NFM 2023

Modelling-based large surface testing of LTCC and ULTCC substrates for antenna array design

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Overview

- ❑ Motivation
- ❑ Characterisation method - fundamentals, modelling, and measurement methodology
- ❑ LTCC and ULTCC materials
- ❑ Measurement results
- ❑ Summary

Motivation (1)

- Low temperature co-fired ceramics (LTCC) and novel ultra-low temperature co-fired ceramic (ULTCC) materials gain continuously growing interest:
  - Lowered sintering temperature (compared to HTCC) - keeping compatibility with existing fabrication methods
  - Lowered energy consumption
  - Lower production costs
  - Environmental friendliness
- Application to demanding 5G and 6G systems
  - Telecommunication
  - Computer industry
  - Automotive industry

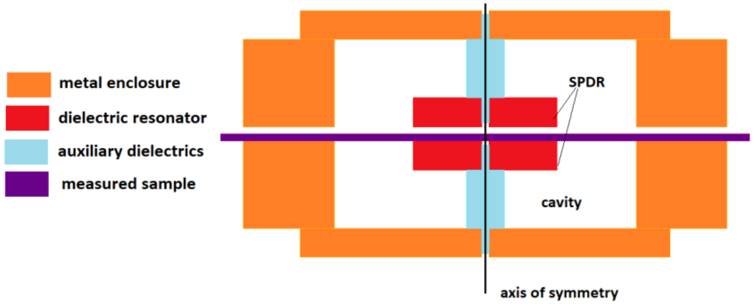
Motivation (2)

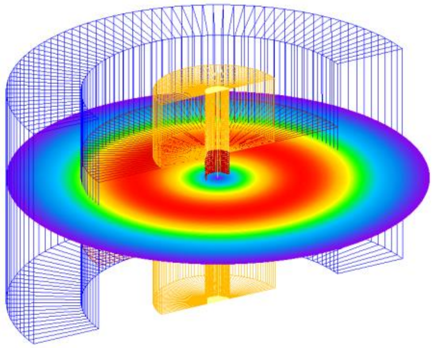
- LTCC and ULTCC materials are foreseen to deliver enhanced
  - manufacturing flexibility
  - miniaturization
  - packaging degree

- Need: Precise dielectric characterisation across substrate surface
  - Quality testing
  - Uniformity of dielectric properties
  - Detection of defects
  - Measure of repeatability of technological process
  - Antenna arrays

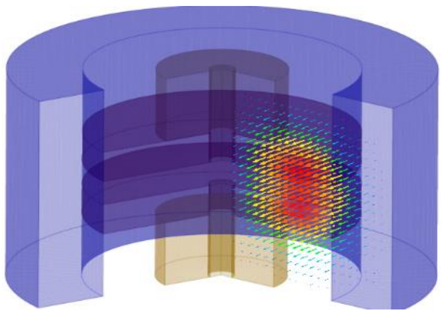
2D SPDR scanner for materials testing (1)

- Based on Split-Post Dielectric Resonator (SPDR) [1]
- Resonant mode with EM fields mostly confined in and between those ceramic posts
- H-field is only vertical at the side wall of the enclosure
- E-field tangential to SUT
- easy SUT insertion through slot
- Non-destructive measurement
- Field patterns remain practically unchanged
- Resonant frequencies and Q-factors change, upon SUT insertion

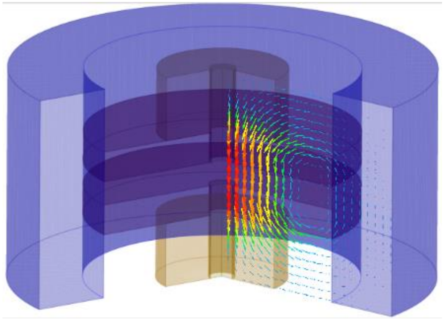


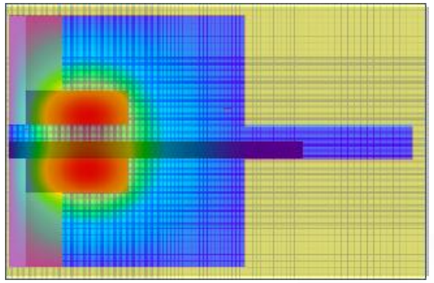


Electric field



Magnetic field

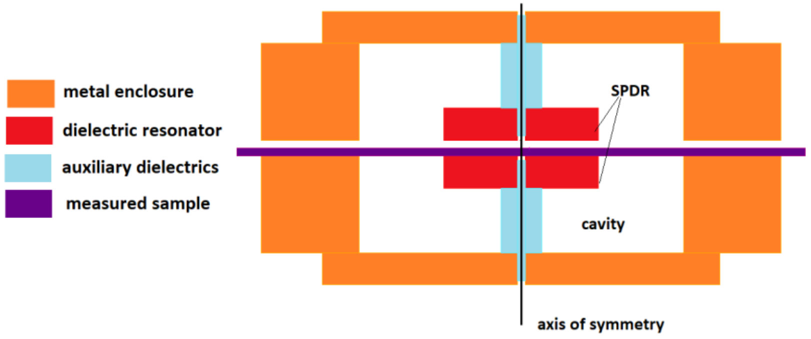




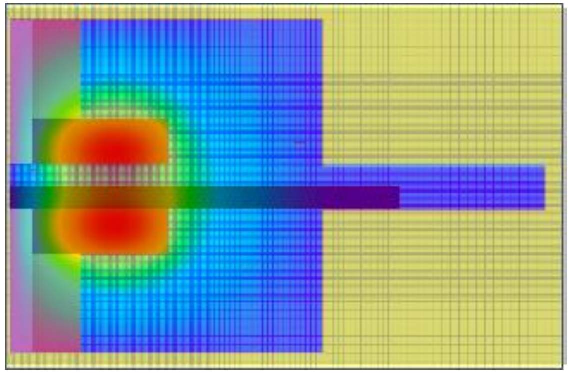
SPDR @ 5 GHz

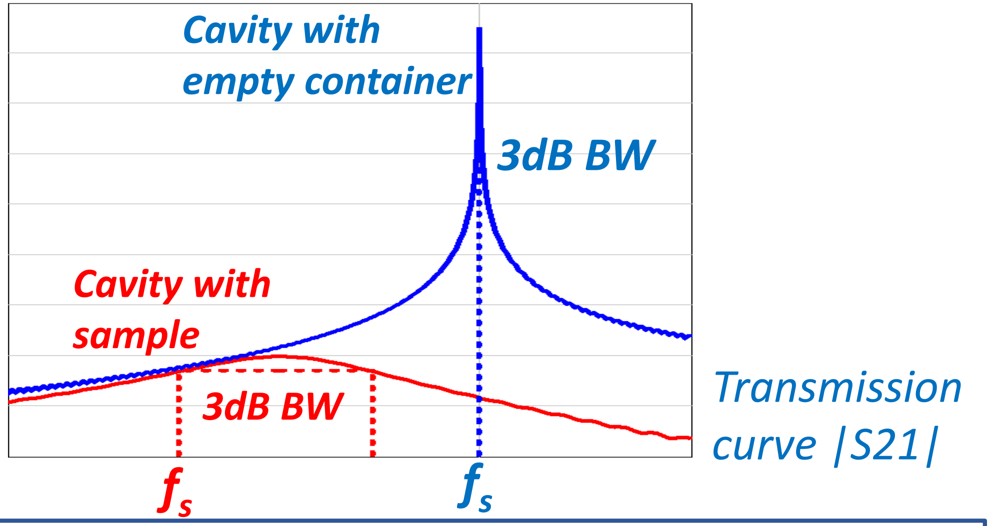
[1] J. Krupka, A. P. Gregory, O. C. Rochard, R. N. Clarke, B. Riddle, and J. Baker-Jarvis, "Uncertainty of complex permittivity measurements by split-post dielectric resonator technique", J. Eur. Ceramic Soc., vol. 21, pp. 2673-2676, 2001.

Split-Post Dielectric Resonator - modelling



Electric field





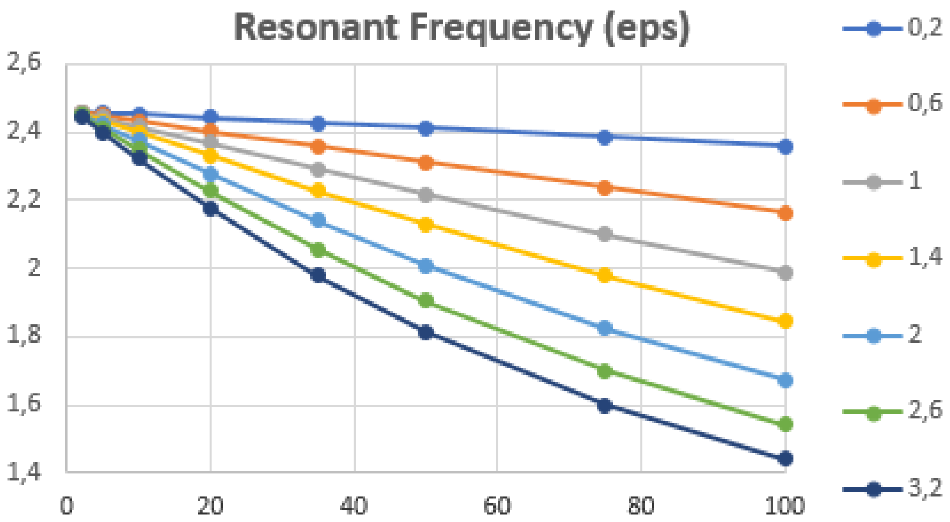
SUT of $\varepsilon_s = \varepsilon_s' - j\,\varepsilon_s''$ is inserted into DR: resonant frequency changes from f_e to f_s and Q-factor changes from Q_e to Q_s.

Non-linear functions – a need for electromagnetic modelling

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

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

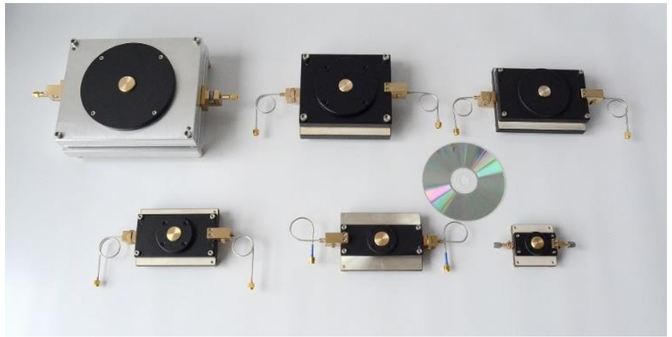
$$C = \iiint_V \left| E(x,y) \right|^2 dV$$



QuickWave BOR simulations of 2.5GHz SPDR – economies in computer effort by 10^3 or more compared to 3D simulations

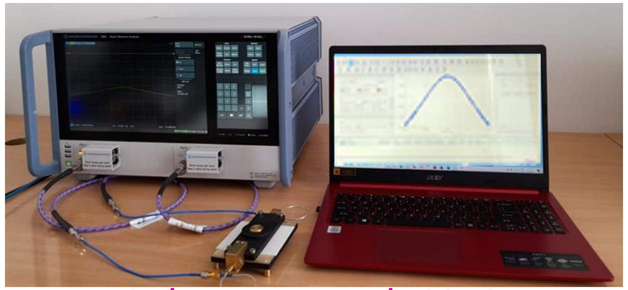
Data for dedicated software for material parameters extraction

Family of SPDR test-fixtures

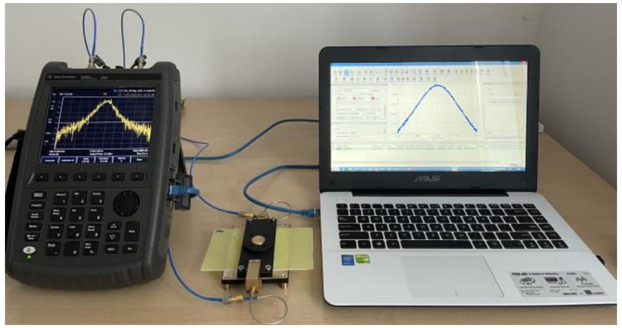


Split-Post Dielectric Resonator – measurements

Measurement setups



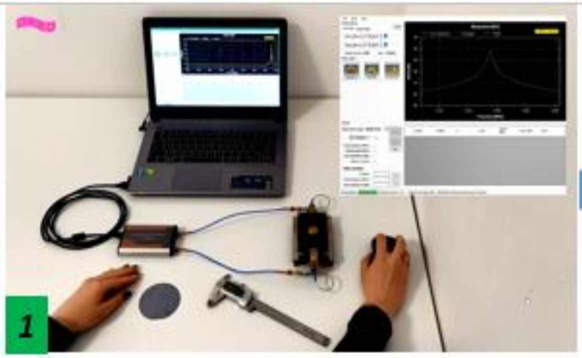
Laboratory-scale VNA

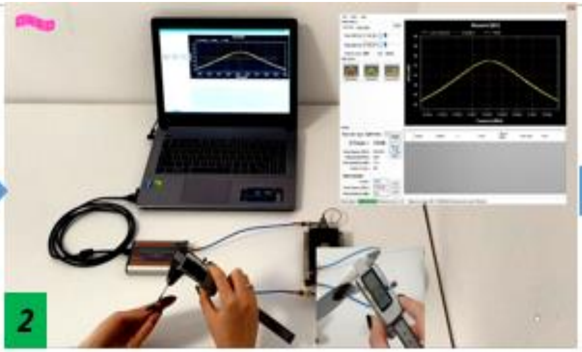


Hand-held VNA

Portable Microwave Q-Meter

Operation workflow – with the use of Q-Meter

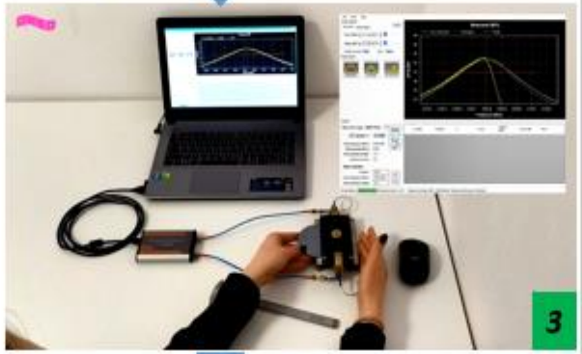




2. ***Measure thickness of the sample***

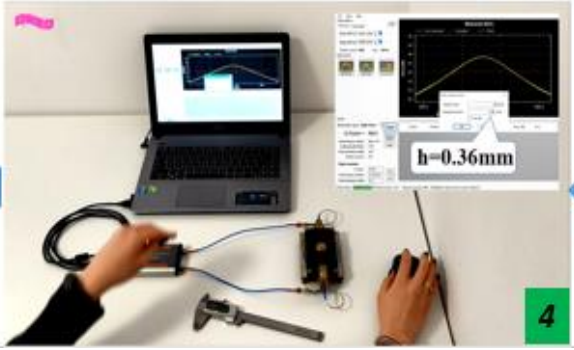
0. Connect the SPDR to Q-Meter using SMA cables.
Connect Q-Meter to PC using USB cable.

1. ***Measure "empty SPDR" – app invoked measurement.***

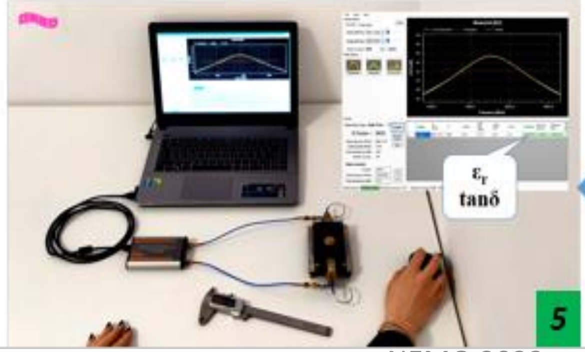


Total measurement time: 30sec

3. ***Insert the sample into SPDR***



4. ***Insert the sample thickness into the PC app***



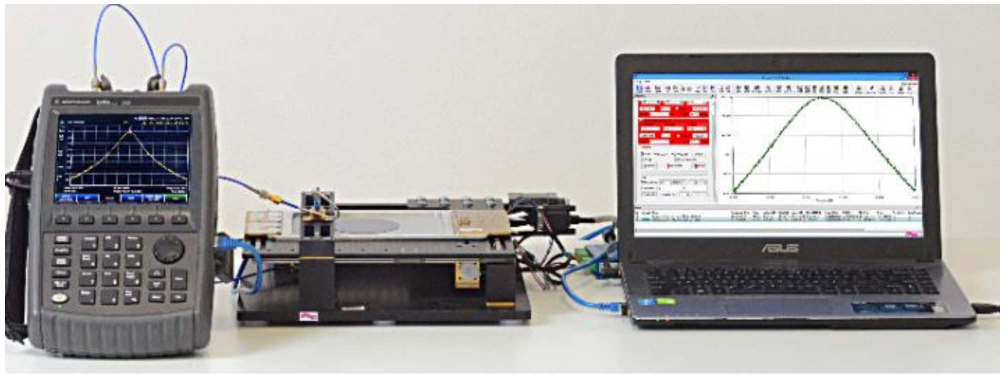
5. ***Material parameters are extracted automatically***

2D SPDR scanner for materials testing (2)

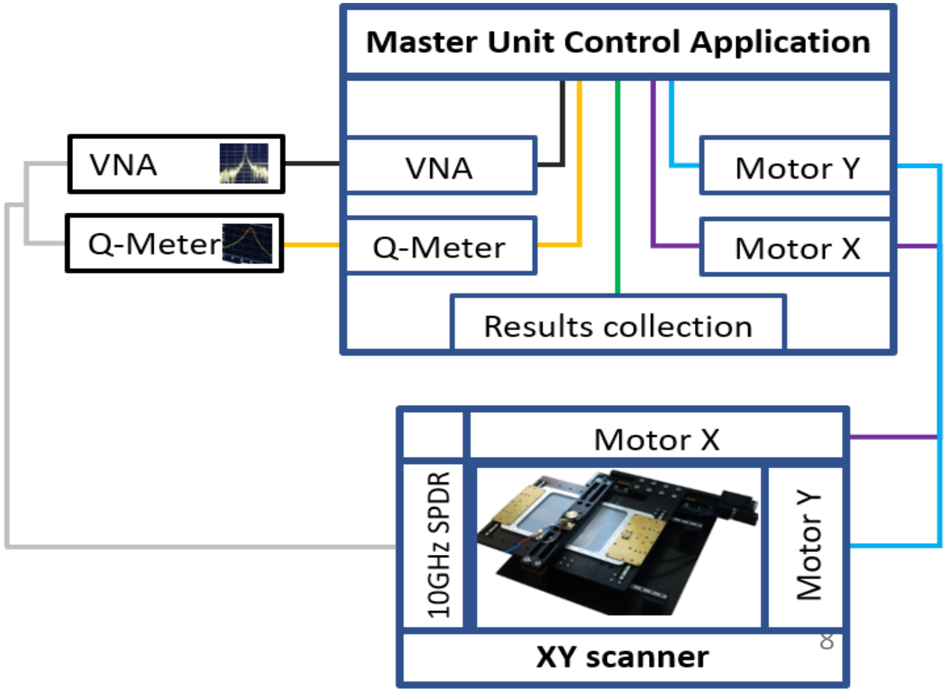
- 2D SPDR scanner operating at 10GHz – compromise between sample thickness and raw lateral resolution
- XY-motorized table (Standa and Nanotec motors)
- Movement resolution as low as 5 μm
- SUT placed on a Teflon foil (stable and intact)

- Positioning and measurement controlled and invoked with dedicated *Master Unit Control Application* (PC app)
- Microwave measurement (resonance frequency and Q-factor) performed over a grid of points across SUT surface
- Extracted parameters' values aggregated into 2D maps of Dk, Df, and resistivity

2D SPDR scanner measurement setup



Measurement control concept



SPDR accuracy and uncertainty

Rigorous EM modelling behind the SPDR software and dedicated calibration of each device unit allows achieving accuracy of:

±0.15% for dielectric constant (Dk)
±3% (or $2 \cdot 10^{-5}$, whichever is higher) for loss tangent (Df)

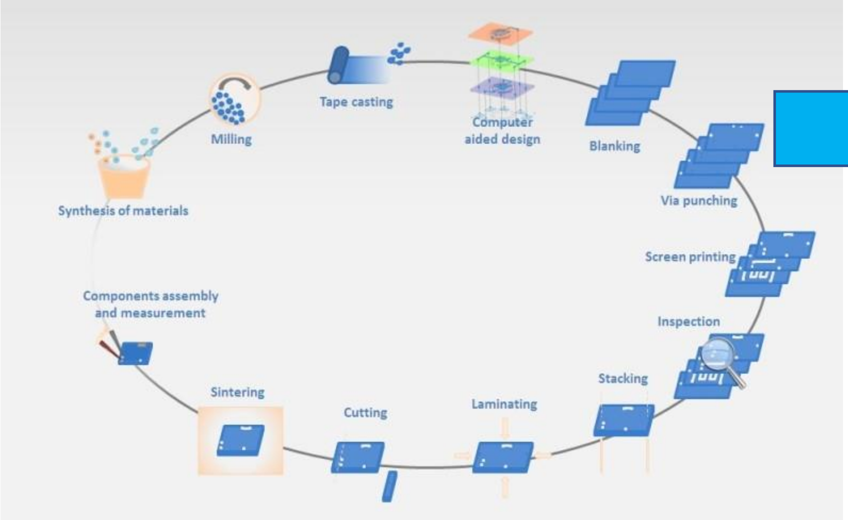
Total measurement uncertainty shall account for uncertainty of:

sample thickness evaluation,

resonant frequency and Q-factor extraction

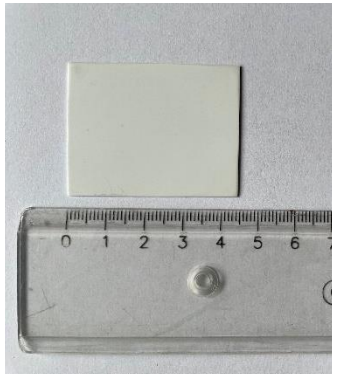
LTCC & ULTCC materials testing (1)

LTCC substrate fabrication scheme



Flexible tape to substrate

$Zn_4B_6O_{13}$_Zn_2SiO_4 ***Test sample by***



Expected by chemical composition:

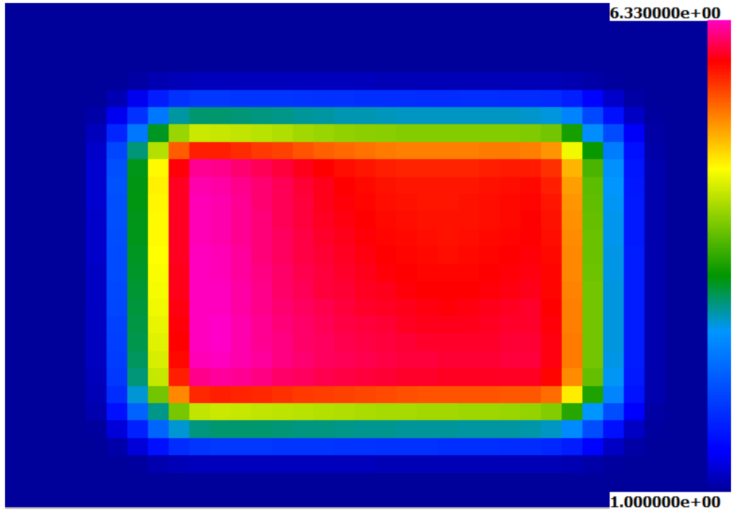
Dk= 5-6

Df= 0.0005-0.01

35 x 45 mm

2D surface imaging with SPDR 10GHz scanner

Dielectric constant

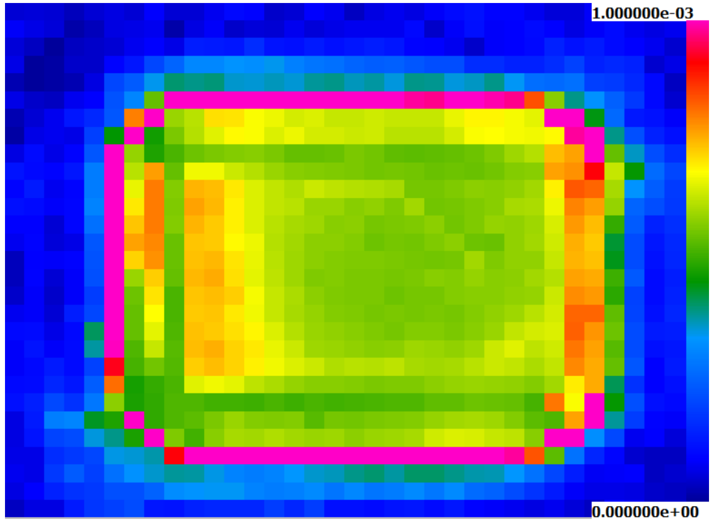


Scanning range:	70 x 60 mm
Scanning step:	2 mm
Number of meas. Points:	1116
Scanning time:	ca. 1.5 hour

Dielectric constant variation: ca. 5.7 – 6.3
Loss tangent variation: ca. 0.0005 – 0.0007

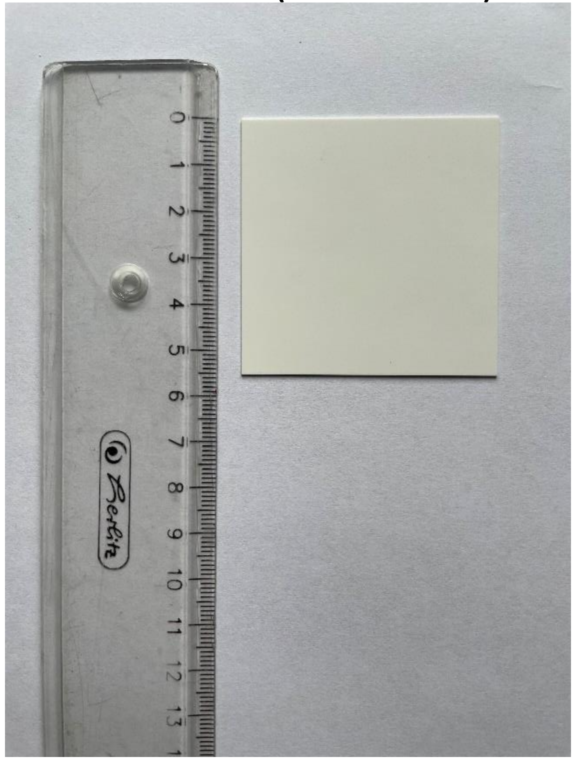
Uncertainty due to thickness variation – ±5%

Loss tangent

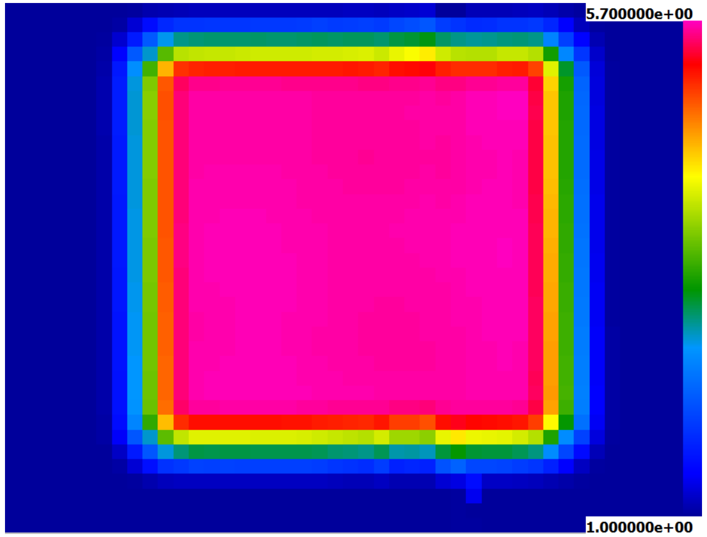


LTCC & ULTCC materials testing (2)

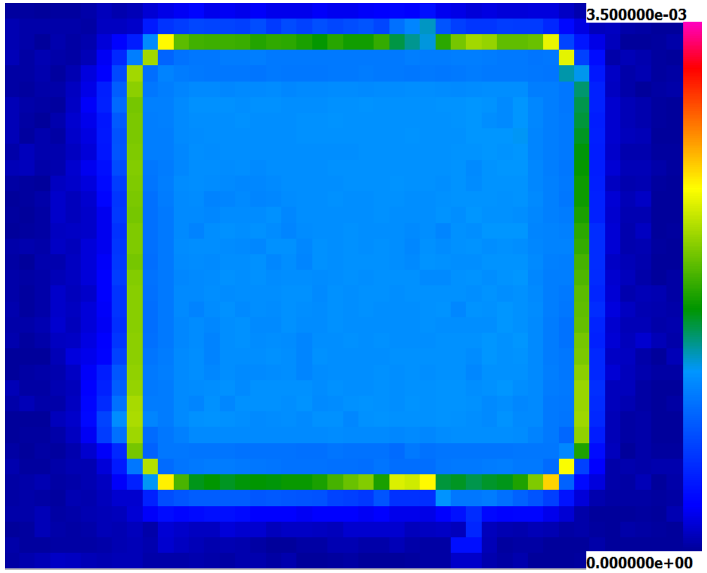
Commercial Ferro A6M substrate (50x50mm)



Dielectric constant



Loss tangent



2D surface imaging with SPDR 10GHz scanner

Scanning range:	85 x 70 mm
Scanning step:	2 mm
Number of meas. Points:	1548
Scanning time:	ca. 2 hour

Dielectric constant variation: ca. 5.56 – 5.68
Loss tangent variation: ca. 0.00101 – 0.00118

Uncertainty due to thickness variation – ±1%

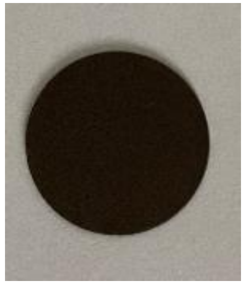
LTCC & ULTCC materials testing (3)

ULTCC material fabrication scheme

- Material fabrication procedure:
  - solid state synthesis of oxide components,
  - ball milling,
  - uniaxial pressing of pellets.
- Sintering at 610-650° C for 1 - 2h.

Test samples by Łukasiewicz IMiF

Li_2WO_4+4% $CuBi_2O_4$



ϕ=20 mm

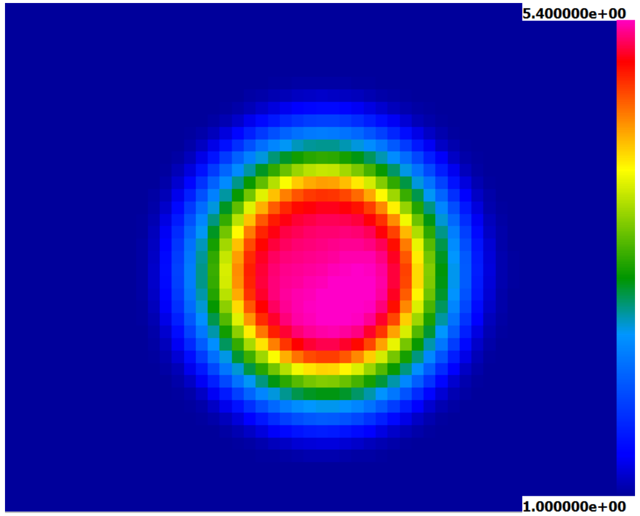
$LiBO_2$+4%$AlF_3CaB_4O_7$

Expected by chemical composition: Dk= 4-6.5

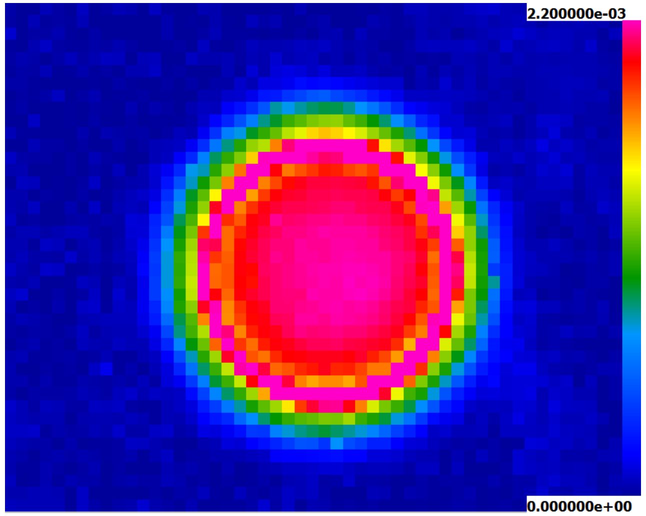
Df= 0.0005-0.005

LTCC & ULTCC materials testing (4)

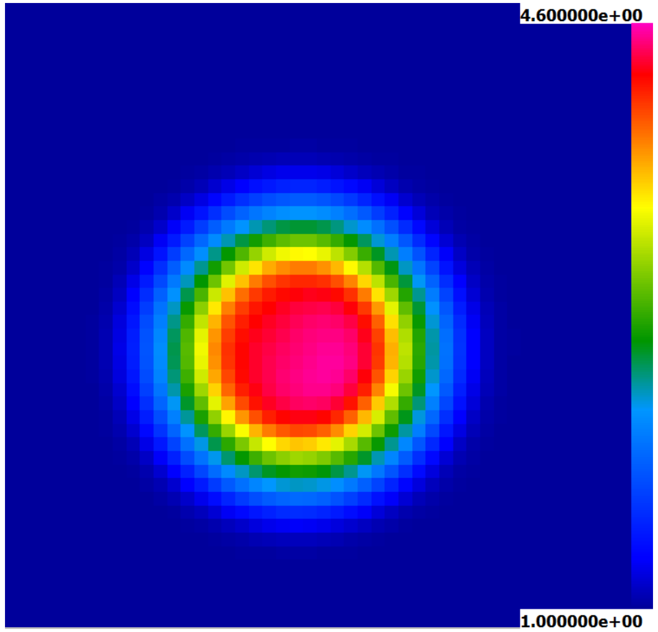
Dielectric constant



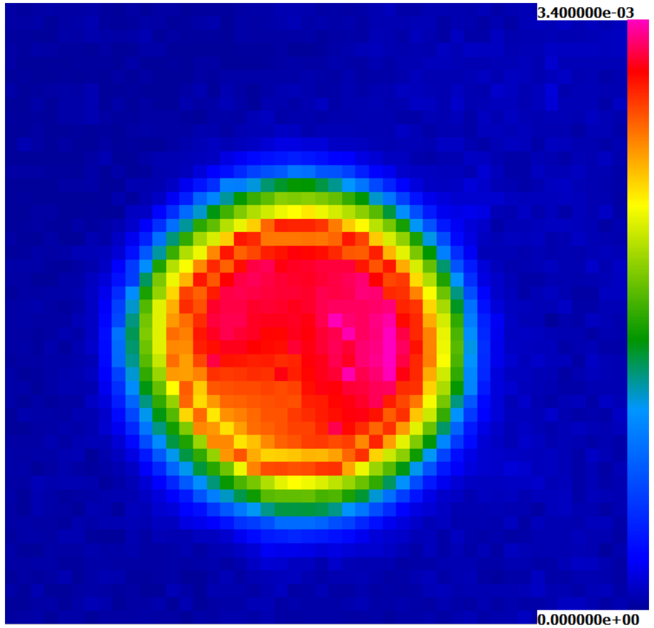
Loss tangent



Dielectric constant



Loss tangent



ULTCC Sample 1

Scanning range:	50 x 40 mm
Scanning step:	1 mm
Number of meas. Points:	2091
Scanning time:	ca. 2.5 hour

Dielectric constant variation: ca. 5 – 5.5
Loss tangent variation: ca. 0.00202 – 0.00219

Uncertainty due to thickness variation – ±2.5%

ULTCC Sample 2

Scanning range:	50 x 55 mm
Scanning step:	1 mm
Number of meas. Points:	2856
Scanning time:	ca. 3.5 hour

Dielectric constant variation: ca. 4.25 – 4.53
Loss tangent variation: ca. 0.003 – 0.00339

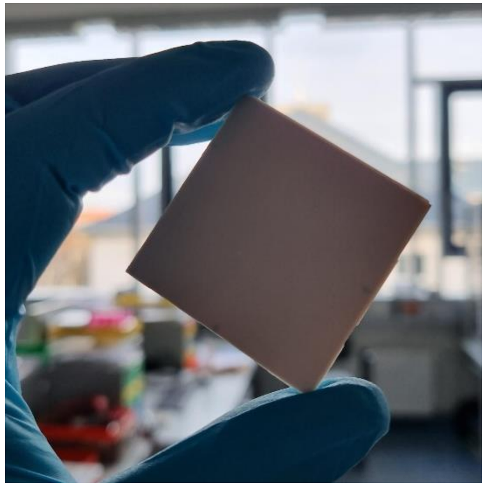
Uncertainty due to thickness variation – ±3%

LTCC & ULTCC materials testing (5)

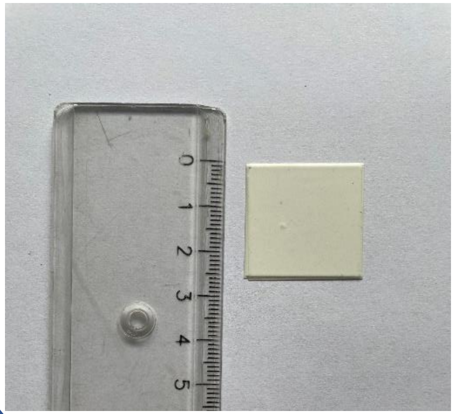
ULTCC tapes to substrates (ULTCC40)

- Fabrication procedures:
  - Solid state mixing of raw materials (Al_2O_3, SiO_2 Bi based glass powders)
  - Tape casting
  - Multilayer lamination
  - Binderburnout and sintering
- Sintering at 650°C/30min

Test samples by Fraunhofer IKTS



50 x 50 x 0.5 mm



Expected by chemical composition:

Dk= 10

Df= 0.002 at 10 GHz

TCDk ~ 600-750 ppm/K

LTCC & ULTCC materials testing (6)

Fraunhofer IKTS

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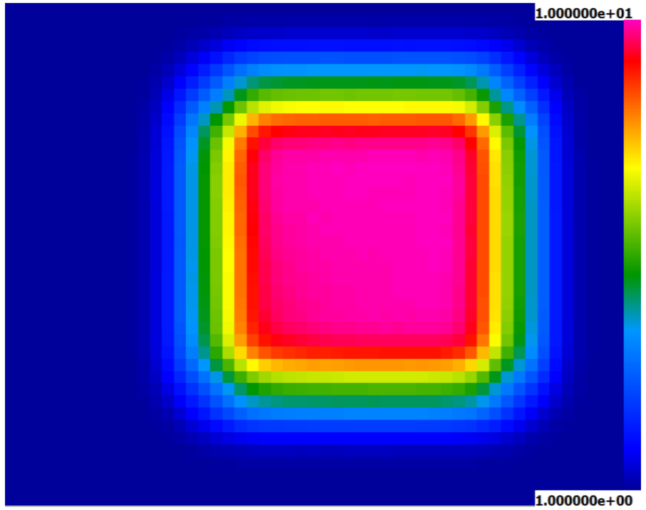
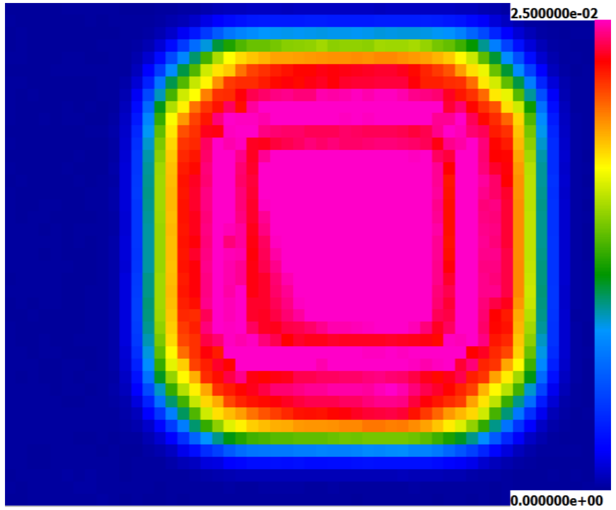
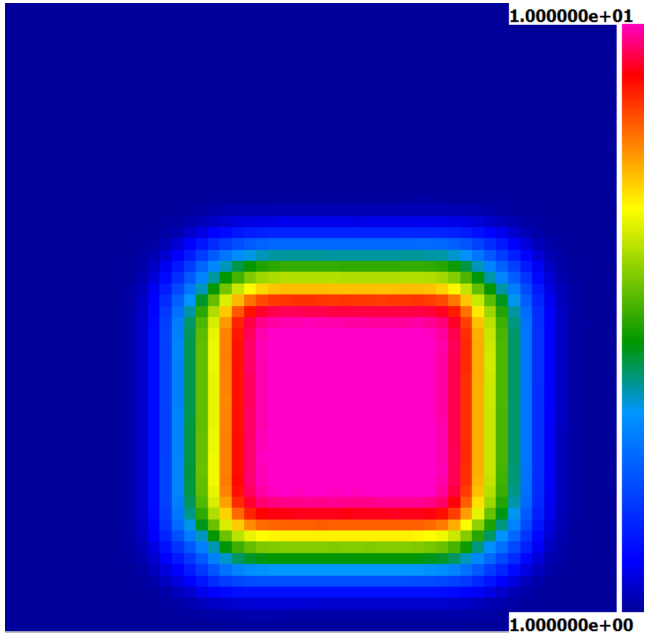
Dielectric constant



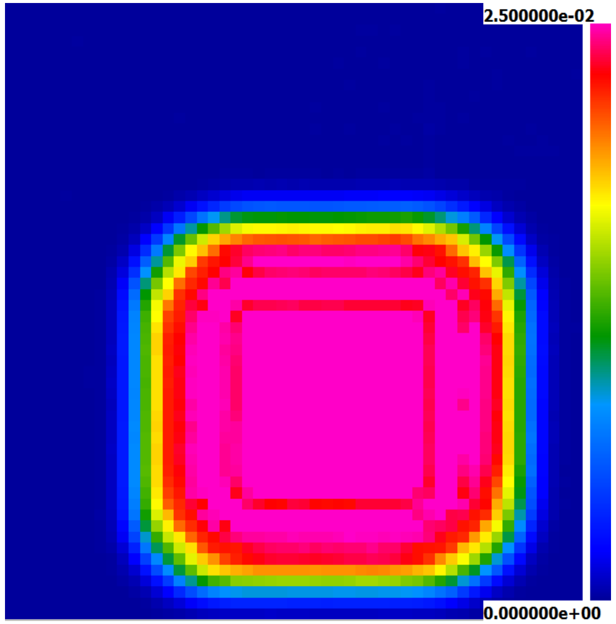
Loss tangent



Dielectric constant



Loss tangent



ULTCC Sample 1

Scanning range:	50 x 40 mm
Scanning step:	1 mm
Number of meas. Points:	2091
Scanning time:	ca. 2.5 hour

Dielectric constant variation: ca. 9.6 – 9.99
Loss tangent variation: ca. 0.022 – 0.0275

Uncertainty due to thickness variation – ±2%

ULTCC Sample 2

Scanning range:	50 x 55 mm
Scanning step:	1 mm
Number of meas. Points:	2856
Scanning time:	ca. 3.5 hour

Dielectric constant variation: ca. 10.02 – 10.13
Loss tangent variation: ca. 0.028 – 0.038

Uncertainty due to thickness variation – ±0.5%

Summary

- Resonant-based method for complex permittivity measurement of laminar dielectrics has been discussed
- 2D SPDR scanner for surface imaging of dielectric properties has been presented
- Test samples of LTCC and ULTCC materials have been fabricated and tested
- High uniformity of dielectric properties of manufactured materials has been reported
- High repeatability of manufacturing technological process has been reported
- Good candidates for dielectric substrates for high density 5G/6G systems

Acknowledgement

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M-ERA.NET

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

International Consortium:

Fraunhofer IKTS

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Thank you for attention!

Questions?

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