IMPI's
57TH ANNUAL MICROWAVE POWER SYMPOSIUM (IMPI 57)

Microwave Characterization of Liquids with Resonant Methods

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Outline

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- Motivation
- Measurement techniques
  - Cavity resonators
  - New Fabry-Perot open resonator
- Measurement results
- Temperature dependent measurements
- Summary

Motivation

- Dielectric characterization of “loose” materials
  - Liquids
  - Powders
- Electronic coolants
- Food industry
- Raw materials producers
- Characterization with resonant methods
- Wideband characterization in 1 – 50 GHz
  - Cavity devices
  - Fabry-Perot Open Resonator

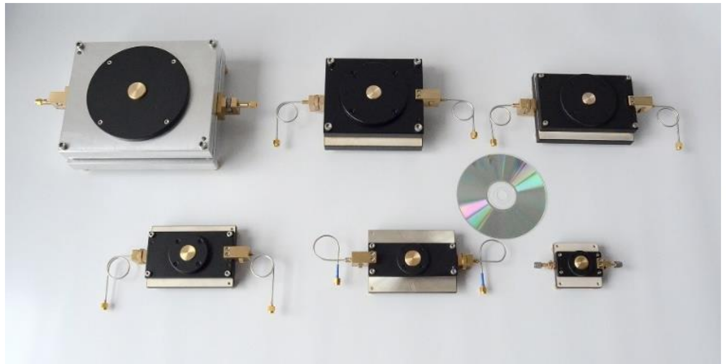
Materials characterization (1)

- Resonant methods well established for materials characterization

- International initiatives benchmarking existing materials characterization methods (iNEMI: www.inemi.org)

- Resonant methods are proven to be the most accurate among microwave material characterisation methods

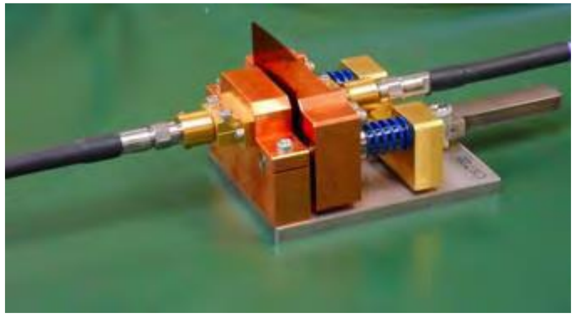
Family of Split-Post Dielectric Resonators



Fabry-Perot Open Resonator

Balanced Circular Disk Resonator

Split-Cavity Resonator

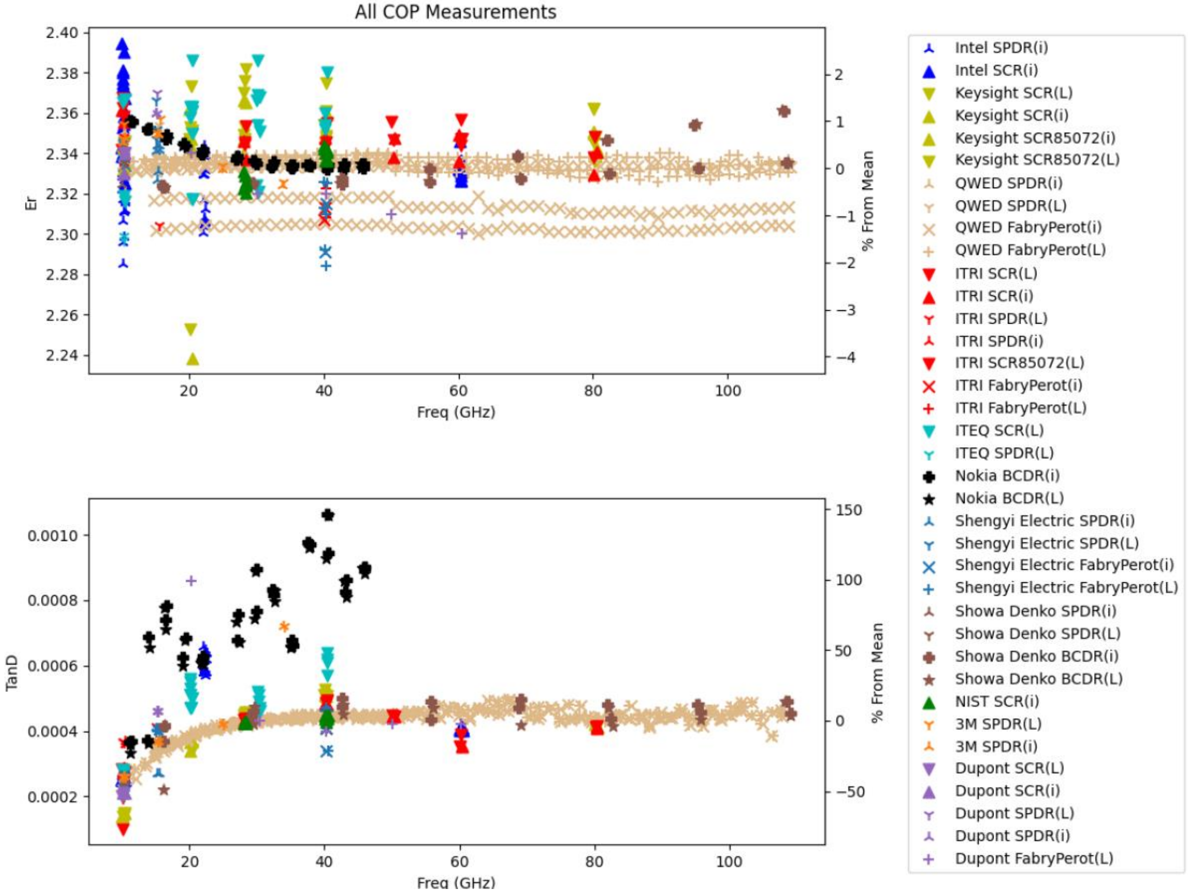


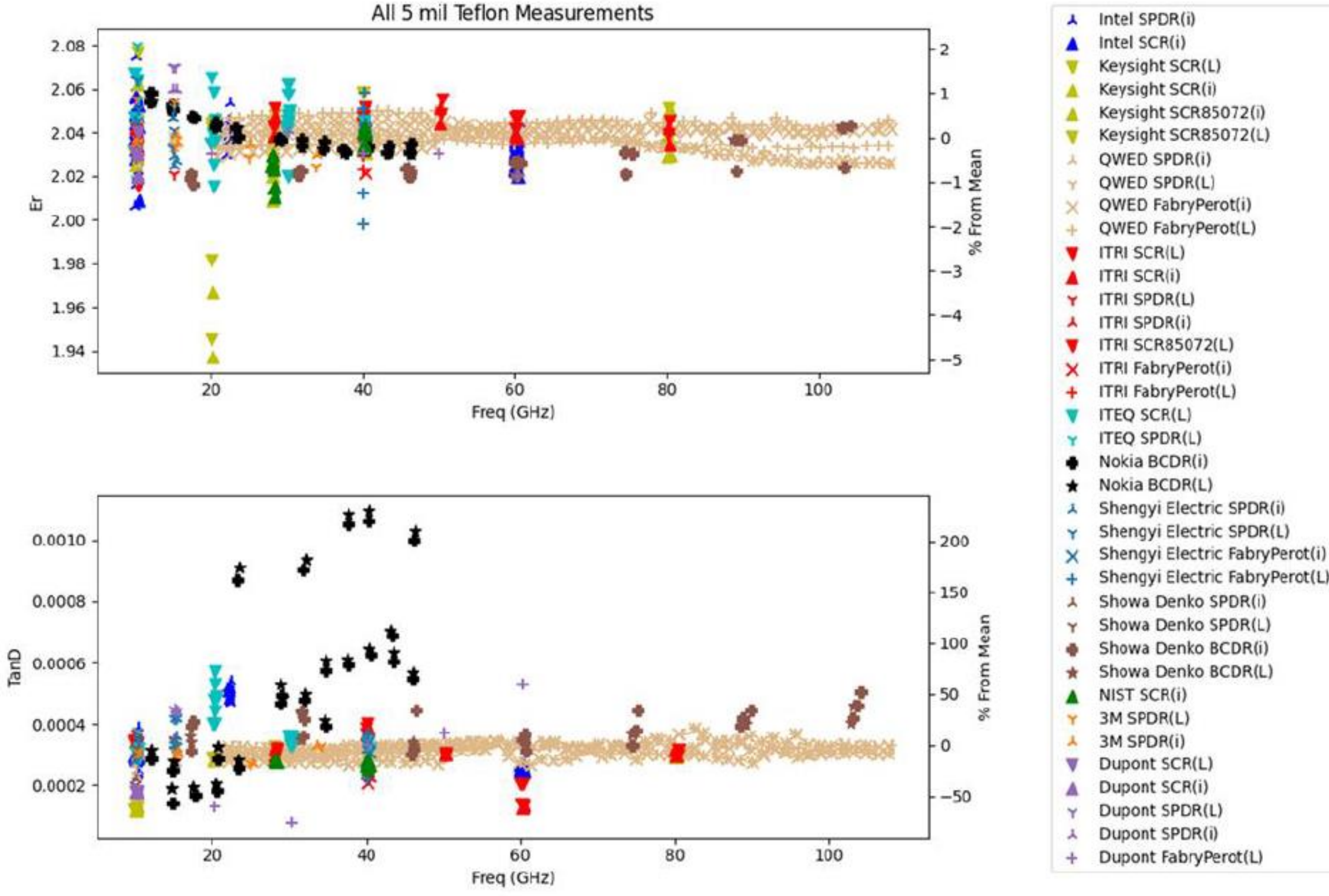
Materials characterization (2)

iNEMI ***5G/mmWave Materials Assessment and Characterization*** **project results**

Over 1000 measurement points in total

Round 1



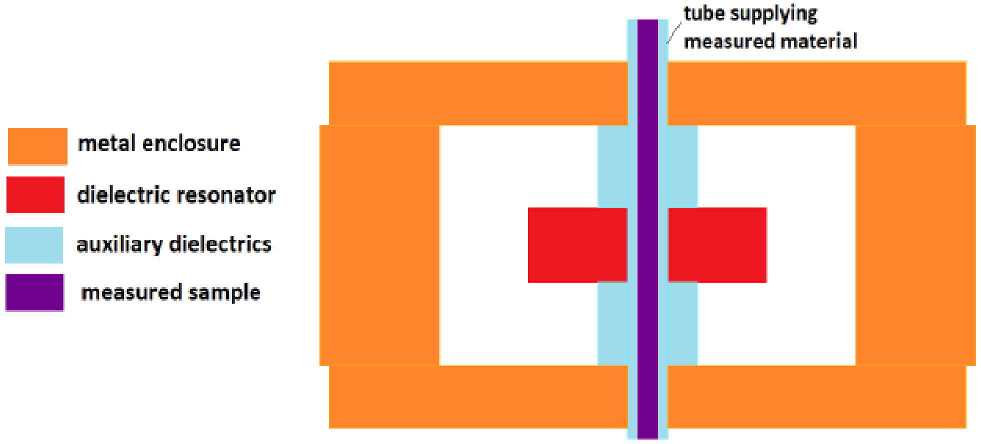


Spread of Dk: ±2%

Measurement methods (1)

Resonant methods are proven to be the most accurate among microwave material characterisation methods

Low frequency dielectric resonator cavities



Schematic concept of the dielectric resonator cavity

Dielectric resonator cavity at 1 GHz

Measurement methods (2)

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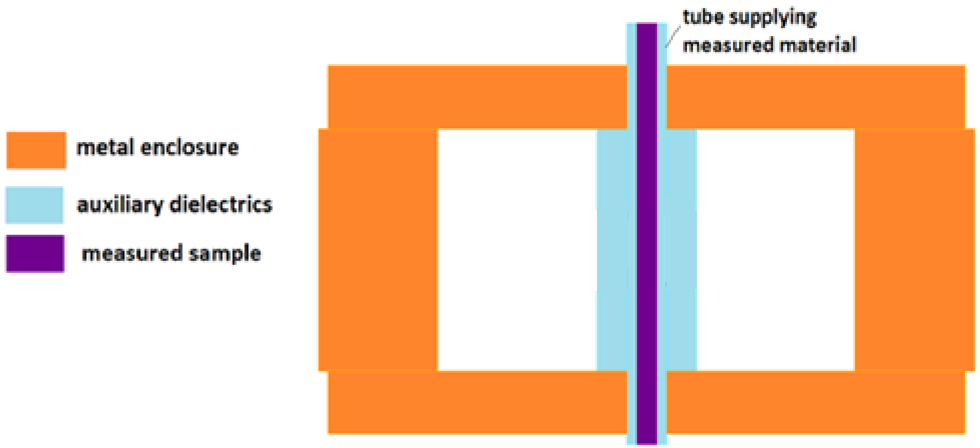
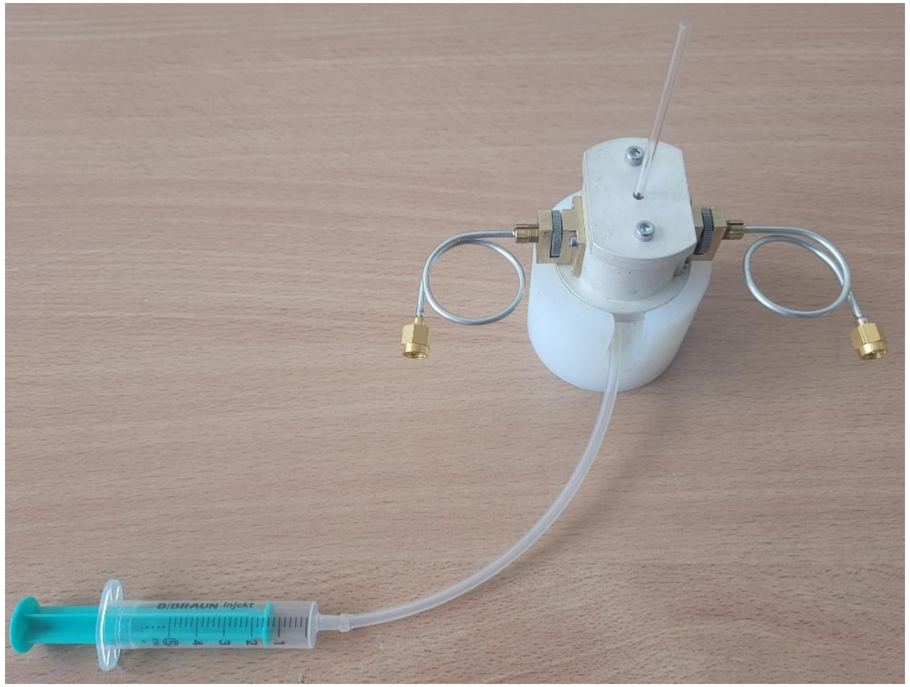
Resonant methods are proven to be the most accurate among microwave material characterisation methods

Higher frequency cavity resonators



Schematic concept of the resonance cavity

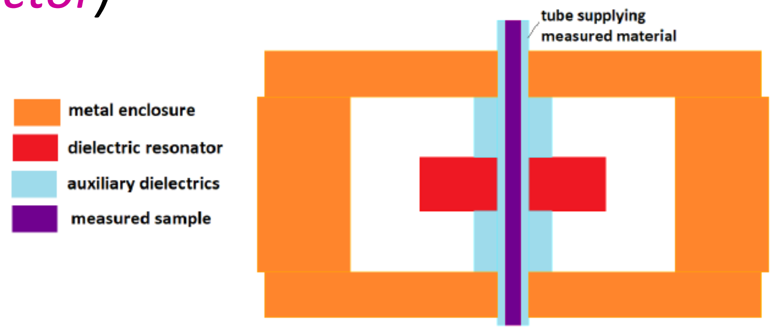


24-GHz Cavity resonator

(with fused silica tube, rubber tube and syringe)

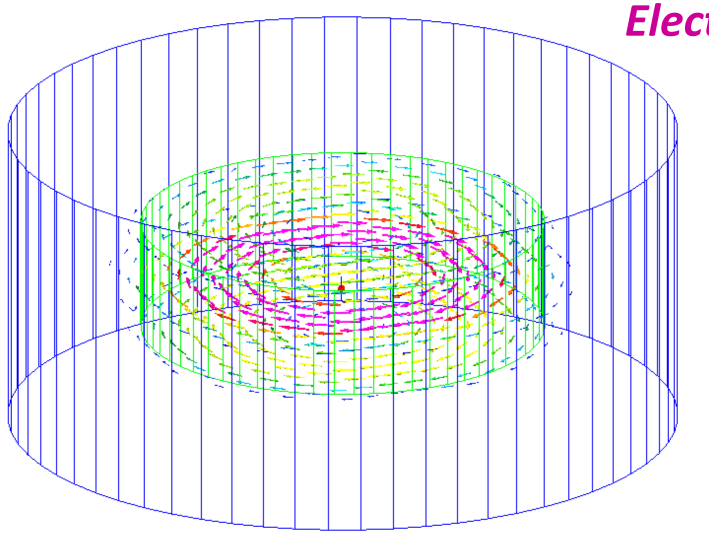
Measurement methods (3)

- $TE_{01\delta}$ resonance mode *(described with resonant frequency and Q-factor)*
- Electric field mostly confined within the dielectric pill
- Circumferential electric field
  - → no issues with galvanic connection of the lid
- Zero electric field at $\rho=0$
  - → no risk of supressing resonance if lossy sample is inserted

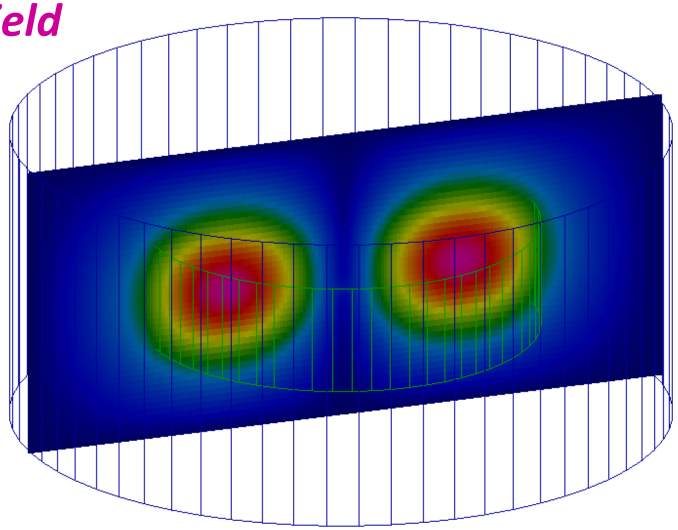


Resonance mode within dielectric resonator cavity *

Electric field

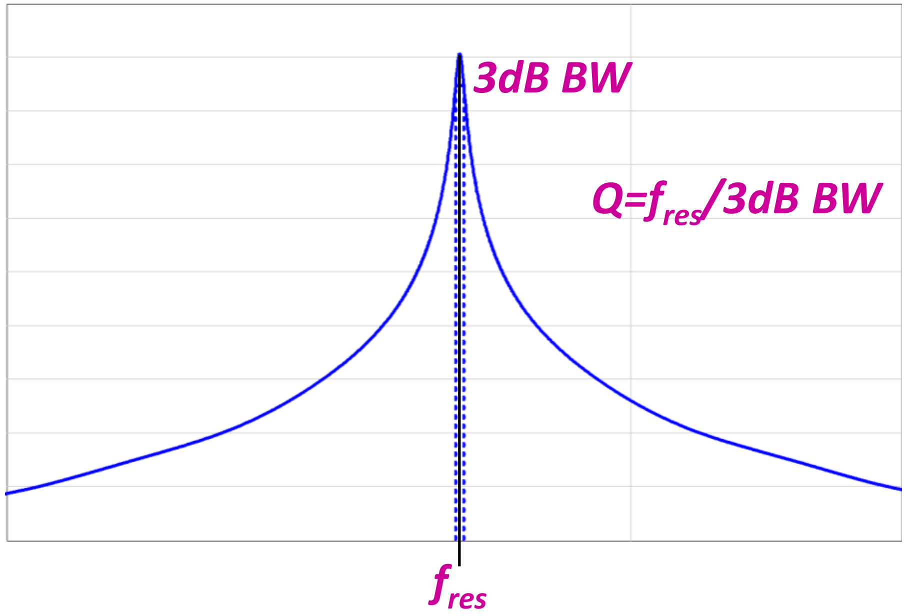


Vector view



Amplitude view (cross section)

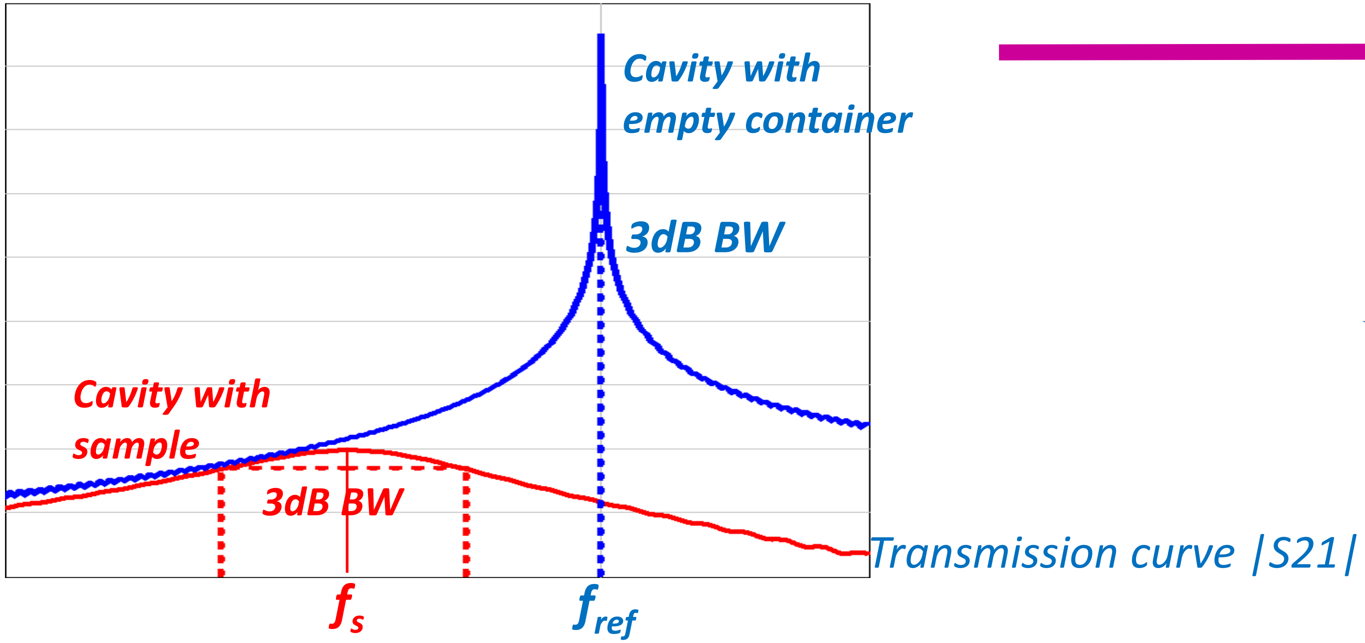
Transmission curve |S21|



*** Obtained with QuickWave 3D software**

Measurement methods (4)

- Two/three stage measurement
- Reference measurement – cavity with empty container (f_{ref} and Q_{ref})
  → the inner diameter of the container/container needs to be precisely calibrated
- Measurement of sample-loaded cavity (f_s and Q_s)
- Scalar measurement of transmission curve (|S21|) is typically sufficient



→ Δf, ΔQ

Precise EM model of the resonator

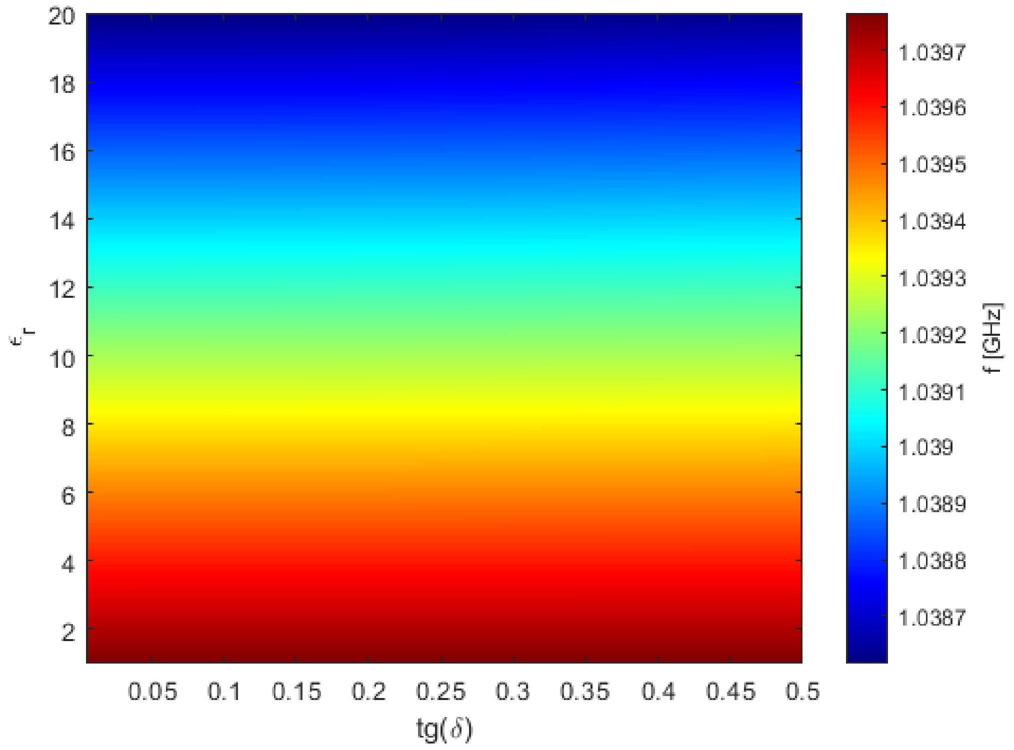
(embedded in the dedicated software)

ε_r, $\tan\delta$

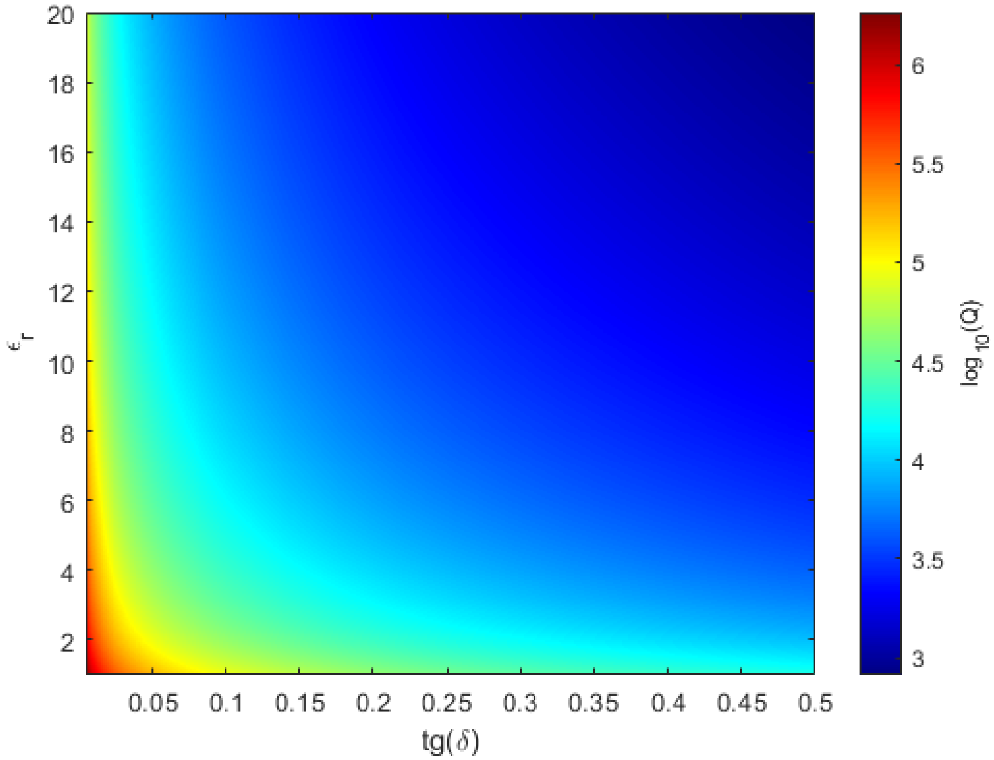
Lookup Tables

In a low-loss regime, resonance frequency depends mostly on the Dk,

whereas the Q-factor decreases with both Dk & Df.



Resonance frequency



Q-factor (log-scale)

Measurement methods (5)

Low frequency dielectric resonator cavities
Dielectric resonator cavity at 2.5 GHz

Specification

Fluid diameter < 16 mm

$TE_{01\delta}$: f = 2.45 GHz (Q = 29,400)

$TE_{02\delta}$: f = 5.16 GHz (Q = 27,200)

Higher frequency cavity resonators
24-GHz Cavity resonator

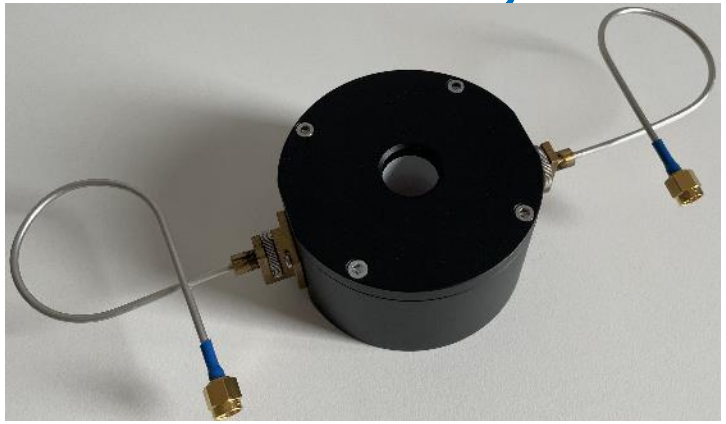
Specification

Fluid diameter < 3 mm

TE_{011}: f = 23.8 GHz (Q = 14,200)

Measurement methods (6)

Low frequency dielectric resonator cavities
Dielectric resonator cavity at 2.5 GHz



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Higher frequency cavity resonators
24-GHz Cavity resonator

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TE_{011}: f = 23.8 GHz (Q = 14,200)

Fabry-Perot Open Resonator

Single solution for 15-50GHz

f ↑ manufacturing tolerances of FS tubes ↑

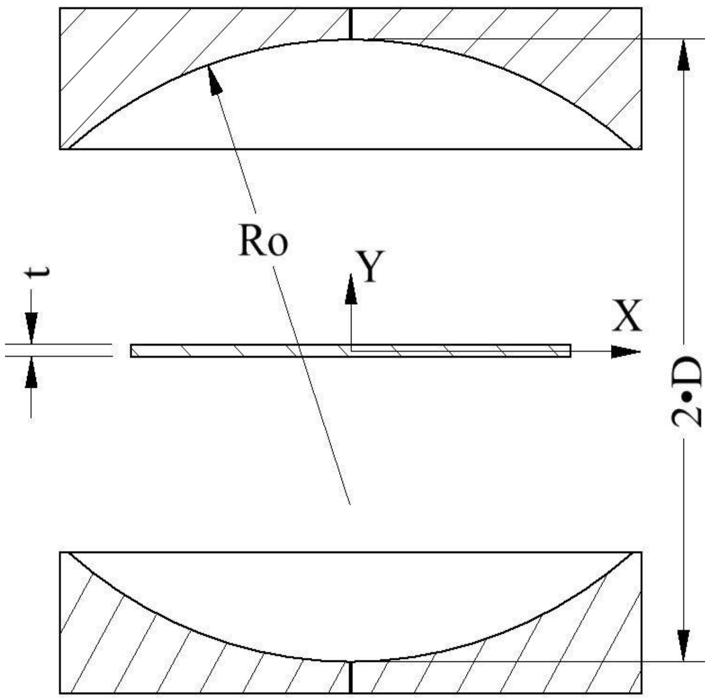
prohibitively large ***Din*** variation

uncertainty of the measurement ↑

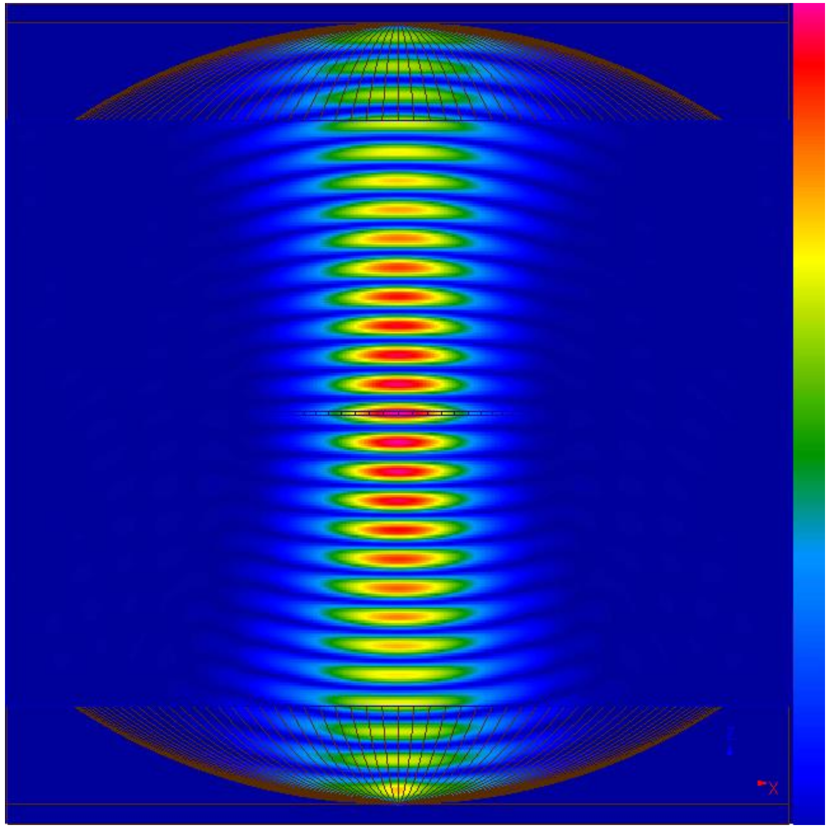
Fabry-Perot Open Resonator

Fabry-Perot Open resonator

Bridging the gap between classical resonant methods and free space methods



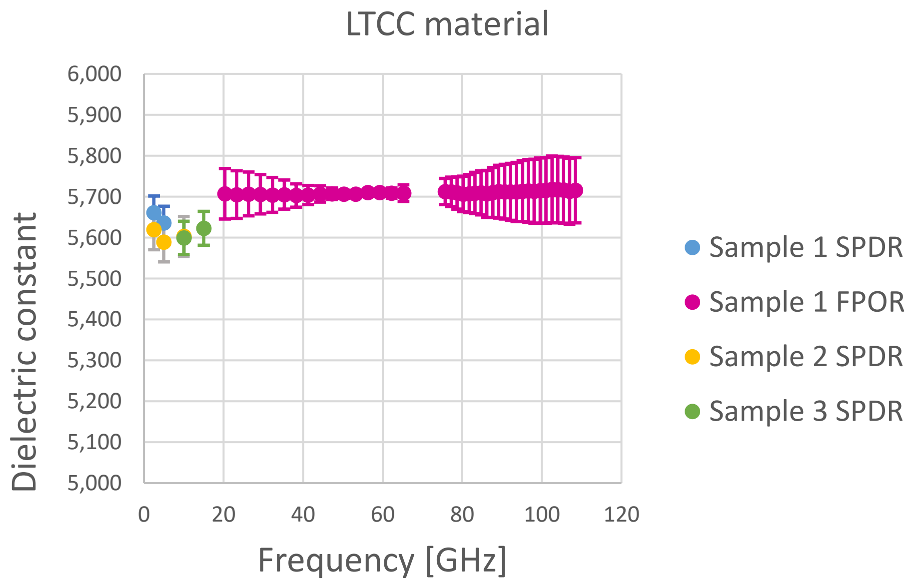
*Gaussian **TEM00q** modes*

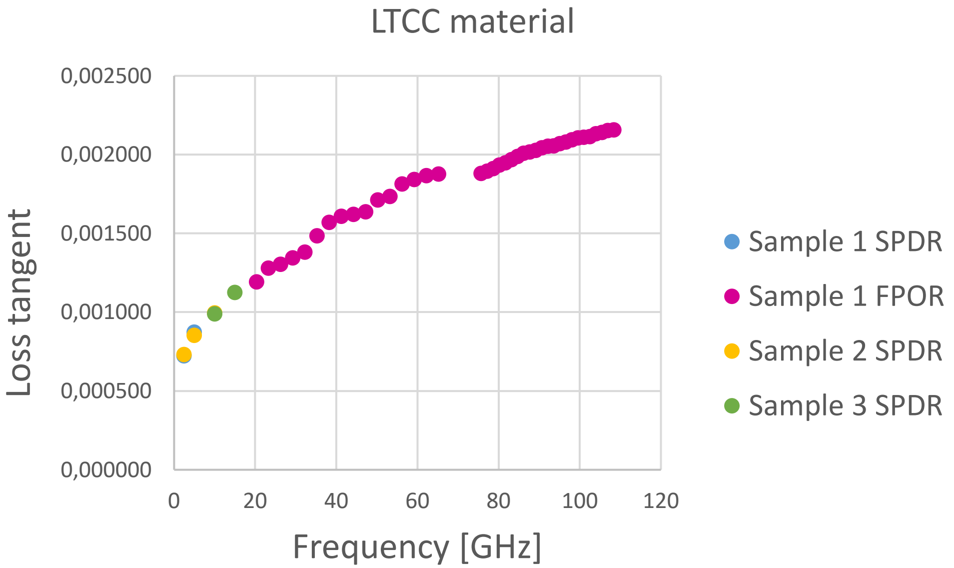


Electric field distribution - simulation model in QuickWave software

FPOR for sheet dielectrics characterization

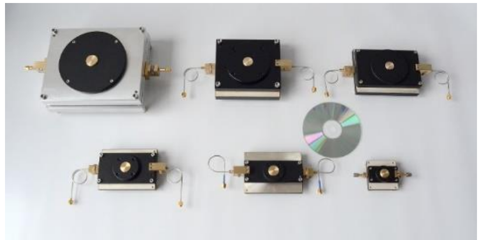
Commercial A6M material



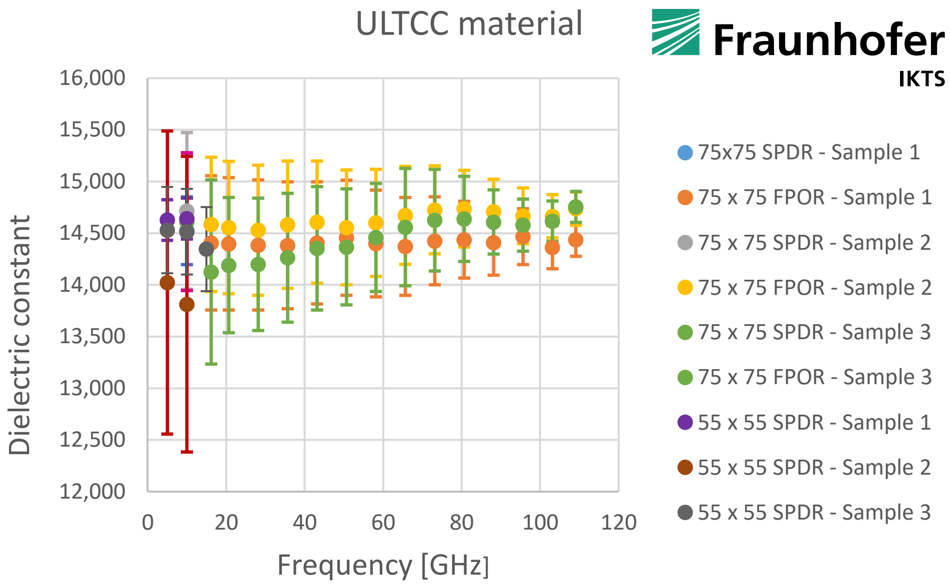


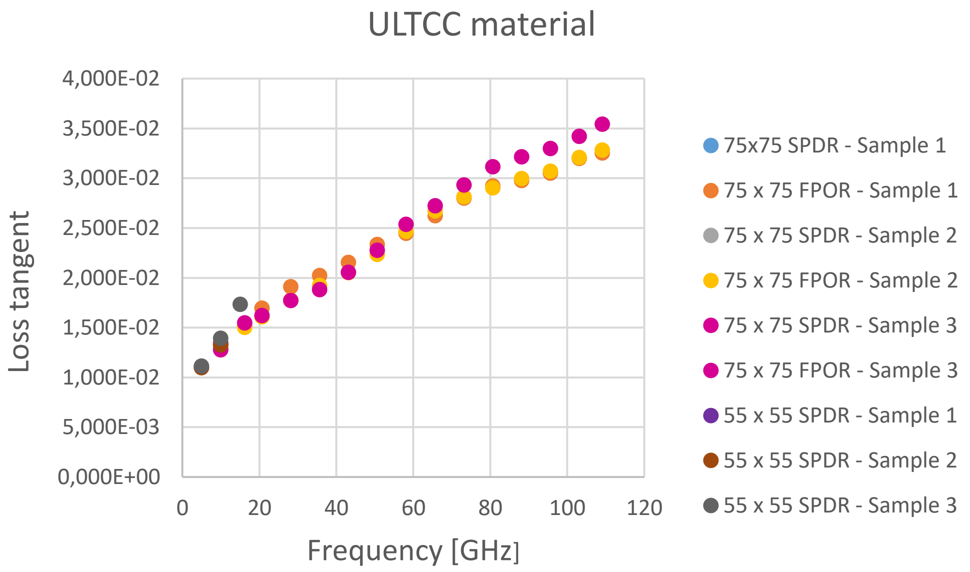
Wideband FPOR solution

Family of SPDR fixtures



ULTCC material developed in ULTCC6G_EPac





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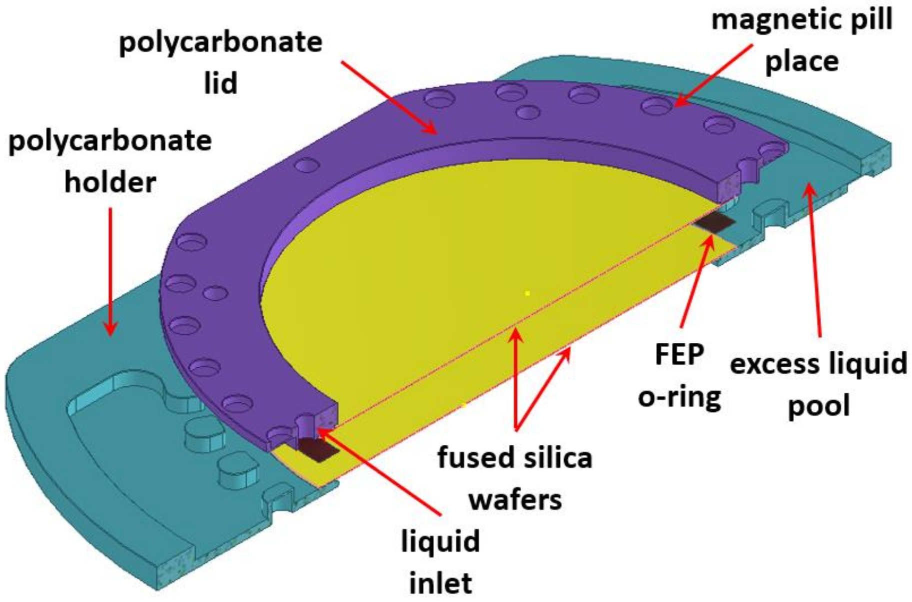
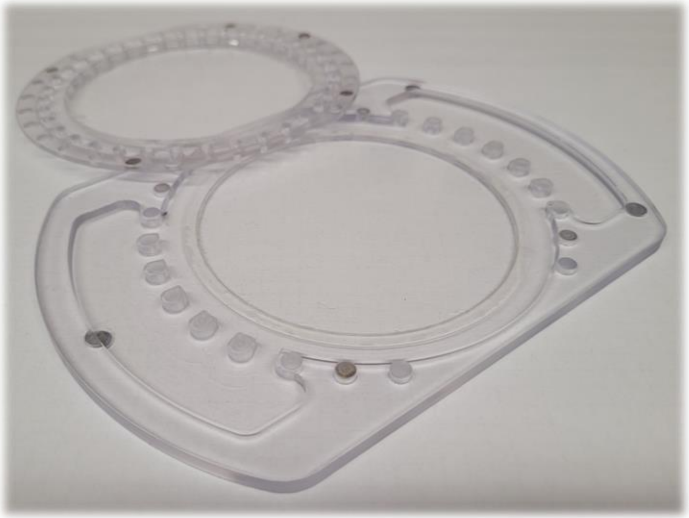
Fraunhofer IKTS

Ultra-Low Temperature Co-fired Ceramics for 6th Generation Electronic Packaging (ULTCC6G_EPac) project

FPOR for fluids characterization

Fabry-Perot open resonator with a dedicated fluid container



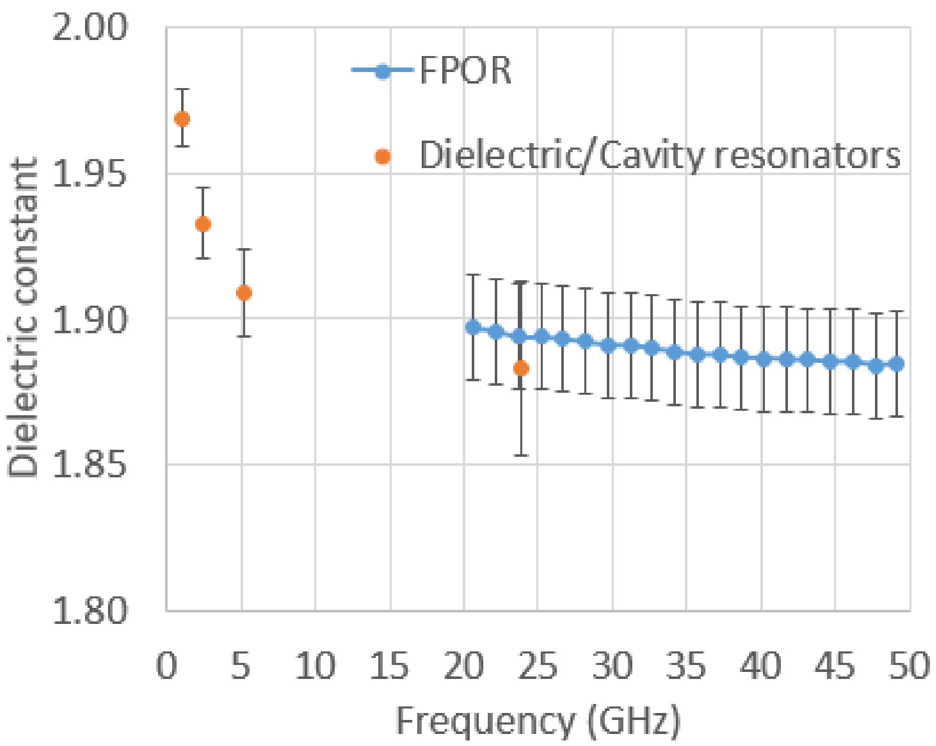


Specification

Fluid thickness: 100-400 µm
Frequency: 15-50 GHz

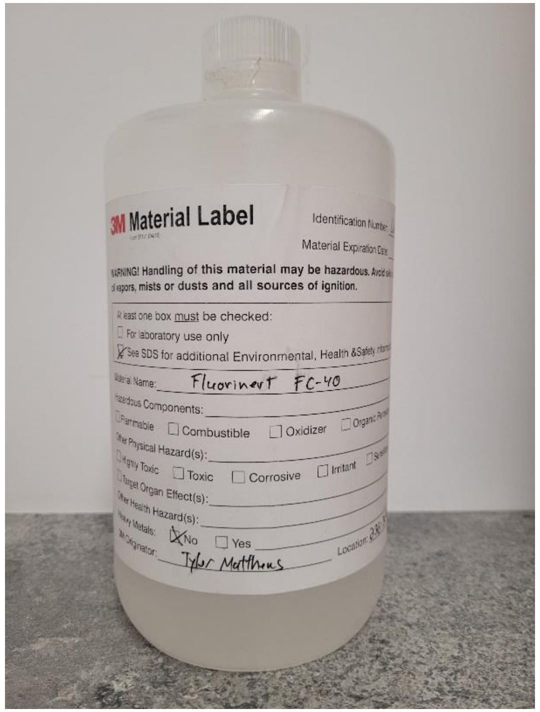
Requires dedicated EM model and measurement software

Measurements results - electronic coolants

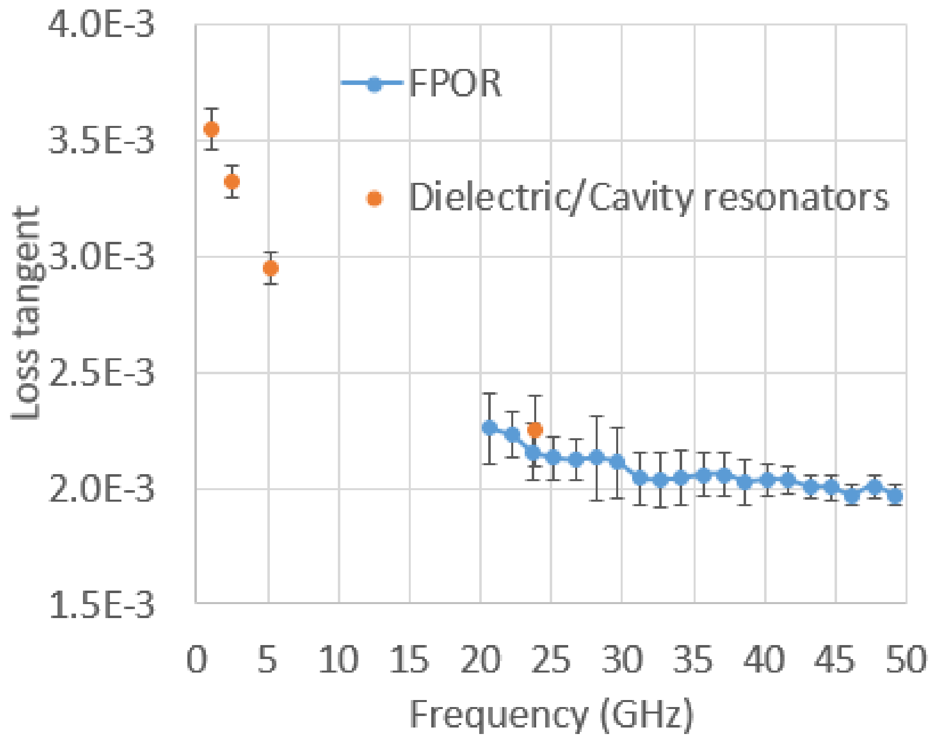


Dielectric constant

Uncertainty of Dk <1%



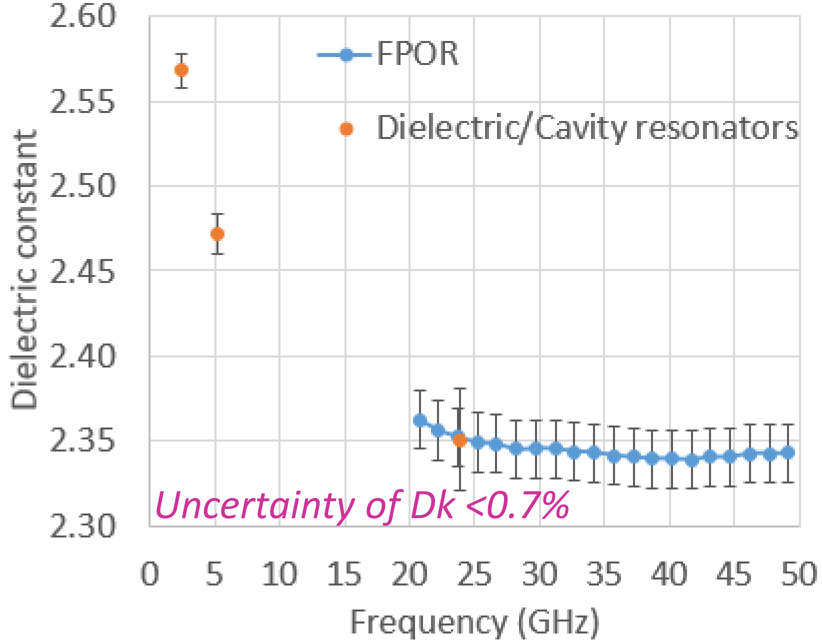
Fluorinert
(3M FC-40)

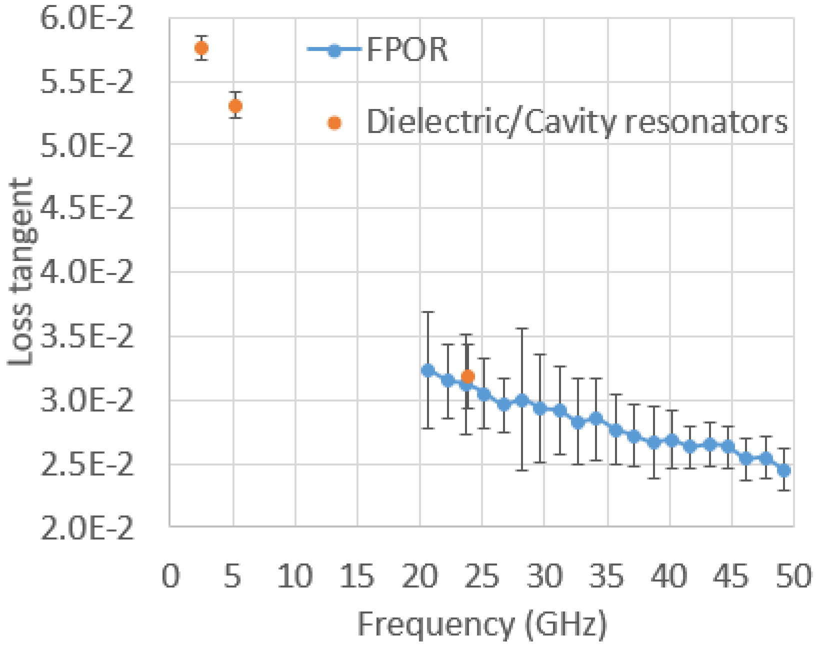


Loss tangent

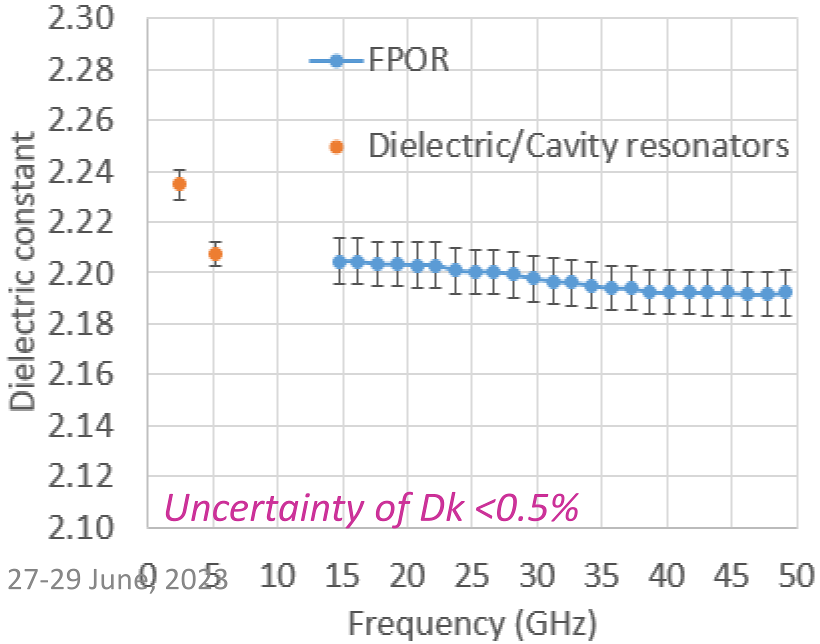
Low-loss liquids typically exhibit dispersive properties at microwaves (Debye-like relaxation)

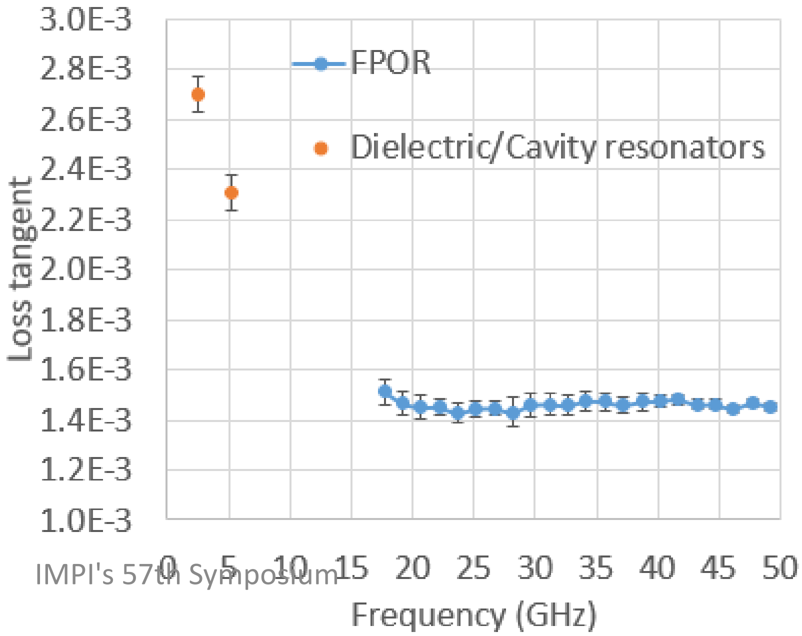
Measurements results - oils





Canola oil





Engine oil

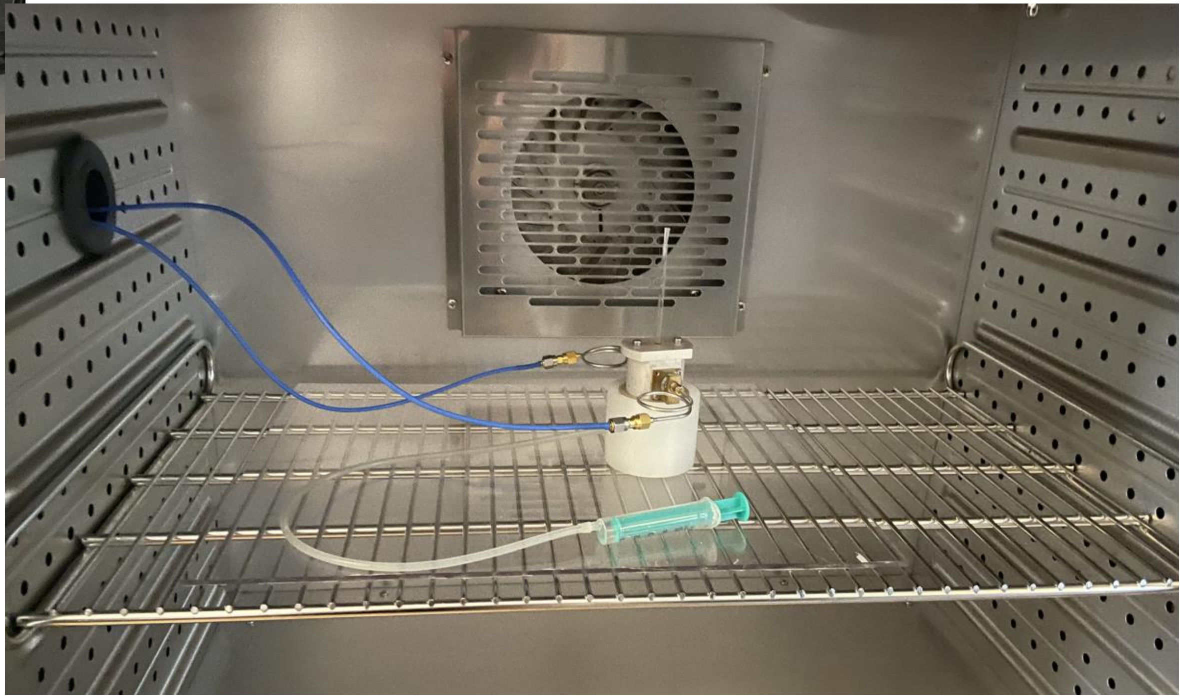
Temperature measurements (1)

Dielectric characterization versus temperature

PC with control app

VNA

Climatic chamber with cavity resonator @24GHz

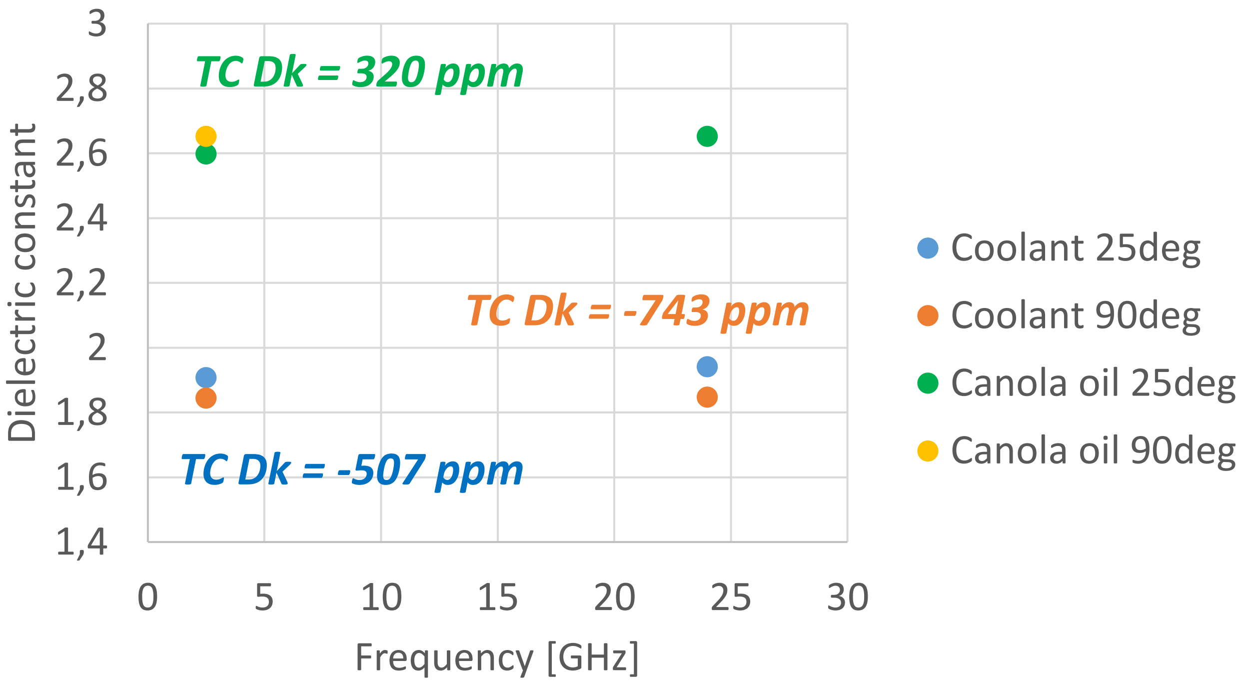


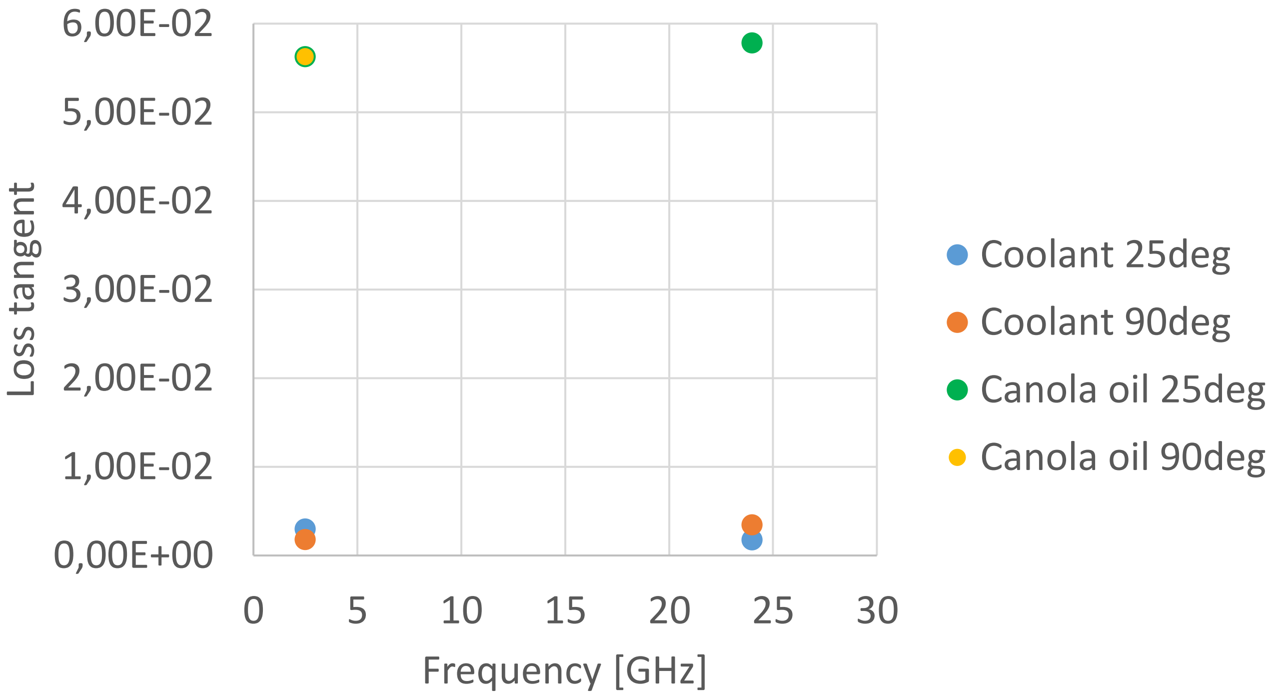
- ✓ ***Material parameters versus frequency***
- ✓ ***TC of dielectric constant of liquid***
- ✓ ***Cavity and dielectric resonators suitable***

Temperature measurements (2)

Dielectric characterization versus temperature

coolant liquid and canola oil





Uncertainty of Dk due to variation of diameter of quartz tube

@2.5 GHz – 0.1% *@24GHz – 0.7%*

Quartz sand measurements

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Intrinsic properties of mixture components can be evaluated (e.g. using Maxwell-Garnett model)

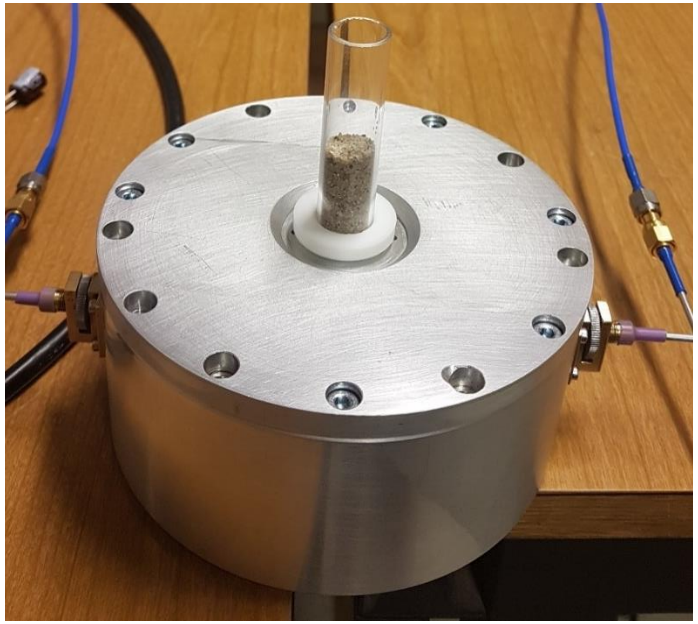
Effective parameters

Dk = 2.851 @ 1 GHz

Dk = 2.758 @ 2.5 GHz

Df = 3.367×10^{-3} @ 1 GHz

Df = 2.539×10^{-3} @ 2.5 GHz



Dielectric resonator (1.04 GHz)

Intrinsic parameters

Dk = 4.275 @ 1 GHz

Dk = 4.104 @ 2.5 GHz

Df = 4.117×10^{-3} @ 1 GHz

Df = 3.124×10^{-3} @ 2.5 GHz

Air volume fraction: 36.4%

Sand and saline water

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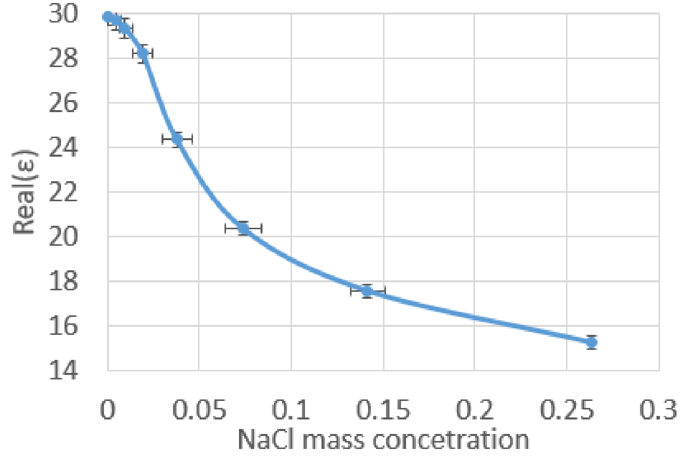
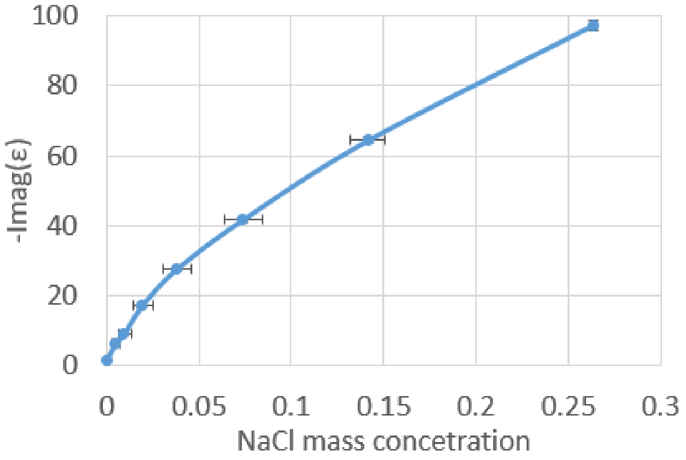
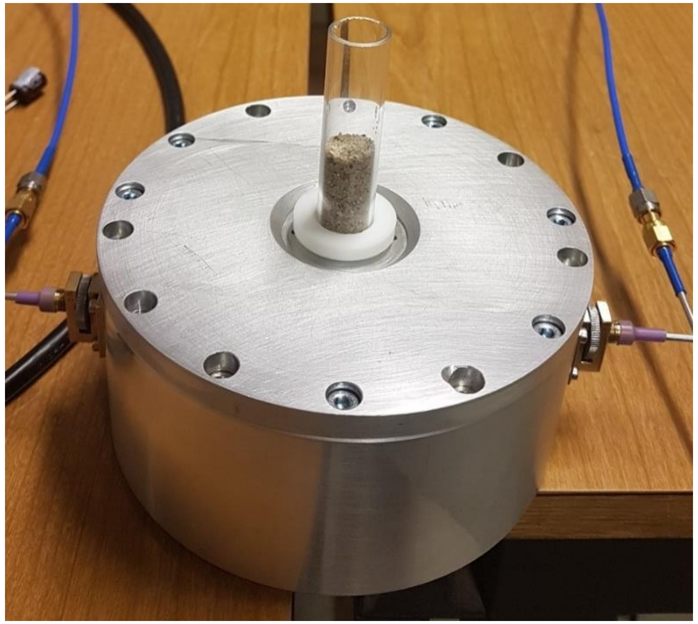
Intrinsic properties of mixture components can be evaluated (e.g. using Maxwell-Garnett model)

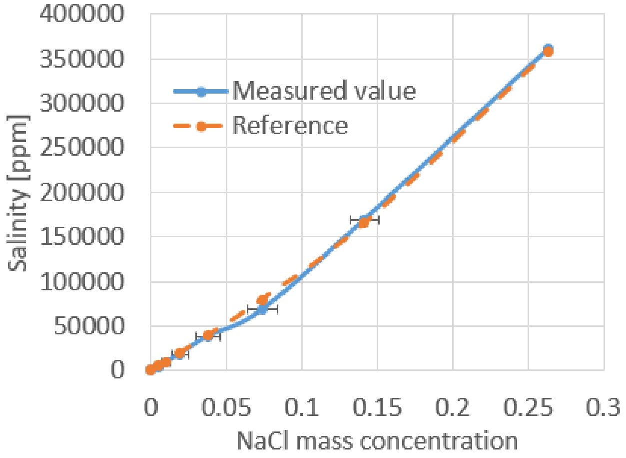


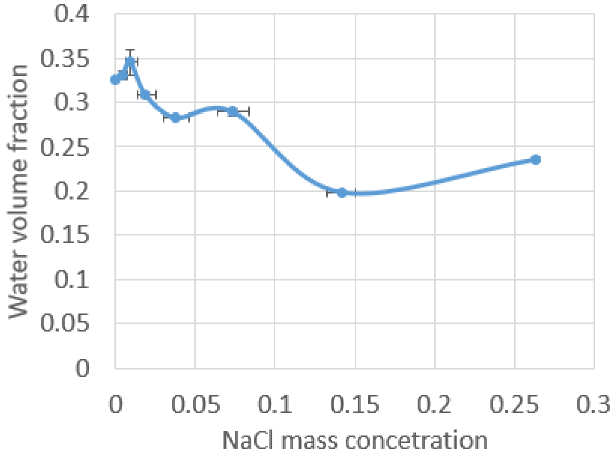


T = 22 ^{0}C



Dielectric resonator (1.04 GHz)





Summary

- Resonant cavity methods for fluids characterisation has been presented and discussed
- New Fabry-Perot open resonator has been presented and applied to liquid materials measurements
- Three liquid materials have been characterised within 1 – 50GHz frequency range
- Good agreement between the methods is observed
- Dielectric/Cavity methods are well applied for temperature measurements and TC extraction

Acknowledgement

The work has been conducted within ULTCC6G_EPac and I4BAGS projects under M-ERA.NET2 and M-ERA.NET3 programs.

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*under **M-ERA.NET2/2020/1/2021** contract*

Ultra-Low Temperature Co-fired Ceramics for 6th Generation Electronic Packaging

*under **M-ERA.NET3/2021/83/I4BAGS/2022** contract*

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ionics surface technologies

Thank you for the attention!

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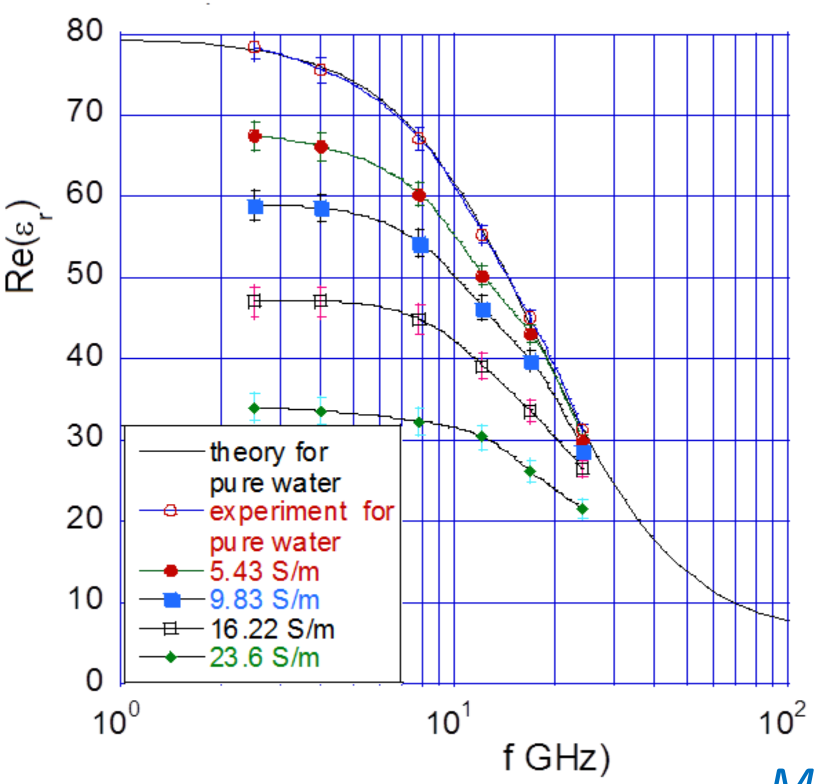
Visit QWED booth

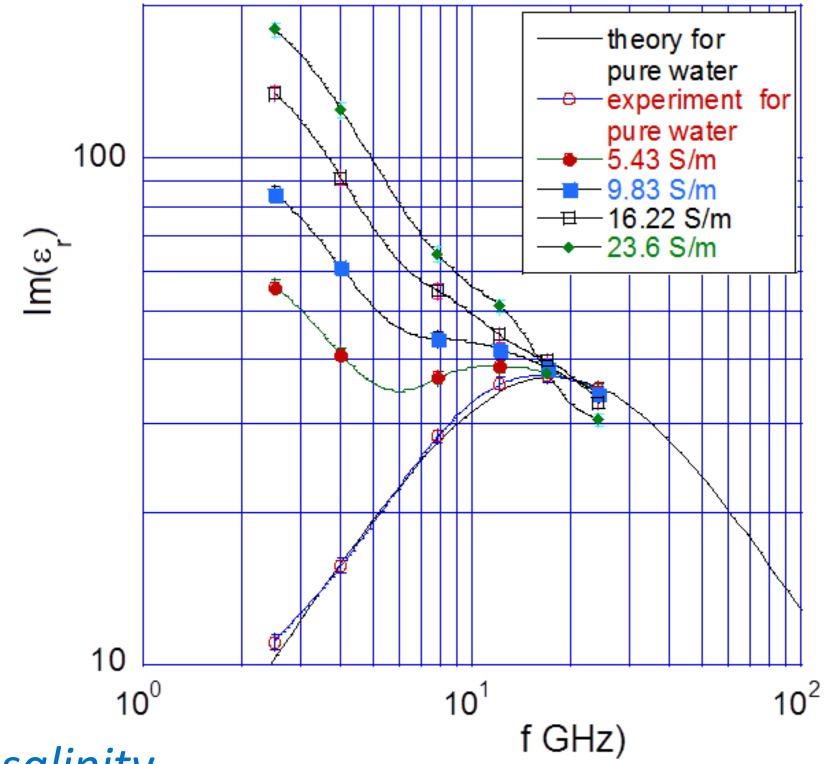
Water

TE_{0mn} cylindrical modes provides superior accuracy in the characterization of lossy liquids, like saline water.



$$\varepsilon(\omega) = \varepsilon_{\infty} + \frac{[\varepsilon_s - \varepsilon_{\infty}]}{(1 + j\omega\tau)} - j\frac{\sigma}{\omega\varepsilon_0}$$

ε_s	low-frequency limit
ε_{∞}	high-frequency limit
τ	relaxation time
σ	ionic conductivity



Measurements of saline water for different salinity,
at 2.5 GHz, 4 GHz, 7.86 GHz, 12.2 GHz, 16.9 GHz, 24.3 GHz

* J. Krupka, Measurements of the complex permittivity of highly concentrated aqueous NaCl solutions and ferrofluid employing microwave cylindrical cavities, Meas. Sci. Technol. 26 (2015).