Characterisation of dielectric material parameters at PTB

Gia Ngoc Phung, David Ulm, Uwe Arz, Thomas Kleine-Ostmann

Physikalisch-Technische Bundesanstalt
National Metrology Institute
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PTB METROLOGY PARTNERSHIP EURAMET

Federal Ministry for Economic Affairs and Energy

OnMicro

Outline

- Motivation
  - Applications
  - Challenges
  - Measurement setups at PTB
- Euramet pilot study 1514
- Summary and conclusion
- Acknowledement

Motivation

- Precise knowledge of dielectric material parameters
  - Basis for the precise design of transistors, lines and complete RF circuits in modern high-frequency systems
  - Basis for traceability on-wafer scattering parameters back to industrial substrates

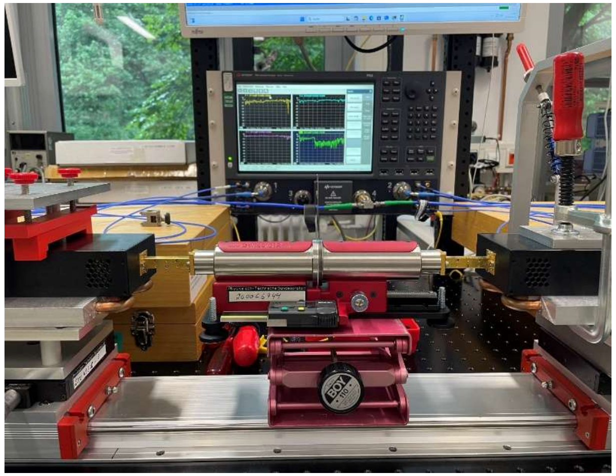
$$\varepsilon = \varepsilon_r' - j\varepsilon_r''$$ frequency-dependent complex permittivity

$$\tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'}$$ frequency-dependent dissipation factor

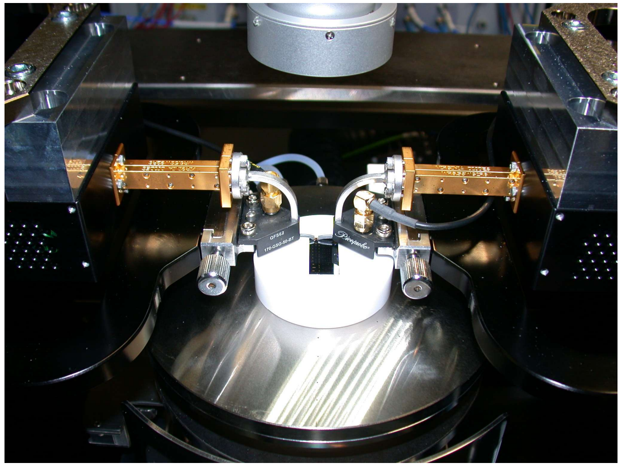
Challenges in material characterization

- Problem
  - Multiple measurement techniques exist (VNA, TDS, FDS, MCK, etc.)
  - Each method has different principles, setups, and limitations
  - Results can vary between methods and laboratories
- Consequence
  - Inconsistent material parameters (ε_r', $\tan\delta$)
  - Reduced confidence in measurement data
  - Difficulties in comparing results across studies
- Need
  - Systematic comparison of methods
  - Interlaboratory validation
  - Development of standards and best practices

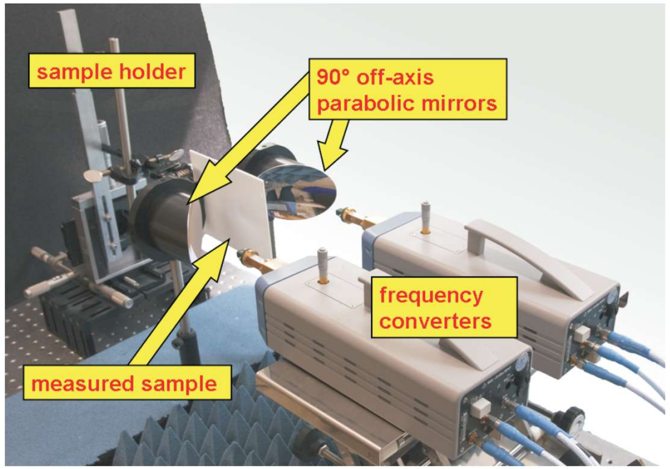
Measurement setups at PTB



Material Characterisation Kits (MCKs): available in waveguide bands ranging from 26 GHz to 170 GHz



On-wafer method: based on scattering parameter measurement and CPW model, valid up to 330 GHz



Quasi-optical free-space setup in the 50–500 GHz range

Requested CMCs for quasi-optical free-space measurement setups ranging from 50 to 220 GHz (world-leading).

Euramet pilot study 1514

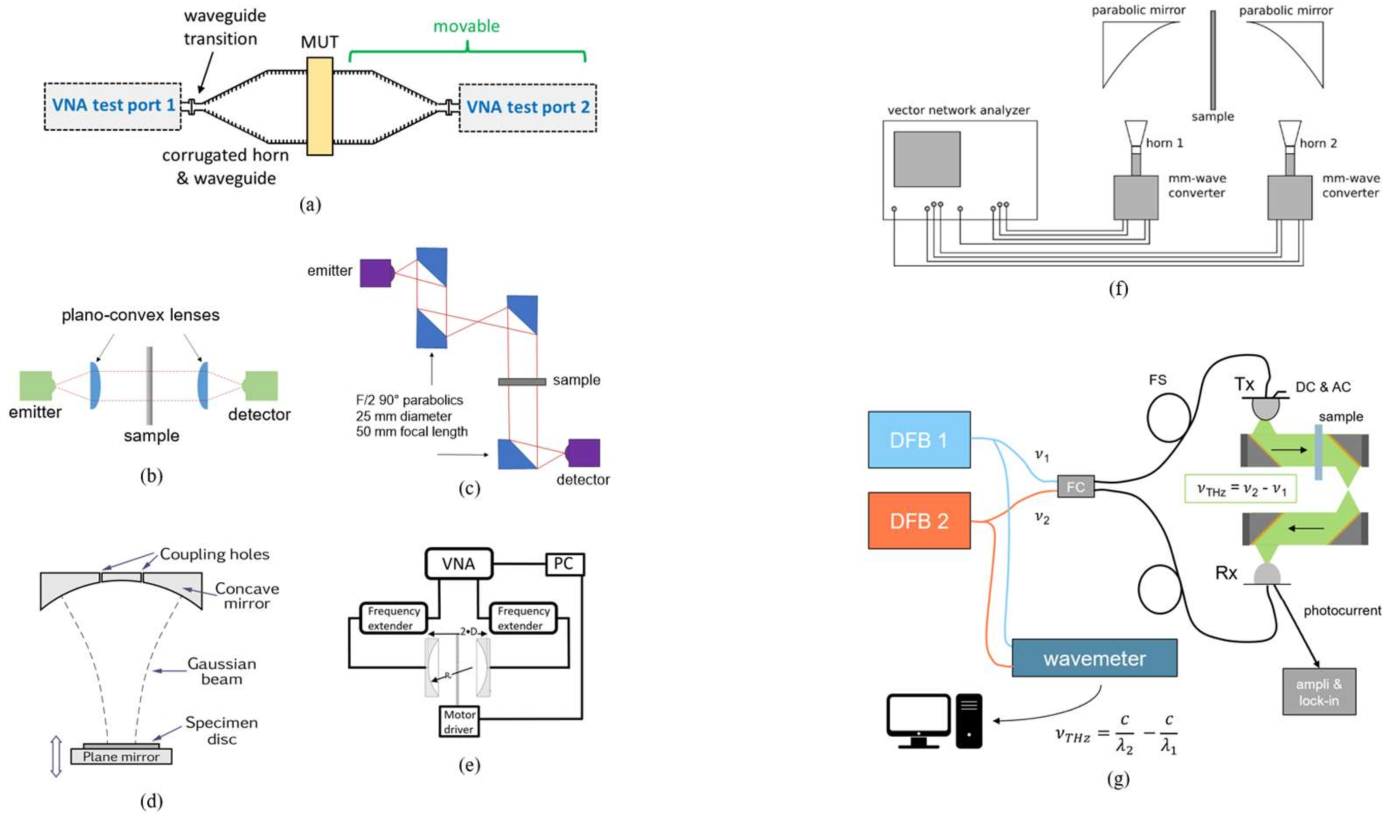
- Material parameter measurements in the THz spectral range with optical, resonant and VNA based setups

[Report describing the comparison of material parameter measurements at millimetre-wave and THz frequencies]

- Main Goal:
  - Comparison of different dielectric measurement techniques (VNA-based vs. optical methods)
  - Specific Objectives
    - Evaluate accuracy and consistency across methods
    - Assess agreement between laboratories
    - Identify systematic deviations and uncertainties
- Outcome
  - Establish confidence in measured material properties
  - Support standardization and best practices

X. Shang, M. Naftaly, J. Skinner, L. Ausden, A. Gregory, N. Ridler, U. Arz, G. Phung, D. Ulm, T. Kleine-Ostmann, A. Djamel, M. Wojciechowski, A. Kpour, G. Gäumann, and M. Hudlicka, "Interlaboratory Comparison of Dielectric Measurements from Microwave to Terahertz Frequencies Using VNA-based and Optical-based Methods", IEEE Transactions on Microwave Theory and Techniques , vol. 72, no. 11, pp. 6473-6484, Nov. 2024.

Different measurement setups



(a) MCK at NPL; (b) TDS at LNE; (c) TDS at NPL; (d) OR at NPL; (e) OR at GUM; (f) FS at PTB; (g) FDS at METAS.

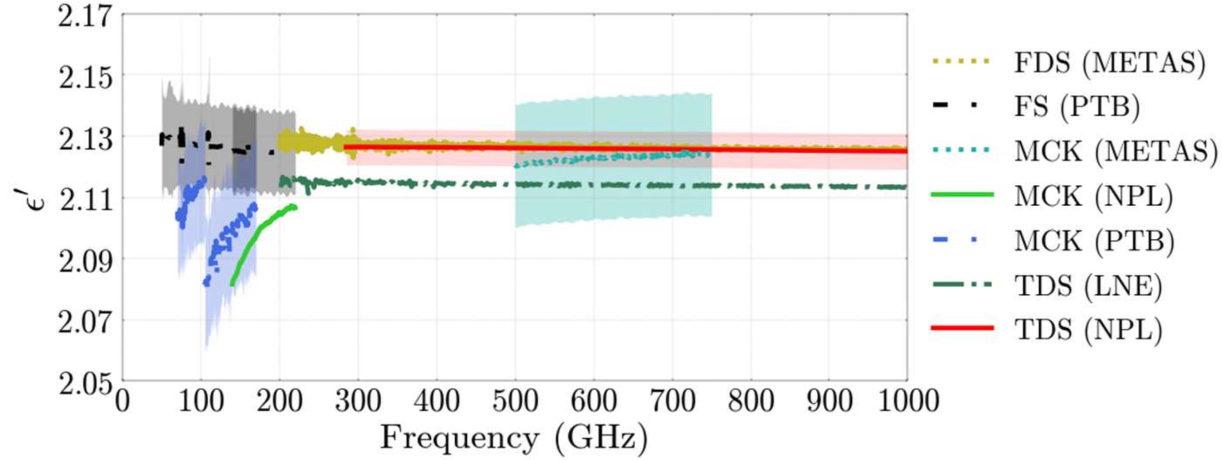
Participants

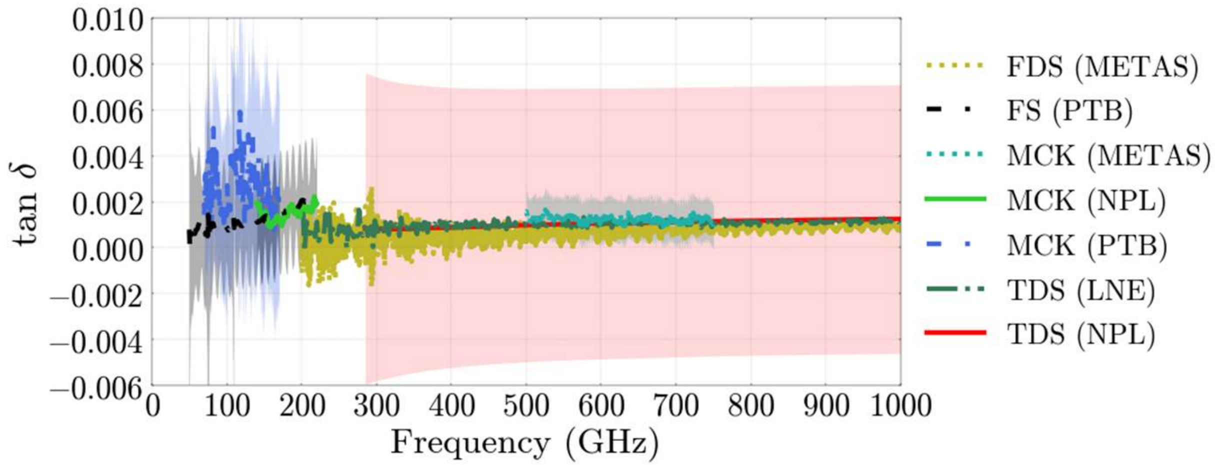
Laboratory	Measurement setup	Operating frequencies (GHz)
Central Office of Measures (GUM), Poland	Open resonator (OR)	2 – 110
Laboratoire national de métrologie et d'essais (LNE), France	TDS	100 – 1000
Federal Institute of Metrology (METAS), Switzerland	MCK	500 – 750
	FDS	50 – 1000
Physikalisch-Technische Bundesanstalt (PTB), Germany	Free-space system (FS)	50 – 220
	MCK	67 – 170
National Physical Laboratory (NPL), UK	Open resonator	36, 144
	MCK	140 – 220
	TDS	100 – 1000

Material samples

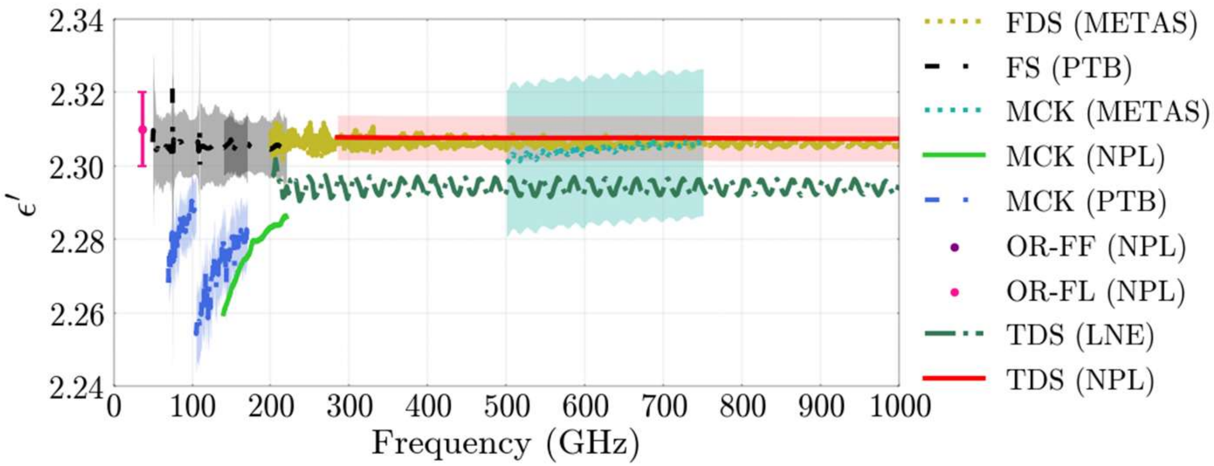
Sample number	Name	Nominal diameter (mm)	Thickness (µm) ± 2s
1	Polymethylpentene (TPX)	100	6146.5 ± 16.4
2	UHMW Polyethylene	80	4967.0 ± 6.0
3	Fused silica	80	2068.0 ± 4.0
4	Borofloat	100	500.6 ± 0.1
5	Yttrium aluminium garnet (YAG)	60	2504.0 ± 8.0
6	High-resistivity silicon	100	416.2 ± 2.2
7	Doped silicon	100	595.9 ± 3.4

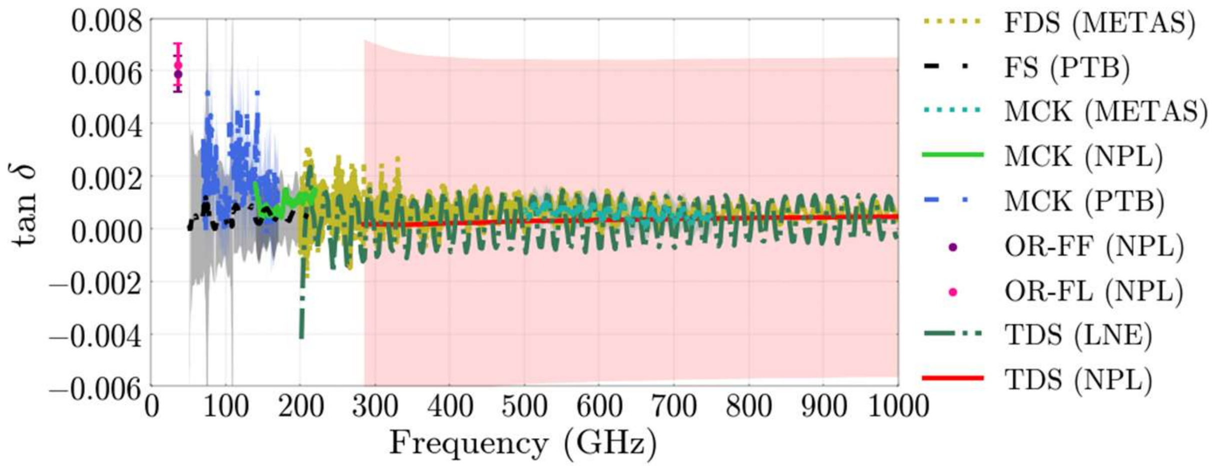
Sample 1: Polymethylpentene (TPX)



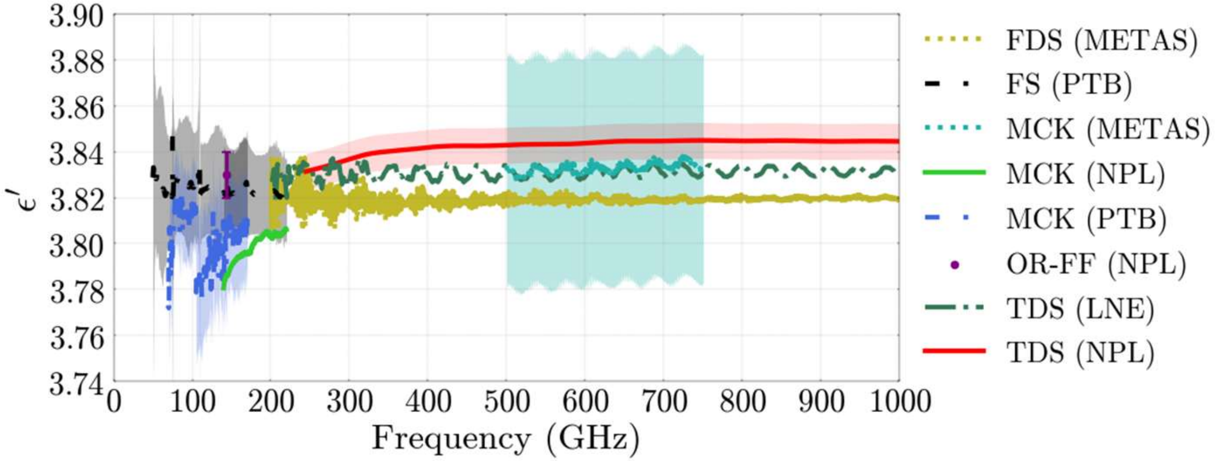


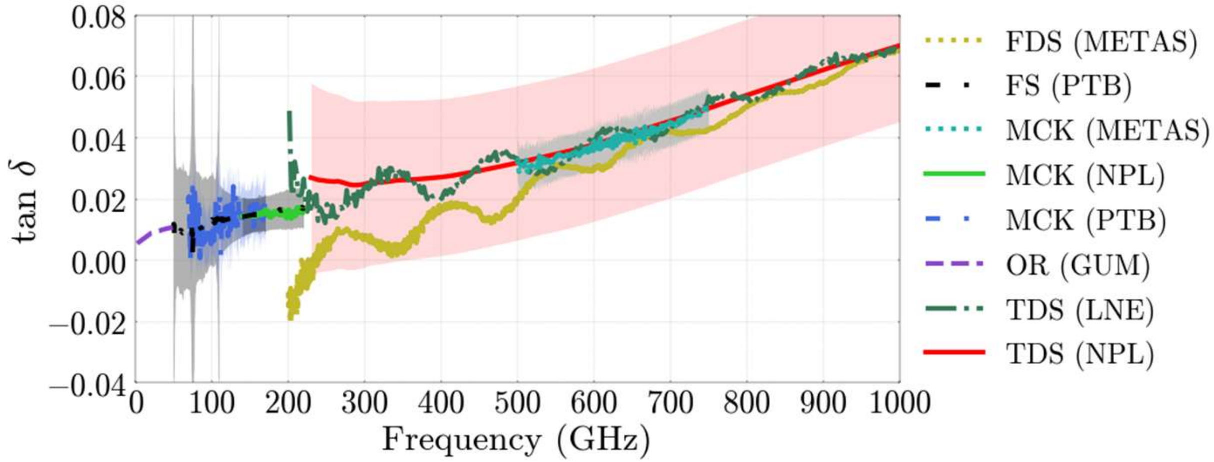
Sample 2: UHMW Polyethylene



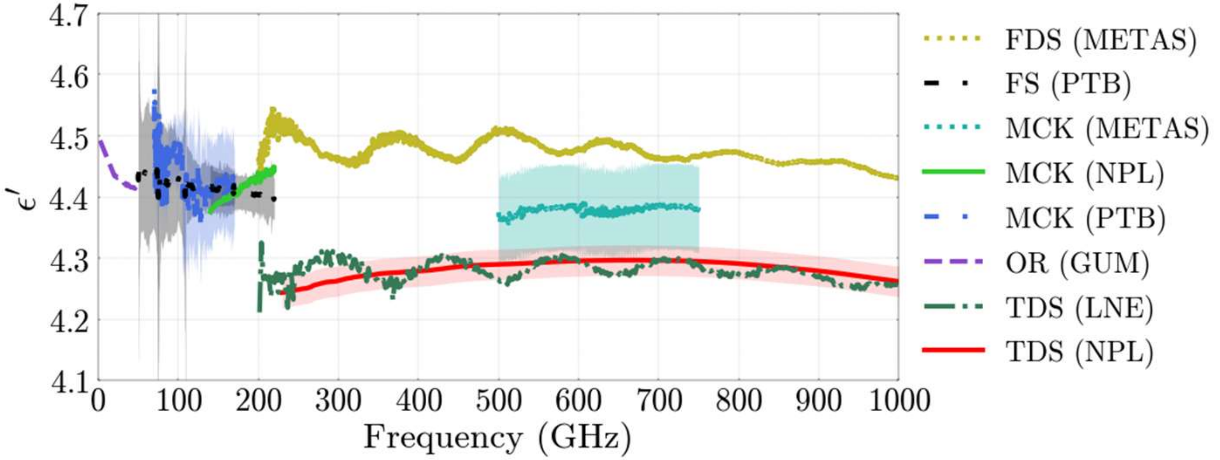


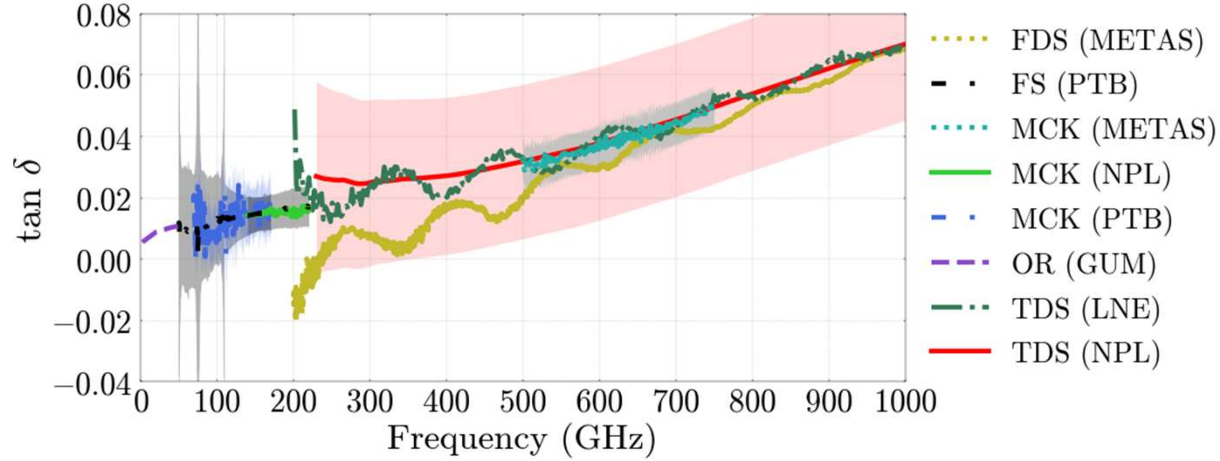
Sample 3: Fused silica



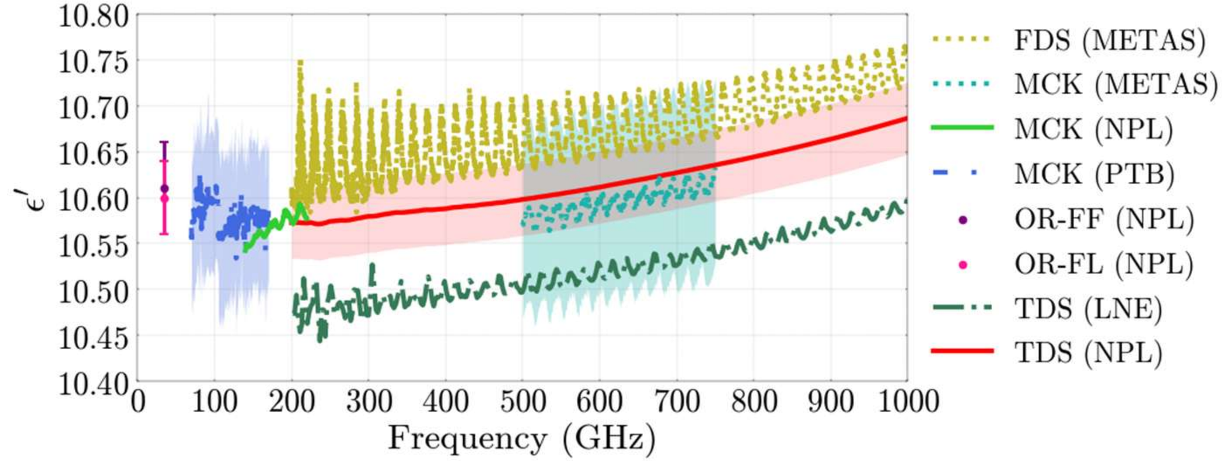


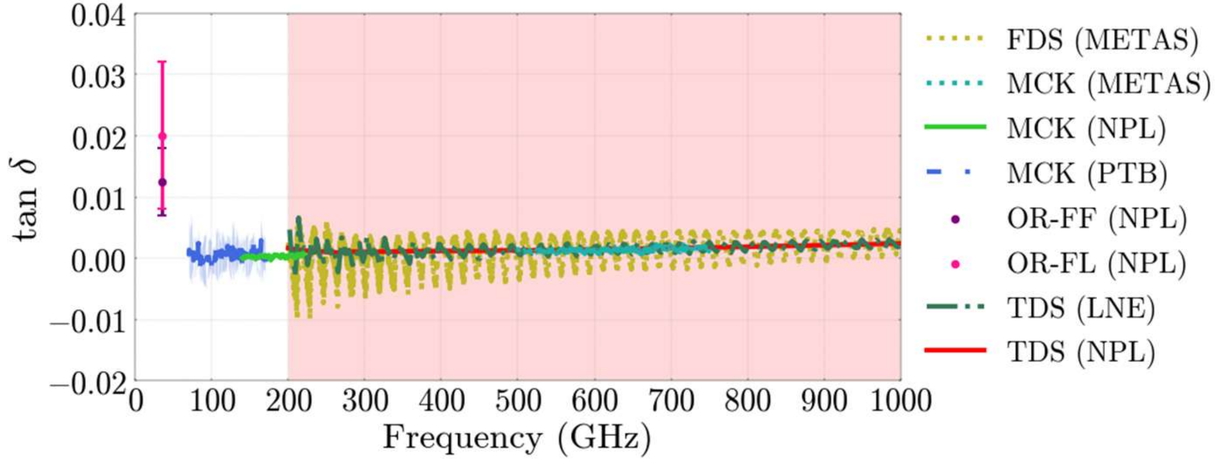
Sample 4: Borofloat



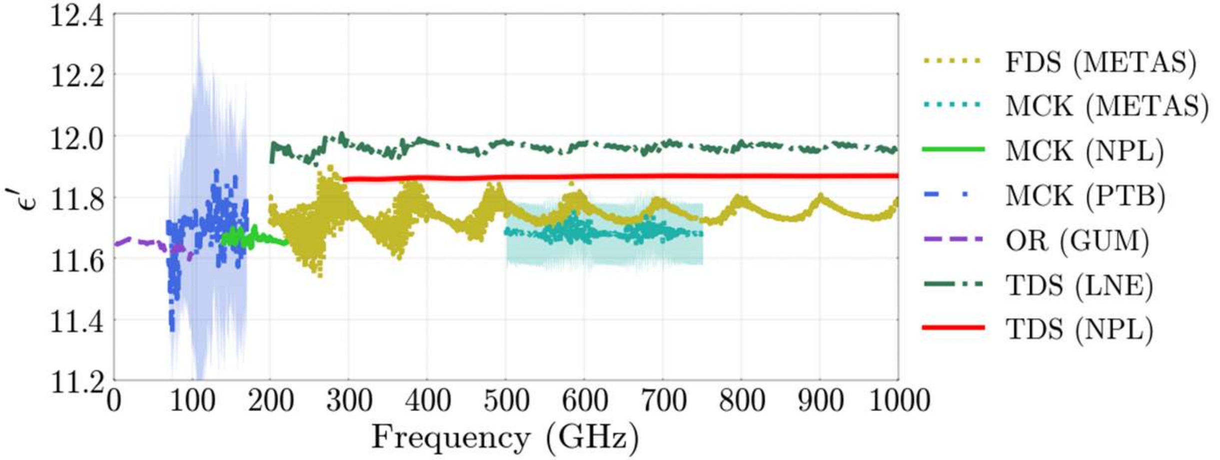


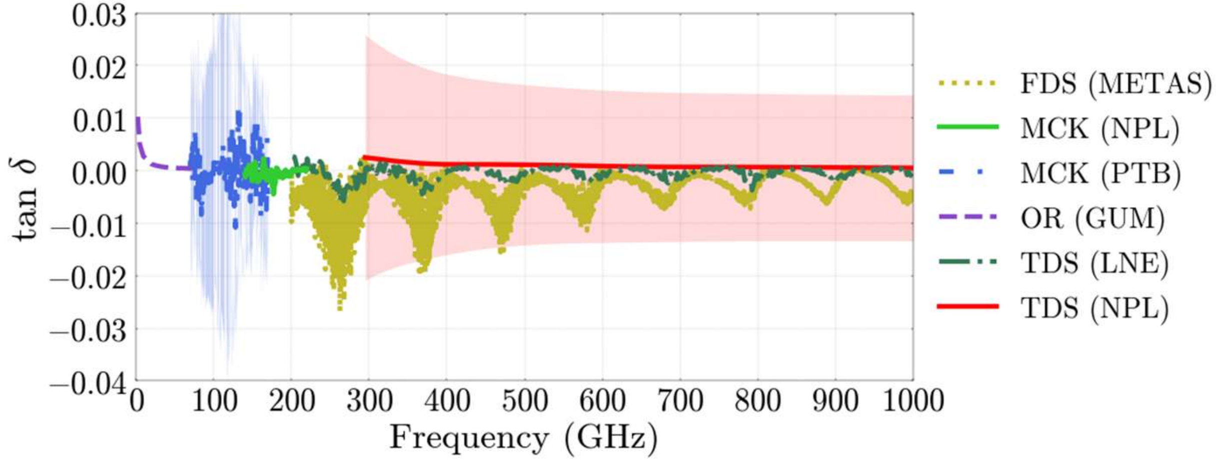
Sample 5: Yttrium aluminium garnet (YAG)



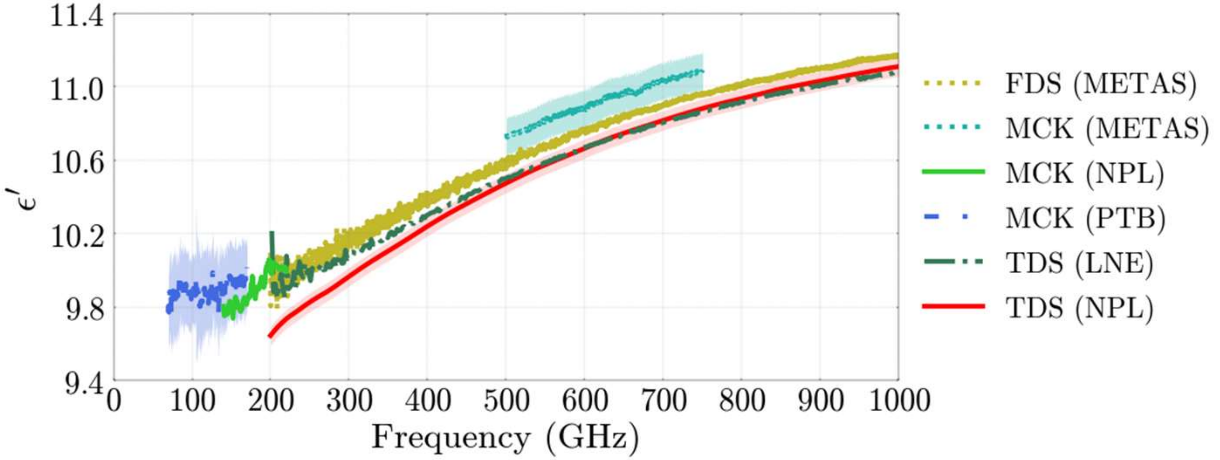


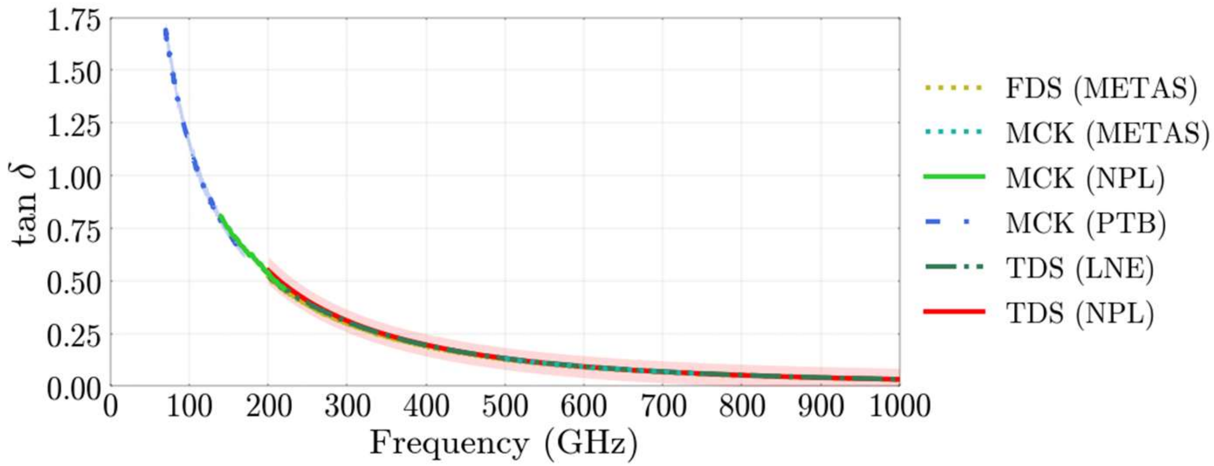
Sample 6: High-resistivity silicon





Sample 7: Doped silicon





Summarized table: Samples 1,2

Sample	Technique											
	MCK				TDS/FDS				FS			
	Lab	**Freq (GHz)**	**Mean**	**SD (×10^{-3})**	**Lab**	**Freq (GHz)**	**Mean**	**SD (×10^{-3})**	**Lab**	**Freq (GHz)**	**Mean**	**SD (×10^{-3})**
TPX	PTB	70-105	2.11	4.11	LNE (TDS)	202-1000	2.11	0.65	PTB	50-75	2.13	0.86
		105-170	2.10	7.29	NPL (TDS)	285-1000	2.13	0.44		75-110	2.13	1.13
	NPL	140-220	2.10	7.16	METAS (FDS)	200-1000	2.13	0.90		110-170	2.13	0.16
	METAS	500-750	2.12	1.06	–					140-220	2.12	0.22
	Overall	70-750	2.11	11.07	Overall	200-1000	2.12	1.19	Overall	50-220	2.13	1.44

Sample	Technique											
	MCK				TDS/FDS				FS			
	Lab	**Freq (GHz)**	**Mean**	**SD (×10^{-3})**	**Lab**	**Freq (GHz)**	**Mean**	**SD (×10^{-3})**	**Lab**	**Freq (GHz)**	**Mean**	**SD (×10^{-3})**
UHMW Polyethylene	PTB	70-105	2.28	5.07	LNE (TDS)	202-1000	2.29	1.75	PTB	50-75	2.30	1.57
		105-170	2.27	7.68	NPL (TDS)	285-1000	2.31	0.10		75-110	2.31	1.23
	NPL	140-220	2.28	7.28	METAS (FDS)	200-1000	2.31	0.89		110-170	2.30	0.41
	METAS	500-750	2.30	1.32	–					140-220	2.31	0.58
	Overall	70-750	2.28	11.81	Overall	200-1000	2.30	1.96	Overall	50-220	2.31	2.12

Summarized table: Samples 3,4

Sample	Technique											
	MCK				TDS/FDS				FS			
	Lab	Freq (GHz)	Mean	SD ($\times 10^{-3}$)	Lab	Freq (GHz)	Mean	SD ($\times 10^{-3}$)	Lab	Freq (GHz)	Mean	SD ($\times 10^{-3}$)
Fused silica	PTB	70-105	3.81	8.95	LNE (TDS)	202-1000	3.83	2.51	PTB	50-75	3.83	4.18
	PTB	105-170	3.80	8.77	NPL (TDS)	245-1000	3.84	3.09	PTB	75-110	3.83	2.50
	NPL	140-220	3.80	6.29	METAS (FDS)	200-1000	3.82	2.28	PTB	110-170	3.82	1.09
	METAS	500-750	3.83	2.10	–				PTB	140-220	3.82	1.25
	Overall	70-750	3.81	14.18	Overall	200-1000	3.83	4.59	Overall	50-220	3.82	5.15

Sample	Technique											
	MCK				TDS/FDS				FS			
	Lab	Freq (GHz)	Mean	SD ($\times 10^{-3}$)	Lab	Freq (GHz)	Mean	SD ($\times 10^{-3}$)	Lab	Freq (GHz)	Mean	SD ($\times 10^{-3}$)
Borofloat	PTB	70-105	4.47	28.66	LNE (TDS)	202-1000	4.28	16.49	PTB	50-75	4.44	3.98
	PTB	105-170	4.41	15.61	NPL (TDS)	230-1000	4.28	13.56	PTB	75-110	4.42	6.68
	NPL	140-220	4.41	19.48	METAS (FDS)	200-1000	4.47	19.33	PTB	110-170	4.41	2.58
	METAS	500-750	4.38	6.04	–				PTB	140-220	4.41	3.97
	Overall	70-750	4.42	38.49	Overall	200-1000	4.35	28.80	Overall	50-220	4.42	9.10

Summarized table: Samples 5,6

Sample	Technique							
	MCK			TDS/FDS				
	Lab	Freq (GHz)	Mean	SD ($\times 10^{-3}$)	Lab	Freq (GHz)	Mean	SD ($\times 10^{-3}$)
YAG	PTB	70-105	10.59	13.58	LNE (TDS)	202-1000	10.52	33.52
		105-170	10.57	11.83	NPL (TDS)	200-1000	10.62	33.50
	NPL	140-220	10.57	12.37	METAS (FDS)	200-1000	10.67	39.82
	METAS	500-750	10.60	13.93	–			
	Overall	70-750	10.58	25.91	Overall	200-1000	10.60	61.90
High-resistivity silicon	PTB	70-105	11.65	82.16	LNE (TDS)	202-1000	11.96	14.44
		105-170	11.70	61.43	NPL (TDS)	295-1000	11.87	3.59
	NPL	140-220	11.66	12.85	METAS (FDS)	200-1000	11.74	36.66
	METAS	500-750	11.68	13.65	–			
	Overall	70-750	11.68	104.29	Overall	200-1000	11.86	39.56
	GUM	Open resonator results averaged over 2 GHz-101 GHz: 11.64 (SD=15.15×10^{-3})						

Summary and conclusion

- Overall findings
  - Relatively good agreement between different measurement methods
  - Results are generally consistent across laboratories

- Observed differences
  - Systematic deviations between techniques
  - Larger discrepancies at higher frequencies
  - Some methods show oscillations / noise effects

- Key influencing factors
  - Calibration procedures
  - Measurement setup & geometry
  - Sample properties (thickness, loss)

On-going work: Pilot study 1711

- Pilot Study 1711: Comparison of material characterisation for semiconductors using resonators, free-space, and on-wafer techniques

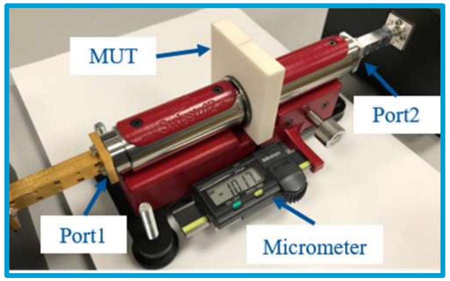
- This pilot study is part of the European Partnership on Metrology (EPM) project [23IND10 OnMicro]

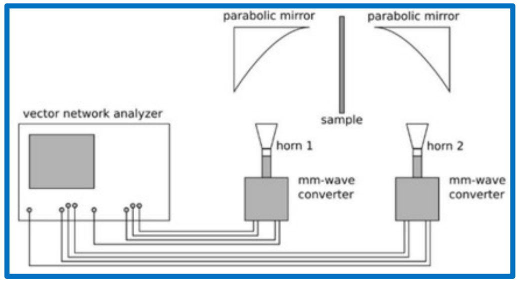
- Focus: accurate methods for measuring material properties (i.e., permittivity and loss tangent) for different types of materials including semiconductors, thin-films, and novel 2D materials.

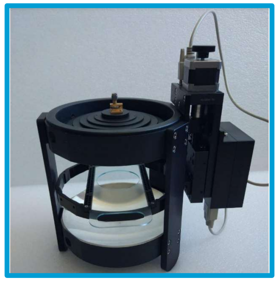
Country	Institute	Acronym	Shipping Address	Contact Person
UK	National Physical Laboratory	NPL	National Physical Laboratory Hampton Road Teddington Middlesex, UK TW11 0LW	Xiaobang Shang +44 (0) 20 8943 6643 xiaobang.shang@npl.co.uk
Poland	Central Office of Measures	GUM	GUM Laboratory of Electricity and Magnetism Elektoralna 2 00-139 Warszawa Poland	Marcin Wojciechowski +48 (0) 22 581 9303 marcin.wojciechowski@gum.gov.pl
France	Laboratoire national de métrologie et d'essais	LNE	LNE 29 avenue Roger Hennequin 78197 Trappes Cedex France	Djamel Allal +33 (0) 130 692 150 djamel.allal@lne.fr
Belgium	Keysight Technologies Belgium	Keysight BE	Wingepark 51 3110 Rotselaar Belgium	Robin Schmidt robin.schmidt@keysight.com
Germany	Physikalisch-Technische Bundesanstalt	PTB	Physikalisch-Technische Bundesanstalt (PTB) Bundesallee 100 38116 Braunschweig Germany	Gia Ngoc Phung +49 531 592 2226 gia.phung@ptb.de
USA	Cornell University	Cornell	424 Philips Hall School of Electrical and Computer Engineering Cornell University, Ithaca, NY 14853	Jim Hwang jch263@cornell.edu
France	Centre National de la Recherche Scientifique	CNRS	Cité Scientifique Avenue Henri Poincaré CS 60069 59 652 Villeneuve d'Ascq Cedex, France	Kamel Haddadi kamel.haddadi@univ-lille.fr

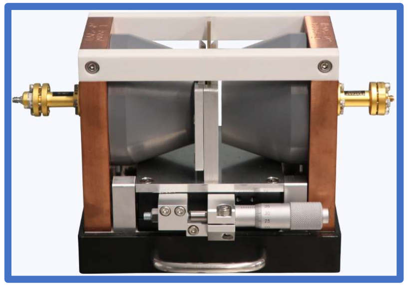
Overview of tasks

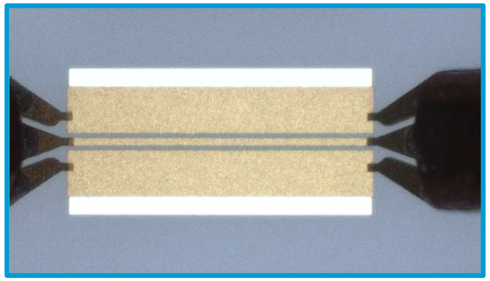
1) Characterisation of bare materials using free-space and resonator methods
2) Characterisation of substrate materials using on-wafer based methods with deposited metal structures
3) Comparison of material characterisation using different methods such as resonator, free-space and on-wafer based methods











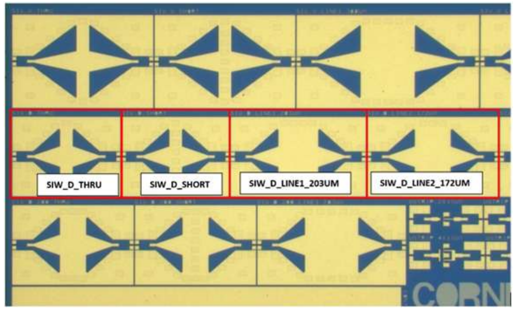
Laboratory capability

	MCK	Resonator	Free-space or TDS
NPL	WR15, WR10, WR5, WR1.5		TDS
Lille			TDS, FS
PTB	WR15, WR10, WR6.5		FS (WR15, WR10, WR6, WR5)
GUM		up to 110 GHz	
LNE			TDS
Keysight BE		WR6.5 or lower	
Cornell		WR6.5	

Characterisation of bare materials using free-space and resonator methods

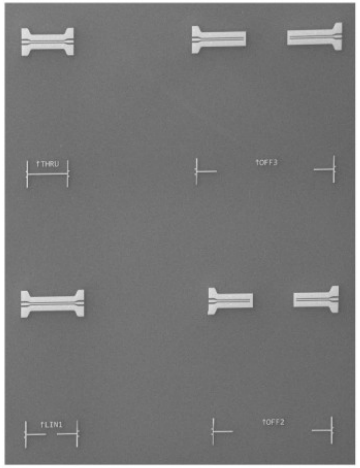
Sample	Material	Nominal ε	Shape/Size (mm)	Nominal Thickness (µm)
1a 1b	Polypropylene	2.1-2.3	80 x 80 80 x 80	8 8
2a 2b	Mylar	3.2	80 x 80 80 x 80	6 6
3a 3b	Kapton	3.4	80 x 80 80 x 80	7.5 7.5
4A1a 4A1b 4A2a 4A2b	Fused Silica	3.8	ø80 ø80 ø80 ø80	300 300 2000 2000
5a 5b	Borosilicate	5-6	ø100 ø100	145 145
6	Silicon Carbide	9.66	ø101.6	350
7	Alumina	9.8	ø75.4	350
8	Doped Silicon	10	ø101.6	380
9	High-Resistivity Silicon	11.7	ø75.4	275
10	Gallium Arsenide	12.9	ø76.2	625

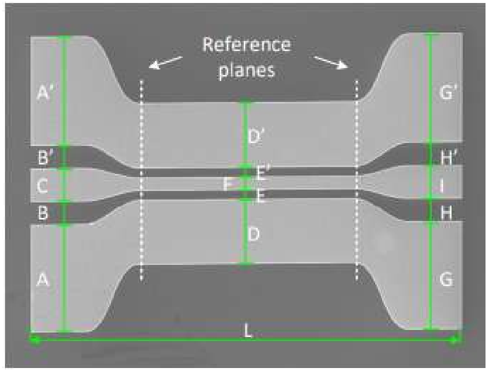
Characterisation of substrate materials using on-wafer based methods with deposited metal structures



Cornell chips - GaAs substrate

mTRL cal kits: Microstrip, **GCPW**, **SIWs** W/D bands





TEMMT chips - High resistivity Si substrate

CPW mTRL cal kits

Outlook

- Standardization
  - Develop harmonized measurement procedures
  - Improve comparability between laboratories
  - Establish reference standards

- More Materials
  - Extend studies to new advanced materials (e.g., composites, metamaterials) frequency-dependent / lossy materials
  - Build comprehensive material databases

Acknowledgements

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  - Funder name: European Partnership on Metrology
  - Funder ID: 10.13039/100019599
  - Grant number: Partnership 23IND10 OnMicro

Accuracy

Objectivity

Passion

Physikalisch-Technische Bundesanstalt
The National Metrology Institute

Gia Ngoc Phung

PTB