Computational Electromagnetics as a Facilitator of Microwave Creativity and Industrial Innovation

Malgorzata Celuch

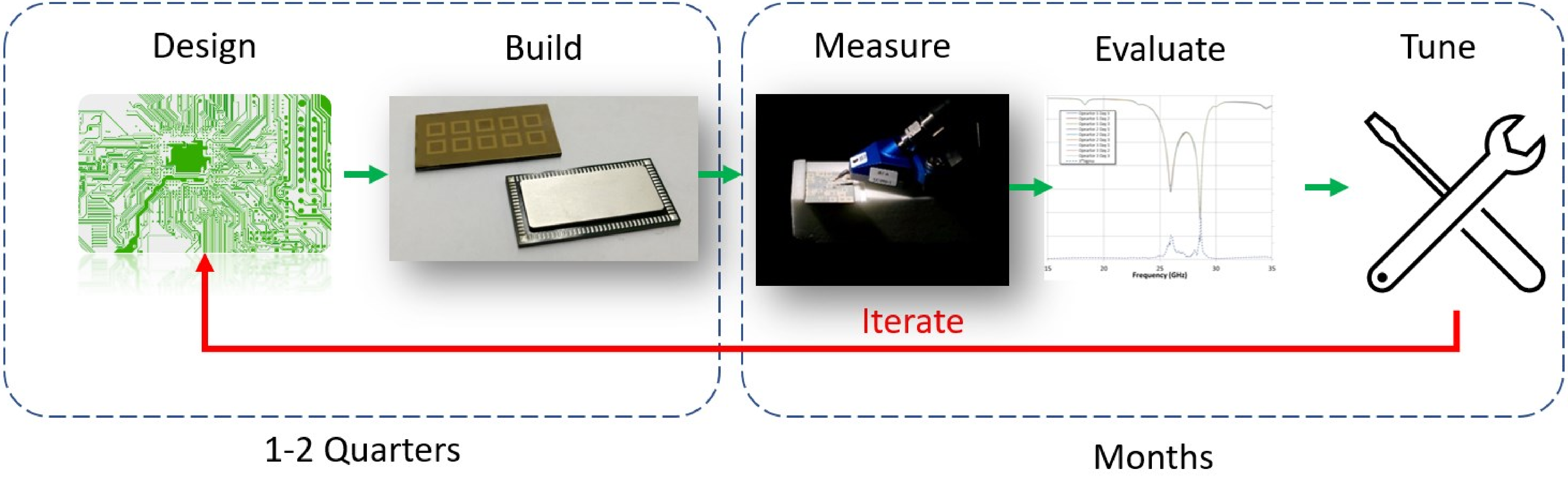
QWED Sp. z o.o.

Outline

- Assumption and scope of this talk.
- Research background of CEM at QWED.
- Case studies from QWED's industrial experience:
  - waveguide components,
  - antennas,
  - microwave ovens,
  - material measurements.
- Acknowledgement and conclusion.

The Problem

Traditional microwave design:
- ❑ hardware prototyping, trimming, and tuning
- ❑ multiple, time-consuming iterations
- ❑ difficult to tolerate in today's competitive environment



from: M.Hill & M.Celuch, IPC APEX EXPO 2021 (iNEMI project presentation)

The Approach

OBJECTIVES:

Innovation
- design faster
- explain & remove glitches

Creativity
- new idea
- crossover ideas

FACILITATORS:

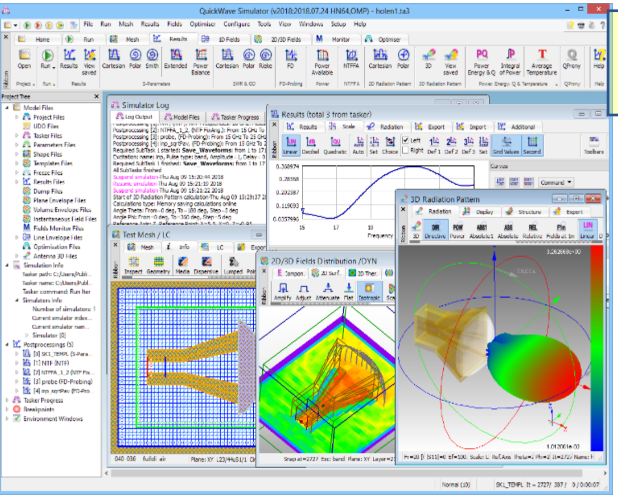
CAD tools
- circuit
- electromagnetic
- multiphysics
- optimization

→ virtual prototyping

↔

Materials' data

3 decades in a nutshell

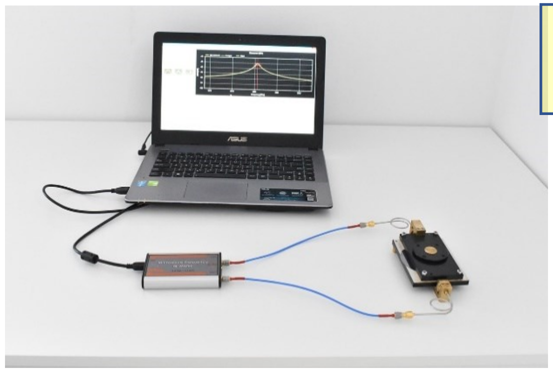


Electromagnetic simulation & design software, 3D & BOR 2D tools

based on 300+ publications by:

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

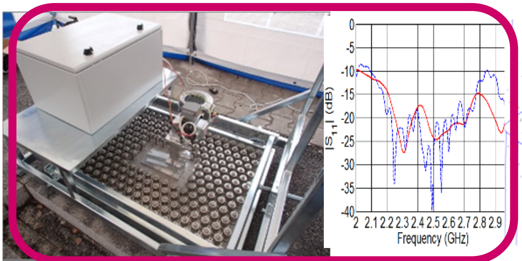
dr. M.Celuch

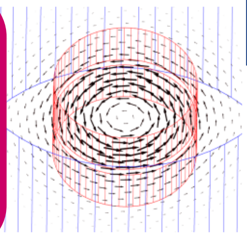


Instruments for precise material measurements

based on 300+ publications

by prof.J.Krupka, IEEE Fellow





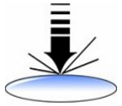
Consultancy & design services based on EM expertise & tools

team of 10+engineers, 4 PhDs, 2 Profs

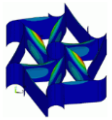
key areas: MW power appliances, customised resonators, antennas &feeds

R&D projects

EU FP4 COPERNICUS 1994-96 – commercial version of QuickWave



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



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

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

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

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

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

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

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

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

M-ERA.NET

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

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

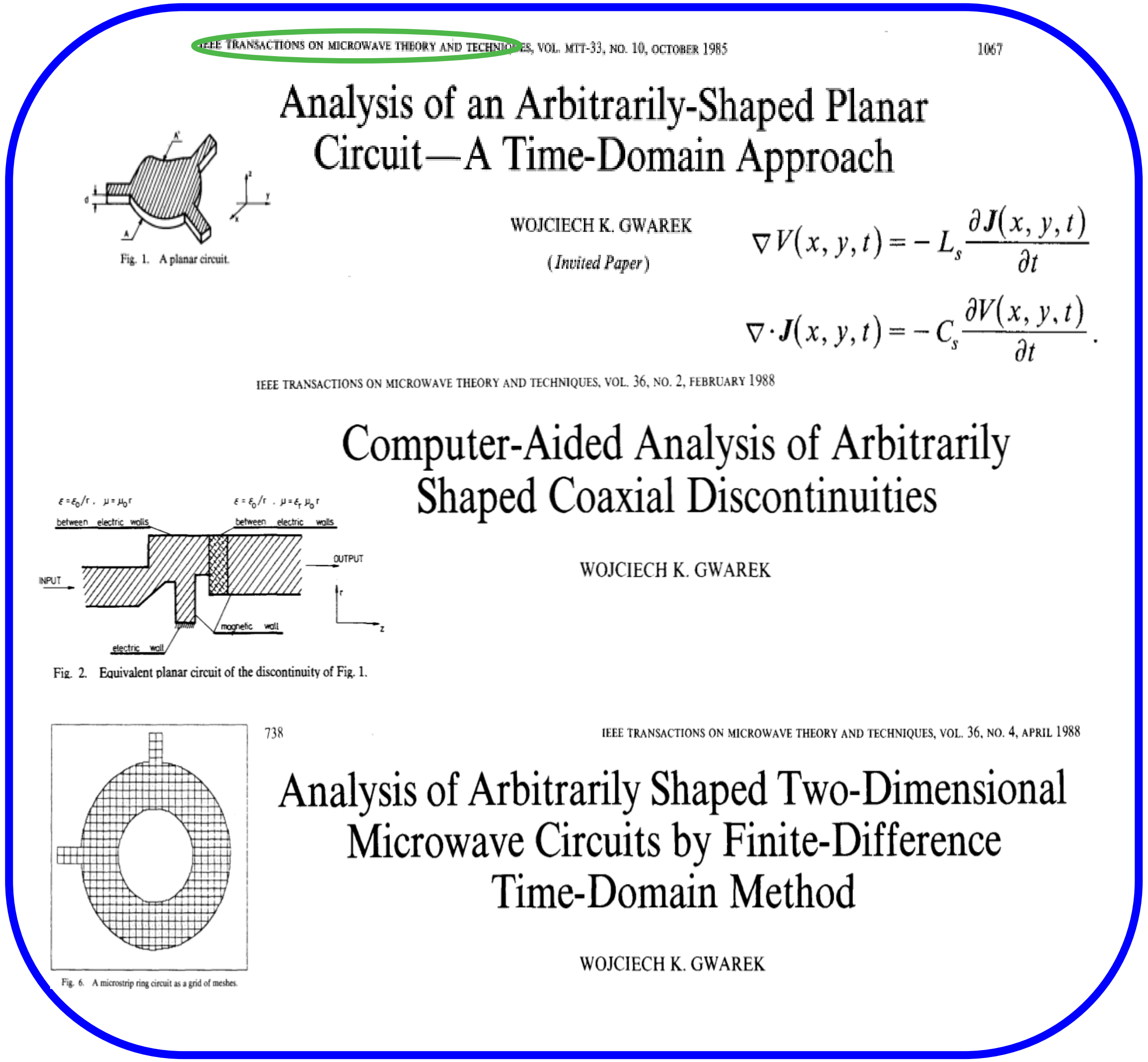
eureka eurostars

5G_Foil – characterisation and modelling of copper foils for 5G industry

Background

The work was initiated in early 1980s by
Prof. Wojciech Gwarek
Warsaw University of Technology
QWED's co-founder (1997) & 1st President (till 2017)

- original conformal 2D FDTD
- IEEE MTT-S Pioneer Award 2011



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

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

WOJCIECH K. GWAREK (Invited Paper)

Fig. 1. A planar circuit.

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

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

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

Computer-Aided Analysis of Arbitrarily Shaped Coaxial Discontinuities

WOJCIECH K. GWAREK

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

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

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

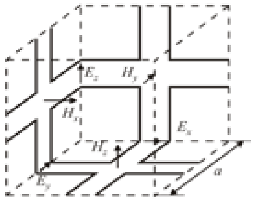
WOJCIECH K. GWAREK

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

I joined the work in 1986,
in 1997 we sold the 1st commercial licence for QuickWave.

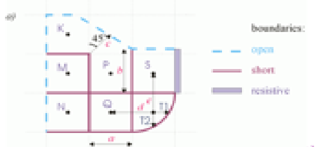
Our Academic Research 1980s – 1990s

FDTD versus TLM
Theorem of Formal Equivalence

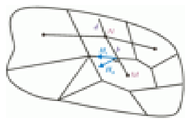


nodes: FDTD discretisation of Maxwell eqs.
connecting lines & stubs: TLM discretisation of Huygens principle

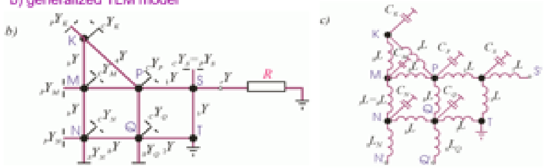
a) generalized gridding of a microwave structure

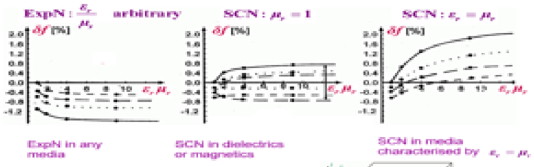


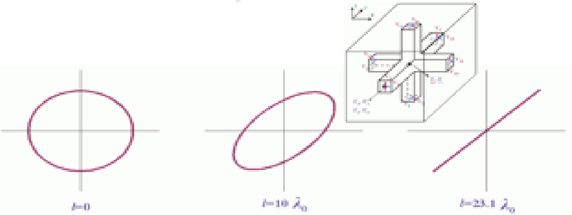
b) generalized TLM model



c) generalized FDTD model





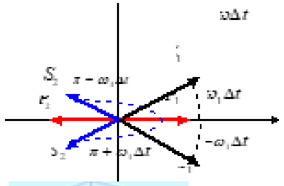


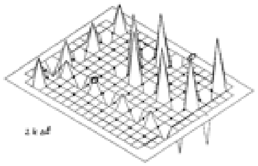
Theory & enhancements

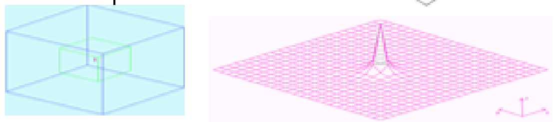
Generalised dispersion relations
Theory of P- and S-eigenmodes

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

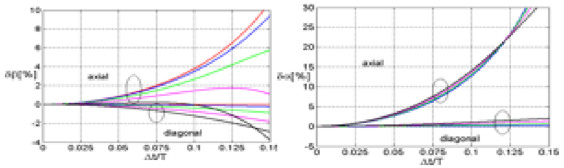
$$\omega_{ph}^2[-\omega_{ph}^2 \mu\varepsilon + \beta_{xph}^2 + \beta_{yph}^2 + \beta_{zph}^2]^2 = 0$$



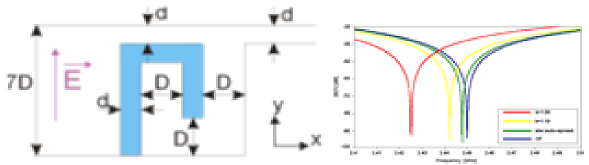




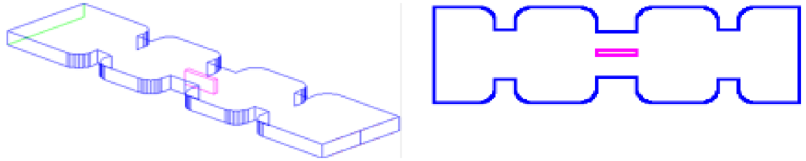
Dispersion in lossy media

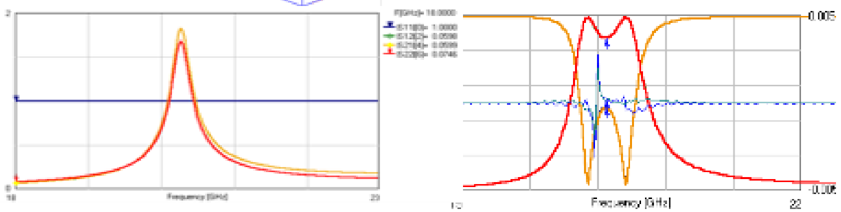


Field singularities

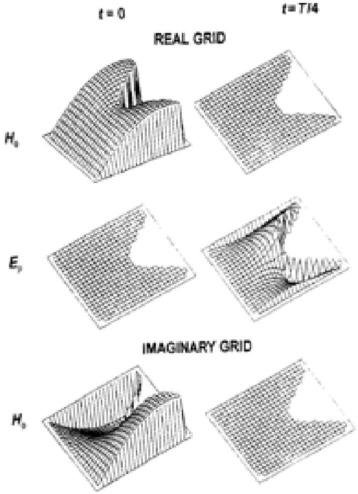


Generalised extraction of S-parameters in multi-modal transmission lines (incl. evanescent modes)

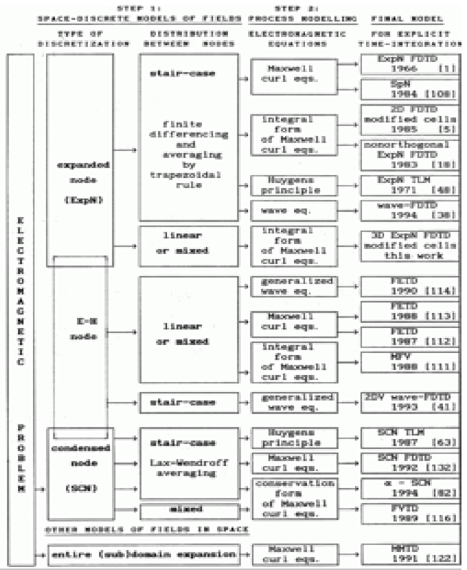




Periodic & vector 2D FDTD and TLM in real & complex form



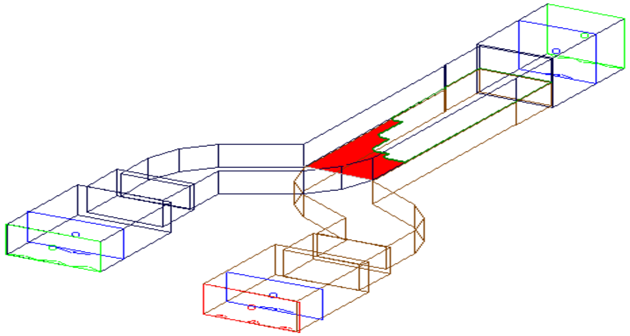
Classification of time-domain methods

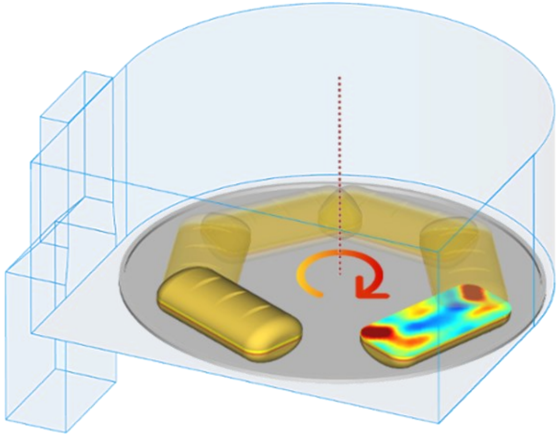


Changing Perspective

Key factors:

- funding by a European project (providing means)
- dissemination & networking (showing direction & needs)



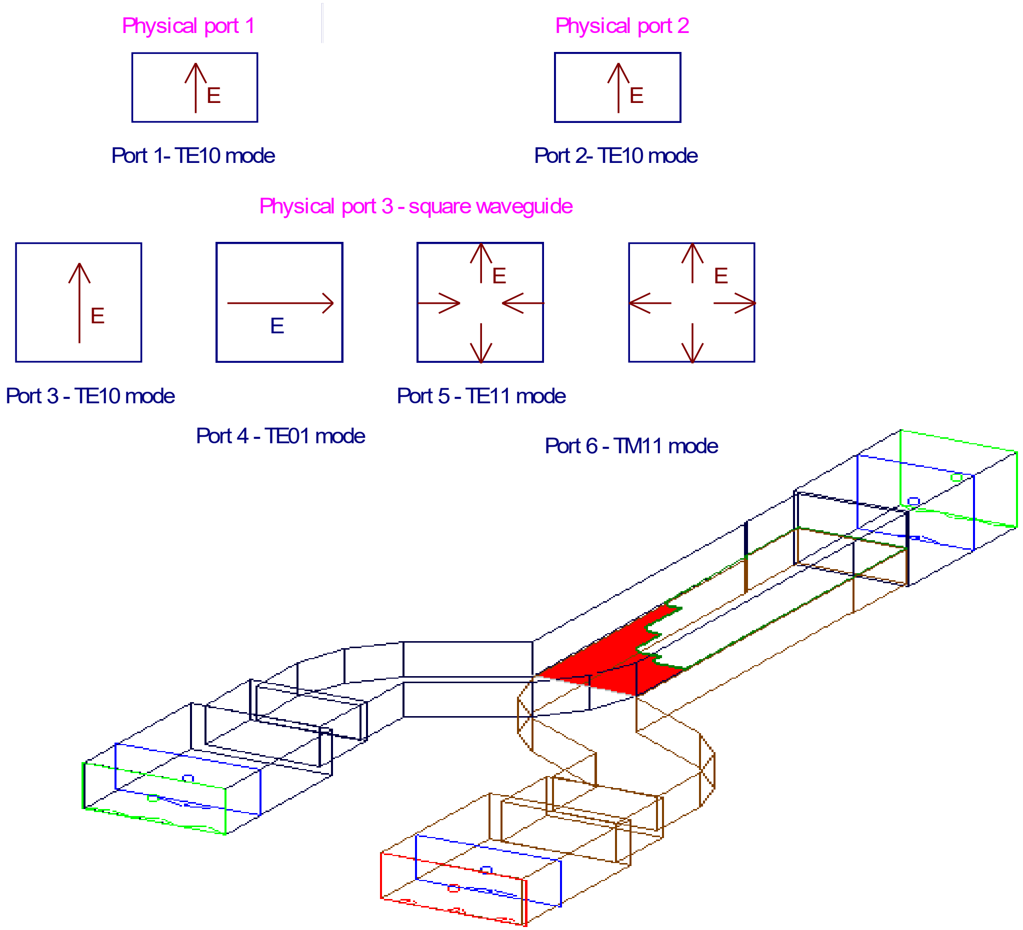


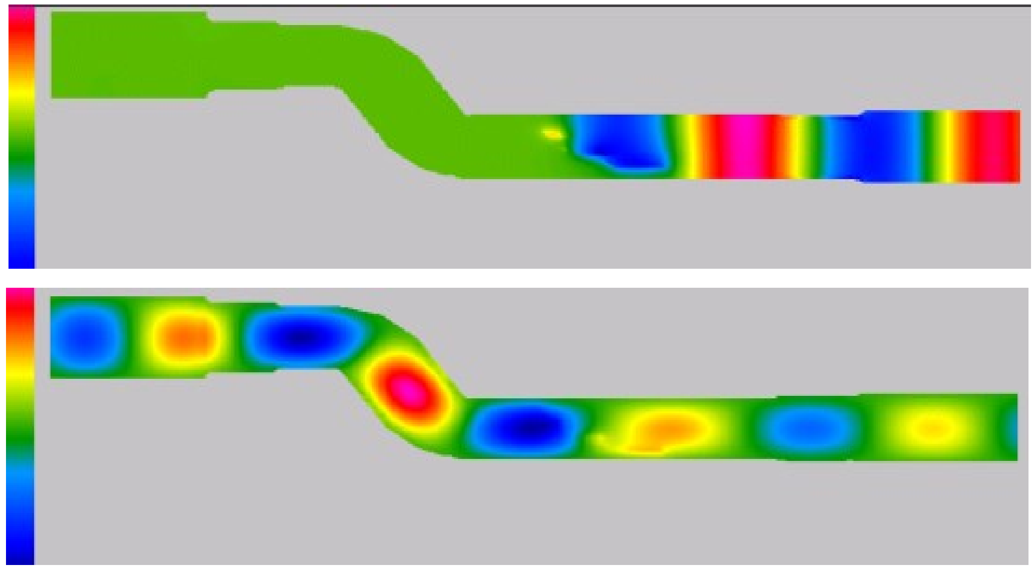
Anaheim, 1999

San Francisco, 2006

Case Study #W1: Industrial Design

Successful redesign of a septum polarizer for higher microwave frequencies



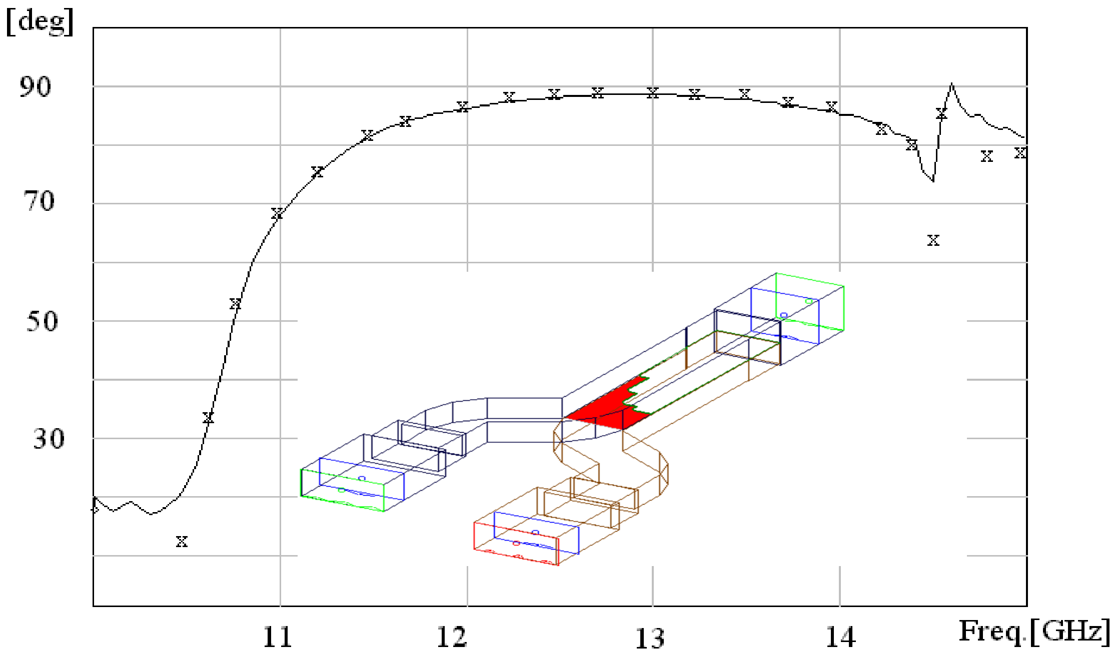


propagation of two polarizations at center frequency

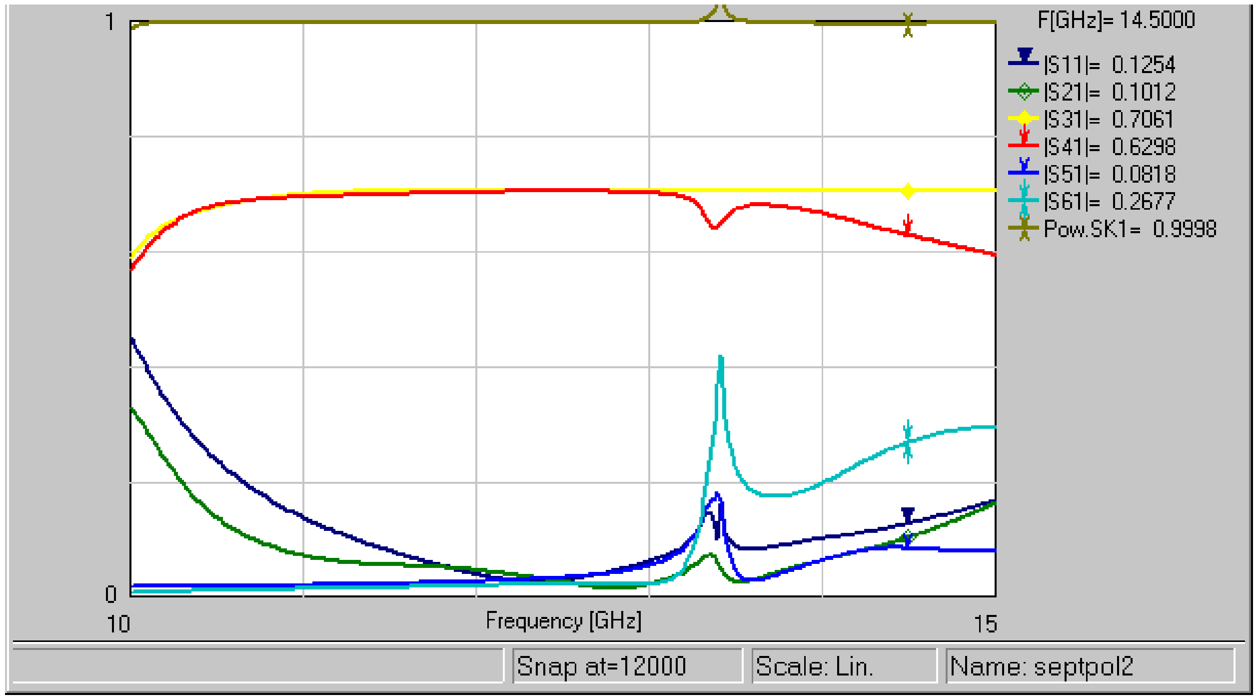
Case Study #W1: Industrial Design

IMS Connecting Minds. Exchanging Ideas.

Successful redesign of a septum polarizer for higher microwave frequencies



measured (x) and simulated (line) differential phase-shift

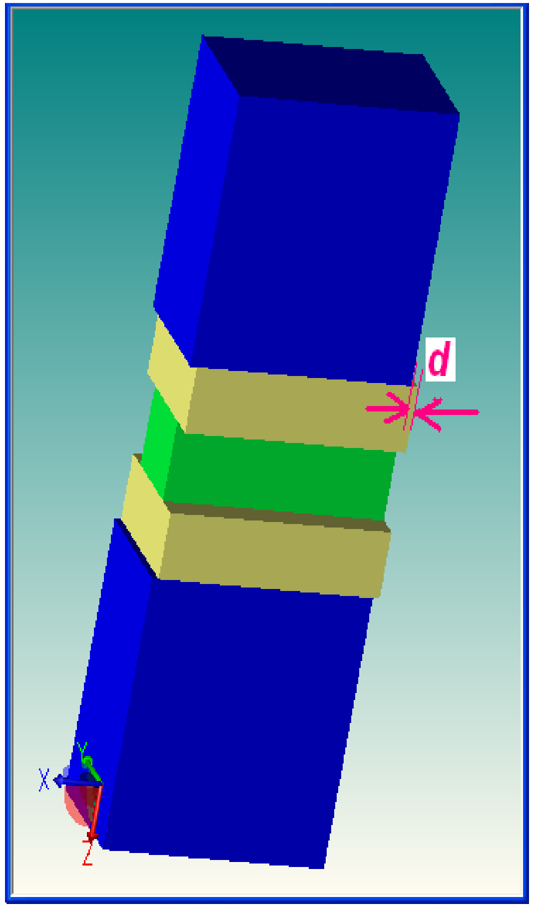


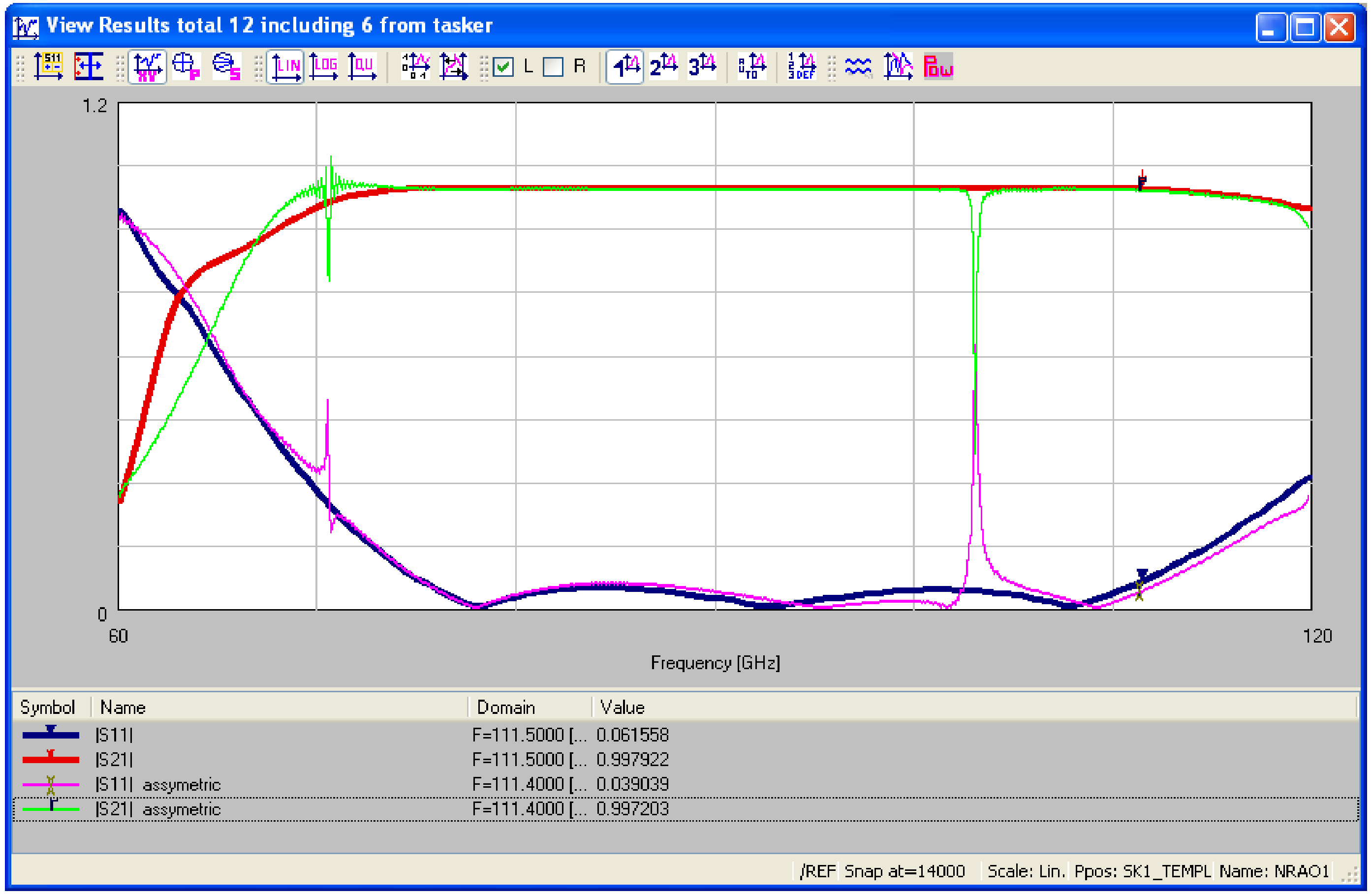
multi-modal S-parameters and power balance

design & measurements: Saab Ericsson Space, Gothenburg, SE
simulations: QuckWave by QWED, spring 1997, FDTD software beta-version for friendly users!

Case Study #W2: Physical Insight

Detection of a suck-off due to manufacturing offset in a quartz window

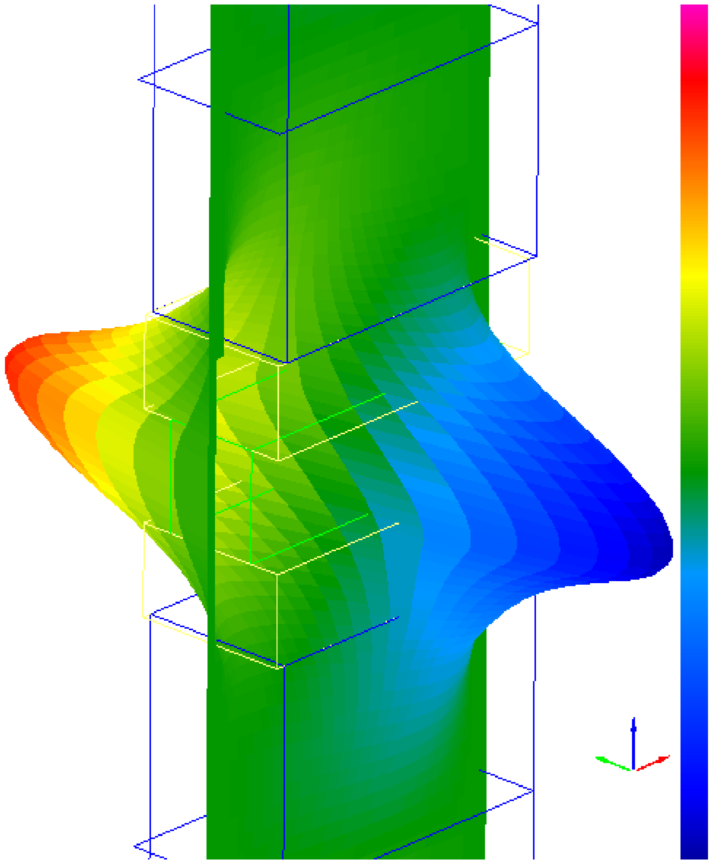




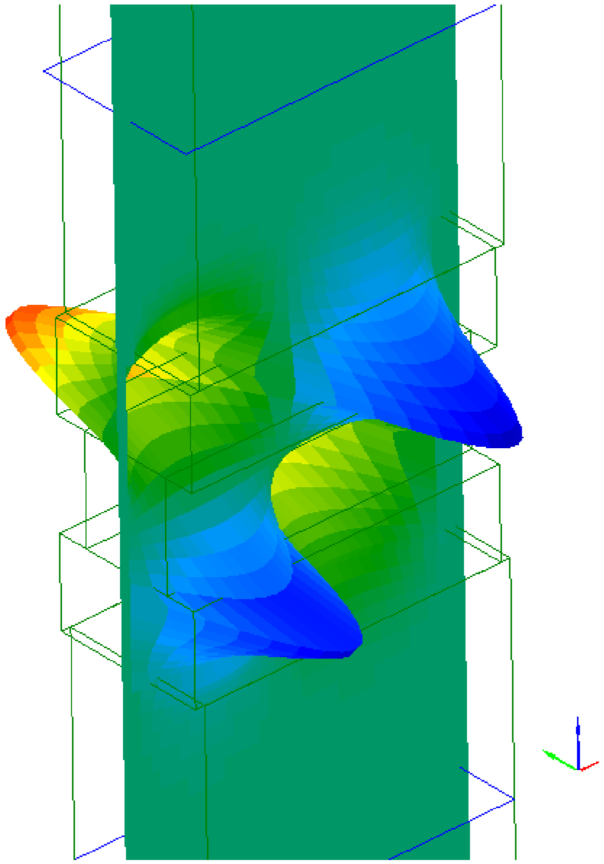
waveguide window made of teflon (yellow) and SiO_2 (green) in air-filled waveguide a very small assymetry (d>0) produces devastating spurious resonances at 70.6 GHz and 103.1 GHz

Case Study #W2: Physical Insight

Detection of a suck-off due to manufacturing offset in a quartz window



70.6 GHz



103.1 GHz

QuickWave FDTD simulations promptly revealed the reason of the glitch and provided physical explanation.

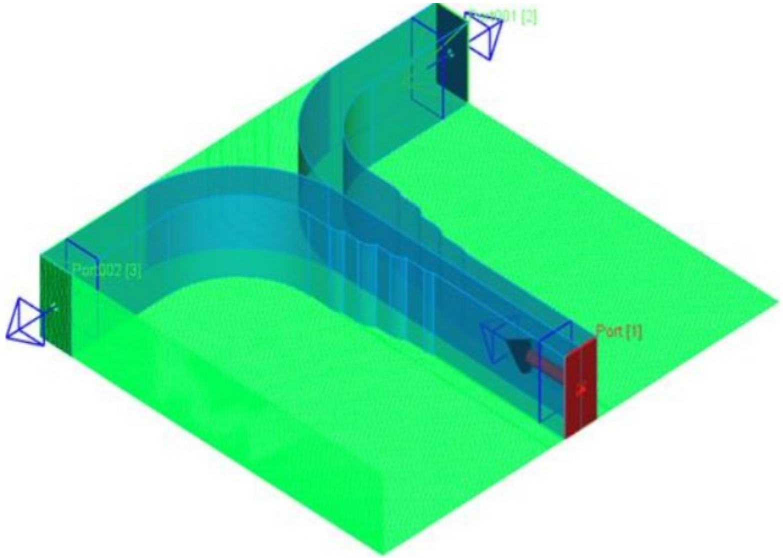
It it advisable to verify simulations by one numerical method with another.

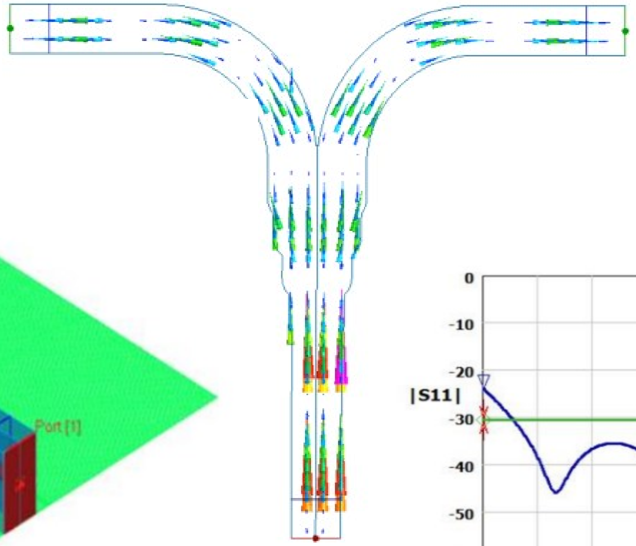
Waveguide Components for Space Applications

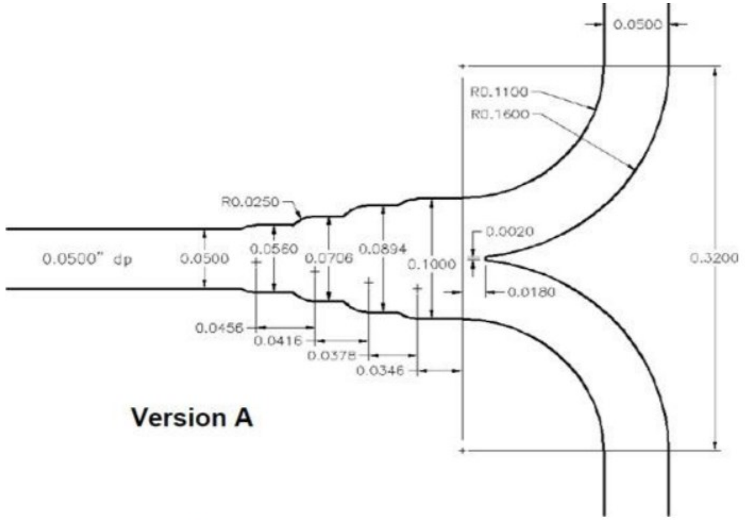
E-plane Y-junction by National Radio Astronomy Observatory, Charlottesvile, VA

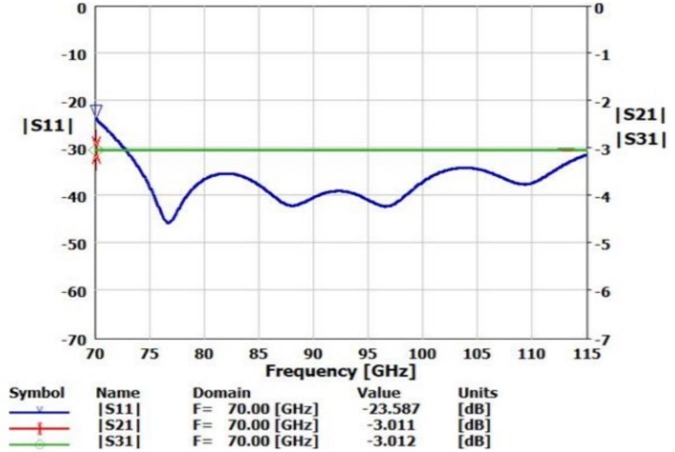
after A. R. Kerr, Elements for E-Plane Split-Block Waveguide Circuits, ALMA Memo 381

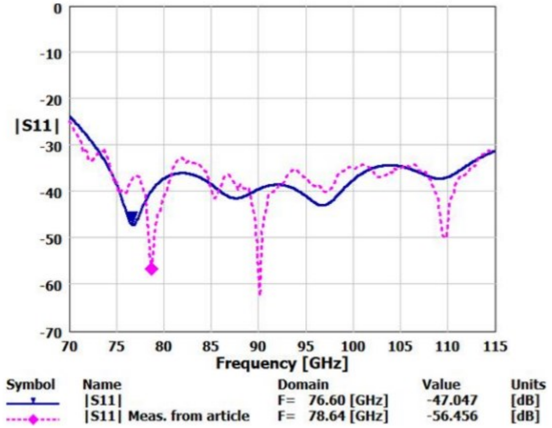
ALMA = Atacama Large Millimiter Array radiotelescope





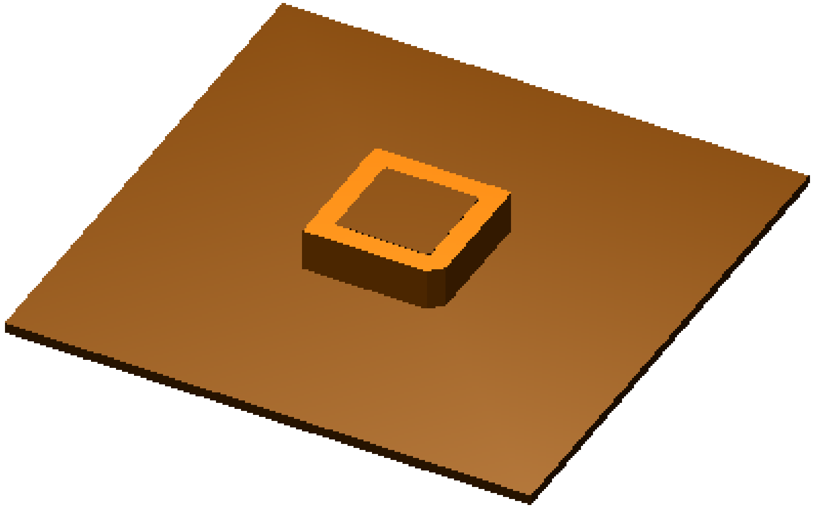


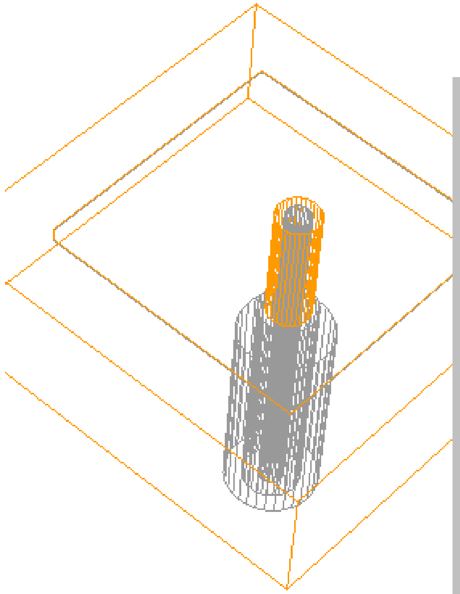


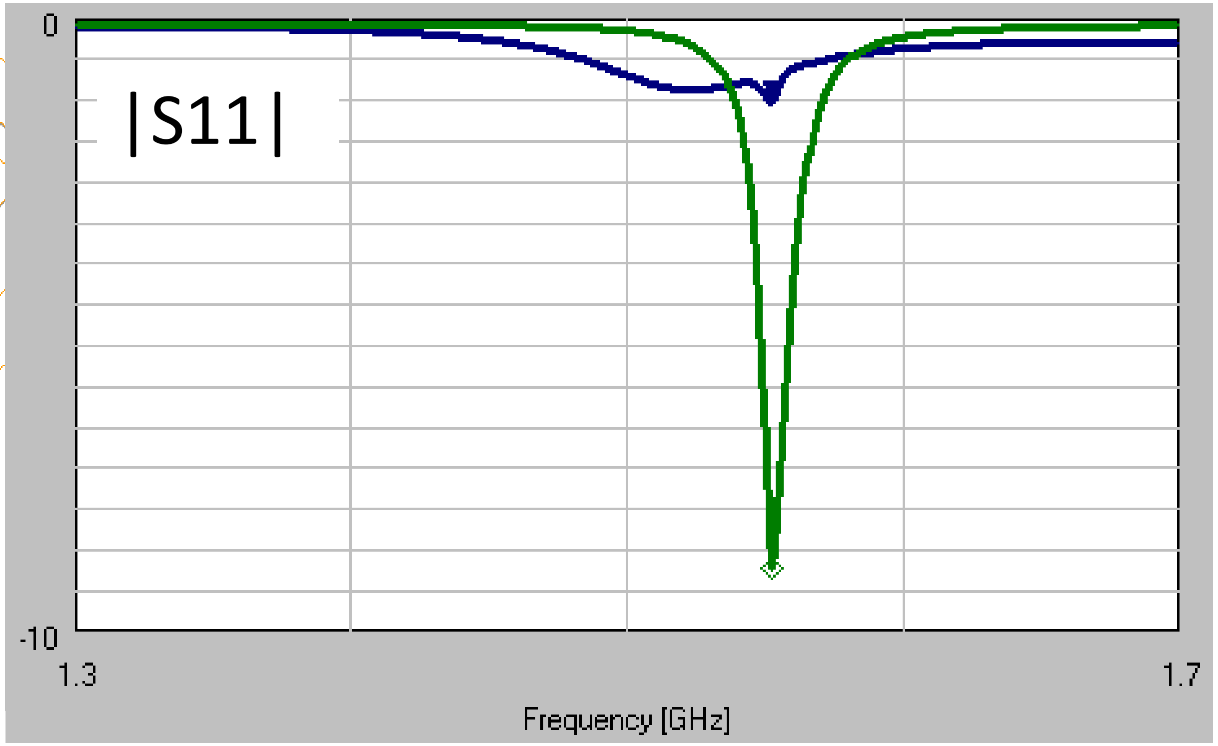


Case Study #A1: Patch GPS Antenna

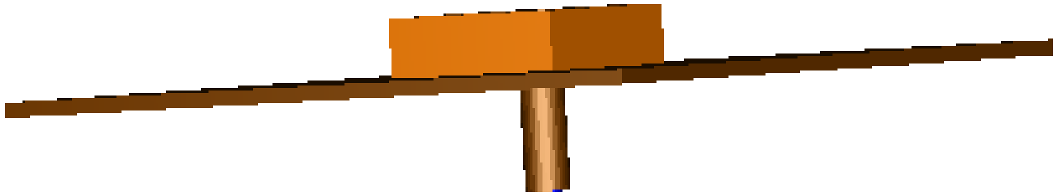
Influence of slots between metal or high-permittivity dielectric parts







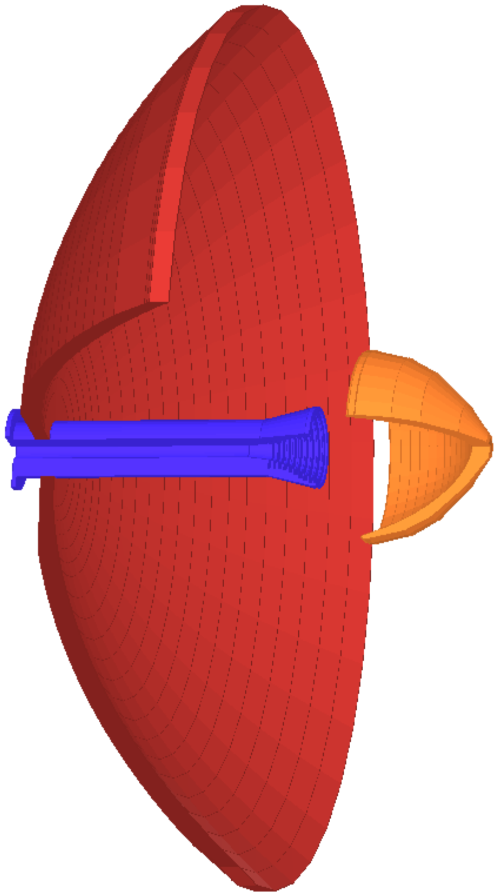
1.55 GHz patch GPS antenna fabricated on ceramic of ε_r=90, fed by coax

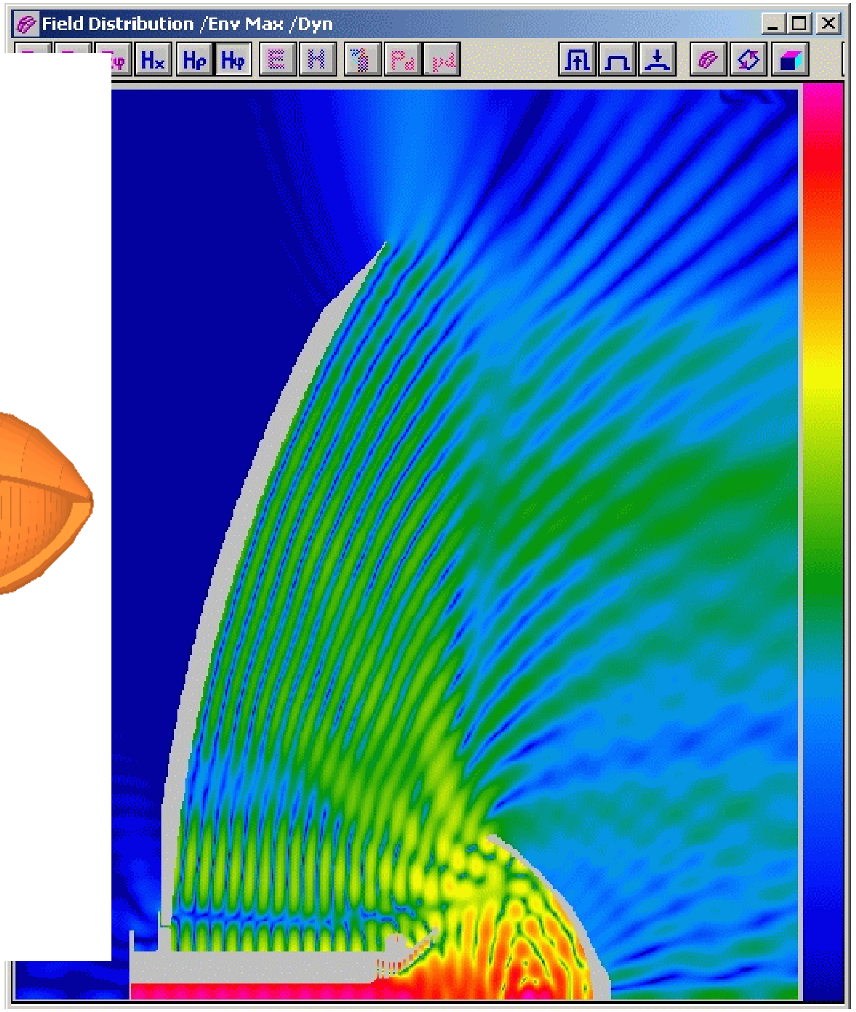


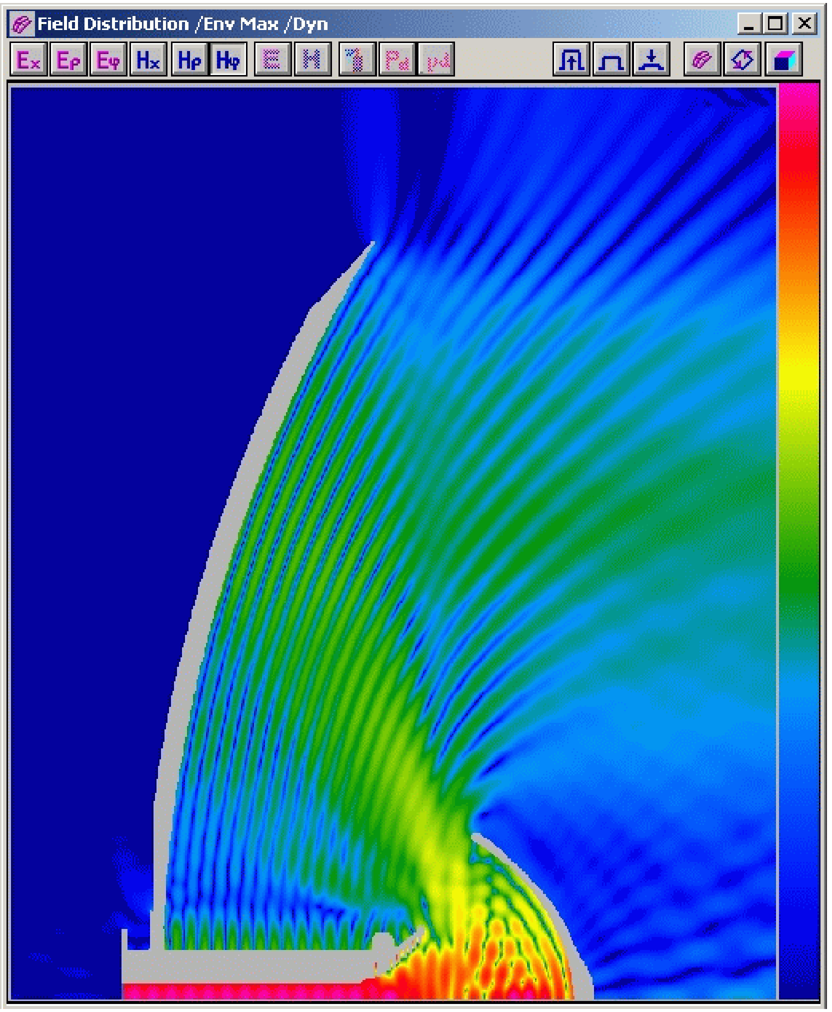
Green – measurement (and simulation with air slot)
Blue – simulation without air slot

Case Study #A2: Dual-Reflector Antenna

Spill-over detection and explanation





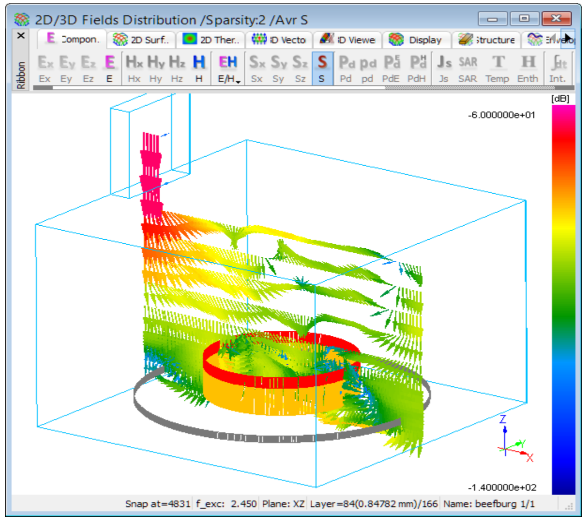


Hϕ amplitude in logarithmic scale at two frequencies different by 3 %

Such antennas are typically used for radioastronomy and satelite Earth Stations.

BoR FDTD solver is over 3 orders of magnitude faster than 3D, hence allows ultra-fast optimization.

Case Studies of Microwave Ovens



#MW1: 1997 benchmark

#MW2: Whirlpool MAX

#MW3: Whirlpool Talent

EMB-1998, Linkoping, Sweden

Problems of MW power and other ISM applications:

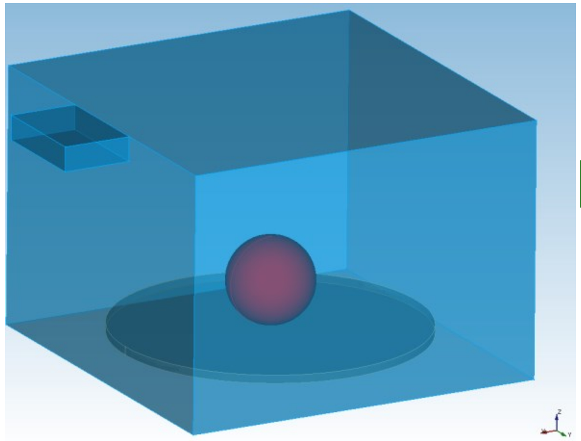
are challenging, even on the pure-EM side

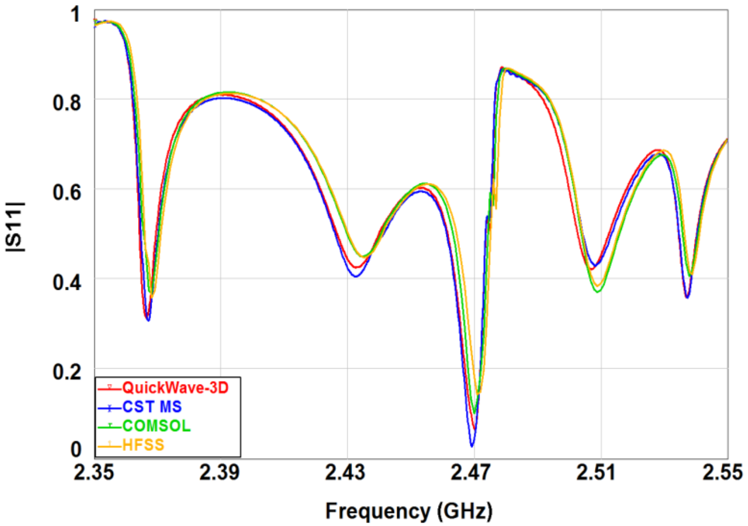
→ by today, capabilities of various FDTD and FEM software have converged (in terms of accuracy – computational efficiency differs).

These problems are particularly sensitive to knowing the material parameters and typically require a multiphysics approach.

Case Studies #MW1, #MW2: pure-EM Model

Simple microwave heating benchmarks & microwave heating phenomena studies*



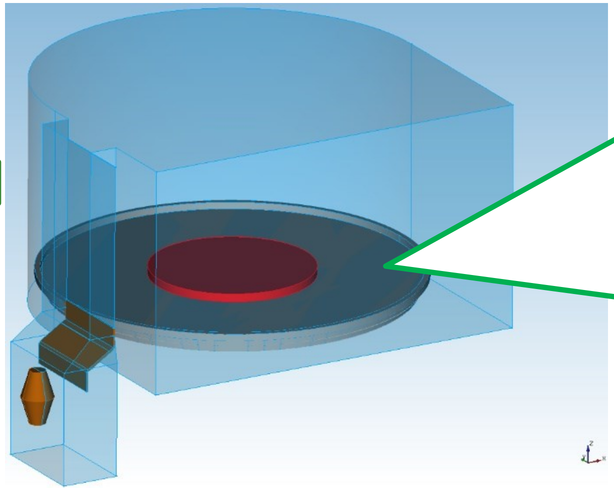


- heat transfer & load dynamics
- Load rotation & arbitrary movement during heating
- Source parameters tuning – regime for solid state sources
- Temperature dependence of material parameters

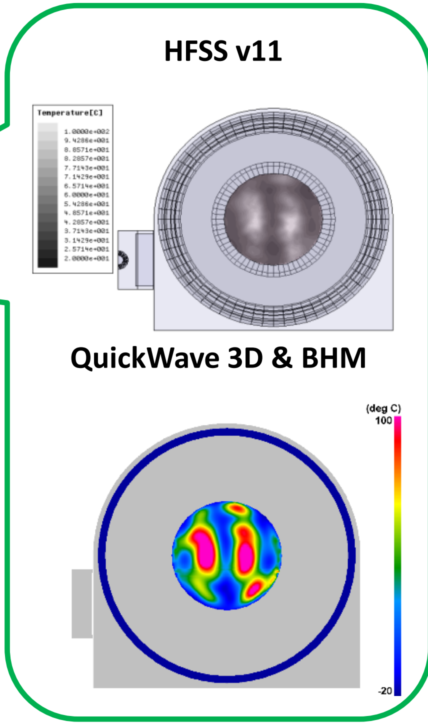
Freezing to file the state of the simulation

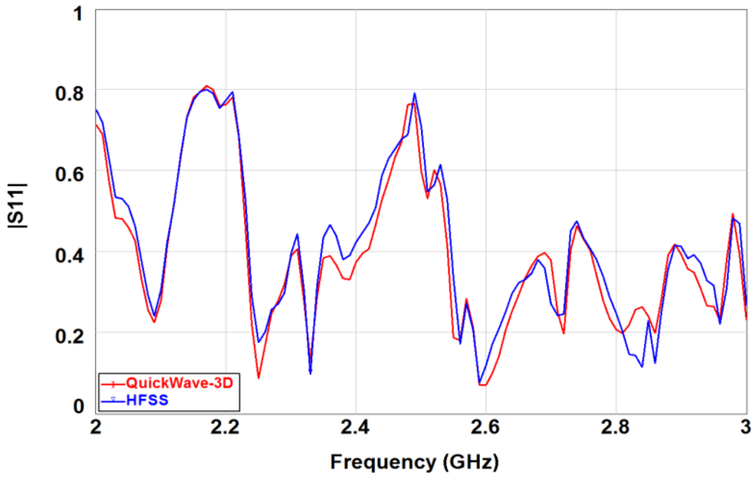
De-freezing on arbitrary computer & at convenient time

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



Courtesy of Whirlpool Inc. – Whirlpool MAX oven

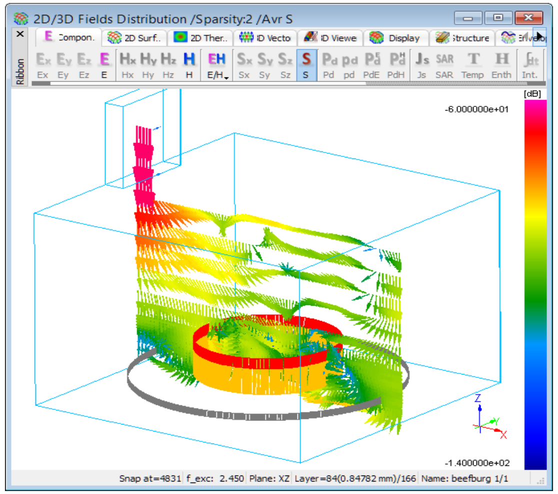


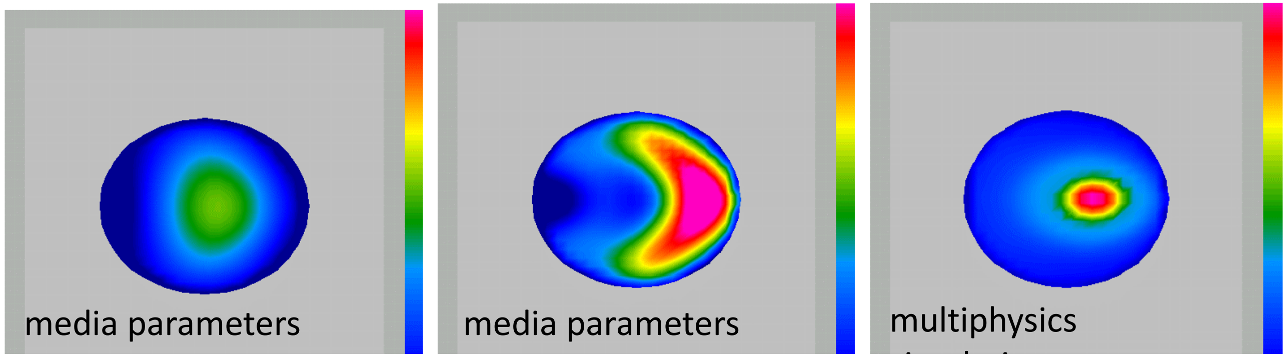


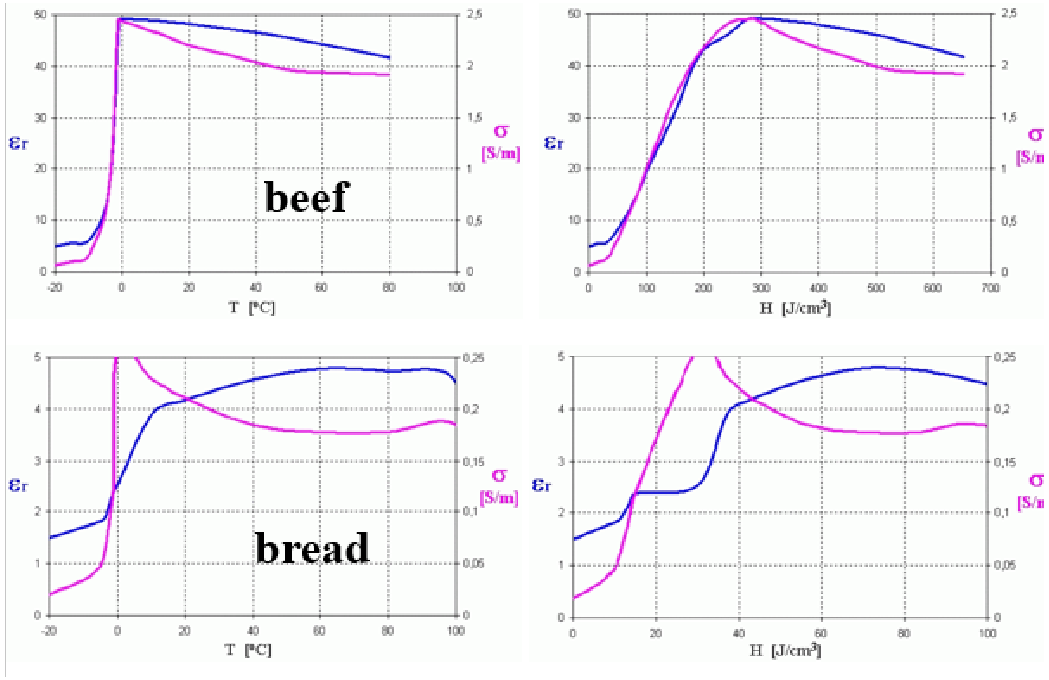
With QuickWave EM computation as fast as **1 min 18s** on a **low-cost video card** – supporting **all** graphic cards **with OpenCL**

* 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.

Case Study #MW1: EM versus multiphysics







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

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

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

Enthalpy update in 3D domain

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

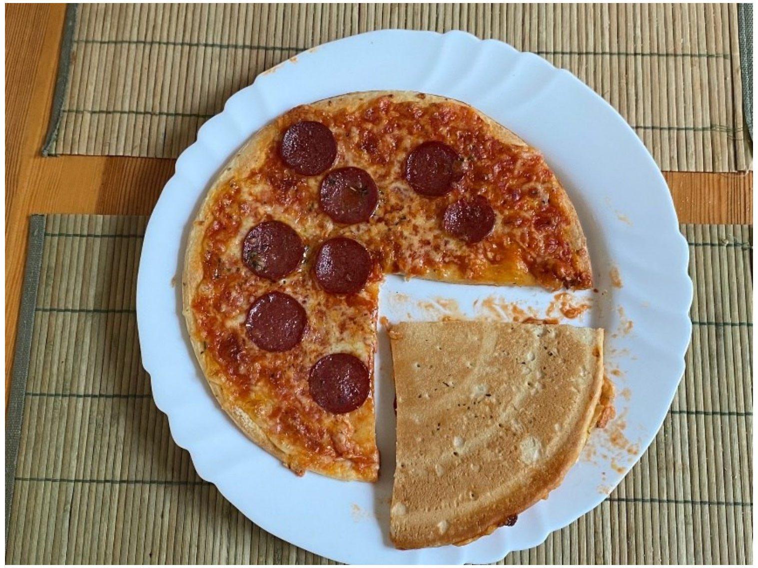
Temperature update in 3D domain
$T(x,y,z) = T[H(x,y,z)]$
from *.pmo file

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

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

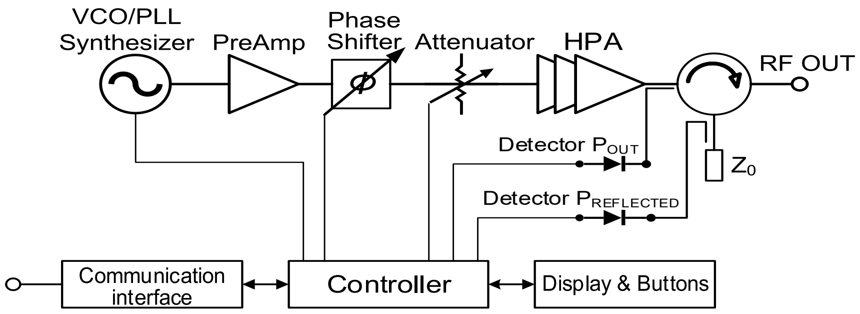
Material and ***thermal parameters*** update in 3D domain $\varepsilon(x,y,z) = \varepsilon[T(x,y,z)]$
$\sigma(x,y,z) = \sigma[T(x,y,z)]$
from *.pmo file

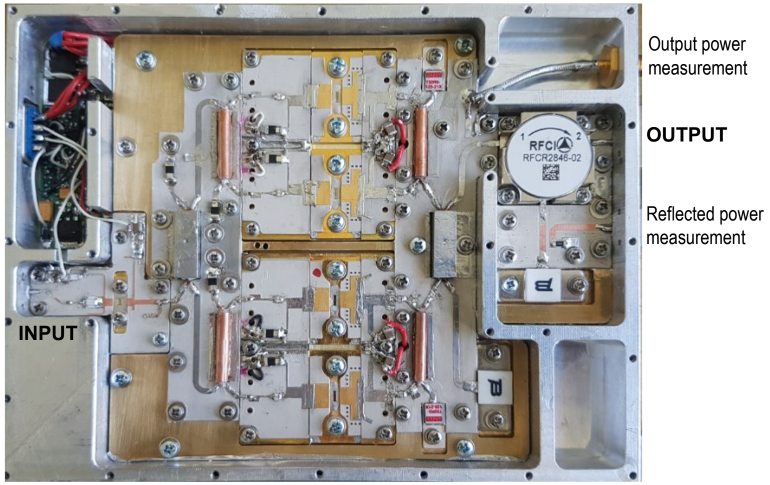
Case Study #MW3: Materials



Typical MW heating is volumetric.
Making crispy pizza requires surface crisping, which is achieved by:
- crisp plate (ferrite giving **magnetic losses**)
- underheating and horizontal polarization component.

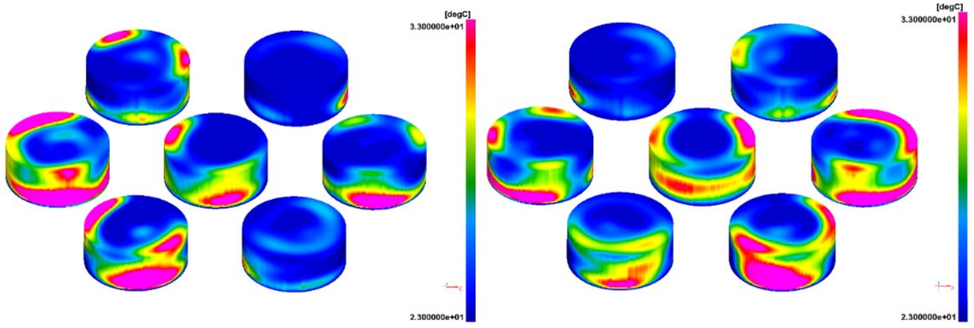
Case Study #MW4: Solid-State-Fed Oven



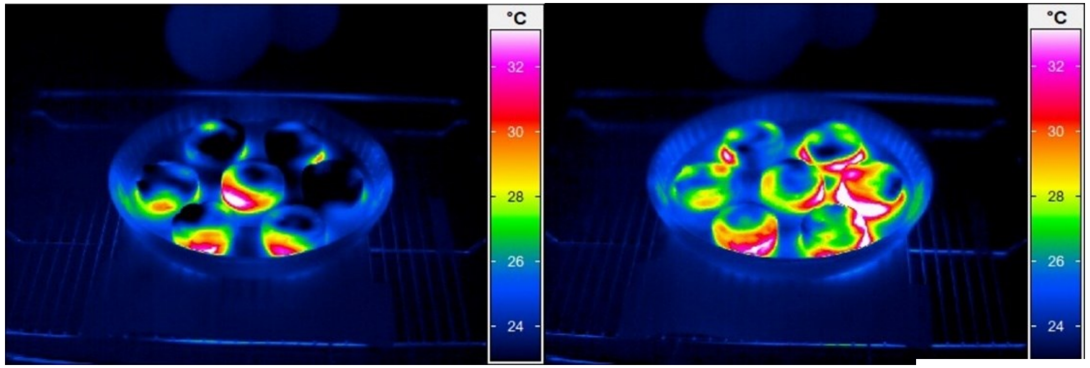


Multifunctional heating source
based on two-stage double-balanced GaN HEMT HPA
(Prof. W.Wojtasiak, Dr. D.Gryglewski Warsaw Univ.Tech.)

Temperature in mashed potato cookies, after 60 s of heating ,
for different relative phase shifts (added 110 degrees) between two sources.
(*Development of packaging and products for use in microwave ovens*, Elsevier, 2020)



QuickWave modelling by QWED

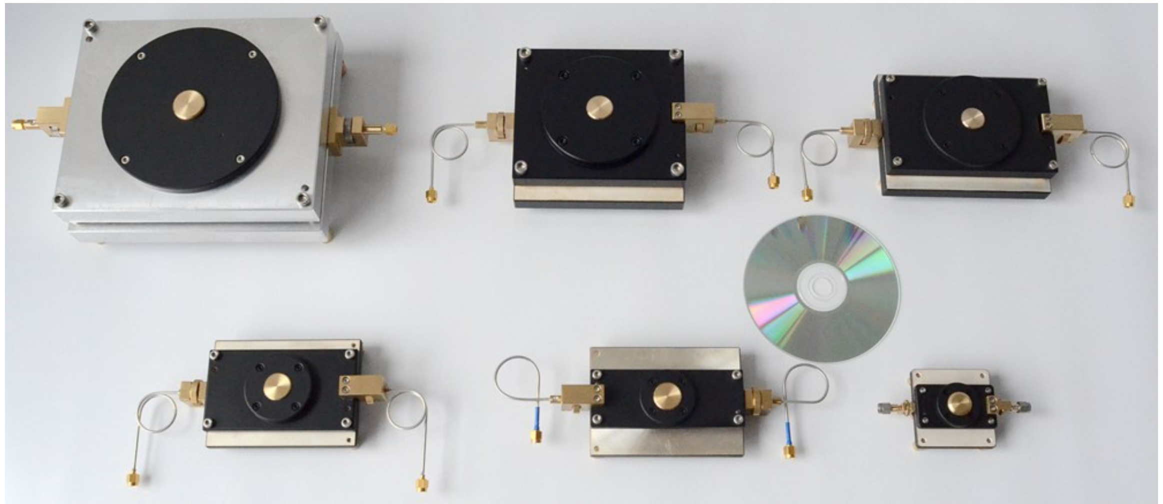


Photos courtesy BSH HAUSGERATE GmbH,
Traunreut, Germany.

B/S/H/

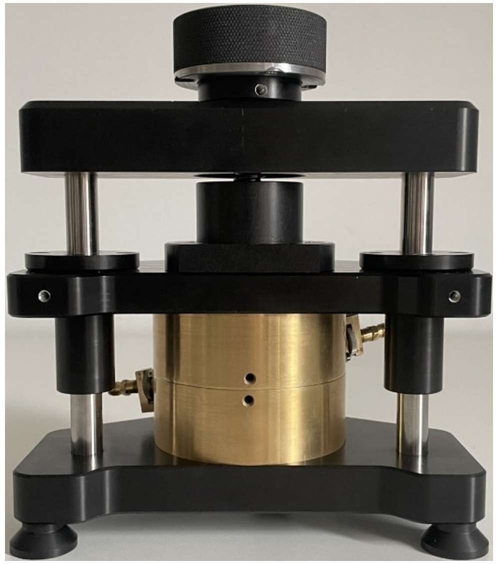
CEM-Enhanced Material Measurements

#MM1:
SPDR 1GHz -15 GHz

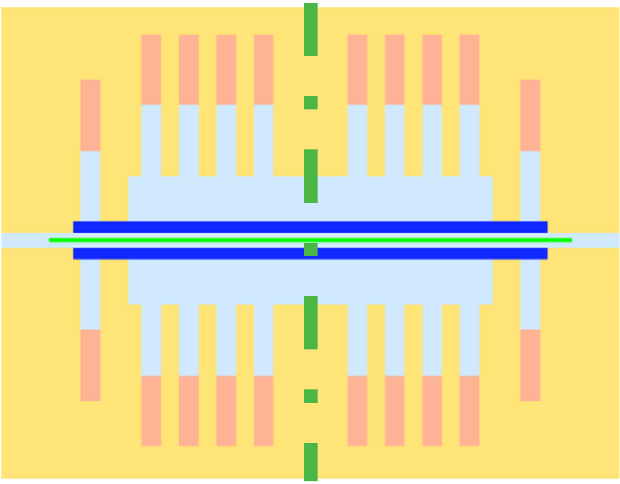


#MM2: FPOR 10-130 GHz
single sweep

#MM3:
Q-Choked resonators
NEW!
IMS2024
IMS2025

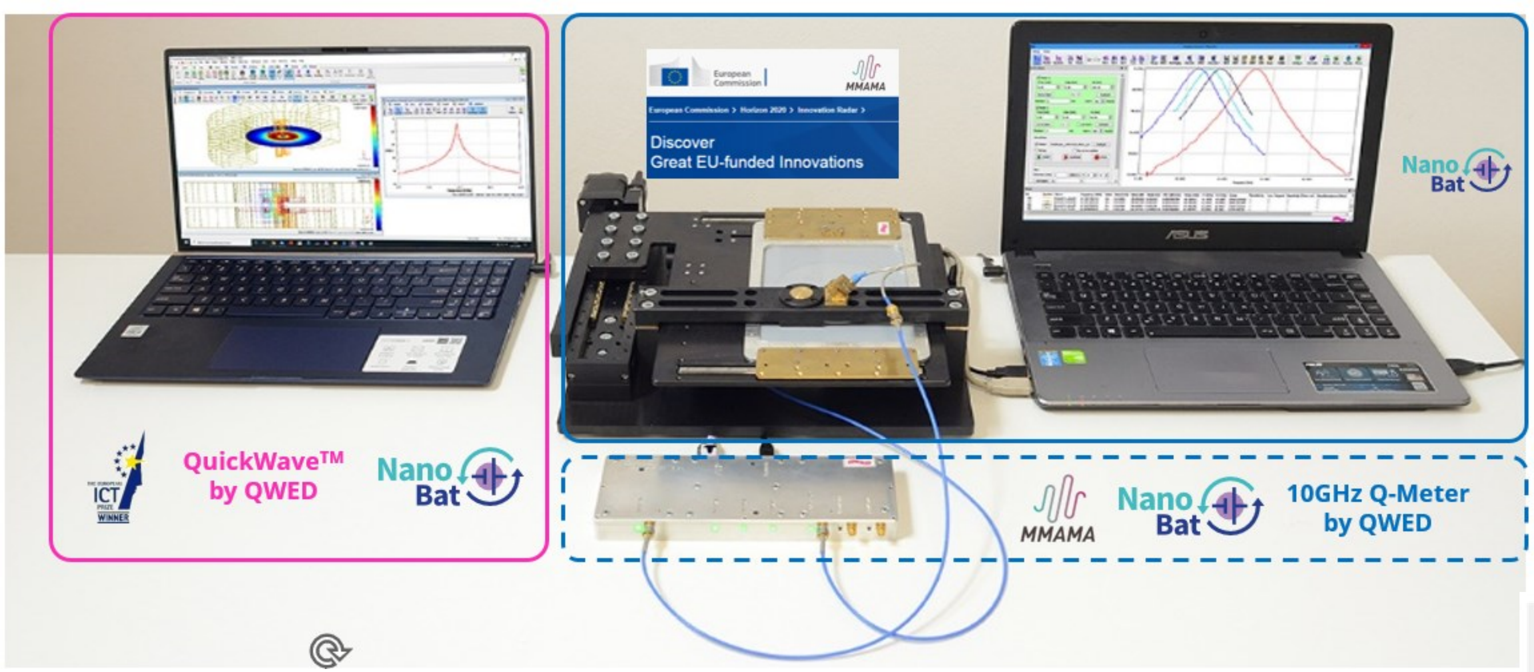


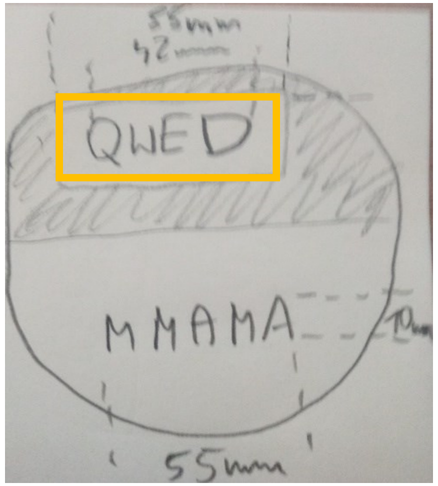
Q-SCR: thick samples

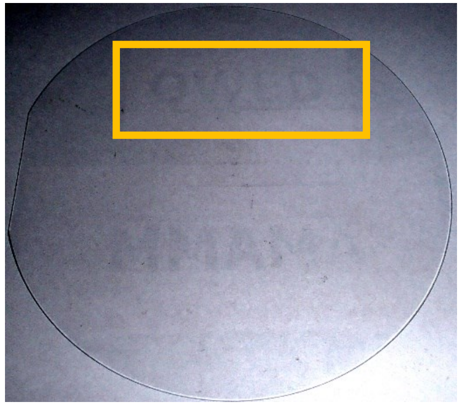


Q-SSR: multimodal,
high sensitivity

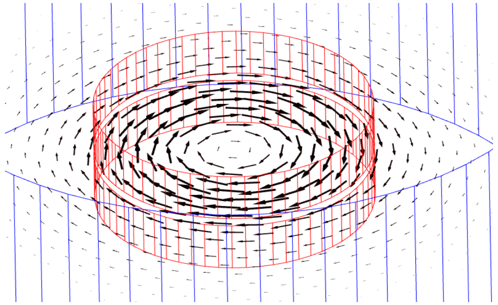
Case Study #MM1: Scanning and Resolution Enhancement

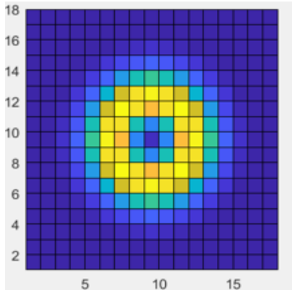


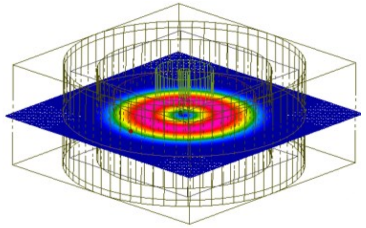




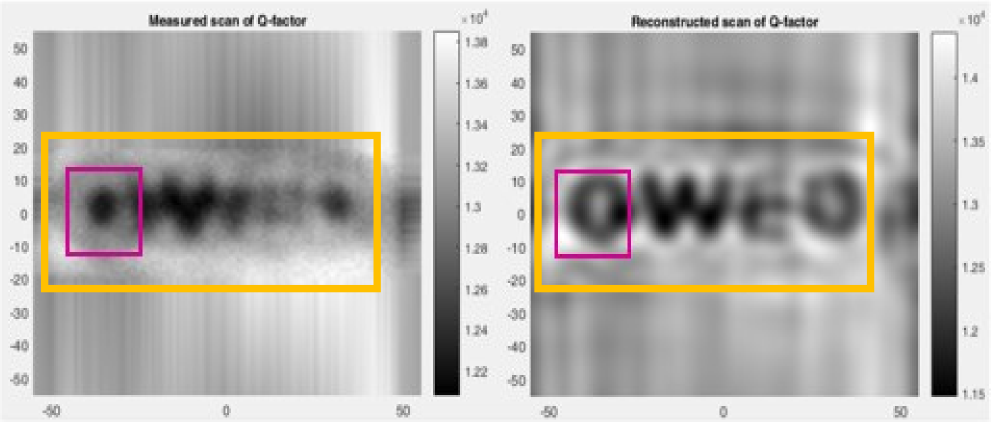
Finalist of the European Innovation Radar Prize 2021







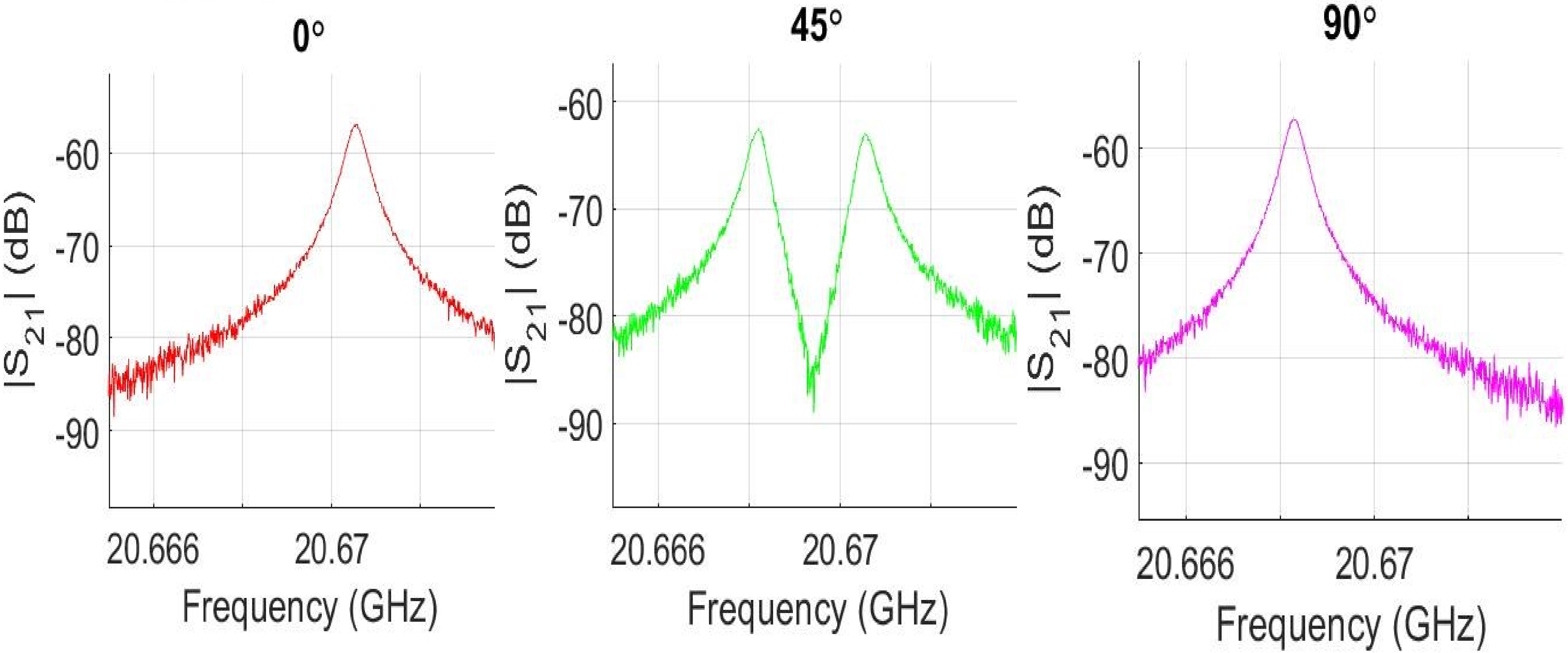
Head-size ca. 10mm at 10 GHz



direct SPDR scan

deconvolved image

Case Study #MM2: FPOR for in-plane anizotropy

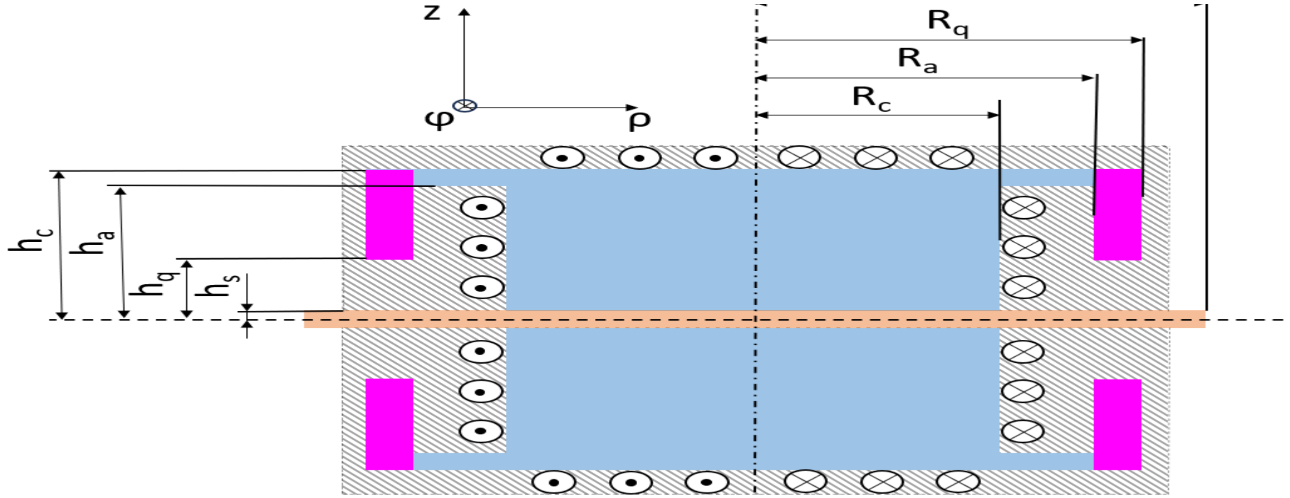


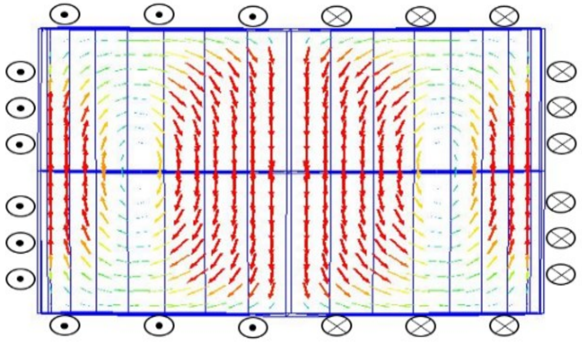
Resonances detected for BoPET sample (t = 0.100 mm), turned in xy plane.

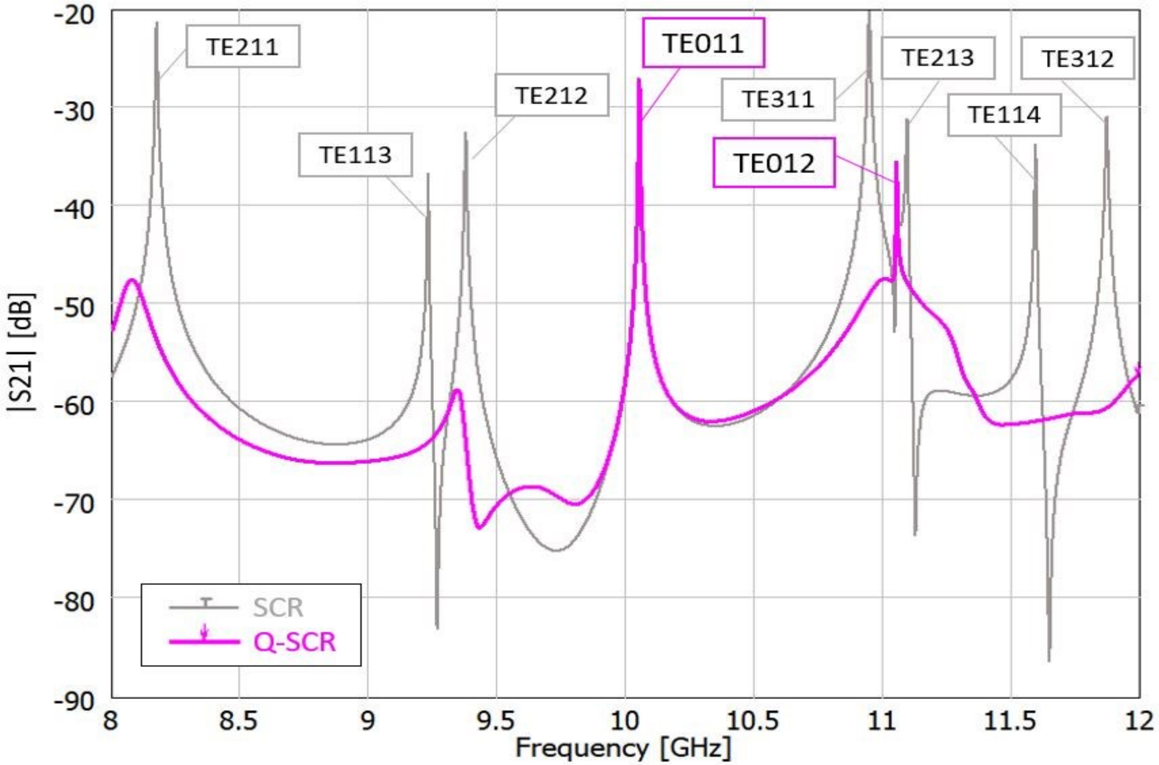
BoPET (biaxially-oriented PET) involves thermal drawing in two in-plane directions with substantially different draw ratios, followed by crystallization. Hence, it is in-plane anizotropic.

T.*Karpisz et al, " Measurement of in-plane anisotropy of dielectric materials with a Fabry-Perot open resonator", MIKON 2020*

Case Study #MM3: Q-Choked Resonators







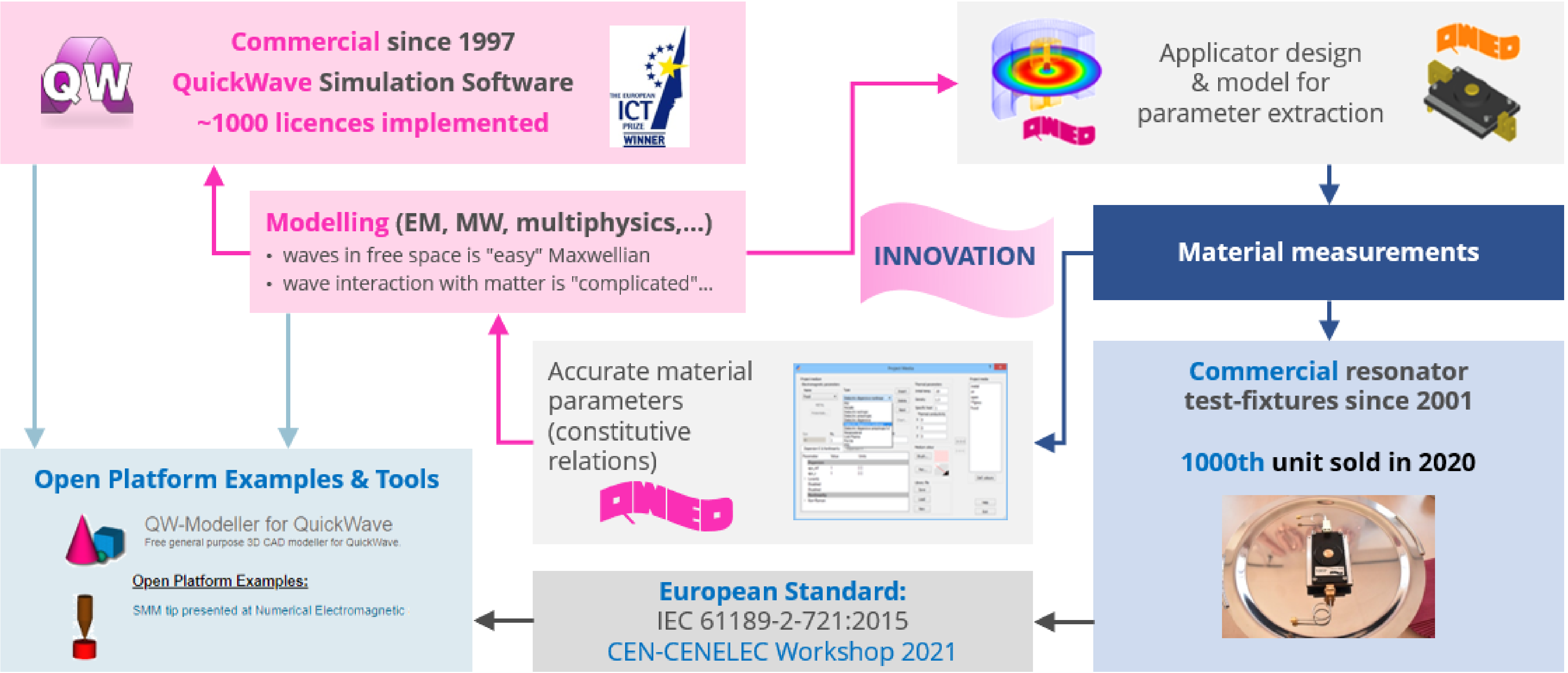
more in TH1D-5

The pure TE0mn spectrum allows measuring thicker and/or higher permittivity samples.

IMS2024 / MWTL June 2024 paper reports measurements of stacks of sapphire up to 2.03 mm (0.2 wavelength) thick, which exceeds by over a factor of 8 the declared thickness limitations of commercially available SCRs.

Conclusion

CEM facilitates innovation and creativity,
especially when combined with modeling-enhanced material measurements.



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M-ERA.NET

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I4Bags

eureka eurostars

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5G Foil

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iNEMI International Electronics Manufacturing Initiative

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MTT-S IEEE MICROWAVE THEORY & TECHNOLOGY SOCIETY

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Booth #326

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