator

FPOR



FPOR & VNA setup
controlled via PC app



Operational frequency range:

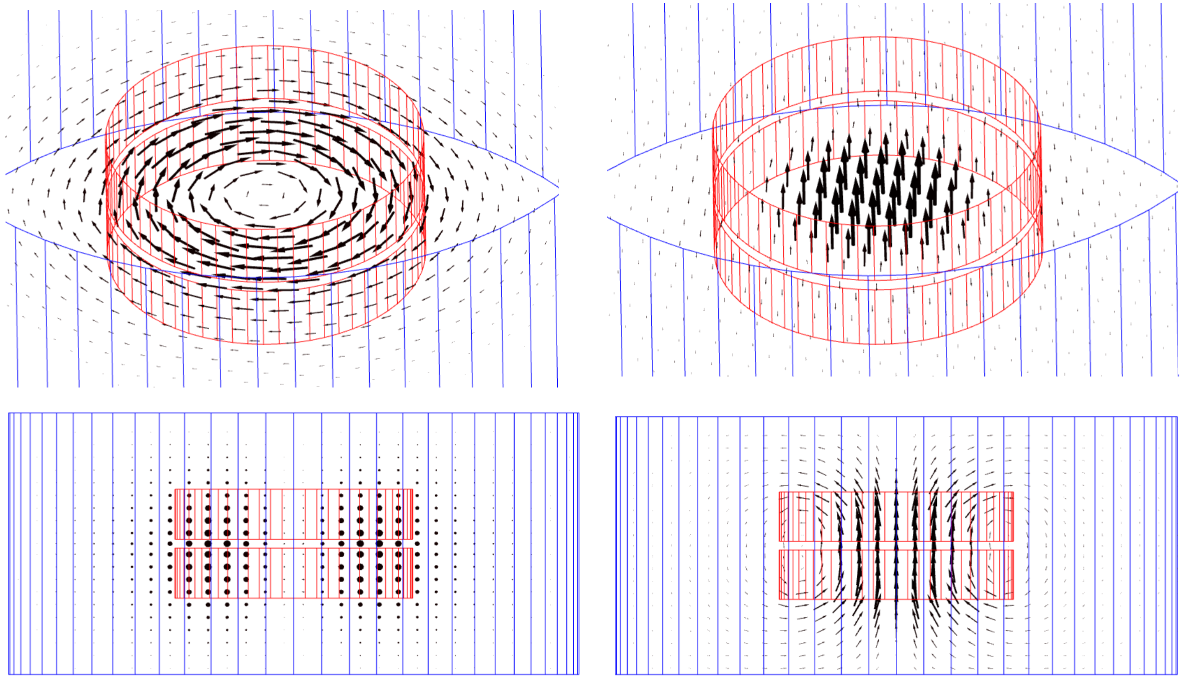
Standard: ***20 – 50 GHz***

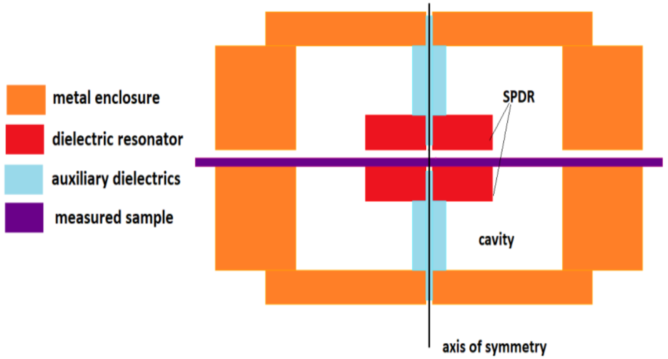
Advanced: ***75 – 110 GHz***

FPOR & in-house Q-meter

Split-Post Dielectric Resonator method for low loss material characterisation

E-field **H-field**





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

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

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

SPDR offers simultaneously:
- outstanding & proven accuracy
- ease-of-use ideal for newcomers to GHz material measurements

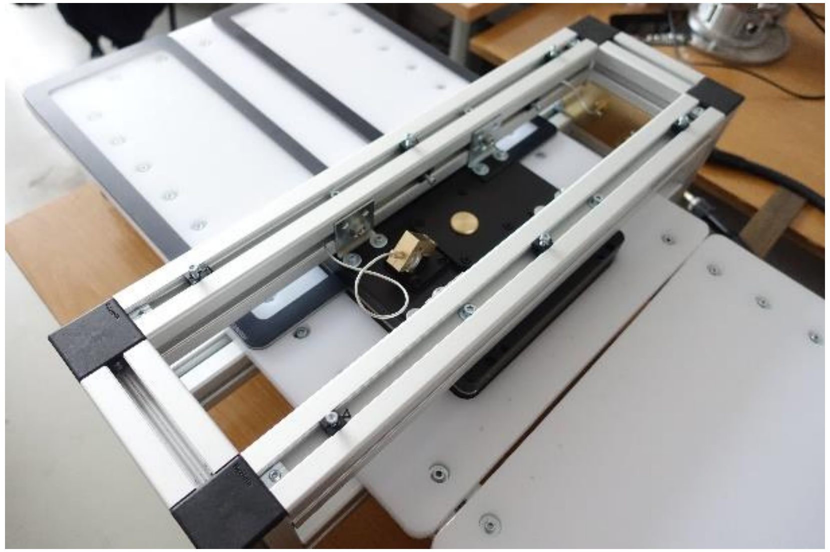
- resonant mode with EM fields mostly confined in and between those ceramic posts → minimial losses in metal enclosure
- H-field is only vertical at the side wall of the enclosure → only circumferential currents in side wall → no radiation through slot
- E-field tangential to SUT → air slots between 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
- **calibration only once, at manufacturing**

Test-fixtures for precise material measurements

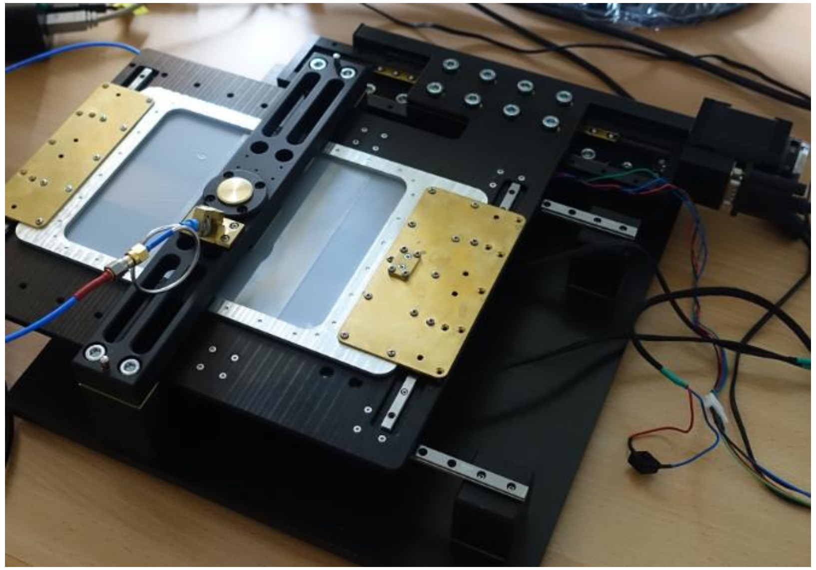
Low-loss laminar dielectrics

Recent SPDR-based designs & prototypes for larger surfaces:

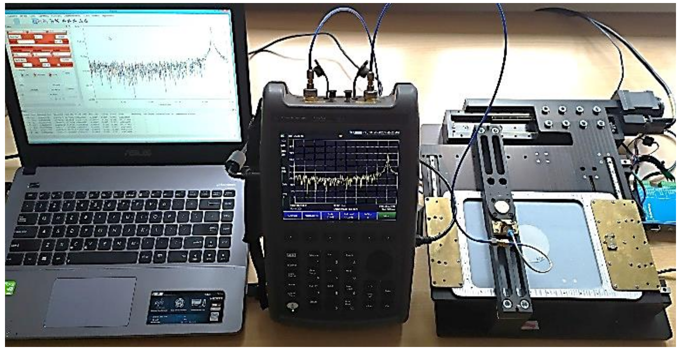
large sheets of glass
manual scan @1.9 GHz



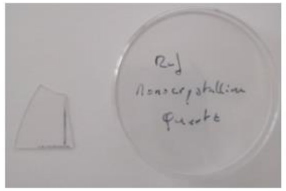
laminar dielectrics & semiconductor wafers
automatic scan @10 GHz

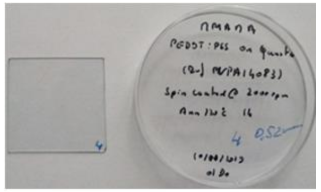


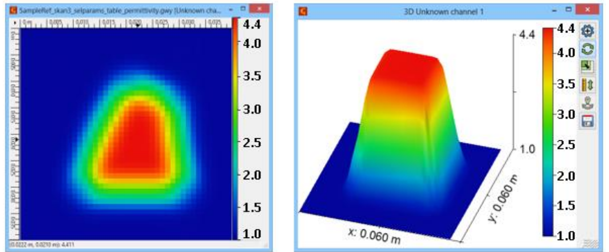
QWED automatic 10GHz scanner with VNA, controlled by PC app



2D relative permittivity maps of the SUT





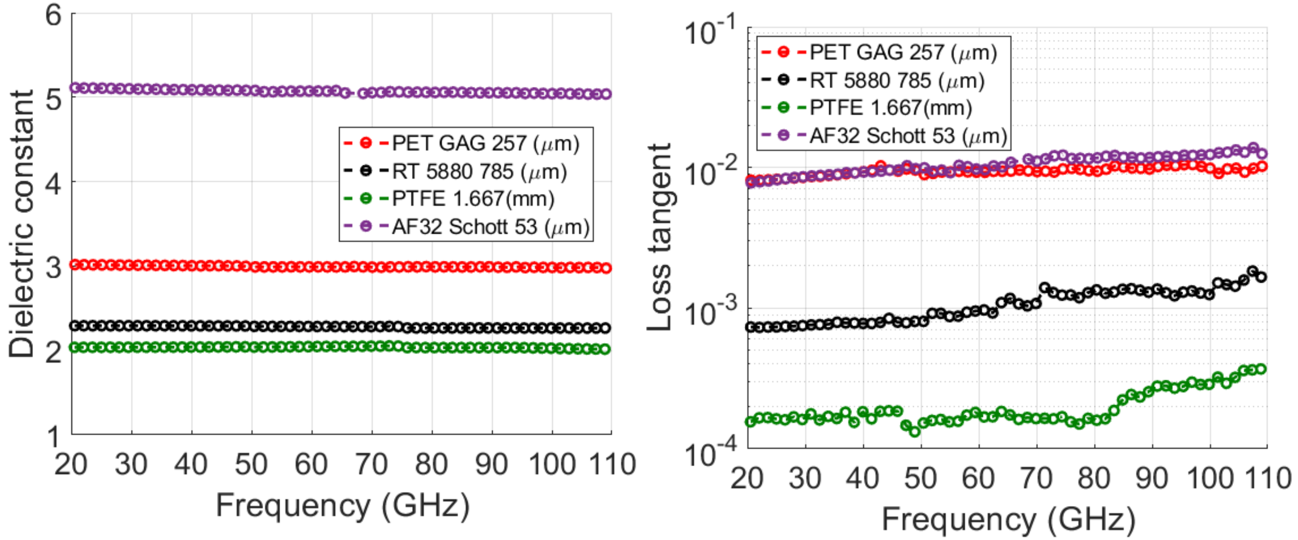


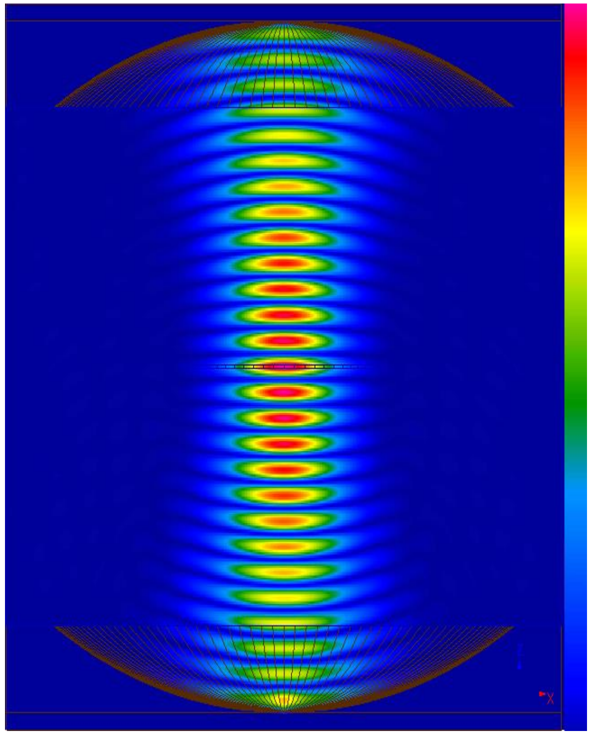
Ref.: www.qwed.eu
J. Krupka et al., *J. Eur. Ceramic Soc.*, vol. 21, pp. 2673-2676, 2001.
J. Krupka & J. Mazierska, *IEEE Trans. Instr. Meas.*, vol. 56, no. 5,2007.
M. Celuch & al., *IEEE MTT-S IMS*, Boston 2019.
www.mmama.eu recent work under H2020-NMBP-07-2017 grant MMAMA No. 761036

MMAMA

Fabry-Perot Open Resonator

Examplary wide-band measurements
of four samples





- Spectrum: 20-110 GHz
- Dk accuracy: De/e < 0.5 %
- Df range: 10^{-5} < tand < 10^{-2}
- Sample diameter: > 3 inches
- Sample thickness: < 2 mm
- Fully automated measurement: (10-15 minutes)

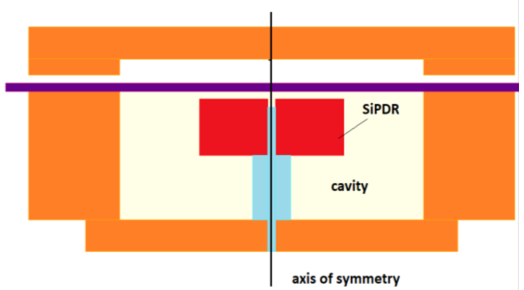
Examplary Gaussian
beam in FPOR
simulated in QuickWave

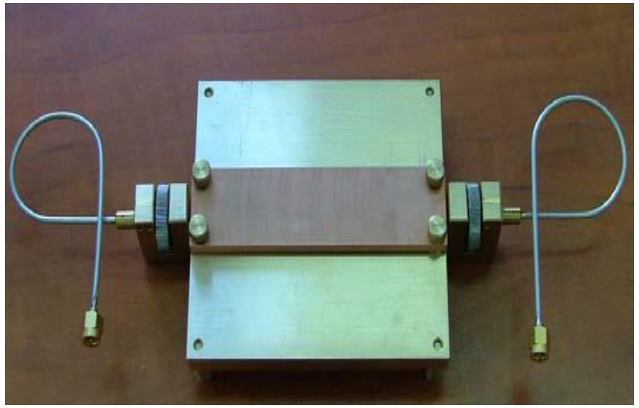
FPOR 20 – 110 GHz

Test-fixtures for precise material measurements

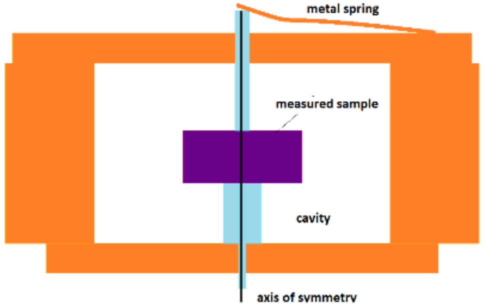
Other commercially available TE01δ resonators for various materials

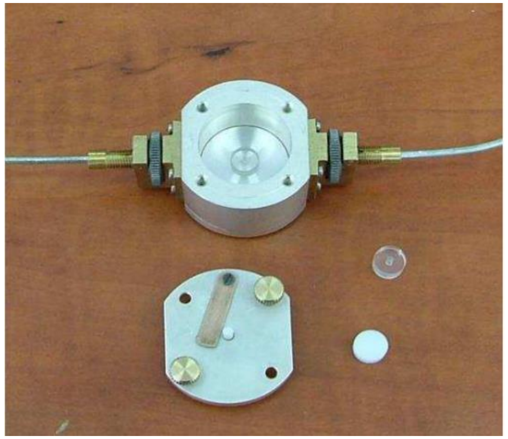
Single-Post Dielectric Resonator
Resistive sheets



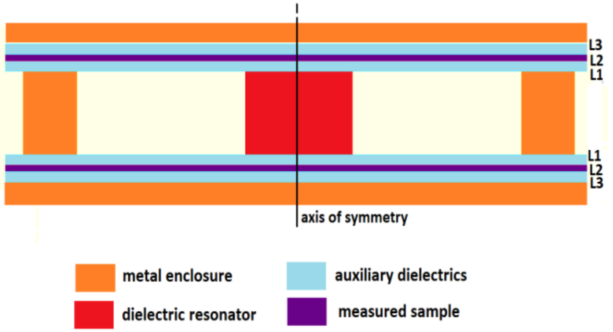


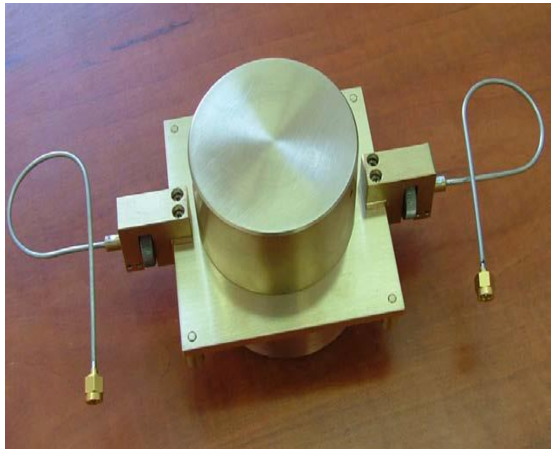
Cavity resonating SUT
Ultra-low-loss SUTs



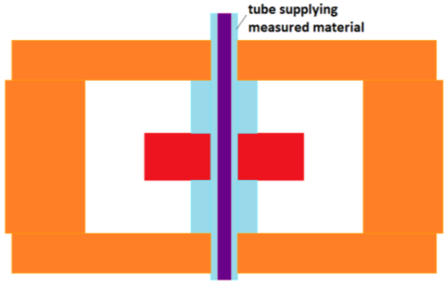


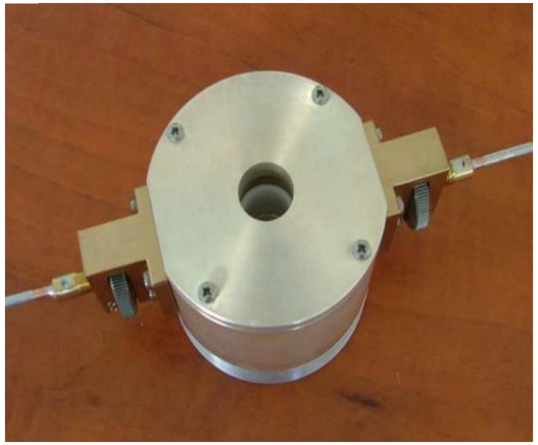
Sapphire resonator
Metal SUTs





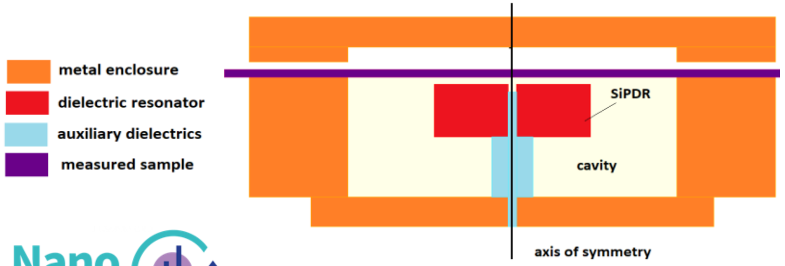
Cavity
Liquids & powders

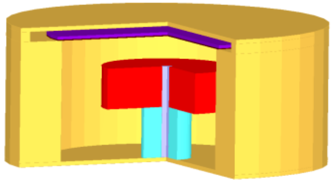




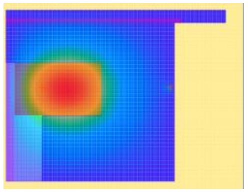
Single- versus Split-Post Dielectric Resonator

SiPDR

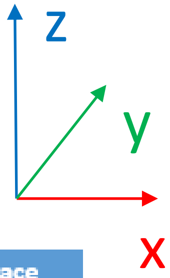




E-field distribution in the half cross-section

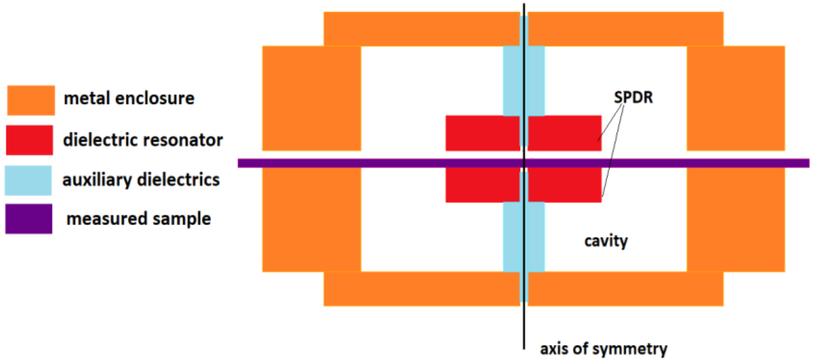


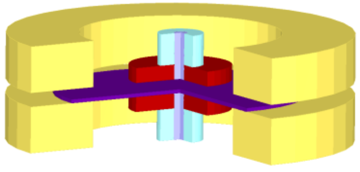
two configurations
used with TE01δ mode
E-field tangential (parallel)
to sample surface (xy-plane)

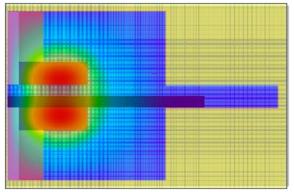


	Conductivity [1/Ωm]	Resistivity [Ω cm]	Surface resistivity [Ω/sq]
SPDR	$2\ 10^{-3}$ to 0.5	$2\ 10^{2}$ to $5\ 10^{4}$	$5\ 10^{3}$ to 10^{7}
SiPDR	10^{-1} to 10^{6}	10^{-4} to 10^{3}	10^{-1} to $2\ 10^{4}$
Sapphire	$> 5\ 10^{6}$		

SPDR







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)

QWED expertise and contributions to iNEMI

- *EM characterisation of materials up to 110 GHz, also 2D imaging at lower GHz frequencies*
- *EM & Multiphysics modelling of materials & devices, also in THz frequency range*
- *Modelling-based design of GHz circuits & devices, including antennas & feeds*
- *Developing dedicated computation and simulation algorithms & postprocessings*

Thank you for your attention and welcome to QuickWave live demo!