Benchmarking of GHz resonator techniques for the characterisation of 5G / mmWave materials

Malgorzata Celuch

QWED Sp. z o.o., Warsaw, Poland

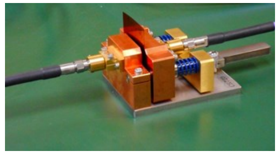
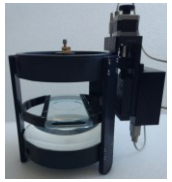
mceluch@qwed.eu

Co-Authors: M. J. Hill[*], T. Karpisz[%#], M. Olszewska-Placha[#], S. Phommakesone[&], U. Ray[^], B. Salski[%#]

[#]QWED Sp. z o.o., Poland
[*]Intel Corp., US
[%]Institute of Radioelectronics and Multimedia Technology, Warsaw University of Technology, Poland
[&]Keysight Technologies, US
[^]The International Electronics Manufacturing Initiative, US

Outline

- **Motivation & Industry Needs**
- **Brief Overview of the iNEMI 5G/mmWave Materials Assesement & Characterisation Project**
- **Why Resonator Techniques & Which Resonators Are Used**

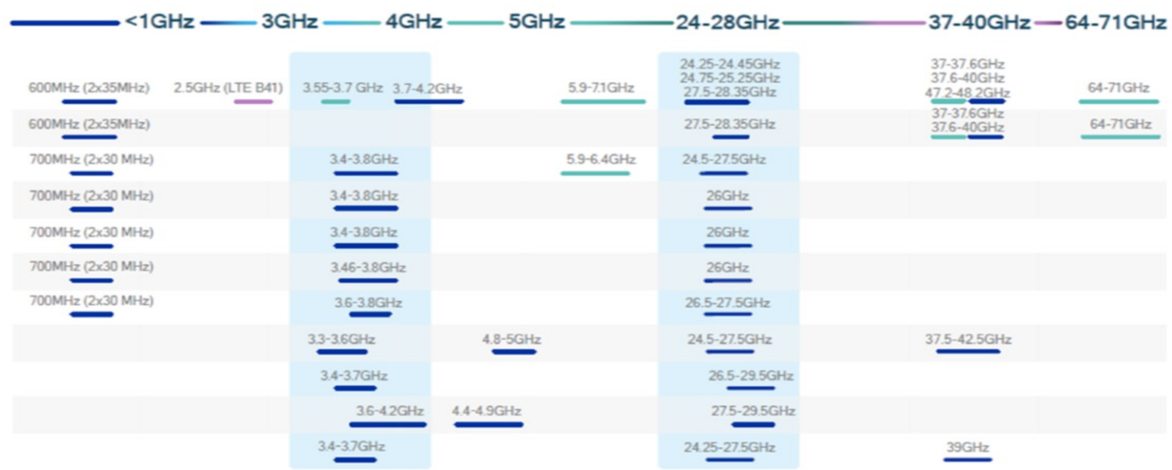

- **Choice of Benchmarking Material Samples**

- **Material Measurement Results & Discussion**
- **Conclusions & Outlook**

Motivation & Industry Needs: Scope

- 5G: Common to only think in terms of ‘radio’ applications
- ‘5G’ extends beyond wireless applications

CPU Clock Speeds | High Speed I/O

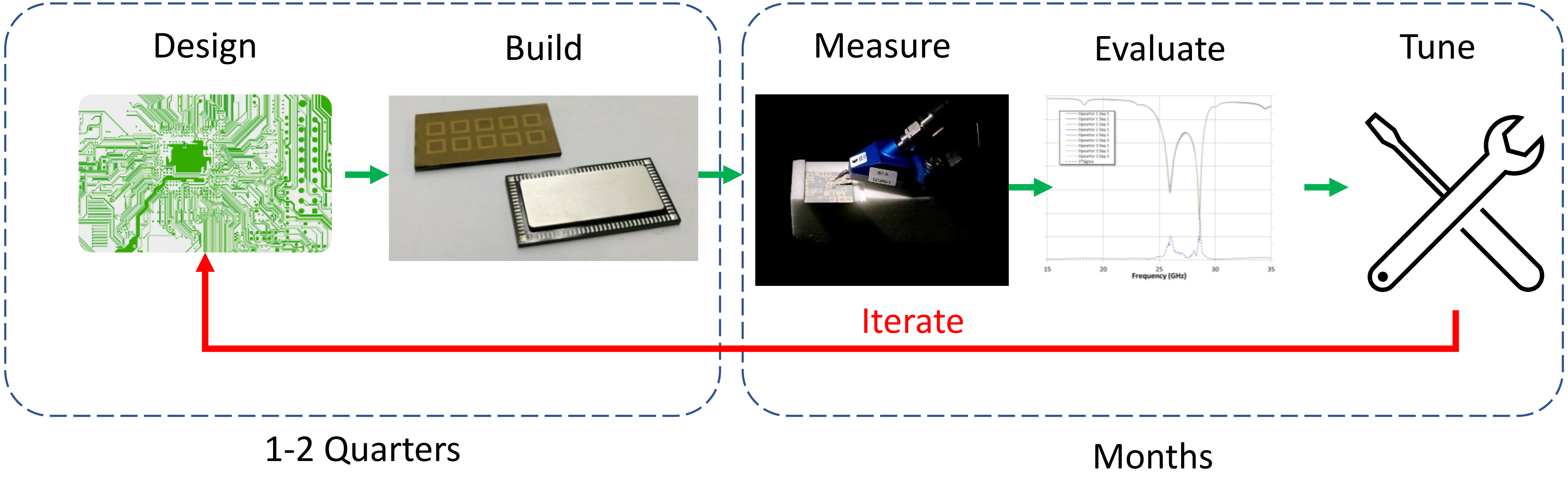


Src: Urmi Ray, 5G/High Frequency Materials Characterization Challenges and Opportunities, EMA 2021, S13

- Many forward-looking wired applications need material data spanning DC to 100+GHz
- Dielectric constant measurements are key enables for many different industries & technologies

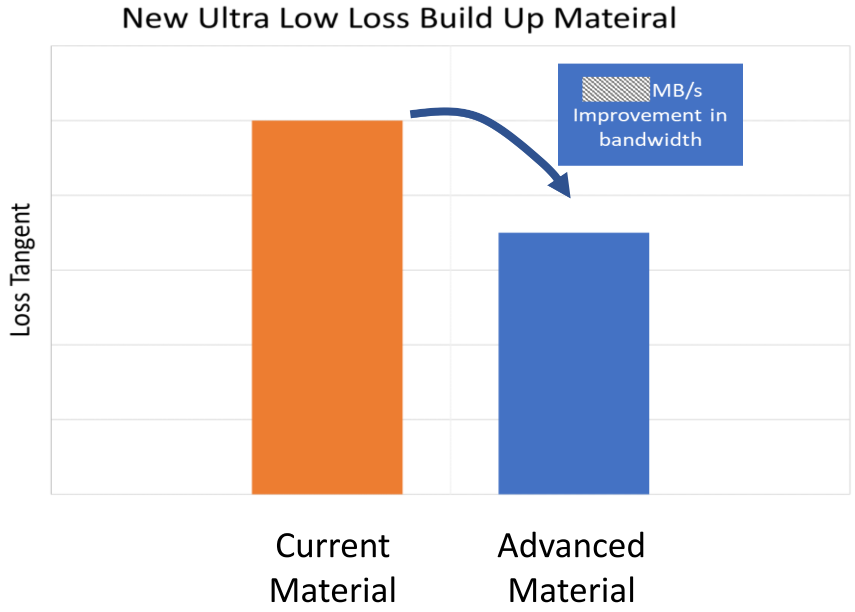
Motivation & Industry Needs: Design

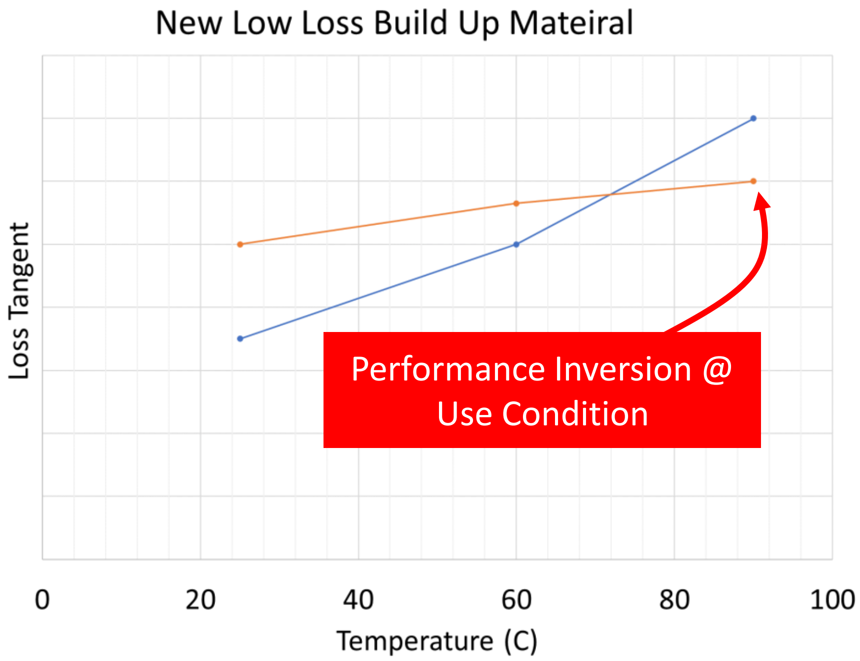
- Traditional methods of microwave design rely on trimming & tuning difficult to tolerate in today's environment…
- Faster & less costly "virtual prototyping" is achieved with today's modelling & simulation tools…
- …but accurate material data is still required
- …errors in materials' characterisation limit accuracy of modeling resulting in time consuming iterations



Motivation & Industry Needs: New Materials

- **5G/mmWave industry is in quest for new ultra-low-loss materials**





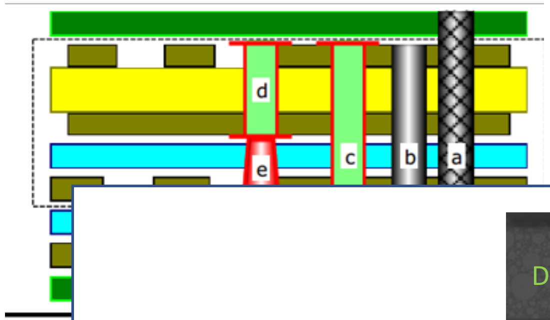
- Developments of new materials require accurate evaluation at use condition

Errors can be very costly, e.g. estimated cost to switch: ~$2 per CPU substrate → x 20M units = $40M

$10’s of millions for a single program, or worse, unexpected product failures

Motivation & Industry Needs: On-Site Use

Modern PCBs make use of many different dielectrics



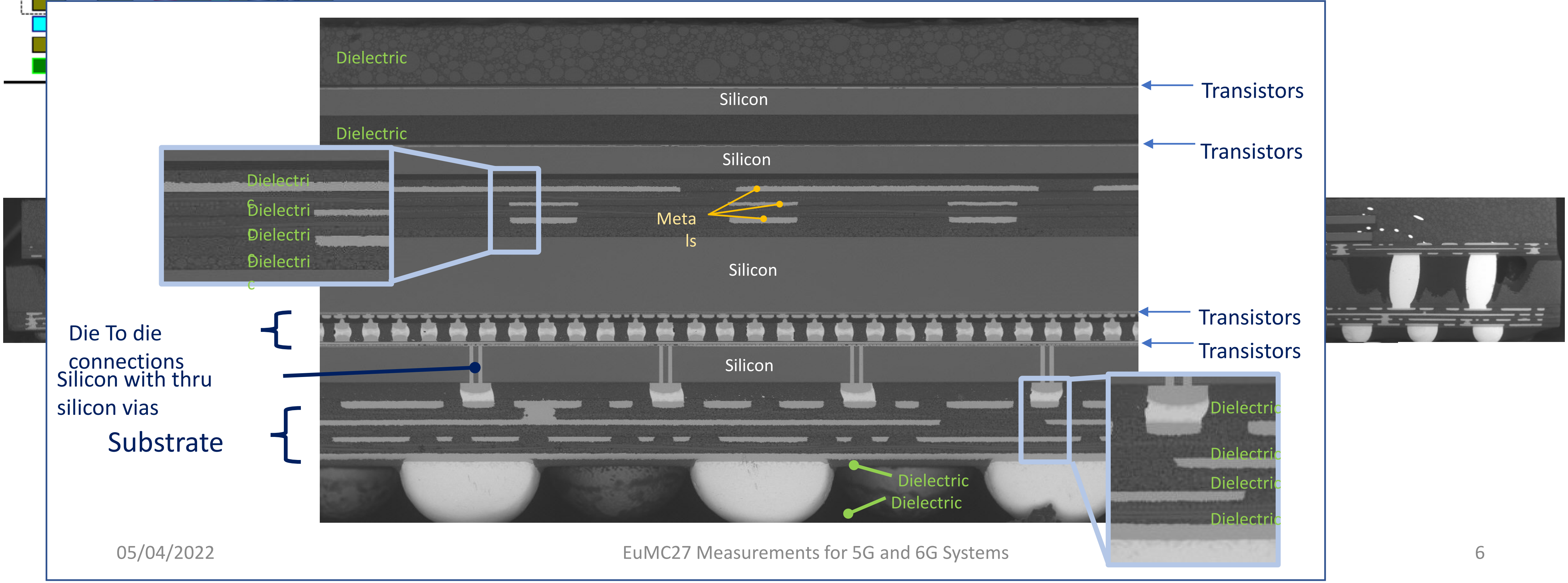
Need to characterise:

- **many materials**
- **across many domains of science & engineering**

Desirable techniques:

- **fast & easy-to-use**
- **robust and reproducible**

Example: Intel measures more than 200 materials per year.



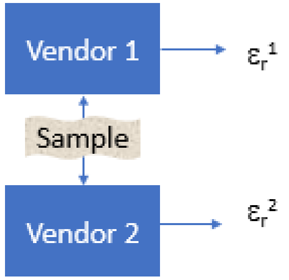
Gaps & Practical Challenges

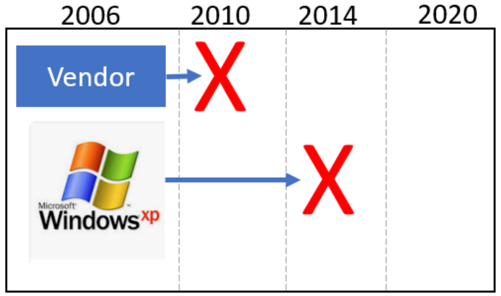
No standards & SRMs for mmWave Permittivity measurements >20 GHz:

- Challenges for ISO and quality control

Few vendors for mmWave Permittivity measurement equipment >10 GHz:

- Explain vendor to vendor differences
- Whom to trust?
- On whom to rely?





Useful 5G materials are typically **very low loss**:

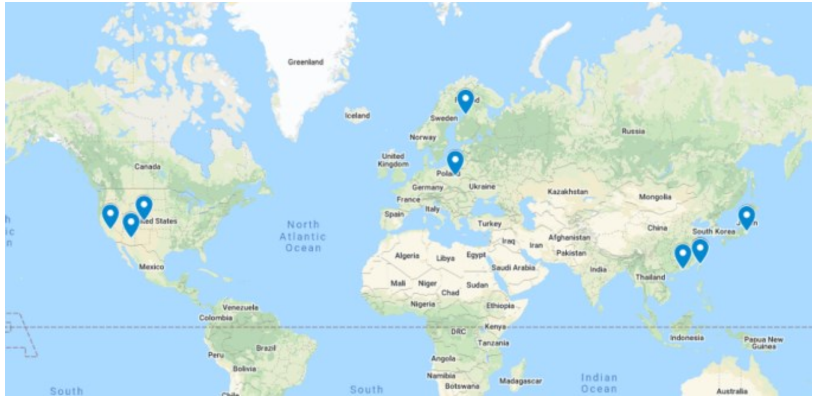
- Eliminates many traditional transmission line techniques

Increasing frequency:

- Severe limitations on **sample thicknesses**
- **Incompatible** sample dimension requirements between techniques
- Higher **sensitivity to operator**

Our project:

- 3M
- AGC-Nelco
- Ajinomoto USA
- AT&S
- Centro Ricerche FIAT-FCA
- Dell
- Dupont
- EMD Electronics (Co-Chair)
- Flex
- Georgia Tech
- Showa Denko Materials
- IBIDEN Co Ltd
- IBM
- Intel
- Isola
- ITRI (Co-Chair)
- Keysight (Co-Chair)
- MacDermid-Alpha
- Mosaic Microsystems
- NIST
- Nokia
- Panasonic
- QWED
- Shengyi Technology Company
- Sheldahl
- Unimicron Technology Corp
- Zestron

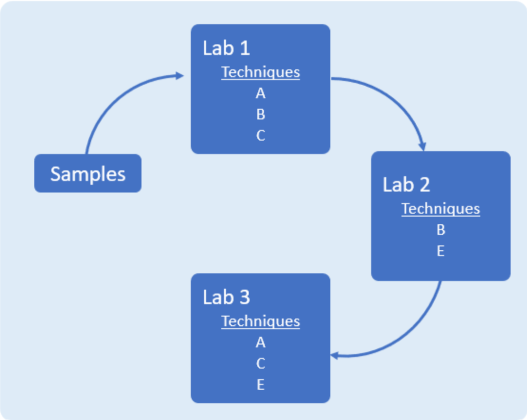


iNEMI 5G Round Robin Overview

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

Current Selection
- Precision Teflon
- Cyclo Olefin Polymer

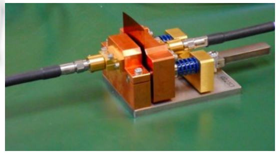
Future additions
- Rexolite
- Fused Silica

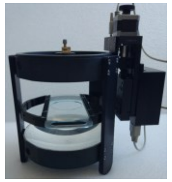


10 Laboratory Round Robin

Our EUMC27-3 paper reports on:
3 resonator techniques
2 sample kits
3 labs, each using 2+ techniques
This presentation further includes
4th lab & 4th technique

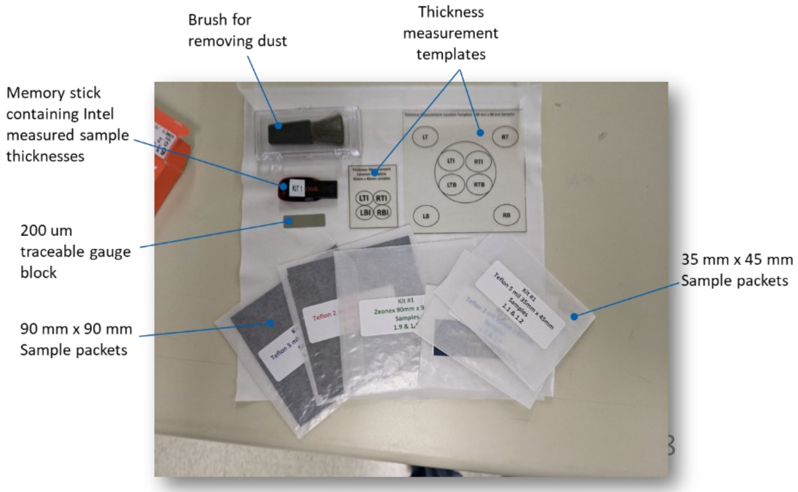
Techniques Included
- Split Post Dielectric Resonator
- Split Cavity Resonator
- Fabry-Perot
- Balanced Circular Disk Resonator





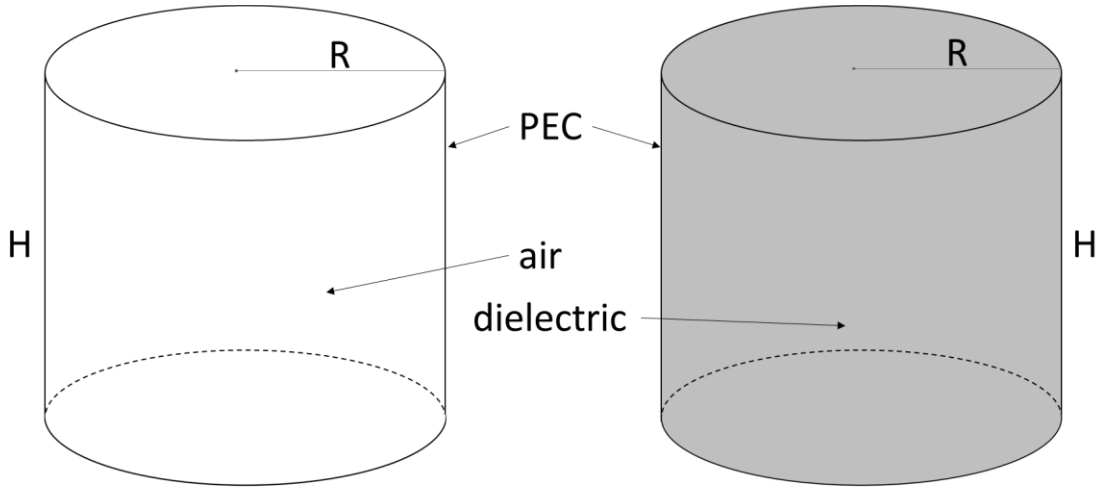
→ Frequency Span : 10GHz – 100GHz with overlaps

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



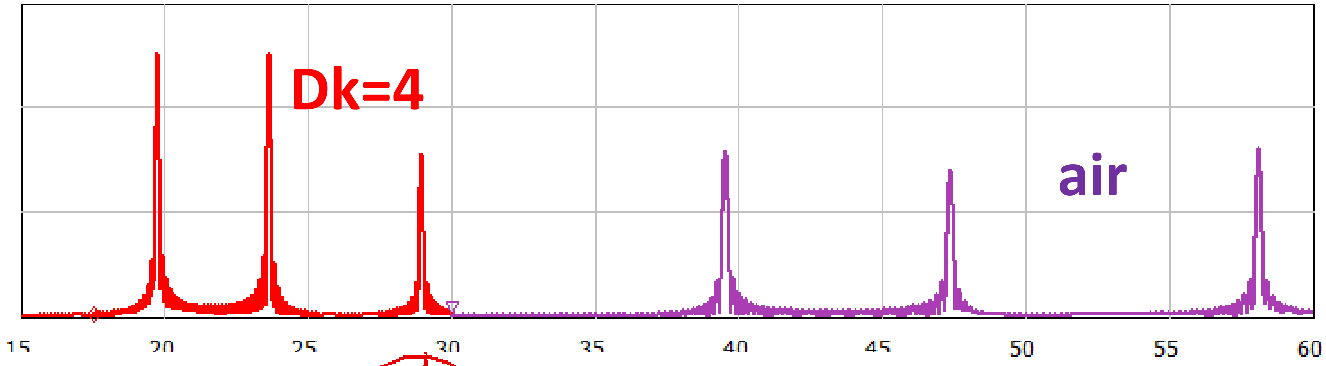
Why Resonator methods

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

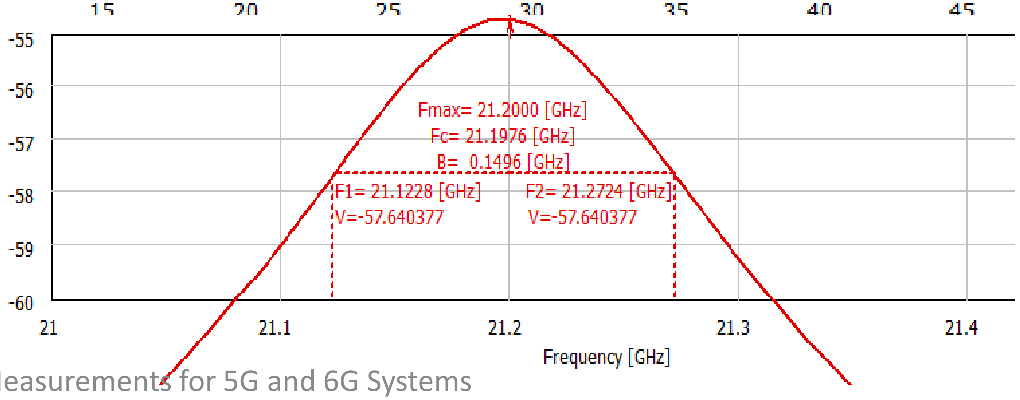


$$f_{r,mnp} = \frac{c}{\sqrt{Dk}} \sqrt{\left(\frac{\kappa_{mn}^{(,)}}{\pi R}\right)^2 + \left(\frac{p}{H}\right)^2}$$

in non-magnetic low-loss dielectrics

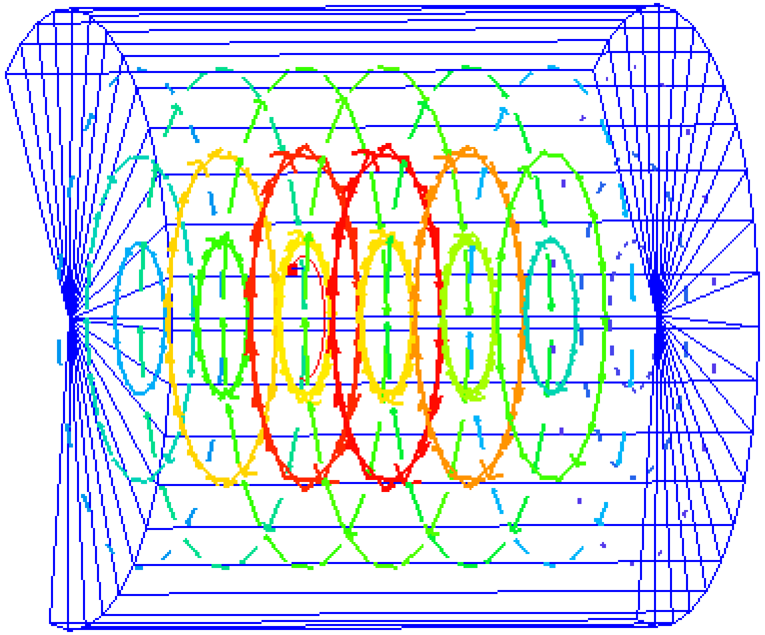


$$Q = 2\pi \frac{\iiint_V \varepsilon \vec{E} \cdot \vec{E}^* dv}{T \iiint_V \sigma \vec{E} \cdot \vec{E}^* dv} = \frac{\omega\varepsilon}{\sigma} = \frac{1}{Df} \approx \frac{fres}{\Delta f}$$

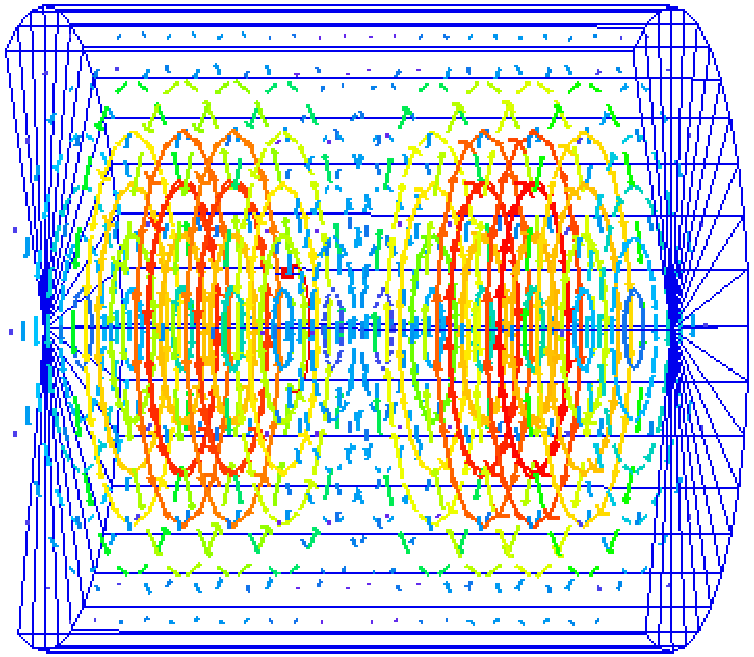


Good sensitivity to low losses

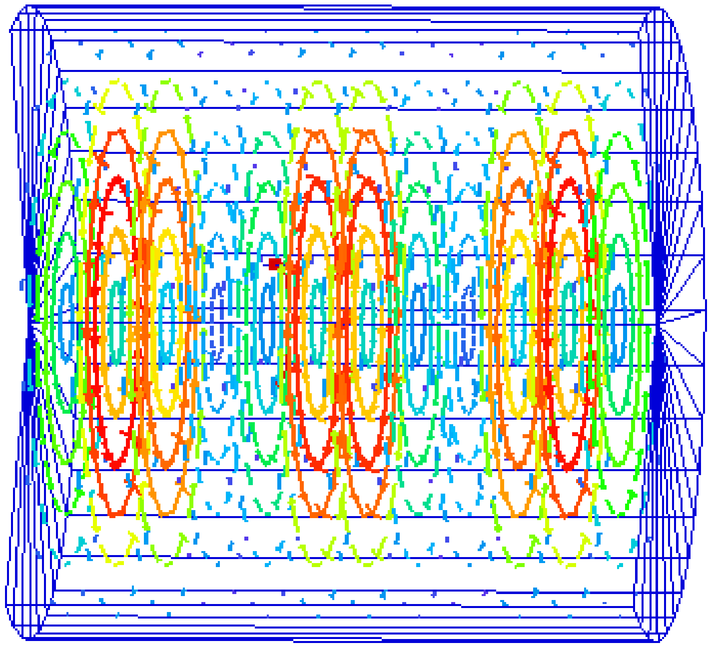
Single- versus Multi-Mode Characterisation



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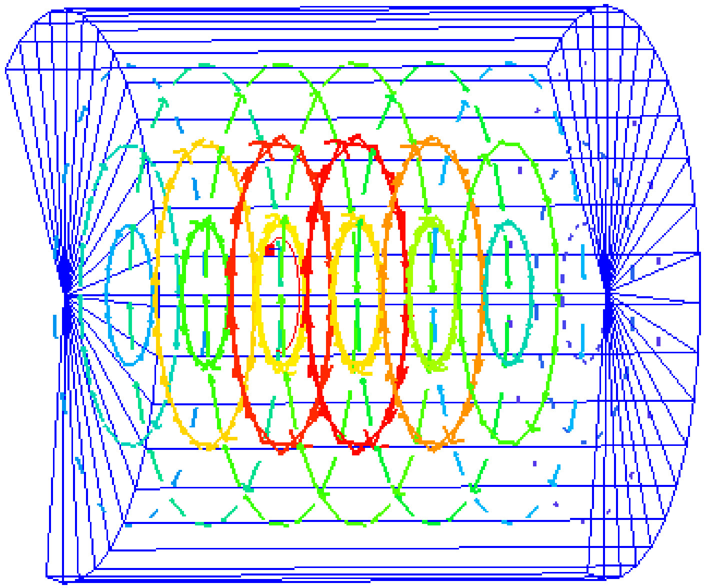
Among the popularly available resonators, BCDR and FPOR work as multi-modal.

In-Plane & Our-of-Plane Permittivity Measurements

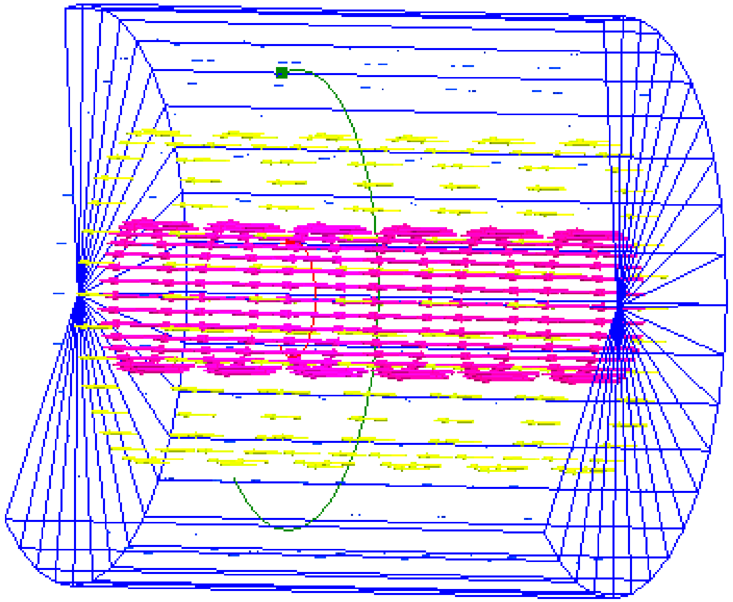
TE010



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

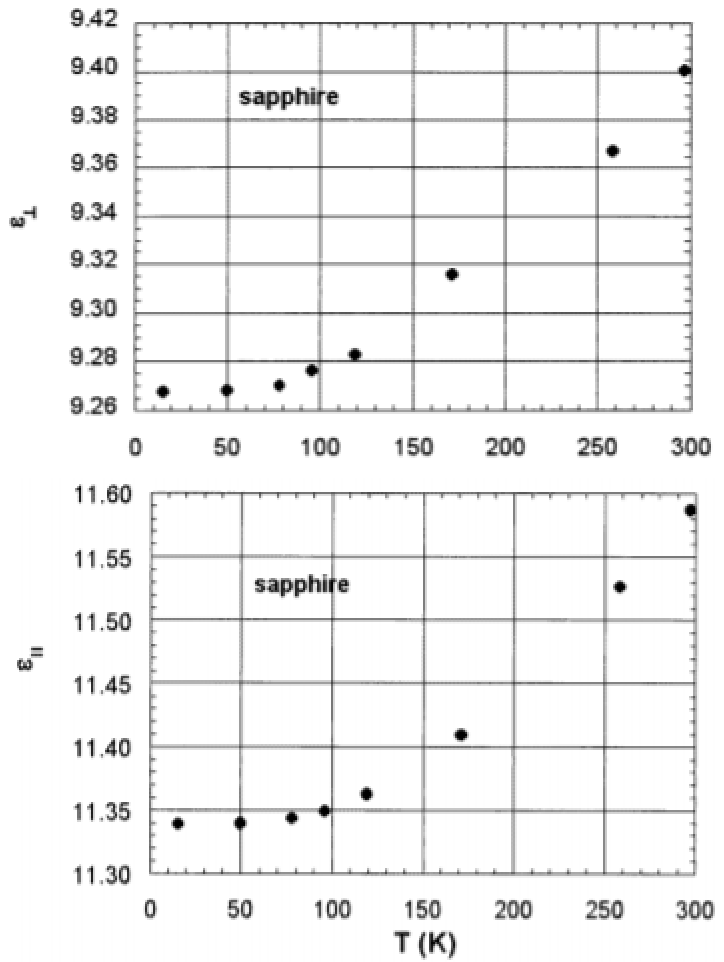
SCR, SPDR, FPOR

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.

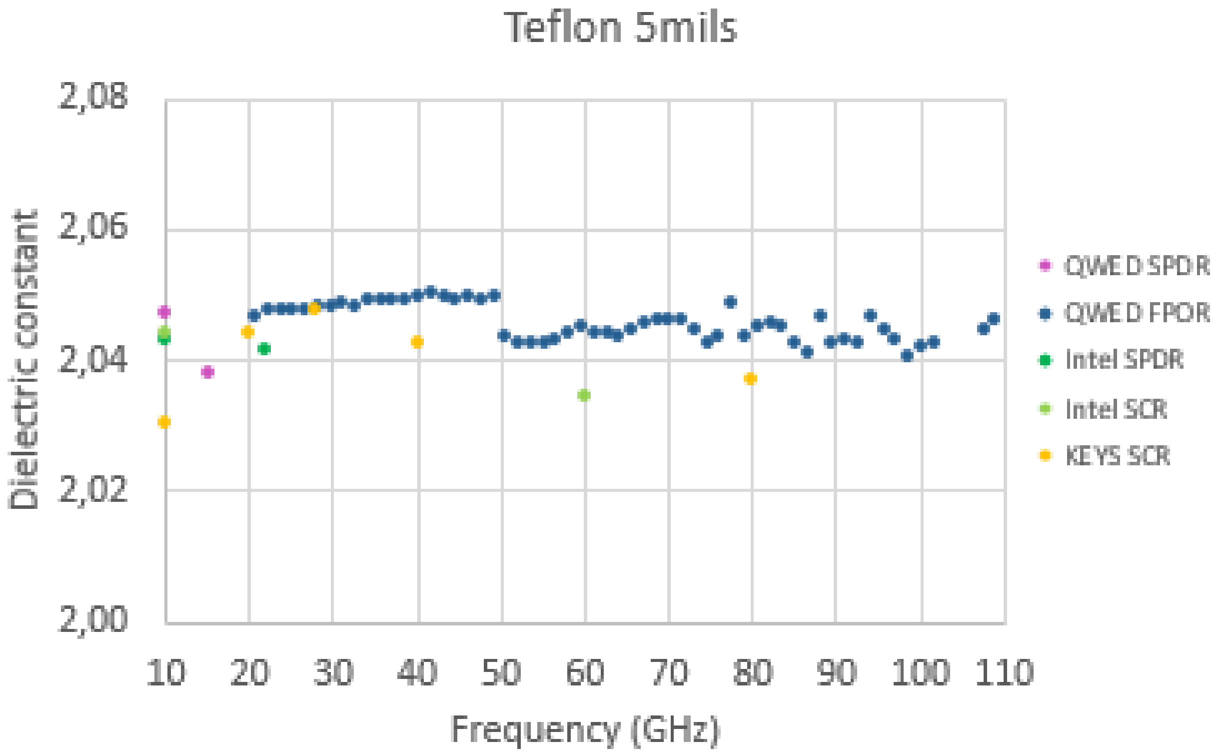
BCDR not included in this presentation.

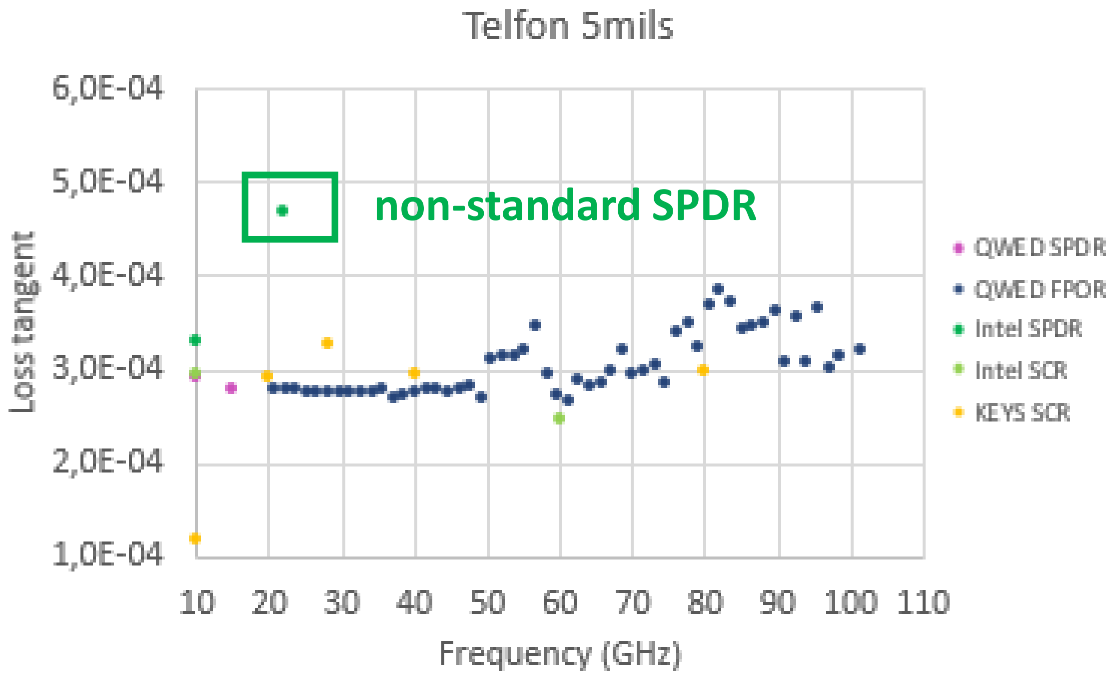
For the benchmarking round-robin, we selected isotropic materials.

Characterisation Results - Consistency

3 labs, 3 techniques, 14 laboratory setups

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





Dk spread < 1% (within ± 0.5% from average)

Characterisation Results - Consistency

EXCEL, LONDON 2-7 APRIL 2022 EuMW 2021 United in Microwaves www.eumw2021.com

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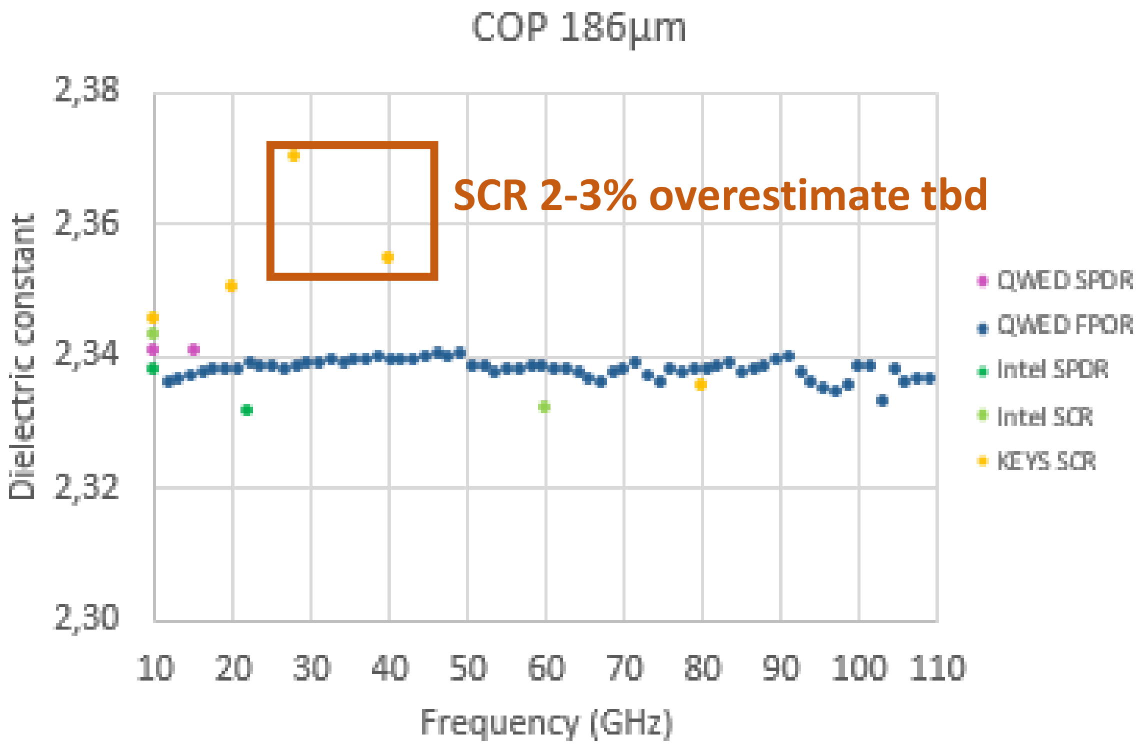
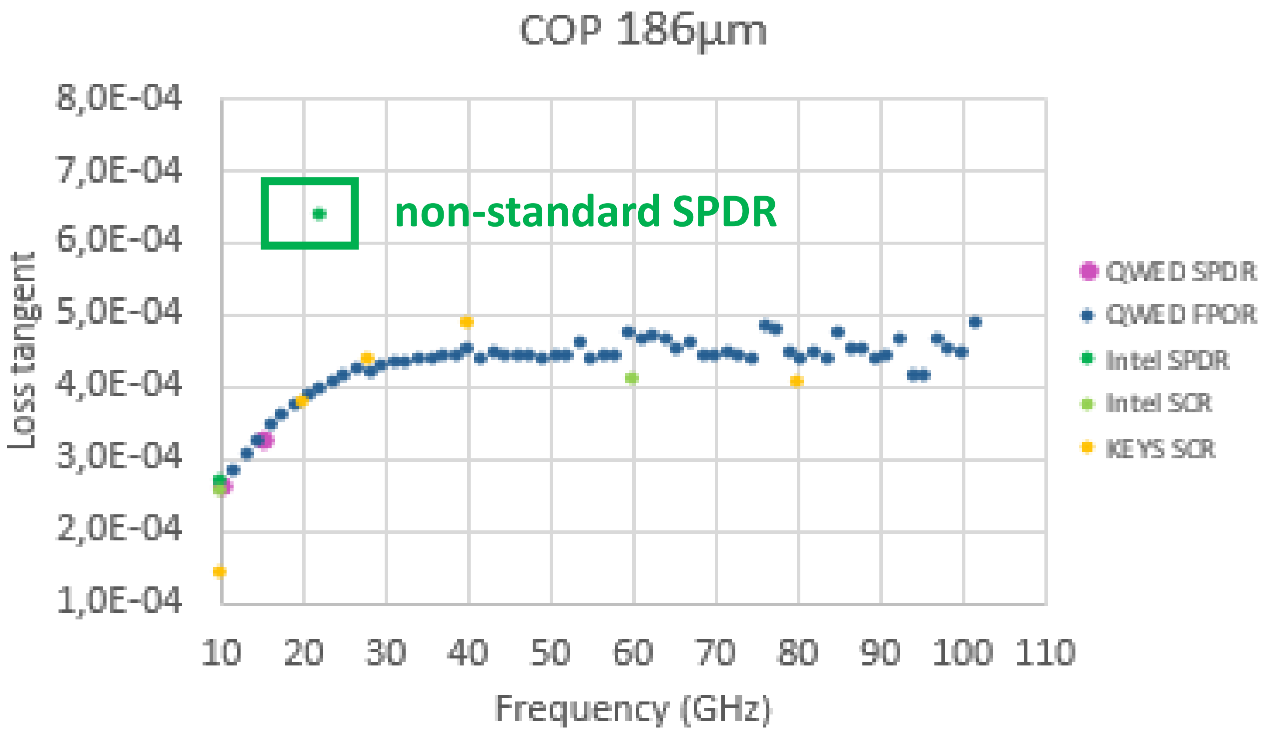




Dk spread < 1% (< 3% incl. outliers)

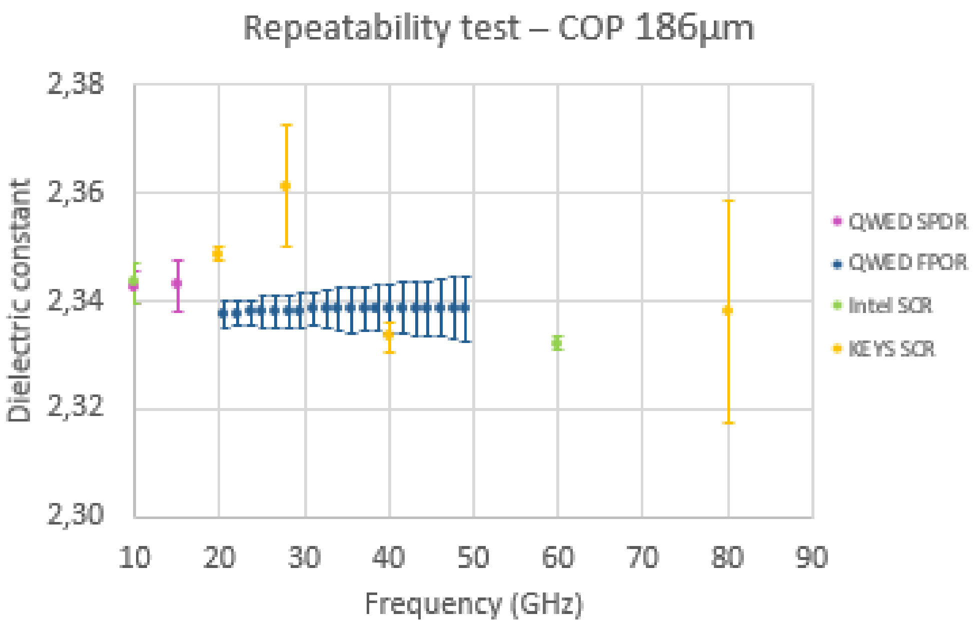
> 40GHz 2x increase in Df compared to 10GHz

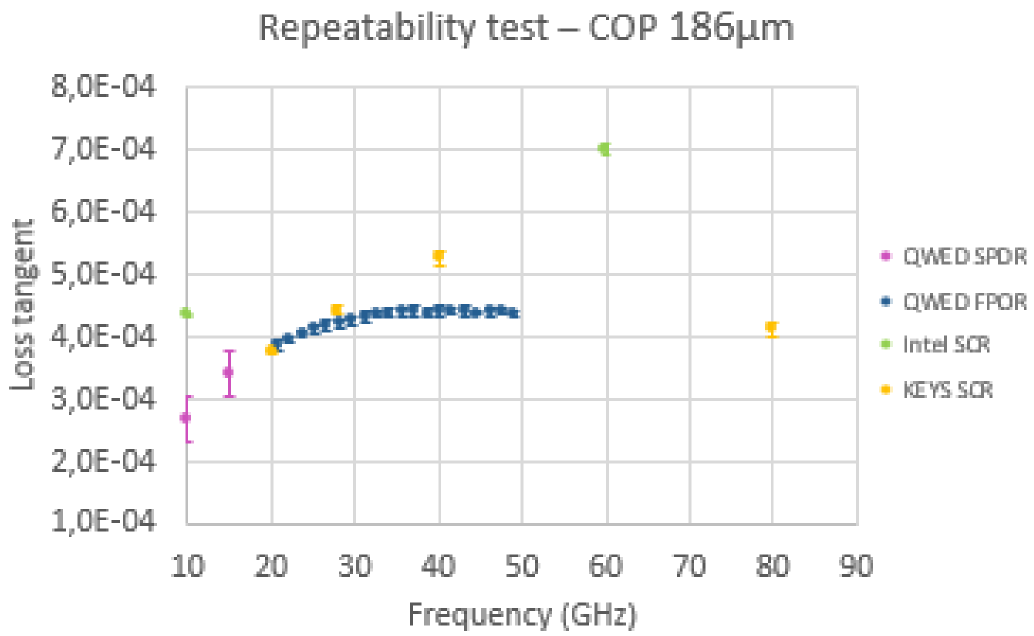
Characterisation Results - Repeatability

EXCEL, LONDON 2-7 APRIL 2022
EuMW 2021 United in Microwaves www.eumw2021.com

3 labs, 3 techniques, 14 laboratory setups
1 operator per setup

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





repeatability of SCR ±1% (one operator spread 2%)
repeatability of SPDR, FPOR better than ±0.5%

each symbol denotes an average of 16 measurements; error bar - triple of standard deviation

Concluding remarks

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

Each resonator technique 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).

Due to the lack of standards & SRMs for 5G/mmWaves, it is crucial to benchmark the techniques against one another, to provide practical guidance to the industry:

- → **samples compatible with more than one metrology are needed,**
- → **35mm x 45mm & 90mm x 90mm together cover all the metrologies with overlaps.**

This paper summarises 112 representative results out of over 1500 measurements performed by 10 labs with 3 techniques on 40 samples (here: from 186 µm – thick Cyclo Olefin Polymer coupon and 5mils –thick Precision Teflon) :

- → **for each technique & lab, typical repeatability (= 3 x std / mean) < 0.5%, (1% incl. outliers),**
- → **Dk spread (between the 3 metrologies) < 1% (3% incl. non-standard outliers),**
- → **for COP at f > 40GHz, 2x increase in Df demonstrated compared to 10GHz.**

Beyond the scope of this paper, the round-robin has continued on other samples (Teflon, fused silica, automotive,…) :

- → **similar & consistent results (rule of thumb: 1% in Dk),**
- → **no obvious bias by lab or by technique,**
- → **differences dominated by sample to sample variation (most likely - thickness variation within a coupon).**

ACKNOWLEDGEMENTS

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https://www.inemi.org/article_content.asp?adminkey=5cc4f4100ebf2ba1f3e6fd6294749139&article=161

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THANK YOU FOR YOUR ATTENTION!