5G/ High Frequency Materials Characterization Challenges and Opportunities

Benchmarking Resonator Based Low dK/dF Material Measurements

Authors:

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Technical Conference March 9–12, 2021

Agenda

- Motivation and Industry needs
- Gaps & Practical Challenges
- Brief overview of the iNEMI 5G/mmWave Materials Characterization Initiative
- Introduction to topics in this session

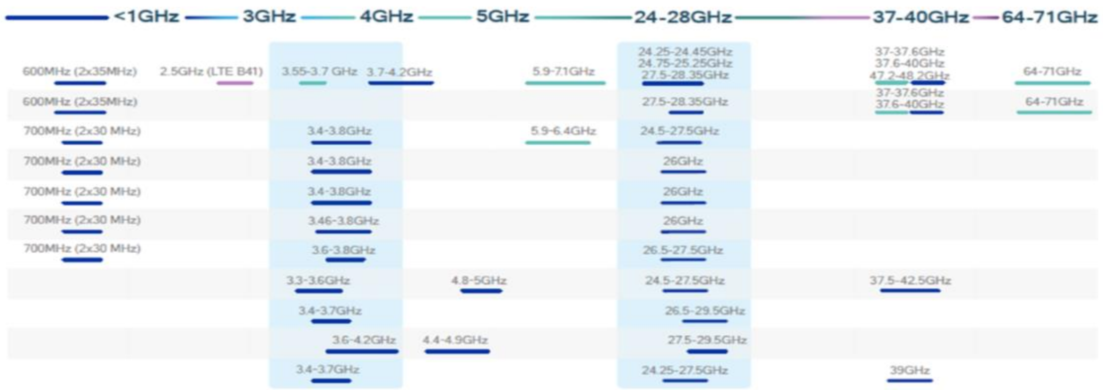
Motivation & Industry Needs

- Dielectric constant measurements are key enables for many different industries & technologies
- ‘5G’ extends beyond wireless applications – many forward-looking wired applications need material data spanning DC to 100+GHz

CPU Clock Speeds

High Speed I/O

Common to only think about ‘radio’ applications



Src: Urmi Ray, 5G/High Frequency Materials Characterization Challenges and Opportunities, EMA 2021, S13

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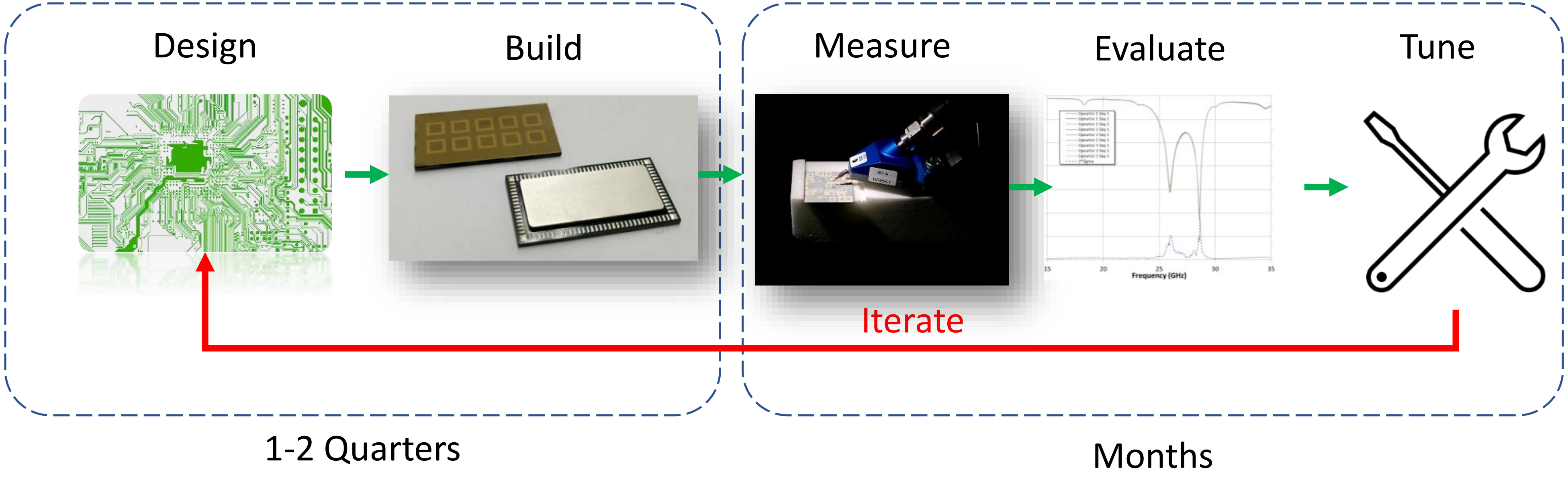
Motivation & Industry Needs

- Traditional methods of microwave design rely on trimming & tuning
- Difficult to tolerate in today's environment
- Errors in characterization limit accuracy of modeling resulting in time consuming iterations

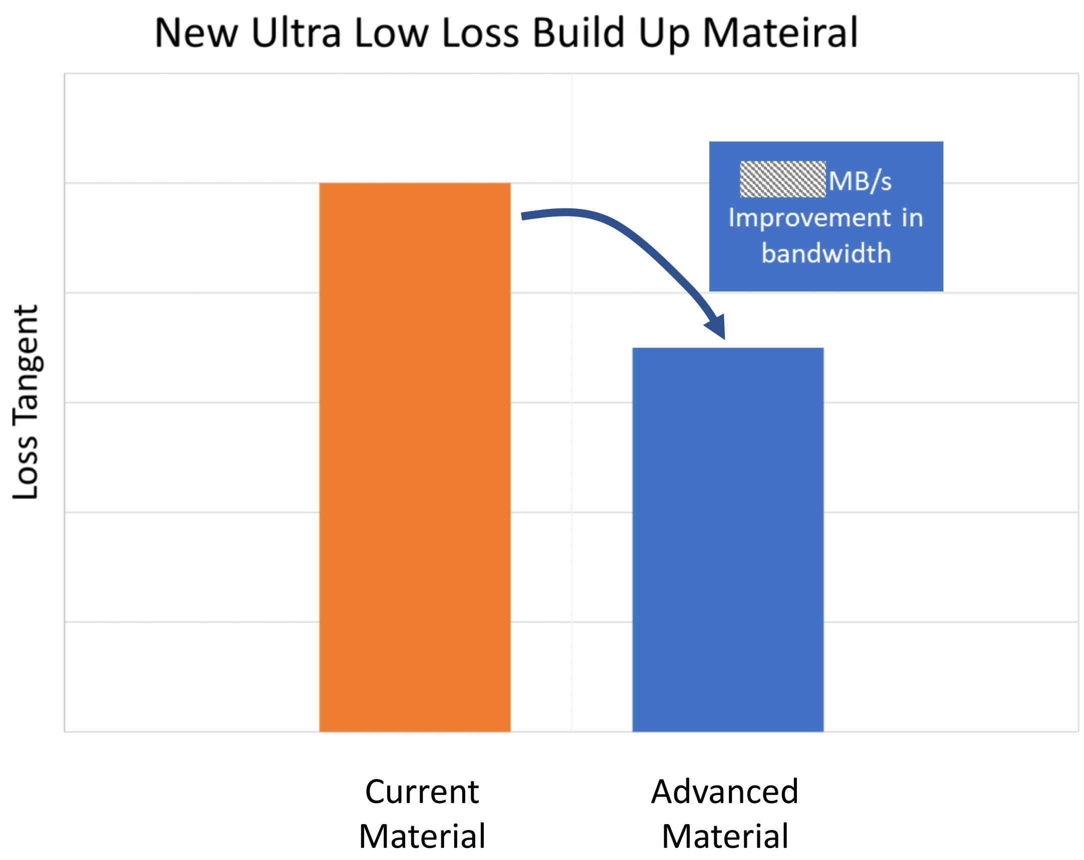


Motivation & Industry Needs

- 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



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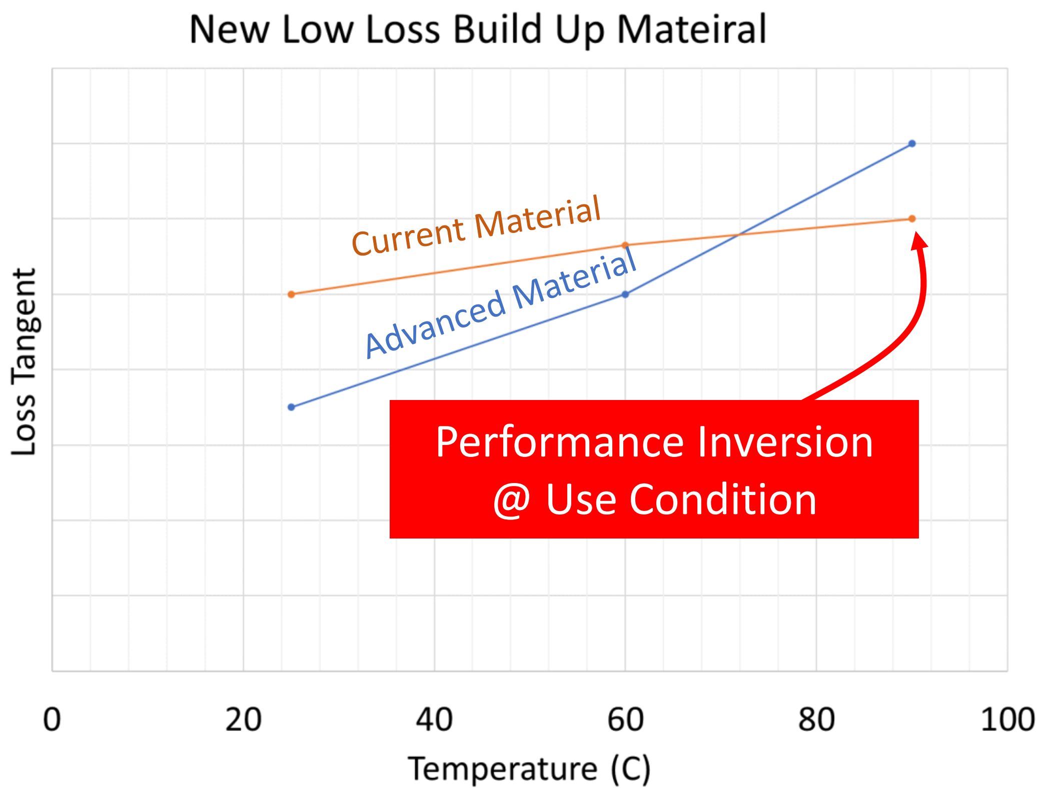
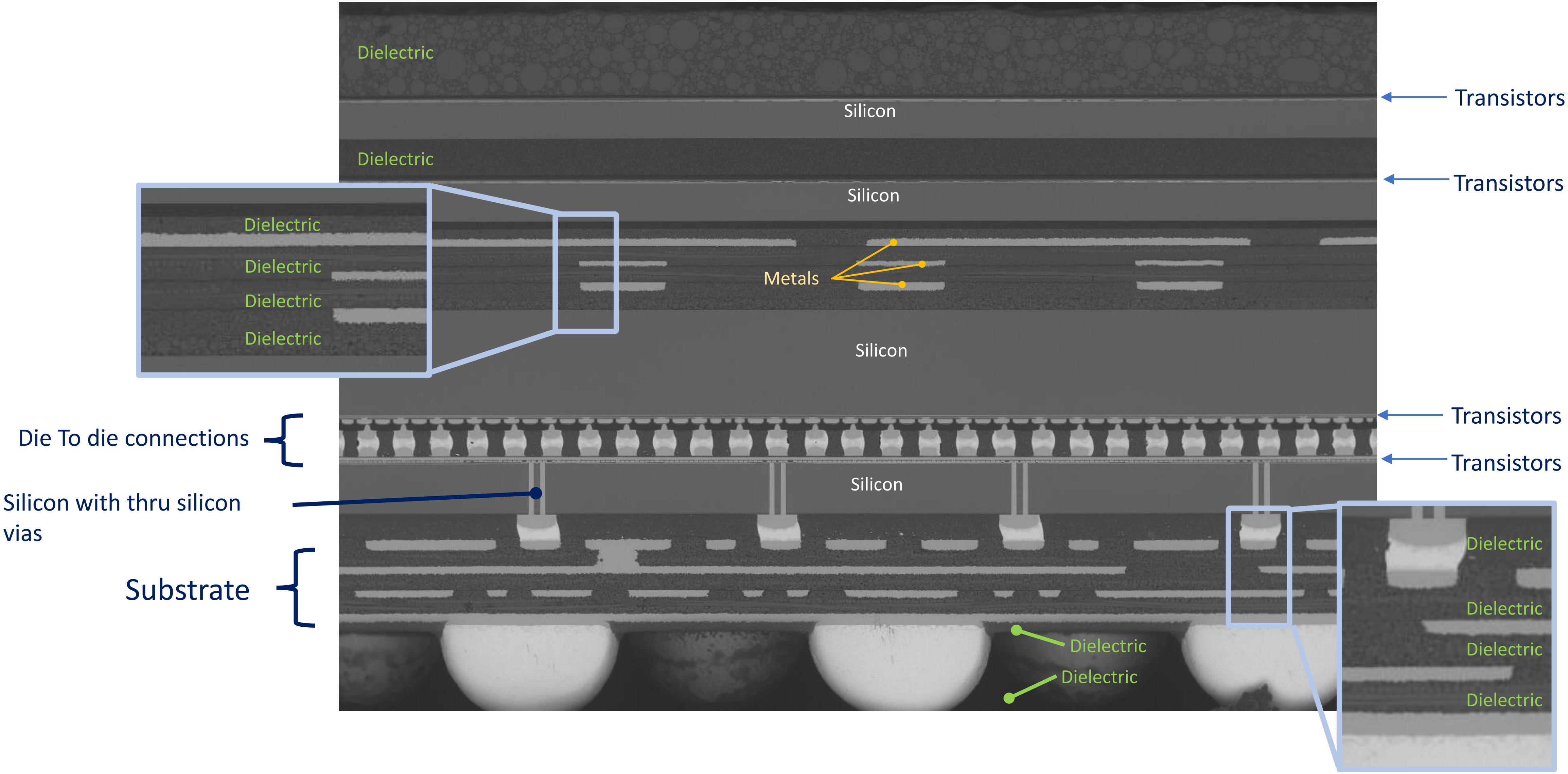


Errors in characterization can cost many $10's of millions for a single program, or worse, induce unexpected product failures


Dielectric
Silicon
Dielectric
Silicon
Dielectric
Dielectric
Dielectric
Dielectric
Metals
Silicon
Transistors
Transistors
Transistors
Transistors
Die To die connections
Silicon
Silicon with thru silicon vias
Substrate
Dielectric
Dielectric
Dielectric
Dielectric
Dielectric
Dielectric

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Gaps & Practical Challenges

Few vendors providing mmWave Permittivity equipment >20 GHz.

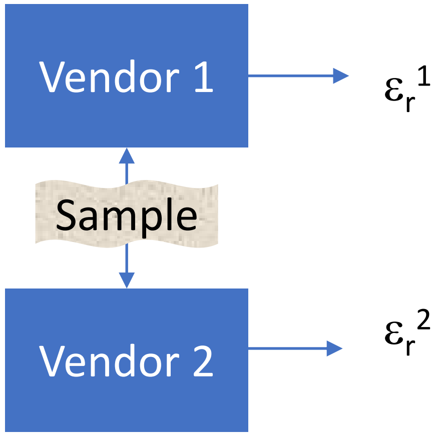
- None are traceable – vendor to vendor differences up to user
- Challenges for ISO and quality control
- Who to trust
- Reliance on small vendors can be problematic

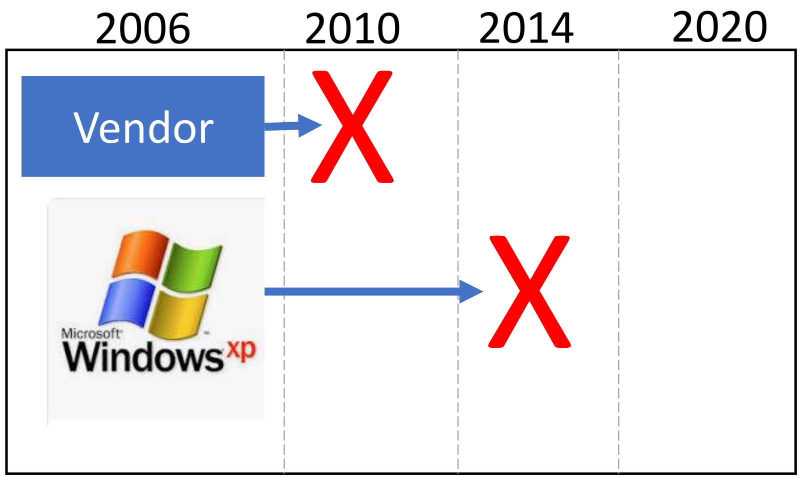
Useful 5G materials typically very lower loss

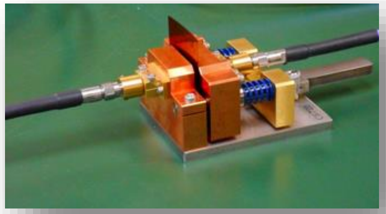
- Eliminates many traditional techniques

Increasing frequency

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







iNEMI – International Electronics Manufacturing Initiative
Project: 5G/mmWave Materials Characterization

- 5G solutions require ultra-low loss laminate materials and PCBs/substrates
- No consistent methodology for measuring dielectric properties at mmWave Frequencies
- Many different approaches in use, requiring different fixtures, sample requirements
- Consistency in results between approaches is unclear

- iNEMI Project team members cover wide range of industry, academia and equipment suppliers
- All have vested interest in mmWave materials characterization

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

Project Goals

- Gather industry experts to understand needs and try to address these problems
- Encourage development of traceable material references by standards organizations
- Better linkage between equipment manufacturers and end users

Task 1

Benchmark
- Current techniques
- Typical material samples
- Potential reference materials
- Common practices & issues

Report complete ✓

Task 2

Benchmark
- Emerging techniques
- Possibilities beyond 100GHz

Report complete ✓

Task 3

Round Robin Tests
- Create reference samples
- Test metrology differences
- Study lab to lab variations

In Progress Round 1

Round Robin Overview – Task 3

Sample Material Requirements

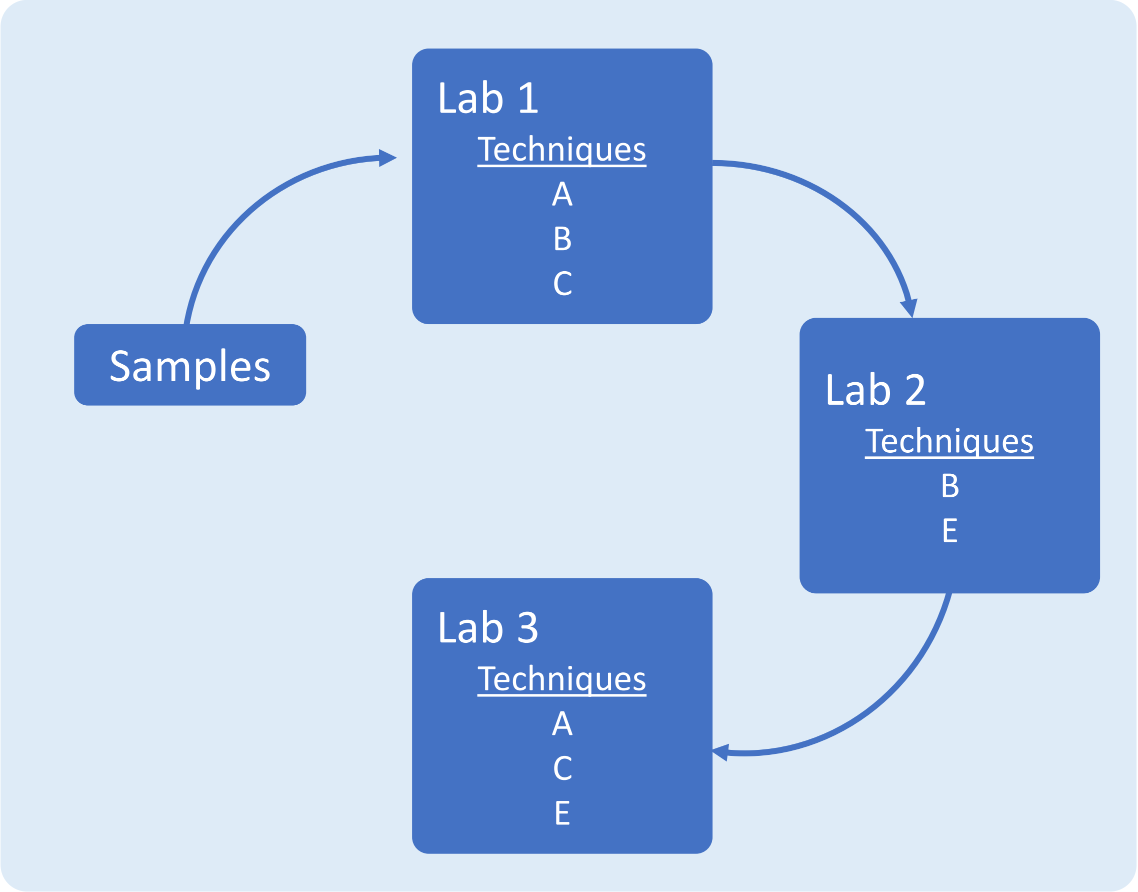
- Stable, Low loss
- Low moisture absorption / temperature dependency
- Isotropic
- Good mechanical & handling properties

Current Selection

- Precision Teflon
- Cyclo Olefin Polymer

Future additions

- Rexolite
- Fused Silica



9 Laboratory Effort

Round Robin Overview – Task 3

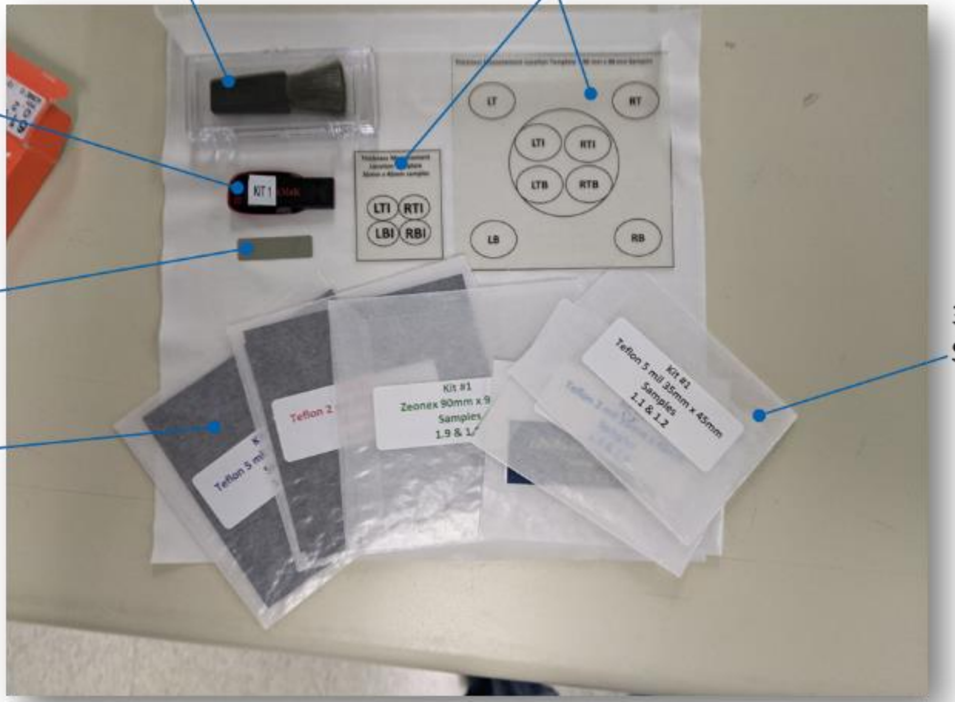
10 Kits Created

- Sample sizes 35 mm x 45 mm, 90 mm x 90 mm
- 9 International labs participating

Techniques included

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

Frequency Span : 10GHz – 100GHz



Expect results to come in over the next few quarters

Upcoming Presentations

Task 1

Benchmark
- Current techniques
- Typical material samples
- Potential reference materials
- Common practices & issues

Report complete ✓

Finding: importance of cavity resonator techniques

Malgorzata from QWED will share an overview of these important techniques

Task 2

Benchmark
- Emerging techniques
- Possibilities beyond 100GHz

Report complete ✓

Highlights: techniques for the future

Nate from NIST will present an overview of techniques on the horizon & potential paths to traceability

Commonalities

Higher frequencies
Tighter dimensions
Challenging sensitivities

Best practices for measurements

Say and Daisuke from Keysight will wrap up this session with recommendations for quality measurements

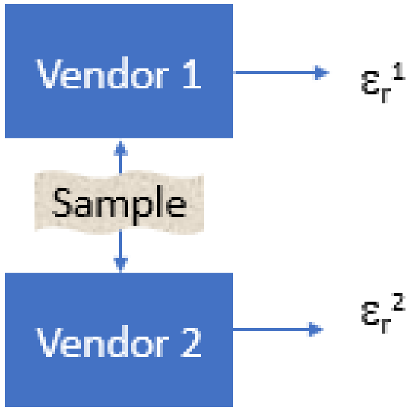
Resonator methods considered in iNEMI 5G project

Why we use resonant methods

How these resonant methods work

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

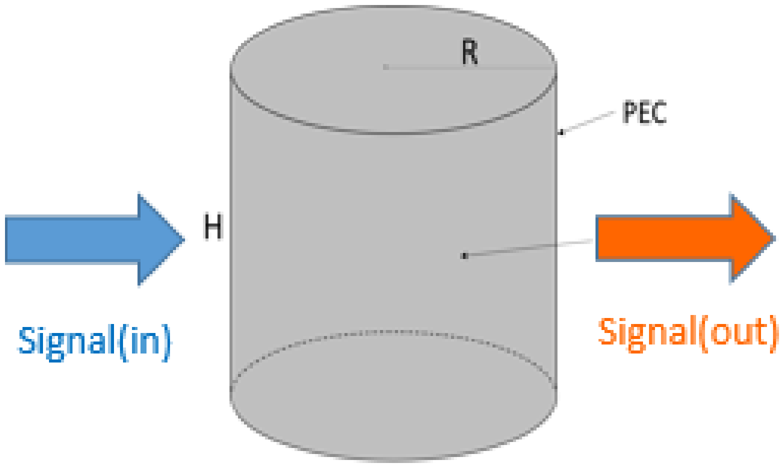
Why these different methods may produce different results

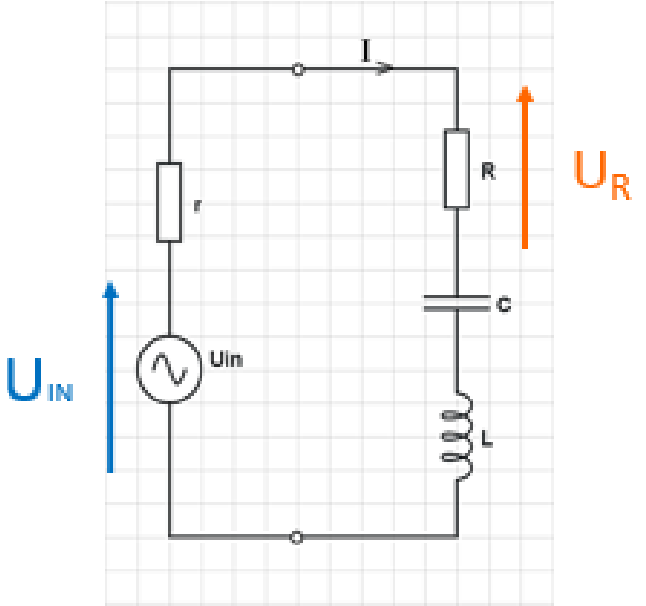


what is vendor-specific,
what is method-specific,
and what other criteria may come into play

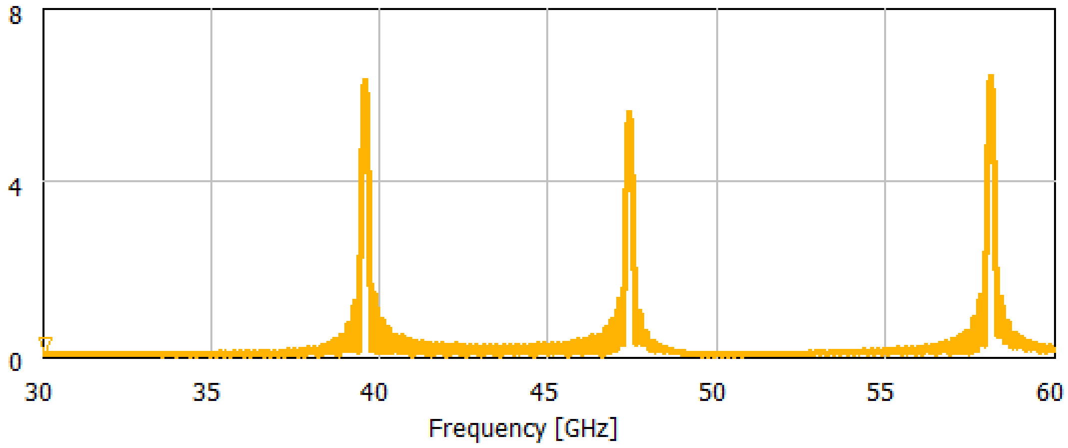
Resonator methods – motivation and background (1)

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



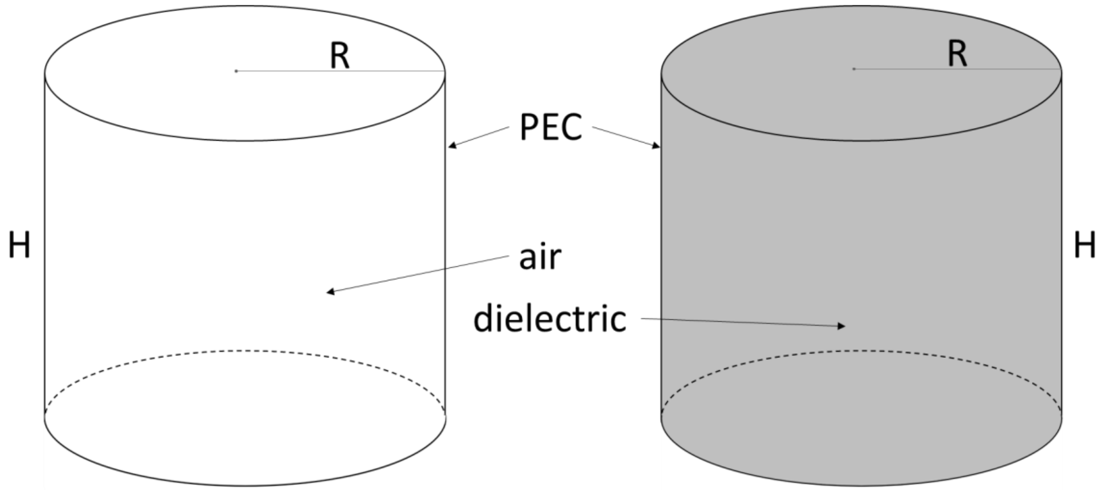


δ(t)



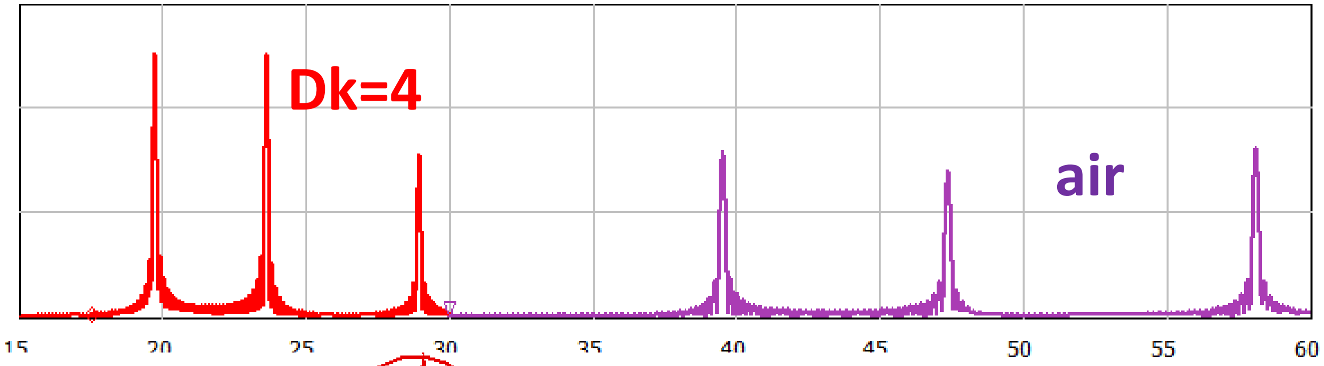
Resonator methods – motivation and background (2)

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

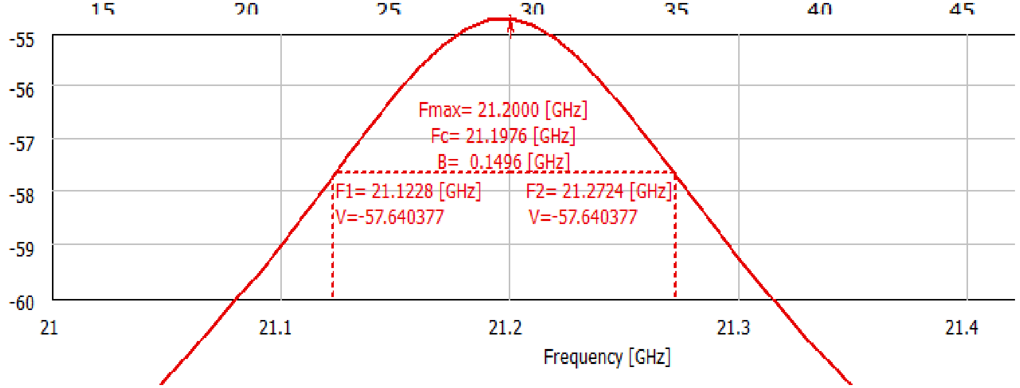


$$f_{r,mnp} = \frac{c}{\sqrt{Dk}} \sqrt{\left(\frac{\kappa_{mn}^{(\prime)}}{\pi R}\right)^2 + \left(\frac{p}{H}\right)^2}$$

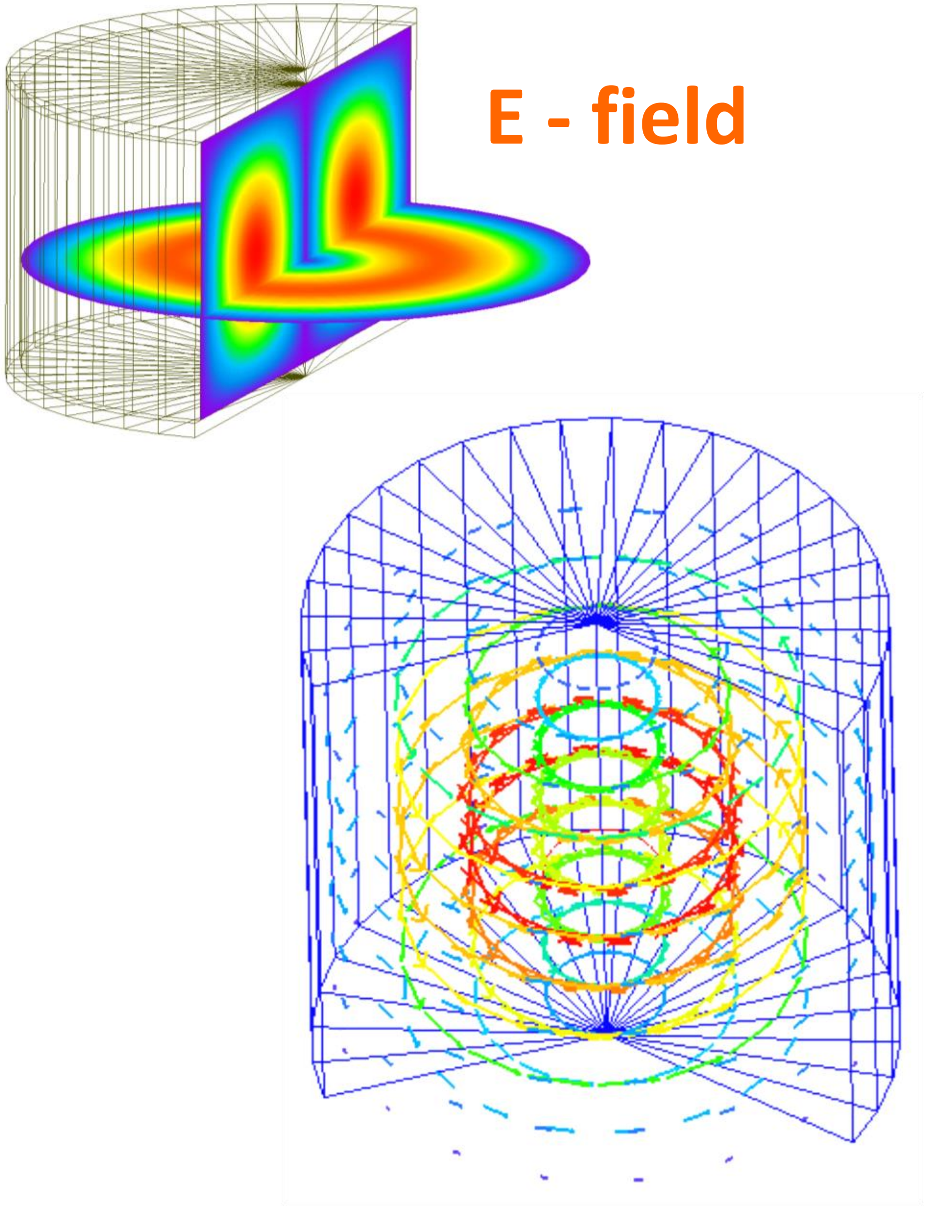
in non-magnetic low-loss dielectrics

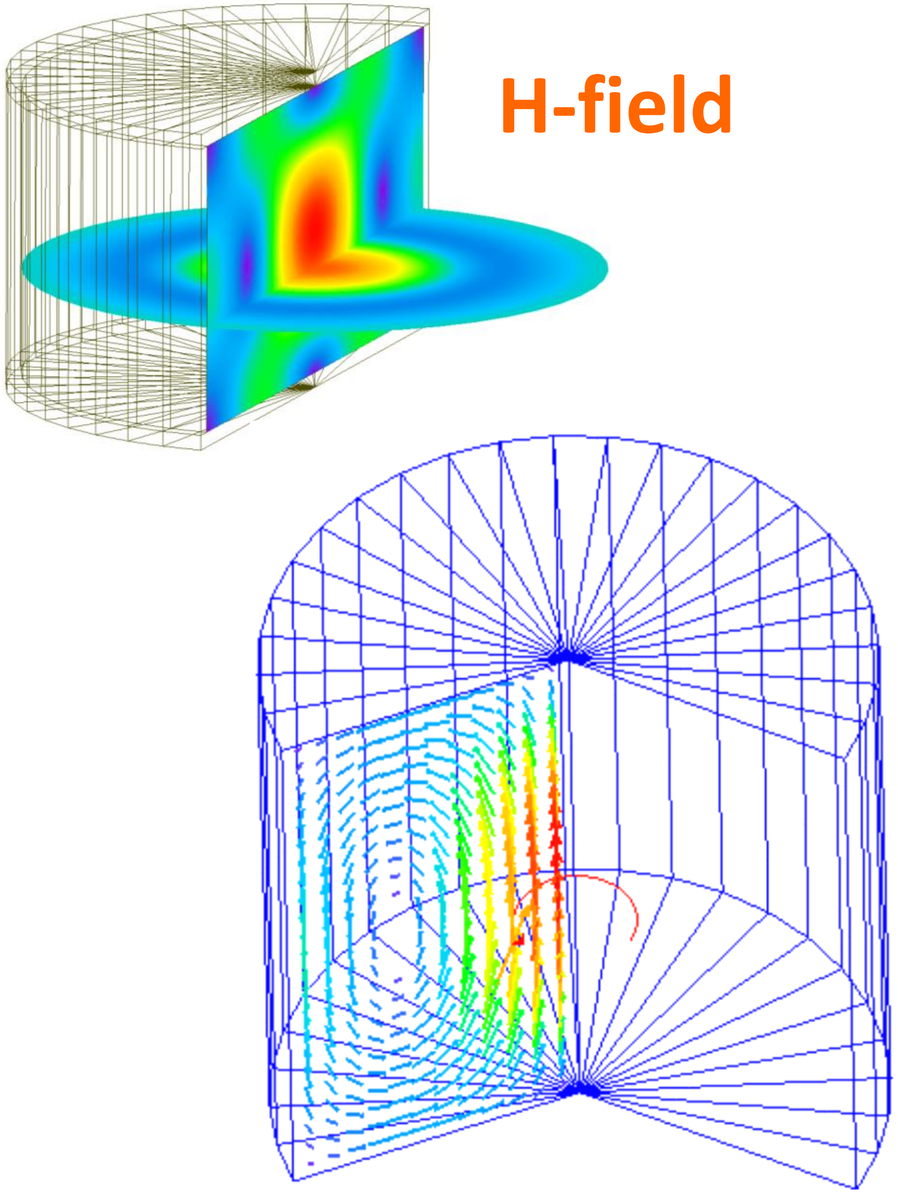


$$Q = 2\pi \frac{\iiint_V \varepsilon \vec{\boldsymbol{E}} \cdot \vec{\boldsymbol{E}}^* dv}{T \iiint_V \sigma \vec{\boldsymbol{E}} \cdot \vec{\boldsymbol{E}}^* dv} = \frac{\omega\varepsilon}{\sigma} = \frac{1}{Df} \approx \frac{fres}{\Delta f}$$

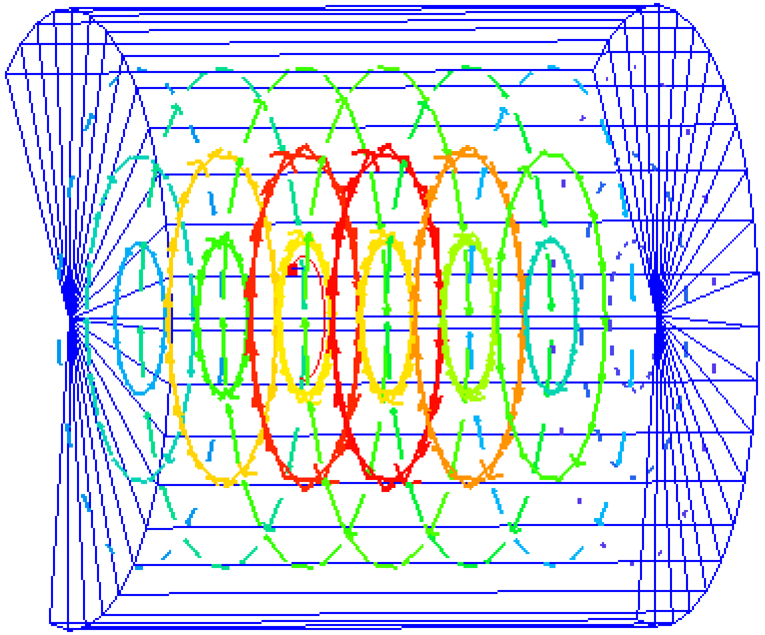


Cylindrical resonator: TE011 mode

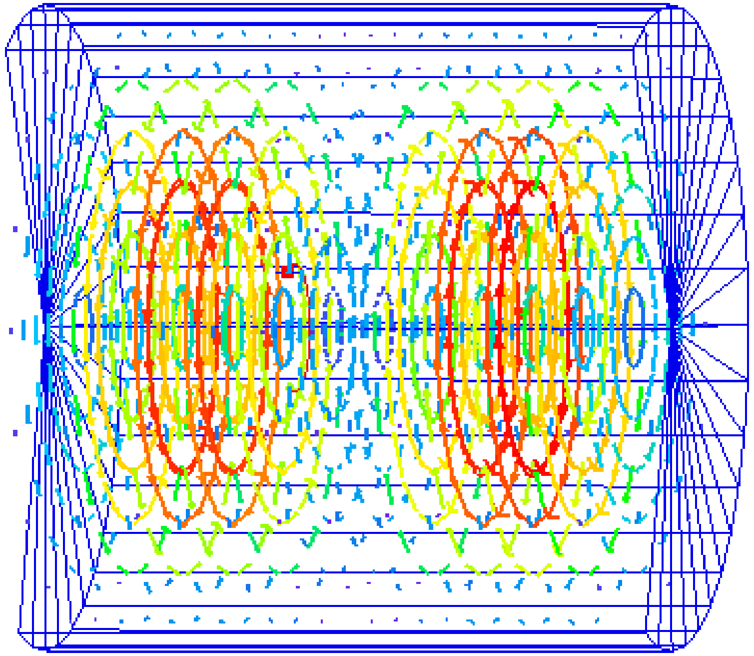




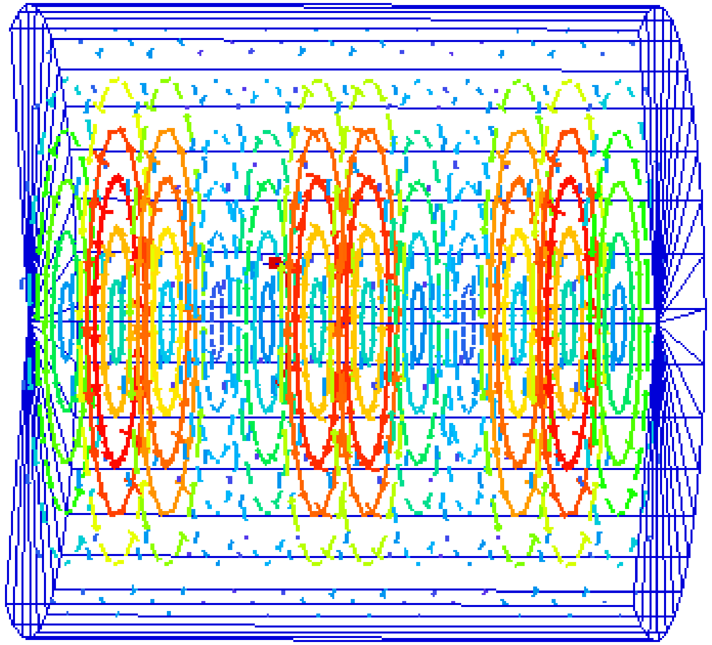
Cylindrical resonator: single-mode versus multi-mode operation



TE011 @ 29.43 GHz



TE012 @ 47.25 GHz



TE013 @ 57.95 GHz

Resonators are multimode devices.

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

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

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

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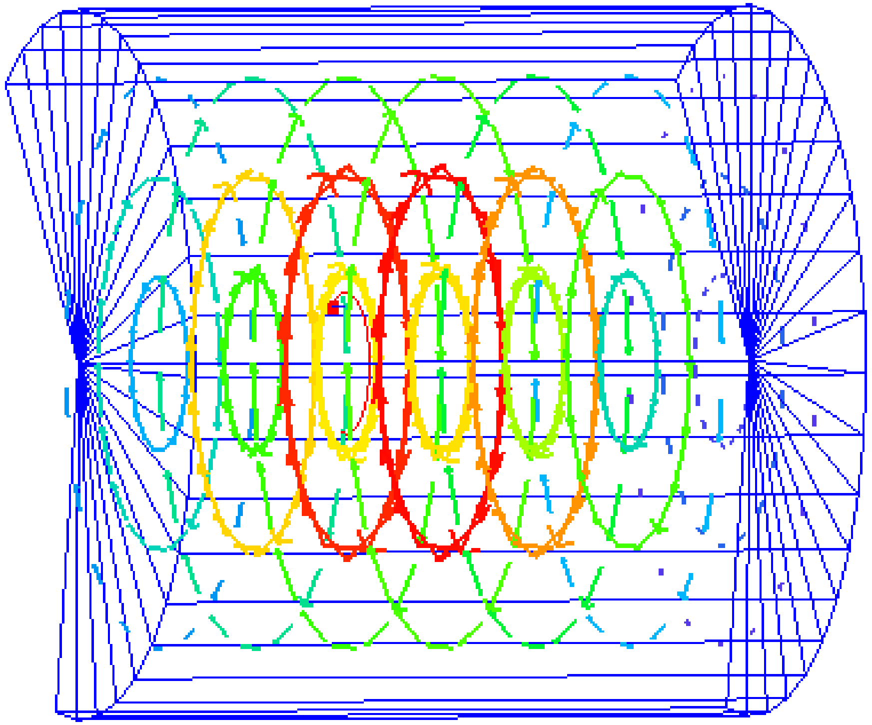
Among the popularly available resonators, BCDR and FPOR work as multi-modal.

Resonator methods – motivation and background (3)

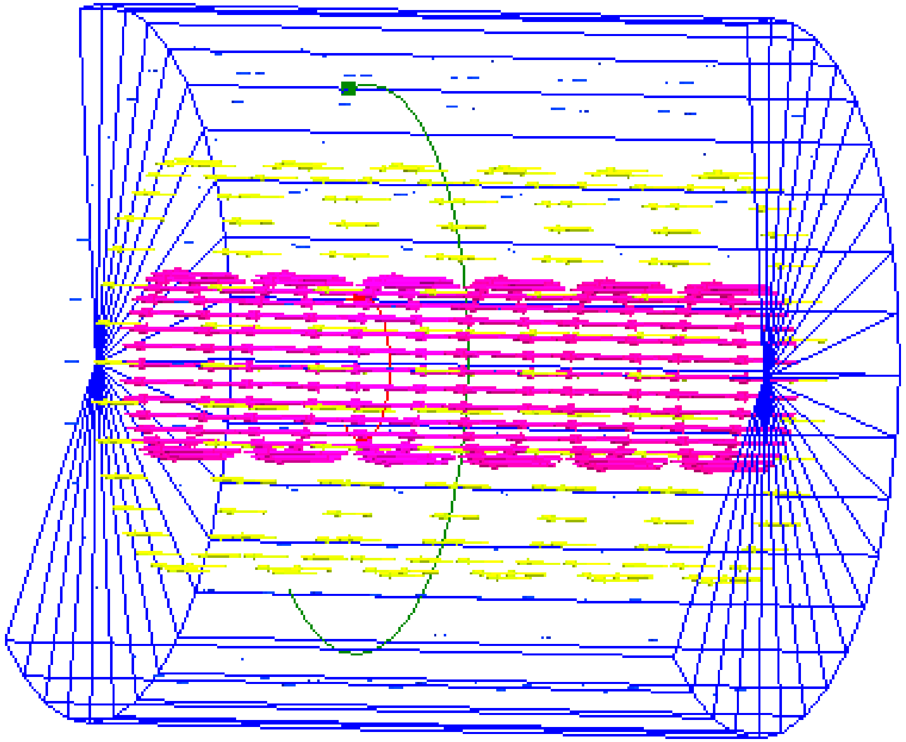
TE010



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

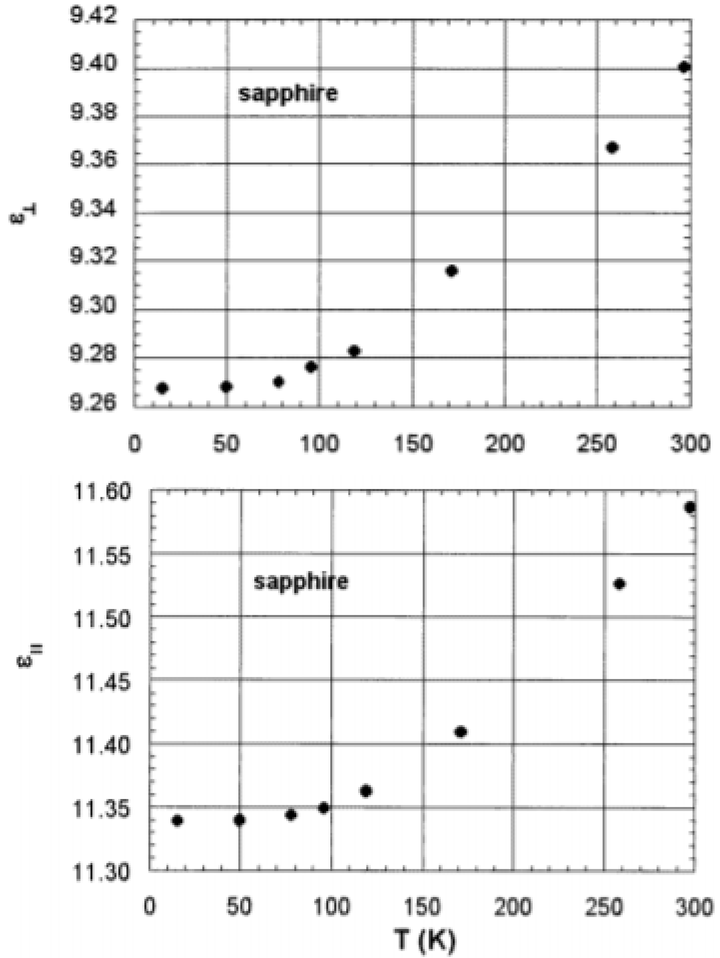
SCR, SPDR, FPOR

TM010



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

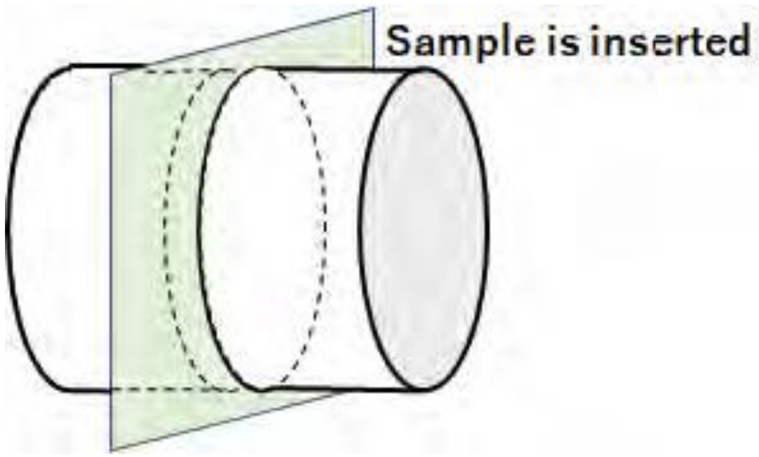
BCDR

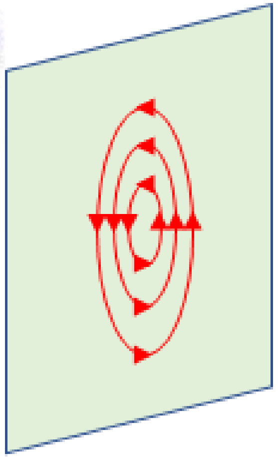


J.Krupka et al., "Complex permittivity of some ultralow loss dielectric crystals..", Meas. Sci. Technol. 10 (1999).

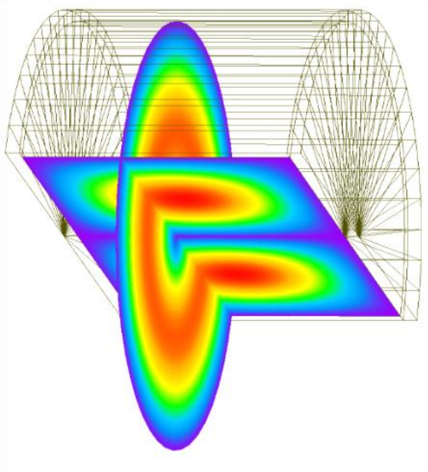
 Full characterisation of anisotropic materials (like crystals) requires both measurements.

Split Cylinder Resonator (SCR) - basics

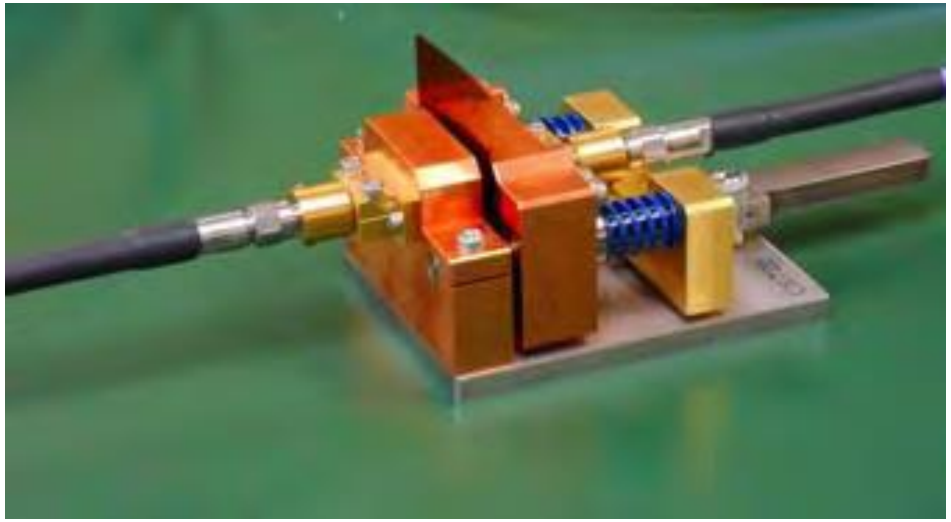




In-plane Electric field is applied to Sample

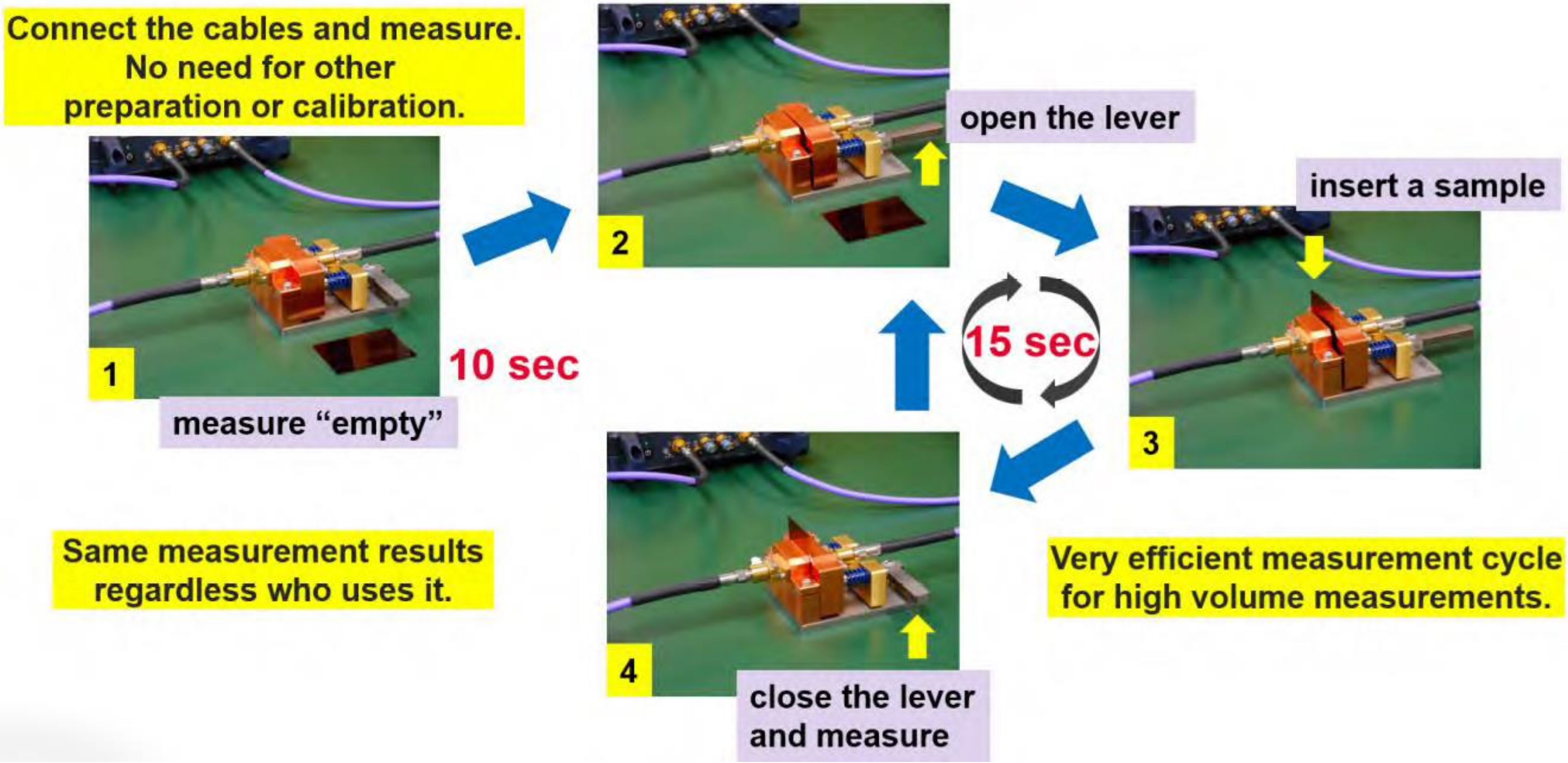


TE011 mode

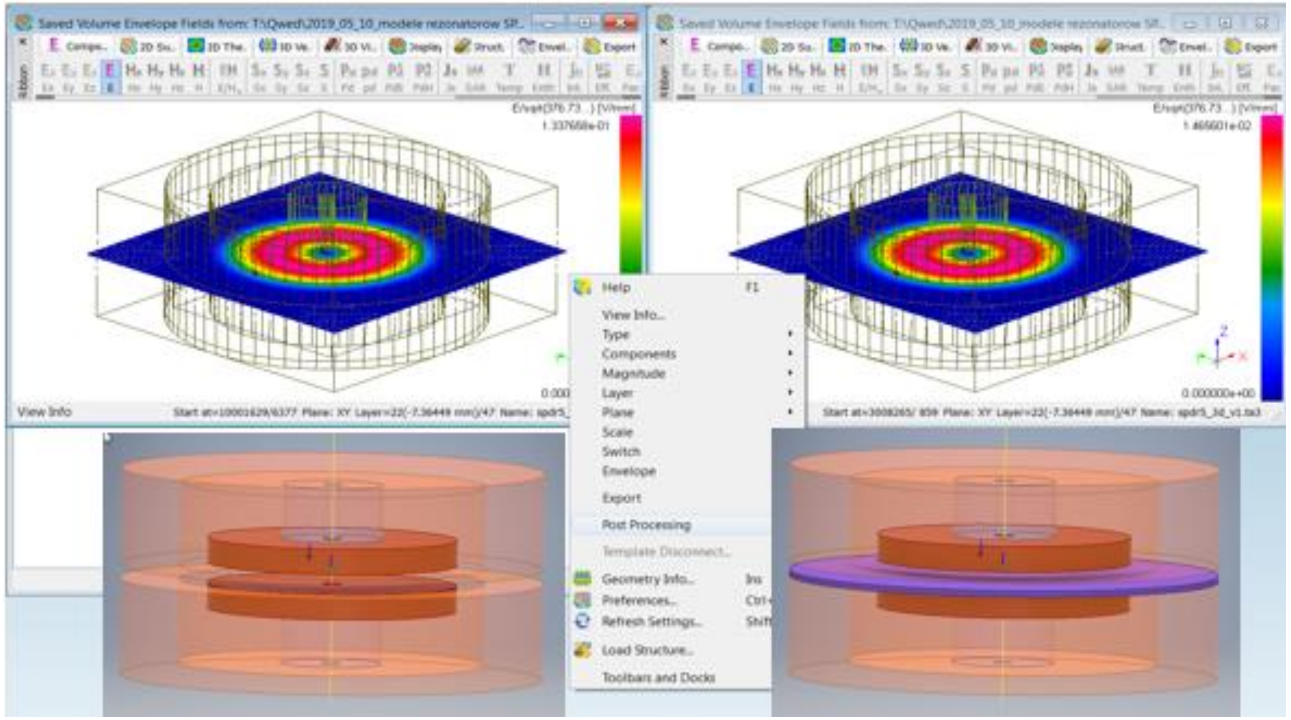


Split cylinder resonator (SCR)	Discrete frequency points from 10 GHz up to 80 GHz	• High measurement precision • Can be sensitive to many user errors • Typically interpolated to 5G mmWaves • Typically in-plane component of permittivity • Typical sample thicknesses around 100 um • Support temperature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

Split Cylinder Resonator (SCR) - operation



Split-Post Dielectric Resonator (SPDR) - basics

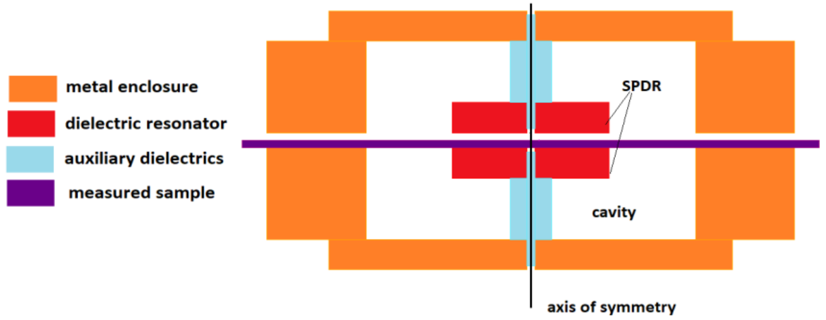


- resonant mode with EM fields mostly confined in and between those ceramic posts

→ minimial losses in metal enclosure
- H-field is only vertical at the side wall of the enclosure → circumferential currents

→ no radiation through slot
- E-field tangential to SUT

→ air slots between SUT and posts have negligible effect
- **easy SUT insertion through slot, no dismatling**



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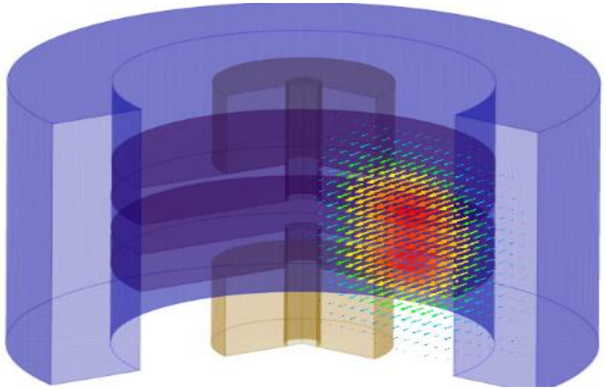
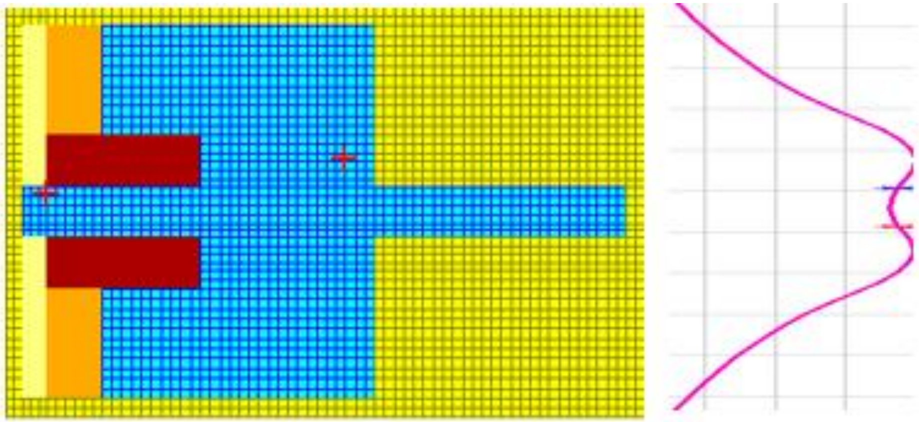
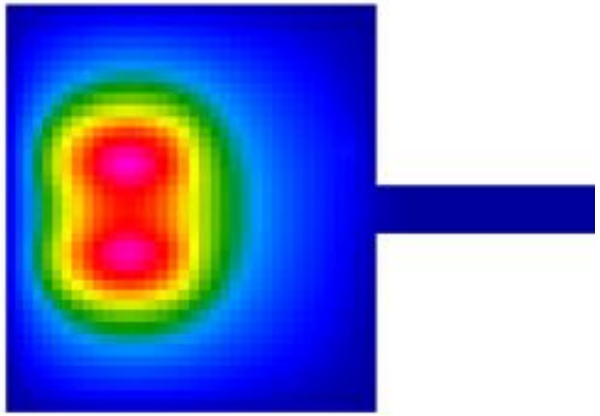
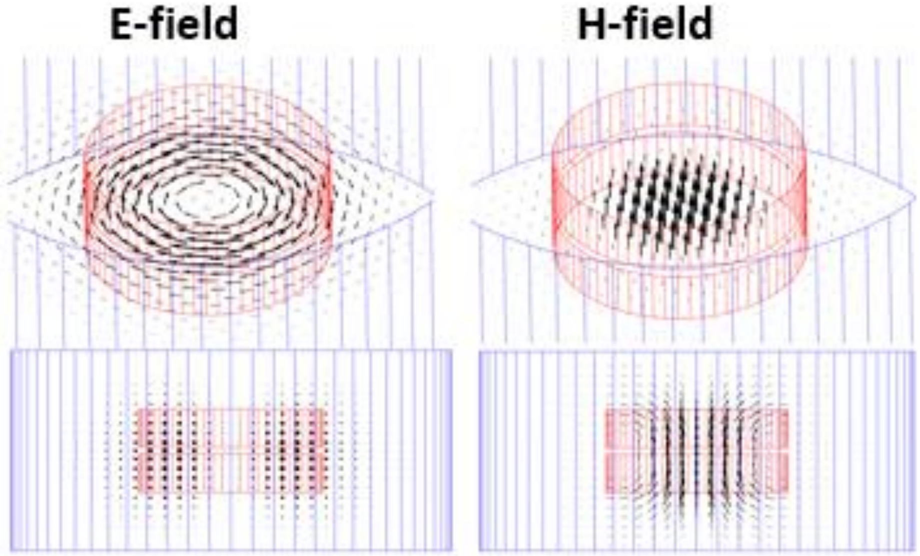
Split-post dielectric resonator (SPDR)	Discrete frequency points from 1 GHz up to 15 GHz	• High measurement precision • Easy to use • Insensitive to many user errors • Typically in-plane component of permittivity • Typically extrapolated to 5G mmWaves • Typical sample thicknesses less than 1 mm • IEC 61189-2-721:2015 • https://www.qwed.com.pl/resonators_spdr.html • https://www.keysight.com/us/en/assets/7018-01416/application-notes/5989-5384.pdf

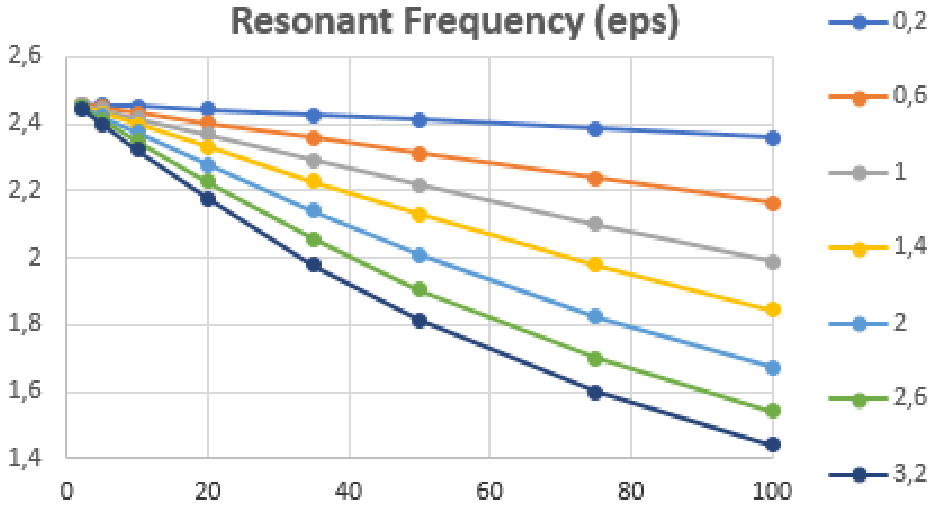
Split-Post Dielectric Resonator (SPDR) – modelling results



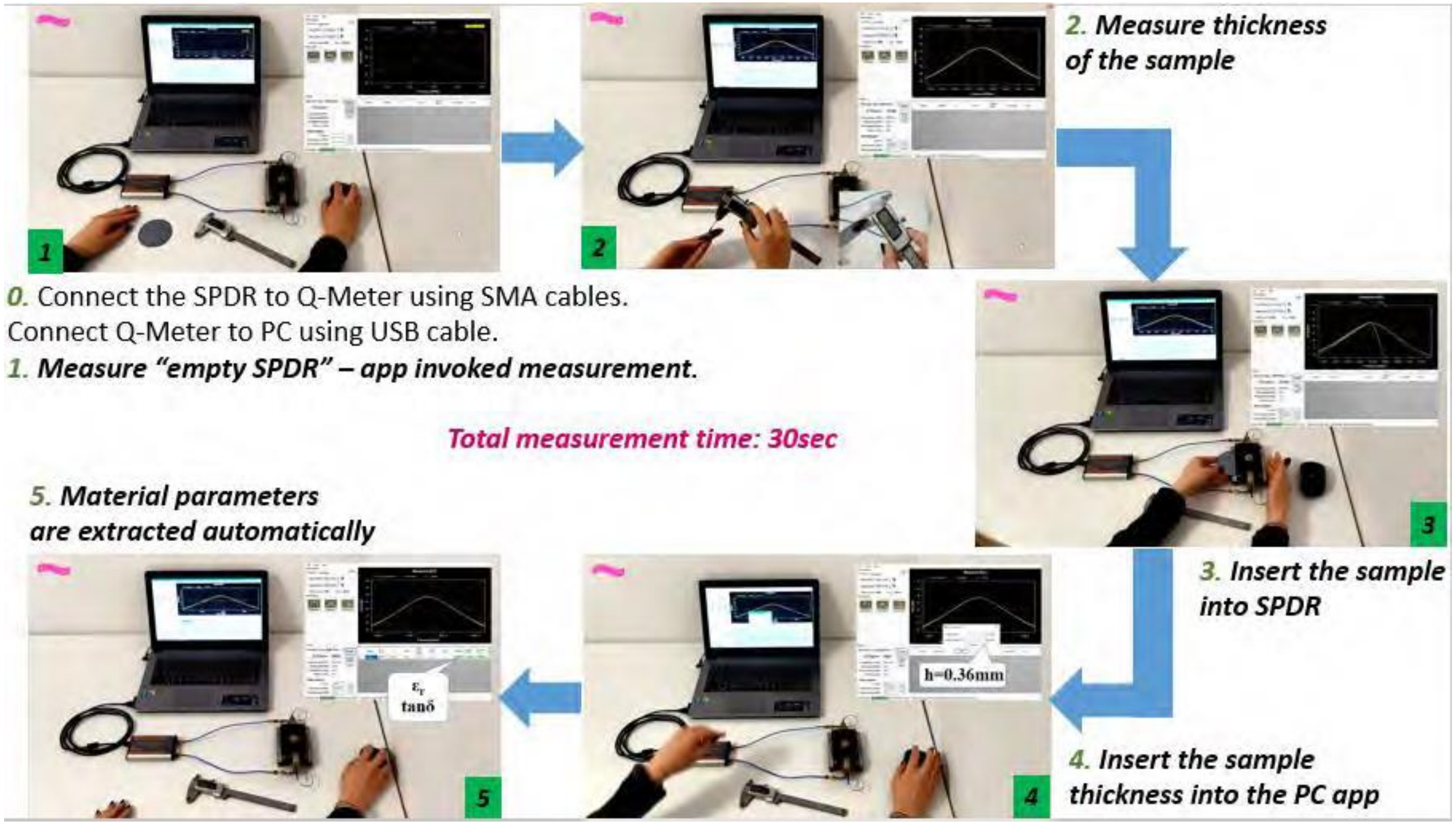




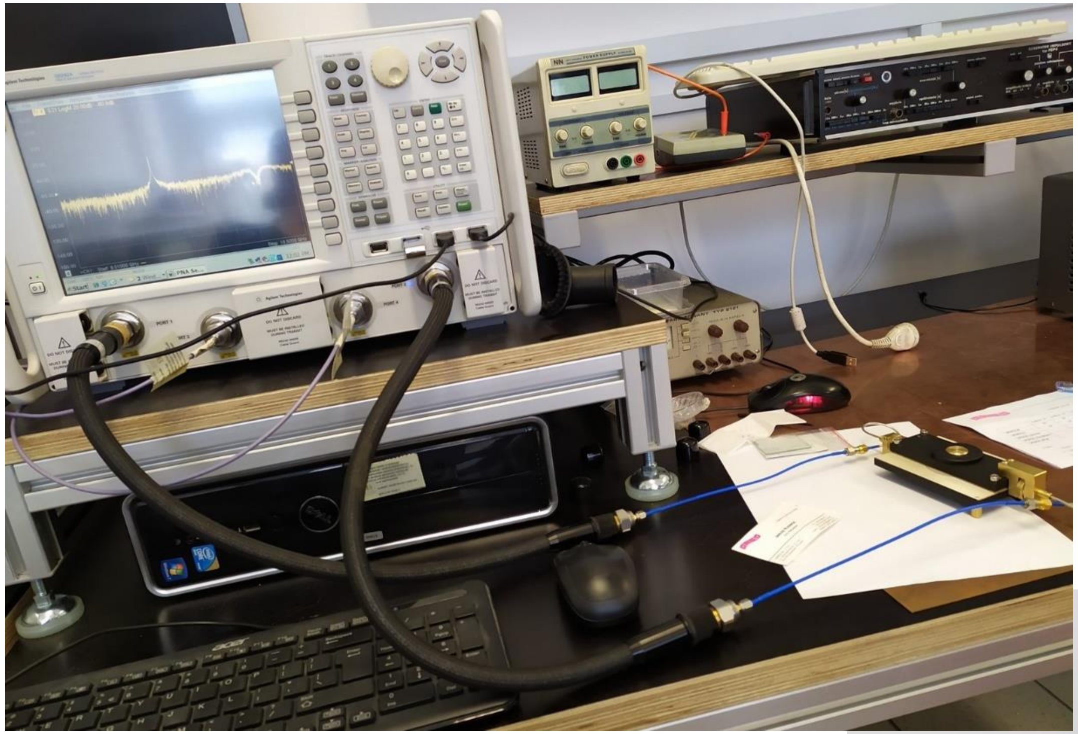




Split-Post Dielectric Resonator (SPDR) – operation (1)



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

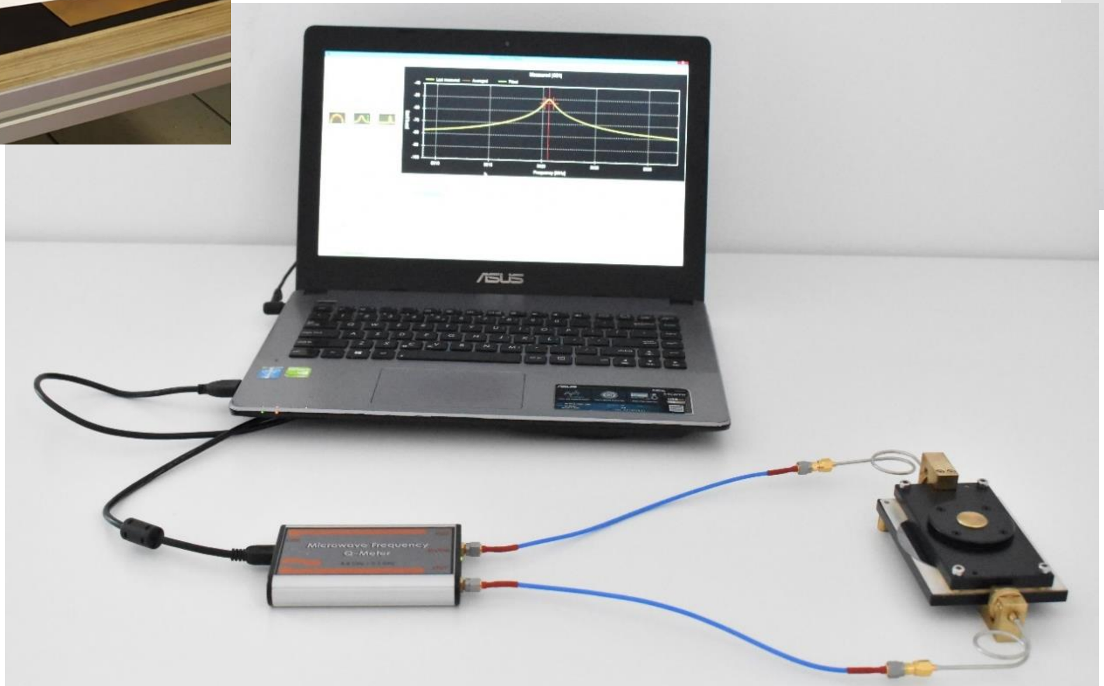


SPDR use in labs...

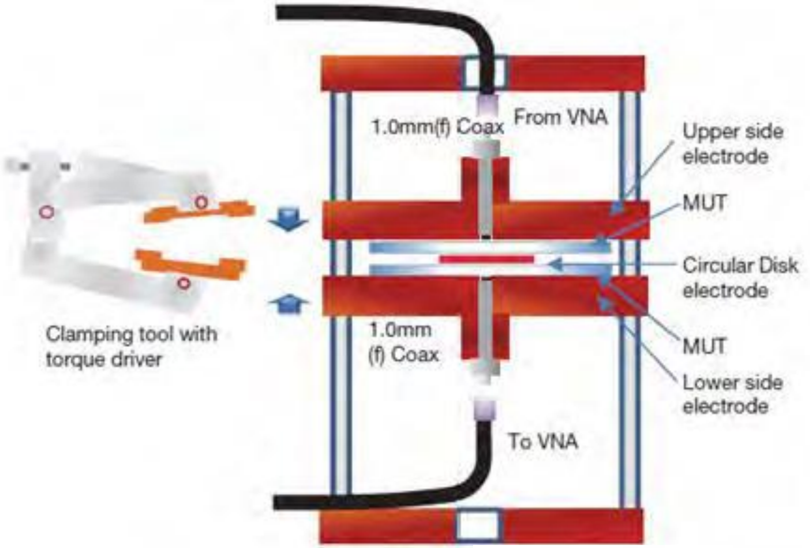
...and at home

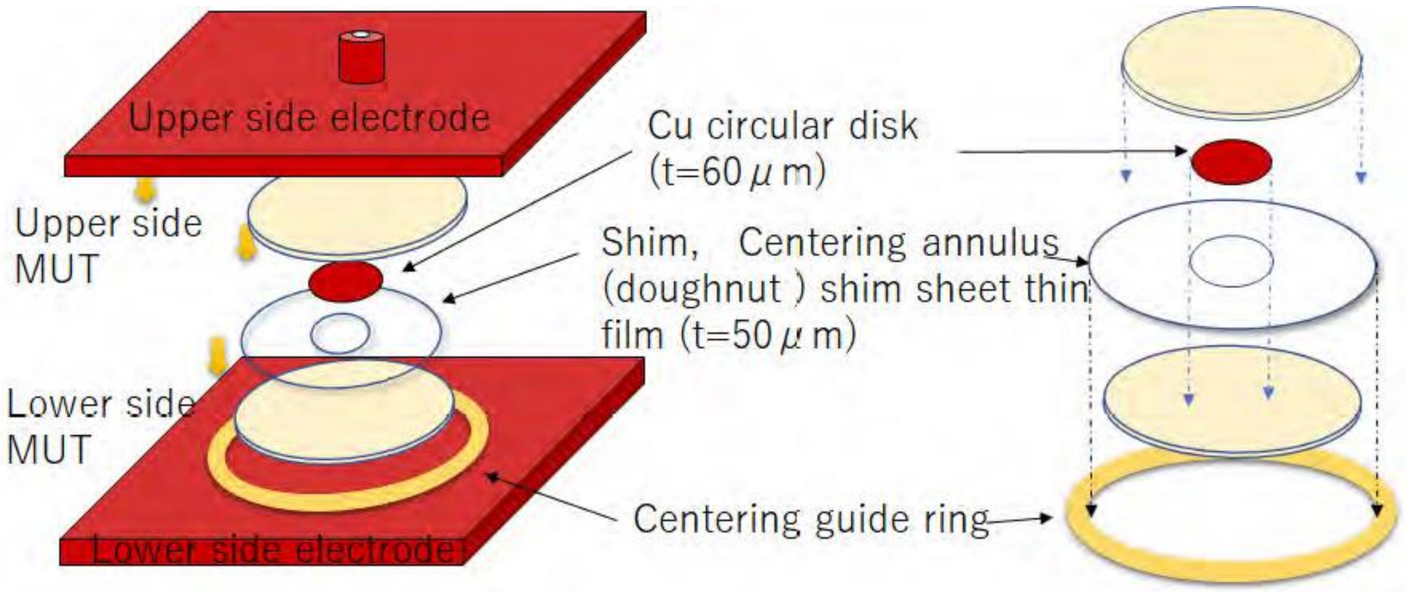
For many practical materials, measuring only abs (S21) provides appropriate accuracy.

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



Balanced-type circular disk resonator (BCDR) - basics

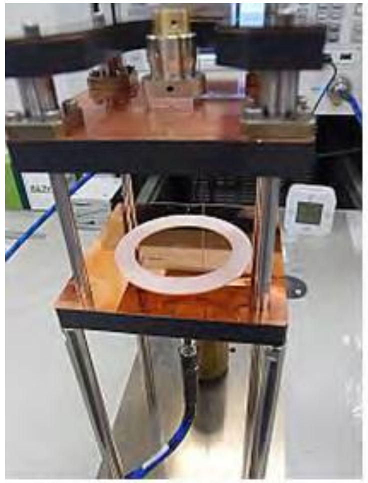


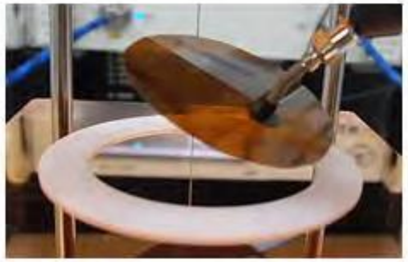


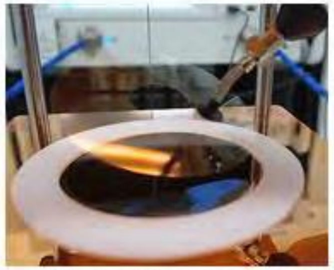
Balanced-type circular disk resonator (BCDR)	Multiple discrete frequency points from 10 GHz up to 120 GHz	• High measurement precision • Requires full 2-port calibration (mechanical to 110 GHz or electrical to 67 GHz) • Typically out-of-plane component of permittivity • Typical sample thicknesses less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

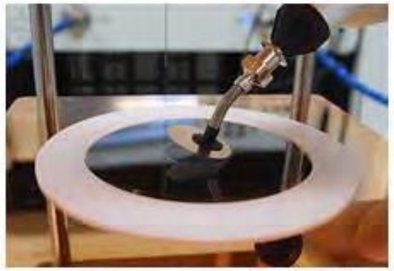
Balanced-type circular disk resonator (BCDR) - operation

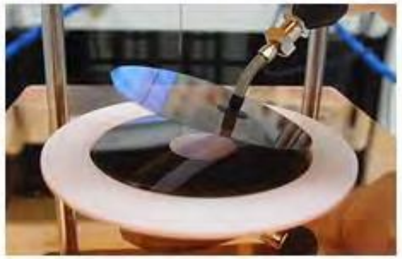
concentricity must be preserved

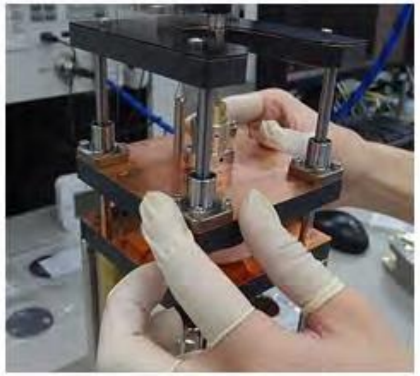

Open the resonator


Set lower side sample

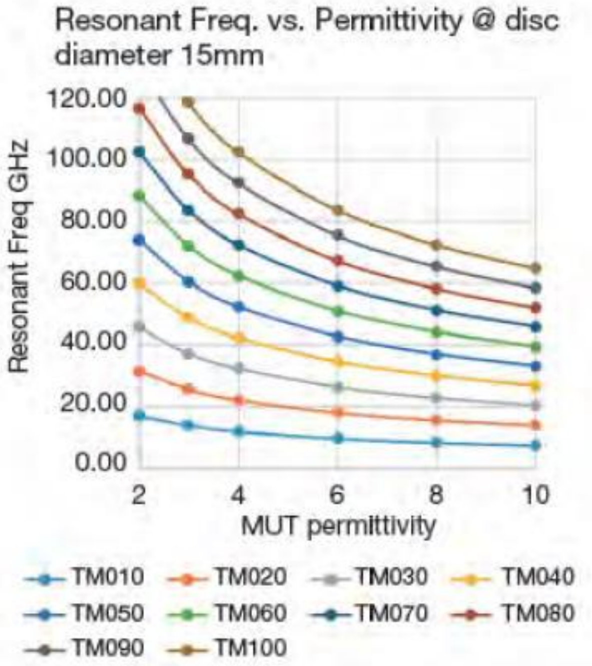

Set shim sheet


Set center electrode

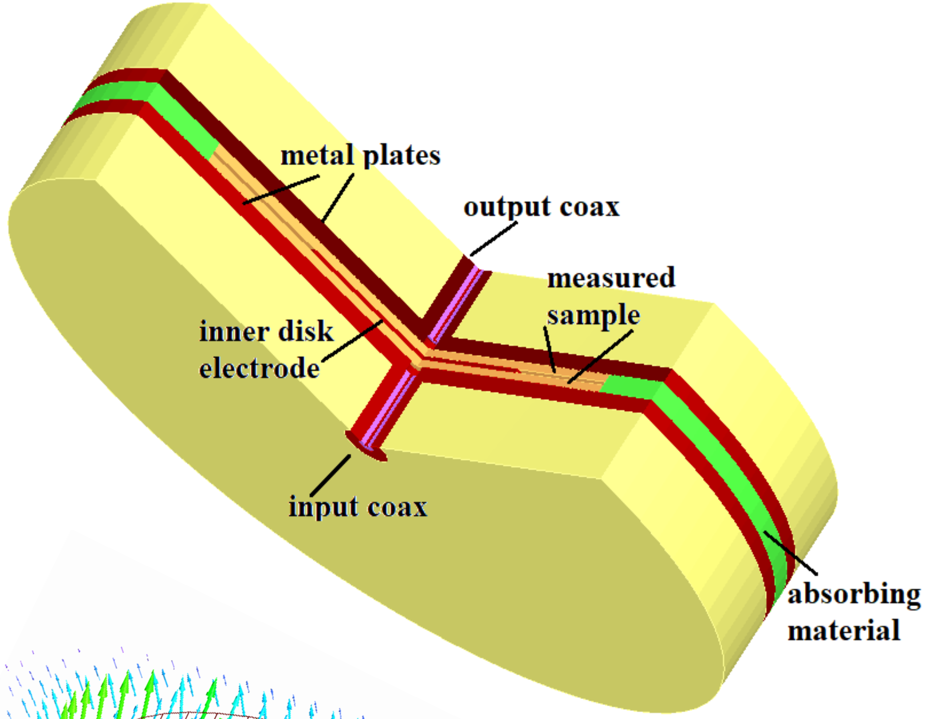

Set upper side sample

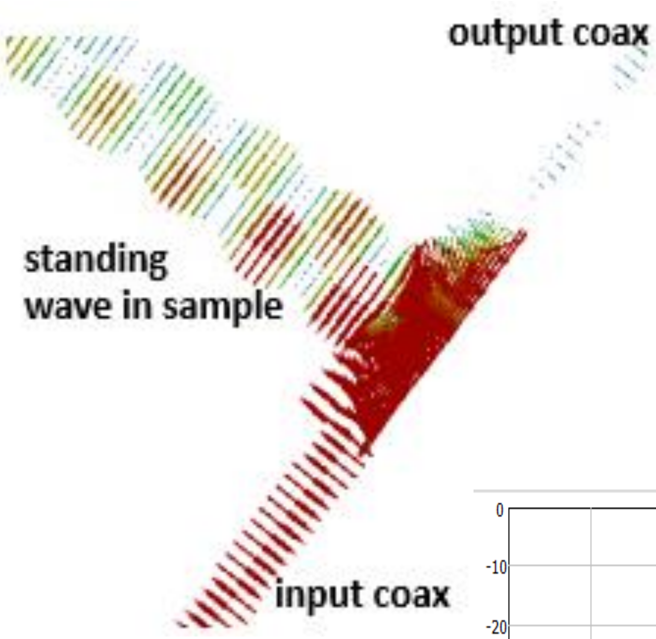

Close the resonator

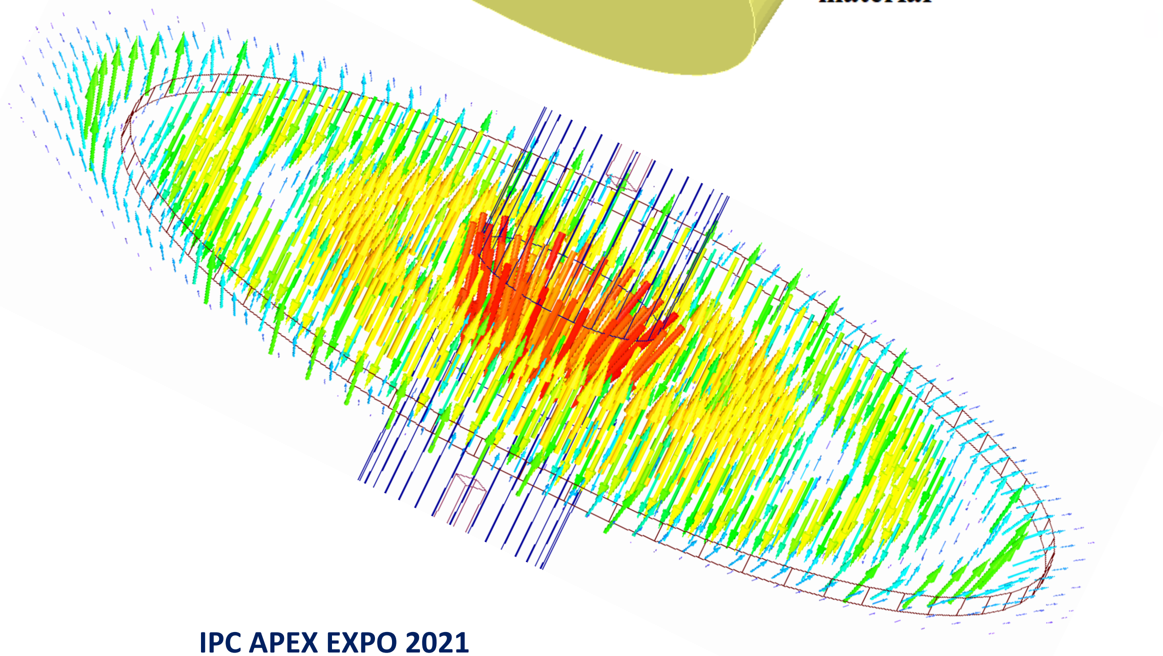

Clamp and measure

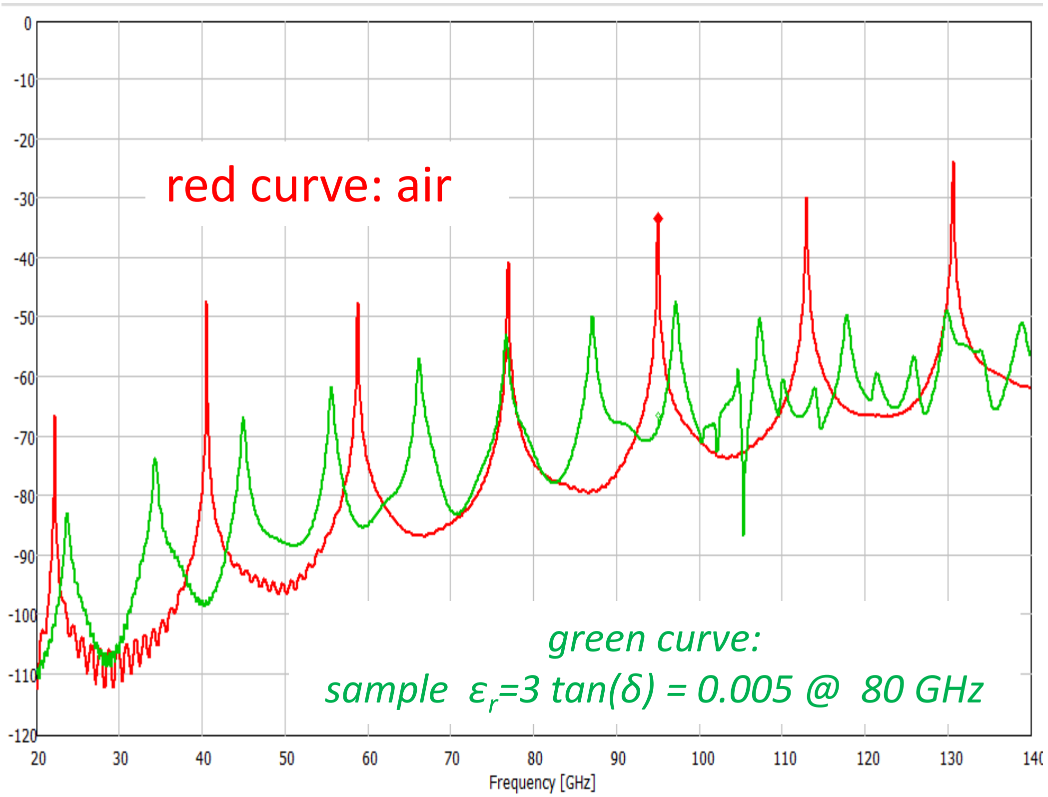


Balanced-type circular disk resonator (BCDR) – modelling

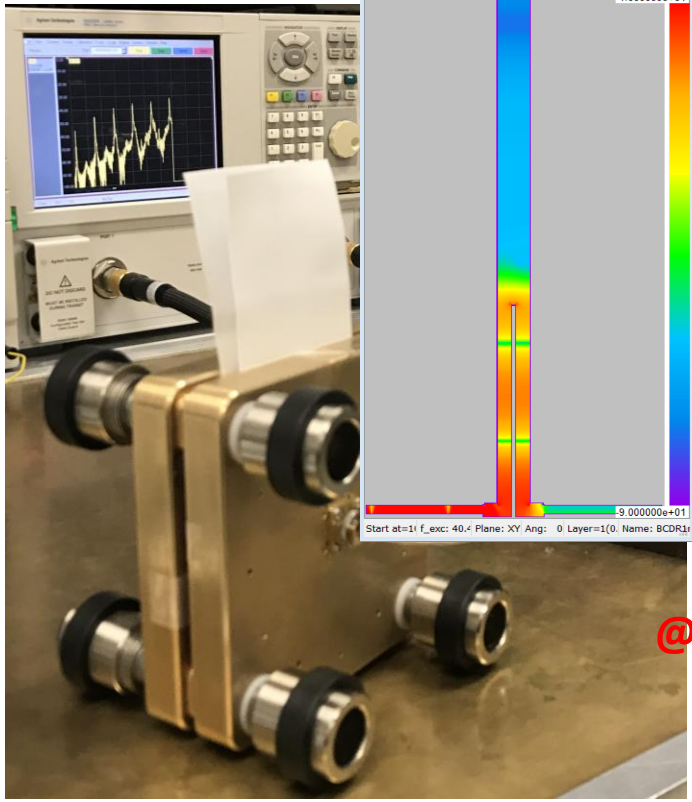


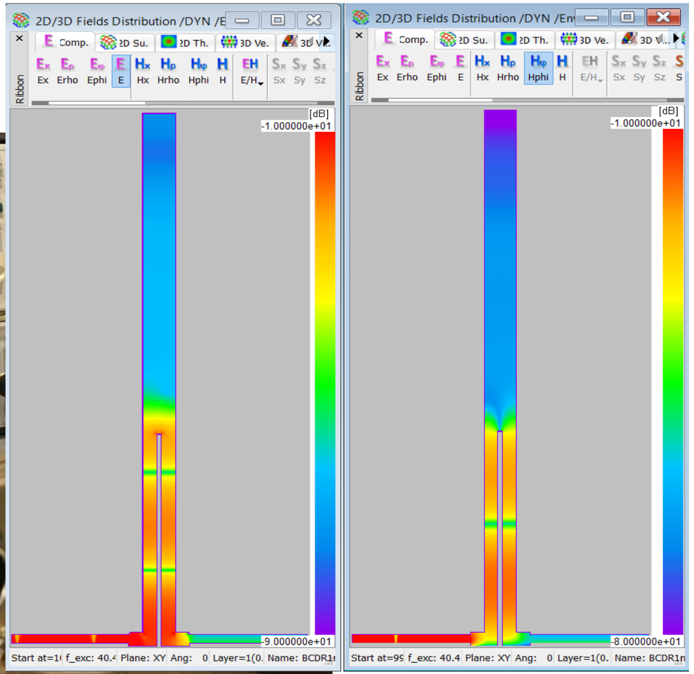




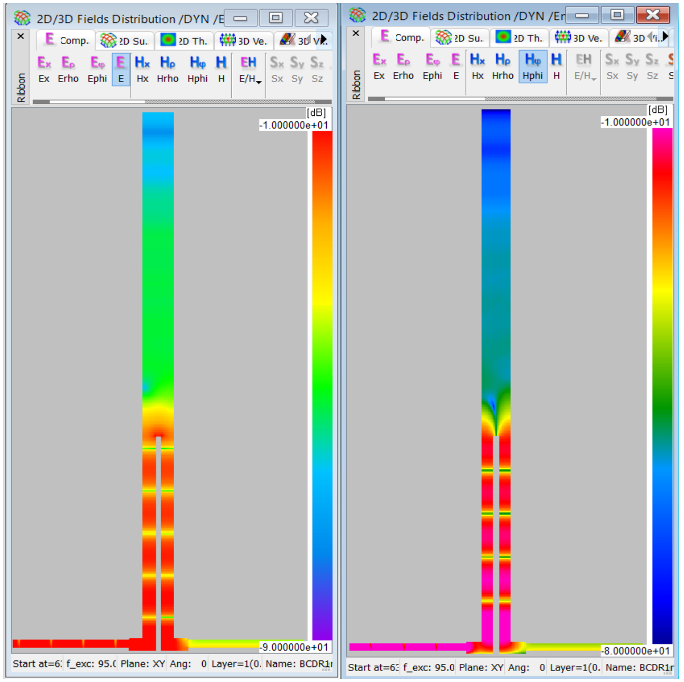


Balanced-type circular disk resonator (BCDR) – modelling

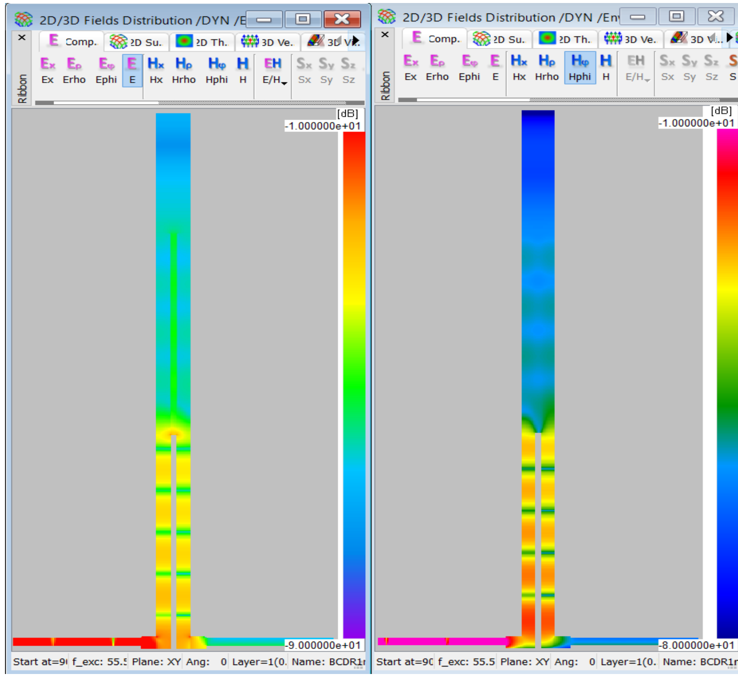




@ 40.49 GHz, air



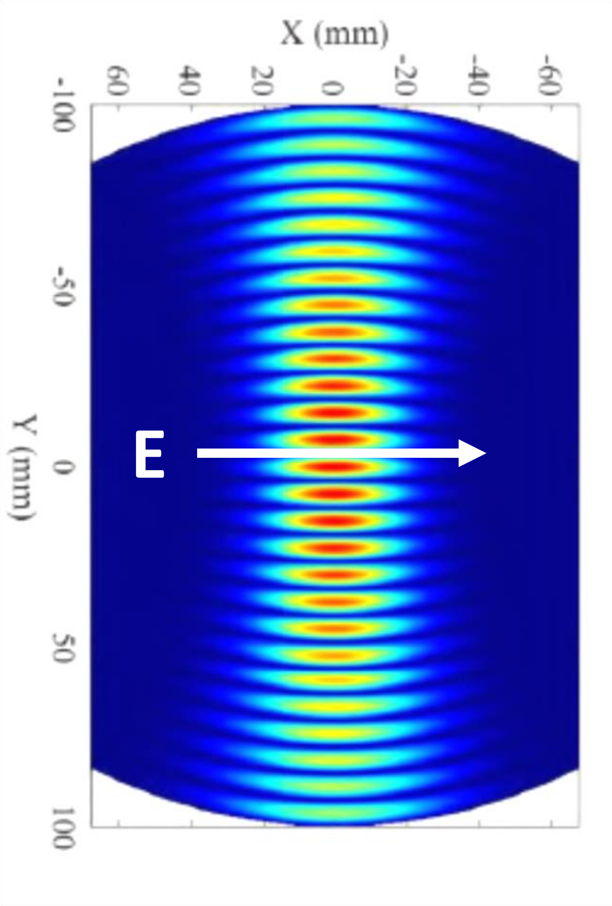
@ 95.06 GHz, air



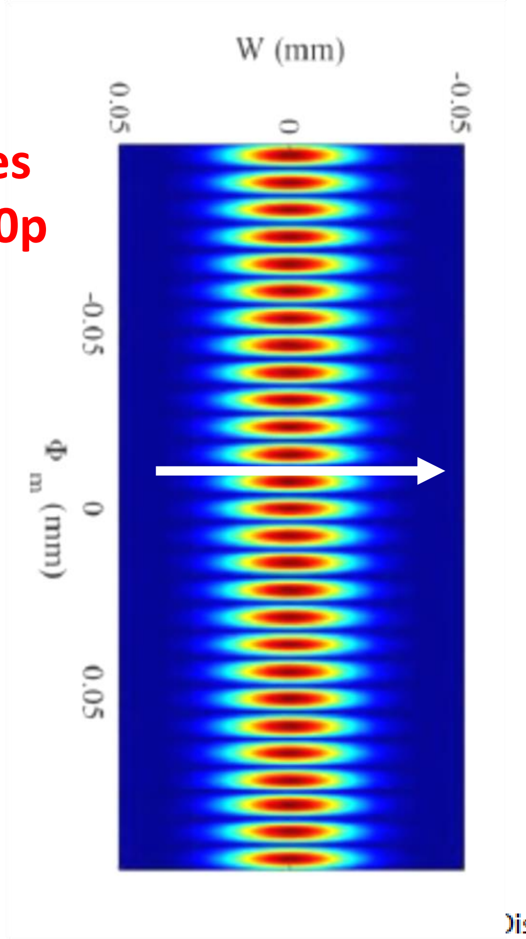
@ 55.57 GHz, sample

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

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



modes
TEM00p



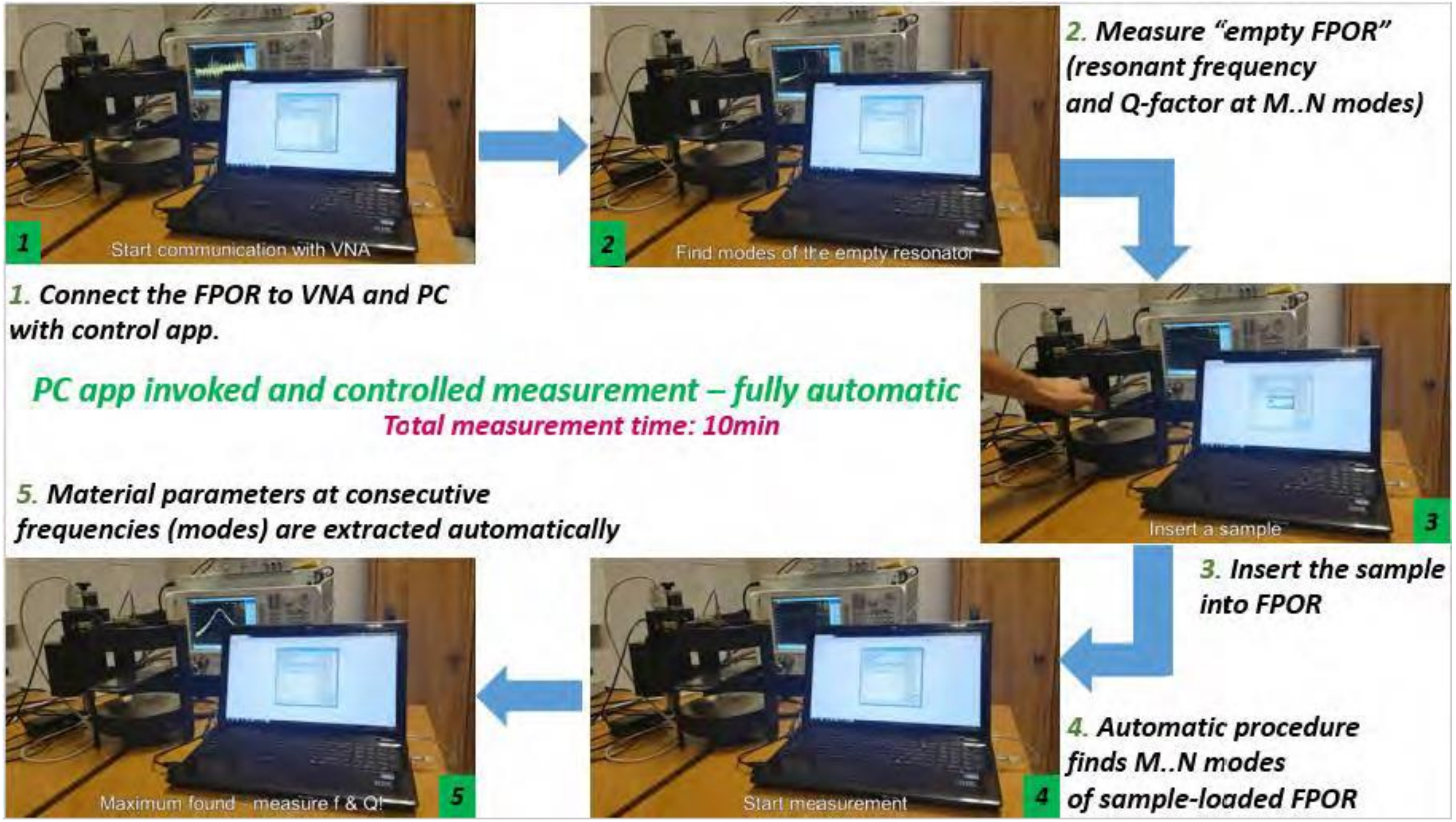
..and modeling

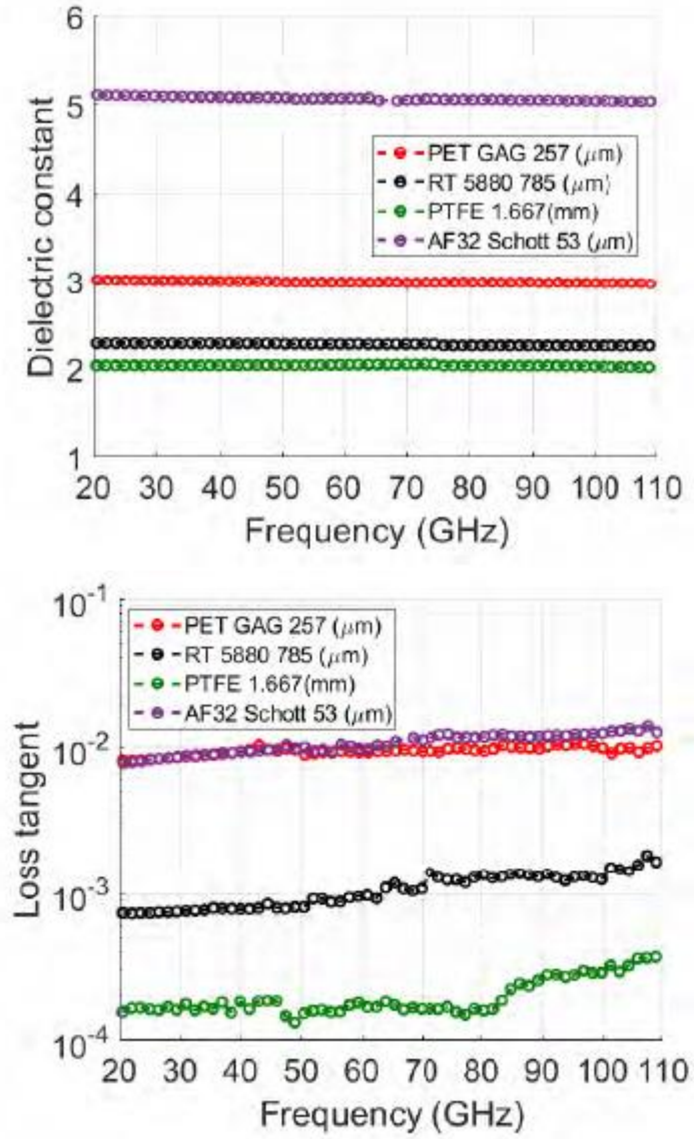
resonator (FPOR, also called open-cavity)

)iscrete frequencies between 20 GHz up to 110 GHz

- High measurement precision
- Can be sensitive to many user errors
- Uncertainty increases with increasing frequency
- Typically in-plane component of permittivity
- JIS R1660-2
- https://www.qwed.com.pl/resonators.html#ResonatorFPOR
- https://www.keysight.com/main/editorial.jspx?cc=US&lc=eng&ckey=2276755&nid=null&id=2276755

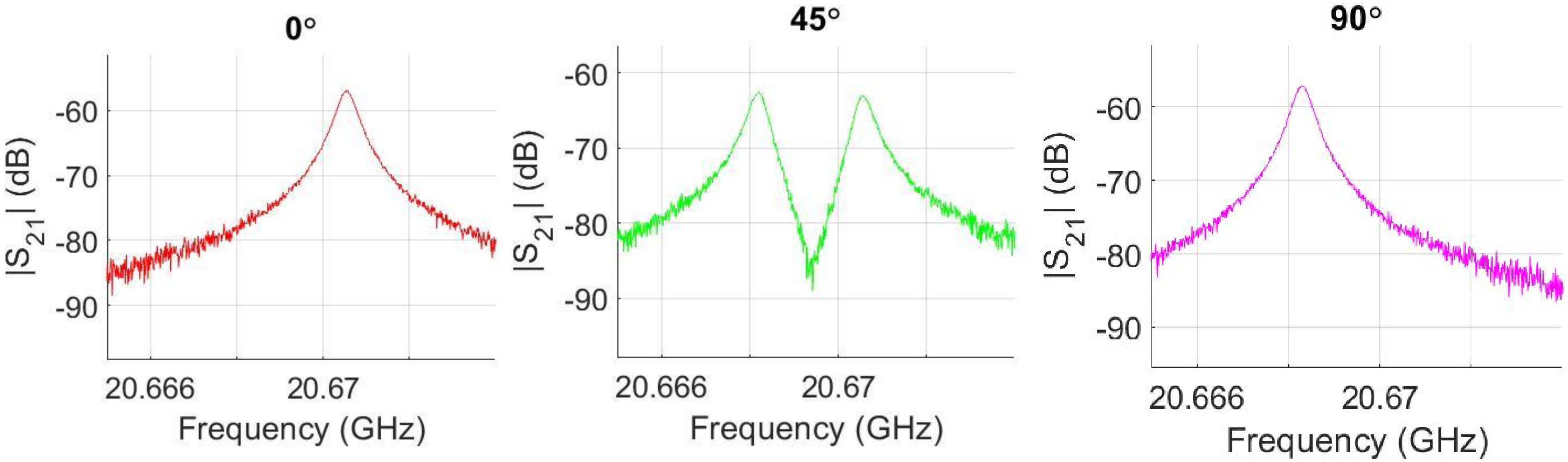
Fabry-Perot Open Resonator (FPOR) - operation





Fabry-Perot Open Resonator (FPOR) - operation

With appropriately designed feeding loops, FPOR is capable of linear E-field polarization and hence detecting in-plane anisotropy:



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

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

For PETG (non-crystalline copolyesters, isotropic), resonant frequency does not depend on angular position of the sample.

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

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

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

Samples under test in Task 3:

35 mm x 45 mm

90 mm x 90 mm

thickness: 50, 125, 188 µm

Concluding remarks

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

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

Attention:

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

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(website: www.nanobat.eu)